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Chapter 1. Preamble

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Chapter 2. Introduction

This document, referred to as the “Vulkan Specification” or just the “Specification” hereafter, describes the Vulkan Application Programming Interface (API). Vulkan is a C99 API designed for explicit control of low-level graphics and compute functionality.

The canonical version of the Specification is available in the official Vulkan Registry (https://registry.khronos.org/vulkan/). The source files used to generate the Vulkan specification are stored in the Vulkan Documentation Repository (https://github.com/KhronosGroup/Vulkan-Docs).

The source repository additionally has a public issue tracker and allows the submission of pull requests that improve the specification.

2.1. Document Conventions

The Vulkan specification is intended for use by both implementors of the API and application developers seeking to make use of the API, forming a contract between these parties. Specification text may address either party; typically the intended audience can be inferred from context, though some sections are defined to address only one of these parties. (For example, Valid Usage sections only address application developers). Any requirements, prohibitions, recommendations or options defined by normative terminology are imposed only on the audience of that text.

Note
Structure and enumerated types defined in extensions that were promoted to core in a later version of Vulkan are now defined in terms of the equivalent Vulkan core interfaces. This affects the Vulkan Specification, the Vulkan header files, and the corresponding XML Registry.

2.1.1. Informative Language

Some language in the specification is purely informative, intended to give background or suggestions to implementors or developers.

If an entire chapter or section contains only informative language, its title will be suffixed with “(Informative)”.

All NOTEs are implicitly informative.

2.1.2. Normative Terminology

Within this specification, the key words must, required, should, recommended, may, and optional are to be interpreted as described in RFC 2119 - Key words for use in RFCs to Indicate Requirement Levels (https://www.ietf.org/rfc/rfc2119.txt). The additional key word optionally is an alternate form of optional, for use where grammatically appropriate.

These key words are highlighted in the specification for clarity. In text addressing application developers, their use expresses requirements that apply to application behavior. In text addressing implementors, their use expresses requirements that apply to implementations.
In text addressing application developers, the additional key words *can* and *cannot* are to be interpreted as describing the capabilities of an application, as follows:

**can**

This word means that the application is able to perform the action described.

**cannot**

This word means that the API and/or the execution environment provide no mechanism through which the application can express or accomplish the action described.

These key words are never used in text addressing implementors.

**Note**

There is an important distinction between *cannot* and *must not*, as used in this Specification. *Cannot* means something the application literally is unable to express or accomplish through the API, while *must not* means something that the application is capable of expressing through the API, but that the consequences of doing so are undefined and potentially unrecoverable for the implementation (see Valid Usage).

Unless otherwise noted in the section heading, all sections and appendices in this document are normative.

### 2.1.3. Technical Terminology

The Vulkan Specification makes use of common engineering and graphics terms such as **Pipeline**, **Shader**, and **Host** to identify and describe Vulkan API constructs and their attributes, states, and behaviors. The **Glossary** defines the basic meanings of these terms in the context of the Specification. The Specification text provides fuller definitions of the terms and may elaborate, extend, or clarify the **Glossary** definitions. When a term defined in the **Glossary** is used in normative language within the Specification, the definitions within the Specification govern and supersede any meanings the terms may have in other technical contexts (i.e. outside the Specification).

### 2.1.4. Normative References

References to external documents are considered normative references if the Specification uses any of the normative terms defined in **Normative Terminology** to refer to them or their requirements, either as a whole or in part.

The following documents are referenced by normative sections of the specification:


Chapter 3. Fundamentals

This chapter introduces fundamental concepts including the Vulkan architecture and execution model, API syntax, queues, pipeline configurations, numeric representation, state and state queries, and the different types of objects and shaders. It provides a framework for interpreting more specific descriptions of commands and behavior in the remainder of the Specification.

3.1. Host and Device Environment

The Vulkan Specification assumes and requires: the following properties of the host environment with respect to Vulkan implementations:

- The host must have runtime support for 8, 16, 32 and 64-bit signed and unsigned twos-complement integers, all addressable at the granularity of their size in bytes.
- The host must have runtime support for 32- and 64-bit floating-point types satisfying the range and precision constraints in the Floating Point Computation section.
- The representation and endianness of these types on the host must match the representation and endianness of the same types on every physical device supported.

Note
Since a variety of data types and structures in Vulkan may be accessible by both host and physical device operations, the implementation should be able to access such data efficiently in both paths in order to facilitate writing portable and performant applications.

3.2. Execution Model

This section outlines the execution model of a Vulkan system.

Vulkan exposes one or more devices, each of which exposes one or more queues which may process work asynchronously to one another. The set of queues supported by a device is partitioned into families. Each family supports one or more types of functionality and may contain multiple queues with similar characteristics. Queues within a single family are considered compatible with one another, and work produced for a family of queues can be executed on any queue within that family. This specification defines the following types of functionality that queues may support: graphics, compute, protected memory management, sparse memory management, and transfer.

Note
A single device may report multiple similar queue families rather than, or as well as, reporting multiple members of one or more of those families. This indicates that while members of those families have similar capabilities, they are not directly compatible with one another.

Device memory is explicitly managed by the application. Each device may advertise one or more heaps, representing different areas of memory. Memory heaps are either device-local or host-local,
but are always visible to the device. Further detail about memory heaps is exposed via memory types available on that heap. Examples of memory areas that may be available on an implementation include:

- **device-local** is memory that is physically connected to the device.
- **device-local, host visible** is device-local memory that is visible to the host.
- **host-local, host visible** is memory that is local to the host and visible to the device and host.

On other architectures, there may only be a single heap that can be used for any purpose.

### 3.2.1. Queue Operation

Vulkan queues provide an interface to the execution engines of a device. Commands for these execution engines are recorded into command buffers ahead of execution time, and then submitted to a queue for execution. Once submitted to a queue, command buffers will begin and complete execution without further application intervention, though the order of this execution is dependent on a number of implicit and explicit ordering constraints.

Work is submitted to queues using **queue submission commands** that typically take the form `vkQueue*` (e.g. `vkQueueSubmit`, `vkQueueBindSparse`), and can take a list of semaphores upon which to wait before work begins and a list of semaphores to signal once work has completed. The work itself, as well as signaling and waiting on the semaphores are all **queue operations**. Queue submission commands return control to the application once queue operations have been submitted - they do not wait for completion.

There are no implicit ordering constraints between queue operations on different queues, or between queues and the host, so these may operate in any order with respect to each other. Explicit ordering constraints between different queues or with the host can be expressed with **semaphores** and **fences**.

Command buffer submissions to a single queue respect **submission order** and other implicit ordering guarantees, but otherwise may overlap or execute out of order. Other types of batches and queue submissions against a single queue (e.g. sparse memory binding) have no implicit ordering constraints with any other queue submission or batch. Additional explicit ordering constraints between queue submissions and individual batches can be expressed with **semaphores** and **fences**.

Before a fence or semaphore is signaled, it is guaranteed that any previously submitted queue operations have completed execution, and that memory writes from those queue operations are available to future queue operations. Waiting on a signaled semaphore or fence guarantees that previous writes that are available are also visible to subsequent commands.

Command buffer boundaries, both between primary command buffers of the same or different batches or submissions as well as between primary and secondary command buffers, do not introduce any additional ordering constraints. In other words, submitting the set of command buffers (which can include executing secondary command buffers) between any semaphore or fence operations execute the recorded commands as if they had all been recorded into a single primary command buffer, except that the current state is reset on each boundary. Explicit ordering constraints can be expressed with **explicit synchronization primitives**.
There are a few implicit ordering guarantees between commands within a command buffer, but only covering a subset of execution. Additional explicit ordering constraints can be expressed with the various explicit synchronization primitives.

Note
Implementations have significant freedom to overlap execution of work submitted to a queue, and this is common due to deep pipelining and parallelism in Vulkan devices.

Commands recorded in command buffers can perform actions, set state that persists across commands, synchronize other commands, or indirectly launch other commands, with some commands fulfilling several of these roles. The “Command Properties” section for each such command lists which of these roles the command takes. State setting commands update the current state of the command buffer. Some commands that perform actions (e.g. draw/dispatch) do so based on the current state set cumulatively since the start of the command buffer. The work involved in performing action commands is often allowed to overlap or to be reordered, but doing so must not alter the state to be used by each action command. In general, action commands are those commands that alter framebuffer attachments, read/write buffer or image memory, or write to query pools.

Synchronization commands introduce explicit execution and memory dependencies between two sets of action commands, where the second set of commands depends on the first set of commands. These dependencies enforce both that the execution of certain pipeline stages in the later set occurs after the execution of certain stages in the source set, and that the effects of memory accesses performed by certain pipeline stages occur in order and are visible to each other. When not enforced by an explicit dependency or implicit ordering guarantees, action commands may overlap execution or execute out of order, and may not see the side effects of each other’s memory accesses.

3.3. Object Model

The devices, queues, and other entities in Vulkan are represented by Vulkan objects. At the API level, all objects are referred to by handles. There are two classes of handles, dispatchable and non-dispatchable. Dispatchable handle types are a pointer to an opaque type. This pointer may be used by layers as part of intercepting API commands, and thus each API command takes a dispatchable type as its first parameter. Each object of a dispatchable type must have a unique handle value during its lifetime.

Non-dispatchable handle types are a 64-bit integer type whose meaning is implementation-dependent. If the privateData feature is enabled for a VkDevice, each object of a non-dispatchable type created on that device must have a handle value that is unique among objects created on that device, for the duration of the object’s lifetime. Otherwise, non-dispatchable handles may encode object information directly in the handle rather than acting as a reference to an underlying object, and thus may not have unique handle values. If handle values are not unique, then destroying one such handle must not cause identical handles of other types to become invalid, and must not cause identical handles of the same type to become invalid if that handle value has been created more times than it has been destroyed.
All objects created or allocated from a VkDevice (i.e. with a VkDevice as the first parameter) are private to that device, and must not be used on other devices.

### 3.3.1. Object Lifetime

Objects are created or allocated by vkCreate* and vkAllocate* commands, respectively. Once an object is created or allocated, its “structure” is considered to be immutable, though the contents of certain object types is still free to change. Objects are destroyed or freed by vkDestroy* and vkFree* commands, respectively.

Objects that are allocated (rather than created) take resources from an existing pool object or memory heap, and when freed return resources to that pool or heap. While object creation and destruction are generally expected to be low-frequency occurrences during runtime, allocating and freeing objects can occur at high frequency. Pool objects help accommodate improved performance of the allocations and frees.

It is an application’s responsibility to track the lifetime of Vulkan objects, and not to destroy them while they are still in use.

The ownership of application-owned memory is immediately acquired by any Vulkan command it is passed into. Ownership of such memory must be released back to the application at the end of the duration of the command, so that the application can alter or free this memory as soon as all the commands that acquired it have returned.

The following object types are consumed when they are passed into a Vulkan command and not further accessed by the objects they are used to create. They must not be destroyed in the duration of any API command they are passed into:

- VkShaderModule
- VkPipelineCache

A VkRenderPass or VkPipelineLayout object passed as a parameter to create another object is not further accessed by that object after the duration of the command it is passed into. A VkRenderPass used in a command buffer follows the rules described below.

VkDescriptorsetLayout objects may be accessed by commands that operate on descriptor sets allocated using that layout, and those descriptor sets must not be updated with vkUpdateDescriptorSets after the descriptor set layout has been destroyed. Otherwise, a VkDescriptorsetLayout object passed as a parameter to create another object is not further accessed by that object after the duration of the command it is passed into.

The application must not destroy any other type of Vulkan object until all uses of that object by the device (such as via command buffer execution) have completed.

The following Vulkan objects must not be destroyed while any command buffers using the object are in the pending state:

- VkEvent
- VkQueryPool
Destroying these objects will move any command buffers that are in the recording or executable state, and are using those objects, to the invalid state.

The following Vulkan objects must not be destroyed while any queue is executing commands that use the object:

- VkFence
- VkSemaphore
- VkCommandBuffer
- VkCommandPool

In general, objects can be destroyed or freed in any order, even if the object being freed is involved in the use of another object (e.g. use of a resource in a view, use of a view in a descriptor set, use of an object in a command buffer, binding of a memory allocation to a resource), as long as any object that uses the freed object is not further used in any way except to be destroyed or to be reset in such a way that it no longer uses the other object (such as resetting a command buffer). If the object has been reset, then it can be used as if it never used the freed object. An exception to this is when there is a parent/child relationship between objects. In this case, the application must not destroy a parent object before its children, except when the parent is explicitly defined to free its children when it is destroyed (e.g. for pool objects, as defined below).

VkCommandPool objects are parents of VkCommandBuffer objects. VkDescriptorPool objects are parents of VkDescriptorSet objects. VkDevice objects are parents of many object types (all that take a VkDevice as a parameter to their creation).

The following Vulkan objects have specific restrictions for when they can be destroyed:

- VkQueue objects cannot be explicitly destroyed. Instead, they are implicitly destroyed when the
**VkDevice** object they are retrieved from is destroyed.

- Destroying a pool object implicitly frees all objects allocated from that pool. Specifically, destroying **VkCommandPool** frees all **VkCommandBuffer** objects that were allocated from it, and destroying **VkDescriptorPool** frees all **VkDescriptorSet** objects that were allocated from it.

- **VkDevice** objects can be destroyed when all **VkQueue** objects retrieved from them are idle, and all objects created from them have been destroyed.
  - This includes the following objects:
    - **VkFence**
    - **VkSemaphore**
    - **VkEvent**
    - **VkQueryPool**
    - **VkBuffer**
    - **VkBufferView**
    - **VkImage**
    - **VkImageView**
    - **VkShaderModule**
    - **VkPipelineCache**
    - **VkPipeline**
    - **VkPipelineLayout**
    - **VkSampler**
    - **VkSamplerYcbcrConversion**
    - **VkDescriptorSetLayout**
    - **VkDescriptorPool**
    - **VkFramebuffer**
    - **VkRenderPass**
    - **VkCommandPool**
    - **VkCommandBuffer**
    - **VkDeviceMemory**

- **VkPhysicalDevice** objects cannot be explicitly destroyed. Instead, they are implicitly destroyed when the **VkInstance** object they are retrieved from is destroyed.

- **VkInstance** objects can be destroyed once all **VkDevice** objects created from any of its **VkPhysicalDevice** objects have been destroyed.

### 3.3.2. External Object Handles

As defined above, the scope of object handles created or allocated from a **VkDevice** is limited to that logical device. Objects which are not in scope are said to be external. To bring an external object
into scope, an external handle **must** be exported from the object in the source scope and imported into the destination scope.

Note

The scope of external handles and their associated resources **may** vary according to their type, but they **can** generally be shared across process and API boundaries.

### 3.4. Application Binary Interface

The mechanism by which Vulkan is made available to applications is platform- or implementation-defined. On many platforms the C interface described in this Specification is provided by a shared library. Since shared libraries can be changed independently of the applications that use them, they present particular compatibility challenges, and this Specification places some requirements on them.

Shared library implementations **must** use the default Application Binary Interface (ABI) of the standard C compiler for the platform, or provide customized API headers that cause application code to use the implementation's non-default ABI. An ABI in this context means the size, alignment, and layout of C data types; the procedure calling convention; and the naming convention for shared library symbols corresponding to C functions. Customizing the calling convention for a platform is usually accomplished by defining calling convention macros appropriately in `vk_platform.h`.

On platforms where Vulkan is provided as a shared library, library symbols beginning with “vk” and followed by a digit or uppercase letter are reserved for use by the implementation. Applications which use Vulkan **must** not provide definitions of these symbols. This allows the Vulkan shared library to be updated with additional symbols for new API versions or extensions without causing symbol conflicts with existing applications.

Shared library implementations **should** provide library symbols for commands in the highest version of this Specification they support, and for Window System Integration extensions relevant to the platform. They **may** also provide library symbols for commands defined by additional extensions.

Note

These requirements and recommendations are intended to allow implementors to take advantage of platform-specific conventions for SDKs, ABIs, library versioning mechanisms, etc. while still minimizing the code changes necessary to port applications or libraries between platforms. Platform vendors, or providers of the de facto standard Vulkan shared library for a platform, are encouraged to document what symbols the shared library provides and how it will be versioned when new symbols are added.

Applications **should** only rely on shared library symbols for commands in the minimum core version required by the application. `vkGetInstanceProcAddr` and `vkGetDeviceProcAddr` **should** be used to obtain function pointers for commands in core versions beyond the application's minimum required version.
3.5. Command Syntax and Duration

The Specification describes Vulkan commands as functions or procedures using C99 syntax. Language bindings for other languages such as C++ and JavaScript may allow for stricter parameter passing, or object-oriented interfaces.

Vulkan uses the standard C types for the base type of scalar parameters (e.g. types from `<stdint.h>`), with exceptions described below, or elsewhere in the text when appropriate:

`VkBool32` represents boolean `True` and `False` values, since C does not have a sufficiently portable built-in boolean type:

```c
// Provided by VK_VERSION_1_0
typedef uint32_t VkBool32;
```

`VK_TRUE` represents a boolean `True` (unsigned integer 1) value, and `VK_FALSE` a boolean `False` (unsigned integer 0) value.

All values returned from a Vulkan implementation in a `VkBool32` will be either `VK_TRUE` or `VK_FALSE`.

Applications must not pass any other values than `VK_TRUE` or `VK_FALSE` into a Vulkan implementation where a `VkBool32` is expected.

`VK_TRUE` is a constant representing a `VkBool32` `True` value.

```c
#define VK_TRUE 1U
```

`VK_FALSE` is a constant representing a `VkBool32` `False` value.

```c
#define VK_FALSE 0U
```

`VkDeviceSize` represents device memory size and offset values:

```c
// Provided by VK_VERSION_1_0
typedef uint64_t VkDeviceSize;
```

`VkDeviceAddress` represents device buffer address values:

```c
// Provided by VK_VERSION_1_0
typedef uint64_t VkDeviceAddress;
```

Commands that create Vulkan objects are of the form `vkCreate*` and take `Vk*CreateInfo` structures with the parameters needed to create the object. These Vulkan objects are destroyed with commands of the form `vkDestroy*`.
The last in-parameter to each command that creates or destroys a Vulkan object is `pAllocator`. The `pAllocator` parameter can be set to a non-NULL value such that allocations for the given object are delegated to an application provided callback; refer to the Memory Allocation chapter for further details.

Commands that allocate Vulkan objects owned by pool objects are of the form `vkAllocate*`, and take `Vk*AllocateInfo` structures. These Vulkan objects are freed with commands of the form `vkFree*`. These objects do not take allocators; if host memory is needed, they will use the allocator that was specified when their parent pool was created.

Commands are recorded into a command buffer by calling API commands of the form `vkCmd*`. Each such command may have different restrictions on where it can be used: in a primary and/or secondary command buffer, inside and/or outside a render pass, and in one or more of the supported queue types. These restrictions are documented together with the definition of each such command.

The duration of a Vulkan command refers to the interval between calling the command and its return to the caller.

### 3.5.1. Lifetime of Retrieved Results

Information is retrieved from the implementation with commands of the form `vkGet*` and `vkEnumerate*`.

Unless otherwise specified for an individual command, the results are invariant; that is, they will remain unchanged when retrieved again by calling the same command with the same parameters, so long as those parameters themselves all remain valid.

### 3.6. Threading Behavior

Vulkan is intended to provide scalable performance when used on multiple host threads. All commands support being called concurrently from multiple threads, but certain parameters, or components of parameters are defined to be externally synchronized. This means that the caller must guarantee that no more than one thread is using such a parameter at a given time.

More precisely, Vulkan commands use simple stores to update the state of Vulkan objects. A parameter declared as externally synchronized may have its contents updated at any time during the host execution of the command. If two commands operate on the same object and at least one of the commands declares the object to be externally synchronized, then the caller must guarantee not only that the commands do not execute simultaneously, but also that the two commands are separated by an appropriate memory barrier (if needed).

>Note

Memory barriers are particularly relevant for hosts based on the ARM CPU architecture, which is more weakly ordered than many developers are accustomed to from x86/x64 programming. Fortunately, most higher-level synchronization primitives (like the pthread library) perform memory barriers as a part of mutual exclusion, so mutexing Vulkan objects via these primitives will have the desired
Similarly the application **must** avoid any potential data hazard of application-owned memory that has its **ownership temporarily acquired** by a Vulkan command. While the ownership of application-owned memory remains acquired by a command the implementation **may** read the memory at any point, and it **may** write non-`const` qualified memory at any point. Parameters referring to non-`const` qualified application-owned memory are not marked explicitly as **externally synchronized** in the Specification.

Many object types are **immutable**, meaning the objects **cannot** change once they have been created. These types of objects never need external synchronization, except that they **must** not be destroyed while they are in use on another thread. In certain special cases mutable object parameters are internally synchronized, making external synchronization unnecessary. Any command parameters that are not labeled as externally synchronized are either not mutated by the command or are internally synchronized. Additionally, certain objects related to a command’s parameters (e.g. command pools and descriptor pools) **may** be affected by a command, and **must** also be externally synchronized. These implicit parameters are documented as described below.

Parameters of commands that are externally synchronized are listed below.

### Externally Synchronized Parameters

- The **instance** parameter in `vkDestroyInstance`
- The **device** parameter in `vkDestroyDevice`
- The **queue** parameter in `vkQueueSubmit`
- The **fence** parameter in `vkQueueSubmit`
- The **queue** parameter in `vkQueueWaitIdle`
- The **memory** parameter in `vkFreeMemory`
- The **memory** parameter in `vkMapMemory`
- The **memory** parameter in `vkUnmapMemory`
- The **buffer** parameter in `vkBindBufferMemory`
- The **image** parameter in `vkBindImageMemory`
- The **queue** parameter in `vkQueueBindSparse`
- The **fence** parameter in `vkQueueBindSparse`
- The **fence** parameter in `vkDestroyFence`
- The **semaphore** parameter in `vkDestroySemaphore`
- The **event** parameter in `vkDestroyEvent`
- The **event** parameter in `vkSetEvent`
- The **event** parameter in `vkResetEvent`
- The **queryPool** parameter in `vkDestroyQueryPool`
- The **buffer** parameter in `vkDestroyBuffer`
The bufferView parameter in VkDestroyBufferView
The image parameter in VkDestroyImage
The imageView parameter in VkDestroyImageView
The shaderModule parameter in VkDestroyShaderModule
The pipelineCache parameter in VkDestroyPipelineCache
The dstCache parameter in VkMergePipelineCaches
The pipeline parameter in VkDestroyPipeline
The pipelineLayout parameter in VkDestroyPipelineLayout
The sampler parameter in VkDestroySampler
The descriptorSetLayout parameter in VkDestroyDescriptorSetLayout
The descriptorPool parameter in VkDestroyDescriptorPool
The descriptorPool parameter in VkResetDescriptorPool
The descriptorPool member of the pAllocateInfo parameter in VkAllocateDescriptorSets
The descriptorPool parameter in VkFreeDescriptorSets
The framebuffer parameter in VkDestroyFramebuffer
The renderPass parameter in VkDestroyRenderPass
The commandPool parameter in VkDestroyCommandPool
The commandPool parameter in VkResetCommandPool
The commandPool member of the pAllocateInfo parameter in VkAllocateCommandBuffers
The commandPool parameter in VkFreeCommandBuffers
The commandBuffer parameter in VkBeginCommandBuffer
The commandBuffer parameter in VkEndCommandBuffer
The commandBuffer parameter in VkResetCommandBuffer
The commandBuffer parameter in VkCmdBindPipeline
The commandBuffer parameter in VkCmdSetViewport
The commandBuffer parameter in VkCmdSetScissor
The commandBuffer parameter in VkCmdSetLineWidth
The commandBuffer parameter in VkCmdSetDepthBias
The commandBuffer parameter in VkCmdSetBlendConstants
The commandBuffer parameter in VkCmdSetDepthBounds
The commandBuffer parameter in VkCmdSetStencilCompareMask
The commandBuffer parameter in VkCmdSetStencilWriteMask
The commandBuffer parameter in VkCmdSetStencilReference
The commandBuffer parameter in VkCmdBindDescriptorSets
The commandBuffer parameter in VkCmdBindIndexBuffer
The `commandBuffer` parameter in `vkCmdBindVertexBuffers`
The `commandBuffer` parameter in `vkCmdDraw`
The `commandBuffer` parameter in `vkCmdDrawIndexed`
The `commandBuffer` parameter in `vkCmdDrawIndirect`
The `commandBuffer` parameter in `vkCmdDrawIndexedIndirect`
The `commandBuffer` parameter in `vkCmdDispatch`
The `commandBuffer` parameter in `vkCmdDispatchIndirect`
The `commandBuffer` parameter in `vkCmdCopyBuffer`
The `commandBuffer` parameter in `vkCmdCopyImage`
The `commandBuffer` parameter in `vkCmdBlitImage`
The `commandBuffer` parameter in `vkCmdCopyBufferToImage`
The `commandBuffer` parameter in `vkCmdCopyImageToBuffer`
The `commandBuffer` parameter in `vkCmdUpdateBuffer`
The `commandBuffer` parameter in `vkCmdFillBuffer`
The `commandBuffer` parameter in `vkCmdClearColorImage`
The `commandBuffer` parameter in `vkCmdClearDepthStencilImage`
The `commandBuffer` parameter in `vkCmdClearAttachments`
The `commandBuffer` parameter in `vkCmdResolveImage`
The `commandBuffer` parameter in `vkCmdSetEvent`
The `commandBuffer` parameter in `vkCmdResetEvent`
The `commandBuffer` parameter in `vkCmdWaitEvents`
The `commandBuffer` parameter in `vkCmdPipelineBarrier`
The `commandBuffer` parameter in `vkCmdBeginQuery`
The `commandBuffer` parameter in `vkCmdEndQuery`
The `commandBuffer` parameter in `vkCmdResetQueryPool`
The `commandBuffer` parameter in `vkCmdWriteTimestamp`
The `commandBuffer` parameter in `vkCmdCopyQueryPoolResults`
The `commandBuffer` parameter in `vkCmdPushConstants`
The `commandBuffer` parameter in `vkCmdBeginRenderPass`
The `commandBuffer` parameter in `vkCmdNextSubpass`
The `commandBuffer` parameter in `vkCmdEndRenderPass`
The `commandBuffer` parameter in `vkCmdExecuteCommands`
The `commandBuffer` parameter in `vkCmdSetDeviceMask`
The `commandBuffer` parameter in `vkCmdDispatchBase`
The `commandPool` parameter in `vkTrimCommandPool`
• The \texttt{ycbcrConversion} parameter in \texttt{vkDestroySamplerYcbcrConversion}
• The \texttt{descriptorUpdateTemplate} parameter in \texttt{vkDestroyDescriptorUpdateTemplate}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdDrawIndirectCount}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdDrawIndexedIndirectCount}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdBeginRenderPass2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdNextSubpass2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdEndRenderPass2}
• The \texttt{privateDataSlot} parameter in \texttt{vkDestroyPrivateDataSlot}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetEvent2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdResetEvent2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdWaitEvents2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdPipelineBarrier2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdWriteTimestamp2}
• The \texttt{queue} parameter in \texttt{vkQueueSubmit2}
• The \texttt{fence} parameter in \texttt{vkQueueSubmit2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdCopyBuffer2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdCopyImage2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdCopyBufferToImage2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdCopyImageToBuffer2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdBlitImage2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdResolveImage2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdBeginRendering}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdEndRendering}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetCullMode}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetFrontFace}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetPrimitiveTopology}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetViewportWithCount}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetScissorWithCount}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdBindVertexBuffers2}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetDepthTestEnable}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetDepthWriteEnable}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetDepthCompareOp}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetDepthBoundsTestEnable}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetStencilTestEnable}
• The \texttt{commandBuffer} parameter in \texttt{vkCmdSetStencilOp}
• The `commandBuffer` parameter in `vkCmdSetRasterizerDiscardEnable`
• The `commandBuffer` parameter in `vkCmdSetDepthBiasEnable`
• The `commandBuffer` parameter in `vkCmdSetPrimitiveRestartEnable`

For `VkPipelineCache` objects created with `flags` containing `VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT`, the above table is extended with the `pipelineCache` parameter to `vkCreate*Pipelines` being externally synchronized.

There are also a few instances where a command can take in a user allocated list whose contents are externally synchronized parameters. In these cases, the caller must guarantee that at most one thread is using a given element within the list at a given time. These parameters are listed below.

### Externally Synchronized Parameter Lists

- Each element of the `pFences` parameter in `vkResetFences`
- Each element of the `pDescriptorSets` parameter in `vkFreeDescriptorSets`
- Each element of the `pCommandBuffers` parameter in `vkFreeCommandBuffers`

In addition, there are some implicit parameters that need to be externally synchronized. For example, when a `commandBuffer` parameter needs to be externally synchronized, it implies that the `commandPool` from which that command buffer was allocated also needs to be externally synchronized. The implicit parameters and their associated object are listed below.

### Implicit Externally Synchronized Parameters

- All `VkPhysicalDevice` objects enumerated from `instance` in `vkDestroyInstance`
- All `VkQueue` objects created from `device` in `vkDestroyDevice`
- All `VkQueue` objects created from `device` in `vkDeviceWaitIdle`
- Any `VkDescriptorSet` objects allocated from `descriptorPool` in `vkResetDescriptorPool`
- The `VkCommandPool` that `commandBuffer` was allocated from in `vkBeginCommandBuffer`
- The `VkCommandPool` that `commandBuffer` was allocated from in `vkEndCommandBuffer`
- The `VkCommandPool` that `commandBuffer` was allocated from in `vkResetCommandBuffer`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdBindPipeline`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetViewport`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetScissor`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetLineWidth`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetDepthBias`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetBlendConstants`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdSetDepthBounds`
The VkCommandPool that commandBuffer was allocated from, in 
vkCmdSetStencilCompareMask
The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilWriteMask
The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilReference
The VkCommandPool that commandBuffer was allocated from, in vkCmdBindDescriptorSets
The VkCommandPool that commandBuffer was allocated from, in vkCmdBindIndexBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdBindVertexBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdDraw
The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexed
The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndirect
The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexedIndirect
The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatch
The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatchIndirect
The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdBlitImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBufferToImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImageToBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdUpdateBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdFillBuffer
The VkCommandPool that commandBuffer was allocated from, in vkCmdClearColorImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdClearDepthStencilImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdClearAttachments
The VkCommandPool that commandBuffer was allocated from, in vkCmdResolveImage
The VkCommandPool that commandBuffer was allocated from, in vkCmdSetEvent
The VkCommandPool that commandBuffer was allocated from, in vkCmdResetEvent
The VkCommandPool that commandBuffer was allocated from, in vkCmdWaitEvents
The VkCommandPool that commandBuffer was allocated from, in vkCmdPipelineBarrier
The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginQuery
The VkCommandPool that commandBuffer was allocated from, in vkCmdEndQuery
The VkCommandPool that commandBuffer was allocated from, in vkCmdResetQueryPool
The VkCommandPool that commandBuffer was allocated from, in vkCmdWriteTimestamp
The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyQueryPoolResults
The VkCommandPool that commandBuffer was allocated from, in vkCmdPushConstants
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRenderPass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdNextSubpass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRenderPass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdExecuteCommands
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDeviceMask
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatchBase
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndirectCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexedIndirectCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRenderPass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdNextSubpass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRenderPass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetEvent2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdResetEvent2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdWaitEvents2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdPipelineBarrier2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdWriteTimestamp2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBuffer2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImage2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBufferToImage2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImageToBuffer2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBlitImage2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdResolveImage2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRendering
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRendering
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetCullMode
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetFrontFace
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetPrimitiveTopology
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetViewportWithCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetScissorWithCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBindVertexBuffers2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthTestEnable
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthWriteEnable
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthCompareOp
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBindVertexBuffers2
vkCmdSetDepthBoundsTestEnable
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilTestEnable
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilOp
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetRasterizerDiscardEnable
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthBiasEnable
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetPrimitiveRestartEnable

3.7. Valid Usage

Valid usage defines a set of conditions which must be met in order to achieve well-defined runtime behavior in an application. These conditions depend only on Vulkan state, and the parameters or objects whose usage is constrained by the condition.

The core layer assumes applications are using the API correctly. Except as documented elsewhere in the Specification, the behavior of the core layer to an application using the API incorrectly is undefined, and may include program termination. However, implementations must ensure that incorrect usage by an application does not affect the integrity of the operating system, the Vulkan implementation, or other Vulkan client applications in the system. In particular, any guarantees made by an operating system about whether memory from one process can be visible to another process or not must not be violated by a Vulkan implementation for any memory allocation. Vulkan implementations are not required to make additional security or integrity guarantees beyond those provided by the OS unless explicitly directed by the application's use of a particular feature or extension.

Note
For instance, if an operating system guarantees that data in all its memory allocations are set to zero when newly allocated, the Vulkan implementation must make the same guarantees for any allocations it controls (e.g. VkDeviceMemory).

Similarly, if an operating system guarantees that use-after-free of host allocations will not result in values written by another process becoming visible, the same guarantees must be made by the Vulkan implementation for device memory.

If the protectedMemory feature is supported, the implementation provides additional guarantees when invalid usage occurs to prevent values in protected memory from being accessed or inferred outside of protected operations, as described in Protected Memory Access Rules.

Some valid usage conditions have dependencies on runtime limits or feature availability. It is possible to validate these conditions against Vulkan’s minimum supported values for these limits and features, or some subset of other known values.

Valid usage conditions do not cover conditions where well-defined behavior (including returning an error code) exists.
Valid usage conditions **should** apply to the command or structure where complete information about the condition would be known during execution of an application. This is such that a validation layer or linter **can** be written directly against these statements at the point they are specified.

*Note*

This does lead to some non-obvious places for valid usage statements. For instance, the valid values for a structure might depend on a separate value in the calling command. In this case, the structure itself will not reference this valid usage as it is impossible to determine validity from the structure that it is invalid - instead this valid usage would be attached to the calling command.

Another example is draw state - the state setters are independent, and can cause a legitimately invalid state configuration between draw calls; so the valid usage statements are attached to the place where all state needs to be valid - at the drawing command.

Valid usage conditions are described in a block labelled “Valid Usage” following each command or structure they apply to.

### 3.7.1. Usage Validation

Vulkan is a layered API. The lowest layer is the core Vulkan layer, as defined by this Specification. The application **can** use additional layers above the core for debugging, validation, and other purposes.

One of the core principles of Vulkan is that building and submitting command buffers **should** be highly efficient. Thus error checking and validation of state in the core layer is minimal, although more rigorous validation **can** be enabled through the use of layers.

Validation of correct API usage is left to validation layers. Applications **should** be developed with validation layers enabled, to help catch and eliminate errors. Once validated, released applications **should** not enable validation layers by default.

### 3.7.2. Implicit Valid Usage

Some valid usage conditions apply to all commands and structures in the API, unless explicitly denoted otherwise for a specific command or structure. These conditions are considered **implicit**, and are described in a block labelled “Valid Usage (Implicit)” following each command or structure they apply to. Implicit valid usage conditions are described in detail below.

**Valid Usage for Object Handles**

Any input parameter to a command that is an object handle **must** be a valid object handle, unless otherwise specified. An object handle is valid if:

- It has been created or allocated by a previous, successful call to the API. Such calls are noted in the Specification.
- It has not been deleted or freed by a previous call to the API. Such calls are noted in the
Specification.

- Any objects used by that object, either as part of creation or execution, **must** also be valid.

The reserved values **VK_NULL_HANDLE** and **NULL** can be used in place of valid non-dispatchable handles and dispatchable handles, respectively, when *explicitly called out in the Specification*. Any command that creates an object successfully **must** not return these values. It is valid to pass these values to `vkDestroy*` or `vkFree*` commands, which will silently ignore these values.

**Valid Usage for Pointers**

Any parameter that is a pointer **must** be a *valid pointer* only if it is explicitly called out by a Valid Usage statement.

A pointer is “valid” if it points at memory containing values of the number and type(s) expected by the command, and all fundamental types accessed through the pointer (e.g. as elements of an array or as members of a structure) satisfy the alignment requirements of the host processor.

**Valid Usage for Strings**

Any parameter that is a pointer to `char` **must** be a finite sequence of values terminated by a null character, or if *explicitly called out in the Specification*, **can** be NULL.

**Valid Usage for Enumerated Types**

Any parameter of an enumerated type **must** be a valid enumerant for that type. Use of an enumerant is valid if the following conditions are true:

- The enumerant is defined as part of the enumerated type.
- The enumerant is not a value suffixed with `_MAX_ENUM`.
  - This value exists only to ensure that C `enum` types are 32 bits in size and **must** not be used by applications.
- If the enumerant is used in a function that has a `VkInstance` as its first parameter and either:
  - it was added by a core version that is supported (as reported by `vkEnumerateInstanceVersion`) and the value of `VkApplicationInfo::apiVersion` is greater than or equal to the version that added it; or
  - it was added by an instance extension that was enabled for the instance.
- If the enumerant is used in a function that has a `VkPhysicalDevice` object as its first parameter and either:
  - it was added by a core version that is supported by that device (as reported by `VkPhysicalDeviceProperties::apiVersion`);  
  - it was added by an instance extension that was enabled for the instance; or
  - it was added by a device extension that is supported by that device.
- If the enumerant is used in a function that has any other dispatchable object as its first parameter and either:
  - it was added by a core version that is supported for the device (as reported by
Any enumerated type returned from a query command or otherwise output from Vulkan to the application must not have a reserved value. Reserved values are values not defined by any extension for that enumerated type.

Note
In some special cases, an enumerant is only meaningful if a feature defined by an extension is also enabled, as well as the extension itself. The global “valid enumerant” rule described here does not address such cases.

Note
This language is intended to accommodate cases such as “hidden” extensions known only to driver internals, or layers enabling extensions without knowledge of the application, without allowing return of values not defined by any extension.

Note
Application developers are encouraged to be careful when using switch statements with Vulkan API enums. This is because new extensions can add new values to existing enums. Using a default: statement within a switch may avoid future compilation issues.

This is particularly true for enums such as VkDriverId, which may have values added that do not belong to a corresponding new extension.

Valid Usage for Flags

A collection of flags is represented by a bitmask using the type VkFlags:

```c
// Provided by VK_VERSION_1_0
typedef uint32_t VkFlags;
```

Bitmasks are passed to many commands and structures to compactly represent options, but VkFlags is not used directly in the API. Instead, a VkFlags type which is an alias of VkFlags, and whose name matches the corresponding VkFlagBits that are valid for that type, is used.

Any VkFlags member or parameter used in the API as an input must be a valid combination of bit flags. A valid combination is either zero or the bitwise OR of valid bit flags.

An individual bit flag is valid for a VkFlags type if it would be a valid enumerant when used with the equivalent VkFlagBits type, where the bits type is obtained by taking the flag type and replacing the trailing Flags with FlagBits. For example, a flag value of type VkColorComponentFlags must contain only bit flags defined by VkColorComponentFlagBits.

Any VkFlags member or parameter returned from a query command or otherwise output from Vulkan to the application may contain bit flags undefined in its corresponding VkFlagBits type. An
application **cannot** rely on the state of these unspecified bits.

Only the low-order 31 bits (bit positions zero through 30) are available for use as flag bits.

**Note**

This restriction is due to poorly defined behavior by C compilers given a C enumerant value of 0x80000000. In some cases adding this enumerant value may increase the size of the underlying Vk*FlagBits type, breaking the ABI.

A collection of 64-bit flags is represented by a bitmask using the type **VkFlags64**: 

```c
// Provided by VK_VERSION_1_3
typedef uint64_t VkFlags64;
```

When the 31 bits available in **VkFlags** are insufficient, the **VkFlags64** type can be passed to commands and structures to represent up to 64 options. **VkFlags64** is not used directly in the API. Instead, a **Vk*Flags2** type which is an alias of **VkFlags64**, and whose name matches the corresponding **Vk*FlagBits2** that are valid for that type, is used.

Any **Vk*Flags2** member or parameter used in the API as an input **must** be a valid combination of bit flags. A valid combination is either zero or the bitwise OR of valid bit flags.

An individual bit flag is valid for a **Vk*Flags2** type if it would be a valid enumerant when used with the equivalent **Vk*FlagBits2** type, where the bits type is obtained by taking the flag type and replacing the trailing **Flags2** with **FlagBits2**. For example, a flag value of type **VkAccessFlags2KHR** **must** contain only bit flags defined by **VkAccessFlagBits2KHR**.

Any **Vk*Flags2** member or parameter returned from a query command or otherwise output from Vulkan to the application **may** contain bit flags undefined in its corresponding **Vk*FlagBits2** type. An application **cannot** rely on the state of these unspecified bits.

**Note**

Both the **Vk*FlagBits2** type, and the individual bits defined for that type, are defined as **uint64_t** integers in the C API. This is in contrast to the 32-bit types, where the **Vk*FlagBits** type is defined as a C **enum** and the individual bits as enumerants belonging to that **enum**. As a result, there is less compile time type checking possible for the 64-bit types. This is unavoidable since there is no sufficiently portable way to define a 64-bit **enum** type in C99.

**Valid Usage for Structure Types**

Any parameter that is a structure containing a **sType** member **must** have a value of **sType** which is a valid **VkStructureType** value matching the type of the structure.

**Valid Usage for Structure Pointer Chains**

Any parameter that is a structure containing a **void* pNext** member **must** have a value of **pNext** that is either **NULL**, or is a pointer to a valid extending structure, containing **sType** and **pNext** members as
described in the Vulkan Documentation and Extensions document in the section “Extending Structures”. The set of structures connected by pNext pointers is referred to as a pNext chain.

Each structure included in the pNext chain must be defined at runtime by either:

- a core version which is supported
- an extension which is enabled
- a supported device extension in the case of physical-device-level functionality added by the device extension

Each type of extending structure must not appear more than once in a pNext chain, including any aliases. This general rule may be explicitly overridden for specific structures.

Any component of the implementation (the loader, any enabled layers, and drivers) must skip over, without processing (other than reading the sType and pNext members) any extending structures in the chain not defined by core versions or extensions supported by that component.

As a convenience to implementations and layers needing to iterate through a structure pointer chain, the Vulkan API provides two base structures. These structures allow for some type safety, and can be used by Vulkan API functions that operate on generic inputs and outputs.

The VkBaseInStructure structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBaseInStructure {
    VkStructureType sType;
    const struct VkBaseInStructure* pNext;
} VkBaseInStructure;
```

- sType is the structure type of the structure being iterated through.
- pNext is NULL or a pointer to the next structure in a structure chain.

VkBaseInStructure can be used to facilitate iterating through a read-only structure pointer chain.

The VkBaseOutStructure structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBaseOutStructure {
    VkStructureType sType;
    struct VkBaseOutStructure* pNext;
} VkBaseOutStructure;
```

- sType is the structure type of the structure being iterated through.
- pNext is NULL or a pointer to the next structure in a structure chain.

VkBaseOutStructure can be used to facilitate iterating through a structure pointer chain that returns data back to the application.
Valid Usage for Nested Structures

The above conditions also apply recursively to members of structures provided as input to a command, either as a direct argument to the command, or themselves a member of another structure.

Specifics on valid usage of each command are covered in their individual sections.

Valid Usage for Extensions

Instance-level functionality or behavior added by an instance extension to the API must not be used unless that extension is supported by the instance as determined by `vkEnumerateInstanceExtensionProperties`, and that extension is enabled in `VkInstanceCreateInfo`.

Physical-device-level functionality or behavior added by an instance extension to the API must not be used unless that extension is supported by the instance as determined by `vkEnumerateInstanceExtensionProperties`, and that extension is enabled in `VkInstanceCreateInfo`.

Physical-device-level functionality or behavior added by a device extension to the API must not be used unless the conditions described in Extending Physical Device Core Functionality are met.

Device-level functionality added by a device extension that is dispatched from a `VkDevice`, or from a child object of a `VkDevice` must not be used unless that extension is supported by the device as determined by `vkEnumerateDeviceExtensionProperties`, and that extension is enabled in `VkDeviceCreateInfo`.

Valid Usage for Newer Core Versions

Instance-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the instance as determined by `vkEnumerateInstanceVersion` and the specified version of `VkApplicationInfo::apiVersion`.

Physical-device-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the physical device as determined by `VkPhysicalDeviceProperties::apiVersion` and the specified version of `VkApplicationInfo::apiVersion`.

Device-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the device as determined by `VkPhysicalDeviceProperties::apiVersion` and the specified version of `VkApplicationInfo::apiVersion`.

3.8. VkResult Return Codes

While the core Vulkan API is not designed to capture incorrect usage, some circumstances still require return codes. Commands in Vulkan return their status via return codes that are in one of two categories:

- Successful completion codes are returned when a command needs to communicate success or status information. All successful completion codes are non-negative values.
- Run time error codes are returned when a command needs to communicate a failure that could only be detected at runtime. All runtime error codes are negative values.
All return codes in Vulkan are reported via `VkResult` return values. The possible codes are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkResult {
    VK_SUCCESS = 0,
    VK_NOT_READY = 1,
    VK_TIMEOUT = 2,
    VK_EVENT_SET = 3,
    VK_EVENT_RESET = 4,
    VK_INCOMPLETE = 5,
    VK_ERROR_OUT_OF_HOST_MEMORY = -1,
    VK_ERROR_OUT_OF_DEVICE_MEMORY = -2,
    VK_ERROR_INITIALIZATION_FAILED = -3,
    VK_ERROR_DEVICE_LOST = -4,
    VK_ERROR_MEMORY_MAP_FAILED = -5,
    VK_ERROR_LAYER_NOT_PRESENT = -6,
    VK_ERROR_EXTENSION_NOT_PRESENT = -7,
    VK_ERROR_FEATURE_NOT_PRESENT = -8,
    VK_ERROR_INCOMPATIBLE_DRIVER = -9,
    VK_ERROR_TOO_MANY_OBJECTS = -10,
    VK_ERROR_FORMAT_NOT_SUPPORTED = -11,
    VK_ERROR_FRAGMENTED_POOL = -12,
    VK_ERROR_UNKNOWN = -13,
    // Provided by VK_VERSION_1_1
    VK_ERROR_OUT_OF_POOL_MEMORY = -1000069000,
    // Provided by VK_VERSION_1_1
    VK_ERROR_INVALID_EXTERNAL_HANDLE = -1000072003,
    // Provided by VK_VERSION_1_2
    VK_ERROR_FRAGMENTATION = -1000161000,
    // Provided by VK_VERSION_1_2
    VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS = -1000257000,
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_COMPILE_REQUIRED = 1000297000,
} VkResult;
```

**Success Codes**

- **VK_SUCCESS** Command successfully completed
- **VK_NOT_READY** A fence or query has not yet completed
- **VK_TIMEOUT** A wait operation has not completed in the specified time
- **VK_EVENT_SET** An event is signaled
- **VK_EVENT_RESET** An event is unsignaled
- **VK_INCOMPLETE** A return array was too small for the result
- **VK_PIPELINE_COMPILE_REQUIRED** A requested pipeline creation would have required compilation, but the application requested compilation to not be performed.

**Error codes**
• **VK_ERROR_OUT_OF_HOST_MEMORY** A host memory allocation has failed.

• **VK_ERROR_OUT_OF_DEVICE_MEMORY** A device memory allocation has failed.

• **VK_ERROR_INITIALIZATION_FAILED** Initialization of an object could not be completed for implementation-specific reasons.

• **VK_ERROR_DEVICE_LOST** The logical or physical device has been lost. See [Lost Device](Lost Device)

• **VK_ERROR_MEMORY_MAP_FAILED** Mapping of a memory object has failed.

• **VK_ERROR_LAYER_NOT_PRESENT** A requested layer is not present or could not be loaded.

• **VK_ERROR_EXTENSION_NOT_PRESENT** A requested extension is not supported.

• **VK_ERROR_FEATURE_NOT_PRESENT** A requested feature is not supported.

• **VK_ERROR_INCOMPATIBLE_DRIVER** The requested version of Vulkan is not supported by the driver or is otherwise incompatible for implementation-specific reasons.

• **VK_ERROR_TOO_MANY_OBJECTS** Too many objects of the type have already been created.

• **VK_ERROR_FORMAT_NOT_SUPPORTED** A requested format is not supported on this device.

• **VK_ERROR_FRAGMENTS_POOL** A pool allocation has failed due to fragmentation of the pool's memory. This must only be returned if no attempt to allocate host or device memory was made to accommodate the new allocation. This should be returned in preference to **VK_ERROR_OUT_OF_POOL_MEMORY**, but only if the implementation is certain that the pool allocation failure was due to fragmentation.

• **VK_ERROR_OUT_OF_POOL_MEMORY** A pool memory allocation has failed. This must only be returned if no attempt to allocate host or device memory was made to accommodate the new allocation. If the failure was definitely due to fragmentation of the pool, **VK_ERROR_FRAGMENTED_POOL** should be returned instead.

• **VK_ERROR_INVALID_EXTERNAL_HANDLE** An external handle is not a valid handle of the specified type.

• **VK_ERROR_FRAGMENTATION** A descriptor pool creation has failed due to fragmentation.

• **VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS** A buffer creation or memory allocation failed because the requested address is not available.

• **VK_ERROR_UNKNOWN** An unknown error has occurred; either the application has provided invalid input, or an implementation failure has occurred.

If a command returns a runtime error, unless otherwise specified any output parameters will have undefined contents, except that if the output parameter is a structure with **sType** and **pNext** fields, those fields will be unmodified. Any structures chained from **pNext** will also have undefined contents, except that **sType** and **pNext** will be unmodified.

**VK_ERROR_OUT_OF_*_MEMORY** errors do not modify any currently existing Vulkan objects. Objects that have already been successfully created can still be used by the application.

---

**Note**

As a general rule, **Free**, **Release**, and **Reset** commands do not return **VK_ERROR_OUT_OF_HOST_MEMORY**, while any other command with a return code may return it. Any exceptions from this rule are described for those commands.
VK_ERROR_UNKNOWN will be returned by an implementation when an unexpected error occurs that cannot be attributed to valid behavior of the application and implementation. Under these conditions, it may be returned from any command returning a VkResult.

Note

VK_ERROR_UNKNOWN is not expected to ever be returned if the application behavior is valid, and if the implementation is bug-free. If VK_ERROR_UNKNOWN is received, the application should be checked against the latest validation layers to verify correct behavior as much as possible. If no issues are identified it could be an implementation issue, and the implementor should be contacted for support.

Performance-critical commands generally do not have return codes. If a runtime error occurs in such commands, the implementation will defer reporting the error until a specified point. For commands that record into command buffers (vkCmd*) runtime errors are reported by vkEndCommandBuffer.

3.9. Numeric Representation and Computation

Implementations normally perform computations in floating-point, and must meet the range and precision requirements defined under “Floating-Point Computation” below.

These requirements only apply to computations performed in Vulkan operations outside of shader execution, such as texture image specification and sampling, and per-fragment operations. Range and precision requirements during shader execution differ and are specified by the Precision and Operation of SPIR-V Instructions section.

In some cases, the representation and/or precision of operations is implicitly limited by the specified format of vertex or texel data consumed by Vulkan. Specific floating-point formats are described later in this section.

3.9.1. Floating-Point Computation

Most floating-point computation is performed in SPIR-V shader modules. The properties of computation within shaders are constrained as defined by the Precision and Operation of SPIR-V Instructions section.

Some floating-point computation is performed outside of shaders, such as viewport and depth range calculations. For these computations, we do not specify how floating-point numbers are to be represented, or the details of how operations on them are performed, but only place minimal requirements on representation and precision as described in the remainder of this section.

We require simply that numbers' floating-point parts contain enough bits and that their exponent fields are large enough so that individual results of floating-point operations are accurate to about 1 part in $10^5$. The maximum representable magnitude for all floating-point values must be at least $2^{32}$.

\[ x \times 0 = 0 \times x = 0 \] for any non-infinite and non-NaN x.
Occasionally, further requirements will be specified. Most single-precision floating-point formats meet these requirements.

The special values Inf and -Inf encode values with magnitudes too large to be represented; the special value NaN encodes “Not A Number” values resulting from undefined arithmetic operations such as 0 / 0. Implementations may support Inf and NaN in their floating-point computations. Any computation which does not support either Inf or NaN, for which that value is an input or output will yield an undefined value.

### 3.9.2. Floating-Point Format Conversions

When a value is converted to a defined floating-point representation, finite values falling between two representable finite values are rounded to one or the other. The rounding mode is not defined. Finite values whose magnitude is larger than that of any representable finite value may be rounded either to the closest representable finite value or to the appropriately signed infinity. For unsigned destination formats any negative values are converted to zero. Positive infinity is converted to positive infinity; negative infinity is converted to negative infinity in signed formats and to zero in unsigned formats; and any NaN is converted to a NaN.

### 3.9.3. 16-Bit Floating-Point Numbers

16-bit floating point numbers are defined in the “16-bit floating point numbers” section of the Khronos Data Format Specification.

### 3.9.4. Unsigned 11-Bit Floating-Point Numbers

Unsigned 11-bit floating point numbers are defined in the “Unsigned 11-bit floating point numbers” section of the Khronos Data Format Specification.

### 3.9.5. Unsigned 10-Bit Floating-Point Numbers

Unsigned 10-bit floating point numbers are defined in the “Unsigned 10-bit floating point numbers” section of the Khronos Data Format Specification.

### 3.9.6. General Requirements

Any representable floating-point value in the appropriate format is legal as input to a Vulkan command that requires floating-point data. The result of providing a value that is not a floating-point number to such a command is unspecified, but must not lead to Vulkan interruption or termination. For example, providing a negative zero (where applicable) or a denormalized number
to a Vulkan command must yield deterministic results, while providing a NaN or Inf yields unspecified results.

Some calculations require division. In such cases (including implied divisions performed by vector normalization), division by zero produces an unspecified result but must not lead to Vulkan interruption or termination.

3.10. Fixed-Point Data Conversions

When generic vertex attributes and pixel color or depth components are represented as integers, they are often (but not always) considered to be normalized. Normalized integer values are treated specially when being converted to and from floating-point values, and are usually referred to as normalized fixed-point.

In the remainder of this section, b denotes the bit width of the fixed-point integer representation. When the integer is one of the types defined by the API, b is the bit width of that type. When the integer comes from an image containing color or depth component texels, b is the number of bits allocated to that component in its specified image format.

The signed and unsigned fixed-point representations are assumed to be b-bit binary two’s-complement integers and binary unsigned integers, respectively.

3.10.1. Conversion from Normalized Fixed-Point to Floating-Point

Unsigned normalized fixed-point integers represent numbers in the range [0,1]. The conversion from an unsigned normalized fixed-point value c to the corresponding floating-point value f is defined as

\[ f = \frac{c}{2^b - 1} \]

Signed normalized fixed-point integers represent numbers in the range [-1,1]. The conversion from a signed normalized fixed-point value c to the corresponding floating-point value f is performed using

\[ f = \max\left(\frac{c}{2^b - 1}; -1.0\right) \]

Only the range \([-2^{b-1} + 1, 2^{b-1} - 1]\) is used to represent signed fixed-point values in the range [-1,1]. For example, if \(b = 8\), then the integer value -127 corresponds to -1.0 and the value 127 corresponds to 1.0. This equation is used everywhere that signed normalized fixed-point values are converted to floating-point.

Note that while zero is exactly expressible in this representation, one value (-128 in the example) is outside the representable range, and implementations must clamp it to -1.0. Where the value is subject to further processing by the implementation, e.g. during texture filtering, values less than -1.0 may be used but the result must be clamped before the value is returned to shaders.
3.10.2. Conversion from Floating-Point to Normalized Fixed-Point

The conversion from a floating-point value \( f \) to the corresponding unsigned normalized fixed-point value \( c \) is defined by first clamping \( f \) to the range \([0,1]\), then computing

\[
c = \text{convertFloatToUint}(f \times (2^b - 1), b)
\]

where \( \text{convertFloatToUint}(r,b) \) returns one of the two unsigned binary integer values with exactly \( b \) bits which are closest to the floating-point value \( r \). Implementations should round to nearest. If \( r \) is equal to an integer, then that integer value must be returned. In particular, if \( f \) is equal to 0.0 or 1.0, then \( c \) must be assigned 0 or \( 2^b - 1 \), respectively.

The conversion from a floating-point value \( f \) to the corresponding signed normalized fixed-point value \( c \) is performed by clamping \( f \) to the range \([-1,1]\), then computing

\[
c = \text{convertFloatToInt}(f \times (2^{b-1} - 1), b)
\]

where \( \text{convertFloatToInt}(r,b) \) returns one of the two signed two’s-complement binary integer values with exactly \( b \) bits which are closest to the floating-point value \( r \). Implementations should round to nearest. If \( r \) is equal to an integer, then that integer value must be returned. In particular, if \( f \) is equal to -1.0, 0.0, or 1.0, then \( c \) must be assigned \(-(2^{b-1} - 1)\), 0, or \( 2^{b-1} - 1 \), respectively.

This equation is used everywhere that floating-point values are converted to signed normalized fixed-point.

3.11. Common Object Types

Some types of Vulkan objects are used in many different structures and command parameters, and are described here. These types include offsets, extents, and rectangles.

3.11.1. Offsets

Offsets are used to describe a pixel location within an image or framebuffer, as an \((x,y)\) location for two-dimensional images, or an \((x,y,z)\) location for three-dimensional images.

A two-dimensional offset is defined by the structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkOffset2D {
    int32_t x;
    int32_t y;
} VkOffset2D;
```

- \( x \) is the x offset.
- \( y \) is the y offset.
A three-dimensional offset is defined by the structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkOffset3D {
    int32_t x;
    int32_t y;
    int32_t z;
} VkOffset3D;
```

- `x` is the x offset.
- `y` is the y offset.
- `z` is the z offset.

### 3.11.2. Extents

Extents are used to describe the size of a rectangular region of pixels within an image or framebuffer, as (width,height) for two-dimensional images, or as (width,height,depth) for three-dimensional images.

A two-dimensional extent is defined by the structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkExtent2D {
    uint32_t width;
    uint32_t height;
} VkExtent2D;
```

- `width` is the width of the extent.
- `height` is the height of the extent.

A three-dimensional extent is defined by the structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkExtent3D {
    uint32_t width;
    uint32_t height;
    uint32_t depth;
} VkExtent3D;
```

- `width` is the width of the extent.
- `height` is the height of the extent.
- `depth` is the depth of the extent.
3.11.3. Rectangles

Rectangles are used to describe a specified rectangular region of pixels within an image or framebuffer. Rectangles include both an offset and an extent of the same dimensionality, as described above. Two-dimensional rectangles are defined by the structure

```c
// Provided by VK_VERSION_1_0
typedef struct VkRect2D {
    VkOffset2D offset;
    VkExtent2D extent;
} VkRect2D;
```

- `offset` is a `VkOffset2D` specifying the rectangle offset.
- `extent` is a `VkExtent2D` specifying the rectangle extent.

3.11.4. Structure Types

Each value corresponds to a particular structure with a `sType` member with a matching name. As a general rule, the name of each `VkStructureType` value is obtained by taking the name of the structure, stripping the leading `Vk`, prefixing each capital letter with `_`, converting the entire resulting string to upper case, and prefixing it with `VK_STRUCTURE_TYPE_`. For example, structures of type `VkImageCreateInfo` correspond to a `VkStructureType` value of `VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO`, and thus a structure of this type must have its `sType` member set to this value before it is passed to the API.

The values `VK_STRUCTURE_TYPE_LOADER_INSTANCE_CREATE_INFO` and `VK_STRUCTURE_TYPE_LOADER_DEVICE_CREATE_INFO` are reserved for internal use by the loader, and do not have corresponding Vulkan structures in this Specification.

Structure types supported by the Vulkan API include:

```c
// Provided by VK_VERSION_1_0
typedef enum VkStructureType {
    VK_STRUCTURE_TYPE_APPLICATION_INFO = 0,
    VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO = 1,
    VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO = 2,
    VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO = 3,
    VK_STRUCTURE_TYPE_SUBMIT_INFO = 4,
    VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO = 5,
    VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE = 6,
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO = 7,
    VK_STRUCTURE_TYPE_FENCE_CREATE_INFO = 8,
    VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO = 9,
    VK_STRUCTURE_TYPE_EVENT_CREATE_INFO = 10,
    VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO = 11,
    VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO = 12,
    VK_STRUCTURE_TYPE_BUFFER_VIEW_CREATE_INFO = 13,
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO = 14,
};
```
VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO = 15,
VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO = 16,
VK_STRUCTURE_TYPE_PIPELINE_CACHE_CREATE_INFO = 17,
VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO = 18,
VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO = 19,
VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO = 20,
VK_STRUCTURE_TYPE_PIPELINE_TESSSELLATION_STATE_CREATE_INFO = 21,
VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO = 22,
VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO = 23,
VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO = 24,
VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO = 25,
VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO = 26,
VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO = 27,
VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO = 28,
VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO = 29,
VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO = 30,
VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO = 31,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO = 32,
VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO = 33,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO = 34,
VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET = 35,
VK_STRUCTURE_TYPE_COPY_DESCRIPTOR_SET = 36,
VK_STRUCTURE_TYPE_FRAMEBUFFER_CREATE_INFO = 37,
VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO = 38,
VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO = 39,
VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO = 40,
VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO = 41,
VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO = 42,
VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO = 43,
VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER = 44,
VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER = 45,
VK_STRUCTURE_TYPE_MEMORY_BARRIER = 46,
VK_STRUCTURE_TYPE_LOADER_INSTANCE_CREATE_INFO = 47,
VK_STRUCTURE_TYPE_LOADER_DEVICE_CREATE_INFO = 48,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_PROPERTIES = 1000094000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO = 1000157000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO = 1000157001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES = 1000083000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS = 1000127000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO = 1000127001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO = 1000060000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO = 1000060003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES = 1000083000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS = 1000127000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO = 1000127001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO = 1000060000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO = 1000060003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO = 1000060004,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO = 1000060005,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO = 1000060006,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO = 1000060013,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO = 1000060014,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES = 1000070000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO = 1000070001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2 = 1000146000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2 = 1000146001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2 = 1000146002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2 = 1000146003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2 = 1000146004,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2 = 1000059000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2 = 1000059001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2 = 1000059002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2 = 1000059003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2 = 1000059004,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2 = 1000059005,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2 = 1000059006,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2 = 1000059007,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2 = 1000059008,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_POINT_CLIPPING_PROPERTIES = 1000117000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO = 1000117001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_IMAGE_VIEW_USAGE_CREATE_INFO = 1000117002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO = 1000117003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO = 1000053000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES = 1000053001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES = 1000053002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES = 1000120000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PROTECTED_SUBMIT_INFO = 1000145000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_FEATURES = 1000145001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_PROPERTIES = 1000145002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DEVICE_QUEUE_INFO_2 = 1000145003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO = 1000156000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO = 1000156001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO = 1000156002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_IMAGE_PLANE_MEMORY_REQUIREMENTS_INFO = 1000156003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_YCBCR_CONVERSION_FEATURES = 1000156004,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_IMAGE_FORMAT_PROPERTIES = 1000156005,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO = 1000085000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_IMAGE_FORMAT_INFO = 1000071000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES = 1000071001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_INFO = 1000071002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES = 1000071003,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES = 1000071004,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO = 1000072000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO = 1000072001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXPORT_MEMORY_ALLOCATE_INFO = 1000072002,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_FENCE_INFO = 1000112000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_FENCE_PROPERTIES = 1000112001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO = 1000113000,
// Provided by VK_VERSION_1_1
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO = 1000077000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO = 1000076000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES = 1000076001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES = 1000168000,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT = 1000168001,
// Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES = 1000063000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_FEATURES = 49,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_PROPERTIES = 50,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_FEATURES = 51,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_PROPERTIES = 52,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO = 1000147000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2 = 1000109000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2 = 1000109001,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_2 = 1000109002,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SUBPASS_DEPENDENCY_2 = 1000109003,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2 = 1000109004,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO = 1000109005,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SUBPASS_END_INFO = 1000109006,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES = 1000177000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES = 1000196000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES = 1000180000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES = 1000082000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES = 1000197000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_BINDING_FLAGS_CREATE_INFO = 1000161000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_FEATURES = 1000161001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_PROPERTIES = 1000161002,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_allocate_info = 1000161003,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_LAYOUT_SUPPORT = 1000161004,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES = 1000199000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE = 1000199001,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SCALAR_BLOCK_LAYOUT_FEATURES = 1000221000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_IMAGE_STENCIL_USAGE_CREATE_INFO = 1000246000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_FILTER_MINMAX_PROPERTIES = 1000130000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SAMPLER_REDUCTION_MODE_CREATE_INFO = 1000130001,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_MEMORY_MODEL_FEATURES = 1000211000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER_FEATURES = 1000108000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO = 1000108001,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO = 1000108002,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO = 1000108003,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_UNIFORM_BUFFER_STANDARD_LAYOUT_FEATURES = 1000253000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES = 1000175000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES = 1000241000,
   // Provided by VK_VERSION_1_2
AttachmentReferenceStencilLayout = 1000241001,
   // Provided by VK_VERSION_1_2
AttachmentDescriptionStencilLayout = 1000241002,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_HOST_QUERY_RESET_FEATURES = 1000261000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_FEATURES = 1000207000,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_PROPERTIES = 1000207001,
   // Provided by VK_VERSION_1_2
SemaphoreTypeCreateInfo = 1000207002,
   // Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_TIMELINE_SEMAPHORE_SUBMIT_INFO = 1000207003,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SEMAPHORE_WAIT_INFO = 1000207004,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_SEMAPHORE_SIGNAL_INFO = 1000207005,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS_FEATURES = 1000257000,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_BUFFER_DEVICE_ADDRESS_INFO = 1000244001,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_BUFFER_OPAQUE_CAPTURE_ADDRESS_CREATE_INFO = 1000257002,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_MEMORY_OPAQUE_CAPTURE_ADDRESS_ALLOCATE_INFO = 1000257003,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_DEVICE_MEMORY_OPAQUE_CAPTURE_ADDRESS_INFO = 1000257004,
// Provided by VK_VERSION_1_2
VK_STRUCTURE_TYPE_PHYSICALDEVICE_VULKAN_1_3_FEATURES = 53,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_VULKAN_1_3_PROPERTIES = 54,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PIPELINE_CREATION_FEEDBACK_CREATE_INFO = 1000192000,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
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// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
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// Provided by VK_VERSION_1_3
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// Provided by VK_VERSION_1_3
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// Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_TERMINATE_INVOCATION_FEATURES = 1000215000,
VK_STRUCTURE_TYPE_COMMAND_BUFFER_SUBMIT_INFO = 1000314006,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SYNCHRONIZATION_2_FEATURES = 1000314007,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ZERO_INITIALIZE_WORKGROUP_MEMORY_FEATURES = 1000325000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_ROBUSTNESS_FEATURES = 1000335000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_COPY_BUFFER_INFO_2 = 1000337000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_COPY_IMAGE_INFO_2 = 1000337001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_COPY_BUFFER_TO_IMAGE_INFO_2 = 1000337002,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_COPY_IMAGE_TO_BUFFER_INFO_2 = 1000337003,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_BLIT_IMAGE_INFO_2 = 1000337004,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_RESOLVE_IMAGE_INFO_2 = 1000337005,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_BUFFER_COPY_2 = 1000337006,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_IMAGE_COPY_2 = 1000337007,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_IMAGE_BLIT_2 = 1000337008,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_BUFFER_IMAGE_COPY_2 = 1000337009,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_IMAGE_RESOLVE_2 = 1000337010,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_SIZE_CONTROL_PROPERTIES = 1000225000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_REQUIRED_SUBGROUP_SIZE_CREATE_INFO = 1000225001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_FEATURES = 1000138000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_PROPERTIES = 1000138001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET_INLINE_UNIFORM_BLOCK = 1000138002,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_INLINE_UNIFORM_BLOCK_CREATE_INFO = 1000138003,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXTURE_COMPRESSION_ASTC_HDR_FEATURES = 1000066000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_RENDERING_INFO = 1000044000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_RENDERING_ATTACHMENT_INFO = 1000044001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PIPELINE_RENDERING_CREATE_INFO = 1000044002,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DYNAMIC_RENDERING_FEATURES = 1000044003,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_RENDERING_INFO = 1000044004,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_FEATURES = 1000280000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_PROPERTIES = 1000280001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXEL_BUFFER_ALIGNMENT_PROPERTIES = 1000281001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_3 = 1000360000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_4_FEATURES = 1000413000,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_4_PROPERTIES = 1000413001,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_DEVICE_BUFFER_MEMORY_REQUIREMENTS = 1000413002,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_DEVICE_IMAGE_MEMORY_REQUIREMENTS = 1000413003,
   // Provided by VK_VERSION_1_3
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTER_FEATURES = VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES,
   // Provided by VK_VERSION_1_1
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETER_FEATURES = VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES,
   // Provided by VK_VERSION_1_1

3.12. API Name Aliases

A small number of APIs did not follow the naming conventions when initially defined. For consistency, when we discover an API name that violates the naming conventions, we rename it in the Specification, XML, and header files. For backwards compatibility, the original (incorrect) name is retained as a “typo alias”. The alias is deprecated and should not be used, but will be retained indefinitely.

**Note**

VK_STENCIL_FRONT_AND_BACK is an example of a typo alias. It was initially defined as part of VkStencilFaceFlagBits. Once the naming inconsistency was noticed, it was renamed to VK_STENCIL_FACE_FRONT_AND_BACK, and the old name was aliased to the correct name.
Chapter 4. Initialization

Before using Vulkan, an application must initialize it by loading the Vulkan commands, and creating a `VkInstance` object.

4.1. Command Function Pointers

Vulkan commands are not necessarily exposed by static linking on a platform. Commands to query function pointers for Vulkan commands are described below.

Note
When extensions are promoted or otherwise incorporated into another extension or Vulkan core version, command aliases may be included. Whilst the behavior of each command alias is identical, the behavior of retrieving each alias's function pointer is not. A function pointer for a given alias can only be retrieved if the extension or version that introduced that alias is supported and enabled, irrespective of whether any other alias is available.

Function pointers for all Vulkan commands can be obtained with the command:

```c
// Provided by VK_VERSION_1_0
PFN_vkVoidFunction vkGetInstanceProcAddr(
    VkInstance instance,
    const char* pName);
```

- `instance` is the instance that the function pointer will be compatible with, or NULL for commands not dependent on any instance.
- `pName` is the name of the command to obtain.

`vkGetInstanceProcAddr` itself is obtained in a platform- and loader- specific manner. Typically, the loader library will export this command as a function symbol, so applications can link against the loader library, or load it dynamically and look up the symbol using platform-specific APIs.

The table below defines the various use cases for `vkGetInstanceProcAddr` and expected return value (“fp” is “function pointer”) for each case. A valid returned function pointer (“fp”) must not be NULL.

The returned function pointer is of type `PFN_vkVoidFunction`, and must be cast to the type of the command being queried before use.

<table>
<thead>
<tr>
<th>instance</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>*¹</td>
<td>NULL</td>
<td>undefined</td>
</tr>
<tr>
<td>invalid non-NULL instance</td>
<td>*¹</td>
<td>undefined</td>
</tr>
<tr>
<td>NULL</td>
<td><code>global command²</code></td>
<td>fp</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>instance</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NULL</td>
<td>vkGetInstanceProcAddr</td>
<td>fp&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td>instance</td>
<td>vkGetInstanceProcAddr</td>
<td>fp</td>
</tr>
<tr>
<td>instance</td>
<td>core dispatchable command</td>
<td>fp&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>instance</td>
<td>enabled instance extension dispatchable command for instance</td>
<td>fp&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>instance</td>
<td>available device extension&lt;sup&gt;4&lt;/sup&gt; dispatchable command for instance</td>
<td>fp&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>any other case, not covered above</td>
<td></td>
<td>NULL</td>
</tr>
</tbody>
</table>

1. "*" means any representable value for the parameter (including valid values, invalid values, and NULL).

2. The global commands are: `vkEnumerateInstanceVersion`, `vkEnumerateInstanceExtensionProperties`, `vkEnumerateInstanceLayerProperties`, and `vkCreateInstance`. Dispatchable commands are all other commands which are not global.

3. The returned function pointer **must** only be called with a dispatchable object (the first parameter) that is `instance` or a child of `instance`, e.g. `VkInstance`, `VkPhysicalDevice`, `VkDevice`, `VkQueue`, or `VkCommandBuffer`.

4. An “available device extension” is a device extension supported by any physical device enumerated by `instance`.

5. Starting with Vulkan 1.2, `vkGetInstanceProcAddr` can resolve itself with a NULL instance pointer.

### Valid Usage (Implicit)

- VUID-vkGetInstanceProcAddr-instance-parameter
  - If `instance` is not NULL, `instance` **must** be a valid `VkInstance` handle
- VUID-vkGetInstanceProcAddr-pName-parameter
  - `pName` **must** be a null-terminated UTF-8 string

In order to support systems with multiple Vulkan implementations, the function pointers returned by `vkGetInstanceProcAddr` **may** point to dispatch code that calls a different real implementation for different `VkDevice` objects or their child objects. The overhead of the internal dispatch for `VkDevice`...
objects can be avoided by obtaining device-specific function pointers for any commands that use a
device or device-child object as their dispatchable object. Such function pointers can be obtained
with the command:

```c
// Provided by VK_VERSION_1_0
PFN_vkVoidFunction vkGetDeviceProcAddr(
    VkDevice device,
    const char* pName)
```

The table below defines the various use cases for `vkGetDeviceProcAddr` and expected return value
(“fp” is “function pointer”) for each case. A valid returned function pointer (“fp”) must not be NULL.

<table>
<thead>
<tr>
<th>device</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NULL</td>
<td>*1</td>
<td>undefined</td>
</tr>
<tr>
<td>invalid device</td>
<td>*1</td>
<td>undefined</td>
</tr>
<tr>
<td>device</td>
<td>NULL</td>
<td>undefined</td>
</tr>
<tr>
<td>device</td>
<td>requested core version2</td>
<td>fp4</td>
</tr>
<tr>
<td></td>
<td>device-level dispatchable command3</td>
<td></td>
</tr>
<tr>
<td>device</td>
<td>enabled extension device-level dispatchable command3</td>
<td>fp4</td>
</tr>
<tr>
<td>any other case, not covered above</td>
<td>NULL</td>
<td></td>
</tr>
</tbody>
</table>

1

“*” means any representable value for the parameter (including valid values, invalid values, and NULL).

2

Device-level commands which are part of the core version specified by `VkApplicationInfo::apiVersion` when creating the instance will always return a valid function pointer. Core commands beyond that version which are supported by the implementation may either return NULL or a function pointer, though the function pointer must not be called.

3

In this function, device-level excludes all physical-device-level commands.

4

The returned function pointer must only be called with a dispatchable object (the first parameter) that is device or a child of device e.g. `VkDevice`, `VkQueue`, or `VkCommandBuffer`.


Valid Usage (Implicit)

- VUID-vkGetDeviceProcAddr-device-parameter
  device must be a valid VkDevice handle

- VUID-vkGetDeviceProcAddr-pName-parameter
  pName must be a null-terminated UTF-8 string

The definition of PFN_vkVoidFunction is:

```c
// Provided by VK_VERSION_1_0
typedef void (VKAPI_PTR *PFN_vkVoidFunction)(void);
```

This type is returned from command function pointer queries, and must be cast to an actual command function pointer before use.

### 4.1.1. Extending Physical Device Core Functionality

New core physical-device-level functionality can be used when the physical-device version is greater than or equal to the version of Vulkan that added the new functionality. The Vulkan version supported by a physical device can be obtained by calling vkGetPhysicalDeviceProperties.

### 4.1.2. Extending Physical Device From Device Extensions

When the VK_KHR_get_physical_device_properties2 extension is enabled, or when both the instance and the physical-device versions are at least 1.1, physical-device-level functionality of a device extension can be used with a physical device if the corresponding extension is enumerated by vkEnumerateDeviceExtensionProperties for that physical device, even before a logical device has been created.

To obtain a function pointer for a physical-device-level command from a device extension, an application can use vkGetInstanceProcAddr. This function pointer may point to dispatch code, which calls a different real implementation for different VkPhysicalDevice objects. Applications must not use a VkPhysicalDevice in any command added by an extension or core version that is not supported by that physical device.

Device extensions may define structures that can be added to the pNext chain of physical-device-level commands.

### 4.2. Instances

There is no global state in Vulkan and all per-application state is stored in a VkInstance object. Creating a VkInstance object initializes the Vulkan library and allows the application to pass information about itself to the implementation.

Instances are represented by VkInstance handles:
To query the version of instance-level functionality supported by the implementation, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkEnumerateInstanceVersion(
    uint32_t* pApiVersion);
```

- `pApiVersion` is a pointer to a `uint32_t`, which is the version of Vulkan supported by instance-level functionality, encoded as described in Version Numbers.

**Note**

The intended behaviour of `vkEnumerateInstanceVersion` is that an implementation should not need to perform memory allocations and should unconditionally return `VK_SUCCESS`. The loader, and any enabled layers, may return `VK_ERROR_OUT_OF_HOST_MEMORY` in the case of a failed memory allocation.

### Valid Usage (Implicit)

- VUID-vkEnumerateInstanceVersion-pApiVersion-parameter
  - `pApiVersion` must be a valid pointer to a `uint32_t` value

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`

To create an instance object, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateInstance(
    const VkInstanceCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkInstance* pInstance);
```

- `pCreateInfo` is a pointer to a `VkInstanceCreateInfo` structure controlling creation of the instance.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pInstance` points a `VkInstance` handle in which the resulting instance is returned.
vkCreateInstance verifies that the requested layers exist. If not, vkCreateInstance will return VK_ERROR_LAYER_NOT_PRESENT. Next vkCreateInstance verifies that the requested extensions are supported (e.g. in the implementation or in any enabled instance layer) and if any requested extension is not supported, vkCreateInstance must return VK_ERROR_EXTENSION_NOT_PRESENT. After verifying and enabling the instance layers and extensions the VkInstance object is created and returned to the application. If a requested extension is only supported by a layer, both the layer and the extension need to be specified at vkCreateInstance time for the creation to succeed.

Valid Usage

- VUID-vkCreateInstance-ppEnabledExtensionNames-01388
  All required extensions for each extension in the VkInstanceCreateInfo::ppEnabledExtensionNames list must also be present in that list

Valid Usage (Implicit)

- VUID-vkCreateInstance-pCreateInfo-parameter
  pCreateInfo must be a valid pointer to a valid VkInstanceCreateInfo structure

- VUID-vkCreateInstance-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkCreateInstance-pInstance-parameter
  pInstance must be a valid pointer to a VkInstance handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_INITIALIZATION_FAILED
- VK_ERROR_LAYER_NOT_PRESENT
- VK_ERROR_EXTENSION_NOT_PRESENT
- VK_ERROR_INCOMPATIBLE_DRIVER

The VkInstanceCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkInstanceCreateInfo {
    VkStructureType sType;
```
```c
const void* pNext;
VkInstanceCreateFlags flags;
const VkApplicationInfo* pApplicationInfo;
uint32_t enabledLayerCount;
const char* const* ppEnabledLayerNames;
const char* const* ppEnabledExtensionNames;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **flags** is a bitmask of **VkInstanceCreateFlagBits** indicating the behavior of the instance.
- **pApplicationInfo** is **NULL** or a pointer to a **VkApplicationInfo** structure. If not NULL, this information helps implementations recognize behavior inherent to classes of applications. **VkApplicationInfo** is defined in detail below.
- **enabledLayerCount** is the number of global layers to enable.
- **ppEnabledLayerNames** is a pointer to an array of **enabledLayerCount** null-terminated UTF-8 strings containing the names of layers to enable for the created instance. The layers are loaded in the order they are listed in this array, with the first array element being the closest to the application, and the last array element being the closest to the driver. See the **Layers** section for further details.
- **enabledExtensionCount** is the number of global extensions to enable.
- **ppEnabledExtensionNames** is a pointer to an array of **enabledExtensionCount** null-terminated UTF-8 strings containing the names of extensions to enable.

### Valid Usage (Implicit)

- **VUID-VkInstanceCreateInfo-sType-sType**
  - **sType** must be **VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO**

- **VUID-VkInstanceCreateInfo-pNext-pNext**
  - **pNext** must be **NULL**

- **VUID-VkInstanceCreateInfo-flags-zerobitmask**
  - **flags** must be **0**

- **VUID-VkInstanceCreateInfo-pApplicationInfo-parameter**
  - If **pApplicationInfo** is not **NULL**, **pApplicationInfo** must be a valid pointer to a valid **VkApplicationInfo** structure

- **VUID-VkInstanceCreateInfo-ppEnabledLayerNames-parameter**
  - If **enabledLayerCount** is not **0**, **ppEnabledLayerNames** must be a valid pointer to an array of **enabledLayerCount** null-terminated UTF-8 strings

- **VUID-VkInstanceCreateInfo-ppEnabledExtensionNames-parameter**
  - If **enabledExtensionCount** is not **0**, **ppEnabledExtensionNames** must be a valid pointer to an array of **enabledExtensionCount** null-terminated UTF-8 strings
```c
// Provided by VK_VERSION_1_0
typedef enum VkInstanceCreateFlagBits {
} VkInstanceCreateFlagBits;
```

**Note**
All bits for this type are defined by extensions, and none of those extensions are enabled in this build of the specification.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkInstanceCreateFlags;
```

`VkInstanceCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The `VkApplicationInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkApplicationInfo {
    VkStructureType sType;
    const void* pNext;
    const char* pApplicationName;
    uint32_t applicationVersion;
    const char* pEngineName;
    uint32_t engineVersion;
    uint32_t apiVersion;
} VkApplicationInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `pApplicationName` is `NULL` or is a pointer to a null-terminated UTF-8 string containing the name of the application.
- `applicationVersion` is an unsigned integer variable containing the developer-supplied version number of the application.
- `pEngineName` is `NULL` or is a pointer to a null-terminated UTF-8 string containing the name of the engine (if any) used to create the application.
- `engineVersion` is an unsigned integer variable containing the developer-supplied version number of the engine used to create the application.
- `apiVersion` must be the highest version of Vulkan that the application is designed to use, encoded as described in Version Numbers. The patch version number specified in `apiVersion` is ignored when creating an instance object. The variant version of the instance must match that requested in `apiVersion`.

Vulkan 1.0 implementations were required to return `VK_ERROR_INCOMPATIBLE_DRIVER` if `apiVersion` was larger than 1.0. Implementations that support Vulkan 1.1 or later must not return...
VK_ERROR_INCOMPATIBLE_DRIVER for any value of apiVersion.

Note

Because Vulkan 1.0 implementations may fail with VK_ERROR_INCOMPATIBLE_DRIVER, applications should determine the version of Vulkan available before calling vkCreateInstance. If the vkGetInstanceProcAddr returns NULL for vkEnumerateInstanceVersion, it is a Vulkan 1.0 implementation. Otherwise, the application can call vkEnumerateInstanceVersion to determine the version of Vulkan.

As long as the instance supports at least Vulkan 1.1, an application can use different versions of Vulkan with an instance than it does with a device or physical device.

Note

The Khronos validation layers will treat apiVersion as the highest API version the application targets, and will validate API usage against the minimum of that version and the implementation version (instance or device, depending on context). If an application tries to use functionality from a greater version than this, a validation error will be triggered.

For example, if the instance supports Vulkan 1.1 and three physical devices support Vulkan 1.0, Vulkan 1.1, and Vulkan 1.2, respectively, and if the application sets apiVersion to 1.2, the application can use the following versions of Vulkan:

• Vulkan 1.0 can be used with the instance and with all physical devices.
• Vulkan 1.1 can be used with the instance and with the physical devices that support Vulkan 1.1 and Vulkan 1.2.
• Vulkan 1.2 can be used with the physical device that supports Vulkan 1.2.

If we modify the above example so that the application sets apiVersion to 1.1, then the application must not use Vulkan 1.2 functionality on the physical device that supports Vulkan 1.2.

Note

Providing a NULL VkInstanceCreateInfo::pApplicationInfo or providing an apiVersion of 0 is equivalent to providing an apiVersion of VK_MAKE_API_VERSION(0,1,0,0).

Valid Usage

• VUID-VkApplicationInfo-apiVersion-04010
  If apiVersion is not 0, then it must be greater than or equal to VK_API_VERSION_1_0
Valid Usage (Implicit)

• VUID-VkApplicationInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_APPLICATION_INFO

• VUID-VkApplicationInfo-pNext-pNext
  pNext must be NULL

• VUID-VkApplicationInfo-pApplicationName-parameter
  If pApplicationName is not NULL, pApplicationName must be a null-terminated UTF-8 string

• VUID-VkApplicationInfo-pEngineName-parameter
  If pEngineName is not NULL, pEngineName must be a null-terminated UTF-8 string

To destroy an instance, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyInstance(
    VkInstance instance,
    const VkAllocationCallbacks* pAllocator);
```

• instance is the handle of the instance to destroy.
• pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

• VUID-vkDestroyInstance-instance-00629
  All child objects created using instance must have been destroyed prior to destroying instance

• VUID-vkDestroyInstance-instance-00630
  If VkAllocationCallbacks were provided when instance was created, a compatible set of callbacks must be provided here

• VUID-vkDestroyInstance-instance-00631
  If no VkAllocationCallbacks were provided when instance was created, pAllocator must be NULL

Valid Usage (Implicit)

• VUID-vkDestroyInstance-instance-parameter
  If instance is not NULL, instance must be a valid VkInstance handle

• VUID-vkDestroyInstance-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
Host Synchronization

- Host access to instance must be externally synchronized
- Host access to all VkPhysicalDevice objects enumerated from instance must be externally synchronized
Chapter 5. Devices and Queues

Once Vulkan is initialized, devices and queues are the primary objects used to interact with a Vulkan implementation.

Vulkan separates the concept of physical and logical devices. A physical device usually represents a single complete implementation of Vulkan (excluding instance-level functionality) available to the host, of which there are a finite number. A logical device represents an instance of that implementation with its own state and resources independent of other logical devices.

Physical devices are represented by VkPhysicalDevice handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_HANDLE(VkPhysicalDevice)
```

### 5.1. Physical Devices

To retrieve a list of physical device objects representing the physical devices installed in the system, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkEnumeratePhysicalDevices(
    VkInstance instance, 
    uint32_t* pPhysicalDeviceCount, 
    VkPhysicalDevice* pPhysicalDevices);
```

- `instance` is a handle to a Vulkan instance previously created with `vkCreateInstance`.
- `pPhysicalDeviceCount` is a pointer to an integer related to the number of physical devices available or queried, as described below.
- `pPhysicalDevices` is either `NULL` or a pointer to an array of `VkPhysicalDevice` handles.

If `pPhysicalDevices` is `NULL`, then the number of physical devices available is returned in `pPhysicalDeviceCount`. Otherwise, `pPhysicalDeviceCount` must point to a variable set by the user to the number of elements in the `pPhysicalDevices` array, and on return the variable is overwritten with the number of handles actually written to `pPhysicalDevices`. If `pPhysicalDeviceCount` is less than the number of physical devices available, at most `pPhysicalDeviceCount` structures will be written, and `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available physical devices were returned.

### Valid Usage (Implicit)

- `VUID-vkEnumeratePhysicalDevices-instance-parameter`  
  `instance` must be a valid `VkInstance` handle
- `VUID-vkEnumeratePhysicalDevices-pPhysicalDeviceCount-parameter`
\textbf{pPhysicalDeviceCount} must be a valid pointer to a uint32_t value

- VUID-vkEnumeratePhysicalDevices-pPhysicalDevices-parameter
  If the value referenced by \texttt{pPhysicalDeviceCount} is not 0, and \texttt{pPhysicalDevices} is not NULL, \texttt{pPhysicalDevices} must be a valid pointer to an array of \texttt{pPhysicalDeviceCount} \texttt{VkPhysicalDevice} handles

\section*{Return Codes}

\textbf{Success}
- VK\_SUCCESS
- VK\_INCORRECT

\textbf{Failure}
- VK\_ERROR\_OUT\_OF\_HOST\_MEMORY
- VK\_ERROR\_OUT\_OF\_DEVICE\_MEMORY
- VK\_ERROR\_INITIAL\_IZATION\_FAILED

To query general properties of physical devices once enumerated, call:

\begin{verbatim}
// Provided by VK\_VERSION\_1\_0
void vkGetPhysicalDeviceProperties(  
  VkPhysicalDevice physicalDevice,  
  VkPhysicalDeviceProperties* pProperties);
\end{verbatim}

- \texttt{physicalDevice} is the handle to the physical device whose properties will be queried.
- \texttt{pProperties} is a pointer to a \texttt{VkPhysicalDeviceProperties} structure in which properties are returned.

\section*{Valid Usage (Implicit)}

- VUID-vkGetPhysicalDeviceProperties-physicalDevice-parameter
  \texttt{physicalDevice} must be a valid \texttt{VkPhysicalDevice} handle

- VUID-vkGetPhysicalDeviceProperties-pProperties-parameter
  \texttt{pProperties} must be a valid pointer to a \texttt{VkPhysicalDeviceProperties} structure

The \texttt{VkPhysicalDeviceProperties} structure is defined as:

\begin{verbatim}
// Provided by VK\_VERSION\_1\_0
typedef struct VkPhysicalDeviceProperties {  
  uint32_t apiVersion;  
  uint32_t driverVersion;  
  uint32_t vendorID;
};
\end{verbatim}
void vkEnumeratePhysicalDevices(
    VkPhysicalDevice* physicalDevices,
    uint32_t deviceCount,
    void* pAllocator, /* Optional */
);

uint32_t deviceID;
VkPhysicalDeviceType deviceType;
char deviceName[VK_MAX_PHYSICAL_DEVICE_NAME_SIZE];
pipelineCacheUID[VK_UUID_SIZE];
limits;
sparseProperties;

VkPhysicalDeviceProperties

• **apiVersion** is the version of Vulkan supported by the device, encoded as described in Version Numbers.

• **driverVersion** is the vendor-specified version of the driver.

• **vendorID** is a unique identifier for the *vendor* (see below) of the physical device.

• **deviceID** is a unique identifier for the physical device among devices available from the vendor.

• **deviceType** is a VkPhysicalDeviceType specifying the type of device.

• **deviceName** is an array of VK_MAX_PHYSICAL_DEVICE_NAME_SIZE char containing a null-terminated UTF-8 string which is the name of the device.

• **pipelineCacheUUID** is an array of VK_UUID_SIZE uint8_t values representing a universally unique identifier for the device.

• **limits** is the VkPhysicalDeviceLimits structure specifying device-specific limits of the physical device. See Limits for details.

• **sparseProperties** is the VkPhysicalDeviceSparseProperties structure specifying various sparse related properties of the physical device. See Sparse Properties for details.

**Note**

The value of **apiVersion** may be different than the version returned by vkEnumerateInstanceVersion; either higher or lower. In such cases, the application must not use functionality that exceeds the version of Vulkan associated with a given object. The pApiVersion parameter returned by vkEnumerateInstanceVersion is the version associated with a VkInstance and its children, except for a VkPhysicalDevice and its children. VkPhysicalDeviceProperties::apiVersion is the version associated with a VkPhysicalDevice and its children.

**Note**

The encoding of **driverVersion** is implementation-defined. It may not use the same encoding as **apiVersion**. Applications should follow information from the vendor on how to extract the version information from **driverVersion**.

On implementations that claim support for the Roadmap 2022 profile, the major and minor version expressed by **apiVersion** must be at least Vulkan 1.3.

The **vendorID** and **deviceID** fields are provided to allow applications to adapt to device characteristics that are not adequately exposed by other Vulkan queries.
These may include performance profiles, hardware errata, or other characteristics.

The vendor identified by vendorID is the entity responsible for the most salient characteristics of the underlying implementation of the VkPhysicalDevice being queried.

For example, in the case of a discrete GPU implementation, this should be the GPU chipset vendor. In the case of a hardware accelerator integrated into a system-on-chip (SoC), this should be the supplier of the silicon IP used to create the accelerator.

If the vendor has a PCI vendor ID, the low 16 bits of vendorID must contain that PCI vendor ID, and the remaining bits must be set to zero. Otherwise, the value returned must be a valid Khronos vendor ID, obtained as described in the Vulkan Documentation and Extensions: Procedures and Conventions document in the section “Registering a Vendor ID with Khronos”. Khronos vendor IDs are allocated starting at 0x10000, to distinguish them from the PCI vendor ID namespace. Khronos vendor IDs are symbolically defined in the VkVendorId type.

The vendor is also responsible for the value returned in deviceID. If the implementation is driven primarily by a PCI device with a PCI device ID, the low 16 bits of deviceID must contain that PCI device ID, and the remaining bits must be set to zero. Otherwise, the choice of what values to return may be dictated by operating system or platform policies - but should uniquely identify both the device version and any major configuration options (for example, core count in the case of multicore devices).

The same device ID should be used for all physical implementations of that device version and configuration. For example, all uses of a specific silicon IP GPU version and configuration should use the same device ID, even if those uses occur in different SoCs.

Khronos vendor IDs which may be returned in VkPhysicalDeviceProperties::vendorID are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkVendorId {
    VK_VENDOR_ID_VIV = 0x10001,
    VK_VENDOR_ID_VSI = 0x10002,
    VK_VENDOR_ID_KAZAN = 0x10003,
    VK_VENDOR_ID_CODEPLAY = 0x10004,
    VK_VENDOR_ID_MESA = 0x10005,
    VK_VENDOR_ID_Pocl = 0x10006,
    VK_VENDOR_ID_MOBILEYE = 0x10007,
} VkVendorId;
```
Khronos vendor IDs may be allocated by vendors at any time. Only the latest canonical versions of this Specification, of the corresponding *vk.xml* API Registry, and of the corresponding *vulkan_core.h* header file must contain all reserved Khronos vendor IDs.

Only Khronos vendor IDs are given symbolic names at present. PCI vendor IDs returned by the implementation can be looked up in the PCI-SIG database.

`VK_MAX_PHYSICAL_DEVICE_NAME_SIZE` is the length in `char` values of an array containing a physical device name string, as returned in `VkPhysicalDeviceProperties::deviceName`.

```c
#define VK_MAX_PHYSICAL_DEVICE_NAME_SIZE 256U
```

The physical device types which may be returned in `VkPhysicalDeviceProperties::deviceType` are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPhysicalDeviceType {
    VK_PHYSICAL_DEVICE_TYPE_OTHER = 0,
    VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU = 1,
    VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU = 2,
    VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU = 3,
    VK_PHYSICAL_DEVICE_TYPE_CPU = 4,
} VkPhysicalDeviceType;
```

- `VK_PHYSICAL_DEVICE_TYPE_OTHER` - the device does not match any other available types.
- `VK_PHYSICALDEVICE_TYPE_INTEGRATED_GPU` - the device is typically one embedded in or tightly coupled with the host.
- `VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU` - the device is typically a separate processor connected to the host via an interlink.
- `VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU` - the device is typically a virtual node in a virtualization environment.
- `VK_PHYSICAL_DEVICE_TYPE_CPU` - the device is typically running on the same processors as the host.

The physical device type is advertised for informational purposes only, and does not directly affect the operation of the system. However, the device type may correlate with other advertised properties or capabilities of the system, such as how many memory heaps there are.

To query general properties of physical devices once enumerated, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceProperties2(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceProperties2* pProperties);
```
- `physicalDevice` is the handle to the physical device whose properties will be queried.
- `pProperties` is a pointer to a `VkPhysicalDeviceProperties2` structure in which properties are returned.

Each structure in `pProperties` and its `pNext` chain contains members corresponding to implementation-dependent properties, behaviors, or limits. `vkGetPhysicalDeviceProperties2` fills in each member to specify the corresponding value for the implementation.

### Valid Usage (Implicit)

- **VUID-vkGetPhysicalDeviceProperties2-physicalDevice-parameter**
  `physicalDevice` must be a valid `VkPhysicalDevice` handle.

- **VUID-vkGetPhysicalDeviceProperties2-pProperties-parameter**
  `pProperties` must be a valid pointer to a `VkPhysicalDeviceProperties2` structure.

The `VkPhysicalDeviceProperties2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceProperties2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceProperties properties;
} VkPhysicalDeviceProperties2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `properties` is a `VkPhysicalDeviceProperties` structure describing properties of the physical device. This structure is written with the same values as if it were written by `vkGetPhysicalDeviceProperties`.

The `pNext` chain of this structure is used to extend the structure with properties defined by extensions.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceProperties2-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2`.

- **VUID-VkPhysicalDeviceProperties2-pNext-pNext**
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkPhysicalDeviceDepthStencilResolveProperties`, `VkPhysicalDeviceDescriptorIndexingProperties`, `VkPhysicalDeviceDriverProperties`, `VkPhysicalDeviceFloatControlsProperties`, `VkPhysicalDeviceIDProperties`, `VkPhysicalDeviceInlineUniformBlockProperties`, `VkPhysicalDeviceMaintenance3Properties`, `VkPhysicalDeviceMaintenance4Properties`,...
The ** VkPhysicalDeviceVulkan11Properties** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceVulkan11Properties {
    VkStructureType sType;
    void* pNext;
    uint8_t deviceUUID[VK_UUID_SIZE];
    uint8_t driverUUID[VK_UUID_SIZE];
    uint8_t deviceLUID[VK_LUID_SIZE];
    uint32_t deviceNodeMask;
    VkBool32 deviceLUIDValid;
    uint32_t subgroupSize;
    VkShaderStageFlags subgroupSupportedStages;
    VkSubgroupFeatureFlags subgroupSupportedOperations;
    VkBool32 subgroupQuadOperationsInAllStages;
    VkPointClippingBehavior pointClippingBehavior;
    uint32_t maxMultiviewViewCount;
    uint32_t maxMultiviewInstanceIndex;
    VkBool32 protectedNoFault;
    uint32_t maxPerSetDescriptors;
    VkDeviceSize maxMemoryAllocationSize;
} VkPhysicalDeviceVulkan11Properties;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **deviceUUID** is an array of **VK_UUID_SIZE uint8_t** values representing a universally unique identifier for the device.
- **driverUUID** is an array of **VK_UUID_SIZE uint8_t** values representing a universally unique identifier for the driver build in use by the device.
- **deviceLUID** is an array of **VK_LUID_SIZE uint8_t** values representing a locally unique identifier for the device.
- **deviceNodeMask** is a **uint32_t** bitfield identifying the node within a linked device adapter corresponding to the device.
• *deviceLUIDValid* is a boolean value that will be **VK_TRUE** if *deviceLUID* contains a valid LUID and *deviceNodeMask* contains a valid node mask, and **VK_FALSE** if they do not.

• *subgroupSize* is the default number of invocations in each subgroup. *subgroupSize* is at least 1 if any of the physical device's queues support **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT**. *subgroupSize* is a power-of-two.

• *subgroupSupportedStages* is a bitfield of *VkShaderStageFlagBits* describing the shader stages that group operations with subgroup scope are supported in. *subgroupSupportedStages* will have the **VK_SHADER_STAGE_COMPUTE_BIT** bit set if any of the physical device's queues support **VK_QUEUE_COMPUTE_BIT**.

• *subgroupSupportedOperations* is a bitmask of *VkSubgroupFeatureFlagBits* specifying the sets of group operations with subgroup scope supported on this device. *subgroupSupportedOperations* will have the **VK_SUBGROUP_FEATURE_BASIC_BIT** bit set if any of the physical device's queues support **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT**.

• *subgroupQuadOperationsInAllStages* is a boolean specifying whether quad group operations are available in all stages, or are restricted to fragment and compute stages.

• *pointClippingBehavior* is a *VkPointClippingBehavior* value specifying the point clipping behavior supported by the implementation.

• *maxMultiviewViewCount* is one greater than the maximum view index that can be used in a subpass.

• *maxMultiviewInstanceIndex* is the maximum valid value of instance index allowed to be generated by a drawing command recorded within a subpass of a multiview render pass instance.

• *protectedNoFault* specifies how an implementation behaves when an application attempts to write to unprotected memory in a protected queue operation, read from protected memory in an unprotected queue operation, or perform a query in a protected queue operation. If this limit is **VK_TRUE**, such writes will be discarded or have undefined values written, reads and queries will return undefined values. If this limit is **VK_FALSE**, applications must not perform these operations. See Protected Memory Access Rules for more information.

• *maxPerSetDescriptors* is a maximum number of descriptors (summed over all descriptor types) in a single descriptor set that is guaranteed to satisfy any implementation-dependent constraints on the size of a descriptor set itself. Applications can query whether a descriptor set that goes beyond this limit is supported using *vkGetDescriptorSetLayoutSupport*.

• *maxMemoryAllocationSize* is the maximum size of a memory allocation that can be created, even if there is more space available in the heap.

If the *VkPhysicalDeviceVulkan11Properties* structure is included in the *pNext* chain of the *VkPhysicalDeviceProperties2* structure passed to *vkGetPhysicalDeviceProperties2*, it is filled in with each corresponding implementation-dependent property.

These properties correspond to Vulkan 1.1 functionality.

The members of *VkPhysicalDeviceVulkan11Properties* have the same values as the corresponding members of *VkPhysicalDeviceIDProperties*, *VkPhysicalDeviceSubgroupProperties*, *VkPhysicalDevicePointClippingProperties*, *VkPhysicalDeviceMultiviewProperties*, and *VkPhysicalDeviceIDProperties*.
VkPhysicalDeviceProtectedMemoryProperties, and VkPhysicalDeviceMaintenance3Properties.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceVulkan11Properties-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_PROPERTIES

The *VkPhysicalDeviceVulkan12Properties* structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceVulkan12Properties {
    VkStructureType sType;
    void* pNext;
    VkDriverId driverID;
    char driverName[VK_MAX_DRIVER_NAME_SIZE];
    char driverInfo[VK_MAX_DRIVER_INFO_SIZE];
    VkConformanceVersion conformanceVersion;
    VkShaderFloatControlsIndependence denormBehaviorIndependence;
    VkShaderFloatControlsIndependence roundingModeIndependence;
    VkBool32 shaderSignedZeroInfNanPreserveFloat16;
    VkBool32 shaderSignedZeroInfNanPreserveFloat32;
    VkBool32 shaderSignedZeroInfNanPreserveFloat64;
    VkBool32 shaderDenormPreserveFloat16;
    VkBool32 shaderDenormPreserveFloat32;
    VkBool32 shaderDenormPreserveFloat64;
    VkBool32 shaderDenormFlushToZeroFloat16;
    VkBool32 shaderDenormFlushToZeroFloat32;
    VkBool32 shaderDenormFlushToZeroFloat64;
    VkBool32 shaderRoundingModeRTEFloat16;
    VkBool32 shaderRoundingModeRTEFloat32;
    VkBool32 shaderRoundingModeRTEFloat64;
    VkBool32 shaderRoundingModeRTZFloat16;
    VkBool32 shaderRoundingModeRTZFloat32;
    VkBool32 shaderRoundingModeRTZFloat64;
   uint32_t maxUpdateAfterBindDescriptorsInAllPools;
   uint32_t
} VkPhysicalDeviceVulkan12Properties;
```
maxPerStageDescriptorUpdateAfterBindUniformBuffers;
    uint32_t maxPerStageDescriptorUpdateAfterBindStorageBuffers;
    uint32_t maxPerStageDescriptorUpdateAfterBindSampledImages;
    uint32_t maxPerStageDescriptorUpdateAfterBindStorageImages;
    uint32_t maxPerStageDescriptorUpdateAfterBindInputAttachments;
    uint32_t maxPerStageUpdateAfterBindResources;
    uint32_t maxDescriptorSetUpdateAfterBindSamplers;
    uint32_t maxDescriptorSetUpdateAfterBindUniformBuffers;
    uint32_t maxDescriptorSetUpdateAfterBindUniformBuffersDynamic;
    uint32_t maxDescriptorSetUpdateAfterBindStorageBuffers;
    uint32_t maxDescriptorSetUpdateAfterBindStorageBuffersDynamic;
    uint32_t maxDescriptorSetUpdateAfterBindSampledImages;
    uint32_t maxDescriptorSetUpdateAfterBindStorageImages;
    uint32_t maxDescriptorSetUpdateAfterBindInputAttachments;
    VkResolveModeFlags supportedDepthResolveModes;
    VkResolveModeFlags supportedStencilResolveModes;
    VkBool32 independentResolveNone;
    VkBool32 independentResolve;
    VkBool32 filterMinmaxSingleComponentFormats;
    VkBool32 filterMinmaxImageComponentMapping;
    uint64_t maxTimelineSemaphoreValueDifference;
    VkSampleCountFlags framebufferIntegerColorSampleCounts;
} VkPhysicalDeviceVulkan12Properties;

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **driverID** is a unique identifier for the driver of the physical device.
- **driverName** is an array of `VK_MAX_DRIVER_NAME_SIZE` `char` containing a null-terminated UTF-8 string which is the name of the driver.
- **driverInfo** is an array of `VK_MAX_DRIVER_INFO_SIZE` `char` containing a null-terminated UTF-8 string with additional information about the driver.
- **conformanceVersion** is the version of the Vulkan conformance test this driver is conformant against (see `VkConformanceVersion`).
- **denormBehaviorIndependence** is a `VkShaderFloatControlsIndependence` value indicating whether, and how, denorm behavior can be set independently for different bit widths.
- **roundingModeIndependence** is a `VkShaderFloatControlsIndependence` value indicating whether, and how, rounding modes can be set independently for different bit widths.
• shaderSignedZeroInfNanPreserveFloat16 is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 16-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 16-bit floating-point types.

• shaderSignedZeroInfNanPreserveFloat32 is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 32-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 32-bit floating-point types.

• shaderSignedZeroInfNanPreserveFloat64 is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 64-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 64-bit floating-point types.

• shaderDenormPreserveFloat16 is a boolean value indicating whether denormals can be preserved in 16-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 16-bit floating-point types.

• shaderDenormPreserveFloat32 is a boolean value indicating whether denormals can be preserved in 32-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 32-bit floating-point types.

• shaderDenormPreserveFloat64 is a boolean value indicating whether denormals can be preserved in 64-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 64-bit floating-point types.

• shaderDenormFlushToZeroFloat16 is a boolean value indicating whether denormals can be flushed to zero in 16-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 16-bit floating-point types.

• shaderDenormFlushToZeroFloat32 is a boolean value indicating whether denormals can be flushed to zero in 32-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 32-bit floating-point types.

• shaderDenormFlushToZeroFloat64 is a boolean value indicating whether denormals can be flushed to zero in 64-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 64-bit floating-point types.

• shaderRoundingModeRTEFloat16 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 16-bit floating-point types.

• shaderRoundingModeRTEFloat32 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 32-bit floating-point types.

• shaderRoundingModeRTEFloat64 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 64-bit floating-point types.

• shaderRoundingModeRTZFloat16 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 16-bit floating-point types.
shaderRoundingModeRTZFloat32 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 32-bit floating-point types.

shaderRoundingModeRTZFloat64 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 64-bit floating-point types.

maxUpdateAfterBindDescriptorsInAllPools is the maximum number of descriptors (summed over all descriptor types) that can be created across all pools that are created with the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT bit set. Pool creation may fail when this limit is exceeded, or when the space this limit represents is unable to satisfy a pool creation due to fragmentation.

shaderUniformBufferArrayNonUniformIndexingNative is a boolean value indicating whether uniform buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of uniform buffers may execute multiple times in order to access all the descriptors.

shaderSampledImageArrayNonUniformIndexingNative is a boolean value indicating whether sampler and image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of samplers or images may execute multiple times in order to access all the descriptors.

shaderStorageBufferArrayNonUniformIndexingNative is a boolean value indicating whether storage buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage buffers may execute multiple times in order to access all the descriptors.

shaderStorageImageArrayNonUniformIndexingNative is a boolean value indicating whether storage image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage images may execute multiple times in order to access all the descriptors.

shaderInputAttachmentArrayNonUniformIndexingNative is a boolean value indicating whether input attachment descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of input attachments may execute multiple times in order to access all the descriptors.

robustBufferAccessUpdateAfterBind is a boolean value indicating whether robustBufferAccess can be enabled on a device simultaneously with descriptorBindingUniformBufferUpdateAfterBind, descriptorBindingStorageBufferUpdateAfterBind, descriptorBindingUniformTexelBufferUpdateAfterBind, and/or descriptorBindingStorageTexelBufferUpdateAfterBind. If this is VK_FALSE, then either robustBufferAccess must be disabled or all of these update-after-bind features must be disabled.

quadDivergentImplicitLod is a boolean value indicating whether implicit LOD calculations for image operations have well-defined results when the image and/or sampler objects used for the instruction are not uniform within a quad. See Derivative Image Operations.

maxPerStageDescriptorUpdateAfterBindSamplers is similar to maxPerStageDescriptorSamplers but counts descriptors from descriptor sets created with or without the
VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageDescriptorUpdateAfterBindUniformBuffers is similar to maxPerStageDescriptorUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageDescriptorUpdateAfterBindStorageBuffers is similar to maxPerStageDescriptorStorageBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageDescriptorUpdateAfterBindSampledImages is similar to maxPerStageDescriptorSampledImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageDescriptorUpdateAfterBindStorageImages is similar to maxPerStageDescriptorStorageImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageDescriptorUpdateAfterBindInputAttachments is similar to maxPerStageDescriptorInputAttachments but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxPerStageUpdateAfterBindResources is similar to maxPerStageResources but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxDescriptorSetUpdateAfterBindSamplers is similar to maxDescriptorSetSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxDescriptorSetUpdateAfterBindUniformBuffers is similar to maxDescriptorSetUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxDescriptorSetUpdateAfterBindUniformBuffersDynamic is similar to maxDescriptorSetUniformBuffersDynamic but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set. While an application can allocate dynamic uniform buffer descriptors from a pool created with the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT, bindings for these descriptors must not be present in any descriptor set layout that includes bindings created with VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT.

- maxDescriptorSetUpdateAfterBindStorageBuffers is similar to maxDescriptorSetStorageBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- maxDescriptorSetUpdateAfterBindStorageBuffersDynamic is similar to maxDescriptorSetStorageBuffersDynamic but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set. While an application can allocate dynamic storage buffer descriptors from a pool created with the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT, bindings for these descriptors must not be present in any descriptor set layout that includes bindings created with VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT.

- maxDescriptorSetUpdateAfterBindSampledImages is similar to maxDescriptorSetSampledImages but
counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageImages` is similar to `maxDescriptorSetStorageImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindInputAttachments` is similar to `maxDescriptorSetInputAttachments` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `supportedDepthResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported depth resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations *may* support additional modes.

- `supportedStencilResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported stencil resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations *may* support additional modes. `VK_RESOLVE_MODE_AVERAGE_BIT` must not be included in the set.

- `independentResolveNone` is `VK_TRUE` if the implementation supports setting the depth and stencil resolve modes to different values when one of those modes is `VK_RESOLVE_MODE_NONE`. Otherwise the implementation only supports setting both modes to the same value.

- `independentResolve` is `VK_TRUE` if the implementation supports all combinations of the supported depth and stencil resolve modes, including setting either depth or stencil resolve mode to `VK_RESOLVE_MODE_NONE`. An implementation that supports `independentResolve` must also support `independentResolveNone`.

- `filterMinmaxSingleComponentFormats` is a boolean value indicating whether a minimum set of required formats support min/max filtering.

- `filterMinmaxImageComponentMapping` is a boolean value indicating whether the implementation supports non-identity component mapping of the image when doing min/max filtering.

- `maxTimelineSemaphoreValueDifference` indicates the maximum difference allowed by the implementation between the current value of a timeline semaphore and any pending signal or wait operations.

- `framebufferIntegerColorSampleCounts` is a bitmask of `VkSampleCountFlagBits` indicating the color sample counts that are supported for all framebuffer color attachments with integer formats.

If the `VkPhysicalDeviceVulkan12Properties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

These properties correspond to Vulkan 1.2 functionality.

The members of `VkPhysicalDeviceVulkan12Properties` must have the same values as the corresponding members of `VkPhysicalDeviceDriverProperties`, `VkPhysicalDeviceFloatControlsProperties`, `VkPhysicalDeviceDescriptorIndexingProperties`, `VkPhysicalDeviceDepthStencilResolveProperties`, `VkPhysicalDeviceSamplerFilterMinmaxProperties`, and `VkPhysicalDeviceTimelineSemaphoreProperties`. 
Valid Usage (Implicit)

- VUID-VkPhysicalDeviceVulkan12Properties-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_PROPERTIES

The `VkPhysicalDeviceVulkan13Properties` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceVulkan13Properties {
    VkStructureType sType;
    void* pNext;
    uint32_t minSubgroupSize;
    uint32_t maxSubgroupSize;
    uint32_t maxComputeWorkgroupSubgroups;
    VkShaderStageFlags requiredSubgroupSizeStages;
    uint32_t maxInlineUniformBlockSize;
    uint32_t maxPerStageDescriptorInlineUniformBlocks;
    uint32_t maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks;
    uint32_t maxDescriptorSetInlineUniformBlocks;
    uint32_t maxDescriptorSetUpdateAfterBindInlineUniformBlocks;
    uint32_t maxInlineUniformTotalSize;
    VkBool32 integerDotProduct8BitUnsignedAccelerated;
    VkBool32 integerDotProduct8BitSignedAccelerated;
    VkBool32 integerDotProduct8BitMixedSignednessAccelerated;
    VkBool32 integerDotProduct4x8BitPackedUnsignedAccelerated;
    VkBool32 integerDotProduct4x8BitPackedSignedAccelerated;
    VkBool32 integerDotProduct4x8BitPackedMixedSignednessAccelerated;
    VkBool32 integerDotProduct16BitUnsignedAccelerated;
    VkBool32 integerDotProduct16BitSignedAccelerated;
    VkBool32 integerDotProduct16BitMixedSignednessAccelerated;
    VkBool32 integerDotProduct32BitUnsignedAccelerated;
    VkBool32 integerDotProduct32BitSignedAccelerated;
    VkBool32 integerDotProduct32BitMixedSignednessAccelerated;
    VkBool32 integerDotProduct64BitUnsignedAccelerated;
    VkBool32 integerDotProduct64BitSignedAccelerated;
    VkBool32 integerDotProduct64BitMixedSignednessAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating8BitUnsignedAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating8BitSignedAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating8BitMixedSignednessAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedUnsignedAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedSignedAccelerated;
    VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedMixedSignednessAccelerated;
} VkPhysicalDeviceVulkan13Properties;
```
integerDotProductAccumulatingSaturating16BitUnsignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating16BitSignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating16BitMixedSignednessAccelerated;
VkBool32
integerDotProductAccumulatingSaturating32BitUnsignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating32BitSignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating32BitMixedSignednessAccelerated;
VkBool32
integerDotProductAccumulatingSaturating64BitUnsignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating64BitSignedAccelerated;
VkBool32
integerDotProductAccumulatingSaturating64BitMixedSignednessAccelerated;
VkDeviceSize storageTexelBufferOffsetAlignmentBytes;
VkBool32 storageTexelBufferOffsetSingleTexelAlignment;
VkDeviceSize uniformTexelBufferOffsetAlignmentBytes;
VkBool32 uniformTexelBufferOffsetSingleTexelAlignment;
VkDeviceSize maxBufferSize;
} VkPhysicalDeviceVulkan13Properties;

- **sType** is a *VkStructureType* value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.

- **minSubgroupSize** is the minimum subgroup size supported by this device. minSubgroupSize is at least one if any of the physical device’s queues support VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT. minSubgroupSize is a power-of-two. minSubgroupSize is less than or equal to maxSubgroupSize. minSubgroupSize is less than or equal to subgroupSize.

- **maxSubgroupSize** is the maximum subgroup size supported by this device. maxSubgroupSize is at least one if any of the physical device’s queues support VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT. maxSubgroupSize is a power-of-two. maxSubgroupSize is greater than or equal to minSubgroupSize. maxSubgroupSize is greater than or equal to subgroupSize.

- **maxComputeWorkgroupSubgroups** is the maximum number of subgroups supported by the implementation within a workgroup.

- **requiredSubgroupSizeStages** is a bitfield of what shader stages support having a required subgroup size specified.

- **maxInlineUniformBlockSize** is the maximum size in bytes of an inline uniform block binding.

- **maxPerStageDescriptorInlineUniformBlock** is the maximum number of inline uniform block bindings that can be accessible to a single shader stage in a pipeline layout. Descriptor bindings with a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK count against this limit. Only descriptor bindings in descriptor set layouts created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set count against this limit.

- **maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks** is similar to
**maxPerStageDescriptorInlineUniformBlocks** but counts descriptor bindings from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- **maxDescriptorSetInlineUniformBlocks** is the maximum number of inline uniform block bindings that can be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptor bindings with a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` count against this limit. Only descriptor bindings in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit.

- **maxDescriptorSetUpdateAfterBindInlineUniformBlocks** is similar to `maxDescriptorSetInlineUniformBlocks` but counts descriptor bindings from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- **maxInlineUniformTotalSize** is the maximum total size in bytes of all inline uniform block bindings, across all pipeline shader stages and descriptor set numbers, that can be included in a pipeline layout. Descriptor bindings with a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` count against this limit.

- **integerDotProduct8BitUnsignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit unsigned dot product operations using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct8BitSignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit signed dot product operations using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct8BitMixedSignednessAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit mixed signedness dot product operations using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct4x8BitPackedUnsignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit unsigned dot product operations from operands packed into 32-bit integers using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct4x8BitPackedSignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit signed dot product operations from operands packed into 32-bit integers using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct4x8BitPackedMixedSignednessAccelerated** is a boolean that will be `VK_TRUE` if the support for 8-bit mixed signedness dot product operations from operands packed into 32-bit integers using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct16BitUnsignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 16-bit unsigned dot product operations using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct16BitSignedAccelerated** is a boolean that will be `VK_TRUE` if the support for 16-bit signed dot product operations using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct16BitMixedSignednessAccelerated** is a boolean that will be `VK_TRUE` if the support for 16-bit mixed signedness dot product operations using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

- **integerDotProduct32BitUnsignedAccelerated** is a boolean that will be `VK_TRUE` if the support for...
32-bit unsigned dot product operations using the OpUDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProduct32BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 32-bit signed dot product operations using the OpSDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProduct32BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 32-bit mixed signedness dot product operations using the OpSUDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProduct64BitUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 64-bit unsigned dot product operations using the OpUDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProduct64BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 64-bit signed dot product operations using the OpSDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProduct64BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 64-bit mixed signedness dot product operations using the OpSUDotKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating8BitUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 8-bit unsigned accumulating saturating dot product operations using the OpUDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating8BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 8-bit signed accumulating saturating dot product operations using the OpSDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating8BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 8-bit mixed signedness accumulating saturating dot product operations using the OpSUDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating4x8BitPackedUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 8-bit unsigned accumulating saturating dot product operations from operands packed into 32-bit integers using the OpUDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating4x8BitPackedSignedAccelerated is a boolean that will be VK_TRUE if the support for 8-bit signed accumulating saturating dot product operations from operands packed into 32-bit integers using the OpSDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating4x8BitPackedMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 8-bit mixed signedness accumulating saturating dot product operations from operands packed into 32-bit integers using the OpSUDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating16BitUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 16-bit unsigned accumulating saturating dot product operations using the OpUDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating16BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 16-bit signed accumulating saturating dot product operations using
the OpSDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating16BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 16-bit mixed signedness accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating32BitUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 32-bit unsigned accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating32BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 32-bit signed accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating32BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 32-bit mixed signedness accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating64BitUnsignedAccelerated is a boolean that will be VK_TRUE if the support for 64-bit unsigned accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating64BitSignedAccelerated is a boolean that will be VK_TRUE if the support for 64-bit signed accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- integerDotProductAccumulatingSaturating64BitMixedSignednessAccelerated is a boolean that will be VK_TRUE if the support for 64-bit mixed signedness accumulating saturating dot product operations using the OpSUDDotAccSatKHR SPIR-V instruction is accelerated as defined below.

- storageTexelBufferOffsetAlignmentBytes is a byte alignment that is sufficient for a storage texel buffer of any format. The value must be a power of two.

- storageTexelBufferOffsetSingleTexelAlignment indicates whether single texel alignment is sufficient for a storage texel buffer of any format.

- uniformTexelBufferOffsetAlignmentBytes is a byte alignment that is sufficient for a uniform texel buffer of any format. The value must be a power of two.

- uniformTexelBufferOffsetSingleTexelAlignment indicates whether single texel alignment is sufficient for a uniform texel buffer of any format.

- maxBufferSize is the maximum size VkBuffer that can be created.

If the VkPhysicalDeviceVulkan13Properties structure is included in the pNext chain of the VkPhysicalDeviceProperties2 structure passed to vkGetPhysicalDeviceProperties2, it is filled in with each corresponding implementation-dependent property.

These properties correspond to Vulkan 1.3 functionality.

The members of VkPhysicalDeviceVulkan13Properties must have the same values as the corresponding members of VkPhysicalDeviceInlineUniformBlockProperties and VkPhysicalDeviceSubgroupSizeControlProperties.
Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceVulkan13Properties-sType-sType**
  
  *sType* must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_3_PROPERTIES`

The `VkPhysicalDeviceIDProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceIDProperties {
    VkStructureType sType;
    void* pNext;
    uint8_t deviceUUID[VK_UUID_SIZE];
    uint8_t driverUUID[VK_UUID_SIZE];
    uint8_t deviceLUID[VK_LUID_SIZE];
    uint32_t deviceNodeMask;
    VkBool32 deviceLUIDValid;
} VkPhysicalDeviceIDProperties;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **deviceUUID** is an array of `VK_UUID_SIZE` `uint8_t` values representing a universally unique identifier for the device.
- **driverUUID** is an array of `VK_UUID_SIZE` `uint8_t` values representing a universally unique identifier for the driver build in use by the device.
- **deviceLUID** is an array of `VK_LUID_SIZE` `uint8_t` values representing a locally unique identifier for the device.
- **deviceNodeMask** is a `uint32_t` bitfield identifying the node within a linked device adapter corresponding to the device.
- **deviceLUIDValid** is a boolean value that will be `VK_TRUE` if `deviceLUID` contains a valid LUID and `deviceNodeMask` contains a valid node mask, and `VK_FALSE` if they do not.

If the `VkPhysicalDeviceIDProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

**deviceUUID** must be immutable for a given device across instances, processes, driver APIs, driver versions, and system reboots.

Applications **can** compare the **driverUUID** value across instance and process boundaries, and **can** make similar queries in external APIs to determine whether they are capable of sharing memory objects and resources using them with the device.

**deviceUUID** and/or **driverUUID** must be used to determine whether a particular external object can be shared between driver components, where such a restriction exists as defined in the compatibility table for the particular object type:
• External memory handle types compatibility
• External semaphore handle types compatibility
• External fence handle types compatibility

If `deviceLUIDValid` is `VK_FALSE`, the values of `deviceLUID` and `deviceNodeMask` are undefined. If `deviceLUIDValid` is `VK_TRUE` and Vulkan is running on the Windows operating system, the contents of `deviceLUID` can be cast to an `LUID` object and must be equal to the locally unique identifier of a `IDXGIAdapter1` object that corresponds to `physicalDevice`. If `deviceLUIDValid` is `VK_TRUE`, `deviceNodeMask` must contain exactly one bit. If Vulkan is running on an operating system that supports the Direct3D 12 API and `physicalDevice` corresponds to an individual device in a linked device adapter, `deviceNodeMask` identifies the Direct3D 12 node corresponding to `physicalDevice`. Otherwise, `deviceNodeMask` must be 1.

**Note**
Although they have identical descriptions, `VkPhysicalDeviceIDProperties::deviceUUID` may differ from `VkPhysicalDeviceProperties2::pipelineCacheUUID`. The former is intended to identify and correlate devices across API and driver boundaries, while the latter is used to identify a compatible device and driver combination to use when serializing and de-serializing pipeline state.

Implementations should return `deviceUUID` values which are likely to be unique even in the presence of multiple Vulkan implementations (such as a GPU driver and a software renderer; two drivers for different GPUs; or the same Vulkan driver running on two logically different devices).

Khronos' conformance testing is unable to guarantee that `deviceUUID` values are actually unique, so implementors should make their own best efforts to ensure this. In particular, hard-coded `deviceUUID` values, especially all-0 bits, should never be used.

A combination of values unique to the vendor, the driver, and the hardware environment can be used to provide a `deviceUUID` which is unique to a high degree of certainty. Some possible inputs to such a computation are:

- Information reported by `vkGetPhysicalDeviceProperties`
- PCI device ID (if defined)
- PCI bus ID, or similar system configuration information.
- Driver binary checksums.

**Note**
While `VkPhysicalDeviceIDProperties::deviceUUID` is specified to remain consistent across driver versions and system reboots, it is not intended to be usable as a serializable persistent identifier for a device. It may change when a device is physically added to, removed from, or moved to a different connector in a system while that system is powered down. Further, there is no reasonable way to verify with conformance testing that a given device retains the same UUID in a given
system across all driver versions supported in that system. While implementations should make every effort to report consistent device UUIDs across driver versions, applications should avoid relying on the persistence of this value for uses other than identifying compatible devices for external object sharing purposes.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceIDProperties-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES`

`VK_UUID_SIZE` is the length in `uint8_t` values of an array containing a universally unique device or driver build identifier, as returned in `VkPhysicalDeviceIDProperties::deviceUUID` and `VkPhysicalDeviceIDProperties::driverUUID`.

```
#define VK_UUID_SIZE                      16U
```

`VK_LUID_SIZE` is the length in `uint8_t` values of an array containing a locally unique device identifier, as returned in `VkPhysicalDeviceIDProperties::deviceLUID`.

```
#define VK_LUID_SIZE                      8U
```

The `VkPhysicalDeviceDriverProperties` structure is defined as:

```
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceDriverProperties {
    VkStructureType   sType;
    void*             pNext;
    VkDriverId        driverID;
    char*             driverName[VK_MAX_DRIVER_NAME_SIZE];
    char*             driverInfo[VK_MAX_DRIVER_INFO_SIZE];
    VkConformanceVersion conformanceVersion;
} VkPhysicalDeviceDriverProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `driverID` is a unique identifier for the driver of the physical device.
- `driverName` is an array of `VK_MAX_DRIVER_NAME_SIZE` `char` containing a null-terminated UTF-8 string which is the name of the driver.
- `driverInfo` is an array of `VK_MAX_DRIVER_INFO_SIZE` `char` containing a null-terminated UTF-8 string with additional information about the driver.
- `conformanceVersion` is the version of the Vulkan conformance test this driver is conformant against (see `VkConformanceVersion`).
If the `VkPhysicalDeviceDriverProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

These are properties of the driver corresponding to a physical device.

driverID must be immutable for a given driver across instances, processes, driver versions, and system reboots.

**Valid Usage (Implicit)**

- `VUID-VkPhysicalDeviceDriverProperties-sType-sType`
  
sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES`

Khronos driver IDs which may be returned in `VkPhysicalDeviceDriverProperties::driverID` are:

```c
// Provided by VK_VERSION_1_2
typedef enum VkDriverId {
    VK_DRIVER_ID_AMD_PROPRIETARY = 1,
    VK_DRIVER_ID_AMD_OPEN_SOURCE = 2,
    VK_DRIVER_ID_MESA_RADV = 3,
    VK_DRIVER_ID_NVIDIA_PROPRIETARY = 4,
    VK_DRIVER_ID_INTEL_PROPRIETARY_WINDOWS = 5,
    VK_DRIVER_ID_INTEL_OPEN_SOURCE_MESA = 6,
    VK_DRIVER_ID_IMAGINATION_PROPRIETARY = 7,
    VK_DRIVER_ID_QUALCOMM_PROPRIETARY = 8,
    VK_DRIVER_ID_ARM_PROPRIETARY = 9,
    VK_DRIVER_ID_GOOGLE_SWIFTSHADER = 10,
    VK_DRIVER_ID_GGP_PROPRIETARY = 11,
    VK_DRIVER_ID_BROADCOM_PROPRIETARY = 12,
    VK_DRIVER_ID_MESA_LLVMPipe = 13,
    VK_DRIVER_ID_MOLTENVK = 14,
    VK_DRIVER_ID_COREAVI_PROPRIETARY = 15,
    VK_DRIVER_ID_JUICE_PROPRIETARY = 16,
    VK_DRIVER_ID_VERISILICON_PROPRIETARY = 17,
    VK_DRIVER_ID_MESA_TURNIP = 18,
    VK_DRIVER_ID_MESA_V3DV = 19,
    VK_DRIVER_ID_MESA_PANVK = 20,
    VK_DRIVER_ID_SAMSUNG_PROPRIETARY = 21,
    VK_DRIVER_ID_MESA_VENUS = 22,
    VK_DRIVER_ID_MESA_DOZEN = 23,
    VK_DRIVER_ID_MESA_NVK = 24,
    VK_DRIVER_ID_IMAGINATION_OPEN_SOURCE_MESA = 25,
} VkDriverId;
```

**Note**

Khronos driver IDs may be allocated by vendors at any time. There may be multiple driver IDs for the same vendor, representing different drivers (for e.g.
different platforms, proprietary or open source, etc.). Only the latest canonical versions of this Specification, of the corresponding \texttt{vk.xml} API Registry, and of the corresponding \texttt{vulkan_core.h} header file must contain all reserved Khronos driver IDs.

Only driver IDs registered with Khronos are given symbolic names. There may be unregistered driver IDs returned.

\texttt{VK\_MAX\_DRIVER\_NAME\_SIZE} is the length in \texttt{char} values of an array containing a driver name string, as returned in \texttt{VkPhysicalDeviceDriverProperties::driverName}.

\begin{verbatim}
#define VK_MAX_DRIVER_NAME_SIZE 256U
\end{verbatim}

\texttt{VK\_MAX\_DRIVER\_INFO\_SIZE} is the length in \texttt{char} values of an array containing a driver information string, as returned in \texttt{VkPhysicalDeviceDriverProperties::driverInfo}.

\begin{verbatim}
#define VK_MAX_DRIVER_INFO_SIZE 256U
\end{verbatim}

The conformance test suite version an implementation is compliant with is described with the \texttt{VkConformanceVersion} structure:

\begin{verbatim}
// Provided by VK\_VERSION\_1\_2
typedef struct VkConformanceVersion {
    uint8_t major;
    uint8_t minor;
    uint8_t subminor;
    uint8_t patch;
} VkConformanceVersion;
\end{verbatim}

- \texttt{major} is the major version number of the conformance test suite.
- \texttt{minor} is the minor version number of the conformance test suite.
- \texttt{subminor} is the subminor version number of the conformance test suite.
- \texttt{patch} is the patch version number of the conformance test suite.

The \texttt{VkPhysicalDeviceShaderIntegerDotProductProperties} structure is defined as:

\begin{verbatim}
// Provided by VK\_VERSION\_1\_3
typedef struct VkPhysicalDeviceShaderIntegerDotProductProperties {
    VkStructureType sType;
    void* pNext;
    VkBool32 integerDotProduct8BitUnsignedAccelerated;
    VkBool32 integerDotProduct8BitSignedAccelerated;
    VkBool32 integerDotProduct8BitMixedSignednessAccelerated;
    VkBool32 integerDotProduct4x8BitPackedUnsignedAccelerated;
    VkBool32 integerDotProduct4x8BitPackedSignedAccelerated;
} VkPhysicalDeviceShaderIntegerDotProductProperties;
\end{verbatim}
VkBool32 integerDotProduct4x8BitPackedMixedSignednessAccelerated;
VkBool32 integerDotProduct16BitUnsignedAccelerated;
VkBool32 integerDotProduct16BitSignedAccelerated;
VkBool32 integerDotProduct16BitMixedSignednessAccelerated;
VkBool32 integerDotProduct32BitUnsignedAccelerated;
VkBool32 integerDotProduct32BitSignedAccelerated;
VkBool32 integerDotProduct32BitMixedSignednessAccelerated;
VkBool32 integerDotProduct64BitUnsignedAccelerated;
VkBool32 integerDotProduct64BitSignedAccelerated;
VkBool32 integerDotProduct64BitMixedSignednessAccelerated;
VkBool32 integerDotProductAccumulatingSaturating8BitUnsignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating8BitSignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating8BitMixedSignednessAccelerated;
VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedUnsignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedSignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating4x8BitPackedMixedSignednessAccelerated;
VkBool32 integerDotProductAccumulatingSaturating16BitUnsignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating16BitSignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating16BitMixedSignednessAccelerated;
VkBool32 integerDotProductAccumulatingSaturating32BitUnsignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating32BitSignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating32BitMixedSignednessAccelerated;
VkBool32 integerDotProductAccumulatingSaturating64BitUnsignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating64BitSignedAccelerated;
VkBool32 integerDotProductAccumulatingSaturating64BitMixedSignednessAccelerated;
}
VkPhysicalDeviceShaderIntegerDotProductProperties;

• **sType** is a VkStructureType value identifying this structure.

• **pNext** is NULL or a pointer to a structure extending this structure.

• **integerDotProduct8BitUnsignedAccelerated** is a boolean that will be VK_TRUE if the support for 8-bit unsigned dot product operations using the OpUDotKHR SPIR-V instruction is accelerated as defined below.

• **integerDotProduct8BitSignedAccelerated** is a boolean that will be VK_TRUE if the support for 8-bit signed dot product operations using the OpSDotKHR SPIR-V instruction is accelerated as defined below.

• **integerDotProduct8BitMixedSignednessAccelerated** is a boolean that will be VK_TRUE if the support for 8-bit mixed signedness dot product operations using the OpSUDotKHR SPIR-V instruction is accelerated as defined below.
• `integerDotProduct4x8BitPackedUnsignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 8-bit unsigned dot product operations from operands packed into 32-bit integers using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct4x8BitPackedSignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 8-bit signed dot product operations from operands packed into 32-bit integers using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct4x8BitPackedMixedSignednessAccelerated` is a boolean that will be `VK_TRUE` if the support for 8-bit mixed signedness dot product operations from operands packed into 32-bit integers using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct16BitUnsignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 16-bit unsigned dot product operations using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct16BitSignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 16-bit signed dot product operations using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct16BitMixedSignednessAccelerated` is a boolean that will be `VK_TRUE` if the support for 16-bit mixed signedness dot product operations using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct32BitUnsignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 32-bit unsigned dot product operations using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct32BitSignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 32-bit signed dot product operations using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct32BitMixedSignednessAccelerated` is a boolean that will be `VK_TRUE` if the support for 32-bit mixed signedness dot product operations using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct64BitUnsignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 64-bit unsigned dot product operations using the `OpUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct64BitSignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 64-bit signed dot product operations using the `OpSDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProduct64BitMixedSignednessAccelerated` is a boolean that will be `VK_TRUE` if the support for 64-bit mixed signedness dot product operations using the `OpSUDotKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProductAccumulatingSaturating8BitUnsignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 8-bit unsigned accumulating saturating dot product operations using the `OpUDotAccSatKHR` SPIR-V instruction is accelerated as defined below.

• `integerDotProductAccumulatingSaturating8BitSignedAccelerated` is a boolean that will be `VK_TRUE` if the support for 8-bit signed accumulating saturating dot product operations using the `OpSDotAccSatKHR` SPIR-V instruction is accelerated as defined below.
• **integerDotProductAccumulatingSaturating8BitMixedSignednessAccelerated** is a boolean that will be **VK_TRUE** if the support for 8-bit mixed signedness accumulating saturating dot product operations using the **OpSUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating4x8BitPackedUnsignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 8-bit unsigned accumulating saturating dot product operations from operands packed into 32-bit integers using the **OpUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating4x8BitPackedSignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 8-bit signed accumulating saturating dot product operations from operands packed into 32-bit integers using the **OpSDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating4x8BitPackedMixedSignednessAccelerated** is a boolean that will be **VK_TRUE** if the support for 8-bit mixed signedness accumulating saturating dot product operations from operands packed into 32-bit integers using the **OpSUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating16BitUnsignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 16-bit unsigned accumulating saturating dot product operations using the **OpUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating16BitSignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 16-bit signed accumulating saturating dot product operations using the **OpSDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating16BitMixedSignednessAccelerated** is a boolean that will be **VK_TRUE** if the support for 16-bit mixed signedness accumulating saturating dot product operations using the **OpSUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating32BitUnsignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 32-bit unsigned accumulating saturating dot product operations using the **OpUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating32BitSignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 32-bit signed accumulating saturating dot product operations using the **OpSDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating32BitMixedSignednessAccelerated** is a boolean that will be **VK_TRUE** if the support for 32-bit mixed signedness accumulating saturating dot product operations using the **OpSUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating64BitUnsignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 64-bit unsigned accumulating saturating dot product operations using the **OpUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating64BitSignedAccelerated** is a boolean that will be **VK_TRUE** if the support for 64-bit signed accumulating saturating dot product operations using the **OpSDotAccSatKHR** SPIR-V instruction is accelerated as defined below.

• **integerDotProductAccumulatingSaturating64BitMixedSignednessAccelerated** is a boolean that will be **VK_TRUE** if the support for 64-bit mixed signedness accumulating saturating dot product operations using the **OpSUDotAccSatKHR** SPIR-V instruction is accelerated as defined below.
If the `VkPhysicalDeviceShaderIntegerDotProductProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

These are properties of the integer dot product acceleration information of a physical device.

**Note**
A dot product operation is deemed accelerated if its implementation provides a performance advantage over application-provided code composed from elementary instructions and/or other dot product instructions, either because the implementation uses optimized machine code sequences whose generation from application-provided code cannot be guaranteed or because it uses hardware features that cannot otherwise be targeted from application-provided code.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceShaderIntegerDotProductProperties-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_PROPERTIES`

To query properties of queues available on a physical device, call:

```c
// Provided by VK_VERSION_1_0
void vkGetPhysicalDeviceQueueFamilyProperties(
    VkPhysicalDevice physicalDevice,
    uint32_t* pQueueFamilyPropertyCount,
    VkQueueFamilyProperties* pQueueFamilyProperties);
```

- `physicalDevice` is the handle to the physical device whose properties will be queried.
- `pQueueFamilyPropertyCount` is a pointer to an integer related to the number of queue families available or queried, as described below.
- `pQueueFamilyProperties` is either `NULL` or a pointer to an array of `VkQueueFamilyProperties` structures.

If `pQueueFamilyProperties` is `NULL`, then the number of queue families available is returned in `pQueueFamilyPropertyCount`. Implementations must support at least one queue family. Otherwise, `pQueueFamilyPropertyCount` must point to a variable set by the user to the number of elements in the `pQueueFamilyProperties` array, and on return the variable is overwritten with the number of structures actually written to `pQueueFamilyProperties`. If `pQueueFamilyPropertyCount` is less than the number of queue families available, at most `pQueueFamilyPropertyCount` structures will be written.

**Valid Usage (Implicit)**

- VUID-vkGetPhysicalDeviceQueueFamilyProperties-physicalDevice-parameter
  `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkGetPhysicalDeviceQueueFamilyProperties-pQueueFamilyPropertyCount-

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The `VkQueueFamilyProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkQueueFamilyProperties {
    VkQueueFlags queueFlags;
    uint32_t queueCount;
    uint32_t timestampValidBits;
    VkExtent3D minImageTransferGranularity;
} VkQueueFamilyProperties;
```

- `queueFlags` is a bitmask of `VkQueueFlagBits` indicating capabilities of the queues in this queue family.
- `queueCount` is the unsigned integer count of queues in this queue family. Each queue family must support at least one queue.
- `timestampValidBits` is the unsigned integer count of meaningful bits in the timestamps written via `vkCmdWriteTimestamp2` or `vkCmdWriteTimestamp`. The valid range for the count is 36 to 64 bits, or a value of 0, indicating no support for timestamps. Bits outside the valid range are guaranteed to be zeros.
- `minImageTransferGranularity` is the minimum granularity supported for image transfer operations on the queues in this queue family.

The value returned in `minImageTransferGranularity` has a unit of compressed texel blocks for images having a block-compressed format, and a unit of texels otherwise.

Possible values of `minImageTransferGranularity` are:

- `(0,0,0)` specifies that only whole mip levels must be transferred using the image transfer operations on the corresponding queues. In this case, the following restrictions apply to all offset and extent parameters of image transfer operations:
  - The `x`, `y`, and `z` members of a `VkOffset3D` parameter must always be zero.
  - The `width`, `height`, and `depth` members of a `VkExtent3D` parameter must always match the width, height, and depth of the image subresource corresponding to the parameter, respectively.
- `(A_x, A_y, A_z)` where `A_x`, `A_y`, and `A_z` are all integer powers of two. In this case the following restrictions apply to all image transfer operations:
  - `x`, `y`, and `z` of a `VkOffset3D` parameter must be integer multiples of `A_x`, `A_y`, and `A_z`, respectively.
width of a VkExtent3D parameter must be an integer multiple of $A_w$, or else $x + width$ must equal the width of the image subresource corresponding to the parameter.

height of a VkExtent3D parameter must be an integer multiple of $A_h$, or else $y + height$ must equal the height of the image subresource corresponding to the parameter.

depth of a VkExtent3D parameter must be an integer multiple of $A_z$, or else $z + depth$ must equal the depth of the image subresource corresponding to the parameter.

If the format of the image corresponding to the parameters is one of the block-compressed formats then for the purposes of the above calculations the granularity must be scaled up by the compressed texel block dimensions.

Queues supporting graphics and/or compute operations must report (1,1,1) in minImageTransferGranularity, meaning that there are no additional restrictions on the granularity of image transfer operations for these queues. Other queues supporting image transfer operations are only required to support whole mip level transfers, thus minImageTransferGranularity for queues belonging to such queue families may be (0,0,0).

The Device Memory section describes memory properties queried from the physical device.

For physical device feature queries see the Features chapter.

Bits which may be set in VkQueueFamilyProperties::queueFlags, indicating capabilities of queues in a queue family are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkQueueFlagBits {
    VK_QUEUE_GRAPHICS_BIT = 0x00000001,
    VK.Queue_COMPUTE_BIT = 0x00000002,
    VK_QUEUE_TRANSFER_BIT = 0x00000004,
    VK_QUEUE_SPARSE_BINDING_BIT = 0x00000008,
    // Provided by VK_VERSION_1_1
    VK_QUEUE_PROTECTED_BIT = 0x00000010,
} VkQueueFlagBits;
```

- **VK_QUEUE_GRAPHICS_BIT** specifies that queues in this queue family support graphics operations.
- **VK_QUEUE_COMPUTE_BIT** specifies that queues in this queue family support compute operations.
- **VK_QUEUE_TRANSFER_BIT** specifies that queues in this queue family support transfer operations.
- **VK_QUEUE_SPARSE_BINDING_BIT** specifies that queues in this queue family support sparse memory management operations (see Sparse Resources). If any of the sparse resource features are enabled, then at least one queue family must support this bit.
- **VK_QUEUE_PROTECTED_BIT** specifies that queues in this queue family support the VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT bit. (see Protected Memory). If the physical device supports the protectedMemory feature, at least one of its queue families must support this bit.

If an implementation exposes any queue family that supports graphics operations, at least one queue family of at least one physical device exposed by the implementation must support both graphics and compute operations.
Furthermore, if the **protectedMemory** physical device feature is supported, then at least one queue family of at least one physical device exposed by the implementation **must** support graphics operations, compute operations, and protected memory operations.

**Note**

All commands that are allowed on a queue that supports transfer operations are also allowed on a queue that supports either graphics or compute operations. Thus, if the capabilities of a queue family include **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT**, then reporting the **VK_QUEUE_TRANSFER_BIT** capability separately for that queue family is **optional**.

For further details see **Queues**.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkQueueFlags;
```

**VkQueueFlags** is a bitmask type for setting a mask of zero or more **VkQueueFlagBits**.

To query properties of queues available on a physical device, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceQueueFamilyProperties2(
    VkPhysicalDevice physicalDevice,
    uint32_t* pQueueFamilyPropertyCount,
    VkQueueFamilyProperties2* pQueueFamilyProperties);
```

- **physicalDevice** is the handle to the physical device whose properties will be queried.
- **pQueueFamilyPropertyCount** is a pointer to an integer related to the number of queue families available or queried, as described in **vkGetPhysicalDeviceQueueFamilyProperties**.
- **pQueueFamilyProperties** is either **NULL** or a pointer to an array of **VkQueueFamilyProperties2** structures.

**vkGetPhysicalDeviceQueueFamilyProperties2** behaves similarly to **vkGetPhysicalDeviceQueueFamilyProperties**, with the ability to return extended information in a **pNext** chain of output structures.

**Valid Usage (Implicit)**

- **VUID-vkGetPhysicalDeviceQueueFamilyProperties2-physicalDevice-parameter**
  - **physicalDevice** must be a valid **VkPhysicalDevice** handle
- **VUID-vkGetPhysicalDeviceQueueFamilyProperties2-pQueueFamilyPropertyCount-parameter**
  - **pQueueFamilyPropertyCount** must be a valid pointer to a **uint32_t** value
- **VUID-vkGetPhysicalDeviceQueueFamilyProperties2-pQueueFamilyProperties-parameter**
  - If the value referenced by **pQueueFamilyPropertyCount** is not 0, and **pQueueFamilyProperties**
is not NULL, pQueueFamilyProperties must be a valid pointer to an array of pQueueFamilyPropertyCount VkQueueFamilyProperties2 structures.

The VkQueueFamilyProperties2 structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkQueueFamilyProperties2 {
    VkStructureType sType;
    void*pNext;
    VkQueueFamilyProperties queueFamilyProperties;
} VkQueueFamilyProperties2;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **queueFamilyProperties** is a VkQueueFamilyProperties structure which is populated with the same values as in vkGetPhysicalDeviceQueueFamilyProperties.

### Valid Usage (Implicit)

- VUID-VkQueueFamilyProperties2-sType-sType
  - **sType** must be VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2
- VUID-VkQueueFamilyProperties2-pNext-pNext
  - **pNext** must be NULL

### 5.2. Devices

Device objects represent logical connections to physical devices. Each device exposes a number of queue families each having one or more queues. All queues in a queue family support the same operations.

As described in Physical Devices, a Vulkan application will first query for all physical devices in a system. Each physical device can then be queried for its capabilities, including its queue and queue family properties. Once an acceptable physical device is identified, an application will create a corresponding logical device. The created logical device is then the primary interface to the physical device.

How to enumerate the physical devices in a system and query those physical devices for their queue family properties is described in the Physical Device Enumeration section above.

A single logical device can be created from multiple physical devices, if those physical devices belong to the same device group. A device group is a set of physical devices that support accessing each other's memory and recording a single command buffer that can be executed on all the physical devices. Device groups are enumerated by calling `vkEnumeratePhysicalDeviceGroups`, and a logical device is created from a subset of the physical devices in a device group by passing the physical devices through `VkDeviceGroupDeviceCreateInfo`. For two physical devices to be in the
same device group, they must support identical extensions, features, and properties.

**Note**
Physical devices in the same device group must be so similar because there are no rules for how different features/properties would interact. They must return the same values for nearly every invariant vkGetPhysicalDevice* feature, property, capability, etc., but could potentially differ for certain queries based on things like having a different display connected, or a different compositor. The specification does not attempt to enumerate which state is in each category, because such a list would quickly become out of date.

To retrieve a list of the device groups present in the system, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkEnumeratePhysicalDeviceGroups(
    VkInstance instance,
    uint32_t* pPhysicalDeviceGroupCount,
    VkPhysicalDeviceGroupProperties* pPhysicalDeviceGroupProperties);
```

- **instance** is a handle to a Vulkan instance previously created with vkCreateInstance.
- **pPhysicalDeviceGroupCount** is a pointer to an integer related to the number of device groups available or queried, as described below.
- **pPhysicalDeviceGroupProperties** is either NULL or a pointer to an array of VkPhysicalDeviceGroupProperties structures.

If `pPhysicalDeviceGroupProperties` is NULL, then the number of device groups available is returned in `pPhysicalDeviceGroupCount`. Otherwise, `pPhysicalDeviceGroupCount` must point to a variable set by the user to the number of elements in the `pPhysicalDeviceGroupProperties` array, and on return the variable is overwritten with the number of structures actually written to `pPhysicalDeviceGroupProperties`. If `pPhysicalDeviceGroupCount` is less than the number of device groups available, at most `pPhysicalDeviceGroupCount` structures will be written, and `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available device groups were returned.

Every physical device must be in exactly one device group.

---

**Valid Usage (Implicit)**

- VUID-vkEnumeratePhysicalDeviceGroups-instance-parameter
  instance must be a valid VkInstance handle
- VUID-vkEnumeratePhysicalDeviceGroups-pPhysicalDeviceGroupCount-parameter
  pPhysicalDeviceGroupCount must be a valid pointer to a uint32_t value
- VUID-vkEnumeratePhysicalDeviceGroups-pPhysicalDeviceGroupProperties-parameter
  If the value referenced by pPhysicalDeviceGroupCount is not 0, and pPhysicalDeviceGroupProperties is not NULL, pPhysicalDeviceGroupProperties must be a
valid pointer to an array of `pPhysicalDeviceGroupCount` `VkPhysicalDeviceGroupProperties` structures

## Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INITIALIZATION_FAILED`

The `VkPhysicalDeviceGroupProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceGroupProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t physicalDeviceCount;
    VkPhysicalDevice physicalDevices[VK_MAX_DEVICE_GROUP_SIZE];
    VkBool32 subsetAllocation;
} VkPhysicalDeviceGroupProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `physicalDeviceCount` is the number of physical devices in the group.
- `physicalDevices` is an array of `VK_MAX_DEVICE_GROUP_SIZE` `VkPhysicalDevice` handles representing all physical devices in the group. The first `physicalDeviceCount` elements of the array will be valid.
- `subsetAllocation` specifies whether logical devices created from the group support allocating device memory on a subset of devices, via the `deviceMask` member of the `VkMemoryAllocateFlagsInfo`. If this is `VK_FALSE`, then all device memory allocations are made across all physical devices in the group. If `physicalDeviceCount` is 1, then `subsetAllocation` must be `VK_FALSE`.

## Valid Usage (Implicit)

- VUID-VkPhysicalDeviceGroupProperties-sType-sType
  - `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES`
- VUID-VkPhysicalDeviceGroupProperties-pNext-pNext
**pNext** must be **NULL**

VK_MAX_DEVICE_GROUP_SIZE is the length of an array containing VkPhysicalDevice handle values representing all physical devices in a group, as returned in VkPhysicalDeviceGroupProperties::physicalDevices.

```c
#define VK_MAX_DEVICE_GROUP_SIZE 32U
```

### 5.2.1. Device Creation

Logical devices are represented by **VkDevice** handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_HANDLE(VkDevice)
```

A logical device is created as a *connection* to a physical device. To create a logical device, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateDevice(
    VkPhysicalDevice physicalDevice,
    const VkDeviceCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkDevice* pDevice);
```

- **physicalDevice** must be one of the device handles returned from a call to `vkEnumeratePhysicalDevices` (see Physical Device Enumeration).
- **pCreateInfo** is a pointer to a VkDeviceCreateInfo structure containing information about how to create the device.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pDevice** is a pointer to a handle in which the created VkDevice is returned.

`vkCreateDevice` verifies that extensions and features requested in the ppEnabledExtensionNames and pEnabledFeatures members of pCreateInfo, respectively, are supported by the implementation. If any requested extension is not supported, `vkCreateDevice` must return VK_ERROR_EXTENSION_NOT_PRESENT. If any requested feature is not supported, `vkCreateDevice` must return VK_ERROR_FEATURE_NOT_PRESENT. Support for extensions can be checked before creating a device by querying `vkEnumerateDeviceExtensionProperties`. Support for features can similarly be checked by querying `vkGetPhysicalDeviceFeatures`.

After verifying and enabling the extensions the **VkDevice** object is created and returned to the application.

Multiple logical devices can be created from the same physical device. Logical device creation may fail due to lack of device-specific resources (in addition to other errors). If that occurs,
vkCreateDevice will return VK_ERROR_TOO_MANY_OBJECTS.

**Valid Usage**

- **VUID-vkCreateDevice-ppEnabledExtensionNames-01387**
  All required device extensions for each extension in the VkDeviceCreateInfo ::ppEnabledExtensionNames list must also be present in that list.

**Valid Usage (Implicit)**

- **VUID-vkCreateDevice-physicalDevice-parameter**
  physicalDevice must be a valid VkPhysicalDevice handle.

- **VUID-vkCreateDevice-pCreateInfo-parameter**
  pCreateInfo must be a valid pointer to a valid VkDeviceCreateInfo structure.

- **VUID-vkCreateDevice-pAllocator-parameter**
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure.

- **VUID-vkCreateDevice-pDevice-parameter**
  pDevice must be a valid pointer to a VkDevice handle.

**Return Codes**

**Success**

- **VK_SUCCESS**

**Failure**

- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**
- **VK_ERROR_INITIALIZATION_FAILED**
- **VK_ERROR_EXTENSION_NOT_PRESENT**
- **VK_ERROR_FEATURE_NOT_PRESENT**
- **VK_ERROR_TOO_MANY_OBJECTS**
- **VK_ERROR_DEVICE_LOST**

The VkDeviceCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDeviceCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDeviceCreateFlags flags;
} VkDeviceCreateInfo;
```
uint32_t queueCreateInfoCount;
const VkDeviceQueueCreateInfo* pQueueCreateInfos;
uint32_t enabledLayerCount;
const char* const* ppEnabledLayerNames;
uint32_t enabledExtensionCount;
const char* const* ppEnabledExtensionNames;
const VkPhysicalDeviceFeatures* pEnabledFeatures;
}

VkDeviceCreateInfo

• `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `flags` is reserved for future use.
• `queueCreateInfoCount` is the unsigned integer size of the `pQueueCreateInfos` array. Refer to the Queue Creation section below for further details.
• `pQueueCreateInfos` is a pointer to an array of `VkDeviceQueueCreateInfo` structures describing the queues that are requested to be created along with the logical device. Refer to the Queue Creation section below for further details.
• `enabledLayerCount` is deprecated and ignored.
• `ppEnabledLayerNames` is deprecated and ignored. See Device Layer Deprecation.
• `enabledExtensionCount` is the number of device extensions to enable.
• `ppEnabledExtensionNames` is a pointer to an array of `enabledExtensionCount` null-terminated UTF-8 strings containing the names of extensions to enable for the created device. See the Extensions section for further details.
• `pEnabledFeatures` is `NULL` or a pointer to a `VkPhysicalDeviceFeatures` structure containing boolean indicators of all the features to be enabled. Refer to the Features section for further details.

Valid Usage

- VUID-VkDeviceCreateInfo-queueFamilyIndex-02802
  The `queueFamilyIndex` member of each element of `pQueueCreateInfos` must be unique within `pQueueCreateInfos`, except that two members can share the same `queueFamilyIndex` if one describes protected-capable queues and one describes queues that are not protected-capable.

- VUID-VkDeviceCreateInfo-pQueueCreateInfos-06755
  If multiple elements of `pQueueCreateInfos` share the same `queueFamilyIndex`, the sum of their `queueCount` members must be less than or equal to the `queueCount` member of the `VkQueueFamilyProperties` structure, as returned by `vkGetPhysicalDeviceQueueFamilyProperties` in the `pQueueFamilyProperties[queueFamilyIndex]`.

- VUID-VkDeviceCreateInfo-pNext-00373
  If the `pNext` chain includes a `VkPhysicalDeviceFeatures2` structure, then `pEnabledFeatures` must be `NULL`.

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• VUID-VkDeviceCreateInfo-pNext-02829
If the \textit{pNext} chain includes a \texttt{VkPhysicalDeviceVulkan11Features} structure, then it \textbf{must not} include a \texttt{VkPhysicalDevice16BitStorageFeatures}, \texttt{VkPhysicalDeviceMultiviewFeatures}, \texttt{VkPhysicalDeviceVariablePointersFeatures}, \texttt{VkPhysicalDeviceProtectedMemoryFeatures}, \texttt{VkPhysicalDeviceSamplerYcbcrConversionFeatures}, or \texttt{VkPhysicalDeviceShaderDrawParametersFeatures} structure

• VUID-VkDeviceCreateInfo-pNext-02830
If the \textit{pNext} chain includes a \texttt{VkPhysicalDeviceVulkan12Features} structure, then it \textbf{must not} include a \texttt{VkPhysicalDevice8BitStorageFeatures}, \texttt{VkPhysicalDeviceShaderAtomicInt64Features}, \texttt{VkPhysicalDeviceDescriptorIndexingFeatures}, \texttt{VkPhysicalDeviceScalarBlockLayoutFeatures}, \texttt{VkPhysicalDeviceImagelessFramebufferFeatures}, \texttt{VkPhysicalDeviceUniformBufferStandardLayoutFeatures}, \texttt{VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures}, \texttt{VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures}, \texttt{VkPhysicalDeviceHostQueryResetFeatures}, \texttt{VkPhysicalDeviceTimelineSemaphoreFeatures}, \texttt{VkPhysicalDeviceBufferDeviceAddressFeatures}, or \texttt{VkPhysicalDeviceVulkanMemoryModelFeatures} structure

• VUID-VkDeviceCreateInfo-pNext-06532
If the \textit{pNext} chain includes a \texttt{VkPhysicalDeviceVulkan13Features} structure, then it \textbf{must not} include a \texttt{VkPhysicalDeviceDynamicRenderingFeatures}, \texttt{VkPhysicalDeviceImageRobustnessFeatures}, \texttt{VkPhysicalDeviceInlineUniformBlockFeatures}, \texttt{VkPhysicalDeviceMaintenance4Features}, \texttt{VkPhysicalDevicePipelineCreationCacheControlFeatures}, \texttt{VkPhysicalDevicePrivateDataFeatures}, \texttt{VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures}, \texttt{VkPhysicalDeviceShaderIntegerDotProductFeatures}, \texttt{VkPhysicalDeviceShaderTerminateInvocationFeatures}, \texttt{VkPhysicalDeviceSubgroupSizeControlFeatures}, \texttt{VkPhysicalDeviceSynchronization2Features}, \texttt{VkPhysicalDeviceTextureCompressionASTCHDRFeatures}, or \texttt{VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures} structure

Valid Usage (Implicit)

• VUID-VkDeviceCreateInfo-sType-sType
\textit{sType} \textbf{must} be \texttt{VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO}

• VUID-VkDeviceCreateInfo-pNext-pNext
Each \textit{pNext} member of any structure (including this one) in the \textit{pNext} chain \textbf{must} be either \texttt{NULL} or a pointer to a valid instance of \texttt{VkDeviceGroupDeviceCreateInfo}, \texttt{VkDevicePrivateDataCreateInfo}, \texttt{VkPhysicalDevice16BitStorageFeatures},

- VUID-VkDeviceCreateInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique, with the exception of structures of type VkDevicePrivateDataCreateInfo

- VUID-VkDeviceCreateInfo-flags-zerobitmask
  flags must be 0

- VUID-VkDeviceCreateInfo-pQueueCreateInfos-parameter
  pQueueCreateInfos must be a valid pointer to an array of queueCreateInfoCount valid VkDeviceQueueCreateInfo structures

- VUID-VkDeviceCreateInfo-ppEnabledLayerNames-parameter
  If enabledLayerCount is not 0, ppEnabledLayerNames must be a valid pointer to an array of enabledLayerCount null-terminated UTF-8 strings

- VUID-VkDeviceCreateInfo-ppEnabledExtensionNames-parameter
  If enabledExtensionCount is not 0, ppEnabledExtensionNames must be a valid pointer to an array of enabledExtensionCount null-terminated UTF-8 strings

- VUID-VkDeviceCreateInfo-pEnabledFeatures-parameter
  If pEnabledFeatures is not NULL, pEnabledFeatures must be a valid pointer to a valid VkPhysicalDeviceFeatures structure
• **VUID-VkDeviceCreateInfo-queueCreateInfoCount-arraylength**
  `queueCreateInfoCount` **must** be greater than 0

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkDeviceCreateFlags;
```

**VkDeviceCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

A logical device **can** be created that connects to one or more physical devices by adding a **VkDeviceGroupDeviceCreateInfo** structure to the `pNext` chain of **VkDeviceCreateInfo**. The **VkDeviceGroupDeviceCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceGroupDeviceCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t physicalDeviceCount;
    const VkPhysicalDevice* pPhysicalDevices;
} VkDeviceGroupDeviceCreateInfo;
```

• `sType` is a **VkStructureType** value identifying this structure.

• `pNext` is `NULL` or a pointer to a structure extending this structure.

• `physicalDeviceCount` is the number of elements in the `pPhysicalDevices` array.

• `pPhysicalDevices` is a pointer to an array of physical device handles belonging to the same device group.

The elements of the `pPhysicalDevices` array are an ordered list of the physical devices that the logical device represents. These **must** be a subset of a single device group, and need not be in the same order as they were enumerated. The order of the physical devices in the `pPhysicalDevices` array determines the *device index* of each physical device, with element `i` being assigned a device index of `i`. Certain commands and structures refer to one or more physical devices by using device indices or *device masks* formed using device indices.

A logical device created without using **VkDeviceGroupDeviceCreateInfo**, or with `physicalDeviceCount` equal to zero, is equivalent to a `physicalDeviceCount` of one and `pPhysicalDevices` pointing to the `physicalDevice` parameter to **vkCreateDevice**. In particular, the device index of that physical device is zero.

**Valid Usage**

• **VUID-VkDeviceGroupDeviceCreateInfo-pPhysicalDevices-00375**
  Each element of `pPhysicalDevices` **must** be unique

• **VUID-VkDeviceGroupDeviceCreateInfo-pPhysicalDevices-00376**
  All elements of `pPhysicalDevices` **must** be in the same device group as enumerated by
vkEnumeratePhysicalDeviceGroups

• VUID-VkDeviceGroupDeviceCreateInfo-physicalDeviceCount-00377
  If physicalDeviceCount is not 0, the physicalDevice parameter of vkCreateDevice must be an element of pPhysicalDevices

Valid Usage (Implicit)

• VUID-VkDeviceGroupDeviceCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO
• VUID-VkDeviceGroupDeviceCreateInfo-pPhysicalDevices-parameter
  If physicalDeviceCount is not 0, pPhysicalDevices must be a valid pointer to an array of physicalDeviceCount valid VkPhysicalDevice handles

To reserve private data storage slots, add a VkDevicePrivateDataCreateInfo structure to the pNext chain of the VkDeviceCreateInfo structure. Reserving slots in this manner is not strictly necessary, but doing so may improve performance.

```c
// Provided by VK_VERSION_1_3
typedef struct VkDevicePrivateDataCreateInfo {
  VkStructureType sType;
  const void* pNext;
  uint32_t privateDataSlotRequestCount;
} VkDevicePrivateDataCreateInfo;
```

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• privateDataSlotRequestCount is the amount of slots to reserve.

Valid Usage (Implicit)

• VUID-VkDevicePrivateDataCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DEVICE_PRIVATE_DATA_CREATE_INFO

5.2.2. Device Use

The following is a high-level list of VkDevice uses along with references on where to find more information:

• Creation of queues. See the Queues section below for further details.
• Creation and tracking of various synchronization constructs. See Synchronization and Cache Control for further details.
• Allocating, freeing, and managing memory. See Memory Allocation and Resource Creation for
further details.

- Creation and destruction of command buffers and command buffer pools. See Command Buffers for further details.

- Creation, destruction, and management of graphics state. See Pipelines and Resource Descriptors, among others, for further details.

5.2.3. Lost Device

A logical device may become lost for a number of implementation-specific reasons, indicating that pending and future command execution may fail and cause resources and backing memory to become undefined.

Note

Typical reasons for device loss will include things like execution timing out (to prevent denial of service), power management events, platform resource management, implementation errors.

Applications not adhering to valid usage may also result in device loss being reported, however this is not guaranteed. Even if device loss is reported, the system may be in an unrecoverable state, and further usage of the API is still considered invalid.

When this happens, certain commands will return VK_ERROR_DEVICE_LOST. After any such event, the logical device is considered lost. It is not possible to reset the logical device to a non-lost state, however the lost state is specific to a logical device (VkDevice), and the corresponding physical device (VkPhysicalDevice) may be otherwise unaffected.

In some cases, the physical device may also be lost, and attempting to create a new logical device will fail, returning VK_ERROR_DEVICE_LOST. This is usually indicative of a problem with the underlying implementation, or its connection to the host. If the physical device has not been lost, and a new logical device is successfully created from that physical device, it must be in the non-lost state.

Note

Whilst logical device loss may be recoverable, in the case of physical device loss, it is unlikely that an application will be able to recover unless additional, unaffected physical devices exist on the system. The error is largely informational and intended only to inform the user that a platform issue has occurred, and should be investigated further. For example, underlying hardware may have developed a fault or become physically disconnected from the rest of the system. In many cases, physical device loss may cause other more serious issues such as the operating system crashing; in which case it may not be reported via the Vulkan API.

When a device is lost, its child objects are not implicitly destroyed and their handles are still valid. Those objects must still be destroyed before their parents or the device can be destroyed (see the Object Lifetime section). The host address space corresponding to device memory mapped using vkMapMemory is still valid, and host memory accesses to these mapped regions are still valid, but
the contents are undefined. It is still legal to call any API command on the device and child objects.

Once a device is lost, command execution may fail, and certain commands that return a VkResult may return VK_ERROR_DEVICE_LOST. These commands can be identified by the inclusion of VK_ERROR_DEVICE_LOST in the Return Codes section for each command. Commands that do not allow runtime errors must still operate correctly for valid usage and, if applicable, return valid data.

Commands that wait indefinitely for device execution (namely vkDeviceWaitIdle, vkQueueWaitIdle, vkWaitForFences with a maximum timeout, and vkGetQueryPoolResults with the VK_QUERY_RESULT_WAIT_BIT bit set in flags) must return in finite time even in the case of a lost device, and return either VK_SUCCESS or VK_ERROR_DEVICE_LOST. For any command that may return VK_ERROR_DEVICE_LOST, for the purpose of determining whether a command buffer is in the pending state, or whether resources are considered in-use by the device, a return value of VK_ERROR_DEVICE_LOST is equivalent to VK_SUCCESS.

The content of any external memory objects that have been exported from or imported to a lost device become undefined. Objects on other logical devices or in other APIs which are associated with the same underlying memory resource as the external memory objects on the lost device are unaffected other than their content becoming undefined. The layout of subresources of images on other logical devices that are bound to VkDeviceMemory objects associated with the same underlying memory resources as external memory objects on the lost device becomes VK_IMAGE_LAYOUT_UNDEFINED.

The state of VkSemaphore objects on other logical devices created by importing a semaphore payload with temporary permanence which was exported from the lost device is undefined. The state of VkSemaphore objects on other logical devices that permanently share a semaphore payload with a VkSemaphore object on the lost device is undefined, and remains undefined following any subsequent signal operations. Implementations must ensure pending and subsequently submitted wait operations on such semaphores behave as defined in Semaphore State Requirements For Wait Operations for external semaphores not in a valid state for a wait operation.

5.2.4. Device Destruction

To destroy a device, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyDevice(
    VkDevice device,
    const VkAllocationCallbacks* pAllocator);
```

- device is the logical device to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

To ensure that no work is active on the device, vkDeviceWaitIdle can be used to gate the destruction of the device. Prior to destroying a device, an application is responsible for destroying/freeing any Vulkan objects that were created using that device as the first parameter of the corresponding vkCreate* or vkAllocate* command.
Note

The lifetime of each of these objects is bound by the lifetime of the `VkDevice` object. Therefore, to avoid resource leaks, it is critical that an application explicitly free all of these resources prior to calling `vkDestroyDevice`.

Valid Usage

- VUID-vkDestroyDevice-device-00378
  All child objects created on `device` must have been destroyed prior to destroying `device`

- VUID-vkDestroyDevice-device-00379
  If `VkAllocationCallbacks` were provided when `device` was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyDevice-device-00380
  If no `VkAllocationCallbacks` were provided when `device` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- VUID-vkDestroyDevice-device-parameter
  If `device` is not `NULL`, `device` must be a valid `VkDevice` handle

- VUID-vkDestroyDevice-pAllocator-parameter
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

Host Synchronization

- Host access to `device` must be externally synchronized
- Host access to all `VkQueue` objects created from `device` must be externally synchronized

5.3. Queues

5.3.1. Queue Family Properties

As discussed in the Physical Device Enumeration section above, the `vkGetPhysicalDeviceQueueFamilyProperties` command is used to retrieve details about the queue families and queues supported by a device.

Each index in the `pQueueFamilyProperties` array returned by `vkGetPhysicalDeviceQueueFamilyProperties` describes a unique queue family on that physical device. These indices are used when creating queues, and they correspond directly with the `queueFamilyIndex` that is passed to the `vkCreateDevice` command via the `VkDeviceQueueCreateInfo` structure as described in the Queue Creation section below.
Grouping of queue families within a physical device is implementation-dependent.

**Note**
The general expectation is that a physical device groups all queues of matching capabilities into a single family. However, while implementations should do this, it is possible that a physical device may return two separate queue families with the same capabilities.

Once an application has identified a physical device with the queue(s) that it desires to use, it will create those queues in conjunction with a logical device. This is described in the following section.

### 5.3.2. Queue Creation

Creating a logical device also creates the queues associated with that device. The queues to create are described by a set of `VkDeviceQueueCreateInfo` structures that are passed to `vkCreateDevice` in `pQueueCreateInfos`.

Queues are represented by `VkQueue` handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_HANDLE(VkQueue)
```

The `VkDeviceQueueCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDeviceQueueCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDeviceQueueCreateFlags flags;
    uint32_t queueFamilyIndex;
    uint32_t queueCount;
    const float* pQueuePriorities;
} VkDeviceQueueCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is a bitmask indicating behavior of the queues.
- `queueFamilyIndex` is an unsigned integer indicating the index of the queue family in which to create the queues on this device. This index corresponds to the index of an element of the `pQueueFamilyProperties` array that was returned by `vkGetPhysicalDeviceQueueFamilyProperties`.
- `queueCount` is an unsigned integer specifying the number of queues to create in the queue family indicated by `queueFamilyIndex`, and with the behavior specified by `flags`.
- `pQueuePriorities` is a pointer to an array of `queueCount` normalized floating point values, specifying priorities of work that will be submitted to each created queue. See **Queue Priority** for more information.
Valid Usage

- VUID-VkDeviceQueueCreateInfo-queueFamilyIndex-00381
  queueFamilyIndex must be less than pQueueFamilyPropertyCount returned by vkGetPhysicalDeviceQueueFamilyProperties

- VUID-VkDeviceQueueCreateInfo-queueCount-00382
  queueCount must be less than or equal to the queueCount member of the VkQueueFamilyProperties structure, as returned by vkGetPhysicalDeviceQueueFamilyProperties in the pQueueFamilyProperties[queueFamilyIndex]

- VUID-VkDeviceQueueCreateInfo-pQueuePriorities-00383
  Each element of pQueuePriorities must be between 0.0 and 1.0 inclusive

- VUID-VkDeviceQueueCreateInfo-flags-02861
  If the protectedMemory feature is not enabled, the VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT bit of flags must not be set

- VUID-VkDeviceQueueCreateInfo-flags-06449
  If flags includes VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT, queueFamilyIndex must be the index of a queue family that includes the VK_QUEUE_PROTECTED_BIT capability

Valid Usage (Implicit)

- VUID-VkDeviceQueueCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO

- VUID-VkDeviceQueueCreateInfo-pNext-pNext
  pNext must be NULL

- VUID-VkDeviceQueueCreateInfo-flags-parameter
  flags must be a valid combination of VkDeviceQueueCreateFlagBits values

- VUID-VkDeviceQueueCreateInfo-pQueuePriorities-parameter
  pQueuePriorities must be a valid pointer to an array of queueCount float values

- VUID-VkDeviceQueueCreateInfo-queueCount-arraylength
  queueCount must be greater than 0

Bits which can be set in VkDeviceQueueCreateInfo::flags, specifying usage behavior of a queue, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkDeviceQueueCreateFlagBits {
    // Provided by VK_VERSION_1_1
    VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT = 0x00000001,
} VkDeviceQueueCreateFlagBits;
```

- VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT specifies that the device queue is a protected-capable
queue.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkDeviceQueueCreateFlags;
```

**VkDeviceQueueCreateFlags** is a bitmask type for setting a mask of zero or more **VkDeviceQueueCreateFlagBits**.

To retrieve a handle to a **VkQueue** object, call:

```c
// Provided by VK_VERSION_1_0
void vkGetDeviceQueue(
    VkDevice device,
    uint32_t queueFamilyIndex,
    uint32_t queueIndex,
    VkQueue* pQueue);
```

- **device** is the logical device that owns the queue.
- **queueFamilyIndex** is the index of the queue family to which the queue belongs.
- **queueIndex** is the index within this queue family of the queue to retrieve.
- **pQueue** is a pointer to a **VkQueue** object that will be filled with the handle for the requested queue.

**vkGetDeviceQueue** must only be used to get queues that were created with the **flags** parameter of **VkDeviceQueueCreateInfo** set to zero. To get queues that were created with a non-zero **flags** parameter use **vkGetDeviceQueue2**.

### Valid Usage

- **VUID-vkGetDeviceQueue-queueFamilyIndex-00384**
  
  **queueFamilyIndex** must be one of the queue family indices specified when **device** was created, via the **VkDeviceQueueCreateInfo** structure.

- **VUID-vkGetDeviceQueue-queueIndex-00385**
  
  **queueIndex** must be less than the value of **VkDeviceQueueCreateInfo::queueCount** for the queue family indicated by **queueFamilyIndex** when **device** was created.

- **VUID-vkGetDeviceQueue-flags-01841**
  
  **VkDeviceQueueCreateInfo::flags** must have been set to zero when **device** was created.

### Valid Usage (Implicit)

- **VUID-vkGetDeviceQueue-device-parameter**
  
  **device** must be a valid **VkDevice** handle.

- **VUID-vkGetDeviceQueue-pQueue-parameter**
  

pQueue must be a valid pointer to a VkQueue handle

To retrieve a handle to a VkQueue object with specific VkDeviceQueueCreateFlags creation flags, call:

```c
// Provided by VK_VERSION_1_1
void vkGetDeviceQueue2(
    VkDevice device, 
    const VkDeviceQueueInfo2* pQueueInfo, 
    VkQueue* pQueue);
```

- **device** is the logical device that owns the queue.
- **pQueueInfo** is a pointer to a VkDeviceQueueInfo2 structure, describing parameters of the device queue to be retrieved.
- **pQueue** is a pointer to a VkQueue object that will be filled with the handle for the requested queue.

Valid Usage (Implicit)

- VUID-vkGetDeviceQueue2-device-parameter
  device must be a valid VkDevice handle
- VUID-vkGetDeviceQueue2-pQueueInfo-parameter
  pQueueInfo must be a valid pointer to a valid VkDeviceQueueInfo2 structure
- VUID-vkGetDeviceQueue2-pQueue-parameter
  pQueue must be a valid pointer to a VkQueue handle

The VkDeviceQueueInfo2 structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceQueueInfo2 {
    VkStructureType sType;
    const void*pNext;
    VkDeviceQueueCreateFlags flags;
    uint32_t queueFamilyIndex;
    uint32_t queueIndex;
} VkDeviceQueueInfo2;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure. The pNext chain of VkDeviceQueueInfo2 can be used to provide additional device queue parameters to vkGetDeviceQueue2.
- **flags** is a VkDeviceQueueCreateFlags value indicating the flags used to create the device queue.
- **queueFamilyIndex** is the index of the queue family to which the queue belongs.
• `queueIndex` is the index of the queue to retrieve from within the set of queues that share both the queue family and flags specified.

The queue returned by `vkGetDeviceQueue2` must have the same `flags` value from this structure as that used at device creation time in a `VkDeviceQueueCreateInfo` structure.

**Note**

Normally, if you create both protected-capable and non-protected-capable queues with the same family, they are treated as separate lists of queues and `queueIndex` is relative to the start of the list of queues specified by both `queueFamilyIndex` and `flags`. However, for historical reasons, some implementations may exhibit different behavior. These divergent implementations instead concatenate the lists of queues and treat `queueIndex` as relative to the start of the first list of queues with the given `queueFamilyIndex`. This only matters in cases where an application has created both protected-capable and non-protected-capable queues from the same queue family.

For such divergent implementations, the maximum value of `queueIndex` is equal to the sum of `VkDeviceQueueCreateInfo::queueCount` minus one, for all `VkDeviceQueueCreateInfo` structures that share a common `queueFamilyIndex`.

Such implementations will return `NULL` for either the protected or unprotected queues when calling `vkGetDeviceQueue2` with `queueIndex` in the range zero to `VkDeviceQueueCreateInfo::queueCount` minus one. In cases where these implementations returned `NULL`, the corresponding queues are instead located in the extended range described in the preceding two paragraphs.

This behaviour will not be observed on any driver that has passed Vulkan conformance test suite version 1.3.3.0, or any subsequent version. This information can be found by querying `VkPhysicalDeviceDriverProperties::conformanceVersion`.

**Valid Usage**

- VUID-VkDeviceQueueInfo2-queueFamilyIndex-01842
  `queueFamilyIndex` must be one of the queue family indices specified when `device` was created, via the `VkDeviceQueueCreateInfo` structure

- VUID-VkDeviceQueueInfo2-flags-06225
  `flags` must be equal to `VkDeviceQueueCreateInfo::flags` for a `VkDeviceQueueCreateInfo` structure for the queue family indicated by `queueFamilyIndex` when `device` was created

- VUID-VkDeviceQueueInfo2-queueIndex-01843
  `queueIndex` must be less than `VkDeviceQueueCreateInfo::queueCount` for the corresponding queue family and flags indicated by `queueFamilyIndex` and `flags` when `device` was created
5.3.3. Queue Family Index

The queue family index is used in multiple places in Vulkan in order to tie operations to a specific family of queues.

When retrieving a handle to the queue via `vkGetDeviceQueue`, the queue family index is used to select which queue family to retrieve the `VkQueue` handle from as described in the previous section.

When creating a `VkCommandPool` object (see Command Pools), a queue family index is specified in the `VkCommandPoolCreateInfo` structure. Command buffers from this pool can only be submitted on queues corresponding to this queue family.

When creating `VkImage` (see Images) and `VkBuffer` (see Buffers) resources, a set of queue families is included in the `VkImageCreateInfo` and `VkBufferCreateInfo` structures to specify the queue families that can access the resource.

When inserting a `VkBufferMemoryBarrier` or `VkImageMemoryBarrier` (see Pipeline Barriers), a source and destination queue family index is specified to allow the ownership of a buffer or image to be transferred from one queue family to another. See the Resource Sharing section for details.

5.3.4. Queue Priority

Each queue is assigned a priority, as set in the `VkDeviceQueueCreateInfo` structures when creating the device. The priority of each queue is a normalized floating point value between 0.0 and 1.0, which is then translated to a discrete priority level by the implementation. Higher values indicate a higher priority, with 0.0 being the lowest priority and 1.0 being the highest.

Within the same device, queues with higher priority may be allotted more processing time than queues with lower priority. The implementation makes no guarantees with regards to ordering or scheduling among queues with the same priority, other than the constraints defined by any explicit synchronization primitives. The implementation makes no guarantees with regards to queues across different devices.

An implementation may allow a higher-priority queue to starve a lower-priority queue on the same `VkDevice` until the higher-priority queue has no further commands to execute. The relationship of queue priorities must not cause queues on one `VkDevice` to starve queues on another `VkDevice`.

No specific guarantees are made about higher priority queues receiving more processing time or
better quality of service than lower priority queues.

5.3.5. Queue Submission

Work is submitted to a queue via queue submission commands such as `vkQueueSubmit2` or `vkQueueSubmit`. Queue submission commands define a set of queue operations to be executed by the underlying physical device, including synchronization with semaphores and fences.

Submission commands take as parameters a target queue, zero or more batches of work, and an optional fence to signal upon completion. Each batch consists of three distinct parts:

1. Zero or more semaphores to wait on before execution of the rest of the batch.
   - If present, these describe a semaphore wait operation.
2. Zero or more work items to execute.
   - If present, these describe a queue operation matching the work described.
3. Zero or more semaphores to signal upon completion of the work items.
   - If present, these describe a semaphore signal operation.

If a fence is present in a queue submission, it describes a fence signal operation.

All work described by a queue submission command must be submitted to the queue before the command returns.

Sparse Memory Binding

In Vulkan it is possible to sparsely bind memory to buffers and images as described in the Sparse Resource chapter. Sparse memory binding is a queue operation. A queue whose flags include the `VK_QUEUE_SPARSE_BINDING_BIT` must be able to support the mapping of a virtual address to a physical address on the device. This causes an update to the page table mappings on the device. This update must be synchronized on a queue to avoid corrupting page table mappings during execution of graphics commands. By binding the sparse memory resources on queues, all commands that are dependent on the updated bindings are synchronized to only execute after the binding is updated. See the Synchronization and Cache Control chapter for how this synchronization is accomplished.

5.3.6. Queue Destruction

Queues are created along with a logical device during `vkCreateDevice`. All queues associated with a logical device are destroyed when `vkDestroyDevice` is called on that device.
Chapter 6. Command Buffers

Command buffers are objects used to record commands which can be subsequently submitted to a device queue for execution. There are two levels of command buffers - primary command buffers, which can execute secondary command buffers, and which are submitted to queues, and secondary command buffers, which can be executed by primary command buffers, and which are not directly submitted to queues.

Command buffers are represented by VkCommandBuffer handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_HANDLE(VkCommandBuffer)
```

Recorded commands include commands to bind pipelines and descriptor sets to the command buffer, commands to modify dynamic state, commands to draw (for graphics rendering), commands to dispatch (for compute), commands to execute secondary command buffers (for primary command buffers only), commands to copy buffers and images, and other commands.

Each command buffer manages state independently of other command buffers. There is no inheritance of state across primary and secondary command buffers, or between secondary command buffers. When a command buffer begins recording, all state in that command buffer is undefined. When secondary command buffer(s) are recorded to execute on a primary command buffer, the secondary command buffer inherits no state from the primary command buffer, and all state of the primary command buffer is undefined after an execute secondary command buffer command is recorded. There is one exception to this rule - if the primary command buffer is inside a render pass instance, then the render pass and subpass state is not disturbed by executing secondary command buffers. For state dependent commands (such as draws and dispatches), any state consumed by those commands must not be undefined.

Unless otherwise specified, and without explicit synchronization, the various commands submitted to a queue via command buffers may execute in arbitrary order relative to each other, and/or concurrently. Also, the memory side effects of those commands may not be directly visible to other commands without explicit memory dependencies. This is true within a command buffer, and across command buffers submitted to a given queue. See the synchronization chapter for information on implicit and explicit synchronization between commands.

6.1. Command Buffer Lifecycle

Each command buffer is always in one of the following states:

**Initial**

When a command buffer is allocated, it is in the initial state. Some commands are able to reset a command buffer (or a set of command buffers) back to this state from any of the executable, recording or invalid state. Command buffers in the initial state can only be moved to the recording state, or freed.
Recording

`vkBeginCommandBuffer` changes the state of a command buffer from the initial state to the *recording state*. Once a command buffer is in the recording state, `vkCmd*` commands *can* be used to record to the command buffer.

Executable

`vkEndCommandBuffer` ends the recording of a command buffer, and moves it from the recording state to the *executable state*. Executable command buffers *can* be submitted, reset, or recorded to another command buffer.

Pending

*Queue submission* of a command buffer changes the state of a command buffer from the executable state to the *pending state*. Whilst in the pending state, applications *must* not attempt to modify the command buffer in any way - as the device *may* be processing the commands recorded to it. Once execution of a command buffer completes, the command buffer either reverts back to the *executable state*, or if it was recorded with `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT`, it moves to the *invalid state*. A synchronization command *should* be used to detect when this occurs.

Invalid

Some operations, such as modifying or deleting a resource that was used in a command recorded to a command buffer, will transition the state of that command buffer into the *invalid state*. Command buffers in the invalid state *can* only be reset or freed.

![Lifecycle of a command buffer](image)

*Figure 1. Lifecycle of a command buffer*

Any given command that operates on a command buffer has its own requirements on what state a command buffer *must* be in, which are detailed in the valid usage constraints for that command.

Resetting a command buffer is an operation that discards any previously recorded commands and puts a command buffer in the *initial state*. Resetting occurs as a result of `vkResetCommandBuffer` or `vkResetCommandPool`, or as part of `vkBeginCommandBuffer` (which additionally puts the command buffer in the *recording state*).

*Secondary command buffers* *can* be recorded to a primary command buffer via
vkCmdExecuteCommands. This partially ties the lifecycle of the two command buffers together - if the primary is submitted to a queue, both the primary and any secondaries recorded to it move to the pending state. Once execution of the primary completes, so it does for any secondary recorded within it. After all executions of each command buffer complete, they each move to their appropriate completion state (either to the executable state or the invalid state, as specified above).

If a secondary moves to the invalid state or the initial state, then all primary buffers it is recorded in move to the invalid state. A primary moving to any other state does not affect the state of a secondary recorded in it.

Note
Resetting or freeing a primary command buffer removes the lifecycle linkage to all secondary command buffers that were recorded into it.

6.2. Command Pools

Command pools are opaque objects that command buffer memory is allocated from, and which allow the implementation to amortize the cost of resource creation across multiple command buffers. Command pools are externally synchronized, meaning that a command pool must not be used concurrently in multiple threads. That includes use via recording commands on any command buffers allocated from the pool, as well as operations that allocate, free, and reset command buffers or the pool itself.

Command pools are represented by VkCommandPool handles:

// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkCommandPool)

to create a command pool, call:

// Provided by VK_VERSION_1_0
VkResult vkCreateCommandPool(
    VkDevice device, 
    const VkCommandPoolCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkCommandPool* pCommandPool);

- device is the logical device that creates the command pool.
- pCreateInfo is a pointer to a VkCommandPoolCreateInfo structure specifying the state of the command pool object.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pCommandPool is a pointer to a VkCommandPool handle in which the created pool is returned.
Valid Usage

• VUID-vkCreateCommandPool-queueFamilyIndex-01937
  pCreateInfo->queueFamilyIndex must be the index of a queue family available in the logical device device

Valid Usage (Implicit)

• VUID-vkCreateCommandPool-device-parameter
device must be a valid VkDevice handle

• VUID-vkCreateCommandPool-pCreateInfo-parameter
  pCreateInfo must be a valid pointer to a valid VkCommandPoolCreateInfo structure

• VUID-vkCreateCommandPool-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

• VUID-vkCreateCommandPool-pCommandPool-parameter
  pCommandPool must be a valid pointer to a VkCommandPool handle

Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkCommandPoolCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkCommandPoolCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandPoolCreateFlags flags;
    uint32_t queueFamilyIndex;
} VkCommandPoolCreateInfo;
```

• sType is a VkStructureType value identifying this structure.

• pNext is NULL or a pointer to a structure extending this structure.

• flags is a bitmask of VkCommandPoolCreateFlagBits indicating usage behavior for the pool and command buffers allocated from it.
• queueFamilyIndex designates a queue family as described in section Queue Family Properties. All command buffers allocated from this command pool must be submitted on queues from the same queue family.

Valid Usage

• VUID-VkCommandPoolCreateInfo-flags-02860
  If the protectedMemory feature is not enabled, the VK_COMMAND_POOL_CREATE_PROTECTED_BIT bit of flags must not be set

Valid Usage (Implicit)

• VUID-VkCommandPoolCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO

• VUID-VkCommandPoolCreateInfo-pNext-pNext
  pNext must be NULL

• VUID-VkCommandPoolCreateInfo-flags-parameter
  flags must be a valid combination of VkCommandPoolCreateFlagBits values

Bits which can be set in VkCommandPoolCreateInfo::flags, specifying usage behavior for a command pool, are:

// Provided by VK_VERSION_1_0
typedef enum VkCommandPoolCreateFlagBits {
  VK_COMMAND_POOL_CREATE_TRANSIENT_BIT = 0x00000001,
  VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT = 0x00000002,
  // Provided by VK_VERSION_1_1
  VK_COMMAND_POOL_CREATE_PROTECTED_BIT = 0x00000004,
} VkCommandPoolCreateFlagBits;

• VK_COMMAND_POOL_CREATE_TRANSIENT_BIT specifies that command buffers allocated from the pool will be short-lived, meaning that they will be reset or freed in a relatively short timeframe. This flag may be used by the implementation to control memory allocation behavior within the pool.

• VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT allows any command buffer allocated from a pool to be individually reset to the initial state; either by calling vkResetCommandBuffer, or via the implicit reset when calling vkBeginCommandBuffer. If this flag is not set on a pool, then vkResetCommandBuffer must not be called for any command buffer allocated from that pool.

• VK_COMMAND_POOL_CREATE_PROTECTED_BIT specifies that command buffers allocated from the pool are protected command buffers.

// Provided by VK_VERSION_1_0
typedef VkFlags VkCommandPoolCreateFlags;
**VkCommandPoolCreateFlags** is a bitmask type for setting a mask of zero or more **VkCommandPoolCreateFlagBits**.

To trim a command pool, call:

```c
// Provided by VK_VERSION_1_1
void vkTrimCommandPool(
    VkDevice device,
    VkCommandPool commandPool,
    VkCommandPoolTrimFlags flags);
```

- **device** is the logical device that owns the command pool.
- **commandPool** is the command pool to trim.
- **flags** is reserved for future use.

Trimming a command pool recycles unused memory from the command pool back to the system. Command buffers allocated from the pool are not affected by the command.

**Note**
This command provides applications with some control over the internal memory allocations used by command pools.

Unused memory normally arises from command buffers that have been recorded and later reset, such that they are no longer using the memory. On reset, a command buffer can return memory to its command pool, but the only way to release memory from a command pool to the system requires calling **vkResetCommandPool**, which cannot be executed while any command buffers from that pool are still in use. Subsequent recording operations into command buffers will reuse this memory but since total memory requirements fluctuate over time, unused memory can accumulate.

In this situation, trimming a command pool **may** be useful to return unused memory back to the system, returning the total outstanding memory allocated by the pool back to a more “average” value.

Implementations utilize many internal allocation strategies that make it impossible to guarantee that all unused memory is released back to the system. For instance, an implementation of a command pool **may** involve allocating memory in bulk from the system and sub-allocating from that memory. In such an implementation any live command buffer that holds a reference to a bulk allocation would prevent that allocation from being freed, even if only a small proportion of the bulk allocation is in use.

In most cases trimming will result in a reduction in allocated but unused memory, but it does not guarantee the “ideal” behavior.

Trimming **may** be an expensive operation, and **should** not be called frequently. Trimming **should** be treated as a way to relieve memory pressure after...
application-known points when there exists enough unused memory that the cost of trimming is “worth” it.

Valid Usage (Implicit)

- **VUID-vkTrimCommandPool-device-parameter**
  - `device` must be a valid `VkDevice` handle

- **VUID-vkTrimCommandPool-commandPool-parameter**
  - `commandPool` must be a valid `VkCommandPool` handle

- **VUID-vkTrimCommandPool-flags-zerobitmask**
  - `flags` must be 0

- **VUID-vkTrimCommandPool-commandPool-parent**
  - `commandPool` must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `commandPool` must be externally synchronized

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkCommandPoolTrimFlags;
```

`VkCommandPoolTrimFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

To reset a command pool, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkResetCommandPool(
    VkDevice device,
    VkCommandPool commandPool,
    VkCommandPoolResetFlags flags);
```

- `device` is the logical device that owns the command pool.
- `commandPool` is the command pool to reset.
- `flags` is a bitmask of `VkCommandPoolResetFlagBits` controlling the reset operation.

Resetting a command pool recycles all of the resources from all of the command buffers allocated from the command pool back to the command pool. All command buffers that have been allocated from the command pool are put in the initial state.

Any primary command buffer allocated from another `VkCommandPool` that is in the recording or executable state and has a secondary command buffer allocated from `commandPool` recorded into it, becomes invalid.
Valid Usage

• VUID-vkResetCommandPool-commandPool-00040
  All VkCommandBuffer objects allocated from commandPool must not be in the pending state

Valid Usage (Implicit)

• VUID-vkResetCommandPool-device-parameter
  device must be a valid VkDevice handle
• VUID-vkResetCommandPool-commandPool-parameter
  commandPool must be a valid VkCommandPool handle
• VUID-vkResetCommandPool-flags-parameter
  flags must be a valid combination of VkCommandPoolResetFlagBits values
• VUID-vkResetCommandPool-commandPool-parent
  commandPool must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to commandPool must be externally synchronized

Return Codes

Success
• VK_SUCCESS
Failure
• VK_ERROR_OUT_OF_DEVICE_MEMORY

Bits which can be set in vkResetCommandPool::flags, controlling the reset operation, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCommandPoolResetFlagBits {
    VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
} VkCommandPoolResetFlagBits;
```

• VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT specifies that resetting a command pool recycles all of the resources from the command pool back to the system.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkCommandPoolResetFlags;
```
**VkCommandPoolResetFlags** is a bitmask type for setting a mask of zero or more **VkCommandPoolResetFlagBits**.

To destroy a command pool, call:

```c
// Provided by VK_VERSION_1_0
define vkDestroyCommandPool(device, commandPool, pAllocator);
```

- `device` is the logical device that destroys the command pool.
- `commandPool` is the handle of the command pool to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

When a pool is destroyed, all command buffers allocated from the pool are freed.

Any primary command buffer allocated from another **VkCommandPool** that is in the recording or executable state and has a secondary command buffer allocated from `commandPool` recorded into it, becomes invalid.

### Valid Usage

- VUID-vkDestroyCommandPool-commandPool-00041
  All **VkCommandBuffer** objects allocated from `commandPool` must not be in the pending state

- VUID-vkDestroyCommandPool-commandPool-00042
  If **VkAllocationCallbacks** were provided when `commandPool` was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyCommandPool-commandPool-00043
  If no **VkAllocationCallbacks** were provided when `commandPool` was created, `pAllocator` must be NULL

### Valid Usage (Implicit)

- VUID-vkDestroyCommandPool-device-parameter
  `device` must be a valid **VkDevice** handle

- VUID-vkDestroyCommandPool-commandPool-parameter
  If `commandPool` is not VK_NULL_HANDLE, `commandPool` must be a valid **VkCommandPool** handle

- VUID-vkDestroyCommandPool-pAllocator-parameter
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid **VkAllocationCallbacks** structure

- VUID-vkDestroyCommandPool-commandPool-parent
  If `commandPool` is a valid handle, it must have been created, allocated, or retrieved from
Host Synchronization

- Host access to `commandPool` must be externally synchronized

6.3. Command Buffer Allocation and Management

To allocate command buffers, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkAllocateCommandBuffers(
    VkDevice device,
    const VkCommandBufferAllocateInfo* pAllocateInfo,
    VkCommandBuffer* pCommandBuffers);
```

- `device` is the logical device that owns the command pool.
- `pAllocateInfo` is a pointer to a `VkCommandBufferAllocateInfo` structure describing parameters of the allocation.
- `pCommandBuffers` is a pointer to an array of `VkCommandBuffer` handles in which the resulting command buffer objects are returned. The array must be at least the length specified by the `commandBufferCount` member of `pAllocateInfo`. Each allocated command buffer begins in the initial state.

`vkAllocateCommandBuffers` can be used to allocate multiple command buffers. If the allocation of any of those command buffers fails, the implementation must free all successfully allocated command buffer objects from this command, set all entries of the `pCommandBuffers` array to `NULL` and return the error.

**Note**
Filling `pCommandBuffers` with `NULL` values on failure is an exception to the default error behavior that output parameters will have undefined contents.

When command buffers are first allocated, they are in the initial state.

Valid Usage (Implicit)

- VUID-vkAllocateCommandBuffers-device-parameter
  `device` must be a valid `VkDevice` handle
- VUID-vkAllocateCommandBuffers-pAllocateInfo-parameter
  `pAllocateInfo` must be a valid pointer to a valid `VkCommandBufferAllocateInfo` structure
- VUID-vkAllocateCommandBuffers-pCommandBuffers-parameter
  `pCommandBuffers` must be a valid pointer to an array of `pAllocateInfo->commandBufferCount`
**VkCommandBuffer handles**

- \texttt{VUID-vkAllocateCommandBuffers-pAllocateInfo::commandBufferCount-arraylength} \texttt{pAllocateInfo->commandBufferCount} must be greater than 0

**Host Synchronization**

- Host access to \texttt{pAllocateInfo->commandPool} must be externally synchronized

**Return Codes**

- **Success**
  - VK_SUCCESS

- **Failure**
  - VK_ERROR_OUT_OF_HOST_MEMORY
  - VK_ERROR_OUT_OF_DEVICE_MEMORY

The \texttt{VkCommandBufferAllocateInfo} structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkCommandBufferAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandPool commandPool;
    VkCommandBufferLevel level;
    uint32_t commandBufferCount;
} VkCommandBufferAllocateInfo;
```

- \texttt{sType} is a \texttt{VkStructureType} value identifying this structure.
- \texttt{pNext} is NULL or a pointer to a structure extending this structure.
- \texttt{commandPool} is the command pool from which the command buffers are allocated.
- \texttt{level} is a \texttt{VkCommandBufferLevel} value specifying the command buffer level.
- \texttt{commandBufferCount} is the number of command buffers to allocate from the pool.

**Valid Usage (Implicit)**

- \texttt{VUID-VkCommandBufferAllocateInfo-sType-sType} \texttt{sType} must be VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO
- \texttt{VUID-VkCommandBufferAllocateInfo-pNext-pNext} \texttt{pNext} must be NULL
- \texttt{VUID-VkCommandBufferAllocateInfo-commandPool-parameter}
**commandPool** must be a valid **VkCommandPool** handle

- VUID-VkCommandBufferAllocateInfo-level-parameter
  **level** must be a valid **VkCommandBufferLevel** value

Possible values of **VkCommandBufferAllocateInfo::level**, specifying the command buffer level, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCommandBufferLevel {
    VK_COMMAND_BUFFER_LEVEL_PRIMARY = 0,
    VK_COMMAND_BUFFER_LEVEL_SECONDARY = 1,
} VkCommandBufferLevel;
```

- **VK_COMMAND_BUFFER_LEVEL_PRIMARY** specifies a primary command buffer.
- **VK_COMMAND_BUFFER_LEVEL_SECONDARY** specifies a secondary command buffer.

To reset a command buffer, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkResetCommandBuffer(
    VkCommandBuffer commandBuffer,
    VkCommandBufferResetFlags flags);
```

- **commandBuffer** is the command buffer to reset. The command buffer can be in any state other than pending, and is moved into the initial state.
- **flags** is a bitmask of **VkCommandBufferResetFlagBits** controlling the reset operation.

Any primary command buffer that is in the recording or executable state and has **commandBuffer** recorded into it, becomes invalid.

---

### Valid Usage

- VUID-vkResetCommandBuffer-commandBuffer-00045  
  **commandBuffer** must not be in the pending state

- VUID-vkResetCommandBuffer-commandBuffer-00046  
  **commandBuffer** must have been allocated from a pool that was created with the **VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT**

---

### Valid Usage (Implicit)

- VUID-vkResetCommandBuffer-commandBuffer-parameter  
  **commandBuffer** must be a valid **VkCommandBuffer** handle

- VUID-vkResetCommandBuffer-flags-parameter  
  **flags** must be a valid combination of **VkCommandBufferResetFlagBits** values
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_DEVICE_MEMORY

Bits which can be set in VkResetCommandBuffer::flags, controlling the reset operation, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCommandBufferResetFlagBits {
    VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
} VkCommandBufferResetFlagBits;
```

- VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT specifies that most or all memory resources currently owned by the command buffer should be returned to the parent command pool. If this flag is not set, then the command buffer may hold onto memory resources and reuse them when recording commands. commandBuffer is moved to the initial state.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkCommandBufferResetFlags;
```

VkCommandBufferResetFlags is a bitmask type for setting a mask of zero or more VkCommandBufferResetFlagBits.

To free command buffers, call:

```c
// Provided by VK_VERSION_1_0
void vkFreeCommandBuffers(
    VkDevice device,  // Logical device that owns the command buffer.
    VkCommandPool commandPool,  // Command pool from which the command buffers were allocated.
    uint32_t commandBufferCount,  // Number of command buffers to free.
    const VkCommandBuffer* pCommandBuffers);  // Pointer to an array of command buffers.
```
• `commandBufferCount` is the length of the `pCommandBuffers` array.
• `pCommandBuffers` is a pointer to an array of handles of command buffers to free.

Any primary command buffer that is in the `recording` or `executable state` and has any element of `pCommandBuffers` recorded into it, becomes `invalid`.

**Valid Usage**

- VUID-vkFreeCommandBuffers-pCommandBuffers-00047
  All elements of `pCommandBuffers` must not be in the `pending state`
- VUID-vkFreeCommandBuffers-pCommandBuffers-00048
  `pCommandBuffers` must be a valid pointer to an array of `commandBufferCount` `VkCommandBuffer` handles, each element of which must either be a valid handle or `NULL`

**Valid Usage (Implicit)**

- VUID-vkFreeCommandBuffers-device-parameter
  `device` must be a valid `VkDevice` handle
- VUID-vkFreeCommandBuffers-commandPool-parameter
  `commandPool` must be a valid `VkCommandPool` handle
- VUID-vkFreeCommandBuffers-commandBufferCount-arraylength
  `commandBufferCount` must be greater than 0
- VUID-vkFreeCommandBuffers-commandPool-parent
  `commandPool` must have been created, allocated, or retrieved from `device`
- VUID-vkFreeCommandBuffers-pCommandBuffers-parent
  Each element of `pCommandBuffers` that is a valid handle must have been created, allocated, or retrieved from `commandPool`

**Host Synchronization**

- Host access to `commandPool` must be externally synchronized
- Host access to each member of `pCommandBuffers` must be externally synchronized

### 6.4. Command Buffer Recording

To begin recording a command buffer, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkBeginCommandBuffer(
    VkCommandBuffer commandBuffer, 
    const VkCommandBufferBeginInfo* pBeginInfo);
```
• **commandBuffer** is the handle of the command buffer which is to be put in the recording state.
• **pBeginInfo** is a pointer to a **VkCommandBufferBeginInfo** structure defining additional information about how the command buffer begins recording.

### Valid Usage

- VUID-vkBeginCommandBuffer-commandBuffer-00049
  
  **commandBuffer** must not be in the **recording or pending state**

- VUID-vkBeginCommandBuffer-commandBuffer-00050
  
  If **commandBuffer** was allocated from a **VkCommandPool** which did not have the **VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT** flag set, **commandBuffer** must be in the **initial state**

- VUID-vkBeginCommandBuffer-commandBuffer-00051
  
  If **commandBuffer** is a secondary command buffer, the **pInheritanceInfo** member of **pBeginInfo** must be a valid **VkCommandBufferInheritanceInfo** structure

- VUID-vkBeginCommandBuffer-commandBuffer-00052
  
  If **commandBuffer** is a secondary command buffer and either the **occlusionQueryEnable** member of the **pInheritanceInfo** member of **pBeginInfo** is **VK_FALSE**, or the **occlusionQueryPrecise** feature is not enabled, then **pBeginInfo->pInheritanceInfo->queryFlags** must not contain **VK_QUERY_CONTROL_PRECISE_BIT**

- VUID-vkBeginCommandBuffer-commandBuffer-02840
  
  If **commandBuffer** is a primary command buffer, then **pBeginInfo->flags** must not set both the **VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT** and the **VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT** flags

### Valid Usage (Implicit)

- VUID-vkBeginCommandBuffer-commandBuffer-parameter
  
  **commandBuffer** must be a valid **VkCommandBuffer** handle

- VUID-vkBeginCommandBuffer-pBeginInfo-parameter
  
  **pBeginInfo** must be a valid pointer to a valid **VkCommandBufferBeginInfo** structure

### Host Synchronization

- Host access to **commandBuffer** must be externally synchronized

- Host access to the **VkCommandPool** that **commandBuffer** was allocated from must be externally synchronized
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkCommandBufferBeginInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkCommandBufferBeginInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandBufferUsageFlags flags;
    const VkCommandBufferInheritanceInfo* pInheritanceInfo;
} VkCommandBufferBeginInfo;
```

- `sType` is a VkStructureType value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `flags` is a bitmask of VkCommandBufferUsageFlagBits specifying usage behavior for the command buffer.
- `pInheritanceInfo` is a pointer to a VkCommandBufferInheritanceInfo structure, used if `commandBuffer` is a secondary command buffer. If this is a primary command buffer, then this value is ignored.

Valid Usage

- VUID-VkCommandBufferBeginInfo-flags-00055
  If `flags` contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT, the framebuffer member of `pInheritanceInfo` must be either VK_NULL_HANDLE, or a valid VkFramebuffer that is compatible with the `renderPass` member of `pInheritanceInfo`.

- VUID-VkCommandBufferBeginInfo-flags-06000
  If `flags` contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT and the `renderPass` member of `pInheritanceInfo` is not VK_NULL_HANDLE, `renderPass` must be a valid VkRenderPass.

- VUID-VkCommandBufferBeginInfo-flags-06001
  If `flags` contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT and the `renderPass` member of `pInheritanceInfo` is not VK_NULL_HANDLE, the `subpass` member of `pInheritanceInfo` must be a valid subpass index within the `renderPass` member of `pInheritanceInfo`.

- VUID-VkCommandBufferBeginInfo-flags-06002
If flags contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT and the renderPass member of pInheritanceInfo is VK_NULL_HANDLE, the pNext chain of pInheritanceInfo must include a VkCommandBufferInheritanceRenderingInfo structure.

**Valid Usage (Implicit)**

- VUID-VkCommandBufferBeginInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO

- VUID-VkCommandBufferBeginInfo-pNext-pNext
  pNext must be NULL or a pointer to a valid instance of VkDeviceGroupCommandBufferBeginInfo

- VUID-VkCommandBufferBeginInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

- VUID-VkCommandBufferBeginInfo-flags-parameter
  flags must be a valid combination of VkCommandBufferUsageFlagBits values

Bits which can be set in VkCommandBufferBeginInfo::flags, specifying usage behavior for a command buffer, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCommandBufferUsageFlagBits {
    VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT = 0x00000001,
    VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT = 0x00000002,
    VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT = 0x00000004,
} VkCommandBufferUsageFlagBits;
```

- **VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT** specifies that each recording of the command buffer will only be submitted once, and the command buffer will be reset and recorded again between each submission.

- **VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT** specifies that a secondary command buffer is considered to be entirely inside a render pass. If this is a primary command buffer, then this bit is ignored.

- **VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT** specifies that a command buffer can be resubmitted to a queue while it is in the pending state, and recorded into multiple primary command buffers.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkCommandBufferUsageFlags;
```

VkCommandBufferUsageFlags is a bitmask type for setting a mask of zero or more VkCommandBufferUsageFlagBits.

If the command buffer is a secondary command buffer, then the VkCommandBufferInheritanceInfo
structure defines any state that will be inherited from the primary command buffer:

```c
// Provided by VK_VERSION_1_0
typedef struct VkCommandBufferInheritanceInfo {
    VkStructureType sType;
    const void* pNext;
    VkRenderPass renderPass;
    uint32_t subpass;
    VkFramebuffer framebuffer;
    VkBool32 occlusionQueryEnable;
    VkQueryControlFlags queryFlags;
    VkQueryPipelineStatisticFlags pipelineStatistics;
} VkCommandBufferInheritanceInfo;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **renderPass** is a `VkRenderPass` object defining which render passes the `VkCommandBuffer` will be compatible with and can be executed within.
- **subpass** is the index of the subpass within the render pass instance that the `VkCommandBuffer` will be executed within.
- **framebuffer** can refer to the `VkFramebuffer` object that the `VkCommandBuffer` will be rendering to if it is executed within a render pass instance. It can be `VK_NULL_HANDLE` if the framebuffer is not known.

**Note**

Specifying the exact framebuffer that the secondary command buffer will be executed with may result in better performance at command buffer execution time.

- **occlusionQueryEnable** specifies whether the command buffer can be executed while an occlusion query is active in the primary command buffer. If this is `VK_TRUE`, then this command buffer can be executed whether the primary command buffer has an occlusion query active or not. If this is `VK_FALSE`, then the primary command buffer must not have an occlusion query active.
- **queryFlags** specifies the query flags that can be used by an active occlusion query in the primary command buffer when this secondary command buffer is executed. If this value includes the `VK_QUERY_CONTROL_PRECISE_BIT` bit, then the active query can return boolean results or actual sample counts. If this bit is not set, then the active query must not use the `VK_QUERY_CONTROL_PRECISE_BIT` bit.
- **pipelineStatistics** is a bitmask of `VkQueryPipelineStatisticFlagBits` specifying the set of pipeline statistics that can be counted by an active query in the primary command buffer when this secondary command buffer is executed. If this value includes a given bit, then this command buffer can be executed whether the primary command buffer has a pipeline statistics query active that includes this bit or not. If this value excludes a given bit, then the active pipeline statistics query must not be from a query pool that counts that statistic.
If the `VkCommandBuffer` will not be executed within a render pass instance, or if the render pass instance was begun with `vkCmdBeginRendering`, `renderPass`, `subpass`, and `framebuffer` are ignored.

### Valid Usage

- **VUID-VkCommandBufferInheritanceInfo-occlusionQueryEnable-00056**
  If the `inheritedQueries` feature is not enabled, `occlusionQueryEnable` must be `VK_FALSE`

- **VUID-VkCommandBufferInheritanceInfo-queryFlags-00057**
  If the `inheritedQueries` feature is enabled, `queryFlags` must be a valid combination of `VkQueryControlFlagBits` values

- **VUID-VkCommandBufferInheritanceInfo-queryFlags-02788**
  If the `inheritedQueries` feature is not enabled, `queryFlags` must be `0`

- **VUID-VkCommandBufferInheritanceInfo-pipelineStatistics-02789**
  If the `pipelineStatisticsQuery` feature is enabled, `pipelineStatistics` must be a valid combination of `VkQueryPipelineStatisticFlagBits` values

- **VUID-VkCommandBufferInheritanceInfo-pipelineStatistics-00058**
  If the `pipelineStatisticsQuery` feature is not enabled, `pipelineStatistics` must be `0`

### Valid Usage (Implicit)

- **VUID-VkCommandBufferInheritanceInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO`

- **VUID-VkCommandBufferInheritanceInfo-pNext-pNext**
  `pNext` must be `NULL` or a pointer to a valid instance of `VkCommandBufferInheritanceRenderingInfo`

- **VUID-VkCommandBufferInheritanceInfo-sType-unique**
  The `sType` value of each struct in the `pNext` chain must be unique

- **VUID-VkCommandBufferInheritanceInfo-commonparent**
  Both of `framebuffer`, and `renderPass` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

### Note

On some implementations, not using the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` bit enables command buffers to be patched in-place if needed, rather than creating a copy of the command buffer.

If a command buffer is in the invalid, or executable state, and the command buffer was allocated from a command pool with the `VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT` flag set, then `vkBeginCommandBuffer` implicitly resets the command buffer, behaving as if `vkResetCommandBuffer` had been called with `VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT` not set. After the implicit reset, `commandBuffer` is moved to the recording state.

The `VkCommandBufferInheritanceRenderingInfo` structure is defined as:
**VkCommandBufferInheritanceRenderingInfo**

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **flags** is a bitmask of `VkRenderingFlagBits` used by the render pass instance.
- **viewMask** is the view mask used for rendering.
- **colorAttachmentCount** is the number of color attachments specified in the render pass instance.
- **pColorAttachmentFormats** is a pointer to an array of `VkFormat` values defining the format of color attachments.
- **depthAttachmentFormat** is a `VkFormat` value defining the format of the depth attachment.
- **stencilAttachmentFormat** is a `VkFormat` value defining the format of the stencil attachment.
- **rasterizationSamples** is a `VkSampleCountFlagBits` specifying the number of samples used in rasterization.

If the **pNext** chain of **VkCommandBufferInheritanceInfo** includes a `VkCommandBufferInheritanceRenderingInfo` structure, then that structure controls parameters of dynamic render pass instances that the **VkCommandBuffer** can be executed within. If **VkCommandBufferInheritanceInfo::renderPass** is not `VK_NULL_HANDLE`, or **VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT** is not specified in **VkCommandBufferBeginInfo ::flags**, parameters of this structure are ignored.

If **colorAttachmentCount** is 0 and the **variableMultisampleRate** feature is enabled, **rasterizationSamples** is ignored.

If **depthAttachmentFormat**, **stencilAttachmentFormat**, or any element of **pColorAttachmentFormats** is **VK_FORMAT_UNDEFINED**, it indicates that the corresponding attachment is unused within the render pass and writes to those attachments are discarded.

---

**Valid Usage**

- **VUID-VkCommandBufferInheritanceRenderingInfo-colorAttachmentCount-06004**

  If **colorAttachmentCount** is not 0, **rasterizationSamples** must be a valid **VkSampleCountFlagBits** value.
If the `variableMultisampleRate` feature is not enabled, `rasterizationSamples` must be a valid `VkSampleCountFlagBits` value.

If any element of `pColorAttachmentFormats` is not `VK_FORMAT_UNDEFINED`, it must be a format with potential format features that include `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

If `depthAttachmentFormat` is not `VK_FORMAT_UNDEFINED`, it must be a format that includes a depth component.

If `depthAttachmentFormat` is not `VK_FORMAT_UNDEFINED`, it must be a format with potential format features that include `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

If `stencilAttachmentFormat` is not `VK_FORMAT_UNDEFINED`, it must be a format that includes a stencil aspect.

If `stencilAttachmentFormat` is not `VK_FORMAT_UNDEFINED`, it must be a format with potential format features that include `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

If `depthAttachmentFormat` is not `VK_FORMAT_UNDEFINED` and `stencilAttachmentFormat` is not `VK_FORMAT_UNDEFINED`, `depthAttachmentFormat` must equal `stencilAttachmentFormat`.

If the `multiview` feature is not enabled, `viewMask` must be 0.

The index of the most significant bit in `viewMask` must be less than `maxMultiviewViewCount`.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_RENDERING_INFO`.
- `flags` must be a valid combination of `VkRenderingFlagBits` values.
- If `colorAttachmentCount` is not 0, `pColorAttachmentFormats` must be a valid pointer to an array of `colorAttachmentCount` valid `VkFormat` values.
- `depthAttachmentFormat` must be a valid `VkFormat` value.
- `stencilAttachmentFormat` must be a valid `VkFormat` value.
- If `rasterizationSamples` is not 0, `rasterizationSamples` must be a valid `VkSampleCountFlagBits` value.
Once recording starts, an application records a sequence of commands (`vkCmd*`) to set state in the command buffer, draw, dispatch, and other commands.

To complete recording of a command buffer, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkEndCommandBuffer(
    VkCommandBuffer commandBuffer);
```

- `commandBuffer` is the command buffer to complete recording.

The command buffer **must** have been in the **recording state**, and, if successful, is moved to the **executable state**.

If there was an error during recording, the application will be notified by an unsuccessful return code returned by `vkEndCommandBuffer`, and the command buffer will be moved to the **invalid state**.

### Valid Usage

- VUID-vkEndCommandBuffer-commandBuffer-00059  
  `commandBuffer` **must** be in the **recording state**

- VUID-vkEndCommandBuffer-commandBuffer-00060  
  If `commandBuffer` is a primary command buffer, there **must** not be an active render pass instance

- VUID-vkEndCommandBuffer-commandBuffer-00061  
  All queries made **active** during the recording of `commandBuffer` **must** have been made inactive

### Valid Usage (Implicit)

- VUID-vkEndCommandBuffer-commandBuffer-parameter  
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

### Return Codes

**Success**

- `VK_SUCCESS`
When a command buffer is in the executable state, it can be submitted to a queue for execution.

### 6.5. Command Buffer Submission

**Note**
Submission can be a high overhead operation, and applications should attempt to batch work together into as few calls to `vkQueueSubmit` or `vkQueueSubmit2` as possible.

To submit command buffers to a queue, call:

```c
// Provided by VK_VERSION_1_3
VkResult vkQueueSubmit2(  
    VkQueue queue,  
    uint32_t submitCount,  
    const VkSubmitInfo2* pSubmits,  
    VkFence fence);
```

- `queue` is the queue that the command buffers will be submitted to.
- `submitCount` is the number of elements in the `pSubmits` array.
- `pSubmits` is a pointer to an array of `VkSubmitInfo2` structures, each specifying a command buffer submission batch.
- `fence` is an optional handle to a fence to be signaled once all submitted command buffers have completed execution. If `fence` is not `VK_NULL_HANDLE`, it defines a fence signal operation.

`vkQueueSubmit2` is a queue submission command, with each batch defined by an element of `pSubmits`.

Semaphore operations submitted with `vkQueueSubmit2` have additional ordering constraints compared to other submission commands, with dependencies involving previous and subsequent queue operations. Information about these additional constraints can be found in the semaphore section of the synchronization chapter.

If any command buffer submitted to this queue is in the executable state, it is moved to the pending state. Once execution of all submissions of a command buffer complete, it moves from the pending state, back to the executable state. If a command buffer was recorded with the `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT` flag, it instead moves back to the invalid state.

If `vkQueueSubmit2` fails, it may return `VK_ERROR_OUT_OF_HOST_MEMORY` or `VK_ERROR_OUT_OF_DEVICE_MEMORY`. If it does, the implementation must ensure that the state and contents of any resources or synchronization primitives referenced by the submitted command buffers and any semaphores referenced by `pSubmits` is unaffected by the call or its failure. If `vkQueueSubmit2` fails in such a way
that the implementation is unable to make that guarantee, the implementation must return `VK_ERROR_DEVICE_LOST`. See Lost Device.

### Valid Usage

- **VUID-vkQueueSubmit2-fence-04894**  
  If `fence` is not `VK_NULL_HANDLE`, `fence` must be unsignaled

- **VUID-vkQueueSubmit2-fence-04895**  
  If `fence` is not `VK_NULL_HANDLE`, `fence` must not be associated with any other queue command that has not yet completed execution on that queue

- **VUID-vkQueueSubmit2-synchronization2-03866**  
  The `synchronization2` feature must be enabled

- **VUID-vkQueueSubmit2-commandBuffer-03867**  
  If a command recorded into the `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` referenced an `VkEvent`, that event must not be referenced by a command that has been submitted to another queue and is still in the `pending` state

- **VUID-vkQueueSubmit2-semaphore-03868**  
  The `semaphore` member of any binary semaphore element of the `pSignalSemaphoreInfos` member of any element of `pSubmits` must be unsignaled when the semaphore signal operation it defines is executed on the device

- **VUID-vkQueueSubmit2-stageMask-03869**  
  The `stageMask` member of any element of the `pSignalSemaphoreInfos` member of any element of `pSubmits` must only include pipeline stages that are supported by the queue family which `queue` belongs to

- **VUID-vkQueueSubmit2-stageMask-03870**  
  The `stageMask` member of any element of the `pWaitSemaphoreInfos` member of any element of `pSubmits` must only include pipeline stages that are supported by the queue family which `queue` belongs to

- **VUID-vkQueueSubmit2-semaphore-03871**  
  When a semaphore wait operation for a binary semaphore is executed, as defined by the `semaphore` member of any element of the `pWaitSemaphoreInfos` member of any element of `pSubmits`, there must be no other queues waiting on the same semaphore

- **VUID-vkQueueSubmit2-semaphore-03873**  
  Any `semaphore` member of any element of the `pWaitSemaphoreInfos` member of any element of `pSubmits` that was created with a `VkSemaphoreTypeKHR` of `VK_SEMAPHORE_TYPE_BINARY_KHR` must reference a semaphore signal operation that has been submitted for execution and any `semaphore signal operations` on which it depends (if any) must have also been submitted for execution

- **VUID-vkQueueSubmit2-commandBuffer-03874**  
  The `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` must be in the `pending` or `executable` state

- **VUID-vkQueueSubmit2-commandBuffer-03875**
If a command recorded into the `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it **must** not be in the `pending state`.

- **VUID-vkQueueSubmit2-commandBuffer-03876**
  Any secondary command buffers recorded into the `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` **must** be in the pending or executable state.

- **VUID-vkQueueSubmit2-commandBuffer-03877**
  If any secondary command buffers recorded into the `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it **must** not be in the pending state.

- **VUID-vkQueueSubmit2-commandBuffer-03878**
  The `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` **must** have been allocated from a `VkCommandPool` that was created for the same queue family `queue` belongs to.

- **VUID-vkQueueSubmit2-commandBuffer-03879**
  If a command recorded into the `commandBuffer` member of any element of the `pCommandBufferInfos` member of any element of `pSubmits` includes a Queue Family Transfer Acquire Operation, there **must** exist a previously submitted Queue Family Transfer Release Operation on a queue in the queue family identified by the acquire operation, with parameters matching the acquire operation as defined in the definition of such acquire operations, and which happens before the acquire operation.

- **VUID-vkQueueSubmit2-queue-06447**
  If `queue` was not created with `VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT`, the `flags` member of any element of `pSubmits` **must** not include `VK_SUBMIT_PROTECTED_BIT_KHR`.

---

**Valid Usage (Implicit)**

- **VUID-vkQueueSubmit2-queue-parameter**
  `queue` **must** be a valid `VkQueue` handle.

- **VUID-vkQueueSubmit2-pSubmits-parameter**
  If `submitCount` is not 0, `pSubmits` **must** be a valid pointer to an array of `submitCount` valid `VkSubmitInfo2` structures.

- **VUID-vkQueueSubmit2-fence-parameter**
  If `fence` is not `VK_NULL_HANDLE`, `fence` **must** be a valid `VkFence` handle.

- **VUID-vkQueueSubmit2-commonparent**
  Both of `fence`, and `queue` that are valid handles of non-ignored parameters **must** have been created, allocated, or retrieved from the same `VkDevice`.
Host Synchronization

- Host access to queue must be externally synchronized
- Host access to fence must be externally synchronized

Command Properties

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Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

The VkSubmitInfo2 structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkSubmitInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkSubmitFlags flags;
    uint32_t waitSemaphoreInfoCount;
    const VkSemaphoreSubmitInfo* pWaitSemaphoreInfos;
    uint32_t commandBufferInfoCount;
    const VkCommandBufferSubmitInfo* pCommandBufferInfos;
    uint32_t signalSemaphoreInfoCount;
    const VkSemaphoreSubmitInfo* pSignalSemaphoreInfos;
} VkSubmitInfo2;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is a bitmask of VkSubmitFlagBits.
- **waitSemaphoreInfoCount** is the number of elements in pWaitSemaphoreInfos.
- **pWaitSemaphoreInfos** is a pointer to an array of VkSemaphoreSubmitInfo structures defining semaphore wait operations.
• `commandBufferInfoCount` is the number of elements in `pCommandBufferInfos` and the number of command buffers to execute in the batch.

• `pCommandBufferInfos` is a pointer to an array of `VkCommandBufferSubmitInfo` structures describing command buffers to execute in the batch.

• `signalSemaphoreInfoCount` is the number of elements in `pSignalSemaphoreInfos`.

• `pSignalSemaphoreInfos` is a pointer to an array of `VkSemaphoreSubmitInfo` describing semaphore signal operations.

---

**Valid Usage**

• VUID-VkSubmitInfo2-flags-03886  
  If `flags` includes `VK_SUBMIT_PROTECTED_BIT`, all elements of `pCommandBuffers` **must** be protected command buffers

• VUID-VkSubmitInfo2-flags-03887  
  If `flags` does not include `VK_SUBMIT_PROTECTED_BIT`, each element of `pCommandBuffers` **must** not be a protected command buffer

• VUID-VkSubmitInfo2KHR-commandBuffer-06192  
  If any `commandBuffer` member of an element of `pCommandBufferInfos` contains any resumed render pass instances, they **must** be suspended by a render pass instance earlier in submission order within `pCommandBufferInfos`

• VUID-VkSubmitInfo2KHR-commandBuffer-06010  
  If any `commandBuffer` member of an element of `pCommandBufferInfos` contains any suspended render pass instances, they **must** be resumed by a render pass instance later in submission order within `pCommandBufferInfos`

• VUID-VkSubmitInfo2KHR-commandBuffer-06011  
  If any `commandBuffer` member of an element of `pCommandBufferInfos` contains any suspended render pass instances, there **must** be no action or synchronization commands between that render pass instance and the render pass instance that resumes it

• VUID-VkSubmitInfo2KHR-commandBuffer-06012  
  If any `commandBuffer` member of an element of `pCommandBufferInfos` contains any suspended render pass instances, there **must** be no render pass instances between that render pass instance and the render pass instance that resumes it

---

**Valid Usage (Implicit)**

• VUID-VkSubmitInfo2-sType-sType  
  `sType` **must** be `VK_STRUCTURE_TYPE_SUBMIT_INFO_2`

• VUID-VkSubmitInfo2-pNext-pNext  
  `pNext` **must** be `NULL`

• VUID-VkSubmitInfo2-flags-parameter  
  `flags` **must** be a valid combination of `VkSubmitFlagBits` values

• VUID-VkSubmitInfo2-pWaitSemaphoreInfos-parameter
If `waitSemaphoreInfoCount` is not 0, `pWaitSemaphoreInfos` must be a valid pointer to an array of `waitSemaphoreInfoCount` valid `VkSemaphoreSubmitInfo` structures.

- **VUID-VkSubmitInfo2-pCommandBufferInfos-parameter**
  If `commandBufferInfoCount` is not 0, `pCommandBufferInfos` must be a valid pointer to an array of `commandBufferInfoCount` valid `VkCommandBufferSubmitInfo` structures.

- **VUID-VkSubmitInfo2-pSignalSemaphoreInfos-parameter**
  If `signalSemaphoreInfoCount` is not 0, `pSignalSemaphoreInfos` must be a valid pointer to an array of `signalSemaphoreInfoCount` valid `VkSemaphoreSubmitInfo` structures.

Bits which *can* be set in `VkSubmitInfo2::flags`, specifying submission behavior, are:

```c
// Provided by VK_VERSION_1_3
typedef enum VkSubmitFlagBits {
  VK_SUBMIT_PROTECTED_BIT = 0x00000001,
  VK_SUBMIT_PROTECTED_BIT_KHR = VK_SUBMIT_PROTECTED_BIT,
} VkSubmitFlagBits;
```

- **VK_SUBMIT_PROTECTED_BIT** specifies that this batch is a protected submission.

```c
// Provided by VK_VERSION_1_3
typedef VkFlags VkSubmitFlags;
```

`VkSubmitFlags` is a bitmask type for setting a mask of zero or more `VkSubmitFlagBits`.

The `VkSemaphoreSubmitInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkSemaphoreSubmitInfo {
  VkStructureType sType;
  const void* pNext;
  VkSemaphore semaphore;
  uint64_t value;
  VkPipelineStageFlags2 stageMask;
  uint32_t deviceIndex;
} VkSemaphoreSubmitInfo;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **semaphore** is a `VkSemaphore` affected by this operation.
- **value** is ignored.
- **stageMask** is a `VkPipelineStageFlags2` mask of pipeline stages which limit the first synchronization scope of a semaphore signal operation, or second synchronization scope of a semaphore wait operation as described in the semaphore wait operation and semaphore signal
operation sections of the synchronization chapter.

- **deviceIndex** is the index of the device within a device group that executes the semaphore wait or signal operation.

Whether this structure defines a semaphore wait or signal operation is defined by how it is used.

### Valid Usage

- **VUID-VkSemaphoreSubmitInfo-stageMask-03929**
  If the **geometryShader** feature is not enabled, **stageMask** must not contain **VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT**

- **VUID-VkSemaphoreSubmitInfo-stageMask-03930**
  If the **tessellationShader** feature is not enabled, **stageMask** must not contain **VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT** or **VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT**

- **VUID-VkSemaphoreSubmitInfo-device-03888**
  If the device that semaphore was created on is not a device group, **deviceIndex** must be 0

- **VUID-VkSemaphoreSubmitInfo-device-03889**
  If the device that semaphore was created on is a device group, **deviceIndex** must be a valid device index

### Valid Usage (Implicit)

- **VUID-VkSemaphoreSubmitInfo-sType-sType**
  **sType** must be **VK_STRUCTURE_TYPE_SEMAPHORE_SUBMIT_INFO**

- **VUID-VkSemaphoreSubmitInfo-pNext-pNext**
  **pNext** must be NULL

- **VUID-VkSemaphoreSubmitInfo-semaphore-parameter**
  **semaphore** must be a valid **VkSemaphore** handle

- **VUID-VkSemaphoreSubmitInfo-stageMask-parameter**
  **stageMask** must be a valid combination of **VkPipelineStageFlagBits2** values

The **VkCommandBufferSubmitInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkCommandBufferSubmitInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandBuffer commandBuffer;
    uint32_t deviceMask;
} VkCommandBufferSubmitInfo;
```

- **sType** is a **VkStructureType** value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• commandBuffer is a VkCommandBuffer to be submitted for execution.
• deviceMask is a bitmask indicating which devices in a device group execute the command buffer. A deviceMask of 0 is equivalent to setting all bits corresponding to valid devices in the group to 1.

Valid Usage

• VUID-VkCommandBufferSubmitInfo-commandBuffer-03890
  commandBuffer must not have been allocated with VK_COMMAND_BUFFER_LEVEL_SECONDARY
• VUID-VkCommandBufferSubmitInfo-deviceMask-03891
  If deviceMask is not 0, it must be a valid device mask

Valid Usage (Implicit)

• VUID-VkCommandBufferSubmitInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_COMMAND_BUFFER_SUBMIT_INFO
• VUID-VkCommandBufferSubmitInfo-pNext-pNext
  pNext must be NULL
• VUID-VkCommandBufferSubmitInfo-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

To submit command buffers to a queue, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkQueueSubmit(
    VkQueue queue,  
    uint32_t submitCount,  
    const VkSubmitInfo* pSubmits,  
    VkFence fence);  
```

• queue is the queue that the command buffers will be submitted to.
• submitCount is the number of elements in the pSubmits array.
• pSubmits is a pointer to an array of VkSubmitInfo structures, each specifying a command buffer submission batch.
• fence is an optional handle to a fence to be signaled once all submitted command buffers have completed execution. If fence is not VK_NULL_HANDLE, it defines a fence signal operation.

vkQueueSubmit is a queue submission command, with each batch defined by an element of pSubmits. Batches begin execution in the order they appear in pSubmits, but may complete out of order.

Fence and semaphore operations submitted with vkQueueSubmit have additional ordering constraints compared to other submission commands, with dependencies involving previous and subsequent queue operations. Information about these additional constraints can be found in the
semaphore and fence sections of the synchronization chapter.

Details on the interaction of \texttt{pWaitDstStageMask} with synchronization are described in the semaphore wait operation section of the synchronization chapter.

The order that batches appear in \texttt{pSubmits} is used to determine submission order, and thus all the implicit ordering guarantees that respect it. Other than these implicit ordering guarantees and any explicit synchronization primitives, these batches \textbf{may} overlap or otherwise execute out of order.

If any command buffer submitted to this queue is in the \texttt{executable state}, it is moved to the \texttt{pending state}. Once execution of all submissions of a command buffer complete, it moves from the \texttt{pending state}, back to the \texttt{executable state}. If a command buffer was recorded with the \texttt{VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT} flag, it instead moves to the \texttt{invalid state}.

If \texttt{vkQueueSubmit} fails, it \textbf{may} return \texttt{VK_ERROR_OUT_OF_HOST_MEMORY} or \texttt{VK_ERROR_OUT_OF DEVICE_MEMORY}. If it does, the implementation \textbf{must} ensure that the state and contents of any resources or synchronization primitives referenced by the submitted command buffers and any semaphores referenced by \texttt{pSubmits} is unaffected by the call or its failure. If \texttt{vkQueueSubmit} fails in such a way that the implementation is unable to make that guarantee, the implementation \textbf{must} return \texttt{VK_ERROR_DEVICE_LOST}. See Lost Device.

### Valid Usage

- **VUID-vkQueueSubmit-fence-00063**
  If \texttt{fence} is not \texttt{VK_NULL_HANDLE}, \texttt{fence} \textbf{must} be unsignaled

- **VUID-vkQueueSubmit-fence-00064**
  If \texttt{fence} is not \texttt{VK_NULL_HANDLE}, \texttt{fence} \textbf{must} not be associated with any other queue command that has not yet completed execution on that queue

- **VUID-vkQueueSubmit-pCommandBuffers-00065**
  Any calls to \texttt{vkCmdSetEvent}, \texttt{vkCmdResetEvent} or \texttt{vkCmdWaitEvents} that have been recorded into any of the command buffer elements of the \texttt{pCommandBuffers} member of any element of \texttt{pSubmits}, \textbf{must} not reference any \texttt{VkEvent} that is referenced by any of those commands in a command buffer that has been submitted to another queue and is still in the \texttt{pending state}

- **VUID-vkQueueSubmit-pWaitDstStageMask-00066**
  Any stage flag included in any element of the \texttt{pWaitDstStageMask} member of any element of \texttt{pSubmits} \textbf{must} be a pipeline stage supported by one of the capabilities of \texttt{queue}, as specified in the table of supported pipeline stages

- **VUID-vkQueueSubmit-pSignalSemaphores-00067**
  Each binary semaphore element of the \texttt{pSignalSemaphores} member of any element of \texttt{pSubmits} \textbf{must} be unsignaled when the semaphore signal operation it defines is executed on the device

- **VUID-vkQueueSubmit-pWaitSemaphores-00068**
  When a semaphore wait operation referring to a binary semaphore defined by any element of the \texttt{pWaitSemaphores} member of any element of \texttt{pSubmits} executes on \texttt{queue}, there \textbf{must} be no other queues waiting on the same semaphore
All elements of the `pWaitSemaphores` member of all elements of `pSubmits` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` must reference a semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) must have also been submitted for execution.

Each element of the `pCommandBuffers` member of each element of `pSubmits` must be in the pending or executable state.

If any element of the `pCommandBuffers` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it must not be in the pending state.

Any secondary command buffers recorded into any element of the `pCommandBuffers` member of any element of `pSubmits` must be in the pending or executable state.

If any secondary command buffers recorded into any element of the `pCommandBuffers` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it must not be in the pending state.

Each element of the `pCommandBuffers` member of each element of `pSubmits` must have been allocated from a `VkCommandPool` that was created for the same queue family queue belongs to.

If any element of `pSubmits->pCommandBuffers` includes a Queue Family Transfer Acquire Operation, there must exist a previously submitted Queue Family Transfer Release Operation on a queue in the queue family identified by the acquire operation, with parameters matching the acquire operation as defined in the definition of such acquire operations, and which happens-before the acquire operation.

Any resource created with `VK_SHARING_MODE_EXCLUSIVE` that is read by an operation specified by `pSubmits` must not be owned by any queue family other than the one which queue belongs to, at the time it is executed.

Any resource created with `VK_SHARING_MODE_CONCURRENT` that is accessed by an operation specified by `pSubmits` must have included the queue family of queue at resource creation time.

If queue was not created with `VKDEVICEQUEUECREATEPROTECTED_BIT`, there must be no element of `pSubmits` that includes an `VkProtectedSubmitInfo` structure in its `pNext` chain with `protectedSubmit` equal to `VK_TRUE`
Valid Usage (Implicit)

- VUID-vkQueueSubmit-queue-parameter
  queue must be a valid VkQueue handle

- VUID-vkQueueSubmit-pSubmits-parameter
  If submitCount is not 0, pSubmits must be a valid pointer to an array of submitCount valid VkSubmitInfo structures

- VUID-vkQueueSubmit-fence-parameter
  If fence is not VK_NULL_HANDLE, fence must be a valid VkFence handle

- VUID-vkQueueSubmit-commonparent
  Both of fence, and queue that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to queue must be externally synchronized
- Host access to fence must be externally synchronized

Command Properties

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Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

The VkSubmitInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSubmitInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t waitSemaphoreCount;
    const VkSemaphore* pWaitSemaphores;
} VkSubmitInfo;
```
const VkPipelineStageFlags* pWaitDstStageMask;
uint32_t commandBufferCount;
const VkCommandBuffer* pCommandBuffers;
uint32_t signalSemaphoreCount;
const VkSemaphore* pSignalSemaphores;
} VkSubmitInfo;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **waitSemaphoreCount** is the number of semaphores upon which to wait before executing the command buffers for the batch.
- **pWaitSemaphores** is a pointer to an array of VkSemaphore handles upon which to wait before the command buffers for this batch begin execution. If semaphores to wait on are provided, they define a semaphore wait operation.
- **pWaitDstStageMask** is a pointer to an array of pipeline stages at which each corresponding semaphore wait will occur.
- **commandBufferCount** is the number of command buffers to execute in the batch.
- **pCommandBuffers** is a pointer to an array of VkCommandBuffer handles to execute in the batch.
- **signalSemaphoreCount** is the number of semaphores to be signaled once the commands specified in pCommandBuffers have completed execution.
- **pSignalSemaphores** is a pointer to an array of VkSemaphore handles which will be signaled when the command buffers for this batch have completed execution. If semaphores to be signaled are provided, they define a semaphore signal operation.

The order that command buffers appear in pCommandBuffers is used to determine submission order, and thus all the implicit ordering guarantees that respect it. Other than these implicit ordering guarantees and any explicit synchronization primitives, these command buffers may overlap or otherwise execute out of order.

**Valid Usage**

- VUID-VkSubmitInfo-pWaitDstStageMask-04090
  If the geometryShader feature is not enabled, pWaitDstStageMask must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT

- VUID-VkSubmitInfo-pWaitDstStageMask-04091
  If the tessellationShader feature is not enabled, pWaitDstStageMask must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT

- VUID-VkSubmitInfo-pWaitDstStageMask-03937
  If the synchronization2 feature is not enabled, pWaitDstStageMask must not be 0

- VUID-VkSubmitInfo-pCommandBuffers-00075
  Each element of pCommandBuffers must not have been allocated with VK_COMMAND_BUFFER_LEVEL_SECONDARY
Each element of `pWaitDstStageMask` must not include `VK_PIPELINE_STAGE_HOST_BIT`.

If any element of `pWaitSemaphores` or `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then the `pNext` chain must include a `VkTimelineSemaphoreSubmitInfo` structure.

If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pWaitSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then its `waitSemaphoreValueCount` member must equal `waitSemaphoreCount`.

If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then its `signalSemaphoreValueCount` member must equal `signalSemaphoreCount`.

For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` must have a value greater than the current value of the semaphore when the semaphore signal operation is executed.

For each element of `pWaitSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pWaitSemaphoreValues` must have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`.

For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` must have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`.

If the `pNext` chain of this structure does not include a `VkProtectedSubmitInfo` structure with `protectedSubmit` set to `VK_TRUE`, then each element of the `pCommandBuffers` array must be an unprotected command buffer.

If the `pNext` chain of this structure includes a `VkProtectedSubmitInfo` structure with `protectedSubmit` set to `VK_TRUE`, then each element of the `pCommandBuffers` array must be a protected command buffer.
• VUID-VkSubmitInfo-pCommandBuffers-06193
  If pCommandBuffers contains any resumed render pass instances, they must be suspended by a render pass instance earlier in submission order within pCommandBuffers

• VUID-VkSubmitInfo-pCommandBuffers-06014
  If pCommandBuffers contains any suspended render pass instances, they must be resumed by a render pass instance later in submission order within pCommandBuffers

• VUID-VkSubmitInfo-pCommandBuffers-06015
  If pCommandBuffers contains any suspended render pass instances, there must be no action or synchronization commands executed in a primary or secondary command buffer between that render pass instance and the render pass instance that resumes it

• VUID-VkSubmitInfo-pCommandBuffers-06016
  If pCommandBuffers contains any suspended render pass instances, there must be no render pass instances between that render pass instance and the render pass instance that resumes it

Valid Usage (Implicit)

• VUID-VkSubmitInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_SUBMIT_INFO

• VUID-VkSubmitInfo-pNext-pNext
  Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkDeviceGroupSubmitInfo, VkProtectedSubmitInfo, or VkTimelineSemaphoreSubmitInfo

• VUID-VkSubmitInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

• VUID-VkSubmitInfo-pWaitSemaphores-parameter
  If waitSemaphoreCount is not 0, pWaitSemaphores must be a valid pointer to an array of waitSemaphoreCount valid VkSemaphore handles

• VUID-VkSubmitInfo-pWaitDstStageMask-parameter
  If waitSemaphoreCount is not 0, pWaitDstStageMask must be a valid pointer to an array of waitSemaphoreCount valid combinations of VkPipelineStageFlagBits values

• VUID-VkSubmitInfo-pCommandBuffers-parameter
  If commandBufferCount is not 0, pCommandBuffers must be a valid pointer to an array of commandBufferCount valid VkCommandBuffer handles

• VUID-VkSubmitInfo-pSignalSemaphores-parameter
  If signalSemaphoreCount is not 0, pSignalSemaphores must be a valid pointer to an array of signalSemaphoreCount valid VkSemaphore handles

• VUID-VkSubmitInfo-commonparent
  Each of the elements of pCommandBuffers, the elements of pSignalSemaphores, and the elements of pWaitSemaphores that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice
To specify the values to use when waiting for and signaling semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, add a `VkTimelineSemaphoreSubmitInfo` structure to the `pNext` chain of the `VkSubmitInfo` structure when using `vkQueueSubmit` or the `VkBindSparseInfo` structure when using `vkQueueBindSparse`. The `VkTimelineSemaphoreSubmitInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkTimelineSemaphoreSubmitInfo {
    VkStructureType sType;
    const void*pNext;
    uint32_t waitSemaphoreValueCount;
    const uint64_t*pWaitSemaphoreValues;
    uint32_t signalSemaphoreValueCount;
    const uint64_t*pSignalSemaphoreValues;
} VkTimelineSemaphoreSubmitInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `waitSemaphoreValueCount` is the number of semaphore wait values specified in `pWaitSemaphoreValues`.
- `pWaitSemaphoreValues` is a pointer to an array of `waitSemaphoreValueCount` values for the corresponding semaphores in `VkSubmitInfo::pWaitSemaphores` to wait for.
- `signalSemaphoreValueCount` is the number of semaphore signal values specified in `pSignalSemaphoreValues`.
- `pSignalSemaphoreValues` is a pointer to an array of `signalSemaphoreValueCount` values for the corresponding semaphores in `VkSubmitInfo::pSignalSemaphores` to set when signaled.

If the semaphore in `VkSubmitInfo::pWaitSemaphores` or `VkSubmitInfo::pSignalSemaphores` corresponding to an entry in `pWaitSemaphoreValues` or `pSignalSemaphoreValues` respectively was not created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, the implementation must ignore the value in the `pWaitSemaphoreValues` or `pSignalSemaphoreValues` entry.

### Valid Usage (Implicit)

- VUID-VkTimelineSemaphoreSubmitInfo-sType-sType `sType` must be `VK_STRUCTURE_TYPE_TIMELINE_SEMAPHORE_SUBMIT_INFO`
- VUID-VkTimelineSemaphoreSubmitInfo-pWaitSemaphoreValues-parameter If `waitSemaphoreValueCount` is not 0, and `pWaitSemaphoreValues` is not `NULL`, `pWaitSemaphoreValues` must be a valid pointer to an array of `waitSemaphoreValueCount` `uint64_t` values
- VUID-VkTimelineSemaphoreSubmitInfo-pSignalSemaphoreValues-parameter If `signalSemaphoreValueCount` is not 0, and `pSignalSemaphoreValues` is not `NULL`, `pSignalSemaphoreValues` must be a valid pointer to an array of `signalSemaphoreValueCount` `uint64_t` values
If the `pNext` chain of `VkSubmitInfo` includes a `VkProtectedSubmitInfo` structure, then the structure indicates whether the batch is protected. The `VkProtectedSubmitInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkProtectedSubmitInfo {
    VkStructureType sType;
    const void* pNext;
    VkBool32 protectedSubmit;
} VkProtectedSubmitInfo;
```

- `protectedSubmit` specifies whether the batch is protected. If `protectedSubmit` is `VK_TRUE`, the batch is protected. If `protectedSubmit` is `VK_FALSE`, the batch is unprotected. If the `VkSubmitInfo::pNext` chain does not include this structure, the batch is unprotected.

**Valid Usage (Implicit)**

- VUID-VkProtectedSubmitInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PROTECTED_SUBMIT_INFO`

If the `pNext` chain of `VkSubmitInfo` includes a `VkDeviceGroupSubmitInfo` structure, then that structure includes device indices and masks specifying which physical devices execute semaphore operations and command buffers.

The `VkDeviceGroupSubmitInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceGroupSubmitInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t waitSemaphoreCount;
    const uint32_t* pWaitSemaphoreDeviceIndices;
    uint32_t commandBufferCount;
    const uint32_t* pCommandBufferDeviceMasks;
    uint32_t signalSemaphoreCount;
    const uint32_t* pSignalSemaphoreDeviceIndices;
} VkDeviceGroupSubmitInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `waitSemaphoreCount` is the number of elements in the `pWaitSemaphoreDeviceIndices` array.
- `pWaitSemaphoreDeviceIndices` is a pointer to an array of `waitSemaphoreCount` device indices indicating which physical device executes the semaphore wait operation in the corresponding element of `VkSubmitInfo::pWaitSemaphores`.
- `commandBufferCount` is the number of elements in the `pCommandBufferDeviceMasks` array.
• `pCommandBufferDeviceMasks` is a pointer to an array of `commandBufferCount` device masks indicating which physical devices execute the command buffer in the corresponding element of `VkSubmitInfo::pCommandBuffers`. A physical device executes the command buffer if the corresponding bit is set in the mask.

• `signalSemaphoreCount` is the number of elements in the `pSignalSemaphoreDeviceIndices` array.

• `pSignalSemaphoreDeviceIndices` is a pointer to an array of `signalSemaphoreCount` device indices indicating which physical device executes the semaphore signal operation in the corresponding element of `VkSubmitInfo::pSignalSemaphores`.

If this structure is not present, semaphore operations and command buffers execute on device index zero.

---

### Valid Usage

- **VUID-VkDeviceGroupSubmitInfo-waitSemaphoreCount-00082**
  - `waitSemaphoreCount` must equal `VkSubmitInfo::waitSemaphoreCount`

- **VUID-VkDeviceGroupSubmitInfo-commandBufferCount-00083**
  - `commandBufferCount` must equal `VkSubmitInfo::commandBufferCount`

- **VUID-VkDeviceGroupSubmitInfo-signalSemaphoreCount-00084**
  - `signalSemaphoreCount` must equal `VkSubmitInfo::signalSemaphoreCount`

- **VUID-VkDeviceGroupSubmitInfo-pWaitSemaphoreDeviceIndices-00085**
  - All elements of `pWaitSemaphoreDeviceIndices` and `pSignalSemaphoreDeviceIndices` must be valid device indices

- **VUID-VkDeviceGroupSubmitInfo-pCommandBufferDeviceMasks-00086**
  - All elements of `pCommandBufferDeviceMasks` must be valid device masks

---

### Valid Usage (Implicit)

- **VUID-VkDeviceGroupSubmitInfo-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO`

- **VUID-VkDeviceGroupSubmitInfo-pWaitSemaphoreDeviceIndices-parameter**
  - If `waitSemaphoreCount` is not 0, `pWaitSemaphoreDeviceIndices` must be a valid pointer to an array of `waitSemaphoreCount` `uint32_t` values

- **VUID-VkDeviceGroupSubmitInfo-pCommandBufferDeviceMasks-parameter**
  - If `commandBufferCount` is not 0, `pCommandBufferDeviceMasks` must be a valid pointer to an array of `commandBufferCount` `uint32_t` values

- **VUID-VkDeviceGroupSubmitInfo-pSignalSemaphoreDeviceIndices-parameter**
  - If `signalSemaphoreCount` is not 0, `pSignalSemaphoreDeviceIndices` must be a valid pointer to an array of `signalSemaphoreCount` `uint32_t` values
6.6. Queue Forward Progress

When using binary semaphores, the application must ensure that command buffer submissions will be able to complete without any subsequent operations by the application on any queue. After any call to `vkQueueSubmit` (or other queue operation), for every queued wait on a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` there must be a prior signal of that semaphore that will not be consumed by a different wait on the semaphore.

When using timeline semaphores, wait-before-signal behavior is well-defined and applications can submit work via `vkQueueSubmit` defining a timeline semaphore wait operation before submitting a corresponding semaphore signal operation. For each timeline semaphore wait operation defined by a call to `vkQueueSubmit`, the application must ensure that a corresponding semaphore signal operation is executed before forward progress can be made.

If a command buffer submission waits for any events to be signaled, the application must ensure that command buffer submissions will be able to complete without any subsequent operations by the application. Events signaled by the host must be signaled before the command buffer waits on those events.

Note

The ability for commands to wait on the host to set an events was originally added to allow low-latency updates to resources between host and device. However, to ensure quality of service, implementations would necessarily detect extended stalls in execution and timeout after a short period. As this period is not defined in the Vulkan specification, it is impossible to correctly validate any application with any wait period. Since the original users of this functionality were highly limited and platform-specific, this functionality is now considered defunct and should not be used.

6.7. Secondary Command Buffer Execution

A secondary command buffer must not be directly submitted to a queue. Instead, secondary command buffers are recorded to execute as part of a primary command buffer with the command:

```c
// Provided by VK_VERSION_1_0
void vkCmdExecuteCommands(
    VkCommandBuffer commandBuffer, 
    uint32_t commandBufferCount, 
    const VkCommandBuffer* pCommandBuffers);
```

- `commandBuffer` is a handle to a primary command buffer that the secondary command buffers are executed in.
- `commandBufferCount` is the length of the `pCommandBuffers` array.
- `pCommandBuffers` is a pointer to an array of `commandBufferCount` secondary command buffer handles, which are recorded to execute in the primary command buffer in the order they are
If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, and it was recorded into any other primary command buffer which is currently in the executable or recording state, that primary command buffer becomes invalid.

## Valid Usage

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00088**
  Each element of `pCommandBuffers` must have been allocated with a level of `VK_COMMAND_BUFFER_LEVEL_SECONDARY`

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00089**
  Each element of `pCommandBuffers` must be in the pending or executable state

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00091**
  If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not be in the pending state

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00092**
  If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not have already been recorded to `commandBuffer`

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00093**
  If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not appear more than once in `pCommandBuffers`

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00094**
  Each element of `pCommandBuffers` must have been allocated from a `VkCommandPool` that was created for the same queue family as the `VkCommandPool` from which `commandBuffer` was allocated

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00096**
  If `vkCmdExecuteCommands` is being called within a render pass instance, each element of `pCommandBuffers` must have been recorded with the `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`

- **VUID-vkCmdExecuteCommands-pCommandBuffers-00099**
  If `vkCmdExecuteCommands` is being called within a render pass instance, and any element of `pCommandBuffers` was recorded with `VkCommandBufferInheritanceInfo::framebuffer` not equal to `VK_NULL_HANDLE`, that `VkFramebuffer` must match the `VkFramebuffer` used in the current render pass instance

- **VUID-vkCmdExecuteCommands-contents-06018**
  If `vkCmdExecuteCommands` is being called within a render pass instance begun with `vkCmdBeginRenderPass`, its `contents` parameter must have been set to `VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS`

- **VUID-vkCmdExecuteCommands-pCommandBuffers-06019**
  If `vkCmdExecuteCommands` is being called within a render pass instance begun with...
vkCmdBeginRenderPass, each element of pCommandBuffers must have been recorded with VkCommandBufferInheritanceInfo::subpass set to the index of the subpass which the given command buffer will be executed in.

- VUID-vkCmdExecuteCommands-pBeginInfo-06020
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRenderPass, the render passes specified in the pBeginInfo->pInheritanceInfo->renderPass members of the vkBeginCommandBuffer commands used to begin recording each element of pCommandBuffers must be compatible with the current render pass.

- VUID-vkCmdExecuteCommands-pCommandBuffers-00100
  If vkCmdExecuteCommands is not being called within a render pass instance, each element of pCommandBuffers must not have been recorded with the VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT.

- VUID-vkCmdExecuteCommands-commandBuffer-00101
  If the inheritedQueries feature is not enabled, commandBuffer must not have any queries active.

- VUID-vkCmdExecuteCommands-commandBuffer-00102
  If commandBuffer has a VK_QUERY_TYPE_OCCLUSION query active, then each element of pCommandBuffers must have been recorded with VkCommandBufferInheritanceInfo::occlusionQueryEnable set to VK_TRUE.

- VUID-vkCmdExecuteCommands-commandBuffer-00103
  If commandBuffer has a VK_QUERY_TYPE_OCCLUSION query active, then each element of pCommandBuffers must have been recorded with VkCommandBufferInheritanceInfo::queryFlags having all bits set that are set for the query.

- VUID-vkCmdExecuteCommands-commandBuffer-00104
  If commandBuffer has a VK_QUERY_TYPE_PIPELINE_STATISTICS query active, then each element of pCommandBuffers must have been recorded with VkCommandBufferInheritanceInfo::pipelineStatistics having all bits set that are set in the VkQueryPool the query uses.

- VUID-vkCmdExecuteCommands-pCommandBuffers-00105
  Each element of pCommandBuffers must not begin any query types that are active in commandBuffer.

- VUID-vkCmdExecuteCommands-commandBuffer-07594
  commandBuffer must not have any queries other than VK_QUERY_TYPE_OCCLUSION and VK_QUERY_TYPE_PIPELINE_STATISTICS active.

- VUID-vkCmdExecuteCommands-commandBuffer-01820
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, each element of pCommandBuffers must be a protected command buffer.

- VUID-vkCmdExecuteCommands-commandBuffer-01821
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, each element of pCommandBuffers must be an unprotected command buffer.

- VUID-vkCmdExecuteCommands-commandBuffer-06533
  If vkCmdExecuteCommands is being called within a render pass instance and any recorded command in commandBuffer in the current subpass will write to an image subresource as an attachment, commands recorded in elements of pCommandBuffers must not read from
the memory backing that image subresource in any other way

• VUID-vkCmdExecuteCommands-commandBuffer-06534
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance and any recorded command in \texttt{commandBuffer} in the current subpass will read from an image subresource used as an attachment in any way other than as an attachment, commands recorded in elements of \texttt{pCommandBuffers} \textbf{must} not write to that image subresource as an attachment

• VUID-vkCmdExecuteCommands-pCommandBuffers-06535
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance and any recorded command in a given element of \texttt{pCommandBuffers} will write to an image subresource as an attachment, commands recorded in elements of \texttt{pCommandBuffers} at a higher index \textbf{must} not read from the memory backing that image subresource in any other way

• VUID-vkCmdExecuteCommands-pCommandBuffers-06536
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance and any recorded command in a given element of \texttt{pCommandBuffers} will read from an image subresource used as an attachment in any way other than as an attachment, commands recorded in elements of \texttt{pCommandBuffers} at a higher index \textbf{must} not write to that image subresource as an attachment

• VUID-vkCmdExecuteCommands-pCommandBuffers-06021
  If \texttt{pCommandBuffers} contains any suspended render pass instances, there \textbf{must} be no action or synchronization commands between that render pass instance and any render pass instance that resumes it

• VUID-vkCmdExecuteCommands-pCommandBuffers-06022
  If \texttt{pCommandBuffers} contains any suspended render pass instances, there \textbf{must} be no render pass instances between that render pass instance and any render pass instance that resumes it

• VUID-vkCmdExecuteCommands-flags-06024
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance begun with \texttt{vkCmdBeginRendering}, its \texttt{VkRenderingInfo::flags} parameter \textbf{must} have included \texttt{VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT}

• VUID-vkCmdExecuteCommands-pBeginInfo-06025
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance begun with \texttt{vkCmdBeginRendering}, the render passes specified in the \texttt{pBeginInfo->pInheritanceInfo->renderPass} members of the \texttt{vkBeginCommandBuffer} commands used to begin recording each element of \texttt{pCommandBuffers} \textbf{must} be \texttt{VK_NULL_HANDLE}

• VUID-vkCmdExecuteCommands-flags-06026
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance begun with \texttt{vkCmdBeginRendering}, the \texttt{flags} member of the \texttt{VkCommandBufferInheritanceRenderingInfo} structure included in the \texttt{pNext} chain of \texttt{VkCommandBufferBeginInfo::pInheritanceInfo} used to begin recording each element of \texttt{pCommandBuffers} \textbf{must} be equal to the \texttt{VkRenderingInfo::flags} parameter to \texttt{vkCmdBeginRendering}, excluding \texttt{VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT}

• VUID-vkCmdExecuteCommands-colorAttachmentCount-06027
  If \texttt{vkCmdExecuteCommands} is being called within a render pass instance begun with \texttt{vkCmdBeginRendering}, the \texttt{colorAttachmentCount} member of the
VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be equal to the VkRenderingInfo::colorAttachmentCount parameter to vkCmdBeginRendering

- VUID-vkCmdExecuteCommands-imageView-06028
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering, if the imageView member of an element of the VkRenderingInfo::pColorAttachments parameter to vkCmdBeginRendering is not VK_NULL_HANDLE, the corresponding element of the pColorAttachmentFormats member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be equal to the format used to create that image view

- VUID-vkCmdExecuteCommands-imageView-07606
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering, if the imageView member of an element of the VkRenderingInfo::pColorAttachments parameter to vkCmdBeginRendering is VK_NULL_HANDLE, the corresponding element of the pColorAttachmentFormats member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be VK_FORMAT_UNDEFINED

- VUID-vkCmdExecuteCommands-pDepthAttachment-06029
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering, if the VkRenderingInfo::pDepthAttachment->imageView parameter to vkCmdBeginRendering is not VK_NULL_HANDLE, the value of the depthAttachmentFormat member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be equal to the format used to create that image view

- VUID-vkCmdExecuteCommands-pStencilAttachment-06030
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering, if the VkRenderingInfo::pStencilAttachment->imageView parameter to vkCmdBeginRendering is not VK_NULL_HANDLE, the value of the stencilAttachmentFormat member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be equal to the format used to create that image view

- VUID-vkCmdExecuteCommands-pDepthAttachment-06774
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering and the VkRenderingInfo::pDepthAttachment->imageView parameter to vkCmdBeginRendering was VK_NULL_HANDLE, the value of the depthAttachmentFormat member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be VK_FORMAT_UNDEFINED

- VUID-vkCmdExecuteCommands-pStencilAttachment-06775
  If vkCmdExecuteCommands is being called within a render pass instance begun with
vkCmdBeginRendering and the VkRenderingInfo::pStencilAttachment->imageView parameter to vkCmdBeginRendering was VK_NULL_HANDLE, the value of the stencilAttachmentFormat member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be VK_FORMAT_UNDEFINED

- VUID-vkCmdExecuteCommands-viewMask-06031
  If vkCmdExecuteCommands is being called within a render pass instance begun with vkCmdBeginRendering, the viewMask member of the VkCommandBufferInheritanceRenderingInfo structure included in the pNext chain of VkCommandBufferBeginInfo::pInheritanceInfo used to begin recording each element of pCommandBuffers must be equal to the VkRenderingInfo::viewMask parameter to vkCmdBeginRendering

Valid Usage (Implicit)

- VUID-vkCmdExecuteCommands-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdExecuteCommands-pCommandBuffers-parameter
  pCommandBuffers must be a valid pointer to an array of commandBufferCount valid VkCommandBuffer handles

- VUID-vkCmdExecuteCommands-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdExecuteCommands-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support transfer, graphics, or compute operations

- VUID-vkCmdExecuteCommands-bufferlevel
  commandBuffer must be a primary VkCommandBuffer

- VUID-vkCmdExecuteCommands-commandBufferCount-arraylength
  commandBufferCount must be greater than 0

- VUID-vkCmdExecuteCommands-commonparent
  Both of commandBuffer, and the elements of pCommandBuffers must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
6.8. Command Buffer Device Mask

Each command buffer has a piece of state storing the current device mask of the command buffer. This mask controls which physical devices within the logical device all subsequent commands will execute on, including state-setting commands, action commands, and synchronization commands.

Scissor and viewport state (excluding the count of each) can be set to different values on each physical device (only when set as dynamic state), and each physical device will render using its local copy of the state. Other state is shared between physical devices, such that all physical devices use the most recently set values for the state. However, when recording an action command that uses a piece of state, the most recent command that set that state must have included all physical devices that execute the action command in its current device mask.

The command buffer’s device mask is orthogonal to the pCommandBufferDeviceMasks member of VkDeviceGroupSubmitInfo. Commands only execute on a physical device if the device index is set in both device masks.

If the pNext chain of VkCommandBufferBeginInfo includes a VkDeviceGroupCommandBufferBeginInfo structure, then that structure includes an initial device mask for the command buffer.

The VkDeviceGroupCommandBufferBeginInfo structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceGroupCommandBufferBeginInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t deviceMask;
} VkDeviceGroupCommandBufferBeginInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **deviceMask** is the initial value of the command buffer’s device mask.

The initial device mask also acts as an upper bound on the set of devices that can ever be in the device mask in the command buffer.

If this structure is not present, the initial value of a command buffer’s device mask is set to include
all physical devices in the logical device when the command buffer begins recording.

**Valid Usage**

- VUID-VkDeviceGroupCommandBufferBeginInfo-deviceMask-00106
  
  `deviceMask` **must** be a valid device mask value

- VUID-VkDeviceGroupCommandBufferBeginInfo-deviceMask-00107
  
  `deviceMask` **must** not be zero

**Valid Usage (Implicit)**

- VUID-VkDeviceGroupCommandBufferBeginInfo-sType-sType
  
  `sType` **must** be `VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO`

To update the current device mask of a command buffer, call:

```c
// Provided by VK_VERSION_1_1
void vkCmdSetDeviceMask(
    VkCommandBuffer commandBuffer,
    uint32_t deviceMask);
```

- `commandBuffer` is command buffer whose current device mask is modified.
- `deviceMask` is the new value of the current device mask.

deviceMask is used to filter out subsequent commands from executing on all physical devices whose bit indices are not set in the mask, except commands beginning a render pass instance, commands transitioning to the next subpass in the render pass instance, and commands ending a render pass instance, which always execute on the set of physical devices whose bit indices are included in the `deviceMask` member of the `VkDeviceGroupRenderPassBeginInfo` structure passed to the command beginning the corresponding render pass instance.

**Valid Usage**

- VUID-vkCmdSetDeviceMask-deviceMask-00108
  
  `deviceMask` **must** be a valid device mask value

- VUID-vkCmdSetDeviceMask-deviceMask-00109
  
  `deviceMask` **must** not be zero

- VUID-vkCmdSetDeviceMask-deviceMask-00110
  
  `deviceMask` **must** not include any set bits that were not in the `VkDeviceGroupCommandBufferBeginInfo::deviceMask` value when the command buffer began recording

- VUID-vkCmdSetDeviceMask-deviceMask-00111
  
  If `vkCmdSetDeviceMask` is called inside a render pass instance, `deviceMask` **must** not include
any set bits that were not in the `VkDeviceGroupRenderPassBeginInfo::deviceMask` value when the render pass instance began recording

**Valid Usage (Implicit)**

- VUID-vkCmdSetDeviceMask-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- VUID-vkCmdSetDeviceMask-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdSetDeviceMask-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, compute, or transfer operations

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

**Command Properties**

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Chapter 7. Synchronization and Cache Control

Synchronization of access to resources is primarily the responsibility of the application in Vulkan. The order of execution of commands with respect to the host and other commands on the device has few implicit guarantees, and needs to be explicitly specified. Memory caches and other optimizations are also explicitly managed, requiring that the flow of data through the system is largely under application control.

Whilst some implicit guarantees exist between commands, five explicit synchronization mechanisms are exposed by Vulkan:

**Fences**
Fences can be used to communicate to the host that execution of some task on the device has completed, controlling resource access between host and device.

**Semaphores**
Semaphores can be used to control resource access across multiple queues.

**Events**
Events provide a fine-grained synchronization primitive which can be signaled either within a command buffer or by the host, and can be waited upon within a command buffer or queried on the host. Events can be used to control resource access within a single queue.

**Pipeline Barriers**
Pipeline barriers also provide synchronization control within a command buffer, but at a single point, rather than with separate signal and wait operations. Pipeline barriers can be used to control resource access within a single queue.

**Render Passes**
Render passes provide a useful synchronization framework for most rendering tasks, built upon the concepts in this chapter. Many cases that would otherwise need an application to use other synchronization primitives can be expressed more efficiently as part of a render pass. Render pass objects can be used to control resource access within a single queue.

7.1. Execution and Memory Dependencies

An operation is an arbitrary amount of work to be executed on the host, a device, or an external entity such as a presentation engine. Synchronization commands introduce explicit execution dependencies, and memory dependencies between two sets of operations defined by the command’s two synchronization scopes.

The synchronization scopes define which other operations a synchronization command is able to create execution dependencies with. Any type of operation that is not in a synchronization command’s synchronization scopes will not be included in the resulting dependency. For example, for many synchronization commands, the synchronization scopes can be limited to just operations executing in specific pipeline stages, which allows other pipeline stages to be excluded from a
dependency. Other scoping options are possible, depending on the particular command.

An execution dependency is a guarantee that for two sets of operations, the first set must happen-before the second set. If an operation happens-before another operation, then the first operation must complete before the second operation is initiated. More precisely:

- Let $\text{Ops}_1$ and $\text{Ops}_2$ be separate sets of operations.
- Let $\text{Sync}$ be a synchronization command.
- Let $\text{Scope}_{\text{1st}}$ and $\text{Scope}_{\text{2nd}}$ be the synchronization scopes of $\text{Sync}$.
- Let $\text{ScopedOps}_1$ be the intersection of sets $\text{Ops}_1$ and $\text{Scope}_{\text{1st}}$.
- Let $\text{ScopedOps}_2$ be the intersection of sets $\text{Ops}_2$ and $\text{Scope}_{\text{2nd}}$.
- Submitting $\text{Ops}_1$, $\text{Sync}$ and $\text{Ops}_2$ for execution, in that order, will result in execution dependency $\text{ExeDep}$ between $\text{ScopedOps}_1$ and $\text{ScopedOps}_2$.
- Execution dependency $\text{ExeDep}$ guarantees that $\text{ScopedOps}_1$ happen-before $\text{ScopedOps}_2$.

An execution dependency chain is a sequence of execution dependencies that form a happens-before relation between the first dependency's $\text{ScopedOps}_1$ and the final dependency's $\text{ScopedOps}_2$. For each consecutive pair of execution dependencies, a chain exists if the intersection of $\text{Scope}_{\text{2nd}}$ in the first dependency and $\text{Scope}_{\text{1st}}$ in the second dependency is not an empty set. The formation of a single execution dependency from an execution dependency chain can be described by substituting the following in the description of execution dependencies:

- Let $\text{Sync}$ be a set of synchronization commands that generate an execution dependency chain.
- Let $\text{Scope}_{\text{1st}}$ be the first synchronization scope of the first command in $\text{Sync}$.
- Let $\text{Scope}_{\text{2nd}}$ be the second synchronization scope of the last command in $\text{Sync}$.

Execution dependencies alone are not sufficient to guarantee that values resulting from writes in one set of operations can be read from another set of operations.

Three additional types of operations are used to control memory access. Availability operations cause the values generated by specified memory write accesses to become available to a memory domain for future access. Any available value remains available until a subsequent write to the same memory location occurs (whether it is made available or not) or the memory is freed. Memory domain operations cause writes that are available to a source memory domain to become available to a destination memory domain (an example of this is making writes available to the host domain available to the device domain). Visibility operations cause values available to a memory domain to become visible to specified memory accesses.

Availability, visibility, memory domains, and memory domain operations are formally defined in the Availability and Visibility section of the Memory Model chapter. Which API operations perform each of these operations is defined in Availability, Visibility, and Domain Operations.

A memory dependency is an execution dependency which includes availability and visibility operations such that:

- The first set of operations happens-before the availability operation.
The availability operation happens-before the visibility operation.

The visibility operation happens-before the second set of operations.

Once written values are made visible to a particular type of memory access, they can be read or written by that type of memory access. Most synchronization commands in Vulkan define a memory dependency.

The specific memory accesses that are made available and visible are defined by the access scopes of a memory dependency. Any type of access that is in a memory dependency’s first access scope and occurs in ScopedOps₁ is made available. Any type of access that is in a memory dependency’s second access scope and occurs in ScopedOps₂ has any available writes made visible to it. Any type of operation that is not in a synchronization command’s access scopes will not be included in the resulting dependency.

A memory dependency enforces availability and visibility of memory accesses and execution order between two sets of operations. Adding to the description of execution dependency chains:

- Let MemOps₁ be the set of memory accesses performed by ScopedOps₁.
- Let MemOps₂ be the set of memory accesses performed by ScopedOps₂.
- Let AccessScope₁st be the first access scope of the first command in the Sync chain.
- Let AccessScope₂nd be the second access scope of the last command in the Sync chain.
- Let ScopedMemOps₁ be the intersection of sets MemOps₁ and AccessScope₁st.
- Let ScopedMemOps₂ be the intersection of sets MemOps₂ and AccessScope₂nd.
- Submitting Ops₁, Sync, and Ops₂ for execution, in that order, will result in a memory dependency MemDep between ScopedOps₁ and ScopedOps₂.
- Memory dependency MemDep guarantees that:
  - Memory writes in ScopedMemOps₁ are made available.
  - Available memory writes, including those from ScopedMemOps₁, are made visible to ScopedMemOps₂.

Note
Execution and memory dependencies are used to solve data hazards, i.e. to ensure that read and write operations occur in a well-defined order. Write-after-read hazards can be solved with just an execution dependency, but read-after-write and write-after-write hazards need appropriate memory dependencies to be included between them. If an application does not include dependencies to solve these hazards, the results and execution orders of memory accesses are undefined.

7.1.1. Image Layout Transitions

Image subresources can be transitioned from one layout to another as part of a memory dependency (e.g. by using an image memory barrier). When a layout transition is specified in a memory dependency, it happens-after the availability operations in the memory dependency, and happens-before the visibility operations. Image layout transitions may perform read and write
accesses on all memory bound to the image subresource range, so applications **must** ensure that all memory writes have been made **available** before a layout transition is executed. Available memory is automatically made visible to a layout transition, and writes performed by a layout transition are automatically made available.

Layout transitions always apply to a particular image subresource range, and specify both an old layout and new layout. The old layout **must** either be `VK_IMAGE_LAYOUT_UNDEFINED`, or match the current layout of the image subresource range. If the old layout matches the current layout of the image subresource range, the transition preserves the contents of that range. If the old layout is `VK_IMAGE_LAYOUT_UNDEFINED`, the contents of that range **may** be discarded.

**Note**

Image layout transitions with `VK_IMAGE_LAYOUT_UNDEFINED` allow the implementation to discard the image subresource range, which can provide performance or power benefits. Tile-based architectures may be able to avoid flushing tile data to memory, and immediate style renderers may be able to achieve fast metadata clears to reinitialize frame buffer compression state, or similar.

If the contents of an attachment are not needed after a render pass completes, then applications **should** use `VK_ATTACHMENT_STORE_OP_DONT_CARE`.

As image layout transitions **may** perform read and write accesses on the memory bound to the image, if the image subresource affected by the layout transition is bound to peer memory for any device in the current device mask then the memory heap the bound memory comes from **must** support the `VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT` and `VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT` capabilities as returned by `vkGetDeviceGroupPeerMemoryFeatures`.

**Note**

Applications **must** ensure that layout transitions happen-after all operations accessing the image with the old layout, and happen-before any operations that will access the image with the new layout. Layout transitions are potentially read/write operations, so not defining appropriate memory dependencies to guarantee this will result in a data race.

Image layout transitions interact with **memory aliasing**.

Layout transitions that are performed via image memory barriers execute in their entirety in **submission order**, relative to other image layout transitions submitted to the same queue, including those performed by **render passes**. In effect there is an implicit execution dependency from each such layout transition to all layout transitions previously submitted to the same queue.

### 7.1.2. Pipeline Stages

The work performed by an **action or synchronization command** consists of multiple operations, which are performed as a sequence of logically independent steps known as **pipeline stages**. The exact pipeline stages executed depend on the particular command that is used, and current command buffer state when the command was recorded. **Drawing commands**, **dispatching commands**, **copy commands**, **clear commands**, and **synchronization commands** all execute in
different sets of pipeline stages. Synchronization commands do not execute in a defined pipeline stage.

**Note**

Operations performed by synchronization commands (e.g. availability and visibility operations) are not executed by a defined pipeline stage. However other commands can still synchronize with them by using the synchronization scopes to create a dependency chain.

Execution of operations across pipeline stages must adhere to implicit ordering guarantees, particularly including pipeline stage order. Otherwise, execution across pipeline stages may overlap or execute out of order with regards to other stages, unless otherwise enforced by an execution dependency.

Several of the synchronization commands include pipeline stage parameters, restricting the synchronization scopes for that command to just those stages. This allows fine grained control over the exact execution dependencies and accesses performed by action commands. Implementations should use these pipeline stages to avoid unnecessary stalls or cache flushing.

Bits which can be set in a VkPipelineStageFlags2 mask, specifying stages of execution, are:

```c
// Provided by VK_VERSION_1_3
// Flag bits for VkPipelineStageFlagBits2
typedef VkFlags64 VkPipelineStageFlagBits2;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_NONE = 0ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_NONE_KHR = 0ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TOP_OF_PIPE_BIT = 0x00000001ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TOP_OF_PIPE_BIT_KHR = 0x00000001ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT = 0x00000002ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT_KHR = 0x00000002ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT = 0x00000004ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT_KHR = 0x00000004ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT = 0x00000008ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT_KHR = 0x00000008ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT = 0x00000010ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT_KHR = 0x00000010ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT = 0x00000020ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT_KHR = 0x00000020ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT = 0x00000040ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT_KHR = 0x00000040ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_RESOLVE_IMAGE_BIT = 0x00000080ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_RESOLVE_IMAGE_BIT_KHR = 0x00000080ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_LOAD_RESOLVE_IMAGE_BIT = 0x00000100ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_LOAD_RESOLVE_IMAGE_BIT_KHR = 0x00000100ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_STORE_IMAGE_BIT = 0x00000200ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_STORE_IMAGE_BIT_KHR = 0x00000200ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_STORE_IMAGE_WITH_DATA_BIT = 0x00000400ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_STORE_IMAGE_WITH_DATA_BIT_KHR = 0x00000400ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_INCREMENT_IMAGEActionCreators1
```
VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT_KHR = 0x00000020ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT = 0x00000040ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT_KHR = 0x00000040ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT = 0x00000080ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT_KHR = 0x00000080ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT = 0x00000100ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT_KHR = 0x00000100ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT = 0x00000200ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT_KHR = 0x00000200ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT = 0x00000400ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT_KHR = 0x00000400ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT = 0x00000800ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT_KHR = 0x00000800ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT = 0x00001000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT_KHR = 0x00001000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_BOTTOM_OF_PIPE_BIT = 0x00002000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_BOTTOM_OF_PIPE_BIT_KHR = 0x00002000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_HOST_BIT = 0x00004000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_HOST_BIT_KHR = 0x00004000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT = 0x00008000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT_KHR = 0x00008000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT = 0x00010000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT_KHR = 0x00010000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COPY_BIT = 0x100000000ULL;
static const VkPipelineStageFlagBits2 VK_PIPELINE_STAGE_2_COPY_BIT_KHR = 0x100000000ULL;
The code snippet above defines constants for various pipeline stages in Vulkan. Here's a breakdown of the constants:

- `VK_PIPELINE_STAGE_2_RESOLVE_BIT` and `VK_PIPELINE_STAGE_2_RESOLVE_BIT_KHR`
- `VK_PIPELINE_STAGE_2_BLIT_BIT` and `VK_PIPELINE_STAGE_2_BLIT_BIT_KHR`
- `VK_PIPELINE_STAGE_2_CLEAR_BIT` and `VK_PIPELINE_STAGE_2_CLEAR_BIT_KHR`
- `VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT` and `VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT_KHR`
- `VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT` and `VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT_KHR`
- `VK_PIPELINE_STAGE_2_PRE_RASTERIZATION_SHADERS_BIT` and `VK_PIPELINE_STAGE_2_PRE_RASTERIZATION_SHADERS_BIT_KHR`

These stages specify different phases of the pipeline execution, such as resolving textures, blitting, clearing, inputting index and vertex buffers, and executing various shader stages.

### Relevant Stages:

- **`VK_PIPELINE_STAGE_2_NONE`** specifies no stages of execution.
- **`VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT`** specifies the stage of the pipeline where indirect command parameters are consumed.
- **`VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT`** specifies the stage of the pipeline where index buffers are consumed.
- **`VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT`** specifies the stage of the pipeline where vertex buffers are consumed.
- **`VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT`** is equivalent to the logical OR of:
  - `VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT`
  - `VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT`
- **`VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT`** specifies the vertex shader stage.
- **`VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT`** specifies the tessellation control shader stage.
- **`VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT`** specifies the tessellation evaluation shader stage.
- **`VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT`** specifies the geometry shader stage.
- **`VK_PIPELINE_STAGE_2_PRE_RASTERIZATION_SHADERS_BIT`** is equivalent to specifying all supported pre-rasterization shader stages:
  - `VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT`
  - `VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT`
• VK_PIPELINE_STAGE_2_TESSellation_EVALUATION_SHADER_BIT
• VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT

• VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT specifies the fragment shader stage.

• VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT specifies the stage of the pipeline where early fragment tests (depth and stencil tests before fragment shading) are performed. This stage also includes render pass load operations for framebuffer attachments with a depth/stencil format.

• VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT specifies the stage of the pipeline where late fragment tests (depth and stencil tests after fragment shading) are performed. This stage also includes render pass store operations for framebuffer attachments with a depth/stencil format.

• VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT specifies the stage of the pipeline where final color values are output from the pipeline. This stage includes blending, logic operations, render pass load and store operations for color attachments, render pass multisample resolve operations, and vkCmdClearColorAttachments.

• VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT specifies the compute shader stage.

• VK_PIPELINE_STAGE_2_HOST_BIT specifies a pseudo-stage indicating execution on the host of reads/writes of device memory. This stage is not invoked by any commands recorded in a command buffer.

• VK_PIPELINE_STAGE_2_COPY_BIT specifies the execution of all copy commands, including vkCmdCopyQueryPoolResults.

• VK_PIPELINE_STAGE_2_BLIT_BIT specifies the execution of vkCmdBlitImage.

• VK_PIPELINE_STAGE_2_RESOLVE_BIT specifies the execution of vkCmdResolveImage.

• VK_PIPELINE_STAGE_2_CLEAR_BIT specifies the execution of clear commands, with the exception of vkCmdClearColorAttachments.

• VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT is equivalent to specifying all of:
  ◦ VK_PIPELINE_STAGE_2_COPY_BIT
  ◦ VK_PIPELINE_STAGE_2_BLIT_BIT
  ◦ VK_PIPELINE_STAGE_2_RESOLVE_BIT
  ◦ VK_PIPELINE_STAGE_2_CLEAR_BIT

• VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT specifies the execution of all graphics pipeline stages, and is equivalent to the logical OR of:
  ◦ VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT
  ◦ VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT
  ◦ VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT
  ◦ VK_PIPELINE_STAGE_2_TESSellation_CONTROL_SHADER_BIT
  ◦ VK_PIPELINE_STAGE_2_TESSellation_EVALUATION_SHADER_BIT
  ◦ VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT
  ◦ VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT
  ◦ VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT
*VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT*
*VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT*
*VK_PIPELINE_STAGE_2_SHADING_RATE_IMAGE_BIT_NV*

*VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT* specifies all operations performed by all commands supported on the queue it is used with.

*VK_PIPELINE_STAGE_2_TOP_OF_PIPE_BIT* is equivalent to *VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT* with *VkAccessFlags2* set to 0 when specified in the second synchronization scope, but equivalent to *VK_PIPELINE_STAGE_2_NONE* in the first scope.

*VK_PIPELINE_STAGE_2_BOTTOM_OF_PIPE_BIT* is equivalent to *VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT* with *VkAccessFlags2* set to 0 when specified in the first synchronization scope, but equivalent to *VK_PIPELINE_STAGE_2_NONE* in the second scope.

**Note**
The TOP and BOTTOM pipeline stages are deprecated, and applications should prefer *VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT* and *VK_PIPELINE_STAGE_2_NONE*.

**Note**
The *VkPipelineStageFlags2* bitmask goes beyond the 31 individual bit flags allowable within a C99 enum, which is how *VkPipelineStageFlagBits* is defined. The first 31 values are common to both, and are interchangeable.

*VkPipelineStageFlags2* is a bitmask type for setting a mask of zero or more *VkPipelineStageFlagBits2* flags:

```c
// Provided by VK_VERSION_1_3
typedef VkFlags64 VkPipelineStageFlags2;
```

Bits which can be set in a *VkPipelineStageFlags* mask, specifying stages of execution, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPipelineStageFlagBits {
    VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT = 0x00000001,
    VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT = 0x00000002,
    VK_PIPELINE_STAGE_VERTEX_INPUT_BIT = 0x00000004,
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT = 0x00000008,
    VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT = 0x00000010,
    VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT = 0x00000020,
    VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT = 0x00000040,
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT = 0x00000080,
    VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT = 0x00000100,
    VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT = 0x00000200,
    VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT = 0x00000400,
    VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT = 0x00000800,
    VK_PIPELINE_STAGE_TRANSFER_BIT = 0x00001000,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT = 0x00002000,
};
```
These values all have the same meaning as the equivalently named values for `VkPipelineStageFlags2`.

- **VK_PIPELINE_STAGE_NONE** specifies no stages of execution.
- **VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT** specifies the stage of the pipeline where `VkDrawIndirect* / VkDispatchIndirect* / VkTraceRaysIndirect*` data structures are consumed.
- **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT** specifies the stage of the pipeline where vertex and index buffers are consumed.
- **VK_PIPELINE_STAGE_VERTEX_SHADER_BIT** specifies the vertex shader stage.
- **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT** specifies the tessellation control shader stage.
- **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT** specifies the tessellation evaluation shader stage.
- **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT** specifies the geometry shader stage.
- **VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT** specifies the fragment shader stage.
- **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT** specifies the stage of the pipeline where early fragment tests (depth and stencil tests before fragment shading) are performed. This stage also includes render pass load operations for framebuffer attachments with a depth/stencil format.
- **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT** specifies the stage of the pipeline where late fragment tests (depth and stencil tests after fragment shading) are performed. This stage also includes render pass store operations for framebuffer attachments with a depth/stencil format.
- **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** specifies the stage of the pipeline after blending where the final color values are output from the pipeline. This stage includes blending, logic operations, render pass load and store operations for color attachments, render pass multisample resolve operations, and `vkCmdClearAttachments`.
- **VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT** specifies the execution of a compute shader.
- **VK_PIPELINE_STAGE_TRANSFER_BIT** specifies the following commands:
  - All copy commands, including `vkCmdCopyQueryPoolResults`
  - `vkCmdBlitImage2` and `vkCmdBlitImage`
  - `vkCmdResolveImage2` and `vkCmdResolveImage`
  - All clear commands, with the exception of `vkCmdClearAttachments`
- **VK_PIPELINE_STAGE_HOST_BIT** specifies a pseudo-stage indicating execution on the host of reads/writes of device memory. This stage is not invoked by any commands recorded in a command buffer.
• **VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT** specifies the execution of all graphics pipeline stages, and is equivalent to the logical OR of:
  
  - **VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT**
  - **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT**
  - **VK_PIPELINE_STAGE_VERTEX_SHADER_BIT**
  - **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT**
  - **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT**
  - **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT**
  - **VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT**
  - **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT**
  - **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT**
  - **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT**

• **VK_PIPELINE_STAGE_ALL_COMMANDS_BIT** specifies all operations performed by all commands supported on the queue it is used with.

• **VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT** is equivalent to **VK_PIPELINE_STAGE_ALL_COMMANDS_BIT** with **VkAccessFlags** set to 0 when specified in the second synchronization scope, but specifies no stage of execution when specified in the first scope.

• **VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT** is equivalent to **VK_PIPELINE_STAGE_ALL_COMMANDS_BIT** with **VkAccessFlags** set to 0 when specified in the first synchronization scope, but specifies no stage of execution when specified in the second scope.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineStageFlags;
```

*VkPipelineStageFlags* is a bitmask type for setting a mask of zero or more *VkPipelineStageFlagBits*.

If a synchronization command includes a source stage mask, its first *synchronization scope* only includes execution of the pipeline stages specified in that mask and any *logically earlier* stages. Its first *access scope* only includes memory accesses performed by pipeline stages explicitly specified in the source stage mask.

If a synchronization command includes a destination stage mask, its second *synchronization scope* only includes execution of the pipeline stages specified in that mask and any *logically later* stages. Its second *access scope* only includes memory accesses performed by pipeline stages explicitly specified in the destination stage mask.

*Note*

Note that *access scopes* do not interact with the logically earlier or later stages for either scope - only the stages the app specifies are considered part of each access scope.

Certain pipeline stages are only available on queues that support a particular set of operations. The
following table lists, for each pipeline stage flag, which queue capability flag must be supported by the queue. When multiple flags are enumerated in the second column of the table, it means that the pipeline stage is supported on the queue if it supports any of the listed capability flags. For further details on queue capabilities see Physical Device Enumeration and Queues.

Table 3. Supported pipeline stage flags

<table>
<thead>
<tr>
<th>Pipeline stage flag</th>
<th>Required queue capability flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_PIPELINE_STAGE_2_NONE</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_TOP_OF_PIPE_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2VERTEX_INPUT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
<td>VK_QUEUE_COMPUTE_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_BOTTOM_OF_PIPE_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_HOST_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_COPY_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_RESOLVE_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_BLIT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_CLEAR_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
</tbody>
</table>
Pipeline stages that execute as a result of a command logically complete execution in a specific order, such that completion of a logically later pipeline stage must not happen-before completion of a logically earlier stage. This means that including any stage in the source stage mask for a particular synchronization command also implies that any logically earlier stages are included in Scope\textsubscript{1st} for that command.

Similarly, initiation of a logically earlier pipeline stage must not happen-after initiation of a logically later pipeline stage. Including any given stage in the destination stage mask for a particular synchronization command also implies that any logically later stages are included in Scope\textsubscript{2nd} for that command.

**Note**

Implementations may not support synchronization at every pipeline stage for every synchronization operation. If a pipeline stage that an implementation does not support synchronization for appears in a source stage mask, it may substitute any logically later stage in its place for the first synchronization scope. If a pipeline stage that an implementation does not support synchronization for appears in a destination stage mask, it may substitute any logically earlier stage in its place for the second synchronization scope.

For example, if an implementation is unable to signal an event immediately after vertex shader execution is complete, it may instead signal the event after color attachment output has completed.

If an implementation makes such a substitution, it must not affect the semantics of execution or memory dependencies or image and buffer memory barriers.

Graphics pipelines are executable on queues supporting VK\_QUEUE\_GRAPHICS\_BIT. Stages executed by graphics pipelines can only be specified in commands recorded for queues supporting VK\_QUEUE\_GRAPHICS\_BIT.

The graphics pipeline executes the following stages, with the logical ordering of the stages matching the order specified here:

- VK\_PIPELINE\_STAGE\_2\_DRAW\_INDIRECT\_BIT
- VK\_PIPELINE\_STAGE\_2\_INDEX\_INPUT\_BIT
- VK\_PIPELINE\_STAGE\_2\_VERTEX\_ATTRIBUTE\_INPUT\_BIT
- VK\_PIPELINE\_STAGE\_2\_VERTEX\_SHADER\_BIT
- VK\_PIPELINE\_STAGE\_2\_TESSELLATION\_CONTROL\_SHADER\_BIT
- VK\_PIPELINE\_STAGE\_2\_TESSELLATION\_EVALUATION\_SHADER\_BIT
- VK\_PIPELINE\_STAGE\_2\_GEOMETRY\_SHADER\_BIT
For the compute pipeline, the following stages occur in this order:

• VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT
• VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT

For the transfer pipeline, the following stages occur in this order:

• VK_PIPELINE_STAGE_2_TRANSFER_BIT

For host operations, only one pipeline stage occurs, so no order is guaranteed:

• VK_PIPELINE_STAGE_2_HOST_BIT

### 7.1.3. Access Types

Memory in Vulkan can be accessed from within shader invocations and via some fixed-function stages of the pipeline. The access type is a function of the descriptor type used, or how a fixed-function stage accesses memory.

Some synchronization commands take sets of access types as parameters to define the access scopes of a memory dependency. If a synchronization command includes a source access mask, its first access scope only includes accesses via the access types specified in that mask. Similarly, if a synchronization command includes a destination access mask, its second access scope only includes accesses via the access types specified in that mask.

Bits which can be set in the srcAccessMask and dstAccessMask members of VkMemoryBarrier2KHR, VKImageMemoryBarrier2KHR, and VkBufferMemoryBarrier2KHR, specifying access behavior, are:

```c
// Provided by VK_VERSION_1_3
// Flag bits for VkAccessFlagBits2
typedef VkFlags64 VkAccessFlagBits2;
static const VkAccessFlagBits2 VK_ACCESS_2_NONE = 0ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_NONE_KHR = 0ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT = 0x00000001ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_INDEX_READ_BIT = 0x00000002ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT = 0x00000004ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_UNIFORM_READ_BIT = 0x00000008ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_INDEX_READ_BIT_KHR = 0x00000002ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_INDEX_READ_BIT_KHR = 0x00000002ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT = 0x00000004ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT_KHR = 0x00000004ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_UNIFORM_READ_BIT_KHR = 0x00000008ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT = 0x000000010ULL;
```
static const VkAccessFlagBits2 VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT_KHR = 0x00000010ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_READ_BIT = 0x00000020ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_READ_BIT_KHR = 0x00000020ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_WRITE_BIT = 0x00000040ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_WRITE_BIT_KHR = 0x00000040ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT = 0x00000080ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT_KHR = 0x00000080ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT = 0x00000100ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT_KHR = 0x00000100ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT = 0x00000200ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT_KHR = 0x00000200ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT = 0x00000400ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT_KHR = 0x00000400ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_TRANSFER_READ_BIT = 0x00000800ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_TRANSFER_READ_BIT_KHR = 0x00000800ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_TRANSFER_WRITE_BIT = 0x00001000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_TRANSFER_WRITE_BIT_KHR = 0x00001000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_HOST_READ_BIT = 0x00002000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_HOST_READ_BIT_KHR = 0x00002000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_HOST_WRITE_BIT = 0x00004000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_HOST_WRITE_BIT_KHR = 0x00004000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_MEMORY_READ_BIT = 0x00008000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2 MEMORY_READ_BIT_KHR = 0x00008000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_MEMORY_WRITE_BIT = 0x00010000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_MEMORY_WRITE_BIT_KHR = 0x00010000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_SAMPLED_READ_BIT = 0x100000000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_SAMPLED_READ_BIT_KHR = 0x100000000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_STORAGE_READ_BIT = 0x200000000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_STORAGE_READ_BIT_KHR = 0x200000000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT = 0x400000000ULL;
static const VkAccessFlagBits2 VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT_KHR = 0x400000000ULL;

- **VK_ACCESS_2_NONE** specifies no accesses.
- **VK_ACCESS_2_MEMORY_READ_BIT** specifies all read accesses. It is always valid in any access mask, and is treated as equivalent to setting all `READ` access flags that are valid where it is used.
- **VK_ACCESS_2_MEMORY_WRITE_BIT** specifies all write accesses. It is always valid in any access mask, and is treated as equivalent to setting all `WRITE` access flags that are valid where it is used.
- **VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT** specifies read access to command data read from indirect buffers as part of an indirect drawing or dispatch command. Such access occurs in the
VK_PIPELINE_STAGE_2_DRAW_INDCRET BIT pipeline stage.

- **VK_ACCESS_2_INDEX_READ_BIT** specifies read access to an index buffer as part of an indexed drawing command, bound by `vkCmdBindIndexBuffer`. Such access occurs in the VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT pipeline stage.

- **VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT** specifies read access to a vertex buffer as part of a drawing command, bound by `vkCmdBindVertexBuffers`. Such access occurs in the VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT pipeline stage.

- **VK_ACCESS_2_UNIFORM_READ_BIT** specifies read access to a **uniform buffer** in any shader pipeline stage.

- **VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT** specifies read access to an **input attachment** within a render pass during fragment shading. Such access occurs in the VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT pipeline stage.

- **VK_ACCESS_2_SHADER_SAMPLED_READ_BIT** specifies read access to a **uniform texel buffer** or **sampled image** in any shader pipeline stage.

- **VK_ACCESS_2_SHADER_STORAGE_READ_BIT** specifies read access to a **storage buffer, physical storage buffer, storage texel buffer, or storage image** in any shader pipeline stage.

- **VK_ACCESS_2_SHADER_READ_BIT** is equivalent to the logical OR of:
  - VK_ACCESS_2_UNIFORM_READ_BIT
  - VK_ACCESS_2_SHADER_SAMPLED_READ_BIT
  - VK_ACCESS_2_SHADER_STORAGE_READ_BIT

- **VK_ACCESS_2_SHADER_WRITE_BIT** is equivalent to VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT.

- **VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT** specifies read access to a **color attachment**, such as via blending, logic operations or certain render pass load operations. Such access occurs in the VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT pipeline stage.

- **VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT** specifies read access to a **color attachment** in any shader pipeline stage.

- **VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT** specifies read access to a **depth/stencil attachment**, via depth or stencil operations or certain render pass load operations. Such access occurs in the VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT or VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT pipeline stages.

- **VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT** specifies write access to a **depth/stencil attachment**, via depth or stencil operations or certain render pass load and store operations. Such access occurs in the VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT or VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT pipeline stages.

- **VK_ACCESS_2_TRANSFER_READ_BIT** specifies read access to an image or buffer in a **copy** operation. Such access occurs in the VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, or VK_PIPELINE_STAGE_2_RESOLVE_BIT pipeline stages.

- **VK_ACCESS_2_TRANSFER_WRITE_BIT** specifies write access to an image or buffer in a **clear** or **copy** operation.
operation. Such access occurs in the VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, VK_PIPELINE_STAGE_2_CLEAR_BIT, or VK_PIPELINE_STAGE_2.Resolve_BIT pipeline stages.

- **VK_ACCESS_2_HOST_READ_BIT** specifies read access by a host operation. Accesses of this type are not performed through a resource, but directly on memory. Such access occurs in the VK_PIPELINE_STAGE_2_HOST_BIT pipeline stage.

- **VK_ACCESS_2_HOST_WRITE_BIT** specifies write access by a host operation. Accesses of this type are not performed through a resource, but directly on memory. Such access occurs in the VK_PIPELINE_STAGE_2_HOST_BIT pipeline stage.

**Note**
In situations where an application wishes to select all access types for a given set of pipeline stages, VK_ACCESS_2_MEMORY_READ_BIT or VK_ACCESS_2_MEMORY_WRITE_BIT can be used. This is particularly useful when specifying stages that only have a single access type.

**Note**
The VkAccessFlags2 bitmask goes beyond the 31 individual bit flags allowable within a C99 enum, which is how VkAccessFlagBits is defined. The first 31 values are common to both, and are interchangeable.

VkAccessFlags2 is a bitmask type for setting a mask of zero or more VkAccessFlagBits:

```c
// Provided by VK_VERSION_1_3
typedef VkFlags64 VkAccessFlags2;
```

Bits which can be set in the srcAccessMask and dstAccessMask members of VkSubpassDependency, VkMemoryBarrier, VkBufferMemoryBarrier, and VkImageMemoryBarrier, specifying access behavior, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkAccessFlagBits {
    VK_ACCESS_INDIRECT_COMMAND_READ_BIT = 0x00000001,
    VK_ACCESS_INDEX_READ_BIT = 0x00000002,
    VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT = 0x00000004,
    VK_ACCESS_UNIFORM_READ_BIT = 0x00000008,
    VK_ACCESS_INPUT_ATTACHMENT_READ_BIT = 0x00000010,
    VK_ACCESS_SHADER_READ_BIT = 0x00000020,
    VK_ACCESS_SHADER_WRITE_BIT = 0x00000040,
    VK_ACCESS_COLOR_ATTACHMENT_READ_BIT = 0x00000080,
    VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT = 0x00000100,
    VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT = 0x00000200,
    VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT = 0x00000400,
    VK_ACCESS_TRANSFER_READ_BIT = 0x00000800,
    VK_ACCESS_TRANSFER_WRITE_BIT = 0x00001000,
    VK_ACCESS_HOST_READ_BIT = 0x00002000,
```

```c```
VK_ACCESS_HOST_WRITE_BIT = 0x00004000,
VK_ACCESS_MEMORY_READ_BIT = 0x00008000,
VK_ACCESS_MEMORY_WRITE_BIT = 0x00010000,
// Provided by VK_VERSION_1_3
VK_ACCESS_NONE = 0,
} VkAccessFlagBits;

These values all have the same meaning as the equivalently named values for VkAccessFlags2.

- **VK_ACCESS_NONE** specifies no accesses.
- **VK_ACCESS_MEMORY_READ_BIT** specifies all read accesses. It is always valid in any access mask, and is treated as equivalent to setting all **READ** access flags that are valid where it is used.
- **VK_ACCESS_MEMORY_WRITE_BIT** specifies all write accesses. It is always valid in any access mask, and is treated as equivalent to setting all **WRITE** access flags that are valid where it is used.
- **VK_ACCESS_INDIRECT_COMMAND_READ_BIT** specifies read access to indirect command data read as part of an indirect drawing or dispatching command. Such access occurs in the **VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT** pipeline stage.
- **VK_ACCESS_INDEX_READ_BIT** specifies read access to an index buffer as part of an indexed drawing command, bound by `vkCmdBindIndexBuffer`. Such access occurs in the **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT** pipeline stage.
- **VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT** specifies read access to a vertex buffer as part of a drawing command, bound by `vkCmdBindVertexBuffers`. Such access occurs in the **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT** pipeline stage.
- **VK_ACCESS_UNIFORM_READ_BIT** specifies read access to a uniform buffer in any shader pipeline stage.
- **VK_ACCESS_INPUT_ATTACHMENT_READ_BIT** specifies read access to an input attachment within a render pass during fragment shading. Such access occurs in the **VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT** pipeline stage.
- **VK_ACCESS_SHADER_READ_BIT** specifies read access to a uniform buffer, uniform texel buffer, sampled image, storage buffer, physical storage buffer, storage texel buffer, or storage image in any shader pipeline stage.
- **VK_ACCESS_SHADER_WRITE_BIT** specifies write access to a storage buffer, physical storage buffer, storage texel buffer, or storage image in any shader pipeline stage.
- **VK_ACCESS_COLOR_ATTACHMENT_READ_BIT** specifies read access to a color attachment, such as via blending, logic operations or certain render pass load operations. Such access occurs in the **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** pipeline stage.
- **VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT** specifies write access to a color, resolve, or depth/stencil resolve attachment during a render pass or via certain render pass load and store operations. Such access occurs in the **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** pipeline stage.
- **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT** specifies read access to a depth/stencil attachment, via depth or stencil operations or certain render pass load operations. Such access occurs in the **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT** or **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT** pipeline stages.
• **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT** specifies write access to a depth/stencil attachment, via depth or stencil operations or certain render pass load and store operations. Such access occurs in the **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT** or **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT** pipeline stages.

• **VK_ACCESS_TRANSFER_READ_BIT** specifies read access to an image or buffer in a copy operation. Such access occurs in the **VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT** pipeline stage.

• **VK_ACCESS_TRANSFER_WRITE_BIT** specifies write access to an image or buffer in a clear or copy operation. Such access occurs in the **VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT** pipeline stage.

• **VK_ACCESS_HOST_READ_BIT** specifies read access by a host operation. Accesses of this type are not performed through a resource, but directly on memory. Such access occurs in the **VK_PIPELINE_STAGE_HOST_BIT** pipeline stage.

• **VK_ACCESS_HOST_WRITE_BIT** specifies write access by a host operation. Accesses of this type are not performed through a resource, but directly on memory. Such access occurs in the **VK_PIPELINE_STAGE_HOST_BIT** pipeline stage.

Certain access types are only performed by a subset of pipeline stages. Any synchronization command that takes both stage masks and access masks uses both to define the access scopes - only the specified access types performed by the specified stages are included in the access scope. An application must not specify an access flag in a synchronization command if it does not include a pipeline stage in the corresponding stage mask that is able to perform accesses of that type. The following table lists, for each access flag, which pipeline stages can perform that type of access.

**Table 4. Supported access types**

<table>
<thead>
<tr>
<th>Access flag</th>
<th>Supported pipeline stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_ACCESS_2_NONE</td>
<td>Any</td>
</tr>
<tr>
<td>VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT,</td>
</tr>
<tr>
<td>VK_ACCESS_2_INDEX_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT, VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT</td>
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<tr>
<td>VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT, VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_UNIFORM_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT,</td>
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<tr>
<td>VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT,</td>
</tr>
<tr>
<td>Access flag</td>
<td>Supported pipeline stages</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>VK_ACCESS_2_SHADER_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
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<td>VK_ACCESS_2_SHADER_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
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<td>VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT</td>
</tr>
<tr>
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<td>VK_ACCESS_2_TRANSFER_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_TRANSFER_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_HOST_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_HOST_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_HOST_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_2_HOST_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_MEMORY_READ_BIT</td>
<td>Any</td>
</tr>
<tr>
<td>VK_ACCESS_2_MEMORY_WRITE_BIT</td>
<td>Any</td>
</tr>
<tr>
<td>Access flag</td>
<td>Supported pipeline stages</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>VK_ACCESS_2_SHADER_SAMPLED_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_READ_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_2_SHADER_STORAGE_READ_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_READ_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
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<tr>
<td>VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT, VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT, VK_PIPELINE_STAGE_2_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_COMPUTE_SHADER_BIT</td>
</tr>
</tbody>
</table>

// Provided by VK_VERSION_1_0
typedef VkFlags VkAccessFlags;

VkAccessFlags is a bitmask type for setting a mask of zero or more VkAccessFlagBits.

If a memory object does not have the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT property, then vkFlushMappedMemoryRanges must be called in order to guarantee that writes to the memory object from the host are made available to the host domain, where they can be further made available to the device domain via a domain operation. Similarly, vkInvalidateMappedMemoryRanges must be called to guarantee that writes which are available to the host domain are made visible to host operations.

If the memory object does have the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT property flag, writes to the memory object from the host are automatically made available to the host domain. Similarly, writes made available to the host domain are automatically made visible to the host.

Note
Queue submission commands automatically perform a domain operation from host to device for all writes performed before the command executes, so in most cases an explicit memory barrier is not needed for this case. In the few circumstances where a submit does not occur between the host write and the
device read access, writes can be made available by using an explicit memory barrier.

### 7.1.4. Framebuffer Region Dependencies

Pipeline stages that operate on, or with respect to, the framebuffer are collectively the framebuffer-space pipeline stages. These stages are:

- `VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT`
- `VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT`
- `VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT`
- `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`

For these pipeline stages, an execution or memory dependency from the first set of operations to the second set can either be a single framebuffer-global dependency, or split into multiple framebuffer-local dependencies. A dependency with non-framebuffer-space pipeline stages is neither framebuffer-global nor framebuffer-local.

A framebuffer region is a set of sample (x, y, layer, sample) coordinates that is a subset of the entire framebuffer.

Both synchronization scopes of a framebuffer-local dependency include only the operations performed within corresponding framebuffer regions (as defined below). No ordering guarantees are made between different framebuffer regions for a framebuffer-local dependency.

Both synchronization scopes of a framebuffer-global dependency include operations on all framebuffer-regions.

If the first synchronization scope includes operations on pixels/fragments with N samples and the second synchronization scope includes operations on pixels/fragments with M samples, where N does not equal M, then a framebuffer region containing all samples at a given (x, y, layer) coordinate in the first synchronization scope corresponds to a region containing all samples at the same coordinate in the second synchronization scope. In other words, it is a pixel granularity dependency. If N equals M, then a framebuffer region containing a single (x, y, layer, sample) coordinate in the first synchronization scope corresponds to a region containing the same sample at the same coordinate in the second synchronization scope. In other words, it is a sample granularity dependency.

**Note**

Since fragment shader invocations are not specified to run in any particular groupings, the size of a framebuffer region is implementation-dependent, not known to the application, and must be assumed to be no larger than specified above.

**Note**

Practically, the pixel vs. sample granularity dependency means that if an input attachment has a different number of samples than the pipeline's
If a synchronization command includes a `dependencyFlags` parameter, and specifies the `VK_DEPENDENCY_BY_REGION_BIT` flag, then it defines framebuffer-local dependencies for the framebuffer-space pipeline stages in that synchronization command, for all framebuffer regions. If no `dependencyFlags` parameter is included, or the `VK_DEPENDENCY_BY_REGION_BIT` flag is not specified, then a framebuffer-global dependency is specified for those stages. The `VK_DEPENDENCY_BY_REGION_BIT` flag does not affect the dependencies between non-framebuffer-space pipeline stages, nor does it affect the dependencies between framebuffer-space and non-framebuffer-space pipeline stages.

**Note**

Framebuffer-local dependencies are more efficient for most architectures; particularly tile-based architectures - which can keep framebuffer-regions entirely in on-chip registers and thus avoid external bandwidth across such a dependency. Including a framebuffer-global dependency in your rendering will usually force all implementations to flush data to memory, or to a higher level cache, breaking any potential locality optimizations.

### 7.1.5. View-Local Dependencies

In a render pass instance that has multiview enabled, dependencies can be either view-local or view-global.

A view-local dependency only includes operations from a single source view from the source subpass in the first synchronization scope, and only includes operations from a single destination view from the destination subpass in the second synchronization scope. A view-global dependency includes all views in the view mask of the source and destination subpasses in the corresponding synchronization scopes.

If a synchronization command includes a `dependencyFlags` parameter and specifies the `VK_DEPENDENCY_VIEW_LOCAL_BIT` flag, then it defines view-local dependencies for that synchronization command, for all views. If no `dependencyFlags` parameter is included or the `VK_DEPENDENCY_VIEW_LOCAL_BIT` flag is not specified, then a view-global dependency is specified.

### 7.1.6. Device-Local Dependencies

Dependencies can be either device-local or non-device-local. A device-local dependency acts as multiple separate dependencies, one for each physical device that executes the synchronization command, where each dependency only includes operations from that physical device in both synchronization scopes. A non-device-local dependency is a single dependency where both synchronization scopes include operations from all physical devices that participate in the synchronization command. For subpass dependencies, all physical devices in the
VkDeviceGroupRenderPassBeginInfo::deviceMask participate in the dependency, and for pipeline barriers all physical devices that are set in the command buffer's current device mask participate in the dependency.

If a synchronization command includes a dependencyFlags parameter and specifies the VK_DEPENDENCY_DEVICE_GROUP_BIT flag, then it defines a non-device-local dependency for that synchronization command. If no dependencyFlags parameter is included or the VK_DEPENDENCY_DEVICE_GROUP_BIT flag is not specified, then it defines device-local dependencies for that synchronization command, for all participating physical devices.

Semaphore and event dependencies are device-local and only execute on the one physical device that performs the dependency.

7.2. Implicit Synchronization Guarantees

A small number of implicit ordering guarantees are provided by Vulkan, ensuring that the order in which commands are submitted is meaningful, and avoiding unnecessary complexity in common operations.

Submission order is a fundamental ordering in Vulkan, giving meaning to the order in which action and synchronization commands are recorded and submitted to a single queue. Explicit and implicit ordering guarantees between commands in Vulkan all work on the premise that this ordering is meaningful. This order does not itself define any execution or memory dependencies; synchronization commands and other orderings within the API use this ordering to define their scopes.

Submission order for any given set of commands is based on the order in which they were recorded to command buffers and then submitted. This order is determined as follows:

1. The initial order is determined by the order in which vkQueueSubmit and vkQueueSubmit2 commands are executed on the host, for a single queue, from first to last.

2. The order in which VkSubmitInfo structures are specified in the pSubmits parameter of vkQueueSubmit, or in which VkSubmitInfo2 structures are specified in the pSubmits parameter of vkQueueSubmit2, from lowest index to highest.

3. The order in which command buffers are specified in the pCommandBuffers member of VkSubmitInfo or VkSubmitInfo2 from lowest index to highest.

4. The order in which commands were recorded to a command buffer on the host, from first to last:

   ◦ For commands recorded outside a render pass, this includes all other commands recorded outside a render pass, including vkCmdBeginRenderPass and vkCmdEndRenderPass commands; it does not directly include commands inside a render pass.

   ◦ For commands recorded inside a render pass, this includes all other commands recorded inside the same subpass, including the vkCmdBeginRenderPass and vkCmdEndRenderPass commands that delimit the same render pass instance; it does not include commands recorded to other subpasses. State commands do not execute any operations on the device, instead they set the state of the command buffer when they execute on the host, in the order that they are recorded. Action commands consume the current state of the command buffer...
when they are recorded, and will execute state changes on the device as required to match the recorded state.

The order of primitives passing through the graphics pipeline and image layout transitions as part of an image memory barrier provide additional guarantees based on submission order.

Execution of pipeline stages within a given command also has a loose ordering, dependent only on a single command.

Signal operation order is a fundamental ordering in Vulkan, giving meaning to the order in which semaphore and fence signal operations occur when submitted to a single queue. The signal operation order for queue operations is determined as follows:

1. The initial order is determined by the order in which `vkQueueSubmit` and `vkQueueSubmit2` commands are executed on the host, for a single queue, from first to last.

2. The order in which `VkSubmitInfo` structures are specified in the `pSubmits` parameter of `vkQueueSubmit`, or in which `VkSubmitInfo2` structures are specified in the `pSubmits` parameter of `vkQueueSubmit2`, from lowest index to highest.

3. The fence signal operation defined by the `fence` parameter of a `vkQueueSubmit` or `vkQueueSubmit2` or `vkQueueBindSparse` command is ordered after all semaphore signal operations defined by that command.

Semaphore signal operations defined by a single `VkSubmitInfo` or `VkSubmitInfo2` or `VkBindSparseInfo` structure are unordered with respect to other semaphore signal operations defined within the same structure.

The `vkSignalSemaphore` command does not execute on a queue but instead performs the signal operation from the host. The semaphore signal operation defined by executing a `vkSignalSemaphore` command happens-after the `vkSignalSemaphore` command is invoked and happens-before the command returns.

---

**Note**

When signaling timeline semaphores, it is the responsibility of the application to ensure that they are ordered such that the semaphore value is strictly increasing. Because the first synchronization scope for a semaphore signal operation contains all semaphore signal operations which occur earlier in submission order, all semaphore signal operations contained in any given batch are guaranteed to happen-after all semaphore signal operations contained in any previous batches. However, no ordering guarantee is provided between the semaphore signal operations defined within a single batch. This, combined with the requirement that timeline semaphore values strictly increase, means that it is invalid to signal the same timeline semaphore twice within a single batch.

If an application wishes to ensure that some semaphore signal operation happens-after some other semaphore signal operation, it can submit a separate batch containing only semaphore signal operations, which will happen-after the semaphore signal operations in any earlier batches.
When signaling a semaphore from the host, the only ordering guarantee is that the signal operation happens-after when \texttt{vkSignalSemaphore} is called and happens-before it returns. Therefore, it is invalid to call \texttt{vkSignalSemaphore} while there are any outstanding signal operations on that semaphore from any queue submissions unless those queue submissions have some dependency which ensures that they happen-after the host signal operation. One example of this would be if the pending signal operation is, itself, waiting on the same semaphore at a lower value and the call to \texttt{vkSignalSemaphore} signals that lower value. Furthermore, if there are two or more processes or threads signaling the same timeline semaphore from the host, the application must ensure that the \texttt{vkSignalSemaphore} with the lower semaphore value returns before \texttt{vkSignalSemaphore} is called with the higher value.

7.3. Fences

Fences are a synchronization primitive that \textbf{can} be used to insert a dependency from a queue to the host. Fences have two states - signaled and unsignaled. A fence \textbf{can} be signaled as part of the execution of a \texttt{queue submission} command. Fences \textbf{can} be unsignaled on the host with \texttt{vkResetFences}. Fences \textbf{can} be waited on by the host with the \texttt{vkWaitForFences} command, and the current state \textbf{can} be queried with \texttt{vkGetFenceStatus}.

The internal data of a fence \textbf{may} include a reference to any resources and pending work associated with signal or unsignal operations performed on that fence object, collectively referred to as the fence’s \textit{payload}. Mechanisms to import and export that internal data to and from fences are provided \underline{below}. These mechanisms indirectly enable applications to share fence state between two or more fences and other synchronization primitives across process and API boundaries.

Fences are represented by \texttt{VkFence} handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFence)
```

To create a fence, call:

```c
// Provided by VK_VERSION_1_0
VkResult \textbf{vkCreateFence}(  
    VkDevice device,  
    const VkFenceCreateInfo* pCreateInfo,  
    const VkAllocationCallbacks* pAllocator,  
    VkFence* pFence);
```

- \texttt{device} is the logical device that creates the fence.
- \texttt{pCreateInfo} is a pointer to a \texttt{VkFenceCreateInfo} structure containing information about how the fence is to be created.
- \texttt{pAllocator} controls host memory allocation as described in the \texttt{Memory Allocation} chapter.
- \texttt{pFence} is a pointer to a handle in which the resulting fence object is returned.
Valid Usage (Implicit)

- VUID-vkCreateFence-device-parameter
device must be a valid VkDevice handle

- VUID-vkCreateFence-pCreateInfo-parameter
pCreateInfo must be a valid pointer to a valid VkFenceCreateInfo structure

- VUID-vkCreateFence-pAllocator-parameter
If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkCreateFence-pFence-parameter
pFence must be a valid pointer to a VkFence handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkFenceCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkFenceCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkFenceCreateFlags flags;
} VkFenceCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkFenceCreateFlagBits specifying the initial state and behavior of the fence.

Valid Usage (Implicit)

- VUID-VkFenceCreateInfo-sType-sType
sType must be VK_STRUCTURE_TYPE_FENCE_CREATE_INFO

- VUID-VkFenceCreateInfo-pNext-pNext
pNext must be NULL or a pointer to a valid instance of VkExportFenceCreateInfo

- VUID-VkFenceCreateInfo-sType-unique
The `sType` value of each struct in the `pNext` chain must be unique.

- VUID-VkFenceCreateInfo-flags-parameter
  The `flags` must be a valid combination of `VkFenceCreateFlagBits` values.

---

```c
// Provided by VK_VERSION_1_0
typedef enum VkFenceCreateFlagBits {
    VK_FENCE_CREATE_SIGNALED_BIT = 0x00000001,
} VkFenceCreateFlagBits;
```

- `VK_FENCE_CREATE_SIGNALED_BIT` specifies that the fence object is created in the signaled state. Otherwise, it is created in the unsignaled state.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkFenceCreateFlags;
```

`VkFenceCreateFlags` is a bitmask type for setting a mask of zero or more `VkFenceCreateFlagBits`.

To create a fence whose payload can be exported to external handles, add a `VkExportFenceCreateInfo` structure to the `pNext` chain of the `VkFenceCreateInfo` structure. The `VkExportFenceCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkExportFenceCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalFenceHandleTypeFlags handleTypes;
} VkExportFenceCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `handleTypes` is a bitmask of `VkExternalFenceHandleTypeFlagBits` specifying one or more fence handle types the application can export from the resulting fence. The application can request multiple handle types for the same fence.

---

### Valid Usage

- VUID-VkExportFenceCreateInfo-handleTypes-01446
  The bits in `handleTypes` must be supported and compatible, as reported by `VkExternalFenceProperties`.

---

### Valid Usage (Implicit)

- VUID-VkExportFenceCreateInfo-sType-sType
sType must be VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO

- VUID-VkExportFenceCreateInfo-handleTypes-parameter
  handleTypes must be a valid combination of VkExternalFenceHandleTypeFlagBits values

To destroy a fence, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyFence(
    VkDevice device,         // Logical device
    VkFence fence,           // Handle of the fence to destroy
    const VkAllocationCallbacks* pAllocator);
```

- device is the logical device that destroys the fence.
- fence is the handle of the fence to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- VUID-vkDestroyFence-fence-01120
  All queue submission commands that refer to fence must have completed execution

- VUID-vkDestroyFence-fence-01121
  If VkAllocationCallbacks were provided when fence was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyFence-fence-01122
  If no VkAllocationCallbacks were provided when fence was created, pAllocator must be NULL

### Valid Usage (Implicit)

- VUID-vkDestroyFence-device-parameter
  device must be a valid VkDevice handle

- VUID-vkDestroyFence-fence-parameter
  If fence is not VK_NULL_HANDLE, fence must be a valid VkFence handle

- VUID-vkDestroyFence-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkDestroyFence-fence-parent
  If fence is a valid handle, it must have been created, allocated, or retrieved from device
Host Synchronization

- Host access to fence must be externally synchronized

To query the status of a fence from the host, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkGetFenceStatus(
    VkDevice device,
    VkFence fence);
```

- `device` is the logical device that owns the fence.
- `fence` is the handle of the fence to query.

Upon success, `vkGetFenceStatus` returns the status of the fence object, with the following return codes:

<table>
<thead>
<tr>
<th>Status</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_SUCCESS</td>
<td>The fence specified by <code>fence</code> is signaled.</td>
</tr>
<tr>
<td>VK_NOT_READY</td>
<td>The fence specified by <code>fence</code> is unsignaled.</td>
</tr>
<tr>
<td>VK_ERROR_DEVICE_LOST</td>
<td>The device has been lost. See Lost Device.</td>
</tr>
</tbody>
</table>

If a queue submission command is pending execution, then the value returned by this command may immediately be out of date.

If the device has been lost (see Lost Device), `vkGetFenceStatus` may return any of the above status codes. If the device has been lost and `vkGetFenceStatus` is called repeatedly, it will eventually return either VK_SUCCESS or VK_ERROR_DEVICE_LOST.

Valid Usage (Implicit)

- `VUID-vkGetFenceStatus-device-parameter device must be a valid VkDevice handle`
- `VUID-vkGetFenceStatus-fence-parameter fence must be a valid VkFence handle`
- `VUID-vkGetFenceStatus-fence-parent fence must have been created, allocated, or retrieved from device`
Return Codes

Success

• VK_SUCCESS
• VK_NOT_READY

Failure

• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY
• VK_ERROR_DEVICE_LOST

To set the state of fences to unsignaled from the host, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkResetFences(
    VkDevice device,
    uint32_t fenceCount,
    const VkFence* pFences);
```

• `device` is the logical device that owns the fences.
• `fenceCount` is the number of fences to reset.
• `pFences` is a pointer to an array of fence handles to reset.

If any member of `pFences` currently has its payload imported with temporary permanence, that fence’s prior permanent payload is first restored. The remaining operations described therefore operate on the restored payload.

When `vkResetFences` is executed on the host, it defines a fence unsignal operation for each fence, which resets the fence to the unsignaled state.

If any member of `pFences` is already in the unsignaled state when `vkResetFences` is executed, then `vkResetFences` has no effect on that fence.

Valid Usage

• VUID-vkResetFences-pFences-01123
  Each element of `pFences` must not be currently associated with any queue command that has not yet completed execution on that queue

Valid Usage (Implicit)

• VUID-vkResetFences-device-parameter
  `device` must be a valid `VkDevice` handle
Host Synchronization

- Host access to each member of `pFences` must be externally synchronized

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_DEVICE_MEMORY

When a fence is submitted to a queue as part of a `queue submission` command, it defines a memory dependency on the batches that were submitted as part of that command, and defines a `fence signal operation` which sets the fence to the signaled state.

The first **synchronization scope** includes every batch submitted in the same `queue submission` command. Fence signal operations that are defined by `vkQueueSubmit` or `vkQueueSubmit2` additionally include in the first synchronization scope all commands that occur earlier in `submission order`. Fence signal operations that are defined by `vkQueueSubmit` or `vkQueueSubmit2` or `vkQueueBindSparse` additionally include in the first synchronization scope any semaphore and fence signal operations that occur earlier in `signal operation order`.

The second **synchronization scope** only includes the fence signal operation.

The first **access scope** includes all memory access performed by the device.

The second **access scope** is empty.

To wait for one or more fences to enter the signaled state on the host, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkWaitForFences(
    VkDevice device,
    uint32_t fenceCount,
    const VkFence* pFences,
    VkBool32 waitAll,
    uint64_t timeout);
```
• **device** is the logical device that owns the fences.

• **fenceCount** is the number of fences to wait on.

• **pFences** is a pointer to an array of **fenceCount** fence handles.

• **waitAll** is the condition that **must** be satisfied to successfully unblock the wait. If **waitAll** is `VK_TRUE`, then the condition is that all fences in **pFences** are signaled. Otherwise, the condition is that at least one fence in **pFences** is signaled.

• **timeout** is the timeout period in units of nanoseconds. **timeout** is adjusted to the closest value allowed by the implementation-dependent timeout accuracy, which **may** be substantially longer than one nanosecond, and **may** be longer than the requested period.

If the condition is satisfied when **vkWaitForFences** is called, then **vkWaitForFences** returns immediately. If the condition is not satisfied at the time **vkWaitForFences** is called, then **vkWaitForFences** will block and wait until the condition is satisfied or the **timeout** has expired, whichever is sooner.

If **timeout** is zero, then **vkWaitForFences** does not wait, but simply returns the current state of the fences. **VK_TIMEOUT** will be returned in this case if the condition is not satisfied, even though no actual wait was performed.

If the condition is satisfied before the **timeout** has expired, **vkWaitForFences** returns **VK_SUCCESS**. Otherwise, **vkWaitForFences** returns **VK_TIMEOUT** after the **timeout** has expired.

If device loss occurs (see Lost Device) before the timeout has expired, **vkWaitForFences** **must** return in finite time with either **VK_SUCCESS** or **VK_ERROR_DEVICE_LOST**.

**Note**

While we guarantee that **vkWaitForFences** **must** return in finite time, no guarantees are made that it returns immediately upon device loss. However, the client can reasonably expect that the delay will be on the order of seconds and that calling **vkWaitForFences** will not result in a permanently (or seemingly permanently) dead process.

---

**Valid Usage (Implicit)**

- VUID-vkWaitForFences-device-parameter
  device **must** be a valid **VkDevice** handle

- VUID-vkWaitForFences-pFences-parameter
  pFences **must** be a valid pointer to an array of **fenceCount** valid **VkFence** handles

- VUID-vkWaitForFences-fenceCount-arraylength
  fenceCount **must** be greater than 0

- VUID-vkWaitForFences-pFences-parent
  Each element of pFences **must** have been created, allocated, or retrieved from device
An execution dependency is defined by waiting for a fence to become signaled, either via `vkWaitForFences` or by polling on `vkGetFenceStatus`.

The first synchronization scope includes only the fence signal operation.

The second synchronization scope includes the host operations of `vkWaitForFences` or `vkGetFenceStatus` indicating that the fence has become signaled.

**Note**
Signaling a fence and waiting on the host does not guarantee that the results of memory accesses will be visible to the host, as the access scope of a memory dependency defined by a fence only includes device access. A memory barrier or other memory dependency must be used to guarantee this. See the description of host access types for more information.

### 7.3.1. Importing Fence Payloads

Applications can import a fence payload into an existing fence using an external fence handle. The effects of the import operation will be either temporary or permanent, as specified by the application. If the import is temporary, the fence will be restored to its permanent state the next time that fence is passed to `vkResetFences`.

**Note**
Restoring a fence to its prior permanent payload is a distinct operation from resetting a fence payload. See `vkResetFences` for more detail.

Performing a subsequent temporary import on a fence before resetting it has no effect on this requirement; the next unsignal of the fence must still restore its last permanent state. A permanent payload import behaves as if the target fence was destroyed, and a new fence was created with the same handle but the imported payload. Because importing a fence payload temporarily or permanently detaches the existing payload from a fence, similar usage restrictions to those applied to `vkDestroyFence` are applied to any command that imports a fence payload. Which of these import types is used is referred to as the import operation’s *permanence*. Each handle type supports either one or both types of permanence.
The implementation must perform the import operation by either referencing or copying the payload referred to by the specified external fence handle, depending on the handle’s type. The import method used is referred to as the handle type’s transference. When using handle types with reference transference, importing a payload to a fence adds the fence to the set of all fences sharing that payload. This set includes the fence from which the payload was exported. Fence signaling, waiting, and resetting operations performed on any fence in the set must behave as if the set were a single fence. Importing a payload using handle types with copy transference creates a duplicate copy of the payload at the time of import, but makes no further reference to it. Fence signaling, waiting, and resetting operations performed on the target of copy imports must not affect any other fence or payload.

Export operations have the same transference as the specified handle type’s import operations. Additionally, exporting a fence payload to a handle with copy transference has the same side effects on the source fence’s payload as executing a fence reset operation. If the fence was using a temporarily imported payload, the fence’s prior permanent payload will be restored.

External synchronization allows implementations to modify an object’s internal state, i.e. payload, without internal synchronization. However, for fences sharing a payload across processes, satisfying the external synchronization requirements of VkFence parameters as if all fences in the set were the same object is sometimes infeasible. Satisfying valid usage constraints on the state of a fence would similarly require impractical coordination or levels of trust between processes. Therefore, these constraints only apply to a specific fence handle, not to its payload. For distinct fence objects which share a payload:

- If multiple commands which queue a signal operation, or which unsignal a fence, are called concurrently, behavior will be as if the commands were called in an arbitrary sequential order.
- If a queue submission command is called with a fence that is sharing a payload, and the payload is already associated with another queue command that has not yet completed execution, either one or both of the commands will cause the fence to become signaled when they complete execution.
- If a fence payload is reset while it is associated with a queue command that has not yet completed execution, the payload will become unsignaled, but may become signaled again when the command completes execution.
- In the preceding cases, any of the devices associated with the fences sharing the payload may be lost, or any of the queue submission or fence reset commands may return VK_ERROR_INITIALIZATION_FAILED.

Other than these non-deterministic results, behavior is well defined. In particular:

- The implementation must not crash or enter an internally inconsistent state where future valid Vulkan commands might cause undefined results,
- Timeouts on future wait commands on fences sharing the payload must be effective.

Note
These rules allow processes to synchronize access to shared memory without trusting each other. However, such processes must still be cautious not to use the shared fence for more than synchronizing access to the shared memory. For
example, a process should not use a fence with shared payload to tell when commands it submitted to a queue have completed and objects used by those commands may be destroyed, since the other process can accidentally or maliciously cause the fence to signal before the commands actually complete.

When a fence is using an imported payload, its `VkExportFenceCreateInfo::handleTypes` value is specified when creating the fence from which the payload was exported, rather than specified when creating the fence. Additionally, `VkExternalFenceProperties::exportFromImportedHandleTypes` restricts which handle types can be exported from such a fence based on the specific handle type used to import the current payload.

When importing a fence payload, it is the responsibility of the application to ensure the external handles meet all valid usage requirements. However, implementations must perform sufficient validation of external handles to ensure that the operation results in a valid fence which will not cause program termination, device loss, queue stalls, host thread stalls, or corruption of other resources when used as allowed according to its import parameters. If the external handle provided does not meet these requirements, the implementation must fail the fence payload import operation with the error code `VK_ERROR_INVALID_EXTERNAL_HANDLE`.

### 7.4. Semaphores

Semaphores are a synchronization primitive that can be used to insert a dependency between queue operations or between a queue operation and the host. Binary semaphores have two states - signaled and unsignaled. Timeline semaphores have a strictly increasing 64-bit unsigned integer payload and are signaled with respect to a particular reference value. A semaphore can be signaled after execution of a queue operation is completed, and a queue operation can wait for a semaphore to become signaled before it begins execution. A timeline semaphore can additionally be signaled from the host with the `vkSignalSemaphore` command and waited on from the host with the `vkWaitSemaphores` command.

The internal data of a semaphore may include a reference to any resources and pending work associated with signal or unsignal operations performed on that semaphore object, collectively referred to as the semaphore's payload. Mechanisms to import and export that internal data to and from semaphores are provided below. These mechanisms indirectly enable applications to share semaphore state between two or more semaphores and other synchronization primitives across process and API boundaries.

Semaphores are represented by `VkSemaphore` handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSemaphore)
```

To create a semaphore, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateSemaphore(  
    VkDevice device,  
    const VkSemaphoreCreateInfo* createInfo,  
    VkSemaphore* semaphore
)
```
const VkSemaphoreCreateInfo* pCreateInfo, const VkAllocationCallbacks* pAllocator, VkSemaphore* pSemaphore);

• **device** is the logical device that creates the semaphore.

• **pCreateInfo** is a pointer to a `VkSemaphoreCreateInfo` structure containing information about how the semaphore is to be created.

• **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

• **pSemaphore** is a pointer to a handle in which the resulting semaphore object is returned.

### Valid Usage (Implicit)

- **VUID-vkCreateSemaphore-device-parameter**
  - `device` must be a valid `VkDevice` handle

- **VUID-vkCreateSemaphore-pCreateInfo-parameter**
  - `pCreateInfo` must be a valid pointer to a valid `VkSemaphoreCreateInfo` structure

- **VUID-vkCreateSemaphore-pAllocator-parameter**
  - If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- **VUID-vkCreateSemaphore-pSemaphore-parameter**
  - `pSemaphore` must be a valid pointer to a `VkSemaphore` handle

### Return Codes

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkSemaphoreCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSemaphoreCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphoreCreateFlags flags;
} VkSemaphoreCreateInfo;
```

- **sType** is a `VkStructureType` value identifying this structure.

- **pNext** is NULL or a pointer to a structure extending this structure.
• **flags** is reserved for future use.

### Valid Usage (Implicit)

- VUID-VkSemaphoreCreateInfo-sType-sType
  
  *sType** must be **VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO*

- VUID-VkSemaphoreCreateInfo-pNext-pNext
  
  Each **pNext** member of any structure (including this one) in the **pNext** chain **must** be either **NULL** or a pointer to a valid instance of **VkExportSemaphoreCreateInfo** or **VkSemaphoreTypeCreateInfo**

- VUID-VkSemaphoreCreateInfo-sType-unique
  
  The **sType** value of each struct in the **pNext** chain **must** be unique

- VUID-VkSemaphoreCreateInfo-flags-zerobitmask
  
  **flags** must be **0**

---

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkSemaphoreCreateFlags;
```

**VkSemaphoreCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

The **VkSemaphoreTypeCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSemaphoreTypeCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphoreType semaphoreType;
    uint64_t initialValue;
} VkSemaphoreTypeCreateInfo;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **semaphoreType** is a **VkSemaphoreType** value specifying the type of the semaphore.
- **initialValue** is the initial payload value if **semaphoreType** is **VK_SEMAPHORE_TYPE_TIMELINE**.

To create a semaphore of a specific type, add a **VkSemaphoreTypeCreateInfo** structure to the **VkSemaphoreCreateInfo::pNext** chain.

If no **VkSemaphoreTypeCreateInfo** structure is included in the **pNext** chain of **VkSemaphoreCreateInfo**, then the created semaphore will have a default **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_BINARY**.
Valid Usage

• VUID-VkSemaphoreTypeCreateInfo-timelineSemaphore-03252
  If the timelineSemaphore feature is not enabled, semaphoreType must not equal VK_SEMAPHORE_TYPE_TIMELINE

• VUID-VkSemaphoreTypeCreateInfo-semaphoreType-03279
  If semaphoreType is VK_SEMAPHORE_TYPE_BINARY, initialValue must be zero

Valid Usage (Implicit)

• VUID-VkSemaphoreTypeCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_SEMAPHORE_TYPE_CREATE_INFO

• VUID-VkSemaphoreTypeCreateInfo-semaphoreType-parameter
  semaphoreType must be a valid VkSemaphoreType value

Possible values of VkSemaphoreTypeCreateInfo::semaphoreType, specifying the type of a semaphore, are:

```
// Provided by VK_VERSION_1_2
typedef enum VkSemaphoreType {
    VK_SEMAPHORE_TYPE_BINARY = 0,
    VK_SEMAPHORE_TYPE_TIMELINE = 1,
} VkSemaphoreType;
```

- **VK_SEMAPHORE_TYPE_BINARY** specifies a binary semaphore type that has a boolean payload indicating whether the semaphore is currently signaled or unsignaled. When created, the semaphore is in the unsignaled state.

- **VK_SEMAPHORE_TYPE_TIMELINE** specifies a timeline semaphore type that has a strictly increasing 64-bit unsigned integer payload indicating whether the semaphore is signaled with respect to a particular reference value. When created, the semaphore payload has the value given by the initialValue field of VkSemaphoreTypeCreateInfo.

To create a semaphore whose payload can be exported to external handles, add a VkExportSemaphoreCreateInfo structure to the pNext chain of the VkSemaphoreCreateInfo structure. The VkExportSemaphoreCreateInfo structure is defined as:

```
// Provided by VK_VERSION_1_1
typedef struct VkExportSemaphoreCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalSemaphoreHandleTypeFlags handleTypes;
} VkExportSemaphoreCreateInfo;
```
• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• handleTypes is a bitmask of VkExternalSemaphoreHandleTypeFlagBits specifying one or more semaphore handle types the application can export from the resulting semaphore. The application can request multiple handle types for the same semaphore.

Valid Usage

- VUID-VkExportSemaphoreCreateInfo-handleTypes-01124
  The bits in handleTypes must be supported and compatible, as reported by VkExternalSemaphoreProperties

Valid Usage (Implicit)

- VUID-VkExportSemaphoreCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO
- VUID-VkExportSemaphoreCreateInfo-handleTypes-parameter
  handleTypes must be a valid combination of VkExternalSemaphoreHandleTypeFlagBits values

To destroy a semaphore, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroySemaphore(
    VkDevice device,           // Provided by VK_VERSION_1_0
    VkSemaphore semaphore,     // Provided by VK_VERSION_1_0
    const VkAllocationCallbacks* pAllocator);  // Provided by VK_VERSION_1_0
```

- device is the logical device that destroys the semaphore.
- semaphore is the handle of the semaphore to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- VUID-vkDestroySemaphore-semaphore-01137
  All submitted batches that refer to semaphore must have completed execution
- VUID-vkDestroySemaphore-semaphore-01138
  If VkAllocationCallbacks were provided when semaphore was created, a compatible set of callbacks must be provided here
- VUID-vkDestroySemaphore-semaphore-01139
  If no VkAllocationCallbacks were provided when semaphore was created, pAllocator must be NULL
Valid Usage (Implicit)

- VUID-vkDestroySemaphore-device-parameter
  
  *device* must be a valid *VkDevice* handle

- VUID-vkDestroySemaphore-semaphore-parameter
  
  If *semaphore* is not *VK_NULL_HANDLE*, *semaphore* must be a valid *VkSemaphore* handle

- VUID-vkDestroySemaphore-pAllocator-parameter
  
  If *pAllocator* is not NULL, *pAllocator* must be a valid pointer to a valid *VkAllocationCallbacks* structure

- VUID-vkDestroySemaphore-semaphore-parent
  
  If *semaphore* is a valid handle, it must have been created, allocated, or retrieved from *device*

Host Synchronization

- Host access to *semaphore* must be externally synchronized

7.4.1. Semaphore Signaling

When a batch is submitted to a queue via a queue submission, and it includes semaphores to be signaled, it defines a memory dependency on the batch, and defines semaphore signal operations which set the semaphores to the signaled state.

In case of semaphores created with a *VkSemaphoreType* of *VK_SEMAPHORE_TYPE_TIMELINE* the semaphore is considered signaled with respect to the counter value set to be signaled as specified in *VkTimelineSemaphoreSubmitInfo* or *VkSemaphoreSignalInfo*.

The first synchronization scope includes every command submitted in the same batch. In the case of *vkQueueSubmit2*, the first synchronization scope is limited to the pipeline stage specified by *VkSemaphoreSubmitInfo::stageMask*. Semaphore signal operations that are defined by *vkQueueSubmit* or *vkQueueSubmit2* additionally include all commands that occur earlier in submission order. Semaphore signal operations that are defined by *vkQueueSubmit* or *vkQueueSubmit2* or *vkQueueBindSparse* additionally include in the first synchronization scope any semaphore and fence signal operations that occur earlier in signal operation order.

The second synchronization scope includes only the semaphore signal operation.

The first access scope includes all memory access performed by the device.

The second access scope is empty.

7.4.2. Semaphore Waiting

When a batch is submitted to a queue via a queue submission, and it includes semaphores to be waited on, it defines a memory dependency between prior semaphore signal operations and the
batch, and defines semaphore wait operations.

Such semaphore wait operations set the semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_BINARY to the unsignaled state. In case of semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE a prior semaphore signal operation defines a memory dependency with a semaphore wait operation if the value the semaphore is signaled with is greater than or equal to the value the semaphore is waited with, thus the semaphore will continue to be considered signaled with respect to the counter value waited on as specified in VkTimelineSemaphoreSubmitInfo.

The first synchronization scope includes all semaphore signal operations that operate on semaphores waited on in the same batch, and that happen-before the wait completes.

The second synchronization scope includes every command submitted in the same batch. In the case of vkQueueSubmit, the second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by the corresponding element of pWaitDstStageMask. In the case of vkQueueSubmit2, the second synchronization scope is limited to the pipeline stage specified by VkSemaphoreSubmitInfo::stageMask. Also, in the case of either vkQueueSubmit2 or vkQueueSubmit, the second synchronization scope additionally includes all commands that occur later in submission order.

The first access scope is empty.

The second access scope includes all memory access performed by the device.

The semaphore wait operation happens-after the first set of operations in the execution dependency, and happens-before the second set of operations in the execution dependency.

**Note**

Unlike timeline semaphores, fences or events, the act of waiting for a binary semaphore also unsignals that semaphore. Applications must ensure that between two such wait operations, the semaphore is signaled again, with execution dependencies used to ensure these occur in order. Binary semaphore waits and signals should thus occur in discrete 1:1 pairs.

### 7.4.3. Semaphore State Requirements For Wait Operations

Before waiting on a semaphore, the application must ensure the semaphore is in a valid state for a wait operation. Specifically, when a semaphore wait operation is submitted to a queue:

- A binary semaphore must be signaled, or have an associated semaphore signal operation that is pending execution.
- Any semaphore signal operations on which the pending binary semaphore signal operation depends must also be completed or pending execution.
- There must be no other queue waiting on the same binary semaphore when the operation executes.
7.4.4. Host Operations on Semaphores

In addition to semaphore signal operations and semaphore wait operations submitted to device queues, timeline semaphores support the following host operations:

- Query the current counter value of the semaphore using the `vkGetSemaphoreCounterValue` command.
- Wait for a set of semaphores to reach particular counter values using the `vkWaitSemaphores` command.
- Signal the semaphore with a particular counter value from the host using the `vkSignalSemaphore` command.

To query the current counter value of a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` from the host, call:

```c
// Provided by VK_VERSION_1_2
VkResult vkGetSemaphoreCounterValue(
    VkDevice device,         // provided by vkCreateDevice
    VkSemaphore semaphore,   // provided by vkCreateSemaphore
    uint64_t* pValue         // provided by vkCreateSemaphore
);
```

- `device` is the logical device that owns the semaphore.
- `semaphore` is the handle of the semaphore to query.
- `pValue` is a pointer to a 64-bit integer value in which the current counter value of the semaphore is returned.

**Note**
If a queue submission command is pending execution, then the value returned by this command may immediately be out of date.

**Valid Usage**

- VUID-vkGetSemaphoreCounterValue-semaphore-03255: `semaphore` must have been created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`

**Valid Usage (Implicit)**

- VUID-vkGetSemaphoreCounterValue-device-parameter: `device` must be a valid `VkDevice` handle
- VUID-vkGetSemaphoreCounterValue-semaphore-parameter: `semaphore` must be a valid `VkSemaphore` handle
- VUID-vkGetSemaphoreCounterValue-pValue-parameter
pValue must be a valid pointer to a uint64_t value
• VUID-vkGetSemaphoreCounterValue-semaphore-parent
sempahore must have been created, allocated, or retrieved from device

Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY
• VK_ERROR_DEVICE_LOST

To wait for a set of semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE to reach particular counter values on the host, call:

```
// Provided by VK_VERSION_1_2
VkResult vkWaitSemaphores(
    VkDevice device,
    const VkSemaphoreWaitInfo* pWaitInfo,
    uint64_t timeout);
```

• device is the logical device that owns the semaphores.
• pWaitInfo is a pointer to a VkSemaphoreWaitInfo structure containing information about the wait condition.
• timeout is the timeout period in units of nanoseconds. timeout is adjusted to the closest value allowed by the implementation-dependent timeout accuracy, which may be substantially longer than one nanosecond, and may be longer than the requested period.

If the condition is satisfied when vkWaitSemaphores is called, then vkWaitSemaphores returns immediately. If the condition is not satisfied at the time vkWaitSemaphores is called, then vkWaitSemaphores will block and wait until the condition is satisfied or the timeout has expired, whichever is sooner.

If timeout is zero, then vkWaitSemaphores does not wait, but simply returns information about the current state of the semaphores. VK_TIMEOUT will be returned in this case if the condition is not satisfied, even though no actual wait was performed.

If the condition is satisfied before the timeout has expired, vkWaitSemaphores returns VK_SUCCESS. Otherwise, vkWaitSemaphores returns VK_TIMEOUT after the timeout has expired.

If device loss occurs (see Lost Device) before the timeout has expired, vkWaitSemaphores must return in finite time with either VK_SUCCESS or VK_ERROR_DEVICE_LOST.
Valid Usage (Implicit)

- VUID-vkWaitSemaphores-device-parameter
device must be a valid VkDevice handle
- VUID-vkWaitSemaphores-pWaitInfo-parameter
pWaitInfo must be a valid pointer to a valid VkSemaphoreWaitInfo structure

Return Codes

Success
- VK_SUCCESS
- VK_TIMEOUT

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

The VkSemaphoreWaitInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSemaphoreWaitInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphoreWaitFlags flags;
    uint32_t semaphoreCount;
    const VkSemaphore* pSemaphores;
    const uint64_t* pValues;
} VkSemaphoreWaitInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkSemaphoreWaitFlagBits specifying additional parameters for the semaphore wait operation.
- semaphoreCount is the number of semaphores to wait on.
- pSemaphores is a pointer to an array of semaphoreCount semaphore handles to wait on.
- pValues is a pointer to an array of semaphoreCount timeline semaphore values.

Valid Usage

- VUID-VkSemaphoreWaitInfo-pSemaphores-03256
All of the elements of pSemaphores must reference a semaphore that was created with a
VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE

Valid Usage (Implicit)

- VUID-VkSemaphoreWaitInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_SEMAPHORE_WAIT_INFO
- VUID-VkSemaphoreWaitInfo-pNext-pNext
  pNext must be NULL
- VUID-VkSemaphoreWaitInfo-flags-parameter
  flags must be a valid combination of VkSemaphoreWaitFlagBits values
- VUID-VkSemaphoreWaitInfo-pSemaphores-parameter
  pSemaphores must be a valid pointer to an array of semaphoreCount valid VkSemaphore handles
- VUID-VkSemaphoreWaitInfo-pValues-parameter
  pValues must be a valid pointer to an array of semaphoreCount uint64_t values
- VUID-VkSemaphoreWaitInfo-semaphoreCount-arraylength
  semaphoreCount must be greater than 0

Bits which can be set in VkSemaphoreWaitInfo::flags, specifying additional parameters of a semaphore wait operation, are:

```c
// Provided by VK_VERSION_1_2
typedef enum VkSemaphoreWaitFlagBits {
    VK_SEMAPHORE_WAIT_ANY_BIT = 0x00000001,
} VkSemaphoreWaitFlagBits;
```

- VK_SEMAPHORE_WAIT_ANY_BIT specifies that the semaphore wait condition is that at least one of the semaphores in VkSemaphoreWaitInfo::pSemaphores has reached the value specified by the corresponding element of VkSemaphoreWaitInfo::pValues. If VK_SEMAPHORE_WAIT_ANY_BIT is not set, the semaphore wait condition is that all of the semaphores in VkSemaphoreWaitInfo::pSemaphores have reached the value specified by the corresponding element of VkSemaphoreWaitInfo::pValues.

```c
// Provided by VK_VERSION_1_2
typedef VkFlags VkSemaphoreWaitFlags;
```

VkSemaphoreWaitFlags is a bitmask type for setting a mask of zero or more VkSemaphoreWaitFlagBits.

To signal a semaphore created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE with a particular counter value, on the host, call:

```c
// Provided by VK_VERSION_1_2
VkResult vkSignalSemaphore()
```
VkDevice device, const VkSemaphoreSignalInfo* pSignalInfo);

- `device` is the logical device that owns the semaphore.
- `pSignalInfo` is a pointer to a `VkSemaphoreSignalInfo` structure containing information about the signal operation.

When `vkSignalSemaphore` is executed on the host, it defines and immediately executes a *semaphore signal operation* which sets the timeline semaphore to the given value.

The first synchronization scope is defined by the host execution model, but includes execution of `vkSignalSemaphore` on the host and anything that happened-before it.

The second synchronization scope is empty.

### Valid Usage (Implicit)

- `VUID-vkSignalSemaphore-device-parameter`  
  `device` must be a valid `VkDevice` handle
- `VUID-vkSignalSemaphore-pSignalInfo-parameter`  
  `pSignalInfo` must be a valid pointer to a valid `VkSemaphoreSignalInfo` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkSemaphoreSignalInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSemaphoreSignalInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphore semaphore;
    uint64_t value;
} VkSemaphoreSignalInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `semaphore` is the handle of the semaphore to signal.
• value is the value to signal.

Valid Usage

- VUID-VkSemaphoreSignalInfo-semaphore-03257
  semaphore must have been created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE

- VUID-VkSemaphoreSignalInfo-value-03258
  value must have a value greater than the current value of the semaphore

- VUID-VkSemaphoreSignalInfo-value-03259
  value must be less than the value of any pending semaphore signal operations

- VUID-VkSemaphoreSignalInfo-value-03260
  value must have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on semaphore by more than maxTimelineSemaphoreValueDifference

Valid Usage (Implicit)

- VUID-VkSemaphoreSignalInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_SEMAPHORE_SIGNAL_INFO

- VUID-VkSemaphoreSignalInfo-pNext-pNext
  pNext must be NULL

- VUID-VkSemaphoreSignalInfo-semaphore-parameter
  semaphore must be a valid VkSemaphore handle

7.4.5. Importing Semaphore Payloads

Applications can import a semaphore payload into an existing semaphore using an external semaphore handle. The effects of the import operation will be either temporary or permanent, as specified by the application. If the import is temporary, the implementation must restore the semaphore to its prior permanent state after submitting the next semaphore wait operation. Performing a subsequent temporary import on a semaphore before performing a semaphore wait has no effect on this requirement; the next wait submitted on the semaphore must still restore its last permanent state. A permanent payload import behaves as if the target semaphore was destroyed, and a new semaphore was created with the same handle but the imported payload. Because importing a semaphore payload temporarily or permanently detaches the existing payload from a semaphore, similar usage restrictions to those applied to vkDestroySemaphore are applied to any command that imports a semaphore payload. Which of these import types is used is referred to as the import operation’s permanence. Each handle type supports either one or both types of permanence.

The implementation must perform the import operation by either referencing or copying the payload referred to by the specified external semaphore handle, depending on the handle’s type. The import method used is referred to as the handle type’s transference. When using handle types
with reference transference, importing a payload to a semaphore adds the semaphore to the set of all semaphores sharing that payload. This set includes the semaphore from which the payload was exported. Semaphore signaling and waiting operations performed on any semaphore in the set **must** behave as if the set were a single semaphore. Importing a payload using handle types with copy transference creates a duplicate copy of the payload at the time of import, but makes no further reference to it. Semaphore signaling and waiting operations performed on the target of copy imports **must** not affect any other semaphore or payload.

Export operations have the same transference as the specified handle type’s import operations. Additionally, exporting a semaphore payload to a handle with copy transference has the same side effects on the source semaphore’s payload as executing a semaphore wait operation. If the semaphore was using a temporarily imported payload, the semaphore’s prior permanent payload will be restored.

### External Synchronization

External synchronization allows implementations to modify an object’s internal state, i.e. payload, without internal synchronization. However, for semaphores sharing a payload across processes, satisfying the external synchronization requirements of `VkSemaphore` parameters as if all semaphores in the set were the same object is sometimes infeasible. Satisfying the **wait operation state requirements** would similarly require impractical coordination or levels of trust between processes. Therefore, these constraints only apply to a specific semaphore handle, not to its payload. For distinct semaphore objects which share a payload, if the semaphores are passed to separate queue submission commands concurrently, behavior will be as if the commands were called in an arbitrary sequential order. If the **wait operation state requirements** are violated for the shared payload by a queue submission command, or if a signal operation is queued for a shared payload that is already signaled or has a pending signal operation, effects **must** be limited to one or more of the following:

- Returning `VK_ERROR_INITIALIZATION_FAILED` from the command which resulted in the violation.
- Losing the logical device on which the violation occurred immediately or at a future time, resulting in a `VK_ERROR_DEVICE_LOST` error from subsequent commands, including the one causing the violation.
- Continuing execution of the violating command or operation as if the semaphore wait completed successfully after an implementation-dependent timeout. In this case, the state of the payload becomes undefined, and future operations on semaphores sharing the payload will be subject to these same rules. The semaphore **must** be destroyed or have its payload replaced by an import operation to again have a well-defined state.

**Note**

These rules allow processes to synchronize access to shared memory without trusting each other. However, such processes must still be cautious not to use the shared semaphore for more than synchronizing access to the shared memory. For example, a process should not use a shared semaphore as part of an execution dependency chain that, when complete, leads to objects being destroyed, if it does not trust other processes sharing the semaphore payload.

When a semaphore is using an imported payload, its `VkExportSemaphoreCreateInfo::handleTypes` value is specified when creating the semaphore from which the payload was exported, rather than
specified when creating the semaphore. Additionally, `VkExternalSemaphoreProperties::exportFromImportedHandleTypes` restricts which handle types can be exported from such a semaphore based on the specific handle type used to import the current payload.

When importing a semaphore payload, it is the responsibility of the application to ensure the external handles meet all valid usage requirements. However, implementations must perform sufficient validation of external handles to ensure that the operation results in a valid semaphore which will not cause program termination, device loss, queue stalls, or corruption of other resources when used as allowed according to its import parameters, and excepting those side effects allowed for violations of the valid semaphore state for wait operations rules. If the external handle provided does not meet these requirements, the implementation must fail the semaphore payload import operation with the error code `VK_ERROR_INVALID_EXTERNAL_HANDLE`.

In addition, when importing a semaphore payload that is not compatible with the payload type corresponding to the `VkSemaphoreType` the semaphore was created with, the implementation may fail the semaphore payload import operation with the error code `VK_ERROR_INVALID_EXTERNAL_HANDLE`.

Note
As the introduction of the external semaphore handle type `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT` predates that of timeline semaphores, support for importing semaphore payloads from external handles of that type into semaphores created (implicitly or explicitly) with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` is preserved for backwards compatibility. However, applications should prefer importing such handle types into semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`.

7.5. Events

Events are a synchronization primitive that can be used to insert a fine-grained dependency between commands submitted to the same queue, or between the host and a queue. Events must not be used to insert a dependency between commands submitted to different queues. Events have two states - signaled and unsignaled. An application can signal or unsignal an event either on the host or on the device. A device can be made to wait for an event to become signaled before executing further operations. No command exists to wait for an event to become signaled on the host, but the current state of an event can be queried.

Events are represented by `VkEvent` handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkEvent)
```

To create an event, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateEvent(
    VkDevice device,
    const VkEventCreateInfo* pCreateInfo,
```
```c
const VkAllocationCallbacks* pAllocator,
VkEvent* pEvent);
```

- `device` is the logical device that creates the event.
- `pCreateInfo` is a pointer to a `VkEventCreateInfo` structure containing information about how the event is to be created.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pEvent` is a pointer to a handle in which the resulting event object is returned.

When created, the event object is in the unsignaled state.

### Valid Usage

### Valid Usage (Implicit)

- VUID-vkCreateEvent-device-parameter
  
  `device` must be a valid `VkDevice` handle

- VUID-vkCreateEvent-pCreateInfo-parameter
  
  `pCreateInfo` must be a valid pointer to a valid `VkEventCreateInfo` structure

- VUID-vkCreateEvent-pAllocator-parameter
  
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- VUID-vkCreateEvent-pEvent-parameter
  
  `pEvent` must be a valid pointer to a `VkEvent` handle

### Return Codes

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkEventCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkEventCreateInfo {  
    VkStructureType          sType;  
    const void*              pNext;  
    VkEventCreateFlags       flags;  
} VkEventCreateInfo;
```
sType is a `VkStructureType` value identifying this structure.

pNext is `NULL` or a pointer to a structure extending this structure.

flags is a bitmask of `VkEventCreateFlagBits` defining additional creation parameters.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_EVENT_CREATE_INFO`
- `pNext` must be `NULL`
- `flags` must be a valid combination of `VkEventCreateFlagBits` values

```c
// Provided by VK_VERSION_1_0
typedef enum VkEventCreateFlagBits {
    // Provided by VK_VERSION_1_3
    VK_EVENT_CREATE_DEVICE_ONLY_BIT = 0x00000001,
} VkEventCreateFlagBits;
```

- `VK_EVENT_CREATE_DEVICE_ONLY_BIT` specifies that host event commands will not be used with this event.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkEventCreateFlags;
```

`VkEventCreateFlags` is a bitmask type for setting a mask of `VkEventCreateFlagBits`.

To destroy an event, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyEvent(
    VkDevice device,    // Logical device
    VkEvent event,      // Handle of the event to destroy
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the event.
- `event` is the handle of the event to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
Valid Usage

- VUID-vkDestroyEvent-event-01145
  All submitted commands that refer to event must have completed execution

- VUID-vkDestroyEvent-event-01146
  If VkAllocationCallbacks were provided when event was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyEvent-event-01147
  If no VkAllocationCallbacks were provided when event was created, pAllocator must be NULL

Valid Usage (Implicit)

- VUID-vkDestroyEvent-device-parameter
  device must be a valid VkDevice handle

- VUID-vkDestroyEvent-event-parameter
  If event is not VK_NULL_HANDLE, event must be a valid VkEvent handle

- VUID-vkDestroyEvent-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkDestroyEvent-event-parent
  If event is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization

- Host access to event must be externally synchronized

To query the state of an event from the host, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkGetEventStatus(
    VkDevice device,
    VkEvent event);
```

- device is the logical device that owns the event.
- event is the handle of the event to query.

Upon success, vkGetEventStatus returns the state of the event object with the following return codes:

Table 6. Event Object Status Codes
### Status

<table>
<thead>
<tr>
<th>Status</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EVENT_SET</td>
<td>The event specified by <code>event</code> is signaled.</td>
</tr>
<tr>
<td>VK_EVENT_RESET</td>
<td>The event specified by <code>event</code> is unsignaled.</td>
</tr>
</tbody>
</table>

If a `vkCmdSetEvent` or `vkCmdResetEvent` command is in a command buffer that is in the pending state, then the value returned by this command may immediately be out of date.

The state of an event can be updated by the host. The state of the event is immediately changed, and subsequent calls to `vkGetEventStatus` will return the new state. If an event is already in the requested state, then updating it to the same state has no effect.

### Valid Usage

- **VUID-vkGetEventStatus-event-03940**
  
  `event` **must** not have been created with `VK_EVENT_CREATE_DEVICE_ONLY_BIT`  

### Valid Usage (Implicit)

- **VUID-vkGetEventStatus-device-parameter**
  
  `device` **must** be a valid `VkDevice` handle

- **VUID-vkGetEventStatus-event-parameter**
  
  `event` **must** be a valid `VkEvent` handle

- **VUID-vkGetEventStatus-event-parent**
  
  `event` **must** have been created, allocated, or retrieved from `device`

### Return Codes

**Success**

- `VK_EVENT_SET`
- `VK_EVENT_RESET`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_DEVICE_LOST`

To set the state of an event to signaled from the host, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkSetEvent();
```
VkDevice device, VkEvent event);

- `device` is the logical device that owns the event.
- `event` is the event to set.

When `vkSetEvent` is executed on the host, it defines an event signal operation which sets the event to the signaled state.

If `event` is already in the signaled state when `vkSetEvent` is executed, then `vkSetEvent` has no effect, and no event signal operation occurs.

**Note**

If a command buffer is waiting for an event to be signaled from the host, the application must signal the event before submitting the command buffer, as described in the queue forward progress section.

---

### Valid Usage

- VUID-vkSetEvent-event-03941
  - `event` must not have been created with `VK_EVENT_CREATE_DEVICE_ONLY_BIT`

### Valid Usage (Implicit)

- VUID-vkSetEvent-device-parameter
  - `device` must be a valid `VkDevice` handle

- VUID-vkSetEvent-event-parameter
  - `event` must be a valid `VkEvent` handle

- VUID-vkSetEvent-event-parent
  - `event` must have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to `event` must be externally synchronized

### Return Codes

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
To set the state of an event to unsignaled from the host, call:

```
// Provided by VK_VERSION_1_0
VkResult vkResetEvent(
    VkDevice device,
    VkEvent event);
```

- `device` is the logical device that owns the event.
- `event` is the event to reset.

When `vkResetEvent` is executed on the host, it defines an *event unsignal operation* which resets the event to the unsignaled state.

If `event` is already in the unsignaled state when `vkResetEvent` is executed, then `vkResetEvent` has no effect, and no event unsignal operation occurs.

### Valid Usage

- **VUID-vkResetEvent-event-03821**
  There **must** be an execution dependency between `vkResetEvent` and the execution of any `vkCmdWaitEvents` that includes `event` in its `pEvents` parameter

- **VUID-vkResetEvent-event-03822**
  There **must** be an execution dependency between `vkResetEvent` and the execution of any `vkCmdWaitEvents2` that includes `event` in its `pEvents` parameter

- **VUID-vkResetEvent-event-03823**
  `event` **must** not have been created with `VK_EVENT_CREATE_DEVICE_ONLY_BIT`

### Valid Usage (Implicit)

- **VUID-vkResetEvent-device-parameter**
  `device` **must** be a valid `VkDevice` handle

- **VUID-vkResetEvent-event-parameter**
  `event` **must** be a valid `VkEvent` handle

- **VUID-vkResetEvent-event-parent**
  `event` **must** have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to `event` **must** be externally synchronized
The state of an event can also be updated on the device by commands inserted in command buffers.

To signal an event from a device, call:

```
// Provided by VK_VERSION_1_3
void vkCmdSetEvent2(
    VkCommandBuffer commandBuffer,
    VkEvent event,
    const VkDependencyInfo* pDependencyInfo);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `event` is the event that will be signaled.
- `pDependencyInfo` is a pointer to a `VkDependencyInfo` structure defining the first scopes of this operation.

When `vkCmdSetEvent2` is submitted to a queue, it defines the first half of memory dependencies defined by `pDependencyInfo`, as well as an event signal operation which sets the event to the signaled state. A memory dependency is defined between the event signal operation and commands that occur earlier in submission order.

The first synchronization scope and access scope are defined by the union of all the memory dependencies defined by `pDependencyInfo`, and are applied to all operations that occur earlier in submission order. Queue family ownership transfers and image layout transitions defined by `pDependencyInfo` are also included in the first scopes.

The second synchronization scope includes only the event signal operation, and any queue family ownership transfers and image layout transitions defined by `pDependencyInfo`.

The second access scope includes only queue family ownership transfers and image layout transitions.

Future `vkCmdWaitEvents2` commands rely on all values of each element in `pDependencyInfo` matching exactly with those used to signal the corresponding event. `vkCmdWaitEvents` must not be used to wait on the result of a signal operation defined by `vkCmdSetEvent2`.

**Note**

The extra information provided by `vkCmdSetEvent2` compared to `vkCmdSetEvent` allows implementations to more efficiently schedule the operations required to
satisfy the requested dependencies. With `vkCmdSetEvent`, the full dependency information is not known until `vkCmdWaitEvents` is recorded, forcing implementations to insert the required operations at that point and not before.

If `event` is already in the signaled state when `vkCmdSetEvent2` is executed on the device, then `vkCmdSetEvent2` has no effect, no event signal operation occurs, and no dependency is generated.

### Valid Usage

- **VUID-vkCmdSetEvent2-synchronization2-03824**
  The `synchronization2` feature **must** be enabled

- **VUID-vkCmdSetEvent2-dependencyFlags-03825**
  The `dependencyFlags` member of `pDependencyInfo` **must** be 0

- **VUID-vkCmdSetEvent2-commandBuffer-03826**
  The current device mask of `commandBuffer` **must** include exactly one physical device

- **VUID-vkCmdSetEvent2-srcStageMask-03827**
  The `srcStageMask` member of any element of the `pMemoryBarriers`, `pBufferMemoryBarriers`, or `pImageMemoryBarriers` members of `pDependencyInfo` **must** only include pipeline stages valid for the queue family that was used to create the command pool that `commandBuffer` was allocated from

- **VUID-vkCmdSetEvent2-dstStageMask-03828**
  The `dstStageMask` member of any element of the `pMemoryBarriers`, `pBufferMemoryBarriers`, or `pImageMemoryBarriers` members of `pDependencyInfo` **must** only include pipeline stages valid for the queue family that was used to create the command pool that `commandBuffer` was allocated from

### Valid Usage (Implicit)

- **VUID-vkCmdSetEvent2-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle

- **VUID-vkCmdSetEvent2-event-parameter**
  `event` **must** be a valid `VkEvent` handle

- **VUID-vkCmdSetEvent2-pDependencyInfo-parameter**
  `pDependencyInfo` **must** be a valid pointer to a valid `VkDependencyInfo` structure

- **VUID-vkCmdSetEvent2-commandBuffer-recording**
  `commandBuffer` **must** be in the `recording state`

- **VUID-vkCmdSetEvent2-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations

- **VUID-vkCmdSetEvent2-renderpass**
  This command **must** only be called outside of a render pass instance

- **VUID-vkCmdSetEvent2-commonparent**

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Both of `commandBuffer`, and event **must** have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

**Command Properties**

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<td>Synchronization</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

The `VkDependencyInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkDependencyInfo {
    VkStructureType sType;
    const void* pNext;
    VkDependencyFlags dependencyFlags;
    uint32_t memoryBarrierCount;
    const VkMemoryBarrier2* pMemoryBarriers;
    bufferMemoryBarrierCount;
    pBufferMemoryBarriers;
    imageMemoryBarrierCount;
    pImageMemoryBarriers;
} VkDependencyInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `dependencyFlags` is a bitmask of `VkDependencyFlagBits` specifying how execution and memory dependencies are formed.
- `memoryBarrierCount` is the length of the `pMemoryBarriers` array.
- `pMemoryBarriers` is a pointer to an array of `VkMemoryBarrier2` structures defining memory dependencies between any memory accesses.
- `bufferMemoryBarrierCount` is the length of the `pBufferMemoryBarriers` array.
- `pBufferMemoryBarriers` is a pointer to an array of `VkBufferMemoryBarrier2` structures defining memory dependencies between buffer ranges.
• `imageMemoryBarrierCount` is the length of the `pImageMemoryBarriers` array.

• `pImageMemoryBarriers` is a pointer to an array of `VkImageMemoryBarrier2` structures defining memory dependencies between image subresources.

This structure defines a set of memory dependencies, as well as queue family transfer operations and image layout transitions.

Each member of `pMemoryBarriers`, ` pBufferMemoryBarriers`, and `pImageMemoryBarriers` defines a separate memory dependency.

---

**Valid Usage (Implicit)**

- `VUID-VkDependencyInfo-sType-sType`  
  `sType` must be `VK_STRUCTURE_TYPE_DEPENDENCY_INFO`

- `VUID-VkDependencyInfo-pNext-pNext`  
  `pNext` must be `NULL`

- `VUID-VkDependencyInfo-dependencyFlags-parameter`  
  `dependencyFlags` must be a valid combination of `VkDependencyFlagBits` values

- `VUID-VkDependencyInfo-pMemoryBarriers-parameter`  
  If `memoryBarrierCount` is not 0, `pMemoryBarriers` must be a valid pointer to an array of `VkMemoryBarrier2` structures

- `VUID-VkDependencyInfo-pBufferMemoryBarriers-parameter`  
  If `bufferMemoryBarrierCount` is not 0, ` pBufferMemoryBarriers` must be a valid pointer to an array of `VkBufferMemoryBarrier2` structures

- `VUID-VkDependencyInfo-pImageMemoryBarriers-parameter`  
  If `imageMemoryBarrierCount` is not 0, `pImageMemoryBarriers` must be a valid pointer to an array of ` VkImageMemoryBarrier2` structures

---

To set the state of an event to signaled from a device, call:

```c
// Provided by VK_VERSION_1_0
define void vkCmdSetEvent(  
    VkCommandBuffer commandBuffer,  
    VkEvent event,  
    VkPipelineStageFlags stageMask);
```

- `commandBuffer` is the command buffer into which the command is recorded.

- `event` is the event that will be signaled.

- `stageMask` specifies the source stage mask used to determine the first synchronization scope.

`vkCmdSetEvent` behaves identically to `vkCmdSetEvent2`, except that it does not define an access scope, and **must** only be used with `vkCmdWaitEvents`, not `vkCmdWaitEvents2`. 

---

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Valid Usage

- VUID-vkCmdSetEvent-stageMask-04090
  If the geometryShader feature is not enabled, stageMask must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT

- VUID-vkCmdSetEvent-stageMask-04091
  If the tessellationShader feature is not enabled, stageMask must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT

- VUID-vkCmdSetEvent-stageMask-03937
  If the synchronization2 feature is not enabled, stageMask must not be 0

- VUID-vkCmdSetEvent-stageMask-06457
  Any pipeline stage included in stageMask must be supported by the capabilities of the queue family specified by the queueFamilyIndex member of the VkCommandPoolCreateInfo structure that was used to create the VkCommandPool that commandBuffer was allocated from, as specified in the table of supported pipeline stages

- VUID-vkCmdSetEvent-stageMask-01149
  stageMask must not include VK_PIPELINE_STAGE_HOST_BIT

- VUID-vkCmdSetEvent-commandBuffer-01152
  commandBuffer’s current device mask must include exactly one physical device

Valid Usage (Implicit)

- VUID-vkCmdSetEvent-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdSetEvent-event-parameter
  event must be a valid VkEvent handle

- VUID-vkCmdSetEvent-stageMask-parameter
  stageMask must be a valid combination of VkPipelineStageFlagBits values

- VUID-vkCmdSetEvent-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdSetEvent-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

- VUID-vkCmdSetEvent-renderpass
  This command must only be called outside of a render pass instance

- VUID-vkCmdSetEvent-commonparent
  Both of commandBuffer, and event must have been created, allocated, or retrieved from the same VkDevice
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
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</tr>
</tbody>
</table>

To unsignal the event from a device, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdResetEvent2(
    VkCommandBuffer commandBuffer,
    VkEvent event,
    VkPipelineStageFlags2 stageMask);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `event` is the event that will be unsignaled.
- `stageMask` is a `VkPipelineStageFlags2` mask of pipeline stages used to determine the first synchronization scope.

When `vkCmdResetEvent2` is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and defines an event unsignal operation which resets the event to the unsignaled state.

The first synchronization scope includes all commands that occur earlier in submission order. The synchronization scope is limited to operations by `stageMask` or stages that are logically earlier than `stageMask`.

The second synchronization scope includes only the event unsignal operation.

If `event` is already in the unsignaled state when `vkCmdResetEvent2` is executed on the device, then this command has no effect, no event unsignal operation occurs, and no execution dependency is generated.

Valid Usage

- VUID-vkCmdResetEvent2-stageMask-03929
  If the `geometryShader` feature is not enabled, `stageMask` must not contain

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If the tessellationShader feature is not enabled, stageMask must not contain
VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT or
VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT

The synchronization2 feature must be enabled

stageMask must not include VK_PIPELINE_STAGE_2_HOST_BIT

There must be an execution dependency between vkCmdResetEvent2 and the execution of any vkCmdWaitEvents that includes event in its pEvents parameter

There must be an execution dependency between vkCmdResetEvent2 and the execution of any vkCmdWaitEvents2 that includes event in its pEvents parameter

commandBuffer’s current device mask must include exactly one physical device

commandBuffer must be a valid VkCommandBuffer handle

event must be a valid VkEvent handle

stageMask must be a valid combination of VkPipelineStageFlagBits2 values

commandBuffer must be in the recording state

The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

This command must only be called outside of a render pass instance

Both of commandBuffer, and event must have been created, allocated, or retrieved from the same VkDevice

Host access to commandBuffer must be externally synchronized
Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

### Command Properties

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<td></td>
</tr>
</tbody>
</table>

To set the state of an event to unsignaled from a device, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdResetEvent(
    VkCommandBuffer commandBuffer,  
    VkEvent event,                  
    VkPipelineStageFlags stageMask);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `event` is the event that will be unsignaled.
- `stageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the source stage mask used to determine when the `event` is unsignaled.

`vkCmdResetEvent` behaves identically to `vkCmdResetEvent2`.

### Valid Usage

- VUID-vkCmdResetEvent-stageMask-04090
  If the `geometryShader` feature is not enabled, `stageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`

- VUID-vkCmdResetEvent-stageMask-04091
  If the `tessellationShader` feature is not enabled, `stageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

- VUID-vkCmdResetEvent-stageMask-03937
  If the `synchronization2` feature is not enabled, `stageMask` must not be 0

- VUID-vkCmdResetEvent-stageMask-06458
  Any pipeline stage included in `stageMask` must be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that `commandBuffer` was allocated from, as specified in the table of supported pipeline stages

- VUID-vkCmdResetEvent-stageMask-01153
stageMask must not include VK_PIPELINE_STAGE_HOST_BIT

- VUID-vkCmdResetEvent-event-03834
  There must be an execution dependency between vkCmdResetEvent and the execution of any vkCmdWaitEvents that includes event in its pEvents parameter

- VUID-vkCmdResetEvent-event-03835
  There must be an execution dependency between vkCmdResetEvent and the execution of any vkCmdWaitEvents2 that includes event in its pEvents parameter

- VUID-vkCmdResetEvent-commandBuffer-01157
  commandBuffer's current device mask must include exactly one physical device

### Valid Usage (Implicit)

- VUID-vkCmdResetEvent-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdResetEvent-event-parameter
  event must be a valid VkEvent handle

- VUID-vkCmdResetEvent-stageMask-parameter
  stageMask must be a valid combination of VkPipelineStageFlagBits values

- VUID-vkCmdResetEvent-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdResetEvent-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

- VUID-vkCmdResetEvent-renderpass
  This command must only be called outside of a render pass instance

- VUID-vkCmdResetEvent-commonparent
  Both of commandBuffer, and event must have been created, allocated, or retrieved from the same VkDevice

### Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
Command Properties

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</tr>
</tbody>
</table>

To wait for one or more events to enter the signaled state on a device, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdWaitEvents2(
    VkCommandBuffer commandBuffer,
    uint32_t eventCount,
    const VkEvent* pEvents,
    const VkDependencyInfo* pDependencyInfos);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `eventCount` is the length of the `pEvents` array.
- `pEvents` is a pointer to an array of `eventCount` events to wait on.
- `pDependencyInfos` is a pointer to an array of `eventCount` `VkDependencyInfo` structures, defining the second synchronization scope.

When `vkCmdWaitEvents2` is submitted to a queue, it inserts memory dependencies according to the elements of `pDependencyInfos` and each corresponding element of `pEvents`. `vkCmdWaitEvents2` must not be used to wait on event signal operations occurring on other queues, or signal operations executed by `vkCmdSetEvent`.

The first synchronization scope and access scope of each memory dependency defined by any element `i` of `pDependencyInfos` are applied to operations that occurred earlier in submission order than the last event signal operation on element `i` of `pEvents`.

Signal operations for an event at index `i` are only included if:

- The event was signaled by a `vkCmdSetEvent2` command that occurred earlier in submission order with a `dependencyInfo` parameter exactly equal to the element of `pDependencyInfos` at index `i`; or
- The event was created without `VK_EVENT_CREATE_DEVICE_ONLY_BIT`, and the first synchronization scope defined by the element of `pDependencyInfos` at index `i` only includes host operations (`VK_PIPELINE_STAGE_2_HOST_BIT`).

The second synchronization scope and access scope of each memory dependency defined by any element `i` of `pDependencyInfos` are applied to operations that occurred later in submission order than `vkCmdWaitEvents2`.

Note
vkCmdWaitEvents2 is used with vkCmdSetEvent2 to define a memory dependency between two sets of action commands, roughly in the same way as pipeline barriers, but split into two commands such that work between the two may execute unhindered.

**Note**

Applications should be careful to avoid race conditions when using events. There is no direct ordering guarantee between vkCmdSetEvent2 and vkCmdResetEvent2, vkCmdResetEvent, or vkCmdSetEvent. Another execution dependency (e.g. a pipeline barrier or semaphore with VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT) is needed to prevent such a race condition.

**Valid Usage**

- VUID-vkCmdWaitEvents2-synchronization2-03836
  The synchronization2 feature must be enabled

- VUID-vkCmdWaitEvents2-pEvents-03837
  Members of pEvents must not have been signaled by vkCmdSetEvent

- VUID-vkCmdWaitEvents2-pEvents-03838
  For any element i of pEvents, if that event is signaled by vkCmdSetEvent2, that command's dependencyInfo parameter must be exactly equal to the i-th element of pDependencyInfos

- VUID-vkCmdWaitEvents2-pEvents-03839
  For any element i of pEvents, if that event is signaled by vkSetEvent, barriers in the i-th element of pDependencyInfos must include only host operations in their first synchronization scope

- VUID-vkCmdWaitEvents2-pEvents-03840
  For any element i of pEvents, if barriers in the i-th element of pDependencyInfos include only host operations, the i-th element of pEvents must be signaled before vkCmdWaitEvents2 is executed

- VUID-vkCmdWaitEvents2-pEvents-03841
  For any element i of pEvents, if barriers in the i-th element of pDependencyInfos do not include host operations, the i-th element of pEvents must be signaled by a corresponding vkCmdSetEvent2 that occurred earlier in submission order

- VUID-vkCmdWaitEvents2-srcStageMask-03842
  The srcStageMask member of any element of the pMemoryBarriers, pBufferMemoryBarriers, or pImageMemoryBarriers members of pDependencyInfos must either include only pipeline stages valid for the queue family that was used to create the command pool that commandBuffer was allocated from, or include only VK_PIPELINE_STAGE_2_HOST_BIT

- VUID-vkCmdWaitEvents2-dstStageMask-03843
  The dstStageMask member of any element of the pMemoryBarriers, pBufferMemoryBarriers, or pImageMemoryBarriers members of pDependencyInfos must only include pipeline stages valid for the queue family that was used to create the command pool that commandBuffer was allocated from.
If `vkCmdWaitEvents2` is being called inside a render pass instance, the `srcStageMask` member of any element of the `pMemoryBarriers`, `pBufferMemoryBarriers`, or `pImageMemoryBarriers` members of `pDependencyInfos` must not include `VK_PIPELINE_STAGE_2_HOST_BIT`.

- **VUID-vkCmdWaitEvents2-commandBuffer-03846**
  `commandBuffer`'s current device mask must include exactly one physical device.

---

**Valid Usage (Implicit)**

- **VUID-vkCmdWaitEvents2-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- **VUID-vkCmdWaitEvents2-pEvents-parameter**
  `pEvents` must be a valid pointer to an array of `eventCount` valid `VkEvent` handles.

- **VUID-vkCmdWaitEvents2-pDependencyInfos-parameter**
  `pDependencyInfos` must be a valid pointer to an array of `eventCount` valid `VkDependencyInfo` structures.

- **VUID-vkCmdWaitEvents2-commandBuffer-recording**
  `commandBuffer` must be in the recording state.

- **VUID-vkCmdWaitEvents2-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations.

- **VUID-vkCmdWaitEvents2-eventCount-arraylength**
  `eventCount` must be greater than 0.

- **VUID-vkCmdWaitEvents2-commonparent**
  Both of `commandBuffer`, and the elements of `pEvents` must have been created, allocated, or retrieved from the same `VkDevice`.

---

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized.

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

---

**Command Properties**

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</tr>
</tbody>
</table>

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To wait for one or more events to enter the signaled state on a device, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdWaitEvents(
    VkCommandBuffer commandBuffer,
    uint32_t eventCount,
    const VkEvent* pEvents,
    VkPipelineStageFlags srcStageMask,
    VkPipelineStageFlags dstStageMask,
    uint32_t memoryBarrierCount,
    const VkMemoryBarrier* pMemoryBarriers,
    uint32_t bufferMemoryBarrierCount,
    const VkBufferMemoryBarrier* pBufferMemoryBarriers,
    uint32_t imageMemoryBarrierCount,
    const VkImageMemoryBarrier* pImageMemoryBarriers);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `eventCount` is the length of the `pEvents` array.
- `pEvents` is a pointer to an array of event object handles to wait on.
- `srcStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the source stage mask.
- `dstStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the destination stage mask.
- `memoryBarrierCount` is the length of the `pMemoryBarriers` array.
- `pMemoryBarriers` is a pointer to an array of `VkMemoryBarrier` structures.
- `bufferMemoryBarrierCount` is the length of the ` pBufferMemoryBarriers` array.
- ` pBufferMemoryBarriers` is a pointer to an array of `VkBufferMemoryBarrier` structures.
- `imageMemoryBarrierCount` is the length of the `pImageMemoryBarriers` array.
- `pImageMemoryBarriers` is a pointer to an array of `VkImageMemoryBarrier` structures.

`vkCmdWaitEvents` is largely similar to `vkCmdWaitEvents2`, but can only wait on signal operations defined by `vkCmdSetEvent`. As `vkCmdSetEvent` does not define any access scopes, `vkCmdWaitEvents` defines the first access scope for each event signal operation in addition to its own access scopes.

**Note**

Since `vkCmdSetEvent` does not have any dependency information beyond a stage mask, implementations do not have the same opportunity to perform availability and visibility operations or image layout transitions in advance as they do with `vkCmdSetEvent2` and `vkCmdWaitEvents2`.

When `vkCmdWaitEvents` is submitted to a queue, it defines a memory dependency between prior event signal operations on the same queue or the host, and subsequent commands. `vkCmdWaitEvents` must not be used to wait on event signal operations occurring on other queues.

The first synchronization scope only includes event signal operations that operate on members of `pEvents`, and the operations that happened-before the event signal operations. Event signal
operations performed by `vkCmdSetEvent` that occur earlier in submission order are included in the first synchronization scope, if the logically latest pipeline stage in their `stageMask` parameter is logically earlier than or equal to the logically latest pipeline stage in `srcStageMask`. Event signal operations performed by `vkSetEvent` are only included in the first synchronization scope if `VK_PIPELINE_STAGE_HOST_BIT` is included in `srcStageMask`.

The second synchronization scope includes all commands that occur later in submission order. The second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by `dstStageMask`.

The first access scope is limited to accesses in the pipeline stages determined by the source stage mask specified by `srcStageMask`. Within that, the first access scope only includes the first access scopes defined by elements of the `pMemoryBarriers`, `pBufferMemoryBarriers` and `pImageMemoryBarriers` arrays, which each define a set of memory barriers. If no memory barriers are specified, then the first access scope includes no accesses.

The second access scope is limited to accesses in the pipeline stages determined by the destination stage mask specified by `dstStageMask`. Within that, the second access scope only includes the second access scopes defined by elements of the `pMemoryBarriers`, `pBufferMemoryBarriers` and `pImageMemoryBarriers` arrays, which each define a set of memory barriers. If no memory barriers are specified, then the second access scope includes no accesses.

---

**Valid Usage**

- VUID-vkCmdWaitEvents-srcStageMask-04090
  If the `geometryShader` feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.

- VUID-vkCmdWaitEvents-srcStageMask-04091
  If the `tessellationShader` feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.

- VUID-vkCmdWaitEvents-srcStageMask-03937
  If the `synchronization2` feature is not enabled, `srcStageMask` must not be `0`.

- VUID-vkCmdWaitEvents-dstStageMask-04090
  If the `geometryShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.

- VUID-vkCmdWaitEvents-dstStageMask-04091
  If the `tessellationShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.

- VUID-vkCmdWaitEvents-dstStageMask-03937
  If the `synchronization2` feature is not enabled, `dstStageMask` must not be `0`.

- VUID-vkCmdWaitEvents-srcAccessMask-02815
  The `srcAccessMask` member of each element of `pMemoryBarriers` must only include access flags that are supported by one or more of the pipeline stages in `srcStageMask`, as specified.
in the table of supported access types

- VUID-vkCmdWaitEvents-dstAccessMask-02816
  The `dstAccessMask` member of each element of `pMemoryBarriers` must only include access flags that are supported by one or more of the pipeline stages in `dstStageMask`, as specified in the table of supported access types

- VUID-vkCmdWaitEvents-pBufferMemoryBarriers-02817
  For any element of `pBufferMemoryBarriers`, if its `srcQueueFamilyIndex` and `dstQueueFamilyIndex` members are equal, or if its `srcQueueFamilyIndex` is the queue family index that was used to create the command pool that `commandBuffer` was allocated from, then its `srcAccessMask` member must only contain access flags that are supported by one or more of the pipeline stages in `srcStageMask`, as specified in the table of supported access types

- VUID-vkCmdWaitEvents-pImageMemoryBarriers-02819
  For any element of `pImageMemoryBarriers`, if its `srcQueueFamilyIndex` and `dstQueueFamilyIndex` members are equal, or if its `srcQueueFamilyIndex` is the queue family index that was used to create the command pool that `commandBuffer` was allocated from, then its `srcAccessMask` member must only contain access flags that are supported by one or more of the pipeline stages in `srcStageMask`, as specified in the table of supported access types

- VUID-vkCmdWaitEvents-pImageMemoryBarriers-02820
  For any element of `pImageMemoryBarriers`, if its `srcQueueFamilyIndex` and `dstQueueFamilyIndex` members are equal, or if its `dstQueueFamilyIndex` is the queue family index that was used to create the command pool that `commandBuffer` was allocated from, then its `dstAccessMask` member must only contain access flags that are supported by one or more of the pipeline stages in `dstStageMask`, as specified in the table of supported access types

- VUID-vkCmdWaitEvents-srcStageMask-06459
  Any pipeline stage included in `srcStageMask` must be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that `commandBuffer` was allocated from, as specified in the table of supported pipeline stages

- VUID-vkCmdWaitEvents-dstStageMask-06460
  Any pipeline stage included in `dstStageMask` must be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that `commandBuffer` was allocated from, as specified in the table of supported pipeline stages

- VUID-vkCmdWaitEvents-srcStageMask-01158
  `srcStageMask` must be the bitwise OR of the `stageMask` parameter used in previous calls to
vkCmdSetEvent with any of the elements of pEvents and VK_PIPELINE_STAGE_HOST_BIT if any of the elements of pEvents was set using vkSetEvent

- VUID-vkCmdWaitEvents-srcStageMask-07308
  If vkCmdWaitEvents is being called inside a render pass instance, srcStageMask must not include VK_PIPELINE_STAGE_HOST_BIT

- VUID-vkCmdWaitEvents-srcQueueFamilyIndex-02803
  The srcQueueFamilyIndex and dstQueueFamilyIndex members of any element of pBufferMemoryBarriers or pImageMemoryBarriers must be equal

- VUID-vkCmdWaitEvents-commandBuffer-01167
  commandBuffer’s current device mask must include exactly one physical device

- VUID-vkCmdWaitEvents-pEvents-03847
  Elements of pEvents must not have been signaled by vkCmdSetEvent

Valid Usage (Implicit)

- VUID-vkCmdWaitEvents-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdWaitEvents-pEvents-parameter
  pEvents must be a valid pointer to an array of eventCount valid VkEvent handles

- VUID-vkCmdWaitEvents-srcStageMask-parameter
  srcStageMask must be a valid combination of VkPipelineStageFlagBits values

- VUID-vkCmdWaitEvents-dstStageMask-parameter
  dstStageMask must be a valid combination of VkPipelineStageFlagBits values

- VUID-vkCmdWaitEvents-pMemoryBarriers-parameter
  If memoryBarrierCount is not 0, pMemoryBarriers must be a valid pointer to an array of memoryBarrierCount valid VkMemoryBarrier structures

- VUID-vkCmdWaitEvents-pBufferMemoryBarriers-parameter
  If bufferMemoryBarrierCount is not 0, pBufferMemoryBarriers must be a valid pointer to an array of bufferMemoryBarrierCount valid VkBufferMemoryBarrier structures

- VUID-vkCmdWaitEvents-pImageMemoryBarriers-parameter
  If imageMemoryBarrierCount is not 0, pImageMemoryBarriers must be a valid pointer to an array of imageMemoryBarrierCount valid VkImageMemoryBarrier structures

- VUID-vkCmdWaitEvents-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdWaitEvents-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

- VUID-vkCmdWaitEvents-eventCount-arraylength
  eventCount must be greater than 0

- VUID-vkCmdWaitEvents-commonparent
  Both of commandBuffer, and the elements of pEvents must have been created, allocated, or
Host Synchronization

- Host access to commandBuffer **must** be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from **must** be externally synchronized

Command Properties

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7.6. Pipeline Barriers

To record a pipeline barrier, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdPipelineBarrier2(
    VkCommandBuffer commandBuffer,
    const VkDependencyInfo* pDependencyInfo);
```

- commandBuffer is the command buffer into which the command is recorded.
- pDependencyInfo is a pointer to a VkDependencyInfo structure defining the scopes of this operation.

When vkCmdPipelineBarrier2 is submitted to a queue, it defines memory dependencies between commands that were submitted to the same queue before it, and those submitted to the same queue after it.

The first **synchronization scope** and **access scope** of each memory dependency defined by pDependencyInfo are applied to operations that occurred earlier in submission order.

The second **synchronization scope** and **access scope** of each memory dependency defined by pDependencyInfo are applied to operations that occurred later in submission order.

If vkCmdPipelineBarrier2 is recorded within a render pass instance, the synchronization scopes are limited to operations within the same subpass.
Valid Usage

- VUID-vkCmdPipelineBarrier2-None-07889
  If vkCmdPipelineBarrier2 is called within a render pass instance using a VkRenderPass object, the render pass must have been created with at least one subpass dependency that expresses a dependency from the current subpass to itself, does not include VK_DEPENDENCY_BY_REGION_BIT if this command does not, does not include VK_DEPENDENCY_VIEW_LOCAL_BIT if this command does not, and has synchronization scopes and access scopes that are all supersets of the scopes defined in this command.

- VUID-vkCmdPipelineBarrier2-bufferMemoryBarrierCount-01178
  If vkCmdPipelineBarrier2 is called within a render pass instance using a VkRenderPass object, it must not include any buffer memory barriers.

- VUID-vkCmdPipelineBarrier2-image-04073
  If vkCmdPipelineBarrier2 is called within a render pass instance using a VkRenderPass object, the image member of any image memory barrier included in this command must be an attachment used in the current subpass both as an input attachment, and as either a color or depth/stencil attachment.

- VUID-vkCmdPipelineBarrier2-oldLayout-01181
  If vkCmdPipelineBarrier2 is called within a render pass instance, the oldLayout and newLayout members of any image memory barrier included in this command must be equal.

- VUID-vkCmdPipelineBarrier2-srcQueueFamilyIndex-01182
  If vkCmdPipelineBarrier2 is called within a render pass instance, the srcQueueFamilyIndex and dstQueueFamilyIndex members of any memory barrier included in this command must be equal.

- VUID-vkCmdPipelineBarrier2-None-07890
  If vkCmdPipelineBarrier2 is called within a render pass instance, and the source stage masks of any memory barriers include framebuffer-space stages, destination stage masks of all memory barriers must only include framebuffer-space stages.

- VUID-vkCmdPipelineBarrier2-dependencyFlags-07891
  If vkCmdPipelineBarrier2 is called within a render pass instance, and the source stage masks of any memory barriers include framebuffer-space stages, then dependencyFlags must include VK_DEPENDENCY_BY_REGION_BIT.

- VUID-vkCmdPipelineBarrier2-None-07892
  If vkCmdPipelineBarrier2 is called within a render pass instance, and there is more than one view in the current subpass, dependency flags must include VK_DEPENDENCY_VIEW_LOCAL_BIT.

- VUID-vkCmdPipelineBarrier2-dependencyFlags-01186
  If vkCmdPipelineBarrier2 is called outside of a render pass instance, the dependency flags must not include VK_DEPENDENCY_VIEW_LOCAL_BIT.

- VUID-vkCmdPipelineBarrier2-None-07893
  If vkCmdPipelineBarrier2 is called inside a render pass instance, and there is more than one view in the current subpass, dependency flags must include VK_DEPENDENCY_VIEW_LOCAL_BIT.
If `vkCmdPipelineBarrier2` is called within a render pass instance, the render pass **must** not have been started with `vkCmdBeginRendering`.

The `synchronization2` feature **must** be enabled.

The `srcStageMask` member of any element of the `pMemoryBarriers`, `pBufferMemoryBarriers`, or `pImageMemoryBarriers` members of `pDependencyInfo` **must** only include pipeline stages valid for the queue family that was used to create the command pool that `commandBuffer` was allocated from.

The `dstStageMask` member of any element of the `pMemoryBarriers`, `pBufferMemoryBarriers`, or `pImageMemoryBarriers` members of `pDependencyInfo` **must** only include pipeline stages valid for the queue family that was used to create the command pool that `commandBuffer` was allocated from.

**Valid Usage (Implicit)**

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle.
- `pDependencyInfo` **must** be a valid pointer to a valid `VkDependencyInfo` structure.
- `commandBuffer` **must** be in the `recording` state.
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations.

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized.

**Command Properties**

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</tr>
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</table>
To record a pipeline barrier, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdPipelineBarrier(
    VkCommandBuffer    commandBuffer,
    VkPipelineStageFlags srcStageMask,
    VkPipelineStageFlags dstStageMask,
    VkDependencyFlags  dependencyFlags,
    uint32_t           memoryBarrierCount,
    const VkMemoryBarrier* pMemoryBarriers,
    uint32_t           bufferMemoryBarrierCount,
    const VkBufferMemoryBarrier* pBufferMemoryBarriers,
    uint32_t           imageMemoryBarrierCount,
    const VkImageMemoryBarrier* pImageMemoryBarriers);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `srcStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the source stages.
- `dstStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the destination stages.
- `dependencyFlags` is a bitmask of `VkDependencyFlagBits` specifying how execution and memory dependencies are formed.
- `memoryBarrierCount` is the length of the `pMemoryBarriers` array.
- `pMemoryBarriers` is a pointer to an array of `VkMemoryBarrier` structures.
- `bufferMemoryBarrierCount` is the length of the ` pBufferMemoryBarriers` array.
- ` pBufferMemoryBarriers` is a pointer to an array of `VkBufferMemoryBarrier` structures.
- `imageMemoryBarrierCount` is the length of the ` pImageMemoryBarriers` array.
- `pImageMemoryBarriers` is a pointer to an array of `VkImageMemoryBarrier` structures.

`vkCmdPipelineBarrier` operates almost identically to `vkCmdPipelineBarrier2`, except that the scopes and barriers are defined as direct parameters rather than being defined by an `VkDependencyInfo`.

When `vkCmdPipelineBarrier` is submitted to a queue, it defines a memory dependency between commands that were submitted to the same queue before it, and those submitted to the same queue after it.

If `vkCmdPipelineBarrier` was recorded outside a render pass instance, the first synchronization scope includes all commands that occur earlier in submission order. If `vkCmdPipelineBarrier` was recorded inside a render pass instance, the first synchronization scope includes only commands that occur earlier in submission order within the same subpass. In either case, the first synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by `srcStageMask`.

If `vkCmdPipelineBarrier` was recorded outside a render pass instance, the second synchronization scope includes all commands that occur later in submission order. If `vkCmdPipelineBarrier` was recorded inside a render pass instance, the second synchronization scope includes only commands that occur later in submission order within the same subpass. In either case, the second
synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by \textit{dstStageMask}.

The first access scope is limited to accesses in the pipeline stages determined by the source stage mask specified by \textit{srcStageMask}. Within that, the first access scope only includes the first access scopes defined by elements of the \textit{pMemoryBarriers}, \textit{pBufferMemoryBarriers} and \textit{pImageMemoryBarriers} arrays, which each define a set of memory barriers. If no memory barriers are specified, then the first access scope includes no accesses.

The second access scope is limited to accesses in the pipeline stages determined by the destination stage mask specified by \textit{dstStageMask}. Within that, the second access scope only includes the second access scopes defined by elements of the \textit{pMemoryBarriers}, \textit{pBufferMemoryBarriers} and \textit{pImageMemoryBarriers} arrays, which each define a set of memory barriers. If no memory barriers are specified, then the second access scope includes no accesses.

If \textit{dependencyFlags} includes \textit{VK_DEPENDENCY_BY_REGION_BIT}, then any dependency between framebuffer-space pipeline stages is framebuffer-local - otherwise it is framebuffer-global.

### Valid Usage

- **VUID-vkCmdPipelineBarrier-srcStageMask-04090**
  If the \textit{geometryShader} feature is not enabled, \textit{srcStageMask} must not contain \textit{VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT}

- **VUID-vkCmdPipelineBarrier-srcStageMask-04091**
  If the \textit{tessellationShader} feature is not enabled, \textit{srcStageMask} must not contain \textit{VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT} or \textit{VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT}

- **VUID-vkCmdPipelineBarrier-srcStageMask-03937**
  If the \textit{synchronization2} feature is not enabled, \textit{srcStageMask} must not be \texttt{0}

- **VUID-vkCmdPipelineBarrier-dstStageMask-04090**
  If the \textit{geometryShader} feature is not enabled, \textit{dstStageMask} must not contain \textit{VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT}

- **VUID-vkCmdPipelineBarrier-dstStageMask-04091**
  If the \textit{tessellationShader} feature is not enabled, \textit{dstStageMask} must not contain \textit{VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT} or \textit{VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT}

- **VUID-vkCmdPipelineBarrier-dstStageMask-03937**
  If the \textit{synchronization2} feature is not enabled, \textit{dstStageMask} must not be \texttt{0}

- **VUID-vkCmdPipelineBarrier-srcAccessMask-02815**
  The \textit{srcAccessMask} member of each element of \textit{pMemoryBarriers} must only include access flags that are supported by one or more of the pipeline stages in \textit{srcStageMask}, as specified in the table of supported access types

- **VUID-vkCmdPipelineBarrier-dstAccessMask-02816**
  The \textit{dstAccessMask} member of each element of \textit{pMemoryBarriers} must only include access flags that are supported by one or more of the pipeline stages in \textit{dstStageMask}, as specified
in the table of supported access types

• VUID-vkCmdPipelineBarrier-pBufferMemoryBarriers-02817
  For any element of pBufferMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its srcQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its srcAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in srcStageMask, as specified in the table of supported access types

• VUID-vkCmdPipelineBarrier-pBufferMemoryBarriers-02818
  For any element of pBufferMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its dstQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its dstAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in dstStageMask, as specified in the table of supported access types

• VUID-vkCmdPipelineBarrier-pImageMemoryBarriers-02819
  For any element of pImageMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its srcQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its srcAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in srcStageMask, as specified in the table of supported access types

• VUID-vkCmdPipelineBarrier-pImageMemoryBarriers-02820
  For any element of pImageMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its dstQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its dstAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in dstStageMask, as specified in the table of supported access types

• VUID-vkCmdPipelineBarrier-None-07889
  If vkCmdPipelineBarrier is called within a render pass instance using a VkRenderPass object, the render pass must have been created with at least one subpass dependency that expresses a dependency from the current subpass to itself, does not include VK_DEPENDENCY_BY_REGION_BIT if this command does not, does not include VK_DEPENDENCY_VIEW_LOCAL_BIT if this command does not, and has synchronization scopes and access scopes that are all supersets of the scopes defined in this command

• VUID-vkCmdPipelineBarrier-bufferMemoryBarrierCount-01178
  If vkCmdPipelineBarrier is called within a render pass instance using a VkRenderPass object, it must not include any buffer memory barriers

• VUID-vkCmdPipelineBarrier-image-04073
  If vkCmdPipelineBarrier is called within a render pass instance using a VkRenderPass object, the image member of any image memory barrier included in this command must be an attachment used in the current subpass both as an input attachment, and as either a color or depth/stencil attachment
If `vkCmdPipelineBarrier` is called within a render pass instance, the `oldLayout` and `newLayout` members of any image memory barrier included in this command **must** be equal.

If `vkCmdPipelineBarrier` is called within a render pass instance, the `srcQueueFamilyIndex` and `dstQueueFamilyIndex` members of any memory barrier included in this command **must** be equal.

If `vkCmdPipelineBarrier` is called within a render pass instance, the source stage masks of any memory barriers include **framebuffer-space stages**, destination stage masks of all memory barriers **must** only include **framebuffer-space stages**.

If `vkCmdPipelineBarrier` is called within a render pass instance, and the source stage masks of any memory barriers include **framebuffer-space stages**, then dependency flags **must** include `VK_DEPENDENCY_BY_REGION_BIT`.

If `vkCmdPipelineBarrier` is called outside of a render pass instance, the dependency flags **must** not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

If `vkCmdPipelineBarrier` is called inside a render pass instance, and there is more than one view in the current subpass, dependency flags **must** include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

If `vkCmdPipelineBarrier` is called within a render pass instance, the render pass **must** not have been started with `vkCmdBeginRendering`.

Any pipeline stage included in `srcStageMask` **must** be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that `commandBuffer` was allocated from, as specified in the **table of supported pipeline stages**.

Any pipeline stage included in `dstStageMask` **must** be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that `commandBuffer` was allocated from, as specified in the **table of supported pipeline stages**.

**Valid Usage (Implicit)**

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle.
• VUID-vkCmdPipelineBarrier-srcStageMask-parameter  
**srcStageMask must** be a valid combination of **VkPipelineStageFlagBits values**

• VUID-vkCmdPipelineBarrier-dstStageMask-parameter  
**dstStageMask must** be a valid combination of **VkPipelineStageFlagBits values**

• VUID-vkCmdPipelineBarrier-dependencyFlags-parameter  
**dependencyFlags must** be a valid combination of **VkDependencyFlagBits values**

• VUID-vkCmdPipelineBarrier-pMemoryBarriers-parameter  
If **memoryBarrierCount is not 0**, **pMemoryBarriers must** be a valid pointer to an array of **memoryBarrierCount valid VkMemoryBarrier structures**

• VUID-vkCmdPipelineBarrier-pBufferMemoryBarriers-parameter  
If **bufferMemoryBarrierCount is not 0**, **pBufferMemoryBarriers must** be a valid pointer to an array of **bufferMemoryBarrierCount valid VkBufferMemoryBarrier structures**

• VUID-vkCmdPipelineBarrier-pImageMemoryBarriers-parameter  
If **imageMemoryBarrierCount is not 0**, **pImageMemoryBarriers must** be a valid pointer to an array of **imageMemoryBarrierCount valid VkImageMemoryBarrier structures**

• VUID-vkCmdPipelineBarrier-commandBuffer-recording  
**commandBuffer must** be in the **recording state**

• VUID-vkCmdPipelineBarrier-commandBuffer-cmdpool  
The **VkCommandPool** that **commandBuffer was allocated from must** support transfer, graphics, or compute operations

---

### Host Synchronization

• Host access to **commandBuffer must** be externally synchronized

• Host access to the **VkCommandPool that commandBuffer was allocated from must** be externally synchronized

---

### Command Properties

<table>
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<tr>
<td>Primary</td>
<td>Both</td>
<td>Transfer</td>
<td>Synchronization</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

Bits which **can** be set in **vkCmdPipelineBarrier::dependencyFlags**, specifying how execution and memory dependencies are formed, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkDependencyFlagBits {
    VK_DEPENDENCY_BY_REGION_BIT = 0x00000001,
```
• **VK_DEPENDENCY_BY_REGION_BIT** specifies that dependencies will be framebuffer-local.
• **VK_DEPENDENCY_VIEW_LOCAL_BIT** specifies that dependencies will be view-local.
• **VK_DEPENDENCY_DEVICE_GROUP_BIT** specifies that dependencies are non-device-local.

**VkDependencyFlags** is a bitmask type for setting a mask of zero or more **VkDependencyFlagBits**.

## 7.7. Memory Barriers

*Memory barriers* are used to explicitly control access to buffer and image subresource ranges. Memory barriers are used to transfer ownership between queue families, change image layouts, and define availability and visibility operations. They explicitly define the access types and buffer and image subresource ranges that are included in the access scopes of a memory dependency that is created by a synchronization command that includes them.

### 7.7.1. Global Memory Barriers

Global memory barriers apply to memory accesses involving all memory objects that exist at the time of its execution.

The **VkMemoryBarrier2** structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkMemoryBarrier2 {
    VkStructureType sType;
    const void* pNext;
    VkPipelineStageFlags2 srcStageMask;
    VkAccessFlags2 srcAccessMask;
    VkPipelineStageFlags2 dstStageMask;
    VkAccessFlags2 dstAccessMask;
} VkMemoryBarrier2;
```

• **sType** is a **VkStructureType** value identifying this structure.
• **pNext** is **NULL** or a pointer to a structure extending this structure.
• **srcStageMask** is a **VkPipelineStageFlags2** mask of pipeline stages to be included in the first synchronization scope.
• srcAccessMask is a VkAccessFlags2 mask of access flags to be included in the first access scope.
• dstStageMask is a VkPipelineStageFlags2 mask of pipeline stages to be included in the second synchronization scope.
• dstAccessMask is a VkAccessFlags2 mask of access flags to be included in the second access scope.

This structure defines a memory dependency affecting all device memory.

The first synchronization scope and access scope described by this structure include only operations and memory accesses specified by srcStageMask and srcAccessMask.

The second synchronization scope and access scope described by this structure include only operations and memory accesses specified by dstStageMask and dstAccessMask.

### Valid Usage

- **VUID-VkMemoryBarrier2-srcStageMask-03929**  
  If the geometryShader feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT.

- **VUID-VkMemoryBarrier2-srcStageMask-03930**  
  If the tessellationShader feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT.

- **VUID-VkMemoryBarrier2-srcAccessMask-03900**  
  If srcAccessMask includes VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT, srcStageMask must include VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT.

- **VUID-VkMemoryBarrier2-srcAccessMask-03901**  
  If srcAccessMask includes VK_ACCESS_2_INDEX_READ_BIT, srcStageMask must include VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT, VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT.

- **VUID-VkMemoryBarrier2-srcAccessMask-03902**  
  If srcAccessMask includes VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT, srcStageMask must include VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT, VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT.

- **VUID-VkMemoryBarrier2-srcAccessMask-03903**  
  If srcAccessMask includes VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT, srcStageMask must include VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_SUBPASS_SHADER_BIT_HUAWEI, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT.

- **VUID-VkMemoryBarrier2-srcAccessMask-03904**  
  If srcAccessMask includes VK_ACCESS_2_UNIFORM_READ_BIT, srcStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages.
If `srcAccessMask` includes `VK_ACCESS_2_SHADER_SAMPLED_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

If `srcAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

If `srcAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

If `srcAccessMask` includes `VK_ACCESS_2_SHADER_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

If `srcAccessMask` includes `VK_ACCESS_2_SHADER_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

If `srcAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

If `srcAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

If `srcAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

If `srcAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

If `srcAccessMask` includes `VK_ACCESS_2_TRANSFER_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COPY_BIT`, `VK_PIPELINE_STAGE_2_BLIT_BIT`, `VK_PIPELINE_STAGE_2_RESOLVE_BIT`, `VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages
VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or
VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-srcAccessMask-03915
  If srcAccessMask includes VK_ACCESS_2_TRANSFER_WRITE_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_COPY_BIT,
  VK_PIPELINE_STAGE_2_BLIT_BIT,
  VK_PIPELINE_STAGE_2_RESOLVE_BIT,
  VK_PIPELINE_STAGE_2_CLEAR_BIT,
  VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT,
  VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR,
  VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or
  VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-srcAccessMask-03916
  If srcAccessMask includes VK_ACCESS_2_HOST_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

- VUID-VkMemoryBarrier2-srcAccessMask-03917
  If srcAccessMask includes VK_ACCESS_2_HOST_WRITE_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

- VUID-VkMemoryBarrier2-dstStageMask-03929
  If the geometryShader feature is not enabled, dstStageMask must not contain
  VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT

- VUID-VkMemoryBarrier2-dstStageMask-03930
  If the tessellationShader feature is not enabled, dstStageMask must not contain
  VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT or
  VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03900
  If dstAccessMask includes VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT,
  VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR,
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03901
  If dstAccessMask includes VK_ACCESS_2_INDEX_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT,
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03902
  If dstAccessMask includes VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT,
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03903
  If dstAccessMask includes VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_SUBPASS_SHADER_BIT_HUAWEI, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or
  VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03904
If `dstAccessMask` includes `VK_ACCESS_2_UNIFORM_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03905**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_SAMPLED_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03906**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03907**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03908**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03909**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_WRITE_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkMemoryBarrier2-dstAccessMask-03910**
  If `dstAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT` or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkMemoryBarrier2-dstAccessMask-03911**
  If `dstAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT` or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkMemoryBarrier2-dstAccessMask-03912**
  If `dstAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkMemoryBarrier2-dstAccessMask-03913**
  If `dstAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`, `dstStageMask` **must** include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkMemoryBarrier2-dstAccessMask-03914**
  If `dstAccessMask` includes `VK_ACCESS_2_TRANSFER_READ_BIT`, `dstStageMask` **must** include
VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT,
VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT,
VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR,
VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR,
VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03915
  If dstAccessMask includes VK_ACCESS_2_TRANSFER_WRITE_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT,
  VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_CLEAR_BIT,
  VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT,
  VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR,
  VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR,
  or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03916
  If dstAccessMask includes VK_ACCESS_2_HOST_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

- VUID-VkMemoryBarrier2-dstAccessMask-03917
  If dstAccessMask includes VK_ACCESS_2_HOST_WRITE_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

Valid Usage (Implicit)

- VUID-VkMemoryBarrier2-sType-sType
  sType must be VK_STRUCTURE_TYPE_MEMORY_BARRIER_2

- VUID-VkMemoryBarrier2-srcStageMask-parameter
  srcStageMask must be a valid combination of VkPipelineStageFlagBits2 values

- VUID-VkMemoryBarrier2-srcAccessMask-parameter
  srcAccessMask must be a valid combination of VkAccessFlagBits2 values

- VUID-VkMemoryBarrier2-dstStageMask-parameter
  dstStageMask must be a valid combination of VkPipelineStageFlagBits2 values

- VUID-VkMemoryBarrier2-dstAccessMask-parameter
  dstAccessMask must be a valid combination of VkAccessFlagBits2 values

The VkMemoryBarrier structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkMemoryBarrier {
    VkStructureType          sType;
    const void*               pNext;
    VkAccessFlags            srcAccessMask;
    VkAccessFlags            dstAccessMask;
} VkMemoryBarrier;
```
• **sType** is a `VkStructureType` value identifying this structure.
• **pNext** is NULL or a pointer to a structure extending this structure.
• **srcAccessMask** is a bitmask of `VkAccessFlagBits` specifying a source access mask.
• **dstAccessMask** is a bitmask of `VkAccessFlagBits` specifying a destination access mask.

The first access scope is limited to access types in the source access mask specified by `srcAccessMask`.

The second access scope is limited to access types in the destination access mask specified by `dstAccessMask`.

## Valid Usage (Implicit)

- **VUID-VkMemoryBarrier-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_MEMORY_BARRIER`
- **VUID-VkMemoryBarrier-pNext-pNext**
  - `pNext` must be NULL
- **VUID-VkMemoryBarrier-srcAccessMask-parameter**
  - `srcAccessMask` must be a valid combination of `VkAccessFlagBits` values
- **VUID-VkMemoryBarrier-dstAccessMask-parameter**
  - `dstAccessMask` must be a valid combination of `VkAccessFlagBits` values

### 7.7.2. Buffer Memory Barriers

Buffer memory barriers only apply to memory accesses involving a specific buffer range. That is, a memory dependency formed from a buffer memory barrier is scoped to access via the specified buffer range. Buffer memory barriers can also be used to define a queue family ownership transfer for the specified buffer range.

The `VkBufferMemoryBarrier2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkBufferMemoryBarrier2 {
    VkStructureType sType;
    const void* pNext;
    VkPipelineStageFlags2 srcStageMask;
    VkAccessFlags2 srcAccessMask;
    VkPipelineStageFlags2 dstStageMask;
    VkAccessFlags2 dstAccessMask;
    uint32_t srcQueueFamilyIndex;
    uint32_t dstQueueFamilyIndex;
    VkBuffer buffer;
    VkDeviceSize offset;
    VkDeviceSize size;
} VkBufferMemoryBarrier2;
```
• **sType** is a *VkStructureType* value identifying this structure.

• **pNext** is **NULL** or a pointer to a structure extending this structure.

• **srcStageMask** is a *VkPipelineStageFlags2* mask of pipeline stages to be included in the **first** synchronization scope.

• **srcAccessMask** is a *VkAccessFlags2* mask of access flags to be included in the **first** access scope.

• **dstStageMask** is a *VkPipelineStageFlags2* mask of pipeline stages to be included in the **second** synchronization scope.

• **dstAccessMask** is a *VkAccessFlags2* mask of access flags to be included in the **second** access scope.

• **srcQueueFamilyIndex** is the source queue family for a **queue family ownership transfer**.

• **dstQueueFamilyIndex** is the destination queue family for a **queue family ownership transfer**.

• **buffer** is a handle to the buffer whose backing memory is affected by the barrier.

• **offset** is an offset in bytes into the backing memory for **buffer**; this is relative to the base offset as bound to the buffer (see **vkBindBufferMemory**).

• **size** is a size in bytes of the affected area of backing memory for **buffer**, or **VK_WHOLE_SIZE** to use the range from **offset** to the end of the buffer.

This structure defines a **memory dependency** limited to a range of a buffer, and **can** define a **queue family transfer operation** for that range.

The first **synchronization scope** and **access scope** described by this structure include only operations and memory accesses specified by **srcStageMask** and **srcAccessMask**.

The second **synchronization scope** and **access scope** described by this structure include only operations and memory accesses specified by **dstStageMask** and **dstAccessMask**.

Both **access scopes** are limited to only memory accesses to **buffer** in the range defined by **offset** and **size**.

If **buffer** was created with **VK_SHARING_MODE_EXCLUSIVE**, and **srcQueueFamilyIndex** is not equal to **dstQueueFamilyIndex**, this memory barrier defines a **queue family transfer operation**. When executed on a queue in the family identified by **srcQueueFamilyIndex**, this barrier defines a **queue family release operation** for the specified buffer range, and the second synchronization and access scopes do not synchronize operations on that queue. When executed on a queue in the family identified by **dstQueueFamilyIndex**, this barrier defines a **queue family acquire operation** for the specified buffer range, and the first synchronization and access scopes do not synchronize operations on that queue.

A **queue family transfer operation** is also defined if the values are not equal, and either is one of the special queue family values reserved for external memory ownership transfers, as described in **Queue Family Ownership Transfer**. A **queue family release operation** is defined when **dstQueueFamilyIndex** is one of those values, and a **queue family acquire operation** is defined when **srcQueueFamilyIndex** is one of those values.
Valid Usage

- **VUID-VkBufferMemoryBarrier2-srcStageMask-03929**
  If the `geometryShader` feature is not enabled, `srcStageMask` **must** not contain
  `VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT`

- **VUID-VkBufferMemoryBarrier2-srcStageMask-03930**
  If the `tessellationShader` feature is not enabled, `srcStageMask` **must** not contain
  `VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT`
  or
  `VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT`

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03900**
  If `srcAccessMask` includes `VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT`,
  `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`,
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03901**
  If `srcAccessMask` includes `VK_ACCESS_2_INDEX_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT`,
  `VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT`,
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03902**
  If `srcAccessMask` includes `VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT`,
  `VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT`,
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03903**
  If `srcAccessMask` includes `VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT`,
  `VK_PIPELINE_STAGE_2_SUBPASS_SHADER_BIT_HUAWEI`,
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03904**
  If `srcAccessMask` includes `VK_ACCESS_2_UNIFORM_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of
  the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03905**
  If `srcAccessMask` includes `VK_ACCESS_2_SHADER_SAMPLED_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of
  the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03906**
  If `srcAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_READ_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of
  the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

- **VUID-VkBufferMemoryBarrier2-srcAccessMask-03907**
  If `srcAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT`, `srcStageMask` **must** include
  `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of
  the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages
If `srcAccessMask` includes `VK_ACCESS_2_SHADER_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, or one of the `VK_PIPELINE_STAGE_2_*_SHADER_BIT` stages.

If `srcAccessMask` includes `VK_ACCESS_2_SHADER_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages.

If `srcAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_TRANSFER_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COPY_BIT`, `VK_PIPELINE_STAGE_2_BLIT_BIT`, `VK_PIPELINE_STAGE_2_RESOLVE_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_TRANSFER_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_COPY_BIT`, `VK_PIPELINE_STAGE_2_BLIT_BIT`, `VK_PIPELINE_STAGE_2_RESOLVE_BIT`, `VK_PIPELINE_STAGE_2_CLEAR_BIT`, `VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`.

If `srcAccessMask` includes `VK_ACCESS_2_HOST_READ_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_HOST_BIT`. 
• **VUID-VkBufferMemoryBarrier2-srcAccessMask-03917**
  If `srcAccessMask` includes `VK_ACCESS_2_HOST_WRITE_BIT`, `srcStageMask` must include `VK_PIPELINE_STAGE_2_HOST_BIT`

• **VUID-VkBufferMemoryBarrier2-dstStageMask-03929**
  If the `geometryShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT`

• **VUID-VkBufferMemoryBarrier2-dstStageMask-03930**
  If the `tessellationShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT`

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03900**
  If `dstAccessMask` includes `VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT`, `VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03901**
  If `dstAccessMask` includes `VK_ACCESS_2_INDEX_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT`, `VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03902**
  If `dstAccessMask` includes `VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT`, `VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03903**
  If `dstAccessMask` includes `VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT`, `VK_PIPELINE_STAGE_2_SUBPASS_SHADER_BIT_HUAWEI`, `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, or `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03904**
  If `dstAccessMask` includes `VK_ACCESS_2_UNIFORM_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03905**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_SAMPLED_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03906**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_READ_BIT`, `dstStageMask` must include `VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT`, `VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT`, or one of the `VK_PIPELINE_STAGE_*_SHADER_BIT` stages

• **VUID-VkBufferMemoryBarrier2-dstAccessMask-03907**
  If `dstAccessMask` includes `VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT`, `dstStageMask` must
include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03908
  If dstAccessMask includes VK_ACCESS_2_SHADER_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03909
  If dstAccessMask includes VK_ACCESS_2_SHADER_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03910
  If dstAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03911
  If dstAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03912
  If dstAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03913
  If dstAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_CLEAR_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03914
  If dstAccessMask includes VK_ACCESS_2_TRANSFER_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkBufferMemoryBarrier2-dstAccessMask-03915
  If dstAccessMask includes VK_ACCESS_2_TRANSFER_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT
• VUID-VkBufferMemoryBarrier2-dstAccessMask-03916
  If dstAccessMask includes VK_ACCESS_2_HOST_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_HOST_BIT

• VUID-VkBufferMemoryBarrier2-dstAccessMask-03917
  If dstAccessMask includes VK_ACCESS_2_HOST_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_HOST_BIT

• VUID-VkBufferMemoryBarrier2-offset-01187
  offset must be less than the size of buffer

• VUID-VkBufferMemoryBarrier2-size-01188
  If size is not equal to VK_WHOLE_SIZE, size must be greater than 0

• VUID-VkBufferMemoryBarrier2-size-01189
  If size is not equal to VK_WHOLE_SIZE, size must be less than or equal to than the size of buffer minus offset

• VUID-VkBufferMemoryBarrier2-buffer-01931
  If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

• VUID-VkBufferMemoryBarrier2-buffer-09095
  If buffer was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, and srcQueueFamilyIndex and dstQueueFamilyIndex are not equal, srcQueueFamilyIndex must be VK_QUEUE_FAMILY_EXTERNAL, or a valid queue family

• VUID-VkBufferMemoryBarrier2-buffer-09096
  If buffer was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, and srcQueueFamilyIndex and dstQueueFamilyIndex are not equal, dstQueueFamilyIndex must be VK_QUEUE_FAMILY_EXTERNAL, or a valid queue family

• VUID-VkBufferMemoryBarrier2-srcQueueFamilyIndex-04087
  If srcQueueFamilyIndex is not equal to dstQueueFamilyIndex, at least one of srcQueueFamilyIndex or dstQueueFamilyIndex must not be VK_QUEUE_FAMILY_EXTERNAL

• VUID-VkBufferMemoryBarrier2-None-09097
  If the value of VkApplicationInfo::apiVersion used to create the VkInstance is not greater than or equal to Version 1.1, srcQueueFamilyIndex must not be VK_QUEUE_FAMILY_EXTERNAL

• VUID-VkBufferMemoryBarrier2-None-09098
  If the value of VkApplicationInfo::apiVersion used to create the VkInstance is not greater than or equal to Version 1.1, dstQueueFamilyIndex must not be VK_QUEUE_FAMILY_EXTERNAL

• VUID-VkBufferMemoryBarrier2-srcStageMask-03851
  If either srcStageMask or dstStageMask includes VK_PIPELINE_STAGE_2_HOST_BIT, srcQueueFamilyIndex and dstQueueFamilyIndex must be equal

Valid Usage (Implicit)

• VUID-VkBufferMemoryBarrier2-sType-sType
  sType must be VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER_2

• VUID-VkBufferMemoryBarrier2-pNext-pNext
pNext must be NULL

- VUID-VkBufferMemoryBarrier2-srcStageMask-parameter
  srcStageMask must be a valid combination of VkPipelineStageFlagBits2 values

- VUID-VkBufferMemoryBarrier2-srcAccessMask-parameter
  srcAccessMask must be a valid combination of VkAccessFlagBits2 values

- VUID-VkBufferMemoryBarrier2-dstStageMask-parameter
  dstStageMask must be a valid combination of VkPipelineStageFlagBits2 values

- VUID-VkBufferMemoryBarrier2-dstAccessMask-parameter
  dstAccessMask must be a valid combination of VkAccessFlagBits2 values

- VUID-VkBufferMemoryBarrier2-buffer-parameter
  buffer must be a valid VkBuffer handle

The VkBufferMemoryBarrier structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBufferMemoryBarrier {
    VkStructureType sType;
    const void* pNext;
    VkAccessFlags srcAccessMask;
    VkAccessFlags dstAccessMask;
    uint32_t srcQueueFamilyIndex;
    uint32_t dstQueueFamilyIndex;
    VkBuffer buffer;
    VkDeviceSize offset;
    VkDeviceSize size;
} VkBufferMemoryBarrier;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- srcAccessMask is a bitmask of VkAccessFlagBits specifying a source access mask.
- dstAccessMask is a bitmask of VkAccessFlagBits specifying a destination access mask.
- srcQueueFamilyIndex is the source queue family for a queue family ownership transfer.
- dstQueueFamilyIndex is the destination queue family for a queue family ownership transfer.
- buffer is a handle to the buffer whose backing memory is affected by the barrier.
- offset is an offset in bytes into the backing memory for buffer; this is relative to the base offset as bound to the buffer (see vkBindBufferMemory).
- size is a size in bytes of the affected area of backing memory for buffer, or VK_WHOLE_SIZE to use the range from offset to the end of the buffer.

The first access scope is limited to access to memory through the specified buffer range, via access types in the source access mask specified by srcAccessMask. If srcAccessMask includes VK_ACCESS_HOST_WRITE_BIT, a memory domain operation is performed where available memory in
the host domain is also made available to the device domain.

The second access scope is limited to access to memory through the specified buffer range, via access types in the destination access mask specified by dstAccessMask. If dstAccessMask includes VK_ACCESS_HOST_WRITE_BIT or VK_ACCESS_HOST_READ_BIT, a memory domain operation is performed where available memory in the device domain is also made available to the host domain.

**Note**

When VK_MEMORY_PROPERTY_HOST_COHERENT_BIT is used, available memory in host domain is automatically made visible to host domain, and any host write is automatically made available to host domain.

If srcQueueFamilyIndex is not equal to dstQueueFamilyIndex, and srcQueueFamilyIndex is equal to the current queue family, then the memory barrier defines a queue family release operation for the specified buffer range, and the second access scope includes no access, as if dstAccessMask was 0.

If dstQueueFamilyIndex is not equal to srcQueueFamilyIndex, and dstQueueFamilyIndex is equal to the current queue family, then the memory barrier defines a queue family acquire operation for the specified buffer range, and the first access scope includes no access, as if srcAccessMask was 0.

---

### Valid Usage

- VUID-VkBufferMemoryBarrier-offset-01187
  
  **offset** must be less than the size of **buffer**

- VUID-VkBufferMemoryBarrier-size-01188
  
  If **size** is not equal to **VK_WHOLE_SIZE**, **size** must be greater than 0

- VUID-VkBufferMemoryBarrier-size-01189
  
  If **size** is not equal to **VK_WHOLE_SIZE**, **size** must be less than or equal to the size of **buffer** minus **offset**

- VUID-VkBufferMemoryBarrier-buffer-01931
  
  If **buffer** is non-sparse then it must be bound completely and contiguously to a single **VkDeviceMemory** object

- VUID-VkBufferMemoryBarrier-buffer-09095
  
  If **buffer** was created with a sharing mode of **VK_SHARING_MODE_EXCLUSIVE**, and srcQueueFamilyIndex and dstQueueFamilyIndex are not equal, srcQueueFamilyIndex must be **VK_QUEUE_FAMILY_EXTERNAL**, or a valid queue family

- VUID-VkBufferMemoryBarrier-buffer-09096
  
  If **buffer** was created with a sharing mode of **VK_SHARING_MODE_EXCLUSIVE**, and srcQueueFamilyIndex and dstQueueFamilyIndex are not equal, dstQueueFamilyIndex must be **VK_QUEUE_FAMILY_EXTERNAL**, or a valid queue family

- VUID-VkBufferMemoryBarrier-srcQueueFamilyIndex-04087
  
  If srcQueueFamilyIndex is not equal to dstQueueFamilyIndex, at least one of srcQueueFamilyIndex or dstQueueFamilyIndex must not be **VK_QUEUE_FAMILY_EXTERNAL**

- VUID-VkBufferMemoryBarrier-None-09097
  
  If the value of **VkApplicationInfo::apiVersion** used to create the **VkInstance** is not greater
than or equal to Version 1.1, `srcQueueFamilyIndex` must not be `VK_QUEUE_FAMILY_EXTERNAL`

- VUID-VkBufferMemoryBarrier-None-09098
  If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is not greater than or equal to Version 1.1, `dstQueueFamilyIndex` must not be `VK_QUEUE_FAMILY_EXTERNAL`

- VUID-VkBufferMemoryBarrier-None-09049
  If `buffer` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, at least one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED`

- VUID-VkBufferMemoryBarrier-None-09050
  If `buffer` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, `srcQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED` or `VK_QUEUE_FAMILY_EXTERNAL`

- VUID-VkBufferMemoryBarrier-None-09051
  If `buffer` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED` or `VK_QUEUE_FAMILY_EXTERNAL`

Valid Usage (Implicit)

- VUID-VkBufferMemoryBarrier-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER`

- VUID-VkBufferMemoryBarrier-pNext-pNext
  `pNext` must be `NULL`

- VUID-VkBufferMemoryBarrier-buffer-parameter
  `buffer` must be a valid `VkBuffer` handle

`VK_WHOLE_SIZE` is a special value indicating that the entire remaining length of a buffer following a given offset should be used. It can be specified for `VkBufferMemoryBarrier::size` and other structures.

```c
#define VK_WHOLE_SIZE (~0ULL)
```

7.7.3. Image Memory Barriers

Image memory barriers only apply to memory accesses involving a specific image subresource range. That is, a memory dependency formed from an image memory barrier is scoped to access via the specified image subresource range. Image memory barriers can also be used to define image layout transitions or a queue family ownership transfer for the specified image subresource range.

The `VkImageMemoryBarrier2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkImageMemoryBarrier2 {
    VkStructureType sType;
    const void* pNext;
} VkImageMemoryBarrier2;
```
```
VkPipelineStageFlags2 srcStageMask;
VkAccessFlags2 srcAccessMask;
VkPipelineStageFlags2 dstStageMask;
VkAccessFlags2 dstAccessMask;
VkImageLayout oldLayout;
VkImageLayout newLayout;
uint32_t srcQueueFamilyIndex;
uint32_t dstQueueFamilyIndex;
VkImage image;
VkImageSubresourceRange subresourceRange;
} VkImageMemoryBarrier2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcStageMask` is a `VkPipelineStageFlags2` mask of pipeline stages to be included in the first synchronization scope.
- `srcAccessMask` is a `VkAccessFlags2` mask of access flags to be included in the first access scope.
- `dstStageMask` is a `VkPipelineStageFlags2` mask of pipeline stages to be included in the second synchronization scope.
- `dstAccessMask` is a `VkAccessFlags2` mask of access flags to be included in the second access scope.
- `oldLayout` is the old layout in an image layout transition.
- `newLayout` is the new layout in an image layout transition.
- `srcQueueFamilyIndex` is the source queue family for a queue family ownership transfer.
- `dstQueueFamilyIndex` is the destination queue family for a queue family ownership transfer.
- `image` is a handle to the image affected by this barrier.
- `subresourceRange` describes the image subresource range within `image` that is affected by this barrier.

This structure defines a memory dependency limited to an image subresource range, and can define a queue family transfer operation and image layout transition for that subresource range.

The first synchronization scope and access scope described by this structure include only operations and memory accesses specified by `srcStageMask` and `srcAccessMask`.

The second synchronization scope and access scope described by this structure include only operations and memory accesses specified by `dstStageMask` and `dstAccessMask`.

Both access scopes are limited to only memory accesses to `image` in the subresource range defined by `subresourceRange`.

If `image` was created with `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, this memory barrier defines a queue family transfer operation. When executed on a queue in the family identified by `srcQueueFamilyIndex`, this barrier defines a queue family release operation for the specified image subresource range, and the second synchronization and access scopes do not synchronize operations on that queue. When executed on
a queue in the family identified by \textit{dstQueueFamilyIndex}, this barrier defines a \textit{queue family acquire operation} for the specified image subresource range, and the first synchronization and access scopes do not synchronize operations on that queue.

A \textit{queue family transfer operation} is also defined if the values are not equal, and either is one of the special queue family values reserved for external memory ownership transfers, as described in Queue Family Ownership Transfer. A \textit{queue family release operation} is defined when \textit{dstQueueFamilyIndex} is one of those values, and a \textit{queue family acquire operation} is defined when \textit{srcQueueFamilyIndex} is one of those values.

If \textit{oldLayout} is not equal to \textit{newLayout}, then the memory barrier defines an \textit{image layout transition} for the specified image subresource range. If this memory barrier defines a \textit{queue family transfer operation}, the layout transition is only executed once between the queues.

\textbf{Note}

When the old and new layout are equal, the layout values are ignored - data is preserved no matter what values are specified, or what layout the image is currently in.

If \textit{image} has a multi-planar format and the image is \textit{disjoint}, then including \textit{VK_IMAGE_ASPECT_COLOR_BIT} in the \textit{aspectMask} member of \textit{subresourceRange} is equivalent to including \textit{VK_IMAGE_ASPECT_PLANE_0_BIT}, \textit{VK_IMAGE_ASPECT_PLANE_1_BIT}, and (for three-plane formats only) \textit{VK_IMAGE_ASPECT_PLANE_2_BIT}.

\textbf{Valid Usage}

- \textit{VUID-VkImageMemoryBarrier2-srcStageMask-03929}
  If the \textit{geometryShader} feature is not enabled, \textit{srcStageMask} must not contain \textit{VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT}

- \textit{VUID-VkImageMemoryBarrier2-srcStageMask-03930}
  If the \textit{tessellationShader} feature is not enabled, \textit{srcStageMask} must not contain \textit{VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT} or \textit{VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT}

- \textit{VUID-VkImageMemoryBarrier2-srcAccessMask-03900}
  If \textit{srcAccessMask} includes \textit{VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT}, \textit{srcStageMask} must include \textit{VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT}, \textit{VK_PIPELINE_STAGE_2 ACCELERATION_STRUCTURE_BUILD_BIT_KHR}, \textit{VK_PIPELINE_STAGE_2 ALL_GRAPHICS_BIT}, or \textit{VK_PIPELINE_STAGE_2 ALL COMMANDS_BIT}

- \textit{VUID-VkImageMemoryBarrier2-srcAccessMask-03901}
  If \textit{srcAccessMask} includes \textit{VK_ACCESS_2_INDEX_READ_BIT}, \textit{srcStageMask} must include \textit{VK_PIPELINE_STAGE_2 INDEX_INPUT_BIT}, \textit{VK_PIPELINE_STAGE_2 VERTEX_INPUT_BIT}, \textit{VK_PIPELINE_STAGE_2 ALL_GRAPHICS_BIT}, or \textit{VK_PIPELINE_STAGE_2 ALL_COMMANDS_BIT}

- \textit{VUID-VkImageMemoryBarrier2-srcAccessMask-03902}
  If \textit{srcAccessMask} includes \textit{VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT}, \textit{srcStageMask} must include \textit{VK_PIPELINE_STAGE_2 VERTEX_ATTRIBUTE_INPUT_BIT}, \textit{VK_PIPELINE_STAGE_2 VERTEX_INPUT_BIT}, or \textit{VK_PIPELINE_STAGE_2 ALL_GRAPHICS_BIT}
• VUID-VkImageMemoryBarrier2-srcAccessMask-03903
  If srcAccessMask includes VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_SUBPASS_SHADER_BIT_HUAWEI, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-srcAccessMask-03904
  If srcAccessMask includes VK_ACCESS_2_UNIFORM_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

• VUID-VkImageMemoryBarrier2-srcAccessMask-03905
  If srcAccessMask includes VK_ACCESS_2_SHADER_SAMPLED_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

• VUID-VkImageMemoryBarrier2-srcAccessMask-03906
  If srcAccessMask includes VK_ACCESS_2_SHADER_STORAGE_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

• VUID-VkImageMemoryBarrier2-srcAccessMask-03907
  If srcAccessMask includes VK_ACCESS_2_SHADER_WRITE_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

• VUID-VkImageMemoryBarrier2-srcAccessMask-03908
  If srcAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-srcAccessMask-03909
  If srcAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-srcAccessMask-03910
  If srcAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-srcAccessMask-03911
  If srcAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-srcAccessMask-03912
  If srcAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT, srcStageMask must include
  VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT
If \( \text{srcAccessMask} \) includes \( \text{VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT} \), \( \text{srcStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT} \), \( \text{VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{srcAccessMask} \) includes \( \text{VK_ACCESS_2_TRANSFER_READ_BIT} \), \( \text{srcStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_COPY_BIT} \), \( \text{VK_PIPELINE_STAGE_2_BLIT_BIT} \), \( \text{VK_PIPELINE_STAGE_2_RESOLVE_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR} \), \( \text{VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{srcAccessMask} \) includes \( \text{VK_ACCESS_2_TRANSFER_WRITE_BIT} \), \( \text{srcStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_COPY_BIT} \), \( \text{VK_PIPELINE_STAGE_2_BLIT_BIT} \), \( \text{VK_PIPELINE_STAGE_2_RESOLVE_BIT} \), \( \text{VK_PIPELINE_STAGE_2_CLEAR_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR} \), \( \text{VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{srcAccessMask} \) includes \( \text{VK_ACCESS_2_HOST_READ_BIT} \), \( \text{srcStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_HOST_BIT} \).

If \( \text{srcAccessMask} \) includes \( \text{VK_ACCESS_2_HOST_WRITE_BIT} \), \( \text{srcStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_HOST_BIT} \).

If the \text{geometryShader} feature is not enabled, \( \text{dstStageMask} \) must not contain \( \text{VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT} \).

If the \text{tessellationShader} feature is not enabled, \( \text{dstStageMask} \) must not contain \( \text{VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT} \) or \( \text{VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT} \).

If \( \text{dstAccessMask} \) includes \( \text{VK_ACCESS_2_INDIRECT_COMMAND_READ_BIT} \), \( \text{dstStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_DRAW_INDIRECT_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR} \), \( \text{VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{dstAccessMask} \) includes \( \text{VK_ACCESS_2_INDEX_READ_BIT} \), \( \text{dstStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_INDEX_INPUT_BIT} \), \( \text{VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT} \), \( \text{VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{dstAccessMask} \) includes \( \text{VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT} \), \( \text{dstStageMask} \) must include \( \text{VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT} \), or \( \text{VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT} \).

If \( \text{dstAccessMask} \) includes \( \text{VK_ACCESS_2_VERTEX_ATTRIBUTE_READ_BIT} \), \( \text{dstStageMask} \) must
include VK_PIPELINE_STAGE_2_VERTEX_ATTRIBUTE_INPUT_BIT, VK_PIPELINE_STAGE_2_VERTEX_INPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkImageMemoryBarrier2-dstAccessMask-03903
  If dstAccessMask includes VK_ACCESS_2_INPUT_ATTACHMENT_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_FRAGMENT_SHADER_BIT, VK_PIPELINE_STAGE_2_SUBPASS_SHADER_HUAWEI, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkImageMemoryBarrier2-dstAccessMask-03904
  If dstAccessMask includes VK_ACCESS_2_UNIFORM_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03905
  If dstAccessMask includes VK_ACCESS_2_SHADER_SAMPLED_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03906
  If dstAccessMask includes VK_ACCESS_2_SHADER_STORAGE_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03907
  If dstAccessMask includes VK_ACCESS_2_SHADER_STORAGE_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03908
  If dstAccessMask includes VK_ACCESS_2_SHADER_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03909
  If dstAccessMask includes VK_ACCESS_2_SHADER_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT, or one of the VK_PIPELINE_STAGE_*_SHADER_BIT stages

- VUID-VkImageMemoryBarrier2-dstAccessMask-03910
  If dstAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkImageMemoryBarrier2-dstAccessMask-03911
  If dstAccessMask includes VK_ACCESS_2_COLOR_ATTACHMENT_WRITE_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_COLOR_ATTACHMENT_OUTPUT_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

- VUID-VkImageMemoryBarrier2-dstAccessMask-03912
  If dstAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_READ_BIT, dstStageMask must include VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT,
VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-dstAccessMask-03913
  If dstAccessMask includes VK_ACCESS_2_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_EARLY_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_LATE_FRAGMENT_TESTS_BIT, VK_PIPELINE_STAGE_2_ALL_GRAPHICS_BIT, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-dstAccessMask-03914
  If dstAccessMask includes VK_ACCESS_2_TRANSFER_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-dstAccessMask-03915
  If dstAccessMask includes VK_ACCESS_2_TRANSFER_WRITE_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_COPY_BIT, VK_PIPELINE_STAGE_2_BLIT_BIT, VK_PIPELINE_STAGE_2_RESOLVE_BIT, VK_PIPELINE_STAGE_2_CLEAR_BIT, VK_PIPELINE_STAGE_2_ALL_TRANSFER_BIT, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_BUILD_BIT_KHR, VK_PIPELINE_STAGE_2_ACCELERATION_STRUCTURE_COPY_BIT_KHR, or VK_PIPELINE_STAGE_2_ALL_COMMANDS_BIT

• VUID-VkImageMemoryBarrier2-dstAccessMask-03916
  If dstAccessMask includes VK_ACCESS_2_HOST_READ_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

• VUID-VkImageMemoryBarrier2-dstAccessMask-03917
  If dstAccessMask includes VK_ACCESS_2_HOST_WRITE_BIT, dstStageMask must include
  VK_PIPELINE_STAGE_2_HOST_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01208
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01209
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01210
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01211
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If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then image must have been created with VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01212
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL then image must have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT

• VUID-VkImageMemoryBarrier2-oldLayout-01213
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then image must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT

• VUID-VkImageMemoryBarrier2-newLayout-01198
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, newLayout must not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

• VUID-VkImageMemoryBarrier2-oldLayout-01658
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-04065
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_ATTACHMENT_OPTIMAL then image must have been created with at least one of VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_SAMPLED_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

• VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-04066
If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT set
VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-04067
If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL` then image must have been created with at least one of `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_SAMPLED_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`

VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-04068
If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL` then image must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` set

VUID-VkImageMemoryBarrier2-synchronization2-07793
If the `synchronization2` feature is not enabled, `oldLayout` must not be `VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL_KHR` or `VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR`

VUID-VkImageMemoryBarrier2-synchronization2-07794
If the `synchronization2` feature is not enabled, `newLayout` must not be `VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL_KHR` or `VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR`

VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-03938
If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL`, image must have been created with `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT` or `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`

VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-03939
If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL`, image must have been created with at least one of `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_SAMPLED_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`

VUID-VkImageMemoryBarrier2-image-09117
If image was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not equal, `srcQueueFamilyIndex` must be `VK_QUEUE_FAMILY_EXTERNAL`, or a valid queue family

VUID-VkImageMemoryBarrier2-image-09118
If image was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not equal, `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_EXTERNAL`, or a valid queue family

VUID-VkImageMemoryBarrier2-srcQueueFamilyIndex-04070
If `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, at least one of `srcQueueFamilyIndex` or `dstQueueFamilyIndex` must not be `VK_QUEUE_FAMILY_EXTERNAL`

VUID-VkImageMemoryBarrier2-None-09119
If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is not greater than or equal to Version 1.1, `srcQueueFamilyIndex` must not be `VK_QUEUE_FAMILY_EXTERNAL`

VUID-VkImageMemoryBarrier2-None-09120
If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is not greater
than or equal to Version 1.1, dstQueueFamilyIndex must not be VK_QUEUE_FAMILY_EXTERNAL

• VUID-VkImageMemoryBarrier2-subresourceRange-01486
  subresourceRange.baseMipLevel must be less than the mipLevels specified in VkImageCreateInfo when image was created

• VUID-VkImageMemoryBarrier2-subresourceRange-01724
  If subresourceRange.levelCount is not VK_REMAINING_MIP_LEVELS, subresourceRange.baseMipLevel + subresourceRange.levelCount must be less than or equal to the mipLevels specified in VkImageCreateInfo when image was created

• VUID-VkImageMemoryBarrier2-subresourceRange-01488
  subresourceRange.baseArrayLayer must be less than the arrayLayers specified in VkImageCreateInfo when image was created

• VUID-VkImageMemoryBarrier2-subresourceRange-01725
  If subresourceRange.layerCount is not VK_REMAINING_ARRAY_LAYERS, subresourceRange.baseArrayLayer + subresourceRange.layerCount must be less than or equal to the arrayLayers specified in VkImageCreateInfo when image was created

• VUID-VkImageMemoryBarrier2-image-01932
  If image is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

• VUID-VkImageMemoryBarrier2-image-01671
  If image has a single-plane color format or is not disjoint, then the aspectMask member of subresourceRange must be VK_IMAGE_ASPECT_COLOR_BIT

• VUID-VkImageMemoryBarrier2-image-01672
  If image has a multi-planar format and the image is disjoint, then the aspectMask member of subresourceRange must include at least one multi-planar aspect mask or VK_IMAGE_ASPECT_COLOR_BIT

• VUID-VkImageMemoryBarrier2-image-03319
  If image has a depth/stencil format with both depth and stencil and the separateDepthStencilLayers feature is enabled, then the aspectMask member of subresourceRange must include either or both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT

• VUID-VkImageMemoryBarrier2-image-03320
  If image has a depth/stencil format with both depth and stencil and the separateDepthStencilLayers feature is not enabled, then the aspectMask member of subresourceRange must include both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT

• VUID-VkImageMemoryBarrier2-aspectMask-08702
  If the aspectMask member of subresourceRange includes VK_IMAGE_ASPECT_DEPTH_BIT, oldLayout and newLayout must not be one of VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

• VUID-VkImageMemoryBarrier2-aspectMask-08703
  If the aspectMask member of subresourceRange includes VK_IMAGE_ASPECT_STENCIL_BIT, oldLayout and newLayout must not be one of VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL
If either `srcStageMask` or `dstStageMask` includes `VK_PIPELINE_STAGE_2_HOST_BIT`, `srcQueueFamilyIndex` and `dstQueueFamilyIndex` must be equal.

If `srcStageMask` includes `VK_PIPELINE_STAGE_2_HOST_BIT`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, `oldLayout` must be one of `VK_IMAGE_LAYOUT_PREINITIALIZED`, `VK_IMAGE_LAYOUT_UNDEFINED`, or `VK_IMAGE_LAYOUT_GENERAL`.

Valid Usage (Implicit)

- **VUID-VkImageMemoryBarrier2-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER_2`

- **VUID-VkImageMemoryBarrier2-pNext-pNext**
  - `pNext` must be `NULL`

- **VUID-VkImageMemoryBarrier2-srcStageMask-parameter**
  - `srcStageMask` must be a valid combination of `VkPipelineStageFlagBits2` values

- **VUID-VkImageMemoryBarrier2-srcAccessMask-parameter**
  - `srcAccessMask` must be a valid combination of `VkAccessFlagBits2` values

- **VUID-VkImageMemoryBarrier2-dstStageMask-parameter**
  - `dstStageMask` must be a valid combination of `VkPipelineStageFlagBits2` values

- **VUID-VkImageMemoryBarrier2-dstAccessMask-parameter**
  - `dstAccessMask` must be a valid combination of `VkAccessFlagBits2` values

- **VUID-VkImageMemoryBarrier2-oldLayout-parameter**
  - `oldLayout` must be a valid `VkImageLayout` value

- **VUID-VkImageMemoryBarrier2-newLayout-parameter**
  - `newLayout` must be a valid `VkImageLayout` value

- **VUID-VkImageMemoryBarrier2-image-parameter**
  - `image` must be a valid `VkImage` handle

- **VUID-VkImageMemoryBarrier2-subresourceRange-parameter**
  - `subresourceRange` must be a valid `VkImageSubresourceRange` structure

The `VkImageMemoryBarrier` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageMemoryBarrier {
    VkStructureType sType;
    const void* pNext;
    VkAccessFlags srcAccessMask;
    VkAccessFlags dstAccessMask;
    VkImageLayout oldLayout;
    VkImageLayout newLayout;
} VkImageMemoryBarrier;
```
- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcAccessMask` is a bitmask of `VkAccessFlagBits` specifying a source access mask.
- `dstAccessMask` is a bitmask of `VkAccessFlagBits` specifying a destination access mask.
- `oldLayout` is the old layout in an image layout transition.
- `newLayout` is the new layout in an image layout transition.
- `srcQueueFamilyIndex` is the source queue family for a queue family ownership transfer.
- `dstQueueFamilyIndex` is the destination queue family for a queue family ownership transfer.
- `image` is a handle to the image affected by this barrier.
- `subresourceRange` describes the image subresource range within `image` that is affected by this barrier.

The first access scope is limited to access to memory through the specified image subresource range, via access types in the source access mask specified by `srcAccessMask`. If `srcAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT`, memory writes performed by that access type are also made visible, as that access type is not performed through a resource.

The second access scope is limited to access to memory through the specified image subresource range, via access types in the destination access mask specified by `dstAccessMask`. If `dstAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT` or `VK_ACCESS_HOST_READ_BIT`, available memory writes are also made visible to accesses of those types, as those access types are not performed through a resource.

If `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, and `srcQueueFamilyIndex` is equal to the current queue family, then the memory barrier defines a queue family release operation for the specified image subresource range, and the second access scope includes no access, as if `dstAccessMask` was 0.

If `dstQueueFamilyIndex` is not equal to `srcQueueFamilyIndex`, and `dstQueueFamilyIndex` is equal to the current queue family, then the memory barrier defines a queue family acquire operation for the specified image subresource range, and the first access scope includes no access, as if `srcAccessMask` was 0.

If the synchronization2 feature is not enabled or `oldLayout` is not equal to `newLayout`, `oldLayout` and `newLayout` define an image layout transition for the specified image subresource range.

Note

If the synchronization2 feature is enabled, when the old and new layout are equal, the layout values are ignored - data is preserved no matter what values are specified, or what layout the image is currently in.
If `image` has a multi-planar format and the image is *disjoint*, then including `VK_IMAGE_ASPECT_COLOR_BIT` in the `aspectMask` member of `subresourceRange` is equivalent to including `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, and (for three-plane formats only) `VK_IMAGE_ASPECT_PLANE_2_BIT`.

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### Valid Usage

- **VUID-VkImageMemoryBarrier-oldLayout-01208**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01209**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01210**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01211**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_SAMPLED_BIT` or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01212**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_SRC_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01213**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT`

- **VUID-VkImageMemoryBarrier-oldLayout-01197**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, `oldLayout` must be `VK_IMAGE_LAYOUT_UNDEFINED` or the current layout of the image subresources affected by the barrier

- **VUID-VkImageMemoryBarrier-newLayout-01198**
  If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, `newLayout` must not be
VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

- VUID-VkImageMemoryBarrier-oldLayout-01658
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

- VUID-VkImageMemoryBarrier-oldLayout-01659
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

- VUID-VkImageMemoryBarrier-srcQueueFamilyIndex-04065
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL then image must have been created with at least one of VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_SAMPLED_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

- VUID-VkImageMemoryBarrier-srcQueueFamilyIndex-04066
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_ATTACHMENT_BIT set

- VUID-VkImageMemoryBarrier-srcQueueFamilyIndex-04067
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then image must have been created with at least one of VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_SAMPLED_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

- VUID-VkImageMemoryBarrier-srcQueueFamilyIndex-04068
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL then image must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT set

- VUID-VkImageMemoryBarrier-synchronization2-07793
  If the synchronization2 feature is not enabled, oldLayout must not be VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL_KHR or VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR

- VUID-VkImageMemoryBarrier-synchronization2-07794
  If the synchronization2 feature is not enabled, newLayout must not be VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL_KHR or VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR

- VUID-VkImageMemoryBarrier-srcQueueFamilyIndex-03938
  If srcQueueFamilyIndex and dstQueueFamilyIndex define a queue family ownership transfer or oldLayout and newLayout define an image layout transition, and oldLayout or newLayout is VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL, image must have been created with VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT or VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
If `srcQueueFamilyIndex` and `dstQueueFamilyIndex` define a queue family ownership transfer or `oldLayout` and `newLayout` define an image layout transition, and `oldLayout` or `newLayout` is

\[ VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL, \]

image must have been created with at least one of

\[ VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_SAMPLED_BIT, \]

or

\[ VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT \]

If `image` was created with a sharing mode of \[ VK_SHARING_MODE_EXCLUSIVE, \]

and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are equal, `srcQueueFamilyIndex` must be

\[ VK_QUEUE_FAMILY_EXTERNAL, \]

or a valid queue family.

If `image` was created with a sharing mode of \[ VK_SHARING_MODE_EXCLUSIVE, \]

and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not equal, `srcQueueFamilyIndex` must be

\[ VK_QUEUE_FAMILY_EXTERNAL, \]

or a valid queue family.

If `image` was created with a sharing mode of \[ VK_SHARING_MODE_EXCLUSIVE, \]

and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not equal, `dstQueueFamilyIndex` must be

\[ VK_QUEUE_FAMILY_EXTERNAL, \]

or a valid queue family.

If `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, at least one of `srcQueueFamilyIndex` or `dstQueueFamilyIndex` must not be

\[ VK_QUEUE_FAMILY_EXTERNAL \]

If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is not greater than or equal to Version 1.1, `srcQueueFamilyIndex` must not be

\[ VK_QUEUE_FAMILY_EXTERNAL \]

If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is not greater than or equal to Version 1.1, `dstQueueFamilyIndex` must not be

\[ VK_QUEUE_FAMILY_EXTERNAL \]

If `subresourceRange.baseMipLevel` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.

If `subresourceRange.levelCount` is not `VK_REMAINING_MIP_LEVELS`, `subresourceRange.baseMipLevel + subresourceRange.levelCount` must be less than or equal to the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.

If `subresourceRange.baseArrayLayer` must be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

If `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, `subresourceRange.baseArrayLayer + subresourceRange.layerCount` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

If `image` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

If `image` has a single-plane color format or is not disjoint, then the `aspectMask` member of `subresourceRange` must be `VK_IMAGE_ASPECT_COLOR_BIT`
If `image` has a multi-planar format and the image is `disjoint`, then the `aspectMask` member of `subresourceRange` must include at least one multi-planar aspect mask or `VK_IMAGE_ASPECT_COLOR_BIT`.

If `image` has a depth/stencil format with both depth and stencil and the `separateDepthStencilLayouts` feature is enabled, then the `aspectMask` member of `subresourceRange` must include either or both `VK_IMAGE_ASPECT_DEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT`.

If `image` has a depth/stencil format with both depth and stencil and the `separateDepthStencilLayouts` feature is not enabled, then the `aspectMask` member of `subresourceRange` must include both `VK_IMAGE_ASPECT_DEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT`.

If the `aspectMask` member of `subresourceRange` includes `VK_IMAGE_ASPECT_DEPTH_BIT`, `oldLayout` and `newLayout` must not be one of `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`.

If the `aspectMask` member of `subresourceRange` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, `oldLayout` and `newLayout` must not be one of `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`.

If `image` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, at least one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED`.

If `image` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, `srcQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED` or `VK_QUEUE_FAMILY_EXTERNAL`.

If `image` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED` or `VK_QUEUE_FAMILY_EXTERNAL`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER`.
- `pNext` must be `NULL`.
- `oldLayout` must be a valid `VkImageLayout` value.
- `newLayout` must be a valid `VkImageLayout` value.
7.7.4. Queue Family Ownership Transfer

Resources created with a VkSharingMode of VK_SHARING_MODE_EXCLUSIVE must have their ownership explicitly transferred from one queue family to another in order to access their content in a well-defined manner on a queue in a different queue family.

The special queue family index VK_QUEUE_FAMILY_IGNORED indicates that a queue family parameter or member is ignored.

```c
#define VK_QUEUE_FAMILY_IGNORED (~0U)
```

Resources shared with external APIs or instances using external memory must also explicitly manage ownership transfers between local and external queues (or equivalent constructs in external APIs) regardless of the VkSharingMode specified when creating them.

The special queue family index VK_QUEUE_FAMILY_EXTERNAL represents any queue external to the resource's current Vulkan instance, as long as the queue uses the same underlying device group or physical device, and the same driver version as the resource's VkDevice, as indicated by VkPhysicalDeviceIDProperties::deviceUUID and VkPhysicalDeviceIDProperties::driverUUID.

```c
#define VK_QUEUE_FAMILY_EXTERNAL (~1U)
```

If memory dependencies are correctly expressed between uses of such a resource between two queues in different families, but no ownership transfer is defined, the contents of that resource are undefined for any read accesses performed by the second queue family.

**Note**

If an application does not need the contents of a resource to remain valid when transferring from one queue family to another, then the ownership transfer should be skipped.

A queue family ownership transfer consists of two distinct parts:

1. Release exclusive ownership from the source queue family
2. Acquire exclusive ownership for the destination queue family

An application must ensure that these operations occur in the correct order by defining an execution dependency between them, e.g. using a semaphore.

A release operation is used to release exclusive ownership of a range of a buffer or image
A release operation is defined by executing a buffer memory barrier (for a buffer range) or an image memory barrier (for an image subresource range) using a pipeline barrier command, on a queue from the source queue family. The srcQueueFamilyIndex parameter of the barrier must be set to the source queue family index, and the dstQueueFamilyIndex parameter to the destination queue family index. The release operation happens-after the availability operation, and happens-before operations specified in the second synchronization scope of the calling command.

An acquire operation is used to acquire exclusive ownership of a range of a buffer or image subresource range. An acquire operation is defined by executing a buffer memory barrier (for a buffer range) or an image memory barrier (for an image subresource range) using a pipeline barrier command, on a queue from the destination queue family. The acquire operation specifies a buffer range or image subresource range that must match exactly that of a previous release operation. The srcQueueFamilyIndex parameter of the barrier must be set to the source queue family index, and the dstQueueFamilyIndex parameter to the destination queue family index. The acquire operation will happen-after operations in the first synchronization scope of the calling command, and happens-before the visibility operation.

**Note**

Whilst it is not invalid to provide destination or source access masks for memory barriers used for release or acquire operations, respectively, they have no practical effect. Access after a release operation has undefined results, and so visibility for those accesses has no practical effect. Similarly, write access before an acquire operation will produce undefined results for future access, so availability of those writes has no practical use. In an earlier version of the specification, these were required to match on both sides - but this was subsequently relaxed. These masks should be set to 0.

If the transfer is via an image memory barrier, and an image layout transition is desired, then the values of oldLayout and newLayout in the release operation's memory barrier must be equal to values of oldLayout and newLayout in the acquire operation's memory barrier. Although the image layout transition is submitted twice, it will only be executed once. A layout transition specified in this way happens-after the release operation and happens-before the acquire operation.

If the values of srcQueueFamilyIndex and dstQueueFamilyIndex are equal, no ownership transfer is performed, and the barrier operates as if they were both set to VK_QUEUE_FAMILY_IGNORED.

Queue family ownership transfers may perform read and write accesses on all memory bound to the image subresource or buffer range, so applications must ensure that all memory writes have been made available before a queue family ownership transfer is executed. Available memory is automatically made visible to queue family release and acquire operations, and writes performed by those operations are automatically made available.

Once a queue family has acquired ownership of a buffer range or image subresource range of a VK_SHARING_MODE_EXCLUSIVE resource, its contents are undefined to other queue families unless ownership is transferred. The contents of any portion of another resource which aliases memory
that is bound to the transferred buffer or image subresource range are undefined after a release or acquire operation.

Note
Because events cannot be used directly for inter-queue synchronization, and because vkCmdSetEvent does not have the queue family index or memory barrier parameters needed by a release operation, the release and acquire operations of a queue family ownership transfer can only be performed using vkCmdPipelineBarrier.

7.8. Wait Idle Operations

To wait on the host for the completion of outstanding queue operations for a given queue, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkQueueWaitIdle(
    VkQueue queue);
```

- `queue` is the queue on which to wait.

vkQueueWaitIdle is equivalent to having submitted a valid fence to every previously executed queue submission command that accepts a fence, then waiting for all of those fences to signal using vkWaitForFences with an infinite timeout and `waitAll` set to VK_TRUE.

Valid Usage (Implicit)

- VUID-vkQueueWaitIdle-queue-parameter
  queue must be a valid VkQueue handle

Host Synchronization

- Host access to queue must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
</table>

Return Codes

- Success
  - VK_SUCCESS
To wait on the host for the completion of outstanding queue operations for all queues on a given logical device, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkDeviceWaitIdle(
    VkDevice device);
```

- `device` is the logical device to idle.

`vkDeviceWaitIdle` is equivalent to calling `vkQueueWaitIdle` for all queues owned by `device`.

### Valid Usage (Implicit)
- VUID-vkDeviceWaitIdle-device-parameter
  device must be a valid VkDevice handle

### Host Synchronization
- Host access to all `VkQueue` objects created from `device` must be externally synchronized

### Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

---

### 7.9. Host Write Ordering Guarantees

When batches of command buffers are submitted to a queue via a queue submission command, it defines a memory dependency with prior host operations, and execution of command buffers submitted to the queue.

The first synchronization scope includes execution of `vkQueueSubmit` on the host and anything
that happened-before it, as defined by the host memory model.

Note

Some systems allow writes that do not directly integrate with the host memory model; these have to be synchronized by the application manually. One example of this is non-temporal store instructions on x86; to ensure these happen-before submission, applications should call `_mm_sfence()`.

The second synchronization scope includes all commands submitted in the same queue submission, and all commands that occur later in submission order.

The first access scope includes all host writes to mappable device memory that are available to the host memory domain.

The second access scope includes all memory access performed by the device.

7.10. Synchronization and Multiple Physical Devices

If a logical device includes more than one physical device, then fences, semaphores, and events all still have a single instance of the signaled state.

A fence becomes signaled when all physical devices complete the necessary queue operations.

Semaphore wait and signal operations all include a device index that is the sole physical device that performs the operation. These indices are provided in the `VkDeviceGroupSubmitInfo` and `VkDeviceGroupBindSparseInfo` structures. Semaphores are not exclusively owned by any physical device. For example, a semaphore can be signaled by one physical device and then waited on by a different physical device.

An event can only be waited on by the same physical device that signaled it (or the host).
Chapter 8. Render Pass

Draw commands **must** be recorded within a *render pass instance*. Each render pass instance defines a set of image resources, referred to as *attachments*, used during rendering.

To begin a render pass instance, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdBeginRendering(
    VkCommandBuffer commandBuffer,
    const VkRenderingInfo* pRenderingInfo);
```

- *commandBuffer* is the command buffer in which to record the command.
- *pRenderingInfo* is a pointer to a *VkRenderingInfo* structure specifying details of the render pass instance to begin.

After beginning a render pass instance, the command buffer is ready to record draw commands.

If *pRenderingInfo->flags* includes *VK_RENDERING_RESUMING_BIT* then this render pass is resumed from a render pass instance that has been suspended earlier in submission order.

**Valid Usage**

- VUID-vkCmdBeginRendering-dynamicRendering-06446
  The *dynamicRendering* feature **must** be enabled

- VUID-vkCmdBeginRendering-commandBuffer-06068
  If *commandBuffer* is a secondary command buffer, *pRenderingInfo->flags* **must** not include *VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT*

**Valid Usage (Implicit)**

- VUID-vkCmdBeginRendering-commandBuffer-parameter
  *commandBuffer* **must** be a valid *VkCommandBuffer* handle

- VUID-vkCmdBeginRendering-pRenderingInfo-parameter
  *pRenderingInfo* **must** be a valid pointer to a valid *VkRenderingInfo* structure

- VUID-vkCmdBeginRendering-commandBuffer-recording
  *commandBuffer* **must** be in the *recording state*

- VUID-vkCmdBeginRendering-commandBuffer-cmdpool
  The *VkCommandPool* that *commandBuffer* was allocated from **must** support graphics operations

- VUID-vkCmdBeginRendering-renderpass
  This command **must** only be called outside of a render pass instance
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Action State</td>
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<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkRenderingInfo structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkRenderingInfo {
    VkStructureType sType;
    const void* pNext;
    VkRenderingFlags flags;
    VkRect2D renderArea;
    uint32_t layerCount;
    uint32_t viewMask;
    uint32_t colorAttachmentCount;
    const VkRenderingAttachmentInfo* pColorAttachments;
    const VkRenderingAttachmentInfo* pDepthAttachment;
    const VkRenderingAttachmentInfo* pStencilAttachment;
} VkRenderingInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkRenderingFlagBits.
- renderArea is the render area that is affected by the render pass instance.
- layerCount is the number of layers rendered to in each attachment when viewMask is 0.
- viewMask is the view mask indicating the indices of attachment layers that will be rendered when it is not 0.
- colorAttachmentCount is the number of elements in pColorAttachments.
- pColorAttachments is a pointer to an array of colorAttachmentCount VkRenderingAttachmentInfo structures describing any color attachments used.
- pDepthAttachment is a pointer to a VkRenderingAttachmentInfo structure describing a depth attachment.
• **pStencilAttachment** is a pointer to a VkRenderingAttachmentInfo structure describing a stencil attachment.

If **viewMask** is not 0, multiview is enabled.

If there is an instance of VkDeviceGroupRenderPassBeginInfo included in the **pNext** chain and its **deviceRenderAreaCount** member is not 0, then **renderArea** is ignored, and the render area is defined per-device by that structure.

Each element of the **pColorAttachments** array corresponds to an output location in the shader, i.e. if the shader declares an output variable decorated with a **Location** value of X, then it uses the attachment provided in **pColorAttachments[X]**. If the **imageView** member of any element of **pColorAttachments** is **VK_NULL_HANDLE**, writes to the corresponding location by a fragment are discarded.

---

**Valid Usage**

- **VUID-VkRenderingInfo-viewMask-06069**
  If **viewMask** is 0, **layerCount must not** be 0.

- **VUID-VkRenderingInfo-multisampledRenderToSingleSampled-06857**
  If none of the **VK_AMD_mixed_attachment_samples** extension, the **VK_NV_framebuffer_mixed_samples** extension, or the **multisampledRenderToSingleSampled** feature are enabled, **imageView members of pDepthAttachment, pStencilAttachment, and elements of pColorAttachments that are not VK_NULL_HANDLE must have been created with the same sampleCount.**

- **VUID-VkRenderingInfo-None-08994**
  If **VkDeviceGroupRenderPassBeginInfo::deviceRenderAreaCount** is 0, **renderArea.extent.width must be greater than 0**.

- **VUID-VkRenderingInfo-None-08995**
  If **VkDeviceGroupRenderPassBeginInfo::deviceRenderAreaCount** is 0, **renderArea.extent.height must be greater than 0**.

- **VUID-VkRenderingInfo-pNext-06077**
  If the **pNext** chain does not contain **VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount membership is equal to 0, renderArea.offset.x must be greater than or equal to 0**.

- **VUID-VkRenderingInfo-pNext-06078**
  If the **pNext** chain does not contain **VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount membership is equal to 0, renderArea.offset.y must be greater than or equal to 0**.

- **VUID-VkRenderingInfo-pNext-07815**
  If the **pNext** chain does not contain **VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount membership is equal to 0, the sum of renderArea.extent.width and renderArea.offset.x must be less than or equal to maxFramebufferWidth.**

- **VUID-VkRenderingInfo-pNext-07816**
  If the **pNext** chain does not contain **VkDeviceGroupRenderPassBeginInfo or its...**
deviceRenderAreaCount member is equal to 0, the sum of renderArea.extent.height and renderArea.offset.y must be less than or equal to maxFramebufferHeight

- VUID-VkRenderingInfo-pNext-06079
  If the pNext chain does not contain VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount member is equal to 0, the width of the imageView member of any element of pColorAttachments, pDepthAttachment, or pStencilAttachment that is not VK_NULL_HANDLE must be greater than or equal to renderArea.offset.x + renderArea.extent.width

- VUID-VkRenderingInfo-pNext-06080
  If the pNext chain does not contain VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount member is equal to 0, the height of the imageView member of any element of pColorAttachments, pDepthAttachment, or pStencilAttachment that is not VK_NULL_HANDLE must be greater than or equal to renderArea.offset.y + renderArea.extent.height

- VUID-VkRenderingInfo-pNext-06083
  If the pNext chain contains VkDeviceGroupRenderPassBeginInfo, the width of the imageView member of any element of pColorAttachments, pDepthAttachment, or pStencilAttachment that is not VK_NULL_HANDLE must be greater than or equal to the sum of the offset.x and extent.width members of each element of pDeviceRenderAreas

- VUID-VkRenderingInfo-pNext-06084
  If the pNext chain contains VkDeviceGroupRenderPassBeginInfo, the height of the imageView member of any element of pColorAttachments, pDepthAttachment, or pStencilAttachment that is not VK_NULL_HANDLE must be greater than or equal to the sum of the offset.y and extent.height members of each element of pDeviceRenderAreas

- VUID-VkRenderingInfo-pDepthAttachment-06085
  If neither pDepthAttachment or pStencilAttachment are NULL and the imageView member of either structure is not VK_NULL_HANDLE, the imageView member of each structure must be the same

- VUID-VkRenderingInfo-pDepthAttachment-06086
  If neither pDepthAttachment or pStencilAttachment are NULL, and the resolveMode member of each is not VK_RESOLVE_MODE_NONE, the resolveImageView member of each structure must be the same

- VUID-VkRenderingInfo-colorAttachmentCount-06087
  If colorAttachmentCount is not 0 and the imageView member of an element of pColorAttachments is not VK_NULL_HANDLE, that imageView must have been created with VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT

- VUID-VkRenderingInfo-pDepthAttachment-06547
  If pDepthAttachment is not NULL and pDepthAttachment->imageView is not VK_NULL_HANDLE, pDepthAttachment->imageView must have been created with a format that includes a depth component

- VUID-VkRenderingInfo-pDepthAttachment-06088
  If pDepthAttachment is not NULL and pDepthAttachment->imageView is not VK_NULL_HANDLE, pDepthAttachment->imageView must have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
- **VUID-VkRenderingInfo-pStencilAttachment-06548**
  If `pStencilAttachment` is not `NULL` and `pStencilAttachment->imageView` is not `VK_NULL_HANDLE`, `pStencilAttachment->imageView` must have been created with a format that includes a stencil aspect.

- **VUID-VkRenderingInfo-pStencilAttachment-06089**
  If `pStencilAttachment` is not `NULL` and `pStencilAttachment->imageView` is not `VK_NULL_HANDLE`, `pStencilAttachment->imageView` must have been created with a stencil usage including `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- **VUID-VkRenderingInfo-colorAttachmentCount-06090**
  If `colorAttachmentCount` is not `0` and the `imageView` member of an element of `pColorAttachments` is not `VK_NULL_HANDLE`, the layout member of that element of `pColorAttachments` must not be `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`.

- **VUID-VkRenderingInfo-colorAttachmentCount-06091**
  If `colorAttachmentCount` is not `0` and the `imageView` member of an element of `pColorAttachments` is not `VK_NULL_HANDLE`, if the `resolveMode` member of that element of `pColorAttachments` is not `VK_RESOLVE_MODE_NONE`, its `resolveImageLayout` member must not be `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`.

- **VUID-VkRenderingInfo-pDepthAttachment-06092**
  If `pDepthAttachment` is not `NULL` and `pDepthAttachment->imageView` is not `VK_NULL_HANDLE`, `pDepthAttachment->layout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`.

- **VUID-VkRenderingInfo-pDepthAttachment-06093**
  If `pDepthAttachment` is not `NULL`, `pDepthAttachment->imageView` is not `VK_NULL_HANDLE`, and `pDepthAttachment->resolveMode` is not `VK_RESOLVE_MODE_NONE`, `pDepthAttachment->resolveImageLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`.

- **VUID-VkRenderingInfo-pStencilAttachment-06094**
  If `pStencilAttachment` is not `NULL` and `pStencilAttachment->imageView` is not `VK_NULL_HANDLE`, `pStencilAttachment->layout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`.

- **VUID-VkRenderingInfo-pStencilAttachment-06095**
  If `pStencilAttachment` is not `NULL`, `pStencilAttachment->imageView` is not `VK_NULL_HANDLE`, and `pStencilAttachment->resolveMode` is not `VK_RESOLVE_MODE_NONE`, `pStencilAttachment->resolveImageLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`.

- **VUID-VkRenderingInfo-colorAttachmentCount-06096**
  If `colorAttachmentCount` is not `0` and the `imageView` member of an element of `pColorAttachments` is not `VK_NULL_HANDLE`, the layout member of that element of `pColorAttachments` must not be `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`.

- **VUID-VkRenderingInfo-colorAttachmentCount-06097**
  If `colorAttachmentCount` is not `0` and the `imageView` member of an element of `pColorAttachments` is not `VK_NULL_HANDLE`, if the `resolveMode` member of that element of `pColorAttachments` is not `VK_RESOLVE_MODE_NONE`, its `resolveImageLayout` member must not be
If \texttt{pDepthAttachment} is not \texttt{NULL}, \texttt{pDepthAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, and \texttt{pDepthAttachment->resolveMode} is not \texttt{VK_RESOLVE_MODE_NONE}, \texttt{pDepthAttachment->resolveImageLayout} must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL}.

If \texttt{pStencilAttachment} is not \texttt{NULL}, \texttt{pStencilAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, and \texttt{pStencilAttachment->resolveMode} is not \texttt{VK_RESOLVE_MODE_NONE}, \texttt{pStencilAttachment->resolveImageLayout} must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{colorAttachmentCount} is not \texttt{0} and the \texttt{imageView} member of an element of \texttt{pColorAttachments} is not \texttt{VK_NULL_HANDLE}, the layout member of that element of \texttt{pColorAttachments} must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL}, or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{colorAttachmentCount} is not \texttt{0} and the \texttt{imageView} member of an element of \texttt{pColorAttachments} is not \texttt{VK_NULL_HANDLE}, if the \texttt{resolveMode} member of that element of \texttt{pColorAttachments} is not \texttt{VK_RESOLVE_MODE_NONE}, its \texttt{resolveImageLayout} member must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL}, or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pDepthAttachment} is not \texttt{NULL} and \texttt{pDepthAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, \texttt{pDepthAttachment->layout} must not be \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pDepthAttachment} is not \texttt{NULL} and \texttt{pDepthAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, and \texttt{pDepthAttachment->resolveMode} is not \texttt{VK_RESOLVE_MODE_NONE}, \texttt{pDepthAttachment->resolveImageLayout} must not be \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pStencilAttachment} is not \texttt{NULL} and \texttt{pStencilAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, \texttt{pStencilAttachment->layout} must not be \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pStencilAttachment} is not \texttt{NULL} and \texttt{pStencilAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, and \texttt{pStencilAttachment->resolveMode} is not \texttt{VK_RESOLVE_MODE_NONE}, \texttt{pStencilAttachment->resolveImageLayout} must not be \texttt{VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pDepthAttachment} is not \texttt{NULL} and \texttt{pDepthAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, \texttt{pDepthAttachment->layout} must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL}.

If \texttt{pStencilAttachment} is not \texttt{NULL} and \texttt{pStencilAttachment->imageView} is not \texttt{VK_NULL_HANDLE}, and \texttt{pStencilAttachment->resolveMode} is not \texttt{VK_RESOLVE_MODE_NONE}, \texttt{pStencilAttachment->resolveImageLayout} must not be \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL} or \texttt{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL}.
If pDepthAttachment is not NULL and pDepthAttachment->imageView is not VK_NULL_HANDLE, pDepthAttachment->resolveMode must be one of the bits set in VkPhysicalDeviceDepthStencilResolveProperties::supportedDepthResolveModes

- VUID-VkRenderingInfo-pStencilAttachment-06103
  If pStencilAttachment is not NULL and pStencilAttachment->imageView is not VK_NULL_HANDLE, pStencilAttachment->resolveMode must be one of the bits set in VkPhysicalDeviceDepthStencilResolveProperties::supportedStencilResolveModes

- VUID-VkRenderingInfo-pDepthAttachment-06104
  If pDepthAttachment or pStencilAttachment are both not NULL, pDepthAttachment->imageView and pStencilAttachment->imageView are both not VK_NULL_HANDLE, and VkPhysicalDeviceDepthStencilResolveProperties::independentResolveNone is VK_FALSE, the resolveMode of both structures must be the same value

- VUID-VkRenderingInfo-pDepthAttachment-06105
  If pDepthAttachment or pStencilAttachment are both not NULL, pDepthAttachment->imageView and pStencilAttachment->imageView are both not VK_NULL_HANDLE, VkPhysicalDeviceDepthStencilResolveProperties::independentResolve is VK_FALSE, and the resolveMode of neither structure is VK_RESOLVE_MODE_NONE, the resolveMode of both structures must be the same value

- VUID-VkRenderingInfo-colorAttachmentCount-06106
  colorAttachmentCount must be less than or equal to VkPhysicalDeviceLimits::maxColorAttachments

- VUID-VkRenderingInfo-multiview-06127
  If the multiview feature is not enabled, viewMask must be 0

- VUID-VkRenderingInfo-viewMask-06128
  The index of the most significant bit in viewMask must be less than maxMultiviewViewCount

- VUID-VkRenderingInfo-None-09044
  Valid attachments specified by this structure must not be bound to memory locations that are bound to any other valid attachments specified by this structure

Valid Usage (Implicit)

- VUID-VkRenderingInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_RENDERING_INFO

- VUID-VkRenderingInfo-pNext-pNext
  pNext must be NULL or a pointer to a valid instance of VkDeviceGroupRenderPassBeginInfo

- VUID-VkRenderingInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

- VUID-VkRenderingInfo-flags-parameter
  flags must be a valid combination of VkRenderingFlagBits values

- VUID-VkRenderingInfo-pColorAttachments-parameter
  If colorAttachmentCount is not 0, pColorAttachments must be a valid pointer to an array of colorAttachmentCount valid VkRenderingAttachmentInfo structures
If `pDepthAttachment` is not NULL, `pDepthAttachment` must be a valid pointer to a valid `VkRenderingAttachmentInfo` structure.

If `pStencilAttachment` is not NULL, `pStencilAttachment` must be a valid pointer to a valid `VkRenderingAttachmentInfo` structure.

Bits which can be set in `VkRenderingInfo::flags` describing additional properties of the render pass are:

```c
// Provided by VK_VERSION_1_3
typedef enum VkRenderingFlagBits {
    VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT = 0x00000001,
    VK_RENDERING_SUSPENDING_BIT = 0x00000002,
    VK_RENDERING_RESUMING_BIT = 0x00000004,
    VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT_KHR = VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT,
    VK_RENDERING_SUSPENDING_BIT_KHR = VK_RENDERING_SUSPENDING_BIT,
    VK_RENDERING_RESUMING_BIT_KHR = VK_RENDERING_RESUMING_BIT
} VkRenderingFlagBits;
```

- `VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT` specifies that draw calls for the render pass instance will be recorded in secondary command buffers.
- `VK_RENDERING_RESUMING_BIT` specifies that the render pass instance is resuming an earlier suspended render pass instance.
- `VK_RENDERING_SUSPENDING_BIT` specifies that the render pass instance will be suspended.

The contents of `pRenderingInfo` must match between suspended render pass instances and the render pass instances that resume them, other than the presence or absence of the `VK_RENDERING_RESUMING_BIT`, `VK_RENDERING_SUSPENDING_BIT`, and `VK_RENDERING_CONTENTS_SECONDARY_COMMAND_BUFFERS_BIT` flags. No action or synchronization commands, or other render pass instances, are allowed between suspending and resuming render pass instances.

```c
// Provided by VK_VERSION_1_3
typedef VkFlags VkRenderingFlags;
```

`VkRenderingFlags` is a bitmask type for setting a mask of zero or more `VkRenderingFlagBits`.

The `VkRenderingAttachmentInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkRenderingAttachmentInfo {
    VkStructureType sType;
    const void* pNext;
};
```


```c
VkImageView imageView;
VkImageLayout imageLayout;
VkResolveModeFlagBits resolveMode;
VkImageView resolveImageView;
VkImageLayout resolveImageLayout;
VkAttachmentLoadOp loadOp;
VkAttachmentStoreOp storeOp;
VkClearValue clearValue;
} VkRenderingAttachmentInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **imageView** is the image view that will be used for rendering.
- **imageLayout** is the layout that **imageView** will be in during rendering.
- **resolveMode** is a VkResolveModeFlagBits value defining how multisampled data written to **imageView** will be resolved.
- **resolveImageView** is an image view used to write resolved multisample data at the end of rendering.
- **resolveImageLayout** is the layout that **resolveImageView** will be in during rendering.
- **loadOp** is a VkAttachmentLoadOp value defining the load operation for the attachment.
- **storeOp** is a VkAttachmentStoreOp value defining the store operation for the attachment.
- **clearValue** is a VkClearValue structure defining values used to clear **imageView** when **loadOp** is VK_ATTACHMENT_LOAD_OP_CLEAR.

Values in **imageView** are loaded and stored according to the values of **loadOp** and **storeOp**, within the render area for each device specified in VkRenderingInfo. If **imageView** is VK_NULL_HANDLE, other members of this structure are ignored; writes to this attachment will be discarded, and no load, store, or multisample resolve operations will be performed.

If **resolveMode** is VK_RESOLVE_MODE_NONE, then **resolveImageView** is ignored. If **resolveMode** is not VK_RESOLVE_MODE_NONE, and **resolveImageView** is not VK_NULL_HANDLE, a render pass multisample resolve operation is defined for the attachment subresource.

**Note**

The resolve mode and store operation are independent; it is valid to write both resolved and unresolved values, and equally valid to discard the unresolved values while writing the resolved ones.

Store and resolve operations are only performed at the end of a render pass instance that does not specify the VK_RENDERING_SUSPENDING_BIT_KHR flag.

Load operations are only performed at the beginning of a render pass instance that does not specify the VK_RENDERING_RESUMING_BIT_KHR flag.

Image contents at the end of a suspended render pass instance remain defined for access by a
Valid Usage

- **VUID-VkRenderingAttachmentInfo-imageView-06129**
  If `imageView` is not `VK_NULL_HANDLE` and has a non-integer color format, `resolveMode` must be `VK_RESOLVE_MODE_NONE` or `VK_RESOLVE_MODE_AVERAGE_BIT`.

- **VUID-VkRenderingAttachmentInfo-imageView-06130**
  If `imageView` is not `VK_NULL_HANDLE` and has an integer color format, `resolveMode` must be `VK_RESOLVE_MODE_NONE` or `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT`.

- **VUID-VkRenderingAttachmentInfo-imageView-06132**
  If `imageView` is not `VK_NULL_HANDLE` and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `imageView` must not have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- **VUID-VkRenderingAttachmentInfo-imageView-06860**
  If `imageView` is not `VK_NULL_HANDLE` and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `resolveImageView` must not be `VK_NULL_HANDLE`.

- **VUID-VkRenderingAttachmentInfo-imageView-06864**
  If `imageView` is not `VK_NULL_HANDLE`, `resolveImageView` is not `VK_NULL_HANDLE`, and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `resolveImageView` must have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- **VUID-VkRenderingAttachmentInfo-imageView-06865**
  If `imageView` is not `VK_NULL_HANDLE`, `resolveImageView` is not `VK_NULL_HANDLE`, and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `imageView` and `resolveImageView` must have the same `VkFormat`.

- **VUID-VkRenderingAttachmentInfo-imageView-06135**
  If `imageView` is not `VK_NULL_HANDLE`, `imageLayout` must not be `VK_IMAGE_LAYOUT_UNDEFINED`, `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL`, `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL`, or `VK_IMAGE_LAYOUT_PREINITIALIZED`.

- **VUID-VkRenderingAttachmentInfo-imageView-06136**
  If `imageView` is not `VK_NULL_HANDLE` and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `resolveImageView` must not be `VK_IMAGE_LAYOUT_UNDEFINED`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL`, `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL`, or `VK_IMAGE_LAYOUT_PREINITIALIZED`.

- **VUID-VkRenderingAttachmentInfo-imageView-06137**
  If `imageView` is not `VK_NULL_HANDLE` and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `resolveImageLayout` must not be `VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR`.

- **VUID-VkRenderingAttachmentInfo-imageView-06142**
  If `imageView` is not `VK_NULL_HANDLE` and `resolveMode` is not `VK_RESOLVE_MODE_NONE`, `resolveImageLayout` must not be `VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR`.
Valid Usage (Implicit)

- VUID-VkRenderingAttachmentInfo-sType-sType
  *sType* must be VK_STRUCTURE_TYPE_RENDERING_ATTACHMENT_INFO

- VUID-VkRenderingAttachmentInfo-pNext-pNext
  *pNext* must be NULL

- VUID-VkRenderingAttachmentInfo-imageView-parameter
  If *imageView* is not VK_NULL_HANDLE, *imageView* must be a valid VkImageView handle

- VUID-VkRenderingAttachmentInfo-imageLayout-parameter
  *imageLayout* must be a valid VkImageLayout value

- VUID-VkRenderingAttachmentInfo-resolveMode-parameter
  If *resolveMode* is not 0, *resolveMode* must be a valid VkResolveModeFlagBits value

- VUID-VkRenderingAttachmentInfo-resolveImageView-parameter
  If *resolveImageView* is not VK_NULL_HANDLE, *resolveImageView* must be a valid VkImageView handle

- VUID-VkRenderingAttachmentInfo-resolveImageLayout-parameter
  *resolveImageLayout* must be a valid VkImageLayout value

- VUID-VkRenderingAttachmentInfo-loadOp-parameter
  *loadOp* must be a valid VkAttachmentLoadOp value

- VUID-VkRenderingAttachmentInfo-storeOp-parameter
  *storeOp* must be a valid VkAttachmentStoreOp value

- VUID-VkRenderingAttachmentInfo-clearValue-parameter
  *clearValue* must be a valid VkClearColor union

- VUID-VkRenderingAttachmentInfo-commonparent
  Both of *imageView*, and *resolveImageView* that are valid handles of non-ignored parameters
  must have been created, allocated, or retrieved from the same VkDevice

To end a render pass instance, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdEndRendering(
    VkCommandBuffer commandBuffer);
```

- *commandBuffer* is the command buffer in which to record the command.

If the value of *pRenderingInfo-*flags used to begin this render pass instance included
VK_RENDERING_SUSPENDING_BIT, then this render pass is suspended and will be resumed later in
submission order.

Valid Usage

- VUID-vkCmdEndRendering-None-06161
The current render pass instance **must** have been begun with `vkCmdBeginRendering`

- **VUID-vkCmdEndRendering-commandBuffer-06162**
  The current render pass instance **must** have been begun in `commandBuffer`

- **VUID-vkCmdEndRendering-None-06999**
  If `vkCmdBeginQuery*` was called within the render pass, the corresponding `vkCmdEndQuery*` **must** have been called subsequently within the same subpass

### Valid Usage (Implicit)

- **VUID-vkCmdEndRendering-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle

- **VUID-vkCmdEndRendering-commandBuffer-recording**
  `commandBuffer` **must** be in the **recording** state

- **VUID-vkCmdEndRendering-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

- **VUID-vkCmdEndRendering-renderpass**
  This command **must** only be called inside of a render pass instance

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

### Command Properties

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**Note**

For more complex rendering graphs, it is possible to pre-define a static *render pass* object, which as well as allowing draw commands, allows the definition of framebuffer-local dependencies between multiple subpasses. These objects have a lot of setup cost compared to `vkCmdBeginRendering`, but use of subpass dependencies can confer important performance benefits on some devices.
8.1. Render Pass Objects

A render pass object represents a collection of attachments, subpasses, and dependencies between the subpasses, and describes how the attachments are used over the course of the subpasses.

Render passes are represented by `VkRenderPass` handles:

```cpp
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkRenderPass)
```

An **attachment description** describes the properties of an attachment including its format, sample count, and how its contents are treated at the beginning and end of each render pass instance.

A **subpass** represents a phase of rendering that reads and writes a subset of the attachments in a render pass. Rendering commands are recorded into a particular subpass of a render pass instance.

A **subpass description** describes the subset of attachments that is involved in the execution of a subpass. Each subpass can read from some attachments as **input attachments**, write to some as **color attachments** or **depth/stencil attachments**, and perform **multisample resolve operations** to **resolve attachments**. A subpass description can also include a set of **preserve attachments**, which are attachments that are not read or written by the subpass but whose contents **must** be preserved throughout the subpass.

A subpass uses an attachment if the attachment is a color, depth/stencil, resolve, depth/stencil resolve, or input attachment for that subpass (as determined by the `pColorAttachments`, `pDepthStencilAttachment`, `pResolveAttachments`, `VkSubpassDescriptionDepthStencilResolve::pDepthStencilResolveAttachment`, and `pInputAttachments` members of `VkSubpassDescription`, respectively). A subpass does not use an attachment if that attachment is preserved by the subpass. The **first use of an attachment** is in the lowest numbered subpass that uses that attachment. Similarly, the **last use of an attachment** is in the highest numbered subpass that uses that attachment.

The subpasses in a render pass all render to the same dimensions, and fragments for pixel (x,y,layer) in one subpass can only read attachment contents written by previous subpasses at that same (x,y,layer) location.

**Note**

By describing a complete set of subpasses in advance, render passes provide the implementation an opportunity to optimize the storage and transfer of attachment data between subpasses.

In practice, this means that subpasses with a simple framebuffer-space dependency may be merged into a single tiled rendering pass, keeping the attachment data on-chip for the duration of a render pass instance. However, it is also quite common for a render pass to only contain a single subpass.

**Subpass dependencies** describe execution and memory dependencies between subpasses.
A subpass dependency chain is a sequence of subpass dependencies in a render pass, where the source subpass of each subpass dependency (after the first) equals the destination subpass of the previous dependency.

Execution of subpasses may overlap or execute out of order with regards to other subpasses, unless otherwise enforced by an execution dependency. Each subpass only respects submission order for commands recorded in the same subpass, and the `vkCmdBeginRenderPass` and `vkCmdEndRenderPass` commands that delimit the render pass - commands within other subpasses are not included. This affects most other implicit ordering guarantees.

A render pass describes the structure of subpasses and attachments independent of any specific image views for the attachments. The specific image views that will be used for the attachments, and their dimensions, are specified in `VkFramebuffer` objects. Framebuffers are created with respect to a specific render pass that the framebuffer is compatible with (see Render Pass Compatibility). Collectively, a render pass and a framebuffer define the complete render target state for one or more subpasses as well as the algorithmic dependencies between the subpasses.

The various pipeline stages of the drawing commands for a given subpass may execute concurrently and/or out of order, both within and across drawing commands, whilst still respecting pipeline order. However for a given (x,y,layer,sample) sample location, certain per-sample operations are performed in rasterization order.

`VK_ATTACHMENT_UNUSED` is a constant indicating that a render pass attachment is not used.

```c
#define VK_ATTACHMENT_UNUSED ((-0U))
```

### 8.2. Render Pass Creation

To create a render pass, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateRenderPass(   VkDevice device,   const VkRenderPassCreateInfo* pCreateInfo,   const VkAllocationCallbacks* pAllocator,   VkRenderPass* pRenderPass);
```

- `device` is the logical device that creates the render pass.
- `pCreateInfo` is a pointer to a `VkRenderPassCreateInfo` structure describing the parameters of the render pass.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pRenderPass` is a pointer to a `VkRenderPass` handle in which the resulting render pass object is returned.
**Valid Usage (Implicit)**

- VUID-vkCreateRenderPass-device-parameter
  - `device` must be a valid `VkDevice` handle

- VUID-vkCreateRenderPass-pCreateInfo-parameter
  - `pCreateInfo` must be a valid pointer to a valid `VkRenderPassCreateInfo` structure

- VUID-vkCreateRenderPass-pAllocator-parameter
  - If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- VUID-vkCreateRenderPass-pRenderPass-parameter
  - `pRenderPass` must be a valid pointer to a `VkRenderPass` handle

**Return Codes**

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkRenderPassCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkRenderPassCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkRenderPassCreateFlags flags;
    uint32_t attachmentCount;
    const VkAttachmentDescription* pAttachments;
    uint32_t subpassCount;
    const VkSubpassDescription* pSubpasses;
    uint32_t dependencyCount;
    const VkSubpassDependency* pDependencies;
} VkRenderPassCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `attachmentCount` is the number of attachments used by this render pass.
- `pAttachments` is a pointer to an array of `attachmentCount` `VkAttachmentDescription` structures describing the attachments used by the render pass.
• **subpassCount** is the number of subpasses to create.
• **pSubpasses** is a pointer to an array of **subpassCount** **VkSubpassDescription** structures describing each subpass.
• **dependencyCount** is the number of memory dependencies between pairs of subpasses.
• **pDependencies** is a pointer to an array of **dependencyCount** **VkSubpassDependency** structures describing dependencies between pairs of subpasses.

**Note**
Care should be taken to avoid a data race here; if any subpasses access attachments with overlapping memory locations, and one of those accesses is a write, a subpass dependency needs to be included between them.

**Valid Usage**

• **VUID-VkRenderPassCreateInfo-attachment-00834**
  If the **attachment** member of any element of **pInputAttachments**, **pColorAttachments**, **pResolveAttachments** or **pDepthStencilAttachment**, or any element of **pPreserveAttachments** in any element of **pSubpasses** is not **VK_ATTACHMENT_UNUSED**, then it **must** be less than **attachmentCount**

• **VUID-VkRenderPassCreateInfo-pAttachments-00836**
  For any member of **pAttachments** with a **loadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment **must** not specify a **layout** equal to **VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL** or **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL**

• **VUID-VkRenderPassCreateInfo-pAttachments-02511**
  For any member of **pAttachments** with a **stencilLoadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment **must** not specify a **layout** equal to **VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL** or **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL**

• **VUID-VkRenderPassCreateInfo-pAttachments-01566**
  For any member of **pAttachments** with a **loadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment **must** not specify a **layout** equal to **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL**

• **VUID-VkRenderPassCreateInfo-pAttachments-01567**
  For any member of **pAttachments** with a **stencilLoadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment **must** not specify a **layout** equal to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL**

• **VUID-VkRenderPassCreateInfo-pNext-01926**
  If the **pNext** chain includes a **VkRenderPassInputAttachmentAspectCreateInfo** structure, the **subpass** member of each element of its **pAspectReferences** member **must** be less than **subpassCount**

• **VUID-VkRenderPassCreateInfo-pNext-01927**
  If the **pNext** chain includes a **VkRenderPassInputAttachmentAspectCreateInfo** structure,
the `inputAttachmentIndex` member of each element of its `pAspectReferences` member must be less than the value of `inputAttachmentCount` in the element of `pSubpasses` identified by its `subpass` member.

- **VUID-VkRenderPassCreateInfo-pNext-01963**
  If the `pNext` chain includes a `VkRenderPassInputAttachmentAspectCreateInfo` structure, for any element of the `pInputAttachments` member of any element of `pSubpasses` where the `attachment` member is not `VK_ATTACHMENT_UNUSED`, the `aspectMask` member of the corresponding element of `VkRenderPassInputAttachmentAspectCreateInfo`::`pAspectReferences` must only include aspects that are present in images of the format specified by the element of `pAttachments` at `attachment`.

- **VUID-VkRenderPassCreateInfo-pNext-01928**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, and its `subpassCount` member is not zero, that member must be equal to the value of `subpassCount`.

- **VUID-VkRenderPassCreateInfo-pNext-01929**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, if its `dependencyCount` member is not zero, it must be equal to `dependencyCount`.

- **VUID-VkRenderPassCreateInfo-pNext-01930**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, for each non-zero element of `pViewOffsets`, the `srcSubpass` and `dstSubpass` members of `pDependencies` at the same index must not be equal.

- **VUID-VkRenderPassCreateInfo-pNext-02512**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, for any element of `pDependencies` with a `dependencyFlags` member that does not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`, the corresponding element of the `pViewOffsets` member of that `VkRenderPassMultiviewCreateInfo` instance must be 0.

- **VUID-VkRenderPassCreateInfo-pNext-02513**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, elements of its `pViewMasks` member must either all be 0, or all not be 0.

- **VUID-VkRenderPassCreateInfo-pNext-02514**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, and each element of its `pViewMasks` member is 0, the `dependencyFlags` member of each element of `pDependencies` must not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

- **VUID-VkRenderPassCreateInfo-pNext-02515**
  If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, and each element of its `pViewMasks` member is 0, its `correlationMaskCount` member must be 0.

- **VUID-VkRenderPassCreateInfo-pDependencies-00837**
  For any element of `pDependencies`, if the `srcSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `srcStageMask` member of that dependency must be a pipeline stage supported by the `pipeline` identified by the `pipelineBindPoint` member of the source subpass.

- **VUID-VkRenderPassCreateInfo-pDependencies-00838**
  For any element of `pDependencies`, if the `dstSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `dstStageMask` member of that dependency must be a pipeline stage supported by the `pipeline` identified by the `pipelineBindPoint` member of the destination.
subpass

- VUID-VkRenderPassCreateInfo-pDependencies-06866
  For any element of \( p\text{Dependencies} \), if its \( \text{srcSubpass} \) is not \( \text{VK\_SUBPASS\_EXTERNAL} \), it must be less than \( \text{subpassCount} \)

- VUID-VkRenderPassCreateInfo-pDependencies-06867
  For any element of \( p\text{Dependencies} \), if its \( \text{dstSubpass} \) is not \( \text{VK\_SUBPASS\_EXTERNAL} \), it must be less than \( \text{subpassCount} \)

Valid Usage (Implicit)

- VUID-VkRenderPassCreateInfo-sType-sType
  \( s\text{Type} \) must be \( \text{VK\_STRUCTURE\_TYPE\_RENDER\_PASS\_CREATE\_INFO} \)

- VUID-VkRenderPassCreateInfo-pNext-pNext
  Each \( p\text{Next} \) member of any structure (including this one) in the \( p\text{Next} \) chain must be either \( \text{NULL} \) or a pointer to a valid instance of \( \text{VkRenderPassInputAttachmentAspectCreateInfo} \) or \( \text{VkRenderPassMultiviewCreateInfo} \)

- VUID-VkRenderPassCreateInfo-sType-unique
  The \( s\text{Type} \) value of each struct in the \( p\text{Next} \) chain must be unique

- VUID-VkRenderPassCreateInfo-flags-zerobitmask
  \( \text{flags} \) must be \( 0 \)

- VUID-VkRenderPassCreateInfo-pAttachments-parameter
  If \( \text{attachmentCount} \) is not \( 0 \), \( p\text{Attachments} \) must be a valid pointer to an array of \( \text{attachmentCount} \) valid \( \text{VkAttachmentDescription} \) structures

- VUID-VkRenderPassCreateInfo-pSubpasses-parameter
  \( p\text{Subpasses} \) must be a valid pointer to an array of \( \text{subpassCount} \) valid \( \text{VkSubpassDescription} \) structures

- VUID-VkRenderPassCreateInfo-pDependencies-parameter
  If \( \text{dependencyCount} \) is not \( 0 \), \( p\text{Dependencies} \) must be a valid pointer to an array of \( \text{dependencyCount} \) valid \( \text{VkSubpassDependency} \) structures

- VUID-VkRenderPassCreateInfo-subpassCount-arraylength
  \( \text{subpassCount} \) must be greater than \( 0 \)

Bits which can be set in \( \text{VkRenderPassCreateInfo::flags} \), describing additional properties of the render pass, are:

// Provided by VK\_VERSION\_1\_0
typedef enum VkRenderPassCreateFlagBits {
} VkRenderPassCreateFlagBits;

Note

All bits for this type are defined by extensions, and none of those extensions are
enabled in this build of the specification.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkRenderPassCreateFlags;
```

 VkRenderPassCreateFlags is a bitmask type for setting a mask of zero or more VkRenderPassCreateFlagBits.

If the VkRenderPassCreateInfo::pNext chain includes a VkRenderPassMultiviewCreateInfo structure, then that structure includes an array of view masks, view offsets, and correlation masks for the render pass.

The VkRenderPassMultiviewCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkRenderPassMultiviewCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t subpassCount;
    const uint32_t* pViewMasks;
    uint32_t dependencyCount;
    const int32_t* pViewOffsets;
    uint32_t correlationMaskCount;
    const uint32_t* pCorrelationMasks;
} VkRenderPassMultiviewCreateInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **subpassCount** is zero or the number of subpasses in the render pass.
- **pViewMasks** is a pointer to an array of subpassCount view masks, where each mask is a bitfield of view indices describing which views rendering is broadcast to in each subpass, when multiview is enabled. If subpassCount is zero, each view mask is treated as zero.
- **dependencyCount** is zero or the number of dependencies in the render pass.
- **pViewOffsets** is a pointer to an array of dependencyCount view offsets, one for each dependency. If dependencyCount is zero, each dependency’s view offset is treated as zero. Each view offset controls which views in the source subpass the views in the destination subpass depend on.
- **correlationMaskCount** is zero or the number of correlation masks.
- **pCorrelationMasks** is a pointer to an array of correlationMaskCount view masks indicating sets of views that **may** be more efficient to render concurrently.

When a subpass uses a non-zero view mask, multiview functionality is considered to be enabled. Multiview is all-or-nothing for a render pass - that is, either all subpasses **must** have a non-zero view mask (though some subpasses **may** have only one view) or all **must** be zero. Multiview causes all drawing and clear commands in the subpass to behave as if they were broadcast to each view,
where a view is represented by one layer of the framebuffer attachments. All draws and clears are broadcast to each view index whose bit is set in the view mask. The view index is provided in the ViewIndex shader input variable, and color, depth/stencil, and input attachments all read/write the layer of the framebuffer corresponding to the view index.

If the view mask is zero for all subpasses, multiview is considered to be disabled and all drawing commands execute normally, without this additional broadcasting.

Some implementations may not support multiview in conjunction with geometry shaders or tessellation shaders.

When multiview is enabled, the VK_DEPENDENCY_VIEW_LOCAL_BIT bit in a dependency can be used to express a view-local dependency, meaning that each view in the destination subpass depends on a single view in the source subpass. Unlike pipeline barriers, a subpass dependency can potentially have a different view mask in the source subpass and the destination subpass. If the dependency is view-local, then each view (dstView) in the destination subpass depends on the view dstView + pViewOffsets[dependency] in the source subpass. If there is not such a view in the source subpass, then this dependency does not affect that view in the destination subpass. If the dependency is not view-local, then all views in the destination subpass depend on all views in the source subpass, and the view offset is ignored. A non-zero view offset is not allowed in a self-dependency.

The elements of pCorrelationMasks are a set of masks of views indicating that views in the same mask may exhibit spatial coherency between the views, making it more efficient to render them concurrently. Correlation masks must not have a functional effect on the results of the multiview rendering.

When multiview is enabled, at the beginning of each subpass all non-render pass state is undefined. In particular, each time vkCmdBeginRenderPass or vkCmdNextSubpass is called the graphics pipeline must be bound, any relevant descriptor sets or vertex/index buffers must be bound, and any relevant dynamic state or push constants must be set before they are used.

### Valid Usage

- **VUID-VkRenderPassMultiviewCreateInfo-pCorrelationMasks-00841**
  Each view index must not be set in more than one element of pCorrelationMasks

- **VUID-VkRenderPassMultiviewCreateInfo-multiview-06555**
  If the multiview feature is not enabled, each element of pViewMasks must be 0

- **VUID-VkRenderPassMultiviewCreateInfo-pViewMasks-06697**
  The index of the most significant bit in each element of pViewMasks must be less than maxMultiviewViewCount

### Valid Usage (Implicit)

- **VUID-VkRenderPassMultiviewCreateInfo-sType-sType**
  sType must be VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO

- **VUID-VkRenderPassMultiviewCreateInfo-pViewMasks-parameter**
If `subpassCount` is not 0, `pViewMasks` must be a valid pointer to an array of `subpassCount` uint32_t values

- VUID-VkRenderPassMultiviewCreateInfo-pViewOffsets-parameter
  If `dependencyCount` is not 0, `pViewOffsets` must be a valid pointer to an array of `dependencyCount` int32_t values

- VUID-VkRenderPassMultiviewCreateInfo-pCorrelationMasks-parameter
  If `correlationMaskCount` is not 0, `pCorrelationMasks` must be a valid pointer to an array of `correlationMaskCount` uint32_t values

The **VkAttachmentDescription** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkAttachmentDescription {
    VkAttachmentDescriptionFlags flags;
    VkFormat format;
    VkSampleCountFlagBits samples;
    VkAttachmentLoadOp loadOp;
    VkAttachmentStoreOp storeOp;
    VkAttachmentLoadOp stencilLoadOp;
    VkAttachmentStoreOp stencilStoreOp;
    VkImageLayout initialLayout;
    VkImageLayout finalLayout;
} VkAttachmentDescription;
```

- `flags` is a bitmask of **VkAttachmentDescriptionFlagBits** specifying additional properties of the attachment.
- `format` is a **VkFormat** value specifying the format of the image view that will be used for the attachment.
- `samples` is a **VkSampleCountFlagBits** value specifying the number of samples of the image.
- `loadOp` is a **VkAttachmentLoadOp** value specifying how the contents of color and depth components of the attachment are treated at the beginning of the subpass where it is first used.
- `storeOp` is a **VkAttachmentStoreOp** value specifying how the contents of color and depth components of the attachment are treated at the end of the subpass where it is last used.
- `stencilLoadOp` is a **VkAttachmentLoadOp** value specifying how the contents of stencil components of the attachment are treated at the beginning of the subpass where it is first used.
- `stencilStoreOp` is a **VkAttachmentStoreOp** value specifying how the contents of stencil components of the attachment are treated at the end of the last subpass where it is used.
- `initialLayout` is the layout the attachment image subresource will be in when a render pass instance begins.
- `finalLayout` is the layout the attachment image subresource will be transitioned to when a render pass instance ends.

If the attachment uses a color format, then `loadOp` and `storeOp` are used, and `stencilLoadOp` and
Stencil store operations, `stencilStoreOp`, are ignored. If the format has depth and/or stencil components, `loadOp` and `storeOp` apply only to the depth data, while `stencilLoadOp` and `stencilStoreOp` define how the stencil data is handled. `loadOp` and `stencilLoadOp` define the load operations for the attachment. `storeOp` and `stencilStoreOp` define the store operations for the attachment. If an attachment is not used by any subpass, `loadOp`, `storeOp`, `stencilStoreOp`, and `stencilLoadOp` will be ignored for that attachment, and no load or store ops will be performed. However, any transition specified by `initialLayout` and `finalLayout` will still be executed.

If `flags` includes `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT`, then the attachment is treated as if it shares physical memory with another attachment in the same render pass. This information limits the ability of the implementation to reorder certain operations (like layout transitions and the `loadOp`) such that it is not improperly reordered against other uses of the same physical memory via a different attachment. This is described in more detail below.

If a render pass uses multiple attachments that alias the same device memory, those attachments must each include the `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` bit in their attachment description flags. Attachments aliasing the same memory occurs in multiple ways:

- Multiple attachments being assigned the same image view as part of framebuffer creation.
- Attachments using distinct image views that correspond to the same image subresource of an image.
- Attachments using views of distinct image subresources which are bound to overlapping memory ranges.

Note

Render passes must include subpass dependencies (either directly or via a subpass dependency chain) between any two subpasses that operate on the same attachment or aliasing attachments and those subpass dependencies must include execution and memory dependencies separating uses of the aliases, if at least one of those subpasses writes to one of the aliases. These dependencies must not include the `VK_DEPENDENCY_BY_REGION_BIT` if the aliases are views of distinct image subresources which overlap in memory.

Multiple attachments that alias the same memory must not be used in a single subpass. A given attachment index must not be used multiple times in a single subpass, with one exception: two subpass attachments can use the same attachment index if at least one use is as an input attachment and neither use is as a resolve or preserve attachment. In other words, the same view can be used simultaneously as an input and color or depth/stencil attachment, but must not be used as multiple color or depth/stencil attachments nor as resolve or preserve attachments.

If a set of attachments alias each other, then all except the first to be used in the render pass must use an `initialLayout` of `VK_IMAGE_LAYOUT_UNDEFINED`, since the earlier uses of the other aliases make their contents undefined. Once an alias has been used and a different alias has been used after it, the first alias must not be used in any later subpasses. However, an application can assign the same image view to multiple aliasing attachment indices, which allows that image view to be used multiple times even if other aliases are used in between.

Note
Once an attachment needs the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT bit, there **should** be no additional cost of introducing additional aliases, and using these additional aliases **may** allow more efficient clearing of the attachments on multiple uses via VK_ATTACHMENT_LOAD_OP_CLEAR.

### Valid Usage

- **VUID-VkAttachmentDescription-format-06698**
  
  format **must** not be VK_FORMAT_UNDEFINED

- **VUID-VkAttachmentDescription-format-06699**
  
  If format includes a color or depth component and loadOp is VK_ATTACHMENT_LOAD_OP_LOAD, then initialLayout **must** not be VK_IMAGE_LAYOUT_UNDEFINED

- **VUID-VkAttachmentDescription-finalLayout-00843**
  
  finalLayout must not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

- **VUID-VkAttachmentDescription-format-03280**
  
  If format is a color format, initialLayout **must** not be 
  
  VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or 
  
  VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription-format-03281**
  
  If format is a depth/stencil format, initialLayout **must** not be 
  
  VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription-format-03282**
  
  If format is a color format, finalLayout **must** not be 
  
  VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or 
  
  VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription-format-03283**
  
  If format is a depth/stencil format, finalLayout **must** not be 
  
  VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription-format-06487**
  
  If format is a color format, initialLayout **must** not be 
  
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or 
  
  VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription-format-06488**
  
  If format is a color format, finalLayout **must** not be 
  
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or 
  
  VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription-separateDepthStencilLayouts-03284**
  
  If the separateDepthStencilLayouts feature is not enabled, initialLayout **must** not be 
  
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, 
  
  VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or 
  
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription-separateDepthStencilLayouts-03285**
  
  If the separateDepthStencilLayouts feature is not enabled, finalLayout **must** not be
VUID-VkAttachmentDescription-format-03286
If format is a color format, initialLayout must not be
VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-03287
If format is a color format, finalLayout must not be
VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-06906
If format is a depth/stencil format which includes both depth and stencil components,
initialLayout must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-06907
If format is a depth/stencil format which includes both depth and stencil components,
finalLayout must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-03290
If format is a depth/stencil format which includes only the depth component,
initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-03291
If format is a depth/stencil format which includes only the depth component,
finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-samples-08745
samples must be a bit value that is set in imageCreateSampleCounts (as defined in Image Creation Limits) for the given format

VUID-VkAttachmentDescription-format-06700
If format includes a stencil component and stencilLoadOp is VK_ATTACHMENT_LOAD_OP_LOAD,
then initialLayout must not be VK_IMAGE_LAYOUT_UNDEFINED

VUID-VkAttachmentDescription-format-03292
If format is a depth/stencil format which includes only the stencil component,
initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,

VUID-VkAttachmentDescription-format-03293
If format is a depth/stencil format which includes only the stencil component,
finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL
• VUID-VkAttachmentDescription-format-06242
  If `format` is a depth/stencil format which includes both depth and stencil components,
  `initialLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`.

• VUID-VkAttachmentDescription-format-06243
  If `format` is a depth/stencil format which includes both depth and stencil components,
  `finalLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`.

**Valid Usage (Implicit)**

• VUID-VkAttachmentDescription-flags-parameter
  `flags` must be a valid combination of `VkAttachmentDescriptionFlagBits` values.

• VUID-VkAttachmentDescription-format-parameter
  `format` must be a valid `VkFormat` value.

• VUID-VkAttachmentDescription-samples-parameter
  `samples` must be a valid `VkSampleCountFlagBits` value.

• VUID-VkAttachmentDescription-loadOp-parameter
  `loadOp` must be a valid `VkAttachmentLoadOp` value.

• VUID-VkAttachmentDescription-storeOp-parameter
  `storeOp` must be a valid `VkAttachmentStoreOp` value.

• VUID-VkAttachmentDescription-stencilLoadOp-parameter
  `stencilLoadOp` must be a valid `VkAttachmentLoadOp` value.

• VUID-VkAttachmentDescription-stencilStoreOp-parameter
  `stencilStoreOp` must be a valid `VkAttachmentStoreOp` value.

• VUID-VkAttachmentDescription-initialLayout-parameter
  `initialLayout` must be a valid `VkImageLayout` value.

• VUID-VkAttachmentDescription-finalLayout-parameter
  `finalLayout` must be a valid `VkImageLayout` value.

Bits which **can** be set in `VkAttachmentDescription::flags`, describing additional properties of the attachment, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkAttachmentDescriptionFlagBits {
    VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT = 0x00000001,
} VkAttachmentDescriptionFlagBits;
```

• `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` specifies that the attachment aliases the same device memory as other attachments.
typedef VkFlags VkAttachmentDescriptionFlags;

VkAttachmentDescriptionFlags is a bitmask type for setting a mask of zero or more VkAttachmentDescriptionFlagBits.

The VkRenderPassInputAttachmentAspectCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkRenderPassInputAttachmentAspectCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t aspectReferenceCount;
    const VkInputAttachmentAspectReference* pAspectReferences;
} VkRenderPassInputAttachmentAspectCreateInfo;
```

- `sType` is a VkStructureType value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `aspectReferenceCount` is the number of elements in the `pAspectReferences` array.
- `pAspectReferences` is a pointer to an array of `aspectReferenceCount` VkInputAttachmentAspectReference structures containing a mask describing which aspect(s) can be accessed for a given input attachment within a given subpass.

To specify which aspects of an input attachment can be read, add a `VkRenderPassInputAttachmentAspectCreateInfo` structure to the `pNext` chain of the `VkRenderPassCreateInfo` structure:

An application can access any aspect of an input attachment that does not have a specified aspect mask in the `pAspectReferences` array. Otherwise, an application must not access aspect(s) of an input attachment other than those in its specified aspect mask.

**Valid Usage (Implicit)**

- VUID-VkRenderPassInputAttachmentAspectCreateInfo-sType-sType `sType` must be VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO
- VUID-VkRenderPassInputAttachmentAspectCreateInfo-pAspectReferences-parameter `pAspectReferences` must be a valid pointer to an array of `aspectReferenceCount` valid VkInputAttachmentAspectReference structures
- VUID-VkRenderPassInputAttachmentAspectCreateInfo-aspectReferenceCount-arraylength `aspectReferenceCount` must be greater than 0

The `VkInputAttachmentAspectReference` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkInputAttachmentAspectReference {
```
uint32_t subpass;
uint32_t inputAttachmentIndex;
VkImageAspectFlags aspectMask;
} VkInputAttachmentAspectReference;

- **subpass** is an index into the `pSubpasses` array of the parent `VkRenderPassCreateInfo` structure.
- **inputAttachmentIndex** is an index into the `pInputAttachments` of the specified subpass.
- **aspectMask** is a mask of which aspect(s) can be accessed within the specified subpass.

This structure specifies an aspect mask for a specific input attachment of a specific subpass in the render pass.

**subpass** and **inputAttachmentIndex** index into the render pass as:

```c
pCreateInfo->pSubpasses[subpass].pInputAttachments[inputAttachmentIndex]
```

### Valid Usage

- **VUID-VkInputAttachmentAspectReference-aspectMask-01964**
  - `aspectMask` must not include `VK_IMAGE_ASPECT_METADATA_BIT`

### Valid Usage (Implicit)

- **VUID-VkInputAttachmentAspectReference-aspectMask-parameter**
  - `aspectMask` must be a valid combination of `VkImageAspectFlagBits` values
- **VUID-VkInputAttachmentAspectReference-aspectMask-requiredbitmask**
  - `aspectMask` must not be 0

The **VkSubpassDescription** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSubpassDescription {
    VkSubpassDescriptionFlags flags;
    VkPipelineBindPoint pipelineBindPoint;
    uint32_t inputAttachmentCount;
    const VkAttachmentReference* pInputAttachments;
    uint32_t colorAttachmentCount;
    const VkAttachmentReference* pColorAttachments;
    const VkAttachmentReference* pResolveAttachments;
    const VkAttachmentReference* pDepthStencilAttachment;
    uint32_t preserveAttachmentCount;
    const uint32_t* pPreserveAttachments;
} VkSubpassDescription;
```
• `flags` is a bitmask of `VkSubpassDescriptionFlagBits` specifying usage of the subpass.

• `pipelineBindPoint` is a `VkPipelineBindPoint` value specifying the pipeline type supported for this subpass.

• `inputAttachmentCount` is the number of input attachments.

• `pInputAttachments` is a pointer to an array of `VkAttachmentReference` structures defining the input attachments for this subpass and their layouts.

• `colorAttachmentCount` is the number of color attachments.

• `pColorAttachments` is a pointer to an array of `colorAttachmentCount` `VkAttachmentReference` structures defining the color attachments for this subpass and their layouts.

• `pResolveAttachments` is `NULL` or a pointer to an array of `colorAttachmentCount` `VkAttachmentReference` structures defining the resolve attachments for this subpass and their layouts.

• `pDepthStencilAttachment` is a pointer to a `VkAttachmentReference` structure specifying the depth/stencil attachment for this subpass and its layout.

• `preserveAttachmentCount` is the number of preserved attachments.

• `pPreserveAttachments` is a pointer to an array of `preserveAttachmentCount` render pass attachment indices identifying attachments that are not used by this subpass, but whose contents must be preserved throughout the subpass.

Each element of the `pInputAttachments` array corresponds to an input attachment index in a fragment shader, i.e. if a shader declares an image variable decorated with a `InputAttachmentIndex` value of `X`, then it uses the attachment provided in `pInputAttachments[X]`. Input attachments must also be bound to the pipeline in a descriptor set. If the `attachment` member of any element of `pInputAttachments` is `VK_ATTACHMENT_UNUSED`, the application must not read from the corresponding input attachment index. Fragment shaders can use subpass input variables to access the contents of an input attachment at the fragment’s (x, y, layer) framebuffer coordinates.

Each element of the `pColorAttachments` array corresponds to an output location in the shader, i.e. if the shader declares an output variable decorated with a `Location` value of `X`, then it uses the attachment provided in `pColorAttachments[X]`. If the `attachment` member of any element of `pColorAttachments` is `VK_ATTACHMENT_UNUSED`, then writes to the corresponding location by a fragment shader are discarded.

If `pResolveAttachments` is not `NULL`, each of its elements corresponds to a color attachment (the element in `pColorAttachments` at the same index), and a multisample resolve operation is defined for each attachment unless the resolve attachment index is `VK_ATTACHMENT_UNUSED`.

Similarly, if `VkSubpassDescriptionDepthStencilResolve::pDepthStencilResolveAttachment` is not `NULL` and does not have the value `VK_ATTACHMENT_UNUSED`, it corresponds to the depth/stencil attachment in `pDepthStencilAttachment`, and multisample resolve operation for depth and stencil are defined by `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` and `VkSubpassDescriptionDepthStencilResolve::stencilResolveMode`, respectively. If `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` is `VK_RESOLVE_MODE_NONE` or the `pDepthStencilResolveAttachment` does not have a depth aspect, no resolve operation is performed for the depth attachment. If `VkSubpassDescriptionDepthStencilResolve::stencilResolveMode` is
VK_RESOLVE_MODE_NONE or the pDepthStencilResolveAttachment does not have a stencil aspect, no resolve operation is performed for the stencil attachment.

If pDepthStencilAttachment is NULL, or if its attachment index is VK_ATTACHMENT_UNUSED, it indicates that no depth/stencil attachment will be used in the subpass.

The contents of an attachment within the render area become undefined at the start of a subpass S if all of the following conditions are true:

- The attachment is used as a color, depth/stencil, or resolve attachment in any subpass in the render pass.
- There is a subpass S₁ that uses or preserves the attachment, and a subpass dependency from S₁ to S.
- The attachment is not used or preserved in subpass S.

Once the contents of an attachment become undefined in subpass S, they remain undefined for subpasses in subpass dependency chains starting with subpass S until they are written again. However, they remain valid for subpasses in other subpass dependency chains starting with subpass S₁ if those subpasses use or preserve the attachment.

**Valid Usage**

- VUID-VkSubpassDescription-attachment-06912
  If the attachment member of an element of pInputAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL

- VUID-VkSubpassDescription-attachment-06913
  If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- VUID-VkSubpassDescription-attachment-06914
  If the attachment member of an element of pResolveAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- VUID-VkSubpassDescription-attachment-06915
  If the attachment member of pDepthStencilAttachment is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- VUID-VkSubpassDescription-attachment-06916
  If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- VUID-VkSubpassDescription-attachment-06917
  If the attachment member of an element of pResolveAttachments is not
VK_ATTACHMENT_UNUSED, its layout member must not be
VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or
VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- VUID-VkSubpassDescription-attachment-06918
  If the attachment member of an element of pInputAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL.

- VUID-VkSubpassDescription-attachment-06919
  If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL.

- VUID-VkSubpassDescription-attachment-06920
  If the attachment member of an element of pResolveAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL.

- VUID-VkSubpassDescription-pipelineBindPoint-00844
  pipelineBindPoint must be VK_PIPELINE_BIND_POINT_GRAPHICS.

- VUID-VkSubpassDescription-colorAttachmentCount-00845
  colorAttachmentCount must be less than or equal to VkPhysicalDeviceLimits::maxColorAttachments.

- VUID-VkSubpassDescription-loadOp-00846
  If the first use of an attachment in this render pass is as an input attachment, and the attachment is not also used as a color or depth/stencil attachment in the same subpass, then loadOp must not be VK_ATTACHMENT_LOAD_OP_CLEAR.

- VUID-VkSubpassDescription-pResolveAttachments-00847
  If pResolveAttachments is not NULL, for each resolve attachment that is not VK_ATTACHMENT_UNUSED, the corresponding color attachment must not be VK_ATTACHMENT_UNUSED.

- VUID-VkSubpassDescription-pResolveAttachments-00848
  If pResolveAttachments is not NULL, for each resolve attachment that is not VK_ATTACHMENT_UNUSED, the corresponding color attachment must not have a sample count of VK_SAMPLE_COUNT_1_BIT.

- VUID-VkSubpassDescription-pResolveAttachments-00849
  If pResolveAttachments is not NULL, each resolve attachment that is not VK_ATTACHMENT_UNUSED must have a sample count of VK_SAMPLE_COUNT_1_BIT.

- VUID-VkSubpassDescription-pResolveAttachments-00850
  If pResolveAttachments is not NULL, each resolve attachment that is not VK_ATTACHMENT_UNUSED must have the same VkFormat as its corresponding color attachment.

- VUID-VkSubpassDescription-pColorAttachments-06868
If neither the `VK_AMD_mixed_attachment_samples` extension nor the `VK_NV_framebuffer_mixed_samples` extension is enabled, all attachments in `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED` must have the same sample count.

- **VUID-VkSubpassDescription-pInputAttachments-02647**
  All attachments in `pInputAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain at least `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT` or `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- **VUID-VkSubpassDescription-pColorAttachments-02648**
  All attachments in `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

- **VUID-VkSubpassDescription-pResolveAttachments-02649**
  All attachments in `pResolveAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

- **VUID-VkSubpassDescription-pDepthStencilAttachment-02650**
  If `pDepthStencilAttachment` is not `NULL` and the attachment is not `VK_ATTACHMENT_UNUSED` then it must have an image format whose potential format features contain `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- **VUID-VkSubpassDescription-pDepthStencilAttachment-01418**
  If neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, and if `pDepthStencilAttachment` is not `VK_ATTACHMENT_UNUSED` and any attachments in `pColorAttachments` are not `VK_ATTACHMENT_UNUSED`, they must have the same sample count.

- **VUID-VkSubpassDescription-attachment-00853**
  Each element of `pPreserveAttachments` must not be `VK_ATTACHMENT_UNUSED`.

- **VUID-VkSubpassDescription-pPreserveAttachments-00854**
  Each element of `pPreserveAttachments` must not also be an element of any other member of the subpass description.

- **VUID-VkSubpassDescription-layout-02519**
  If any attachment is used by more than one `VkAttachmentReference` member, then each use must use the same layout.

- **VUID-VkSubpassDescription-pDepthStencilAttachment-04438**
  `pDepthStencilAttachment` and `pColorAttachments` must not contain references to the same attachment.

**Valid Usage (Implicit)**

- **VUID-VkSubpassDescription-flags-zerobitmask**
  Flags must be 0.

- **VUID-VkSubpassDescription-pipelineBindPoint-parameter**
  `pipelineBindPoint` must be a valid `VkPipelineBindPoint` value.
• **VUID-VkSubpassDescription-pInputAttachments-parameter**
  If `inputAttachmentCount` is not 0, `pInputAttachments` must be a valid pointer to an array of `inputAttachmentCount` valid `VkAttachmentReference` structures.

• **VUID-VkSubpassDescription-pColorAttachments-parameter**
  If `colorAttachmentCount` is not 0, `pColorAttachments` must be a valid pointer to an array of `colorAttachmentCount` valid `VkAttachmentReference` structures.

• **VUID-VkSubpassDescription-pResolveAttachments-parameter**
  If `colorAttachmentCount` is not 0, and `pResolveAttachments` is not NULL, `pResolveAttachments` must be a valid pointer to an array of `colorAttachmentCount` valid `VkAttachmentReference` structures.

• **VUID-VkSubpassDescription-pDepthStencilAttachment-parameter**
  If `pDepthStencilAttachment` is not NULL, `pDepthStencilAttachment` must be a valid pointer to a valid `VkAttachmentReference` structure.

• **VUID-VkSubpassDescription-pPreserveAttachments-parameter**
  If `preserveAttachmentCount` is not 0, `pPreserveAttachments` must be a valid pointer to an array of `preserveAttachmentCount` `uint32_t` values.

Bits which can be set in `VkSubpassDescription::flags`, specifying usage of the subpass, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSubpassDescriptionFlagBits {
} VkSubpassDescriptionFlagBits;
```

*Note*

All bits for this type are defined by extensions, and none of those extensions are enabled in this build of the specification.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkSubpassDescriptionFlags;
```

`VkSubpassDescriptionFlags` is a bitmask type for setting a mask of zero or more `VkSubpassDescriptionFlagBits`.

The `VkAttachmentReference` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkAttachmentReference {
    uint32_t attachment;
    VkImageLayout layout;
} VkAttachmentReference;
```

*attachment* is either an integer value identifying an attachment at the corresponding index in `VkRenderPassCreateInfo::pAttachments`, or `VK_ATTACHMENT_UNUSED` to signify that this attachment is
• layout is a VkImageLayout value specifying the layout the attachment uses during the subpass.

Valid Usage

• VUID-VkAttachmentReference-layout-03077
  If attachment is not VK_ATTACHMENT_UNUSED, layout must not be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED, or VK_IMAGE_LAYOUT_PRESENT_SRC_KHR

• VUID-VkAttachmentReference-separateDepthStencilLayouts-03313
  If the separateDepthStencilLayouts feature is not enabled, and attachment is not VK_ATTACHMENT_UNUSED, layout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

Valid Usage (Implicit)

• VUID-VkAttachmentReference-layout-parameter
  layout must be a valid VkImageLayout value

VK_SUBPASS_EXTERNAL is a special subpass index value expanding synchronization scope outside a subpass. It is described in more detail by VkSubpassDependency.

#define VK_SUBPASS_EXTERNAL (~0U)

The VkSubpassDependency structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSubpassDependency {
    uint32_t srcSubpass;
    uint32_t dstSubpass;
    VkPipelineStageFlags srcStageMask;
    VkPipelineStageFlags dstStageMask;
    VkAccessFlags srcAccessMask;
    VkAccessFlags dstAccessMask;
    VkDependencyFlags dependencyFlags;
} VkSubpassDependency;
```

• srcSubpass is the subpass index of the first subpass in the dependency, or VK_SUBPASS_EXTERNAL.
• dstSubpass is the subpass index of the second subpass in the dependency, or VK_SUBPASS_EXTERNAL.
• srcStageMask is a bitmask of VkPipelineStageFlagBits specifying the source stage mask.
• dstStageMask is a bitmask of VkPipelineStageFlagBits specifying the destination stage mask.
• `srcAccessMask` is a bitmask of `VkAccessFlagBits` specifying a source access mask.
• `dstAccessMask` is a bitmask of `VkAccessFlagBits` specifying a destination access mask.
• `dependencyFlags` is a bitmask of `VkDependencyFlagBits`.

If `srcSubpass` is equal to `dstSubpass` then the `VkSubpassDependency` does not directly define a dependency. Instead, it enables pipeline barriers to be used in a render pass instance within the identified subpass, where the scopes of one pipeline barrier must be a subset of those described by one subpass dependency. Subpass dependencies specified in this way that include framebuffer-space stages in the `srcStageMask` must only include framebuffer-space stages in `dstStageMask`, and must include `VK_DEPENDENCY_BY_REGION_BIT`. When a subpass dependency is specified in this way for a subpass that has more than one view in its view mask, its `dependencyFlags` must include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

If `srcSubpass` and `dstSubpass` are not equal, when a render pass instance which includes a subpass dependency is submitted to a queue, it defines a dependency between the subpasses identified by `srcSubpass` and `dstSubpass`.

If `srcSubpass` is equal to `VK_SUBPASS_EXTERNAL`, the first synchronization scope includes commands that occur earlier in submission order than the `vkCmdBeginRenderPass` used to begin the render pass instance. Otherwise, the first set of commands includes all commands submitted as part of the subpass instance identified by `srcSubpass` and any load, store, or multisample resolve operations on attachments used in `srcSubpass`. In either case, the first synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by `srcStageMask`.

If `dstSubpass` is equal to `VK_SUBPASS_EXTERNAL`, the second synchronization scope includes commands that occur later in submission order than the `vkCmdEndRenderPass` used to end the render pass instance. Otherwise, the second set of commands includes all commands submitted as part of the subpass instance identified by `dstSubpass` and any load, store, and multisample resolve operations on attachments used in `dstSubpass`. In either case, the second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by `dstStageMask`.

The first access scope is limited to accesses in the pipeline stages determined by the source stage mask specified by `srcStageMask`. It is also limited to access types in the source access mask specified by `srcAccessMask`.

The second access scope is limited to accesses in the pipeline stages determined by the destination stage mask specified by `dstStageMask`. It is also limited to access types in the destination access mask specified by `dstAccessMask`.

The availability and visibility operations defined by a subpass dependency affect the execution of image layout transitions within the render pass.

**Note**
For non-attachment resources, the memory dependency expressed by subpass dependency is nearly identical to that of a `VkMemoryBarrier` (with matching `srcAccessMask` and `dstAccessMask` parameters) submitted as a part of a `vkCmdPipelineBarrier` (with matching `srcStageMask` and `dstStageMask` parameters).
The only difference being that its scopes are limited to the identified subpasses rather than potentially affecting everything before and after.

For attachments however, subpass dependencies work more like a `VkImageMemoryBarrier` defined similarly to the `VkMemoryBarrier` above, the queue family indices set to `VK_QUEUE_FAMILY_IGNORED`, and layouts as follows:

- The equivalent to `oldLayout` is the attachment's layout according to the subpass description for `srcSubpass`.
- The equivalent to `newLayout` is the attachment's layout according to the subpass description for `dstSubpass`.

### Valid Usage

- **VUID-VkSubpassDependency-srcStageMask-04090**
  If the `geometryShader` feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`

- **VUID-VkSubpassDependency-srcStageMask-04091**
  If the `tessellationShader` feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

- **VUID-VkSubpassDependency-srcStageMask-03937**
  If the `synchronization2` feature is not enabled, `srcStageMask` must not be `0`

- **VUID-VkSubpassDependency-dstStageMask-04090**
  If the `geometryShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`

- **VUID-VkSubpassDependency-dstStageMask-04091**
  If the `tessellationShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

- **VUID-VkSubpassDependency-dstStageMask-03937**
  If the `synchronization2` feature is not enabled, `dstStageMask` must not be `0`

- **VUID-VkSubpassDependency-srcSubpass-00864**
  `srcSubpass` must be less than or equal to `dstSubpass`, unless one of them is `VK_SUBPASS_EXTERNAL`, to avoid cyclic dependencies and ensure a valid execution order

- **VUID-VkSubpassDependency-srcSubpass-00865**
  `srcSubpass` and `dstSubpass` must not both be equal to `VK_SUBPASS_EXTERNAL`

- **VUID-VkSubpassDependency-srcSubpass-06809**
  If `srcSubpass` is equal to `dstSubpass` and `srcStageMask` includes a framebuffer-space stage, `dstStageMask` must only contain framebuffer-space stages

- **VUID-VkSubpassDependency-srcAccessMask-00868**
  Any access flag included in `srcAccessMask` must be supported by one of the pipeline stages in `srcStageMask`, as specified in the table of supported access types
Any access flag included in `dstAccessMask` must be supported by one of the pipeline stages in `dstStageMask`, as specified in the table of supported access types.

If `srcSubpass` equals `dstSubpass`, and `srcStageMask` and `dstStageMask` both include a framebuffer-space stage, then `dependencyFlags` must include `VK_DEPENDENCY_BY_REGION_BIT`.

If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `srcSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`.

If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `dstSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`.

If `srcSubpass` equals `dstSubpass` and that subpass has more than one bit set in the view mask, then `dependencyFlags` must include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

Valid Usage (Implicit)

- `srcStageMask` must be a valid combination of `VkPipelineStageFlagBits` values.
- `dstStageMask` must be a valid combination of `VkPipelineStageFlagBits` values.
- `srcAccessMask` must be a valid combination of `VkAccessFlagBits` values.
- `dstAccessMask` must be a valid combination of `VkAccessFlagBits` values.
- `dependencyFlags` must be a valid combination of `VkDependencyFlagBits` values.

When multiview is enabled, the execution of the multiple views of one subpass may not occur simultaneously or even back-to-back, and rather may be interleaved with the execution of other subpasses. The load and store operations apply to attachments on a per-view basis. For example, an attachment using `VK_ATTACHMENT_LOAD_OP_CLEAR` will have each view cleared on first use, but the first use of one view may be temporally distant from the first use of another view.

**Note**

A good mental model for multiview is to think of a multiview subpass as if it were a collection of individual (per-view) subpasses that are logically grouped together and described as a single multiview subpass in the API. Similarly, a multiview attachment can be thought of like several individual attachments that happen to be layers in a single image. A view-local dependency between two multiview subpasses acts like a set of one-to-one dependencies between corresponding pairs of per-view subpasses. A view-global dependency between two multiview subpasses acts like a set of one-to-one dependencies between corresponding pairs of per-view subpasses.
subpasses acts like a set of $N \times M$ dependencies between all pairs of per-view subpasses in the source and destination. Thus, it is a more compact representation which also makes clear the commonality and reuse that is present between views in a subpass. This interpretation motivates the answers to questions like “when does the load op apply” - it is on the first use of each view of an attachment, as if each view was a separate attachment.

The content of each view follows the description in attachment content behavior. In particular, if an attachment is preserved, all views within the attachment are preserved.

If there is no subpass dependency from VK_SUBPASS_EXTERNAL to the first subpass that uses an attachment, then an implicit subpass dependency exists from VK_SUBPASS_EXTERNAL to the first subpass it is used in. The implicit subpass dependency only exists if there exists an automatic layout transition away from initialLayout. The subpass dependency operates as if defined with the following parameters:

```c
VkSubpassDependency implicitDependency = {
    .srcSubpass = VK_SUBPASS_EXTERNAL,
    .dstSubpass = firstSubpass, // First subpass attachment is used in
    .srcStageMask = VK_PIPELINE_STAGE_NONE,
    .dstStageMask = VK_PIPELINE_STAGE_ALL_COMMANDS_BIT,
    .srcAccessMask = 0,
    .dstAccessMask = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT | VK_ACCESS_COLOR_ATTACHMENT_READ_BIT | VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT | VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT | VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT,
    .dependencyFlags = 0
};
```

Similarly, if there is no subpass dependency from the last subpass that uses an attachment to VK_SUBPASS_EXTERNAL, then an implicit subpass dependency exists from the last subpass it is used in to VK_SUBPASS_EXTERNAL. The implicit subpass dependency only exists if there exists an automatic layout transition into finalLayout. The subpass dependency operates as if defined with the following parameters:

```c
VkSubpassDependency implicitDependency = {
    .srcSubpass = lastSubpass, // Last subpass attachment is used in
    .dstSubpass = VK_SUBPASS_EXTERNAL,
    .srcStageMask = VK_PIPELINE_STAGE_ALL_COMMANDS_BIT,
    .dstStageMask = VK_PIPELINE_STAGE_NONE,
    .srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT | VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT,
    .dstAccessMask = 0,
    .dependencyFlags = 0
};
```
As subpasses **may** overlap or execute out of order with regards to other subpasses unless a subpass dependency chain describes otherwise, the layout transitions required between subpasses **cannot** be known to an application. Instead, an application provides the layout that each attachment **must** be in at the start and end of a render pass, and the layout it **must** be in during each subpass it is used in. The implementation then **must** execute layout transitions between subpasses in order to guarantee that the images are in the layouts required by each subpass, and in the final layout at the end of the render pass.

Automatic layout transitions apply to the entire image subresource attached to the framebuffer. If multiview is not enabled and the attachment is a view of a 1D or 2D image, the automatic layout transitions apply to the number of layers specified by `VkFramebufferCreateInfo::layers`. If multiview is enabled and the attachment is a view of a 1D or 2D image, the automatic layout transitions apply to the layers corresponding to views which are used by some subpass in the render pass, even if that subpass does not reference the given attachment. If the attachment view is a 2D or 2D array view of a 3D image, even if the attachment view only refers to a subset of the slices of the selected mip level of the 3D image, automatic layout transitions apply to the entire subresource referenced which is the entire mip level in this case.

Automatic layout transitions away from the layout used in a subpass happen-after the availability operations for all dependencies with that subpass as the `srcSubpass`.

Automatic layout transitions into the layout used in a subpass happen-before the visibility operations for all dependencies with that subpass as the `dstSubpass`.

Automatic layout transitions away from `initialLayout` happen-after the availability operations for all dependencies with a `srcSubpass` equal to `VK_SUBPASS_EXTERNAL`, where `dstSubpass` uses the attachment that will be transitioned. For attachments created with `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT`, automatic layout transitions away from `initialLayout` happen-after the availability operations for all dependencies with a `srcSubpass` equal to `VK_SUBPASS_EXTERNAL`, where `dstSubpass` uses any aliased attachment.

Automatic layout transitions into `finalLayout` happen-before the visibility operations for all dependencies with a `dstSubpass` equal to `VK_SUBPASS_EXTERNAL`, where `srcSubpass` uses the attachment that will be transitioned. For attachments created with `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT`, automatic layout transitions into `finalLayout` happen-before the visibility operations for all dependencies with a `dstSubpass` equal to `VK_SUBPASS_EXTERNAL`, where `srcSubpass` uses any aliased attachment.

If two subpasses use the same attachment, and both subpasses use the attachment in a read-only layout, no subpass dependency needs to be specified between those subpasses. If an implementation treats those layouts separately, it **must** insert an implicit subpass dependency between those subpasses to separate the uses in each layout. The subpass dependency operates as if defined with the following parameters:

```c
// Used for input attachments
VkPipelineStageFlags inputAttachmentStages = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
VkAccessFlags inputAttachmentDstAccess = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT;

// Used for depth/stencil attachments
```
VkPipelineStageFlags depthStencilAttachmentStages = 
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT |
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT;
VkAccessFlags depthStencilAttachmentDstAccess = 
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT;

VkSubpassDependency implicitDependency = {
    .srcSubpass = firstSubpass;
    .dstSubpass = secondSubpass;
    .srcStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .dstStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .srcAccessMask = 0;
    .dstAccessMask = inputAttachmentDstAccess | depthStencilAttachmentDstAccess;
    .dependencyFlags = 0;
};

A more extensible version of render pass creation is also defined below.

To create a render pass, call:

```c
// Provided by VK_VERSION_1_2
VkResult vkCreateRenderPass2(
    VkDevice device, 
    const VkRenderPassCreateInfo2* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkRenderPass* pRenderPass);
```

- `device` is the logical device that creates the render pass.
- `pCreateInfo` is a pointer to a `VkRenderPassCreateInfo2` structure describing the parameters of the render pass.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pRenderPass` is a pointer to a `VkRenderPass` handle in which the resulting render pass object is returned.

This command is functionally identical to `vkCreateRenderPass`, but includes extensible sub-structures that include `sType` and `pNext` parameters, allowing them to be more easily extended.

### Valid Usage (Implicit)

- **VUID-vkCreateRenderPass2-device-parameter**
  `device` must be a valid `VkDevice` handle

- **VUID-vkCreateRenderPass2-pCreateInfo-parameter**
  `pCreateInfo` must be a valid pointer to a valid `VkRenderPassCreateInfo2` structure

- **VUID-vkCreateRenderPass2-pAllocator-parameter**
  If `pAllocator` is not NULL, `p Allocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
• **VUID-vkCreateRenderPass2-pRenderPass-parameter**
  
  `pRenderPass` **must** be a valid pointer to a `VkRenderPass` handle

---

### Return Codes

**Success**
- **VK_SUCCESS**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

The `VkRenderPassCreateInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkRenderPassCreateInfo2 {
    VkStructureType sType;           // Type of structure
    const void* pNext;               // Pointer to next structure
    VkRenderPassCreateFlags flags;   // Reserved for future use
    uint32_t attachmentCount;        // Number of attachments
    const VkAttachmentDescription2* pAttachments; // Pointer to attachments
    uint32_t subpassCount;           // Number of subpasses
    const VkSubpassDescription2* pSubpasses; // Pointer to subpasses
    uint32_t dependencyCount;        // Number of dependencies
    const VkSubpassDependency2* pDependencies; // Pointer to dependencies
    uint32_t correlatedViewMaskCount; // Number of correlation masks
    const uint32_t* pCorrelatedViewMasks; // Pointer to correlation masks
} VkRenderPassCreateInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `attachmentCount` is the number of attachments used by this render pass.
- `pAttachments` is a pointer to an array of `attachmentCount` `VkAttachmentDescription2` structures describing the attachments used by the render pass.
- `subpassCount` is the number of subpasses to create.
- `pSubpasses` is a pointer to an array of `subpassCount` `VkSubpassDescription2` structures describing each subpass.
- `dependencyCount` is the number of dependencies between pairs of subpasses.
- `pDependencies` is a pointer to an array of `dependencyCount` `VkSubpassDependency2` structures describing dependencies between pairs of subpasses.
- `correlatedViewMaskCount` is the number of correlation masks.
• **pCorrelatedViewMasks** is a pointer to an array of view masks indicating sets of views that may be more efficient to render concurrently.

Parameters defined by this structure with the same name as those in **VkRenderPassCreateInfo** have the identical effect to those parameters; the child structures are variants of those used in **VkRenderPassCreateInfo** which add **sType** and **pNext** parameters, allowing them to be extended.

If the **VkSubpassDescription2::viewMask** member of any element of **pSubpasses** is not zero, *multiview* functionality is considered to be enabled for this render pass.

correlatedViewMaskCount and **pCorrelatedViewMasks** have the same effect as **VkRenderPassMultiviewCreateInfo::correlationMaskCount** and **VkRenderPassMultiviewCreateInfo::pCorrelationMasks**, respectively.

**Valid Usage**

- **VUID-VkRenderPassCreateInfo2-None-03049**
  If any two subpasses operate on attachments with overlapping ranges of the same **VkDeviceMemory** object, and at least one subpass writes to that area of **VkDeviceMemory**, a subpass dependency must be included (either directly or via some intermediate subpasses) between them.

- **VUID-VkRenderPassCreateInfo2-attachment-03050**
  If the **attachment** member of any element of **pInputAttachments**, **pColorAttachments**, **pResolveAttachments** or **pDepthStencilAttachment**, or the attachment indexed by any element of **pPreserveAttachments** in any element of **pSubpasses** is bound to a range of a **VkDeviceMemory** object that overlaps with any other attachment in any subpass (including the same subpass), the **VkAttachmentDescription2** structures describing them must include **VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT** in **flags**.

- **VUID-VkRenderPassCreateInfo2-attachment-03051**
  If the **attachment** member of any element of **pInputAttachments**, **pColorAttachments**, **pResolveAttachments** or **pDepthStencilAttachment**, or any element of **pPreserveAttachments** in any element of **pSubpasses** is not **VK_ATTACHMENT_UNUSED**, then it must be less than **attachmentCount**.

- **VUID-VkRenderPassCreateInfo2-pSubpasses-06473**
  If the **pNext** chain includes a **VkSubpassDescriptionDepthStencilResolve** structure and the **pDepthStencilResolveAttachment** member is not **NULL** and does not have the value **VK_ATTACHMENT_UNUSED**, then **attachment** must be less than **attachmentCount**.

- **VUID-VkRenderPassCreateInfo2-pAttachments-02522**
  For any member of **pAttachments** with a **loadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment must not specify a **layout** equal to **VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL**, **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL**, or **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL**.

- **VUID-VkRenderPassCreateInfo2-pAttachments-02523**
  For any member of **pAttachments** with a **stencilLoadOp** equal to **VK_ATTACHMENT_LOAD_OP_CLEAR**, the first use of that attachment must not specify a **layout** equal to **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL**.
equal to 

\[
\text{VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL,}
\]

\[
\text{VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL}
\]

- **VUID-VkRenderPassCreateInfo2-pDependencies-03054**
  For any element of `pDependencies`, if the `srcSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `srcStageMask` member of that dependency must be a pipeline stage supported by the pipeline identified by the `pipelineBindPoint` member of the source subpass.

- **VUID-VkRenderPassCreateInfo2-pDependencies-03055**
  For any element of `pDependencies`, if the `dstSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `dstStageMask` member of that dependency must be a pipeline stage supported by the pipeline identified by the `pipelineBindPoint` member of the destination subpass.

- **VUID-VkRenderPassCreateInfo2-pCorrelatedViewMasks-03056**
  The set of bits included in any element of `pCorrelatedViewMasks` must not overlap with the set of bits included in any other element of `pCorrelatedViewMasks`.

- **VUID-VkRenderPassCreateInfo2-viewMask-03057**
  If the `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` is 0, `correlatedViewMaskCount` must be 0.

- **VUID-VkRenderPassCreateInfo2-viewMask-03058**
  The `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` must either all be 0, or all not be 0.

- **VUID-VkRenderPassCreateInfo2-viewMask-03059**
  If the `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` is 0, the `dependencyFlags` member of any element of `pDependencies` must not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

- **VUID-VkRenderPassCreateInfo2-pDependencies-03060**
  For any element of `pDependencies` where its `srcSubpass` member equals its `dstSubpass` member, if the `viewMask` member of the corresponding element of `pSubpasses` includes more than one bit, its `dependencyFlags` member must include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

- **VUID-VkRenderPassCreateInfo2-attachment-02525**
  If the `attachment` member of any element of the `pInputAttachments` member of any element of `pSubpasses` is not `VK_ATTACHMENT_UNUSED`, the `aspectMask` member of that element of `pInputAttachments` must only include aspects that are present in images of the format specified by the element of `pAttachments` specified by `attachment`.

- **VUID-VkRenderPassCreateInfo2-srcSubpass-02526**
  The `srcSubpass` member of each element of `pDependencies` must be less than `subpassCount`.

- **VUID-VkRenderPassCreateInfo2-dstSubpass-02527**
  The `dstSubpass` member of each element of `pDependencies` must be less than `subpassCount`.

- **VUID-VkRenderPassCreateInfo2-attachment-06244**
  If the `attachment` member of the `pDepthStencilAttachment` member of an element of `pSubpasses` is not `VK_ATTACHMENT_UNUSED`, the `layout` member of that same structure is either
VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, and the pNext chain of that structure does not include a VkAttachmentReferenceStencilLayout structure, then the element of pAttachments with an index equal to attachment must not have a format that includes both depth and stencil components

- VUID-VkRenderPassCreateInfo2-attachment-06245
  If the attachment member of the pDepthStencilAttachment member of an element of pSubpasses is not VK_ATTACHMENT_UNUSED and the layout member of that same structure is either VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL, then the element of pAttachments with an index equal to attachment must have a format that includes only a stencil component

- VUID-VkRenderPassCreateInfo2-attachment-06246
  If the attachment member of the pDepthStencilAttachment member of an element of pSubpasses is not VK_ATTACHMENT_UNUSED and the layout member of that same structure is either VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, then the element of pAttachments with an index equal to attachment must not have a format that includes only a stencil component

Valid Usage (Implicit)

- VUID-VkRenderPassCreateInfo2-sType-sType
  sType must be VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2

- VUID-VkRenderPassCreateInfo2-pNext-pNext
  pNext must be NULL

- VUID-VkRenderPassCreateInfo2-flags-zerobitmask
  flags must be 0

- VUID-VkRenderPassCreateInfo2-pAttachments-parameter
  If attachmentCount is not 0, pAttachments must be a valid pointer to an array of attachmentCount valid VkAttachmentDescription2 structures

- VUID-VkRenderPassCreateInfo2-pSubpasses-parameter
  pSubpasses must be a valid pointer to an array of subpassCount valid VkSubpassDescription2 structures

- VUID-VkRenderPassCreateInfo2-pDependencies-parameter
  If dependencyCount is not 0, pDependencies must be a valid pointer to an array of dependencyCount valid VkSubpassDependency2 structures

- VUID-VkRenderPassCreateInfo2-pCorrelatedViewMasks-parameter
  If correlatedViewMaskCount is not 0, pCorrelatedViewMasks must be a valid pointer to an array of correlatedViewMaskCount uint32_t values

- VUID-VkRenderPassCreateInfo2-subpassCount-arraylength
  subpassCount must be greater than 0

The VkAttachmentDescription2 structure is defined as:
typedef struct VkAttachmentDescription2 {
    VkStructureType sType;
    const void* pNext;
    VkAttachmentDescriptionFlags flags;
    VkFormat format;
    VkSampleCountFlagBits samples;
    VkAttachmentLoadOp loadOp;
    VkAttachmentStoreOp storeOp;
    VkAttachmentLoadOp stencilLoadOp;
    VkAttachmentStoreOp stencilStoreOp;
    VkImageLayout initialLayout;
    VkImageLayout finalLayout;
} VkAttachmentDescription2;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is a bitmask of VkAttachmentDescriptionFlagBits specifying additional properties of the attachment.
- **format** is a VkFormat value specifying the format of the image that will be used for the attachment.
- **samples** is a VkSampleCountFlagBits value specifying the number of samples of the image.
- **loadOp** is a VkAttachmentLoadOp value specifying how the contents of color and depth components of the attachment are treated at the beginning of the subpass where it is first used.
- **storeOp** is a VkAttachmentStoreOp value specifying how the contents of color and depth components of the attachment are treated at the end of the subpass where it is last used.
- **stencilLoadOp** is a VkAttachmentLoadOp value specifying how the contents of stencil components of the attachment are treated at the beginning of the subpass where it is first used.
- **stencilStoreOp** is a VkAttachmentStoreOp value specifying how the contents of stencil components of the attachment are treated at the end of the last subpass where it is used.
- **initialLayout** is the layout the attachment image subresource will be in when a render pass instance begins.
- **finalLayout** is the layout the attachment image subresource will be transitioned to when a render pass instance ends.

Parameters defined by this structure with the same name as those in VkAttachmentDescription have the identical effect to those parameters.

If the separateDepthStencilLayouts feature is enabled, and **format** is a depth/stencil format, **initialLayout** and **finalLayout** can be set to a layout that only specifies the layout of the depth aspect.

If the pNext chain includes a VkAttachmentDescriptionStencilLayout structure, then the **stencilInitialLayout** and **stencilFinalLayout** members specify the initial and final layouts of the
stencil aspect of a depth/stencil format, and initialLayout and finalLayout only apply to the depth aspect. For depth-only formats, the VkAttachmentDescriptionStencilLayout structure is ignored. For stencil-only formats, the initial and final layouts of the stencil aspect are taken from the VkAttachmentDescriptionStencilLayout structure if present, or initialLayout and finalLayout if not present.

If format is a depth/stencil format, and either initialLayout or finalLayout does not specify a layout for the stencil aspect, then the application must specify the initial and final layouts of the stencil aspect by including a VkAttachmentDescriptionStencilLayout structure in the pNext chain.

### Valid Usage

- **VUID-VkAttachmentDescription2-format-06698**
  
  format must not be VK_FORMAT_UNDEFINED

- **VUID-VkAttachmentDescription2-format-06699**
  
  If format includes a color or depth component and loadOp is VK_ATTACHMENT_LOAD_OP_LOAD, then initialLayout must not be VK_IMAGE_LAYOUT_UNDEFINED

- **VUID-VkAttachmentDescription2-finalLayout-00843**
  
  finalLayout must not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

- **VUID-VkAttachmentDescription2-format-03280**
  
  If format is a color format, initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03281**
  
  If format is a depth/stencil format, initialLayout must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03282**
  
  If format is a color format, finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03283**
  
  If format is a depth/stencil format, finalLayout must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription2-format-06487**
  
  If format is a color format, initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription2-format-06488**
  
  If format is a color format, finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkAttachmentDescription2-separateDepthStencilLayouts-03284**
  
  If the separateDepthStencilLayouts feature is not enabled, initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

- **VUID-VkAttachmentDescription2-separateDepthStencilLayouts-03285**
  
  If the `separateDepthStencilLayouts` feature is not enabled, `finalLayout` must not be
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
  VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,

- **VUID-VkAttachmentDescription2-format-03286**
  
  If `format` is a color format, `initialLayout` must not be
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
  VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03287**
  
  If `format` is a color format, `finalLayout` must not be
  VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
  VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-06906**
  
  If `format` is a depth/stencil format which includes both depth and stencil components,
  `initialLayout` must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-06907**
  
  If `format` is a depth/stencil format which includes both depth and stencil components,
  `finalLayout` must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03290**
  
  If `format` is a depth/stencil format which includes only the depth component,
  `initialLayout` must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-format-03291**
  
  If `format` is a depth/stencil format which includes only the depth component, `finalLayout` must not be
  VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

- **VUID-VkAttachmentDescription2-samples-08745**
  
  `samples` must be a bit value that is set in `imageCreateSampleCounts` (as defined in Image
  Creation Limits) for the given `format`

- **VUID-VkAttachmentDescription2-pNext-06704**
  
  If the `pNext` chain does not include a `VkAttachmentDescriptionStencilLayout` structure,
  `format` includes a stencil component, and `stencilLoadOp` is VK_ATTACHMENT_LOAD_OP_LOAD,
  then `initialLayout` must not be VK_IMAGE_LAYOUT_UNDEFINED

- **VUID-VkAttachmentDescription2-pNext-06705**
  
  If the `pNext` chain does includes a `VkAttachmentDescriptionStencilLayout` structure,
  `format` includes a stencil component, and `stencilLoadOp` is VK_ATTACHMENT_LOAD_OP_LOAD,
  then `VkAttachmentDescriptionStencilLayout::stencilInitialLayout` must not be
If format is a depth/stencil format which includes both depth and stencil components, and initialLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, the pNext chain must include a VkAttachmentDescriptionStencilLayout structure.

If format is a depth/stencil format which includes both depth and stencil components, and finalLayout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, the pNext chain must include a VkAttachmentDescriptionStencilLayout structure.

If the pNext chain does not include a VkAttachmentDescriptionStencilLayout structure and format only includes a stencil component, initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL.

If the pNext chain does not include a VkAttachmentDescriptionStencilLayout structure and format only includes a stencil component, finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL.

Valid Usage (Implicit)

sType must be VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2

pNext must be NULL or a pointer to a valid instance of VkAttachmentDescriptionStencilLayout

The sType value of each struct in the pNext chain must be unique

flags must be a valid combination of VkAttachmentDescriptionFlagBits values

format must be a valid VkFormat value

samples must be a valid VkSampleCountFlagBits value

loadOp must be a valid VkAttachmentLoadOp value

storeOp must be a valid VkAttachmentStoreOp value

stencilLoadOp must be a valid VkAttachmentLoadOp value

stencilStoreOp must be a valid VkAttachmentStoreOp value
**stencilStoreOp** must be a valid `VkAttachmentStoreOp` value

- **VUID-VkAttachmentDescription2-initialLayout-parameter**
  `initialLayout` must be a valid `VkImageLayout` value

- **VUID-VkAttachmentDescription2-finalLayout-parameter**
  `finalLayout` must be a valid `VkImageLayout` value

The `VkAttachmentDescriptionStencilLayout` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkAttachmentDescriptionStencilLayout {
    VkStructureType sType;
    void* pNext;
    VkImageLayout stencilInitialLayout;
    VkImageLayout stencilFinalLayout;
} VkAttachmentDescriptionStencilLayout;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **stencilInitialLayout** is the layout the stencil aspect of the attachment image subresource will be in when a render pass instance begins.
- **stencilFinalLayout** is the layout the stencil aspect of the attachment image subresource will be transitioned to when a render pass instance ends.

### Valid Usage

- **VUID-VkAttachmentDescriptionStencilLayout-stencilInitialLayout-03308**
  `stencilInitialLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`.

- **VUID-VkAttachmentDescriptionStencilLayout-stencilFinalLayout-03309**
  `stencilFinalLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`.

- **VUID-VkAttachmentDescriptionStencilLayout-stencilFinalLayout-03310**
  `stencilFinalLayout` must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`.
Valid Usage (Implicit)

- VUID-VkAttachmentDescriptionStencilLayout-sType-sType
  sType must be VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_STENCIL_LAYOUT

- VUID-VkAttachmentDescriptionStencilLayout-stencilInitialLayout-parameter
  stencilInitialLayout must be a valid VkImageLayout value

- VUID-VkAttachmentDescriptionStencilLayout-stencilFinalLayout-parameter
  stencilFinalLayout must be a valid VkImageLayout value

The VkSubpassDescription2 structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSubpassDescription2 {
    VkStructureType sType;
    const void* pNext;
    VkSubpassDescriptionFlags flags;
    VkPipelineBindPoint pipelineBindPoint;
    uint32_t viewMask;
    uint32_t inputAttachmentCount;
    const VkAttachmentReference2* pInputAttachments;
    uint32_t colorAttachmentCount;
    const VkAttachmentReference2* pColorAttachments;
    const VkAttachmentReference2* pResolveAttachments;
    const VkAttachmentReference2* pDepthStencilAttachment;
    uint32_t preserveAttachmentCount;
    const uint32_t* pPreserveAttachments;
} VkSubpassDescription2;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkSubpassDescriptionFlagBits specifying usage of the subpass.
- pipelineBindPoint is a VkPipelineBindPoint value specifying the pipeline type supported for this subpass.
- viewMask is a bitfield of view indices describing which views rendering is broadcast to in this subpass, when multiview is enabled.
- inputAttachmentCount is the number of input attachments.
- pInputAttachments is a pointer to an array of VkAttachmentReference2 structures defining the input attachments for this subpass and their layouts.
- colorAttachmentCount is the number of color attachments.
- pColorAttachments is a pointer to an array of colorAttachmentCount VkAttachmentReference2 structures defining the color attachments for this subpass and their layouts.
- pResolveAttachments is NULL or a pointer to an array of colorAttachmentCount
VkAttachmentReference2 structures defining the resolve attachments for this subpass and their layouts.

- **pDepthStencilAttachment** is a pointer to a VkAttachmentReference2 structure specifying the depth/stencil attachment for this subpass and its layout.
- **preserveAttachmentCount** is the number of preserved attachments.
- **pPreserveAttachments** is a pointer to an array of preserveAttachmentCount render pass attachment indices identifying attachments that are not used by this subpass, but whose contents must be preserved throughout the subpass.

Parameters defined by this structure with the same name as those in VkSubpassDescription have the identical effect to those parameters.

viewMask has the same effect for the described subpass as VkRenderPassMultiviewCreateInfo::pViewMasks has on each corresponding subpass.

**Valid Usage**

- **VUID-VkSubpassDescription2-attachment-06912**
  If the attachment member of an element of pInputAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkSubpassDescription2-attachment-06913**
  If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- **VUID-VkSubpassDescription2-attachment-06914**
  If the attachment member of an element of pResolveAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- **VUID-VkSubpassDescription2-attachment-06915**
  If the attachment member of pDepthStencilAttachment is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL

- **VUID-VkSubpassDescription2-attachment-06916**
  If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL

- **VUID-VkSubpassDescription2-attachment-06917**
  If the attachment member of an element of pResolveAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL
• VUID-VkSubpassDescription2-attachment-06918
   If the attachment member of an element of pInputAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL

• VUID-VkSubpassDescription2-attachment-06919
   If the attachment member of an element of pColorAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

• VUID-VkSubpassDescription2-attachment-06920
   If the attachment member of an element of pResolveAttachments is not VK_ATTACHMENT_UNUSED, its layout member must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

• VUID-VkSubpassDescription2-attachment-06251
   If the attachment member of pDepthStencilAttachment is not VK_ATTACHMENT_UNUSED and its pNext chain includes a VkAttachmentReferenceStencilLayout structure, the layout member of pDepthStencilAttachment must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

• VUID-VkSubpassDescription2-pipelineBindPoint-03062
   pipelineBindPoint must be VK_PIPELINE_BIND_POINT_GRAPHICS

• VUID-VkSubpassDescription2-colorAttachmentCount-03063
   colorAttachmentCount must be less than or equal to VkPhysicalDeviceLimits::maxColorAttachments

• VUID-VkSubpassDescription2-loadOp-03064
   If the first use of an attachment in this render pass is as an input attachment, and the attachment is not also used as a color or depth/stencil attachment in the same subpass, then loadOp must not be VK_ATTACHMENT_LOAD_OP_CLEAR

• VUID-VkSubpassDescription2-pResolveAttachments-03065
   If pResolveAttachments is not NULL, for each resolve attachment that does not have the value VK_ATTACHMENT_UNUSED, the corresponding color attachment must not have the value VK_ATTACHMENT_UNUSED

• VUID-VkSubpassDescription2-pResolveAttachments-03066
   If pResolveAttachments is not NULL, for each resolve attachment that is not VK_ATTACHMENT_UNUSED, the corresponding color attachment must not have a sample count of VK_SAMPLE_COUNT_1_BIT

• VUID-VkSubpassDescription2-pResolveAttachments-03067
   If pResolveAttachments is not NULL, each resolve attachment that is not VK_ATTACHMENT_UNUSED must have a sample count of VK_SAMPLE_COUNT_1_BIT

• VUID-VkSubpassDescription2-pResolveAttachments-03068
   Each element of pResolveAttachments must have the same VkFormat as its corresponding color attachment
All attachments in `pInputAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain at least `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT` or `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

All attachments in `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

All attachments in `pResolveAttachments` that are not `VK_ATTACHMENT_UNUSED` must have image formats whose potential format features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

If `pDepthStencilAttachment` is not `NULL` and the attachment is not `VK_ATTACHMENT_UNUSED` then it must have an image format whose potential format features contain `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

If none of the `VK_AMD_mixed_attachment_samples` extension, the `VK_NV_framebuffer_mixed_samples` extension, or the multisampledRenderToSingleSampled feature are enabled, all attachments in `pDepthStencilAttachment` or `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED` must have the same sample count.

Each element of `pPreserveAttachments` must not be `VK_ATTACHMENT_UNUSED`.

Each element of `pPreserveAttachments` must not also be an element of any other member of the subpass description.

If any attachment is used by more than one `VkAttachmentReference2` member, then each use must use the same layout.

If the attachment member of any element of `pInputAttachments` is not `VK_ATTACHMENT_UNUSED`, then the `aspectMask` member must be a valid combination of `VkImageAspectFlagBits`.

If the attachment member of any element of `pInputAttachments` is not `VK_ATTACHMENT_UNUSED`, then the `aspectMask` member must not be `0`.

If the attachment member of any element of `pInputAttachments` is not `VK_ATTACHMENT_UNUSED`, then the `aspectMask` member must not include `VK_IMAGE_ASPECT_METADATA_BIT`.

An attachment must not be used in both `pDepthStencilAttachment` and `pColorAttachments`.

If the multiview feature is not enabled, `viewMask` must be `0`.

If the `multiview` feature is not enabled, `viewMask` must be `0`. 
The index of the most significant bit in `viewMask` must be less than `maxMultiviewViewCount`.

### Valid Usage (Implicit)

- **VUID-VkSubpassDescription2-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_2`
- **VUID-VkSubpassDescription2-pNext-pNext**
  - `pNext` must be `NULL` or a pointer to a valid instance of `VkSubpassDescriptionDepthStencilResolve`.
- **VUID-VkSubpassDescription2-sType-unique**
  - The `sType` value of each struct in the `pNext` chain must be unique.
- **VUID-VkSubpassDescription2-flags-zerobitmask**
  - `flags` must be `0`.
- **VUID-VkSubpassDescription2-pipelineBindPoint-parameter**
  - `pipelineBindPoint` must be a valid `VkPipelineBindPoint` value.
- **VUID-VkSubpassDescription2-pInputAttachments-parameter**
  - If `inputAttachmentCount` is not `0`, `pInputAttachments` must be a valid pointer to an array of `VkAttachmentReference2` structures.
- **VUID-VkSubpassDescription2-pColorAttachments-parameter**
  - If `colorAttachmentCount` is not `0`, `pColorAttachments` must be a valid pointer to an array of `VkAttachmentReference2` structures.
- **VUID-VkSubpassDescription2-pResolveAttachments-parameter**
  - If `colorAttachmentCount` is not `0`, and `pResolveAttachments` is not `NULL`, `pResolveAttachments` must be a valid pointer to an array of `VkAttachmentReference2` structures.
- **VUID-VkSubpassDescription2-pDepthStencilAttachment-parameter**
  - If `pDepthStencilAttachment` is not `NULL`, `pDepthStencilAttachment` must be a valid pointer to a `VkAttachmentReference2` structure.
- **VUID-VkSubpassDescription2-pPreserveAttachments-parameter**
  - If `preserveAttachmentCount` is not `0`, `pPreserveAttachments` must be a valid pointer to an array of `uint32_t` values.

The `VkSubpassDescriptionDepthStencilResolve` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSubpassDescriptionDepthStencilResolve {
    VkStructureType sType;
    const void* pNext;
    VkResolveModeFlagBits depthResolveMode;
    VkResolveModeFlagBits stencilResolveMode;
    const VkAttachmentReference2* pDepthStencilResolveAttachment;
} VkSubpassDescriptionDepthStencilResolve;
```
• `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is NULL or a pointer to a structure extending this structure.
• `depthResolveMode` is a `VkResolveModeFlagBits` value describing the depth resolve mode.
• `stencilResolveMode` is a `VkResolveModeFlagBits` value describing the stencil resolve mode.
• `pDepthStencilResolveAttachment` is NULL or a pointer to a `VkAttachmentReference2` structure defining the depth/stencil resolve attachment for this subpass and its layout.

If the `pNext` chain of `VkSubpassDescription2` includes a `VkSubpassDescriptionDepthStencilResolve` structure, then that structure describes multisample resolve operations for the depth/stencil attachment in a subpass. If this structure is not included in the `pNext` chain of `VkSubpassDescription2`, or if it is and either `pDepthStencilResolveAttachment` is NULL or its attachment index is `VK_ATTACHMENT_UNUSED`, it indicates that no depth/stencil resolve attachment will be used in the subpass.

### Valid Usage

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03177**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilAttachment` must not be NULL or have the value `VK_ATTACHMENT_UNUSED`.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03179**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilAttachment` must not have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03180**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilResolveAttachment` must have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-02651**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED` then it must have an image format whose potential format features contain `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03181**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED` and `VkFormat` of `pDepthStencilResolveAttachment` has a depth component, then the `VkFormat` of `pDepthStencilAttachment` must have a depth component with the same number of bits and numeric format.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03182**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, and `VkFormat` of `pDepthStencilResolveAttachment` has a stencil component, then the `VkFormat` of `pDepthStencilAttachment` must have a stencil component with the same number of bits and numeric format.

- **VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03178**
  If `pDepthStencilResolveAttachment` is not NULL and does not have the value...
**VK_ATTACHMENT_UNUSED, depthResolveMode and stencilResolveMode must not both be VK_RESOLVE_MODE_NONE**

- VUID-VkSubpassDescriptionDepthStencilResolve-depthResolveMode-03183
  If pDepthStencilResolveAttachment is not NULL and does not have the value VK_ATTACHMENT_UNUSED and the VkFormat of pDepthStencilResolveAttachment has a depth component, then the value of depthResolveMode must be one of the bits set in VkPhysicalDeviceDepthStencilResolveProperties::supportedDepthResolveModes or VK_RESOLVE_MODE_NONE.

- VUID-VkSubpassDescriptionDepthStencilResolve-stencilResolveMode-03184
  If pDepthStencilResolveAttachment is not NULL and does not have the value VK_ATTACHMENT_UNUSED and the VkFormat of pDepthStencilResolveAttachment has a stencil component, then the value of stencilResolveMode must be one of the bits set in VkPhysicalDeviceDepthStencilResolveProperties::supportedStencilResolveModes or VK_RESOLVE_MODE_NONE.

- VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03185
  If pDepthStencilResolveAttachment is not NULL and does not have the value VK_ATTACHMENT_UNUSED, the VkFormat of pDepthStencilResolveAttachment has both depth and stencil components, VkPhysicalDeviceDepthStencilResolveProperties::independentResolve is VK_FALSE, and VkPhysicalDeviceDepthStencilResolveProperties::independentResolveNone is VK_FALSE, then the values of depthResolveMode and stencilResolveMode must be identical.

- VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-03186
  If pDepthStencilResolveAttachment is not NULL and does not have the value VK_ATTACHMENT_UNUSED, the VkFormat of pDepthStencilResolveAttachment has both depth and stencil components, VkPhysicalDeviceDepthStencilResolveProperties::independentResolve is VK_FALSE and VkPhysicalDeviceDepthStencilResolveProperties::independentResolveNone is VK_TRUE, then the values of depthResolveMode and stencilResolveMode must be identical or one of them must be VK_RESOLVE_MODE_NONE.

**Valid Usage (Implicit)**

- VUID-VkSubpassDescriptionDepthStencilResolve-sType-sType
  sType must be VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE.

- VUID-VkSubpassDescriptionDepthStencilResolve-pDepthStencilResolveAttachment-parameter
  If pDepthStencilResolveAttachment is not NULL, pDepthStencilResolveAttachment must be a valid pointer to a valid VkAttachmentReference2 structure.

The VkAttachmentReference2 structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkAttachmentReference2 {
    VkStructureType sType;
    const void*   pNext;
    uint32_t      attachment;
} VkAttachmentReference2;
```
VkAttachmentReference2

```
VkImageLayout layout;
VkImageAspectFlags aspectMask;
} VkAttachmentReference2;
```

- **sType** is a *VkStructureType* value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **attachment** is either an integer value identifying an attachment at the corresponding index in *VkRenderPassCreateInfo2::pAttachments*, or *VK_ATTACHMENT_UNUSED* to signify that this attachment is not used.
- **layout** is a *VkImageLayout* value specifying the layout the attachment uses during the subpass.
- **aspectMask** is a mask of which aspect(s) can be accessed within the specified subpass as an input attachment.

Parameters defined by this structure with the same name as those in *VkAttachmentReference* have the identical effect to those parameters.

**aspectMask** is ignored when this structure is used to describe anything other than an input attachment reference.

If the **separateDepthStencilLayouts** feature is enabled, and **attachment** has a depth/stencil format, **layout** can be set to a layout that only specifies the layout of the depth aspect.

If **layout** only specifies the layout of the depth aspect of the attachment, the layout of the stencil aspect is specified by the **stencilLayout** member of a *VkAttachmentReferenceStencilLayout* structure included in the **pNext** chain. Otherwise, **layout** describes the layout for all relevant image aspects.

### Valid Usage

- **VUID-VkAttachmentReference2-layout-03077**
  If **attachment** is not *VK_ATTACHMENT_UNUSED*, **layout** must not be *VK_IMAGE_LAYOUT_UNDEFINED*, *VK_IMAGE_LAYOUT_PREINITIALIZED*, or *VK_IMAGE_LAYOUT_PRESENT_SRC_KHR*

- **VUID-VkAttachmentReference2-separateDepthStencilLayouts-03313**
  If the **separateDepthStencilLayouts** feature is not enabled, and **attachment** is not *VK_ATTACHMENT_UNUSED*, **layout** must not be *VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL*, *VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL*, *VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL*, or *VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL*,

### Valid Usage (Implicit)

- **VUID-VkAttachmentReference2-sType-sType**
  **sType** must be *VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2*

- **VUID-VkAttachmentReference2-pNext-pNext**
  **pNext** must be NULL or a pointer to a valid instance of *VkAttachmentReferenceStencilLayout*
The `VkAttachmentReferenceStencilLayout` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkAttachmentReferenceStencilLayout {
    VkStructureType sType;
    void* pNext;
    VkImageLayout stencilLayout;
} VkAttachmentReferenceStencilLayout;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **stencilLayout** is a `VkImageLayout` value specifying the layout the stencil aspect of the attachment uses during the subpass.

**Valid Usage**

- **VUID-VkAttachmentReferenceStencilLayout-stencilLayout-03318**
  
  stencilLayout must not be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED, VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_PRESENT_SRC_KHR or

**Valid Usage (Implicit)**

- **VUID-VkAttachmentReferenceStencilLayout-sType-sType**
  
  sType must be VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_STENCIL_LAYOUT

- **VUID-VkAttachmentReferenceStencilLayout-stencilLayout-parameter**
  
  stencilLayout must be a valid VkImageLayout value

The `VkSubpassDependency2` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSubpassDependency2 {
    VkStructureType sType;
    // ... other members ...
} VkSubpassDependency2;
```
const void* pNext;
uint32_t srcSubpass;
uint32_t dstSubpass;
VkPipelineStageFlags srcStageMask;
VkPipelineStageFlags dstStageMask;
VkAccessFlags srcAccessMask;
VkAccessFlags dstAccessMask;
VkDependencyFlags dependencyFlags;
int32_t viewOffset;
} VkSubpassDependency2;

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- srcSubpass is the subpass index of the first subpass in the dependency, or VK_SUBPASS_EXTERNAL.
- dstSubpass is the subpass index of the second subpass in the dependency, or VK_SUBPASS_EXTERNAL.
- srcStageMask is a bitmask of VkPipelineStageFlagBits specifying the source stage mask.
- dstStageMask is a bitmask of VkPipelineStageFlagBits specifying the destination stage mask.
- srcAccessMask is a bitmask of VkAccessFlagBits specifying a source access mask.
- dstAccessMask is a bitmask of VkAccessFlagBits specifying a destination access mask.
- dependencyFlags is a bitmask of VkDependencyFlagBits.
- viewOffset controls which views in the source subpass the views in the destination subpass depend on.

Parameters defined by this structure with the same name as those in VkSubpassDependency have the identical effect to those parameters.

viewOffset has the same effect for the described subpass dependency as VkRenderPassMultiviewCreateInfo::pViewOffsets has on each corresponding subpass dependency.

If a VkMemoryBarrier2 is included in the pNext chain, srcStageMask, dstStageMask, srcAccessMask, and dstAccessMask parameters are ignored. The synchronization and access scopes instead are defined by the parameters of VkMemoryBarrier2.

**Valid Usage**

- VUID-VkSubpassDependency2-srcStageMask-04090
  If the geometryShader feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT

- VUID-VkSubpassDependency2-srcStageMask-04091
  If the tessellationShader feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT

- VUID-VkSubpassDependency2-srcStageMask-03937
If the `synchronization2` feature is not enabled, `srcStageMask` must not be 0

- VUID-VkSubpassDependency2-dstStageMask-04090
  If the `geometryShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`

- VUID-VkSubpassDependency2-dstStageMask-04091
  If the `tessellationShader` feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

- VUID-VkSubpassDependency2-dstStageMask-03937
  If the `synchronization2` feature is not enabled, `dstStageMask` must not be 0

- VUID-VkSubpassDependency2-srcSubpass-03084
  `srcSubpass` must be less than or equal to `dstSubpass`, unless one of them is `VK_SUBPASS_EXTERNAL`, to avoid cyclic dependencies and ensure a valid execution order

- VUID-VkSubpassDependency2-srcSubpass-03085
  `srcSubpass` and `dstSubpass` must not both be equal to `VK_SUBPASS_EXTERNAL`

- VUID-VkSubpassDependency2-srcSubpass-06810
  If `srcSubpass` is equal to `dstSubpass` and `srcStageMask` includes a framebuffer-space stage, `dstStageMask` must only contain framebuffer-space stages

- VUID-VkSubpassDependency2-srcAccessMask-03088
  Any access flag included in `srcAccessMask` must be supported by one of the pipeline stages in `srcStageMask`, as specified in the table of supported access types

- VUID-VkSubpassDependency2-dstAccessMask-03089
  Any access flag included in `dstAccessMask` must be supported by one of the pipeline stages in `dstStageMask`, as specified in the table of supported access types

- VUID-VkSubpassDependency2-dependencyFlags-03090
  If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `srcSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`

- VUID-VkSubpassDependency2-dependencyFlags-03091
  If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `dstSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`

- VUID-VkSubpassDependency2-srcSubpass-02245
  If `srcSubpass` equals `dstSubpass`, and `srcStageMask` and `dstStageMask` both include a framebuffer-space stage, then `dependencyFlags` must include `VK_DEPENDENCY_BY_REGION_BIT`

- VUID-VkSubpassDependency2-viewOffset-02530
  If `viewOffset` is not equal to 0, `srcSubpass` must not be equal to `dstSubpass`

- VUID-VkSubpassDependency2-dependencyFlags-03092
  If `dependencyFlags` does not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `viewOffset` must be 0

---

**Valid Usage (Implicit)**

- VUID-VkSubpassDependency2-sType-sType
**sType must** be `VK_STRUCTURE_TYPE_SUBPASS_DEPENDENCY_2`

- VUID-VkSubpassDependency2-pNext-pNext
  
  **pNext must** be `NULL` or a pointer to a valid instance of `VkMemoryBarrier2`

- VUID-VkSubpassDependency2-sType-unique
  
  The **sType** value of each struct in the **pNext** chain must be unique

- VUID-VkSubpassDependency2-srcStageMask-parameter
  
  srcStageMask must be a valid combination of `VkPipelineStageFlagBits` values

- VUID-VkSubpassDependency2-dstStageMask-parameter
  
  dstStageMask must be a valid combination of `VkPipelineStageFlagBits` values

- VUID-VkSubpassDependency2-srcAccessMask-parameter
  
  srcAccessMask must be a valid combination of `VkAccessFlagBits` values

- VUID-VkSubpassDependency2-dstAccessMask-parameter
  
  dstAccessMask must be a valid combination of `VkAccessFlagBits` values

- VUID-VkSubpassDependency2-dependencyFlags-parameter
  
  dependencyFlags must be a valid combination of `VkDependencyFlagBits` values

To destroy a render pass, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyRenderPass(
    VkDevice device,
    VkRenderPass renderPass,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the render pass.
- **renderPass** is the handle of the render pass to destroy.
- **pAllocator** controls host memory allocation as described in the **Memory Allocation** chapter.

**Valid Usage**

- VUID-vkDestroyRenderPass-renderPass-00873
  
  All submitted commands that refer to **renderPass must** have completed execution

- VUID-vkDestroyRenderPass-renderPass-00874
  
  If **VkAllocationCallbacks** were provided when **renderPass** was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyRenderPass-renderPass-00875
  
  If no **VkAllocationCallbacks** were provided when **renderPass** was created, **pAllocator must** be **NULL**
8.3. Render Pass Compatibility

Framebuffers and graphics pipelines are created based on a specific render pass object. They must only be used with that render pass object, or one compatible with it.

Two attachment references are compatible if they have matching format and sample count, or are both VK_ATTACHMENT_UNUSED or the pointer that would contain the reference is NULL.

Two arrays of attachment references are compatible if all corresponding pairs of attachments are compatible. If the arrays are of different lengths, attachment references not present in the smaller array are treated as VK_ATTACHMENT_UNUSED.

Two render passes are compatible if their corresponding color, input, resolve, and depth/stencil attachment references are compatible and if they are otherwise identical except for:

- Initial and final image layout in attachment descriptions
- Load and store operations in attachment descriptions
- Image layout in attachment references

As an additional special case, if two render passes have a single subpass, the resolve attachment reference compatibility requirements are ignored.

A framebuffer is compatible with a render pass if it was created using the same render pass or a compatible render pass.
8.4. Framebuffers

Render passes operate in conjunction with framebuffers. Framebuffers represent a collection of specific memory attachments that a render pass instance uses.

Framebuffers are represented by VkFramebuffer handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFramebuffer)
```

To create a framebuffer, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateFramebuffer(
    VkDevice device,
    const VkFramebufferCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkFramebuffer* pFramebuffer);
```

- `device` is the logical device that creates the framebuffer.
- `pCreateInfo` is a pointer to a VkFramebufferCreateInfo structure describing additional information about framebuffer creation.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pFramebuffer` is a pointer to a VkFramebuffer handle in which the resulting framebuffer object is returned.

**Valid Usage**

- VUID-vkCreateFramebuffer-pCreateInfo-02777
  If `pCreateInfo->flags` does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, and `attachmentCount` is not 0, each element of `pCreateInfo->pAttachments` must have been created on `device`

**Valid Usage (Implicit)**

- VUID-vkCreateFramebuffer-device-parameter
  `device` must be a valid VkDevice handle
- VUID-vkCreateFramebuffer-pCreateInfo-parameter
  `pCreateInfo` must be a valid pointer to a valid VkFramebufferCreateInfo structure
- VUID-vkCreateFramebuffer-pAllocator-parameter
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure
- VUID-vkCreateFramebuffer-pFramebuffer-parameter
The `VkFramebufferCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkFramebufferCreateInfo {
    VkStructureType          sType;
    const void*              pNext;
    VkFramebufferCreateFlags flags;
    VkRenderPass             renderPass;
    uint32_t                 attachmentCount;
    const VkImageView*       pAttachments;
    uint32_t                 width;
    uint32_t                 height;
    uint32_t                 layers;
} VkFramebufferCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is a bitmask of `VkFramebufferCreateFlagBits`.
- `renderPass` is a render pass defining what render passes the framebuffer will be compatible with. See Render Pass Compatibility for details.
- `attachmentCount` is the number of attachments.
- `pAttachments` is a pointer to an array of `VkImageView` handles, each of which will be used as the corresponding attachment in a render pass instance. If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, this parameter is ignored.
- `width`, `height` and `layers` define the dimensions of the framebuffer. If the render pass uses multiview, then `layers` must be one and each attachment requires a number of layers that is greater than the maximum bit index set in the view mask in the subpasses in which it is used.

It is legal for a subpass to use no color or depth/stencil attachments, either because it has no attachment references or because all of them are `VK_ATTACHMENT_UNUSED`. This kind of subpass can use shader side effects such as image stores and atomics to produce an output. In this case, the subpass continues to use the `width`, `height`, and `layers` of the framebuffer to define the dimensions of the rendering area, and the `rasterizationSamples` from each pipeline’s...
VkPipelineMultisampleStateCreateInfo to define the number of samples used in rasterization; however, if VkPhysicalDeviceFeatures::variableMultisampleRate is VK_FALSE, then all pipelines to be bound with the subpass must have the same value for VkPipelineMultisampleStateCreateInfo::rasterizationSamples. In all such cases, rasterizationSamples must be a bit value that is set in VkPhysicalDeviceLimits::framebufferNoAttachmentsSampleCounts.

### Valid Usage

- **VUID-VkFramebufferCreateInfo-attachmentCount-00876** attachmentCount must be equal to the attachment count specified in renderPass
- **VUID-VkFramebufferCreateInfo-flags-02778**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT and attachmentCount is not 0, pAttachments must be a valid pointer to an array of attachmentCount valid VkImageView handles
- **VUID-VkFramebufferCreateInfo-pAttachments-00877**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments that is used as a color attachment or resolve attachment by renderPass must have been created with a usage value including VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
- **VUID-VkFramebufferCreateInfo-pAttachments-02633**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments that is used as a depth/stencil attachment by renderPass must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
- **VUID-VkFramebufferCreateInfo-pAttachments-02634**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments that is used as a depth/stencil resolve attachment by renderPass must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
- **VUID-VkFramebufferCreateInfo-pAttachments-00879**
  - If renderPass is not VK_NULL_HANDLE, flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments that is used as an input attachment by renderPass must have been created with a usage value including VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
- **VUID-VkFramebufferCreateInfo-pAttachments-00880**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments must have been created with a VkFormat value that matches the VkFormat specified by the corresponding VkAttachmentDescription in renderPass
- **VUID-VkFramebufferCreateInfo-pAttachments-00881**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments must have been created with a samples value that matches the samples value specified by the corresponding VkAttachmentDescription in renderPass
- **VUID-VkFramebufferCreateInfo-flags-04533**
  - If flags does not include VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of pAttachments that is used as an input, color, resolve, or depth/stencil attachment by renderPass must have been created with a VkImageCreateInfo::extent.width greater than or equal to width
If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageCreateInfo::extent.height` greater than or equal to `height`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageViewCreateInfo::subresourceRange.layerCount` greater than or equal to `layers`.

If `renderPass` was specified with non-zero view masks, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have a `layerCount` greater than the index of the most significant bit set in any of those view masks.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must only specify a single mip level.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with the identity swizzle.

Width must be greater than 0.

Width must be less than or equal to `maxFramebufferWidth`.

Height must be greater than 0.

Height must be less than or equal to `maxFramebufferHeight`.

Layers must be greater than 0.

Layers must be less than or equal to `maxFramebufferLayers`.

If `renderPass` was specified with non-zero view masks, layers must be 1.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is a 2D or 2D array image view taken from a 3D image must not be a depth/stencil format.

If the `imagelessFramebuffer` feature is not enabled, `flags` must not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageCreateInfo::extent.height` greater than or equal to `height`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageViewCreateInfo::subresourceRange.layerCount` greater than or equal to `layers`.

If `renderPass` was specified with non-zero view masks, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have a `layerCount` greater than the index of the most significant bit set in any of those view masks.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must only specify a single mip level.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with the identity swizzle.

Width must be greater than 0.

Width must be less than or equal to `maxFramebufferWidth`.

Height must be greater than 0.

Height must be less than or equal to `maxFramebufferHeight`.

Layers must be greater than 0.

Layers must be less than or equal to `maxFramebufferLayers`.

If `renderPass` was specified with non-zero view masks, layers must be 1.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is a 2D or 2D array image view taken from a 3D image must not be a depth/stencil format.

If the `imagelessFramebuffer` feature is not enabled, `flags` must not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageCreateInfo::extent.height` greater than or equal to `height`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have been created with a `VkImageViewCreateInfo::subresourceRange.layerCount` greater than or equal to `layers`.

If `renderPass` was specified with non-zero view masks, each element of `pAttachments` that is used as an input, color, resolve, or depth/stencil attachment by `renderPass` must have a `layerCount` greater than the index of the most significant bit set in any of those view masks.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must only specify a single mip level.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with the identity swizzle.

Width must be greater than 0.

Width must be less than or equal to `maxFramebufferWidth`.

Height must be greater than 0.

Height must be less than or equal to `maxFramebufferHeight`.

Layers must be greater than 0.

Layers must be less than or equal to `maxFramebufferLayers`.

If `renderPass` was specified with non-zero view masks, layers must be 1.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is a 2D or 2D array image view taken from a 3D image must not be a depth/stencil format.

If the `imagelessFramebuffer` feature is not enabled, `flags` must not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`. 
If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the pNext chain must include a VkFramebufferAttachmentsCreateInfo structure.

- VUID-VkFramebufferCreateInfo-flags-03191
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the attachmentImageInfoCount member of a VkFramebufferAttachmentsCreateInfo structure in the pNext chain must be equal to either zero or attachmentCount.

- VUID-VkFramebufferCreateInfo-flags-04541
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the width member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure in the pNext chain that is used as an input, color, resolve or depth/stencil attachment in renderPass must be greater than or equal to width.

- VUID-VkFramebufferCreateInfo-flags-04542
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the height member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure in the pNext chain that is used as an input, color, resolve or depth/stencil attachment in renderPass must be greater than or equal to height.

- VUID-VkFramebufferCreateInfo-renderPass-03198
  If multiview is enabled for renderPass and flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the layerCount member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure included in the pNext chain used as an input, color, resolve, or depth/stencil attachment in renderPass must be greater than the maximum bit index set in the view mask in the subpasses in which it is used in renderPass.

- VUID-VkFramebufferCreateInfo-renderPass-04546
  If multiview is not enabled for renderPass and flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the layerCount member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure included in the pNext chain used as an input, color, resolve, or depth/stencil attachment in renderPass must be greater than or equal to layers.

- VUID-VkFramebufferCreateInfo-flags-03201
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the usage member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure included in the pNext chain that refers to an attachment used as a color attachment or resolve attachment by renderPass must include VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT.

- VUID-VkFramebufferCreateInfo-flags-03202
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the usage member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure included in the pNext chain that refers to an attachment used as a depth/stencil attachment by renderPass must include VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

- VUID-VkFramebufferCreateInfo-flags-03204
  If flags includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, the usage member of any element of the pAttachmentImageInfos member of a VkFramebufferAttachmentsCreateInfo structure included in the pNext chain that refers to an attachment used as an input attachment by renderPass must include VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT.
If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, at least one element of the `pViewFormats` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be equal to the corresponding value of `VkAttachmentDescription::format` used to create `renderPass`.

If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with `VkImageViewCreateInfo::viewType` not equal to `VK_IMAGE_VIEW_TYPE_3D`.

### Valid Usage (Implicit)

- **VUID-VkFramebufferCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_FRAMEBUFFER_CREATE_INFO`

- **VUID-VkFramebufferCreateInfo-pNext-pNext**
  `pNext` must be `NULL` or a pointer to a valid instance of `VkFramebufferAttachmentsCreateInfo`

- **VUID-VkFramebufferCreateInfo-sType-unique**
  The `sType` value of each struct in the `pNext` chain must be unique

- **VUID-VkFramebufferCreateInfo-flags-parameter**
  `flags` must be a valid combination of `VkFramebufferCreateFlagBits` values

- **VUID-VkFramebufferCreateInfo-renderPass-parameter**
  `renderPass` must be a valid `VkRenderPass` handle

- **VUID-VkFramebufferCreateInfo-commonparent**
  Both of `renderPass`, and the elements of `pAttachments` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

The `VkFramebufferAttachmentsCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkFramebufferAttachmentsCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t attachmentImageInfoCount;
    const VkFramebufferAttachmentImageInfo* pAttachmentImageInfos;
} VkFramebufferAttachmentsCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `attachmentImageInfoCount` is the number of attachments being described.
- `pAttachmentImageInfos` is a pointer to an array of `VkFramebufferAttachmentImageInfo`
structures, each structure describing a number of parameters of the corresponding attachment in a render pass instance.

Valid Usage (Implicit)

- VUID-VkFramebufferAttachmentsCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO

- VUID-VkFramebufferAttachmentsCreateInfo-pAttachmentImageInfos-parameter
  If attachmentImageInfoCount is not 0, pAttachmentImageInfos must be a valid pointer to an array of attachmentImageInfoCount valid VkFramebufferAttachmentImageInfo structures

The VkFramebufferAttachmentImageInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkFramebufferAttachmentImageInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageCreateFlags flags;
    VkImageUsageFlags usage;
    uint32_t width;
    uint32_t height;
    uint32_t layerCount;
    uint32_t viewFormatCount;
    const VkFormat* pViewFormats;
} VkFramebufferAttachmentImageInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is a bitmask of VkImageCreateFlagBits, matching the value of VkImageCreateInfo::flags used to create an image that will be used with this framebuffer.
- **usage** is a bitmask of VkImageUsageFlagBits, matching the value of VkImageCreateInfo::usage used to create an image used with this framebuffer.
- **width** is the width of the image view used for rendering.
- **height** is the height of the image view used for rendering.
- **layerCount** is the number of array layers of the image view used for rendering.
- **viewFormatCount** is the number of entries in the pViewFormats array, matching the value of VkImageFormatListCreateInfo::viewFormatCount used to create an image used with this framebuffer.
- **pViewFormats** is a pointer to an array of VkFormat values specifying all of the formats which can be used when creating views of the image, matching the value of VkImageFormatListCreateInfo::pViewFormats used to create an image used with this framebuffer.
Images that **can** be used with the framebuffer when beginning a render pass, as specified by `VkRenderPassAttachmentBeginInfo`, **must** be created with parameters that are identical to those specified here.

### Valid Usage (Implicit)

- **VUID-VkFramebufferAttachmentImageInfo-sType-sType**
  
  *sType must be* `VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO`

- **VUID-VkFramebufferAttachmentImageInfo-pNext-pNext**
  
  *pNext must be NULL*

- **VUID-VkFramebufferAttachmentImageInfo-flags-parameter**
  
  *flags must be a valid combination of `VkImageCreateFlagBits` values*

- **VUID-VkFramebufferAttachmentImageInfo-usage-parameter**
  
  *usage must be a valid combination of `VkImageUsageFlagBits` values*

- **VUID-VkFramebufferAttachmentImageInfo-usage-requiredbitmask**
  
  *usage must not be 0*

- **VUID-VkFramebufferAttachmentImageInfo-pViewFormats-parameter**
  
  If `viewFormatCount` is not 0, `pViewFormats must be a valid pointer to an array of `viewFormatCount` valid `VkFormat` values

Bits which **can** be set in `VkFramebufferCreateInfo::flags`, specifying options for framebuffers, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkFramebufferCreateFlagBits {
// Provided by VK_VERSION_1_2
    VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT = 0x00000001,
} VkFramebufferCreateFlagBits;
```

- **VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT** specifies that image views are not specified, and only attachment compatibility information will be provided via a `VkFramebufferAttachmentImageInfo` structure.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkFramebufferCreateFlags;
```

`VkFramebufferCreateFlags` is a bitmask type for setting a mask of zero or more `VkFramebufferCreateFlagBits`.

To destroy a framebuffer, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyFramebuffer(
    VkDevice device,
    VkFramebuffer framebuffer,
```
const VkAllocationCallbacks* pAllocator);

- **device** is the logical device that destroys the framebuffer.
- **framebuffer** is the handle of the framebuffer to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- VUID-vkDestroyFramebuffer-framebuffer-00892
  All submitted commands that refer to **framebuffer** must have completed execution

- VUID-vkDestroyFramebuffer-framebuffer-00893
  If **VkAllocationCallbacks** were provided when **framebuffer** was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyFramebuffer-framebuffer-00894
  If no **VkAllocationCallbacks** were provided when **framebuffer** was created, **pAllocator** must be **NULL**

### Valid Usage (Implicit)

- VUID-vkDestroyFramebuffer-device-parameter
  **device** must be a valid **VkDevice** handle

- VUID-vkDestroyFramebuffer-framebuffer-parameter
  If **framebuffer** is not **VK_NULL_HANDLE**, **framebuffer** must be a valid **VkFramebuffer** handle

- VUID-vkDestroyFramebuffer-pAllocator-parameter
  If **pAllocator** is not **NULL**, **pAllocator** must be a valid pointer to a valid **VkAllocationCallbacks** structure

- VUID-vkDestroyFramebuffer-framebuffer-parent
  If **framebuffer** is a valid handle, it must have been created, allocated, or retrieved from **device**

### Host Synchronization

- Host access to **framebuffer** must be externally synchronized

### 8.5. Render Pass Load Operations

Render pass load operations define the initial values of an attachment during a render pass instance.

Load operations for attachments with a depth/stencil format execute in the
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT pipeline stage. Load operations for attachments with a color format execute in the VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT pipeline stage. The load operation for each sample in an attachment happens-before any recorded command which accesses the sample in that render pass instance via that attachment or an alias.

Note
Because load operations always happen first, external synchronization with attachment access only needs to synchronize the load operations with previous commands; not the operations within the render pass instance.

Load operations only update values within the defined render area for the render pass instance. However, any writes performed by a load operation (as defined by its access masks) to a given attachment may read and write back any memory locations within the image subresource bound for that attachment. For depth/stencil images, writes to one aspect may also result in read-modify-write operations for the other aspect.

Note
As entire subresources could be accessed by load operations, applications cannot safely access values outside of the render area during a render pass instance when a load operation that modifies values is used.

Load operations that can be used for a render pass are:

```c
typedef enum VkAttachmentLoadOp {
    VK_ATTACHMENT_LOAD_OP_LOAD = 0,
    VK_ATTACHMENT_LOAD_OP_CLEAR = 1,
    VK_ATTACHMENT_LOAD_OP_DONT_CARE = 2,
} VkAttachmentLoadOp;
```

• **VK_ATTACHMENT_LOAD_OP_LOAD** specifies that the previous contents of the image within the render area will be preserved as the initial values. For attachments with a depth/stencil format, this uses the access type VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT. For attachments with a color format, this uses the access type VK_ACCESS_COLOR_ATTACHMENT_READ_BIT.

• **VK_ATTACHMENT_LOAD_OP_CLEAR** specifies that the contents within the render area will be cleared to a uniform value, which is specified when a render pass instance is begun. For attachments with a depth/stencil format, this uses the access type VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT. For attachments with a color format, this uses the access type VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT.

• **VK_ATTACHMENT_LOAD_OP_DONT_CARE** specifies that the previous contents within the area need not be preserved; the contents of the attachment will be undefined inside the render area. For attachments with a depth/stencil format, this uses the access type VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT. For attachments with a color format, this uses the access type VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT.

During a render pass instance, input and color attachments with color formats that have a
component size of 8, 16, or 32 bits must be represented in the attachment’s format throughout the instance. Attachments with other floating- or fixed-point color formats, or with depth components may be represented in a format with a precision higher than the attachment format, but must be represented with the same range. When such a component is loaded via the loadOp, it will be converted into an implementation-dependent format used by the render pass. Such components must be converted from the render pass format, to the format of the attachment, before they are resolved or stored at the end of a render pass instance via storeOp. Conversions occur as described in Numeric Representation and Computation and Fixed-Point Data Conversions.

8.6. Render Pass Store Operations

Render pass store operations define how values written to an attachment during a render pass instance are stored to memory.

Store operations for attachments with a depth/stencil format execute in the VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT pipeline stage. Store operations for attachments with a color format execute in the VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT pipeline stage. The store operation for each sample in an attachment happens-after any recorded command which accesses the sample via that attachment or an alias.

**Note**
Because store operations always happen after other accesses in a render pass instance, external synchronization with attachment access in an earlier render pass only needs to synchronize with the store operations; not the operations within the render pass instance. This does not apply when using VK_ATTACHMENT_STORE_OP_NONE.

Store operations only update values within the defined render area for the render pass instance. However, any writes performed by a store operation (as defined by its access masks) to a given attachment may read and write back any memory locations within the image subresource bound for that attachment. For depth/stencil images writes to one aspect may also result in read-modify-write operations for the other aspect.

**Note**
As entire subresources could be accessed by store operations, applications cannot safely access values outside of the render area via aliased resources during a render pass instance when a store operation that modifies values is used.

Possible values of VkAttachmentDescription::storeOp and stencilStoreOp, specifying how the contents of the attachment are treated, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkAttachmentStoreOp {
    VK_ATTACHMENT_STORE_OP_STORE = 0,
    VK_ATTACHMENT_STORE_OP_DONT_CARE = 1,
    // Provided by VK_VERSION_1_3
    VK_ATTACHMENT_STORE_OP_NONE = 1000301000,
};
```
• **VK_ATTACHMENT_STORE_OP_STORE** specifies the contents generated during the render pass and within the render area are written to memory. For attachments with a depth/stencil format, this uses the access type **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT**. For attachments with a color format, this uses the access type **VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT**.

• **VK_ATTACHMENT_STORE_OP_DONT_CARE** specifies the contents within the render area are not needed after rendering, and may be discarded; the contents of the attachment will be undefined inside the render area. For attachments with a depth/stencil format, this uses the access type **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT**. For attachments with a color format, this uses the access type **VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT**.

• **VK_ATTACHMENT_STORE_OP_NONE** specifies the contents within the render area are not accessed by the store operation as long as no values are written to the attachment during the render pass. If values are written during the render pass, this behaves identically to **VK_ATTACHMENT_STORE_OP_DONT_CARE** and with matching access semantics.

Note

**VK_ATTACHMENT_STORE_OP_DONT_CARE** can cause contents generated during previous render passes to be discarded before reaching memory, even if no write to the attachment occurs during the current render pass.

### 8.7. Render Pass Multisample Resolve Operations

Render pass multisample resolve operations combine sample values from a single pixel in a multisample attachment and store the result to the corresponding pixel in a single sample attachment.

Multisample resolve operations for attachments execute in the **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** pipeline stage. A final resolve operation for all pixels in the render area happens after any recorded command which writes a pixel via the multisample attachment to be resolved or an explicit alias of it in the subpass that it is specified. Any single sample attachment specified for use in a multisample resolve operation may have its contents modified at any point once rendering begins for the render pass instance. Reads from the multisample attachment can be synchronized with **VK_ACCESS_COLOR_ATTACHMENT_READ_BIT**. Access to the single sample attachment can be synchronized with **VK_ACCESS_COLOR_ATTACHMENT_READ_BIT** and **VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT**. These pipeline stage and access types are used whether the attachments are color or depth/stencil attachments.

When using render pass objects, a subpass dependency specified with the above pipeline stages and access flags will ensure synchronization with multisample resolve operations for any attachments that were last accessed by that subpass. This allows later subpasses to read resolved values as input attachments.

Resolve operations only update values within the defined render area for the render pass instance. However, any writes performed by a resolve operation (as defined by its access masks) to a given attachment may read and write back any memory locations within the image subresource bound.
for that attachment. For depth/stencil images writes to one aspect may also result in read-modify-write operations for the other aspect.

**Note**

As entire subresources could be accessed by multisample resolve operations, applications cannot safely access values outside of the render area via aliased resources during a render pass instance when a multisample resolve operation is performed.

Multisample values in a multisample attachment are combined according to the resolve mode used:

```c
// Provided by VK_VERSION_1_2
typedef enum VkResolveModeFlagBits {
    VK_RESOLVE_MODE_NONE = 0,
    VK_RESOLVE_MODE_SAMPLE_ZERO_BIT = 0x00000001,
    VK_RESOLVE_MODE_AVERAGE_BIT = 0x00000002,
    VK_RESOLVE_MODE_MIN_BIT = 0x00000004,
    VK_RESOLVE_MODE_MAX_BIT = 0x00000008,
} VkResolveModeFlagBits;
```

- **VK_RESOLVE_MODE_NONE** indicates that no resolve operation is done.
- **VK_RESOLVE_MODE_SAMPLE_ZERO_BIT** indicates that result of the resolve operation is equal to the value of sample 0.
- **VK_RESOLVE_MODE_AVERAGE_BIT** indicates that result of the resolve operation is the average of the sample values.
- **VK_RESOLVE_MODE_MIN_BIT** indicates that result of the resolve operation is the minimum of the sample values.
- **VK_RESOLVE_MODE_MAX_BIT** indicates that result of the resolve operation is the maximum of the sample values.

When no resolve mode is specified, **VK_RESOLVE_MODE_AVERAGE_BIT** is used.

```c
// Provided by VK_VERSION_1_2
typedef VkFlags VkResolveModeFlags;
```

**VkResolveModeFlags** is a bitmask type for setting a mask of zero or more **VkResolveModeFlagBits**.

### 8.8. Render Pass Commands

An application records the commands for a render pass instance one subpass at a time, by beginning a render pass instance, iterating over the subpasses to record commands for that subpass, and then ending the render pass instance.

To begin a render pass instance, call:
void vkCmdBeginRenderPass(
    VkCommandBuffer commandBuffer,
    const VkRenderPassBeginInfo* pRenderPassBegin,
    VkSubpassContents contents);

- `commandBuffer` is the command buffer in which to record the command.
- `pRenderPassBegin` is a pointer to a `VkRenderPassBeginInfo` structure specifying the render pass to begin an instance of, and the framebuffer the instance uses.
- `contents` is a `VkSubpassContents` value specifying how the commands in the first subpass will be provided.

After beginning a render pass instance, the command buffer is ready to record the commands for the first subpass of that render pass.

**Valid Usage**

- VUID-vkCmdBeginRenderPass-initialLayout-00895
  If any of the `initialLayout` or `finalLayout` member of the `VkAttachmentDescription` structures or the `layout` member of the `VkAttachmentReference` structures specified when creating the render pass specified in the `renderPass` member of `pRenderPassBegin` is `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL` then the corresponding attachment image view of the framebuffer specified in the `framebuffer` member of `pRenderPassBegin` must have been created with a usage value including `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`

- VUID-vkCmdBeginRenderPass-initialLayout-01758
  If any of the `initialLayout` or `finalLayout` member of the `VkAttachmentDescription` structures or the `layout` member of the `VkAttachmentReference` structures specified when creating the render pass specified in the `renderPass` member of `pRenderPassBegin` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` then the corresponding attachment image view of the framebuffer specified in the `framebuffer` member of `pRenderPassBegin` must have been created with a usage value including `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`

- VUID-vkCmdBeginRenderPass-initialLayout-02842
  If any of the `initialLayout` or `finalLayout` member of the `VkAttachmentDescription` structures or the `layout` member of the `VkAttachmentReference` structures specified when creating the render pass specified in the `renderPass` member of `pRenderPassBegin` is `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL` then the corresponding attachment image view of the framebuffer specified in the `framebuffer` member of `pRenderPassBegin` must have been created with a usage value including `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`
If any of the stencilInitialLayout or stencilFinalLayout member of the VkAttachmentDescriptionStencilLayout structures or the stencilLayout member of the VkAttachmentReferenceStencilLayout structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_SRC_BIT

If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_DST_BIT

If the initialLayout member of any of the VkAttachmentDescription structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is not VK_IMAGE_LAYOUT_UNDEFINED, then each such initialLayout must be equal to the current layout of the corresponding attachment image subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin

The srcStageMask members of any element of the pDependencies member of VkRenderPassCreateInfo used to create renderPass must be supported by the capabilities of the queue family identified by the queueFamilyIndex member of the VkCommandPoolCreateInfo used to create the command pool which commandBuffer was allocated from.

If the initialLayout member of any of the VkAttachmentDescription structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is not VK_IMAGE_LAYOUT_UNDEFINED, then each such initialLayout must be equal to the current layout of the corresponding attachment image subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin
The `dstStageMask` members of any element of the `pDependencies` member of `VkRenderPassCreateInfo` used to create `renderPass` must be supported by the capabilities of the queue family identified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` used to create the command pool which `commandBuffer` was allocated from

- VUID-vkCmdBeginRenderPass-framebuffer-02532
  For any attachment in `framebuffer` that is used by `renderPass` and is bound to memory locations that are also bound to another attachment used by `renderPass`, and if at least one of those uses causes either attachment to be written to, both attachments must have had the `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` set

- VUID-vkCmdBeginRenderPass-framebuffer-09045
  If any attachments specified in `framebuffer` are used by `renderPass` and are bound to overlapping memory locations, there must be only one that is used as a color attachment, depth/stencil, or resolve attachment in any subpass

**Valid Usage (Implicit)**

- VUID-vkCmdBeginRenderPass-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- VUID-vkCmdBeginRenderPass-pRenderPassBegin-parameter
  `pRenderPassBegin` must be a valid pointer to a valid `VkRenderPassBeginInfo` structure

- VUID-vkCmdBeginRenderPass-contents-parameter
  `contents` must be a valid `VkSubpassContents` value

- VUID-vkCmdBeginRenderPass-commandBuffer-recording
  `commandBuffer` must be in the recording state

- VUID-vkCmdBeginRenderPass-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

- VUID-vkCmdBeginRenderPass-renderpass
  This command must only be called outside of a render pass instance

- VUID-vkCmdBeginRenderPass-bufferlevel
  `commandBuffer` must be a primary `VkCommandBuffer`

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
Alternatively to begin a render pass, call:

```c
// Provided by VK_VERSION_1_2
void vkCmdBeginRenderPass2(
    VkCommandBuffer commandBuffer,
    const VkRenderPassBeginInfo* pRenderPassBegin,
    const VkSubpassBeginInfo* pSubpassBeginInfo);
```

- `commandBuffer` is the command buffer in which to record the command.
- `pRenderPassBegin` is a pointer to a `VkRenderPassBeginInfo` structure specifying the render pass to begin an instance of, and the framebuffer the instance uses.
- `pSubpassBeginInfo` is a pointer to a `VkSubpassBeginInfo` structure containing information about the subpass which is about to begin rendering.

After beginning a render pass instance, the command buffer is ready to record the commands for the first subpass of that render pass.
then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-vkCmdBeginRenderPass2-initialLayout-02844
If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_READONLY_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-vkCmdBeginRenderPass2-stencilInitialLayout-02845
If any of the stencilInitialLayout or stencilFinalLayout member of the VkAttachmentDescriptionStencilLayout structures or the stencilLayout member of the VkAttachmentReferenceStencilLayout structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-vkCmdBeginRenderPass2-initialLayout-03097
If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

• VUID-vkCmdBeginRenderPass2-initialLayout-03098
If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_SRC_BIT

• VUID-vkCmdBeginRenderPass2-initialLayout-03099
If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_DST_BIT
If the `initialLayout` member of any of the `VkAttachmentDescription` structures specified when creating the `renderPass` member of `pRenderPassBegin` is not `VK_IMAGE_LAYOUT_UNDEFINED`, then each such `initialLayout` must be equal to the current layout of the corresponding attachment image subresource of the framebuffer specified in the `framebuffer` member of `pRenderPassBegin`.

The `srcStageMask` members of any element of the `pDependencies` member of `VkRenderPassCreateInfo` used to create `renderPass` must be supported by the capabilities of the queue family identified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` used to create the command pool which `commandBuffer` was allocated from.

The `dstStageMask` members of any element of the `pDependencies` member of `VkRenderPassCreateInfo` used to create `renderPass` must be supported by the capabilities of the queue family identified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` used to create the command pool which `commandBuffer` was allocated from.

For any attachment in `framebuffer` that is used by `renderPass` and is bound to memory locations that are also bound to another attachment used by `renderPass`, and if at least one of those uses causes either attachment to be written to, both attachments must have had the `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` set.

If any attachments specified in `framebuffer` are used by `renderPass` and are bound to overlapping memory locations, there must be only one that is used as a color attachment, depth/stencil, or resolve attachment in any subpass.

Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pRenderPassBegin` must be a valid pointer to a valid `VkRenderPassBeginInfo` structure
- `pSubpassBeginInfo` must be a valid pointer to a valid `VkSubpassBeginInfo` structure
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- This command must only be called outside of a render pass instance
**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

**Command Properties**

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The `VkRenderPassBeginInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkRenderPassBeginInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkRenderPass       renderPass;
    VkFramebuffer      framebuffer;
    VkRect2D           renderArea;
    uint32_t           clearValueCount;
    const VkClearValue* pClearValues;
} VkRenderPassBeginInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `renderPass` is the render pass to begin an instance of.
- `framebuffer` is the framebuffer containing the attachments that are used with the render pass.
- `renderArea` is the render area that is affected by the render pass instance, and is described in more detail below.
- `clearValueCount` is the number of elements in `pClearValues`.
- `pClearValues` is a pointer to an array of `clearValueCount` `VkClearValue` structures containing clear values for each attachment, if the attachment uses a `loadOp` value of `VK_ATTACHMENT_LOAD_OP_CLEAR` or if the attachment has a depth/stencil format and uses a `stencilLoadOp` value of `VK_ATTACHMENT_LOAD_OP_CLEAR`. The array is indexed by attachment...
number. Only elements corresponding to cleared attachments are used. Other elements of pClearValues are ignored.

renderArea is the render area that is affected by the render pass instance. The effects of attachment load, store and multisample resolve operations are restricted to the pixels whose x and y coordinates fall within the render area on all attachments. The render area extends to all layers of framebuffer. The application must ensure (using scissor if necessary) that all rendering is contained within the render area. The render area must be contained within the framebuffer dimensions.

**Valid Usage**

- VUID-VkRenderPassBeginInfo-clearValueCount-00902
  
  clearValueCount must be greater than the largest attachment index in renderPass specifying a loadOp (or stencilLoadOp, if the attachment has a depth/stencil format) of VK_ATTACHMENT_LOAD_OP_CLEAR

- VUID-VkRenderPassBeginInfo-clearValueCount-04962
  
  If clearValueCount is not 0, pClearValues must be a valid pointer to an array of clearValueCount VkClearValue unions

- VUID-VkRenderPassBeginInfo-renderPass-00904
  
  renderPass must be compatible with the renderPass member of the VkFramebufferCreateInfo structure specified when creating framebuffer

- VUID-VkRenderPassBeginInfo-None-08996
  
  If VkDeviceGroupRenderPassBeginInfo::deviceRenderAreaCount is 0, renderArea.extent.width must be greater than 0

- VUID-VkRenderPassBeginInfo-None-08997
  
  If VkDeviceGroupRenderPassBeginInfo::deviceRenderAreaCount is 0, renderArea.extent.height must be greater than 0

- VUID-VkRenderPassBeginInfo-pNext-02850
  
  If the pNext chain does not contain VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount member is equal to 0, renderArea.offset.x must be greater than or equal to 0

- VUID-VkRenderPassBeginInfo-pNext-02851
  
  If the pNext chain does not contain VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount member is equal to 0, renderArea.offset.y must be greater than or equal to 0

- VUID-VkRenderPassBeginInfo-pNext-02852
  
  If the pNext chain does not contain VkDeviceGroupRenderPassBeginInfo or its deviceRenderAreaCount member is equal to 0, renderArea.offset.x + renderArea.extent.width must be less than or equal to VkFramebufferCreateInfo::width the framebuffer was created with
If the `pNext` chain does not contain `VkDeviceGroupRenderPassBeginInfo` or its deviceRenderAreaCount member is equal to 0, `renderArea.offset.y + renderArea.extent.height` must be less than or equal to `VkFramebufferCreateInfo::height` the framebuffer was created with.

If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, `offset.x + extent.width` of each element of `pDeviceRenderAreas` must be less than or equal to `VkFramebufferCreateInfo::width` the framebuffer was created with.

If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, `offset.y + extent.height` of each element of `pDeviceRenderAreas` must be less than or equal to `VkFramebufferCreateInfo::height` the framebuffer was created with.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that did not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, and the `pNext` chain includes a `VkRenderPassAttachmentBeginInfo` structure, its `attachmentCount` must be zero.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `attachmentCount` of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be equal to the value of `VkFramebufferAttachmentsCreateInfo::attachmentImageInfoCount` used to create `framebuffer`.

If `framebuffer` was created with a `VkDevice` as `framebuffer` and `renderPass`.

If `framebuffer` was created with a `VkImageView` of an image created with a value of `VkImageCreateInfo::flags` equal to the `flags` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.

If `framebuffer` was created with a `VkImageView` with an inherited usage equal to the `usage` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must have been created on the same `VkDevice` as `framebuffer` and `renderPass`.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be a `VkImageView` of an image created with a value of `VkImageCreateInfo::flags` equal to the `flags` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be a `VkImageView` with an inherited usage equal to the `usage` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be a `VkImageView` of an image created with a value of `VkImageCreateInfo::flags` equal to the `flags` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.

If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be a `VkImageView` with an inherited usage equal to the `usage` member of the corresponding element of `VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos` used to create `framebuffer`.
VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView with a width equal to the width member of the corresponding element of VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos used to create framebuffer

• VUID-VkRenderPassBeginInfo-framebuffer-03212
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView with a height equal to the height member of the corresponding element of VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos used to create framebuffer

• VUID-VkRenderPassBeginInfo-framebuffer-03213
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView of an image created with a value of VkImageViewCreateInfo::subresourceRange.layerCount equal to the layerCount member of the corresponding element of VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos used to create framebuffer

• VUID-VkRenderPassBeginInfo-framebuffer-03214
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView of an image created with a value of VkImageViewCreateInfo::viewFormatCount equal to the viewFormatCount member of the corresponding element of VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos used to create framebuffer

• VUID-VkRenderPassBeginInfo-framebuffer-03215
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView of an image created with a set of elements in VkImageViewCreateInfo::pViewFormats equal to the set of elements in the pViewFormats member of the corresponding element of VkFramebufferAttachmentsCreateInfo::pAttachmentImageInfos used to create framebuffer

• VUID-VkRenderPassBeginInfo-framebuffer-03216
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView of an image created with a value of VkAttachmentDescription::format equal to the corresponding value of VkAttachmentDescription::format in renderPass

• VUID-VkRenderPassBeginInfo-framebuffer-09047
  If framebuffer was created with a VkFramebufferCreateInfo::flags value that included VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, each element of the pAttachments member of a VkRenderPassAttachmentBeginInfo structure included in the pNext chain must be a VkImageView of an image created with a value of VkImageCreateInfo::samples equal to the corresponding value of VkAttachmentDescription::samples in renderPass
Valid Usage (Implicit)

- VUID-VkRenderPassBeginInfo-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO`

- VUID-VkRenderPassBeginInfo-pNext-pNext
  
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkDeviceGroupRenderPassBeginInfo` or `VkRenderPassAttachmentBeginInfo`

- VUID-VkRenderPassBeginInfo-sType-unique
  
  The `sType` value of each struct in the `pNext` chain must be unique

- VUID-VkRenderPassBeginInfo-renderPass-parameter
  
  `renderPass` must be a valid `VkRenderPass` handle

- VUID-VkRenderPassBeginInfo-framebuffer-parameter
  
  `framebuffer` must be a valid `VkFramebuffer` handle

- VUID-VkRenderPassBeginInfo-commonparent
  
  Both of `framebuffer`, and `renderPass` must have been created, allocated, or retrieved from the same `VkDevice`

The `VkSubpassBeginInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSubpassBeginInfo {
    VkStructureType sType;
    const void* pNext;
    VkSubpassContents contents;
} VkSubpassBeginInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `contents` is a `VkSubpassContents` value specifying how the commands in the next subpass will be provided.

Valid Usage (Implicit)

- VUID-VkSubpassBeginInfo-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO`

- VUID-VkSubpassBeginInfo-pNext-pNext
  
  `pNext` must be `NULL`

- VUID-VkSubpassBeginInfo-contents-parameter
  
  `contents` must be a valid `VkSubpassContents` value

Possible values of `vkCmdBeginRenderPass::contents`, specifying how the commands in the first
subpass will be provided, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSubpassContents {
    VK_SUBPASS_CONTENTS_INLINE = 0,
    VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS = 1,
} VkSubpassContents;
```

- **VK_SUBPASS_CONTENTS_INLINE** specifies that the contents of the subpass will be recorded inline in the primary command buffer, and secondary command buffers **must** not be executed within the subpass.

- **VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS** specifies that the contents are recorded in secondary command buffers that will be called from the primary command buffer, and `vkCmdExecuteCommands` is the only valid command in the command buffer until `vkCmdNextSubpass` or `vkCmdEndRenderPass`.

If the `pNext` chain of `VkRenderPassBeginInfo` or `VkRenderingInfo` includes a `VkDeviceGroupRenderPassBeginInfo` structure, then that structure includes a device mask and set of render areas for the render pass instance.

The `VkDeviceGroupRenderPassBeginInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceGroupRenderPassBeginInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t deviceMask;
    uint32_t deviceRenderAreaCount;
    const VkRect2D* pDeviceRenderAreas;
} VkDeviceGroupRenderPassBeginInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `deviceMask` is the device mask for the render pass instance.
- `deviceRenderAreaCount` is the number of elements in the `pDeviceRenderAreas` array.
- `pDeviceRenderAreas` is a pointer to an array of `VkRect2D` structures defining the render area for each physical device.

The `deviceMask` serves several purposes. It is an upper bound on the set of physical devices that can be used during the render pass instance, and the initial device mask when the render pass instance begins. In addition, commands transitioning to the next subpass in a render pass instance and commands ending the render pass instance, and, accordingly render pass load, store, and multisample resolve operations and subpass dependencies corresponding to the render pass instance, are executed on the physical devices included in the device mask provided here.

If `deviceRenderAreaCount` is not zero, then the elements of `pDeviceRenderAreas` override the value of
VkRenderPassBeginInfo::renderArea, and provide a render area specific to each physical device. These render areas serve the same purpose as VkRenderPassBeginInfo::renderArea, including controlling the region of attachments that are cleared by VK_ATTACHMENT_LOAD_OP_CLEAR and that are resolved into resolve attachments.

If this structure is not present, the render pass instance’s device mask is the value of VkDeviceGroupCommandBufferBeginInfo::deviceMask. If this structure is not present or if deviceRenderAreaCount is zero, VkRenderPassBeginInfo::renderArea is used for all physical devices.

Valid Usage

- **VUID-VkDeviceGroupRenderPassBeginInfo-deviceMask-00905**
  deviceMask must be a valid device mask value

- **VUID-VkDeviceGroupRenderPassBeginInfo-deviceMask-00906**
  deviceMask must not be zero

- **VUID-VkDeviceGroupRenderPassBeginInfo-deviceMask-00907**
  deviceMask must be a subset of the command buffer’s initial device mask

- **VUID-VkDeviceGroupRenderPassBeginInfo-deviceRenderAreaCount-00908**
  deviceRenderAreaCount must either be zero or equal to the number of physical devices in the logical device

- **VUID-VkDeviceGroupRenderPassBeginInfo-offset-06166**
  The offset.x member of any element of pDeviceRenderAreas must be greater than or equal to 0

- **VUID-VkDeviceGroupRenderPassBeginInfo-offset-06167**
  The offset.y member of any element of pDeviceRenderAreas must be greater than or equal to 0

- **VUID-VkDeviceGroupRenderPassBeginInfo-offset-06168**
  The sum of the offset.x and extent.width members of any element of pDeviceRenderAreas must be less than or equal to maxFramebufferWidth

- **VUID-VkDeviceGroupRenderPassBeginInfo-offset-06169**
  The sum of the offset.y and extent.height members of any element of pDeviceRenderAreas must be less than or equal to maxFramebufferHeight

- **VUID-VkDeviceGroupRenderPassBeginInfo-extent-08998**
  The extent.width member of any element of pDeviceRenderAreas must be greater than 0

- **VUID-VkDeviceGroupRenderPassBeginInfo-extent-08999**
  The extent.height member of any element of pDeviceRenderAreas must be greater than 0

Valid Usage (Implicit)

- **VUID-VkDeviceGroupRenderPassBeginInfo-sType-sType**
  sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO

- **VUID-VkDeviceGroupRenderPassBeginInfo-pDeviceRenderAreas-parameter**
  If deviceRenderAreaCount is not 0, pDeviceRenderAreas must be a valid pointer to an array of
The `VkRenderPassAttachmentBeginInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkRenderPassAttachmentBeginInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t attachmentCount;
    const VkImageView* pAttachments;
} VkRenderPassAttachmentBeginInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `attachmentCount` is the number of attachments.
- `pAttachments` is a pointer to an array of `VkImageView` handles, each of which will be used as the corresponding attachment in the render pass instance.

### Valid Usage

- VUID-VkRenderPassAttachmentBeginInfo-pAttachments-03218 Each element of `pAttachments` must only specify a single mip level.
- VUID-VkRenderPassAttachmentBeginInfo-pAttachments-03219 Each element of `pAttachments` must have been created with the identity swizzle.
- VUID-VkRenderPassAttachmentBeginInfo-pAttachments-04114 Each element of `pAttachments` must have been created with `VkImageViewCreateInfo`::`viewType` not equal to `VK_IMAGE_VIEW_TYPE_3D`.

### Valid Usage (Implicit)

- VUID-VkRenderPassAttachmentBeginInfo-sType-sType `sType` must be `VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO`.
- VUID-VkRenderPassAttachmentBeginInfo-pAttachments-parameter If `attachmentCount` is not 0, `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkImageView` handles.

To query the render area granularity, call:

```c
// Provided by VK_VERSION_1_0
void vkGetRenderAreaGranularity(
    VkDevice device,
    VkRenderPass renderPass,
    ...);
```
• device is the logical device that owns the render pass.
• renderPass is a handle to a render pass.
• pGranularity is a pointer to a VkExtent2D structure in which the granularity is returned.

The conditions leading to an optimal renderArea are:

• the offset.x member in renderArea is a multiple of the width member of the returned VkExtent2D (the horizontal granularity).
• the offset.y member in renderArea is a multiple of the height member of the returned VkExtent2D (the vertical granularity).
• either the extent.width member in renderArea is a multiple of the horizontal granularity or offset.x+extent.width is equal to the width of the framebuffer in the VkRenderPassBeginInfo.
• either the extent.height member in renderArea is a multiple of the vertical granularity or offset.y+extent.height is equal to the height of the framebuffer in the VkRenderPassBeginInfo.

Subpass dependencies are not affected by the render area, and apply to the entire image subresources attached to the framebuffer as specified in the description of automatic layout transitions. Similarly, pipeline barriers are valid even if their effect extends outside the render area.

Valid Usage (Implicit)

• VUID-vkGetRenderAreaGranularity-device-parameter
device must be a valid VkDevice handle
• VUID-vkGetRenderAreaGranularity-renderPass-parameter
renderPass must be a valid VkRenderPass handle
• VUID-vkGetRenderAreaGranularity-pGranularity-parameter
pGranularity must be a valid pointer to a VkExtent2D structure
• VUID-vkGetRenderAreaGranularity-renderPass-parent
renderPass must have been created, allocated, or retrieved from device

To transition to the next subpass in the render pass instance after recording the commands for a subpass, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdNextSubpass(
    VkCommandBuffer commandBuffer,
    VkSubpassContents contents);
```

• commandBuffer is the command buffer in which to record the command.
• contents specifies how the commands in the next subpass will be provided, in the same fashion
as the corresponding parameter of `vkCmdBeginRenderPass`.

The subpass index for a render pass begins at zero when `vkCmdBeginRenderPass` is recorded, and increments each time `vkCmdNextSubpass` is recorded.

After transitioning to the next subpass, the application can record the commands for that subpass.

### Valid Usage

- **VUID-vkCmdNextSubpass-None-00909**
  The current subpass index must be less than the number of subpasses in the render pass minus one

### Valid Usage (Implicit)

- **VUID-vkCmdNextSubpass-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- **VUID-vkCmdNextSubpass-contents-parameter**
  `contents` must be a valid `VkSubpassContents` value
- **VUID-vkCmdNextSubpass-commandBuffer-recording**
  `commandBuffer` must be in the recording state
- **VUID-vkCmdNextSubpass-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- **VUID-vkCmdNextSubpass-renderpass**
  This command must only be called inside of a render pass instance
- **VUID-vkCmdNextSubpass-bufferlevel**
  `commandBuffer` must be a primary `VkCommandBuffer`

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
To transition to the next subpass in the render pass instance after recording the commands for a subpass, call:

```c
// Provided by VK_VERSION_1_2
void vkCmdNextSubpass2(
    VkCommandBuffer commandBuffer,
    const VkSubpassBeginInfo* pSubpassBeginInfo,
    const VkSubpassEndInfo* pSubpassEndInfo);
```

- `commandBuffer` is the command buffer in which to record the command.
- `pSubpassBeginInfo` is a pointer to a `VkSubpassBeginInfo` structure containing information about the subpass which is about to begin rendering.
- `pSubpassEndInfo` is a pointer to a `VkSubpassEndInfo` structure containing information about how the previous subpass will be ended.

`vkCmdNextSubpass2` is semantically identical to `vkCmdNextSubpass`, except that it is extensible, and that `contents` is provided as part of an extensible structure instead of as a flat parameter.

### Valid Usage

- VUID-vkCmdNextSubpass2-None-03102
  The current subpass index **must** be less than the number of subpasses in the render pass minus one

### Valid Usage (Implicit)

- VUID-vkCmdNextSubpass2-commandBuffer-parameter
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- VUID-vkCmdNextSubpass2-pSubpassBeginInfo-parameter
  `pSubpassBeginInfo` **must** be a valid pointer to a valid `VkSubpassBeginInfo` structure
- VUID-vkCmdNextSubpass2-pSubpassEndInfo-parameter
  `pSubpassEndInfo` **must** be a valid pointer to a valid `VkSubpassEndInfo` structure
- VUID-vkCmdNextSubpass2-commandBuffer-recording
  `commandBuffer` **must** be in the **recording** state
• VUID-vkCmdNextSubpass2-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

• VUID-vkCmdNextSubpass2-renderpass
  This command must only be called inside of a render pass instance

• VUID-vkCmdNextSubpass2-bufferlevel
  `commandBuffer` must be a primary `VkCommandBuffer`

### Host Synchronization

• Host access to `commandBuffer` must be externally synchronized

• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

### Command Properties

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To record a command to end a render pass instance after recording the commands for the last subpass, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdEndRenderPass(
  VkCommandBuffer commandBuffer);
```

• `commandBuffer` is the command buffer in which to end the current render pass instance.

Ending a render pass instance performs any multisample resolve operations on the final subpass.

### Valid Usage

• VUID-vkCmdEndRenderPass-None-00910
  The current subpass index must be equal to the number of subpasses in the render pass minus one

• VUID-vkCmdEndRenderPass-None-06170
  The current render pass instance must not have been begun with `vkCmdBeginRendering`

• VUID-vkCmdEndRenderPass-None-07004
If `vkCmdBeginQuery` was called within a subpass of the render pass, the corresponding `vkCmdEndQuery` must have been called subsequently within the same subpass.

### Valid Usage (Implicit)

- VUID-vkCmdEndRenderPass-commandBuffer-parameter
  
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- VUID-vkCmdEndRenderPass-commandBuffer-recording
  
  `commandBuffer` must be in the recording state.

- VUID-vkCmdEndRenderPass-commandBuffer-cmdpool
  
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.

- VUID-vkCmdEndRenderPass-renderpass
  
  This command must only be called inside of a render pass instance.

- VUID-vkCmdEndRenderPass-bufferlevel
  
  `commandBuffer` must be a primary `VkCommandBuffer`.

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

### Command Properties

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</tr>
</tbody>
</table>

To record a command to end a render pass instance after recording the commands for the last subpass, call:

```c
// Provided by VK_VERSION_1_2
void vkCmdEndRenderPass2(
    VkCommandBuffer commandBuffer,    // Provided by VK_VERSION_1_2
    const VkSubpassEndInfo* pSubpassEndInfo);
```

- `commandBuffer` is the command buffer in which to end the current render pass instance.
• pSubpassEndInfo is a pointer to a VkSubpassEndInfo structure containing information about how the last subpass will be ended.

vkCmdEndRenderPass2 is semantically identical to vkCmdEndRenderPass, except that it is extensible.

### Valid Usage

- VUID-vkCmdEndRenderPass2-None-03103
  The current subpass index must be equal to the number of subpasses in the render pass minus one

- VUID-vkCmdEndRenderPass2-None-06171
  The current render pass instance must not have been begun with vkCmdBeginRendering

- VUID-vkCmdEndRenderPass2-None-07005
  If vkCmdBeginQuery* was called within a subpass of the render pass, the corresponding vkCmdEndQuery* must have been called subsequently within the same subpass

### Valid Usage (Implicit)

- VUID-vkCmdEndRenderPass2-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdEndRenderPass2-pSubpassEndInfo-parameter
  pSubpassEndInfo must be a valid pointer to a valid VkSubpassEndInfo structure

- VUID-vkCmdEndRenderPass2-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdEndRenderPass2-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

- VUID-vkCmdEndRenderPass2-renderpass
  This command must only be called inside of a render pass instance

- VUID-vkCmdEndRenderPass2-bufferlevel
  commandBuffer must be a primary VkCommandBuffer

### Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

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8.9. Common Render Pass Data Races (Informative)

Due to the complexity of how rendering is performed, there are several ways an application can accidentally introduce a data race, usually by doing something that may seem benign but actually cannot be supported. This section indicates a number of the more common cases as guidelines to help avoid them.

8.9.1. Sampling from a read-only attachment

Vulkan includes read-only layouts for depth/stencil images, that allow the images to be both read during a render pass for the purposes of depth/stencil tests, and read as a non-attachment.

However, because VK_ATTACHMENT_STORE_OP_STORE and VK_ATTACHMENT_STORE_OP_DONT_CARE may perform write operations, even if no recorded command writes to an attachment, reading from an image while also using it as an attachment with these store operations can result in a data race. If the reads from the non-attachment are performed in a fragment shader where the accessed samples match those covered by the fragment shader, no data race will occur as store operations...
are guaranteed to operate after fragment shader execution for the set of samples the fragment covers. Notably, input attachments can also be used for this case. Reading other samples or in any other shader stage can result in unexpected behavior due to the potential for a data race, and validation errors should be generated for doing so. In practice, many applications have shipped reading samples outside of the covered fragment without any observable issue, but there is no guarantee that this will always work, and it is not advisable to rely on this in new or re-worked code bases. As VK_ATTACHMENT_STORE_OP_NONE is guaranteed to perform no writes, applications wishing to read an image as both an attachment and a non-attachment should make use of this store operation, coupled with a load operation that also performs no writes.

8.9.2. Non-overlapping access between resources

When relying on non-overlapping accesses between attachments and other resources, it is important to note that load and store operations have fairly wide alignment requirements - potentially affecting entire subresources and adjacent depth/stencil aspects. This makes it invalid to access a non-attachment subresource that is simultaneously being used as an attachment where either access performs a write operation.

8.9.3. Depth/stencil and input attachments

When rendering to only the depth OR stencil aspect of an image, an input attachment accessing the other aspect will always result in a data race.

8.9.4. Synchronization Options

There are several synchronization options available to synchronize between accesses to resources within a render pass. Some of the options are outlined below:

- A VkSubpassDependency in a render pass object can synchronize attachment writes and multisample resolve operations from a prior subpass for subsequent input attachment reads.
- A vkCmdPipelineBarrier inside a subpass can synchronize prior attachment writes in the subpass with subsequent input attachment reads.
Chapter 9. Shaders

A shader specifies programmable operations that execute for each vertex, control point, tessellated vertex, primitive, fragment, or workgroup in the corresponding stage(s) of the graphics and compute pipelines.

Graphics pipelines include vertex shader execution as a result of primitive assembly, followed, if enabled, by tessellation control and evaluation shaders operating on patches, geometry shaders, if enabled, operating on primitives, and fragment shaders, if present, operating on fragments generated by Rasterization. In this specification, vertex, tessellation control, tessellation evaluation and geometry shaders are collectively referred to as pre-rasterization shader stages and occur in the logical pipeline before rasterization. The fragment shader occurs logically after rasterization.

Only the compute shader stage is included in a compute pipeline. Compute shaders operate on compute invocations in a workgroup.

Shaders can read from input variables, and read from and write to output variables. Input and output variables can be used to transfer data between shader stages, or to allow the shader to interact with values that exist in the execution environment. Similarly, the execution environment provides constants describing capabilities.

Shader variables are associated with execution environment-provided inputs and outputs using built-in decorations in the shader. The available decorations for each stage are documented in the following subsections.

9.1. Shader Modules

Shader modules contain shader code and one or more entry points. Shaders are selected from a shader module by specifying an entry point as part of pipeline creation. The stages of a pipeline can use shaders that come from different modules. The shader code defining a shader module must be in the SPIR-V format, as described by the Vulkan Environment for SPIR-V appendix.

Shader modules are represented by VkShaderModule handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkShaderModule)
```

To create a shader module, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateShaderModule(
    VkDevice device,
    const VkShaderModuleCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkShaderModule* pShaderModule);
```

- device is the logical device that creates the shader module.
• `pCreateInfo` is a pointer to a `VkShaderModuleCreateInfo` structure.
• `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
• `pShaderModule` is a pointer to a `VkShaderModule` handle in which the resulting shader module object is returned.

Once a shader module has been created, any entry points it contains can be used in pipeline shader stages as described in Compute Pipelines and Graphics Pipelines.

Valid Usage

• VUID-vkCreateShaderModule-pCreateInfo-06905
  If `pCreateInfo` is not NULL, `pCreateInfo->pNext` must be NULL

Valid Usage (Implicit)

• VUID-vkCreateShaderModule-device-parameter
  `device` must be a valid `VkDevice` handle
• VUID-vkCreateShaderModule-pCreateInfo-parameter
  `pCreateInfo` must be a valid pointer to a valid `VkShaderModuleCreateInfo` structure
• VUID-vkCreateShaderModule-pAllocator-parameter
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
• VUID-vkCreateShaderModule-pShaderModule-parameter
  `pShaderModule` must be a valid pointer to a `VkShaderModule` handle

Return Codes

Success

• `VK_SUCCESS`

Failure

• `VK_ERROR_OUT_OF_HOST_MEMORY`
• `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkShaderModuleCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkShaderModuleCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkShaderModuleCreateFlags flags;
    size_t codeSize;
    const uint32_t* pCode;
} VkShaderModuleCreateInfo;
```
VkShaderModuleCreateInfo;

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **flags** is reserved for future use.
- **codeSize** is the size, in bytes, of the code pointed to by **pCode**.
- **pCode** is a pointer to code that is used to create the shader module. The type and format of the code is determined from the content of the memory addressed by **pCode**.

### Valid Usage

- VUID-VkShaderModuleCreateInfo-codeSize-08735
  - `codeSize` must be a multiple of 4

- VUID-VkShaderModuleCreateInfo-pCode-08736
  - **pCode** must point to valid SPIR-V code, formatted and packed as described by the Khronos SPIR-V Specification

- VUID-VkShaderModuleCreateInfo-pCode-08737
  - **pCode** must adhere to the validation rules described by the Validation Rules within a Module section of the SPIR-V Environment appendix

- VUID-VkShaderModuleCreateInfo-pCode-08738
  - **pCode** must declare the Shader capability for SPIR-V code

- VUID-VkShaderModuleCreateInfo-pCode-08739
  - **pCode** must not declare any capability that is not supported by the API, as described by the Capabilities section of the SPIR-V Environment appendix

- VUID-VkShaderModuleCreateInfo-pCode-08740
  - and **pCode** declares any of the capabilities listed in the SPIR-V Environment appendix, one of the corresponding requirements must be satisfied

- VUID-VkShaderModuleCreateInfo-pCode-08741
  - **pCode** must not declare any SPIR-V extension that is not supported by the API, as described by the Extension section of the SPIR-V Environment appendix

- VUID-VkShaderModuleCreateInfo-pCode-08742
  - and **pCode** declares any of the SPIR-V extensions listed in the SPIR-V Environment appendix, one of the corresponding requirements must be satisfied

- VUID-VkShaderModuleCreateInfo-codeSize-01085
  - `codeSize` must be greater than 0

### Valid Usage (Implicit)

- VUID-VkShaderModuleCreateInfo-sType-sType
  - **sType** must be `VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO`

- VUID-VkShaderModuleCreateInfo-flags-zerobitmask
  - **flags** must be zero
flags must be 0

- VUID-VkShaderModuleCreateInfo-pCode-parameter
  pCode must be a valid pointer to an array of \(\frac{\text{codeSize}}{4}\) uint32_t values

// Provided by VK_VERSION_1_0
typedef VkFlags VkShaderModuleCreateFlags;

\text{VkShaderModuleCreateFlags} is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy a shader module, call:

// Provided by VK_VERSION_1_0
void vkDestroyShaderModule(
    VkDevice device,
    VkShaderModule shaderModule,
    const VkAllocationCallbacks* pAllocator);

- device is the logical device that destroys the shader module.
- shaderModule is the handle of the shader module to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

A shader module can be destroyed while pipelines created using its shaders are still in use.

Valid Usage

- VUID-vkDestroyShaderModule-shaderModule-01092
  If VkAllocationCallbacks were provided when shaderModule was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyShaderModule-shaderModule-01093
  If no VkAllocationCallbacks were provided when shaderModule was created, pAllocator must be NULL

Valid Usage (Implicit)

- VUID-vkDestroyShaderModule-device-parameter
device must be a valid VkDevice handle

- VUID-vkDestroyShaderModule-shaderModule-parameter
  If shaderModule is not VK_NULL_HANDLE, shaderModule must be a valid VkShaderModule handle

- VUID-vkDestroyShaderModule-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid
 VkAllocationCallbacks structure
• VUID-vkDestroyShaderModule-shaderModule-parent
  If shaderModule is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization
• Host access to shaderModule must be externally synchronized

9.2. Binding Shaders

Before a shader can be used it must be first bound to the command buffer.

Calling vkCmdBindPipeline binds all stages corresponding to the VkPipelineBindPoint.

The following table describes the relationship between shader stages and pipeline bind points:

<table>
<thead>
<tr>
<th>Shader stage</th>
<th>Pipeline bind point</th>
<th>behavior controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>• VK_SHADER_STAGE_VERTEX_BIT</td>
<td>VK_PIPELINE_BIND_POINT_GRAPHICS</td>
<td>all drawing commands</td>
</tr>
<tr>
<td>• VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT</td>
<td>VK_PIPELINE_BIND_POINT_GRAPHICS</td>
<td></td>
</tr>
<tr>
<td>• VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT</td>
<td>VK_PIPELINE_BIND_POINT_GRAPHICS</td>
<td></td>
</tr>
<tr>
<td>• VK_SHADER_STAGE_GEOMETRY_BIT</td>
<td>VK_PIPELINE_BIND_POINT_GRAPHICS</td>
<td></td>
</tr>
<tr>
<td>• VK_SHADER_STAGE_FRAGMENT_BIT</td>
<td>VK_PIPELINE_BIND_POINT_GRAPHICS</td>
<td></td>
</tr>
<tr>
<td>• VK_SHADER_STAGE_COMPUTE_BIT</td>
<td>VK_PIPELINE_BIND_POINT_COMPUTE</td>
<td>all dispatch commands</td>
</tr>
</tbody>
</table>

9.3. Shader Execution

At each stage of the pipeline, multiple invocations of a shader may execute simultaneously. Further, invocations of a single shader produced as the result of different commands may execute simultaneously. The relative execution order of invocations of the same shader type is undefined. Shader invocations may complete in a different order than that in which the primitives they originated from were drawn or dispatched by the application. However, fragment shader outputs are written to attachments in rasterization order.

The relative execution order of invocations of different shader types is largely undefined. However, when invoking a shader whose inputs are generated from a previous pipeline stage, the shader invocations from the previous stage are guaranteed to have executed far enough to generate input values for all required inputs.
9.3.1. Shader Termination

A shader invocation that is terminated has finished executing instructions.

Executing `OpReturn` in the entry point, or executing `OpTerminateInvocation` in any function will terminate an invocation. Implementations may also terminate a shader invocation when `OpKill` is executed in any function; otherwise it becomes a helper invocation.

In addition to the above conditions, helper invocations are terminated when all non-helper invocations in the same derivative group either terminate or become helper invocations via `OpKill`.

A shader stage for a given command completes execution when all invocations for that stage have terminated.

9.4. Shader Memory Access Ordering

The order in which image or buffer memory is read or written by shaders is largely undefined. For some shader types (vertex, tessellation evaluation, and in some cases, fragment), even the number of shader invocations that may perform loads and stores is undefined.

In particular, the following rules apply:

- **Vertex** and tessellation evaluation shaders will be invoked at least once for each unique vertex, as defined in those sections.
- **Fragment** shaders will be invoked zero or more times, as defined in that section.
- The relative execution order of invocations of the same shader type is undefined. A store issued by a shader when working on primitive B might complete prior to a store for primitive A, even if primitive A is specified prior to primitive B. This applies even to fragment shaders; while fragment shader outputs are always written to the framebuffer in rasterization order, stores executed by fragment shader invocations are not.
- The relative execution order of invocations of different shader types is largely undefined.

**Note**

The above limitations on shader invocation order make some forms of synchronization between shader invocations within a single set of primitives unimplementable. For example, having one invocation poll memory written by another invocation assumes that the other invocation has been launched and will complete its writes in finite time.

The Memory Model appendix defines the terminology and rules for how to correctly communicate between shader invocations, such as when a write is Visible-To a read, and what constitutes a Data Race.

Applications must not cause a data race.

The SPIR-V SubgroupMemory, CrossWorkgroupMemory, and AtomicCounterMemory memory semantics are ignored. Sequentially consistent atoms and barriers are not supported and SequentiallyConsistent is treated as AcquireRelease. SequentiallyConsistent should not be
9.5. Shader Inputs and Outputs

Data is passed into and out of shaders using variables with input or output storage class, respectively. User-defined inputs and outputs are connected between stages by matching their Location decorations. Additionally, data can be provided by or communicated to special functions provided by the execution environment using BuiltIn decorations.

In many cases, the same BuiltIn decoration can be used in multiple shader stages with similar meaning. The specific behavior of variables decorated as BuiltIn is documented in the following sections.

9.6. Vertex Shaders

Each vertex shader invocation operates on one vertex and its associated vertex attribute data, and outputs one vertex and associated data. Graphics pipelines must include a vertex shader, and the vertex shader stage is always the first shader stage in the graphics pipeline.

9.6.1. Vertex Shader Execution

A vertex shader must be executed at least once for each vertex specified by a drawing command. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view. During execution, the shader is presented with the index of the vertex and instance for which it has been invoked. Input variables declared in the vertex shader are filled by the implementation with the values of vertex attributes associated with the invocation being executed.

If the same vertex is specified multiple times in a drawing command (e.g. by including the same index value multiple times in an index buffer) the implementation may reuse the results of vertex shading if it can statically determine that the vertex shader invocations will produce identical results.

Note

It is implementation-dependent when and if results of vertex shading are reused, and thus how many times the vertex shader will be executed. This is true also if the vertex shader contains stores or atomic operations (see vertexPipelineStoresAndAtomics).

9.7. Tessellation Control Shaders

The tessellation control shader is used to read an input patch provided by the application and to produce an output patch. Each tessellation control shader invocation operates on an input patch (after all control points in the patch are processed by a vertex shader) and its associated data, and outputs a single control point of the output patch and its associated data, and can also output additional per-patch data. The input patch is sized according to the patchControlPoints member of VkPipelineTessellationStateCreateInfo, as part of input assembly.
The size of the output patch is controlled by the OpExecutionMode OutputVertices specified in the tessellation control or tessellation evaluation shaders, which must be specified in at least one of the shaders. The size of the input and output patches must each be greater than zero and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize.

9.7.1. Tessellation Control Shader Execution

A tessellation control shader is invoked at least once for each output vertex in a patch. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

Inputs to the tessellation control shader are generated by the vertex shader. Each invocation of the tessellation control shader can read the attributes of any incoming vertices and their associated data. The invocations corresponding to a given patch execute logically in parallel, with undefined relative execution order. However, the OpControlBarrier instruction can be used to provide limited control of the execution order by synchronizing invocations within a patch, effectively dividing tessellation control shader execution into a set of phases. Tessellation control shaders will read undefined values if one invocation reads a per-vertex or per-patch output written by another invocation at any point during the same phase, or if two invocations attempt to write different values to the same per-patch output in a single phase.

9.8. Tessellation Evaluation Shaders

The Tessellation Evaluation Shader operates on an input patch of control points and their associated data, and a single input barycentric coordinate indicating the invocation’s relative position within the subdivided patch, and outputs a single vertex and its associated data.

9.8.1. Tessellation Evaluation Shader Execution

A tessellation evaluation shader is invoked at least once for each unique vertex generated by the tessellator. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

9.9. Geometry Shaders

The geometry shader operates on a group of vertices and their associated data assembled from a single input primitive, and emits zero or more output primitives and the group of vertices and their associated data required for each output primitive.

9.9.1. Geometry Shader Execution

A geometry shader is invoked at least once for each primitive produced by the tessellation stages, or at least once for each primitive generated by primitive assembly when tessellation is not in use. A shader can request that the geometry shader runs multiple instances. A geometry shader is invoked at least once for each instance. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.
9.10. Fragment Shaders

Fragment shaders are invoked as a fragment operation in a graphics pipeline. Each fragment shader invocation operates on a single fragment and its associated data. With few exceptions, fragment shaders do not have access to any data associated with other fragments and are considered to execute in isolation of fragment shader invocations associated with other fragments.

9.11. Compute Shaders

Compute shaders are invoked via `vkCmdDispatch` and `vkCmdDispatchIndirect` commands. In general, they have access to similar resources as shader stages executing as part of a graphics pipeline.

Compute workloads are formed from groups of work items called workgroups and processed by the compute shader in the current compute pipeline. A workgroup is a collection of shader invocations that execute the same shader, potentially in parallel. Compute shaders execute in global workgroups which are divided into a number of local workgroups with a size that can be set by assigning a value to the `LocalSize` or `LocalSizeId` execution mode or via an object decorated by the `WorkgroupSize` decoration. An invocation within a local workgroup can share data with other members of the local workgroup through shared variables and issue memory and control flow barriers to synchronize with other members of the local workgroup.

9.12. Interpolation decorations

Variables in the Input storage class in a fragment shader's interface are interpolated from the values specified by the primitive being rasterized.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolation decorations can be present on input and output variables in pre-rasterization shaders but have no effect on the interpolation performed.</td>
</tr>
</tbody>
</table>

An undecorated input variable will be interpolated with perspective-correct interpolation according to the primitive type being rasterized. Lines and polygons are interpolated in the same way as the primitive’s clip coordinates. If the `NoPerspective` decoration is present, linear interpolation is instead used for lines and polygons. For points, as there is only a single vertex, input values are never interpolated and instead take the value written for the single vertex.

If the `Flat` decoration is present on an input variable, the value is not interpolated, and instead takes its value directly from the provoking vertex. Fragment shader inputs that are signed or unsigned integers, integer vectors, or any double-precision floating-point type must be decorated with Flat.

Interpolation of input variables is performed at an implementation-defined position within the fragment area being shaded. The position is further constrained as follows:

- If the `Centroid` decoration is used, the interpolation position used for the variable must also fall within the bounds of the primitive being rasterized.
- If the Sample decoration is used, the interpolation position used for the variable must be at the position of the sample being shaded by the current fragment shader invocation.

- If a sample count of 1 is used, the interpolation position must be at the center of the fragment area.

**Note**

As Centroid restricts the possible interpolation position to the covered area of the primitive, the position can be forced to vary between neighboring fragments when it otherwise would not. Derivatives calculated based on these differing locations can produce inconsistent results compared to undecorated inputs. It is recommended that input variables used in derivative calculations are not decorated with Centroid.

### 9.13. Static Use

A SPIR-V module declares a global object in memory using the `OpVariable` instruction, which results in a pointer `x` to that object. A specific entry point in a SPIR-V module is said to **statically use** that object if that entry point’s call tree contains a function containing a instruction with `x` as an `id` operand. A shader entry point also **statically uses** any variables explicitly declared in its interface.


A *scope* describes a set of shader invocations, where each such set is a *scope instance*. Each invocation belongs to one or more scope instances, but belongs to no more than one scope instance for each scope.

The operations available between invocations in a given scope instance vary, with smaller scopes generally able to perform more operations, and with greater efficiency.


All invocations executed in a Vulkan instance fall into a single *cross device scope instance*.

Whilst the CrossDevice scope is defined in SPIR-V, it is disallowed in Vulkan. API synchronization commands can be used to communicate between devices.

#### 9.14.2. Device

All invocations executed on a single device form a *device scope instance*.

If the vulkanMemoryModel and vulkanMemoryModelDeviceScope features are enabled, this scope is represented in SPIR-V by the Device Scope, which can be used as a Memory Scope for barrier and atomic operations.

There is no method to synchronize the execution of these invocations within SPIR-V, and this can only be done with API synchronization primitives.

Invocations executing on different devices in a device group operate in separate device scope
9.14.3. Queue Family

Invocations executed by queues in a given queue family form a queue family scope instance.

This scope is identified in SPIR-V as the QueueFamily Scope if the vulkanMemoryModel feature is enabled, or if not, the Device Scope, which can be used as a Memory Scope for barrier and atomic operations.

There is no method to synchronize the execution of these invocations within SPIR-V, and this can only be done with API synchronization primitives.

Each invocation in a queue family scope instance must be in the same device scope instance.


Any shader invocations executed as the result of a single command such as vkCmdDispatch or vkCmdDraw form a command scope instance. For indirect drawing commands with drawCount greater than one, invocations from separate draws are in separate command scope instances.

There is no specific Scope for communication across invocations in a command scope instance. As this has a clear boundary at the API level, coordination here can be performed in the API, rather than in SPIR-V.

Each invocation in a command scope instance must be in the same queue-family scope instance.

For shaders without defined workgroups, this set of invocations forms an invocation group as defined in the SPIR-V specification.

9.14.5. Primitive

Any fragment shader invocations executed as the result of rasterization of a single primitive form a primitive scope instance.

There is no specific Scope for communication across invocations in a primitive scope instance.

Any generated helper invocations are included in this scope instance.

Each invocation in a primitive scope instance must be in the same command scope instance.

Any input variables decorated with Flat are uniform within a primitive scope instance.


A local workgroup is a set of invocations that can synchronize and share data with each other using memory in the Workgroup storage class.

The Workgroup Scope can be used as both an Execution Scope and Memory Scope for barrier and atomic operations.
Each invocation in a local workgroup must be in the same command scope instance.

Only compute shaders have defined workgroups - other shader types cannot use workgroup functionality. For shaders that have defined workgroups, this set of invocations forms an invocation group as defined in the SPIR-V specification.

The amount of storage consumed by the variables declared with the Workgroup storage class is implementation-dependent. However, the amount of storage consumed may not exceed the largest block size that would be obtained if all active variables declared with Workgroup storage class were assigned offsets in an arbitrary order by successively taking the smallest valid offset according to the Standard Storage Buffer Layout rules, and with Boolean values considered as 32-bit integer values for the purpose of this calculation. (This is equivalent to using the GLSL std430 layout rules.)

9.14.7. Subgroup

A subgroup (see the subsection “Control Flow” of section 2 of the SPIR-V 1.3 Revision 1 specification) is a set of invocations that can synchronize and share data with each other efficiently.

The Subgroup Scope can be used as both an Execution Scope and Memory Scope for barrier and atomic operations. Other subgroup features allow the use of group operations with subgroup scope.

For shaders that have defined workgroups, each invocation in a subgroup must be in the same local workgroup.

In other shader stages, each invocation in a subgroup must be in the same device scope instance.

Only shader stages that support subgroup operations have defined subgroups.

Note

In shaders, there are two kinds of uniformity that are of primary interest to applications: uniform within an invocation group (a.k.a. dynamically uniform), and uniform within a subgroup scope.

While one could make the assumption that being uniform in invocation group implies being uniform in subgroup scope, it is not necessarily the case for shader stages without defined workgroups.

For shader stages with defined workgroups however, the relationship between invocation group and subgroup scope is well defined as a subgroup is a subset of the workgroup, and the workgroup is the invocation group. If a value is uniform in invocation group, it is by definition also uniform in subgroup scope. This is important if writing code like:

```
uniform texture2DTextures[]; uint dynamicallyUniformValue = gl_WorkGroupID.x; vec4 value = texelFetch(Texture
[dynamicallyUniformValue],
coord, 0);

vec4 subgroupUniformValue = 378
```
In shader stages without defined workgroups, this gets complicated. Due to scoping rules, there is no guarantee that a subgroup is a subset of the invocation group, which in turn defines the scope for dynamically uniform. In graphics, the invocation group is a single draw command, except for multi-draw situations, and indirect draws with drawCount > 1, where there are multiple invocation groups, one per `DrawIndex`.

```c
// Assume SubgroupSize = 8, where 3 draws are packed together.
// Two subgroups were generated.
uniform texture2D Textures[];
```

```c
uint dynamicallyUniformValue = gl_DrawID;

uint notActuallyDynamicallyUniformAnymore = subgroupBroadcastFirst(dynamicallyUniformValue);

vec4 value = texelFetch(Textures[notActuallyDynamicallyUniformAnymore], coord, 0);
```

Another problematic scenario is when a shader attempts to help the compiler notice that a value is uniform in subgroup scope to potentially improve performance.

```c
layout(location = 0) flat in dynamicallyUniformIndex;
// Vertex shader might have emitted a value that depends only on gl_DrawID.
// making it dynamically uniform.
// Give knowledge to compiler that the flat input is dynamically uniform,
// as this is not a guarantee otherwise.
```

```c
uint uniformIndex = subgroupBroadcastFirst(dynamicallyUniformIndex);

DrawData d = UBO.perDrawData[uniformIndex];
```

For implementations where subgroups are packed across draws, the implementation must make sure to handle descriptor indexing correctly. From the specification’s point of view, a dynamically uniform index does not require `NonUniform` decoration, and such an implementation will likely either promote descriptor indexing into `NonUniform` on its own, or handle non-uniformity implicitly.


A *quad scope instance* is formed of four shader invocations.
In a fragment shader, each invocation in a quad scope instance is formed of invocations in neighboring framebuffer locations \((x_i, y_i)\), where:

- \(i\) is the index of the invocation within the scope instance.
- \(w\) and \(h\) are the number of pixels the fragment covers in the \(x\) and \(y\) axes.
- \(w\) and \(h\) are identical for all participating invocations.
- \((x_0) = (x_1 - w) = (x_2) = (x_3 - w)\)
- \((y_0) = (y_1) = (y_2 - h) = (y_3 - h)\)
- Each invocation has the same layer and sample indices.

In all shaders, each invocation in a quad scope instance is formed of invocations in adjacent subgroup invocation indices \((s_i)\), where:

- \(i\) is the index of the invocation within the quad scope instance.
- \((s_0) = (s_1 - 1) = (s_2 - 2) = (s_3 - 3)\)
- \(s_0\) is an integer multiple of 4.

Each invocation in a quad scope instance must be in the same subgroup.

In a fragment shader, each invocation in a quad scope instance must be in the same primitive scope instance.

Fragment and compute shaders have defined quad scope instances. If the `quadOperationsInAllStages` limit is supported, any shader stages that support subgroup operations also have defined quad scope instances.

### 9.14.9. Invocation

The smallest `scope` is a single invocation; this is represented by the `Invocation Scope` in SPIR-V.

Fragment shader invocations must be in a primitive scope instance.

Invocations in shaders that have defined workgroups must be in a local workgroup.

Invocations in shaders that have a defined subgroup scope must be in a subgroup.

Invocations in shaders that have a defined quad scope must be in a quad scope instance.

All invocations in all stages must be in a command scope instance.

### 9.15. Group Operations

Group operations are executed by multiple invocations within a scope instance; with each invocation involved in calculating the result. This provides a mechanism for efficient communication between invocations in a particular scope instance.

Group operations all take a `Scope` defining the desired scope instance to operate within. Only the `Subgroup` scope can be used for these operations; the `subgroupSupportedOperations` limit defines
which types of operation can be used.

9.15.1. Basic Group Operations

Basic group operations include the use of \texttt{OpGroupNonUniformElect}, \texttt{OpControlBarrier}, \texttt{OpMemoryBarrier}, and atomic operations.

\texttt{OpGroupNonUniformElect} can be used to choose a single invocation to perform a task for the whole group. Only the invocation with the lowest id in the group will return \texttt{true}.

The \texttt{Memory Model} appendix defines the operation of barriers and atomics.

9.15.2. Vote Group Operations

The vote group operations allow invocations within a group to compare values across a group. The types of votes enabled are:

- Do all active group invocations agree that an expression is true?
- Do any active group invocations evaluate an expression to true?
- Do all active group invocations have the same value of an expression?

\textit{Note}

These operations are useful in combination with control flow in that they allow for developers to check whether conditions match across the group and choose potentially faster code-paths in these cases.

9.15.3. Arithmetic Group Operations

The arithmetic group operations allow invocations to perform scans and reductions across a group. The operators supported are add, mul, min, max, and, or, xor.

For reductions, every invocation in a group will obtain the cumulative result of these operators applied to all values in the group. For exclusive scans, each invocation in a group will obtain the cumulative result of these operators applied to all values in invocations with a lower index in the group. Inclusive scans are identical to exclusive scans, except the cumulative result includes the operator applied to the value in the current invocation.

The order in which these operators are applied is implementation-dependent.

9.15.4. Ballot Group Operations

The ballot group operations allow invocations to perform more complex votes across the group. The ballot functionality allows all invocations within a group to provide a boolean value and get as a result what each invocation provided as their boolean value. The broadcast functionality allows values to be broadcast from an invocation to all other invocations within the group.
9.15.5. Shuffle Group Operations

The shuffle group operations allow invocations to read values from other invocations within a group.

9.15.6. Shuffle Relative Group Operations

The shuffle relative group operations allow invocations to read values from other invocations within the group relative to the current invocation in the group. The relative operations supported allow data to be shifted up and down through the invocations within a group.

9.15.7. Clustered Group Operations

The clustered group operations allow invocations to perform an operation among partitions of a group, such that the operation is only performed within the group invocations within a partition. The partitions for clustered group operations are consecutive power-of-two size groups of invocations and the cluster size must be known at pipeline creation time. The operations supported are add, mul, min, max, and, or, xor.

9.16. Quad Group Operations

Quad group operations (OpGroupNonUniformQuad\*) are a specialized type of group operations that only operate on quad scope instances. Whilst these instructions do include a Scope parameter, this scope is always overridden; only the quad scope instance is included in its execution scope.

Fragment shaders that statically execute quad group operations must launch sufficient invocations to ensure their correct operation; additional helper invocations are launched for framebuffer locations not covered by rasterized fragments if necessary.

The index used to select participating invocations is i, as described for a quad scope instance, defined as the quad index in the SPIR-V specification.

For OpGroupNonUniformQuadBroadcast this value is equal to Index. For OpGroupNonUniformQuadSwap, it is equal to the implicit Index used by each participating invocation.

9.17. Derivative Operations

Derivative operations calculate the partial derivative for an expression \( P \) as a function of an invocation’s \( x \) and \( y \) coordinates.

Derivative operations operate on a set of invocations known as a derivative group as defined in the SPIR-V specification. A derivative group is equivalent to the primitive scope instance for a fragment shader invocation.

Derivatives are calculated assuming that \( P \) is piecewise linear and continuous within the derivative group. All dynamic instances of explicit derivative instructions (OpDPdx\*, OpDPdy\*, and OpFwidth\*) must be executed in control flow that is uniform within a derivative group. For other derivative operations, results are undefined if a dynamic instance is executed in control flow that is not uniform within the derivative group.
Fragment shaders that statically execute derivative operations **must** launch sufficient invocations to ensure their correct operation; additional **helper invocations** are launched for framebuffer locations not covered by rasterized fragments if necessary.

Derivative operations calculate their results as the difference between the result of $P$ across invocations in the quad. For fine derivative operations ($\text{OpDPdxFine}$ and $\text{OpDPdyFine}$), the values of $\text{DPdx}(P_i)$ are calculated as

$$\text{DPdx}(P_0) = \text{DPdx}(P_1) = P_1 - P_0$$

$$\text{DPdx}(P_2) = \text{DPdx}(P_3) = P_3 - P_2$$

and the values of $\text{DPdy}(P_i)$ are calculated as

$$\text{DPdy}(P_0) = \text{DPdy}(P_2) = P_2 - P_0$$

$$\text{DPdy}(P_1) = \text{DPdy}(P_3) = P_3 - P_1$$

where $i$ is the index of each invocation as described in *Quad*.

Coarse derivative operations ($\text{OpDPdxCoarse}$ and $\text{OpDPdyCoarse}$), calculate their results in roughly the same manner, but **may** only calculate two values instead of four (one for each of $\text{DPdx}$ and $\text{DPdy}$), reusing the same result no matter the originating invocation. If an implementation does this, it **should** use the fine derivative calculations described for $P_o$.

---

**Note**

Derivative values are calculated between fragments rather than pixels. If the fragment shader invocations involved in the calculation cover multiple pixels, these operations cover a wider area, resulting in larger derivative values. This in turn will result in a coarser LOD being selected for image sampling operations using derivatives.

Applications may want to account for this when using multi-pixel fragments; if pixel derivatives are desired, applications should use explicit derivative operations and divide the results by the size of the fragment in each dimension as follows:

$$\text{DPdx}(P_n)' = \text{DPdx}(P_n) / w$$

$$\text{DPdy}(P_n)' = \text{DPdy}(P_n) / h$$

where $w$ and $h$ are the size of the fragments in the quad, and $\text{DPdx}(P_n)'$ and $\text{DPdy}(P_n)'$ are the pixel derivatives.
The results for \texttt{OpDPdx} and \texttt{OpDPdy} may be calculated as either fine or coarse derivatives, with implementations favouring the most efficient approach. Implementations must choose coarse or fine consistently between the two.

Executing \texttt{OpFwidthFine}, \texttt{OpFwidthCoarse}, or \texttt{OpFwidth} is equivalent to executing the corresponding \texttt{OpDPdx*} and \texttt{OpDPdy*} instructions, taking the absolute value of the results, and summing them.

Executing an \texttt{OpImage*Sample*ImplicitLod} instruction is equivalent to executing \texttt{OpDPdx(Coordinate)} and \texttt{OpDPdy(Coordinate)}, and passing the results as the \texttt{Grad} operands \texttt{dx} and \texttt{dy}.

\begin{itemize}
  \item \textbf{Note}
  \begin{itemize}
    \item It is expected that using the \texttt{ImplicitLod} variants of sampling functions will be substantially more efficient than using the \texttt{ExplicitLod} variants with explicitly generated derivatives.
  \end{itemize}
\end{itemize}

\section*{9.18. Helper Invocations}

When performing derivative or quad group operations in a fragment shader, additional invocations may be spawned in order to ensure correct results. These additional invocations are known as helper invocations and can be identified by a non-zero value in the \texttt{HelperInvocation} built-in. Stores and atomics performed by helper invocations must not have any effect on memory except for the \texttt{Function}, \texttt{Private} and \texttt{Output} storage classes, and values returned by atomic instructions in helper invocations are undefined.

\begin{itemize}
  \item \textbf{Note}
  \begin{itemize}
    \item While storage to \texttt{Output} storage class has an effect even in helper invocations, it does not mean that helper invocations have an effect on the framebuffer. \texttt{Output} variables in fragment shaders can be read from as well, and they behave more like \texttt{Private} variables for the duration of the shader invocation.
  \end{itemize}
\end{itemize}

For group operations other than derivative and quad group operations, helper invocations may be treated as inactive even if they would be considered otherwise active.

Helper invocations may become permanently inactive if all invocations in a quad scope instance become helper invocations.
Chapter 10. Pipelines

The following figure shows a block diagram of the Vulkan pipelines. Some Vulkan commands specify geometric objects to be drawn or computational work to be performed, while others specify state controlling how objects are handled by the various pipeline stages, or control data transfer between memory organized as images and buffers. Commands are effectively sent through a processing pipeline, either a graphics pipeline, or a compute pipeline.

The first stage of the graphics pipeline (Input Assembler) assembles vertices to form geometric primitives such as points, lines, and triangles, based on a requested primitive topology. In the next stage (Vertex Shader) vertices can be transformed, computing positions and attributes for each vertex. If tessellation and/or geometry shaders are supported, they can then generate multiple primitives from a single input primitive, possibly changing the primitive topology or generating additional attribute data in the process.

The final resulting primitives are clipped to a clip volume in preparation for the next stage, Rasterization. The rasterizer produces a series of fragments associated with a region of the framebuffer, from a two-dimensional description of a point, line segment, or triangle. These fragments are processed by fragment operations to determine whether generated values will be written to the framebuffer. Fragment shading determines the values to be written to the framebuffer attachments. Framebuffer operations then read and write the color and depth/stencil attachments of the framebuffer for a given subpass of a render pass instance. The attachments can be used as input attachments in the fragment shader in a later subpass of the same render pass.

The compute pipeline is a separate pipeline from the graphics pipeline, which operates on one-, two-, or three-dimensional workgroups which can read from and write to buffer and image memory.

This ordering is meant only as a tool for describing Vulkan, not as a strict rule of how Vulkan is implemented, and we present it only as a means to organize the various operations of the pipelines. Actual ordering guarantees between pipeline stages are explained in detail in the synchronization chapter.
Each pipeline is controlled by a monolithic object created from a description of all of the shader stages and any relevant fixed-function stages. 

Linking the whole pipeline together allows the optimization of shaders based on their input/outputs and eliminates expensive draw time state validation.

A pipeline object is bound to the current state using `vkCmdBindPipeline`. Any pipeline object state that is specified as dynamic is not applied to the current state when the pipeline object is bound, but is instead set by dynamic state setting commands.

No state, including dynamic state, is inherited from one command buffer to another.

Compute, and graphics pipelines are each represented by `VkPipeline` handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipeline)
```

### 10.1. Compute Pipelines

Compute pipelines consist of a single static compute shader stage and the pipeline layout.

The compute pipeline represents a compute shader and is created by calling `vkCreateComputePipelines` with `module` and `pName` selecting an entry point from a shader module, where that entry point defines a valid compute shader, in the `VkPipelineShaderStageCreateInfo` structure contained within the `VkComputePipelineCreateInfo` structure.

To create compute pipelines, call:

```c
// Provided by VK_VERSION_1_0
```
VkResult vkCreateComputePipelines(VkDevice device, VkPipelineCache pipelineCache, uint32_t createInfoCount, const VkComputePipelineCreateInfo* pCreateInfos, const VkAllocationCallbacks* pAllocator, VkPipeline* pPipelines);

- **device** is the logical device that creates the compute pipelines.

- **pipelineCache** is either VK_NULL_HANDLE, indicating that pipeline caching is disabled; or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.

- **createInfoCount** is the length of the pCreateInfos and pPipelines arrays.

- **pCreateInfos** is a pointer to an array of VkComputePipelineCreateInfo structures.

- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

- **pPipelines** is a pointer to an array of VkPipeline handles in which the resulting compute pipeline objects are returned.

### Valid Usage

- **VUID-vkCreateComputePipelines-flags-00695**
  If the flags member of any element of pCreateInfos contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and the basePipelineIndex member of that same element is not -1, basePipelineIndex must be less than the index into pCreateInfos that corresponds to that element

- **VUID-vkCreateComputePipelines-flags-00696**
  If the flags member of any element of pCreateInfos contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, the base pipeline must have been created with the VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT flag set

- **VUID-vkCreateComputePipelines-pipelineCache-02873**
  If pipelineCache was created with VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT, host access to pipelineCache must be externally synchronized

### Valid Usage (Implicit)

- **VUID-vkCreateComputePipelines-device-parameter**
  device must be a valid VkDevice handle

- **VUID-vkCreateComputePipelines-pipelineCache-parameter**
  If pipelineCache is not VK_NULL_HANDLE, pipelineCache must be a valid VkPipelineCache handle

- **VUID-vkCreateComputePipelines-pCreateInfos-parameter**
  pCreateInfos must be a valid pointer to an array of createInfoCount valid VkComputePipelineCreateInfo structures
If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.

`pPipelines` must be a valid pointer to an array of `createInfoCount` `VkPipeline` handles.

`createInfoCount` must be greater than 0.

If `pipelineCache` is a valid handle, it must have been created, allocated, or retrieved from device.

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkComputePipelineCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkComputePipelineCreateInfo {
  VkStructureType sType;
  const void* pNext;
  VkPipelineCreateFlags flags;
  VkPipelineShaderStageCreateInfo stage;
  VkPipelineLayout layout;
  VkPipeline basePipelineHandle;
  int32_t basePipelineIndex;
} VkComputePipelineCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is a bitmask of `VkPipelineCreateFlagBits` specifying how the pipeline will be generated.
- `stage` is a `VkPipelineShaderStageCreateInfo` structure describing the compute shader.
- `layout` is the description of binding locations used by both the pipeline and descriptor sets used with the pipeline.
- `basePipelineHandle` is a pipeline to derive from.
- `basePipelineIndex` is an index into the `pCreateInfos` parameter to use as a pipeline to derive from.
The parameters `basePipelineHandle` and `basePipelineIndex` are described in more detail in [Pipeline Derivatives](#).

### Valid Usage

- **VUID-VkComputePipelineCreateInfo-flags-07984**
  If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineIndex` is -1, `basePipelineHandle` **must** be a valid handle to a compute `VkPipeline`

- **VUID-VkComputePipelineCreateInfo-flags-07985**
  If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineHandle` is `VK_NULL_HANDLE`, `basePipelineIndex` **must** be a valid index into the calling command's `pCreateInfos` parameter

- **VUID-VkComputePipelineCreateInfo-flags-07986**
  If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, `basePipelineHandle` **must** be `VK_NULL_HANDLE or basePipelineIndex` **must** be -1

- **VUID-VkComputePipelineCreateInfo-layout-07987**
  If a push constant block is declared in a shader, a push constant range in `layout` **must** match both the shader stage and range

- **VUID-VkComputePipelineCreateInfo-layout-07988**
  If a resource variables is declared in a shader, a descriptor slot in `layout` **must** match the shader stage

- **VUID-VkComputePipelineCreateInfo-layout-07989**
  If a resource variables is declared in a shader, a descriptor slot in `layout` **must** match the descriptor type

- **VUID-VkComputePipelineCreateInfo-layout-07991**
  If a resource variables is declared in a shader as an array, a descriptor slot in `layout` **must** match the descriptor count

- **VUID-VkComputePipelineCreateInfo-stage-00701**
  The `stage` member of `stage` **must** be `VK_SHADER_STAGE_COMPUTE_BIT`

- **VUID-VkComputePipelineCreateInfo-stage-00702**
  The shader code for the entry point identified by `stage` and the rest of the state identified by this structure **must** adhere to the pipeline linking rules described in the [Shader Interfaces](#) chapter

- **VUID-VkComputePipelineCreateInfo-layout-01687**
  The number of resources in `layout` accessible to the compute shader stage **must** be less than or equal to `VkPhysicalDeviceLimits::maxPerStageResources`

- **VUID-VkComputePipelineCreateInfo-pipelineCreationCacheControl-02875**
  If the pipelineCreationCacheControl feature is not enabled, `flags` **must** not include `VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT` or `VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT`

- **VUID-VkComputePipelineCreateInfo-pipelineStageCreationFeedbackCount-06566**
  If ` VkPipelineCreationFeedbackCreateInfo::pipelineStageCreationFeedbackCount` is not 0, it **must** be 1
Valid Usage (Implicit)

- VUID-VkComputePipelineCreateInfo-sType-sType
  
  sType must be VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO

- VUID-VkComputePipelineCreateInfo-pNext-pNext
  
  pNext must be NULL or a pointer to a valid instance of VkPipelineCreationFeedbackCreateInfo

- VUID-VkComputePipelineCreateInfo-sType-unique
  
  The sType value of each struct in the pNext chain must be unique

- VUID-VkComputePipelineCreateInfo-flags-parameter
  
  flags must be a valid combination of VkPipelineCreateFlagBits values

- VUID-VkComputePipelineCreateInfo-stage-parameter
  
  stage must be a valid VkPipelineShaderStageCreateInfo structure

- VUID-VkComputePipelineCreateInfo-layout-parameter
  
  layout must be a valid VkPipelineLayout handle

- VUID-VkComputePipelineCreateInfo-commonparent
  
  Both of basePipelineHandle, and layout that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

The VkPipelineShaderStageCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineShaderStageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineShaderStageCreateFlags flags;
    VkShaderStageFlagBits stage;
    VkShaderModule module;
    const char* pName;
    const VkSpecializationInfo* pSpecializationInfo;
} VkPipelineShaderStageCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkPipelineShaderStageCreateFlagBits specifying how the pipeline shader stage will be generated.
- stage is a VkShaderStageFlagBits value specifying a single pipeline stage.
- module is a VkShaderModule object containing the shader code for this stage.
- pName is a pointer to a null-terminated UTF-8 string specifying the entry point name of the shader for this stage.
- pSpecializationInfo is a pointer to a VkSpecializationInfo structure, as described in Specialization Constants, or NULL.
The shader code used by the pipeline is defined by module.

Valid Usage

- **VUID-VkPipelineShaderStageCreateInfo-stage-00704**
  If the geometryShader feature is not enabled, stage must not be VK_SHADER_STAGE_GEOMETRY_BIT

- **VUID-VkPipelineShaderStageCreateInfo-stage-00705**
  If the tessellationShader feature is not enabled, stage must not be VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT or VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT

- **VUID-VkPipelineShaderStageCreateInfo-stage-00706**
  stage must not be VK_SHADER_STAGE_ALL_GRAPHICS, or VK_SHADER_STAGE_ALL

- **VUID-VkPipelineShaderStageCreateInfo-pName-00707**
  pName must be the name of an OpEntryPoint in module with an execution model that matches stage

- **VUID-VkPipelineShaderStageCreateInfo-maxClipDistances-00708**
  If the identified entry point includes any variable in its interface that is declared with the ClipDistance BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxClipDistances

- **VUID-VkPipelineShaderStageCreateInfo-maxCullDistances-00709**
  If the identified entry point includes any variable in its interface that is declared with the CullDistance BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxCullDistances

- **VUID-VkPipelineShaderStageCreateInfo-maxCombinedClipAndCullDistances-00710**
  If the identified entry point includes any variables in its interface that are declared with the ClipDistance or CullDistance BuiltIn decoration, those variables must not have array sizes which sum to more than VkPhysicalDeviceLimits::maxCombinedClipAndCullDistances

- **VUID-VkPipelineShaderStageCreateInfo-maxSampleMaskWords-00711**
  If the identified entry point includes any variable in its interface that is declared with the SampleMask BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxSampleMaskWords

- **VUID-VkPipelineShaderStageCreateInfo-stage-00712**
  If stage is VK_SHADER_STAGE_VERTEX_BIT, the identified entry point must not include any input variable in its interface that is decorated with CullDistance

- **VUID-VkPipelineShaderStageCreateInfo-stage-00713**
  If stage is VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT or VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, and the identified entry point has an OpExecutionMode instruction specifying a patch size with OutputVertices, the patch size must be greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize

- **VUID-VkPipelineShaderStageCreateInfo-stage-00714**
  If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point must have an
OpExecutionMode instruction specifying a maximum output vertex count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryOutputVertices

- VUID-VkPipelineShaderStageCreateInfo-stage-00715
  If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point must have an OpExecutionMode instruction specifying an invocation count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryShaderInvocations

- VUID-VkPipelineShaderStageCreateInfo-stage-02596
  If stage is either VK_SHADER_STAGE_VERTEX_BIT, VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT, VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, or VK_SHADER_STAGE_GEOMETRY_BIT, and the identified entry point writes to Layer for any primitive, it must write the same value to Layer for all vertices of a given primitive

- VUID-VkPipelineShaderStageCreateInfo-stage-02597
  If stage is either VK_SHADER_STAGE_VERTEX_BIT, VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT, VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, or VK_SHADER_STAGE_GEOMETRY_BIT, and the identified entry point writes to ViewportIndex for any primitive, it must write the same value to ViewportIndex for all vertices of a given primitive

- VUID-VkPipelineShaderStageCreateInfo-stage-00718
  If stage is VK_SHADER_STAGE_FRAGMENT_BIT, the identified entry point must not include any output variables in its interface decorated with CullDistance

- VUID-VkPipelineShaderStageCreateInfo-stage-06685
  If stage is VK_SHADER_STAGE_FRAGMENT_BIT, and the identified entry point writes to FragDepth in any execution path, all execution paths that are not exclusive to helper invocations must either discard the fragment, or write or initialize the value of FragDepth

- VUID-VkPipelineShaderStageCreateInfo-flags-02784
  If flags has the VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT flag set, the subgroupSizeControl feature must be enabled

- VUID-VkPipelineShaderStageCreateInfo-flags-02785
  If flags has the VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT flag set, the computeFullSubgroups feature must be enabled

- VUID-VkPipelineShaderStageCreateInfo-flags-08989
  If flags includes VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT, stage must be VK_SHADER_STAGE_COMPUTE_BIT

- VUID-VkPipelineShaderStageCreateInfo-pNext-02754
  If a VkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure is included in the pNext chain, flags must not have the VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT flag set

- VUID-VkPipelineShaderStageCreateInfo-pNext-02755
  If a VkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure is included in the pNext chain, the subgroupSizeControl feature must be enabled, and stage must be a valid bit specified in requiredSubgroupSizeStages

- VUID-VkPipelineShaderStageCreateInfo-pNext-02756
  If a VkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure is included in the pNext chain and stage is VK_SHADER_STAGE_COMPUTE_BIT, the local workgroup size of the
shader must be less than or equal to the product of

\[ Vk\text{PipelineShaderStageRequiredSubgroupSizeCreateInfo}::\text{requiredSubgroupSize} \times \text{maxComputeWorkgroupSubgroups} \]

- VUID-VkPipelineShaderStageCreateInfo-pNext-02757
  If a `VkPipelineShaderStageRequiredSubgroupSizeCreateInfo` structure is included in the `pNext` chain, and `flags` has the `VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT` flag set, the local workgroup size in the X dimension of the pipeline must be a multiple of `VkPipelineShaderStageRequiredSubgroupSizeCreateInfo::requiredSubgroupSize`

- VUID-VkPipelineShaderStageCreateInfo-flags-02758
  If `flags` has both the `VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT` and `VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT` flags set, the local workgroup size in the X dimension of the pipeline must be a multiple of `maxSubgroupSize`

- VUID-VkPipelineShaderStageCreateInfo-flags-02759
  If `flags` has the `VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT` flag set and `flags` does not have the `VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT` flag set and no `VkPipelineShaderStageRequiredSubgroupSizeCreateInfo` structure is included in the `pNext` chain, the local workgroup size in the X dimension of the pipeline must be a multiple of `subgroupSize`

- VUID-VkPipelineShaderStageCreateInfo-module-06716
  `module` must be a valid `VkShaderModule`

- VUID-VkPipelineShaderStageCreateInfo-pSpecializationInfo-06719
  The shader code used by the pipeline must be valid as described by the Khronos SPIR-V Specification after applying the specializations provided in `pSpecializationInfo`, if any, and then converting all specialization constants into fixed constants

### Valid Usage (Implicit)

- VUID-VkPipelineShaderStageCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO`

- VUID-VkPipelineShaderStageCreateInfo-pNext-pNext
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkPipelineShaderStageRequiredSubgroupSizeCreateInfo` or `VkShaderModuleCreateInfo`

- VUID-VkPipelineShaderStageCreateInfo-sType-unique
  The `sType` value of each struct in the `pNext` chain must be unique

- VUID-VkPipelineShaderStageCreateInfo-flags-parameter
  `flags` must be a valid combination of `VkPipelineShaderStageCreateFlagBits` values

- VUID-VkPipelineShaderStageCreateInfo-stage-parameter
  `stage` must be a valid `VkShaderStageFlagBits` value

- VUID-VkPipelineShaderStageCreateInfo-module-parameter
  If `module` is not `VK_NULL_HANDLE`, `module` must be a valid `VkShaderModule` handle
- VUID-VkPipelineShaderStageCreateInfo-pName-parameter
  *pName* must be a null-terminated UTF-8 string

- VUID-VkPipelineShaderStageCreateInfo-pSpecializationInfo-parameter
  If *pSpecializationInfo* is not NULL, *pSpecializationInfo* must be a valid pointer to a valid *VkSpecializationInfo* structure

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineShaderStageCreateFlags;
```

*VkPipelineShaderStageCreateFlags* is a bitmask type for setting a mask of zero or more *VkPipelineShaderStageCreateFlagBits*.

Possible values of the *flags* member of *VkPipelineShaderStageCreateInfo* specifying how a pipeline shader stage is created, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPipelineShaderStageCreateFlagBits {
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT = 0x00000001,
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT = 0x00000002,
} VkPipelineShaderStageCreateFlagBits;
```

- **VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT** specifies that the *SubgroupSize* may vary in the shader stage.
- **VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT** specifies that the subgroup sizes must be launched with all invocations active in the compute stage.

**Note**

If **VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT_EXT** and **VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT_EXT** are specified and *minSubgroupSize* does not equal *maxSubgroupSize* and no required subgroup size is specified, then the only way to guarantee that the 'X' dimension of the local workgroup size is a multiple of *SubgroupSize* is to make it a multiple of *maxSubgroupSize*. Under these conditions, you are guaranteed full subgroups but not any particular subgroup size.

Bits which can be set by commands and structures, specifying one or more shader stages, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkShaderStageFlagBits {
    VK_SHADER_STAGE_VERTEX_BIT = 0x00000001,
    VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT = 0x00000002,
    VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT = 0x00000004,
    VK_SHADER_STAGE_GEOMETRY_BIT = 0x00000008,
} VkShaderStageFlagBits;
```
VK_SHADER_STAGE_FRAGMENT_BIT = 0x00000010,
VK_SHADER_STAGE_COMPUTE_BIT = 0x00000020,
VK_SHADER_STAGE_ALL_GRAPHICS = 0x0000001F,
VK_SHADER_STAGE_ALL = 0x7FFFFFFF,
} VkShaderStageFlagBits;

- **VK_SHADER_STAGE_VERTEX_BIT** specifies the vertex stage.
- **VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT** specifies the tessellation control stage.
- **VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT** specifies the tessellation evaluation stage.
- **VK_SHADER_STAGE_GEOMETRY_BIT** specifies the geometry stage.
- **VK_SHADER_STAGE_FRAGMENT_BIT** specifies the fragment stage.
- **VK_SHADER_STAGE_COMPUTE_BIT** specifies the compute stage.
- **VK_SHADER_STAGE_ALL_GRAPHICS** is a combination of bits used as shorthand to specify all graphics stages defined above (excluding the compute stage).
- **VK_SHADER_STAGE_ALL** is a combination of bits used as shorthand to specify all shader stages supported by the device, including all additional stages which are introduced by extensions.

**Note**

**VK_SHADER_STAGE_ALL_GRAPHICS** only includes the original five graphics stages included in Vulkan 1.0, and not any stages added by extensions. Thus, it may not have the desired effect in all cases.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkShaderStageFlags;
```

The **VkShaderStageFlags** is a bitmask type for setting a mask of zero or more **VkShaderStageFlagBits**.

The **VkPipelineShaderStageRequiredSubgroupSizeCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPipelineShaderStageRequiredSubgroupSizeCreateInfo {
    VkStructureType sType;
    void* pNext;
    uint32_t requiredSubgroupSize;
} VkPipelineShaderStageRequiredSubgroupSizeCreateInfo;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **requiredSubgroupSize** is an unsigned integer value specifying the required subgroup size for the newly created pipeline shader stage.

If a **VkPipelineShaderStageRequiredSubgroupSizeCreateInfo** structure is included in the **pNext** chain of **VkPipelineShaderStageCreateInfo**, it specifies that the pipeline shader stage being compiled has a...
required subgroup size.

Valid Usage

- VUID-VkPipelineShaderStageRequiredSubgroupSizeCreateInfo-requiredSubgroupSize-02760
  requiredSubgroupSize must be a power-of-two integer

- VUID-VkPipelineShaderStageRequiredSubgroupSizeCreateInfo-requiredSubgroupSize-02761
  requiredSubgroupSize must be greater or equal to minSubgroupSize

- VUID-VkPipelineShaderStageRequiredSubgroupSizeCreateInfo-requiredSubgroupSize-02762
  requiredSubgroupSize must be less than or equal to maxSubgroupSize

Valid Usage (Implicit)

- VUID-VkPipelineShaderStageRequiredSubgroupSizeCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_REQUIRED_SUBGROUP_SIZE_CREATE_INFO

10.2. Graphics Pipelines

Graphics pipelines consist of multiple shader stages, multiple fixed-function pipeline stages, and a pipeline layout.

To create graphics pipelines, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateGraphicsPipelines(
    VkDevice device,
    VkPipelineCache pipelineCache,
    uint32_t createInfoCount,
    const VkGraphicsPipelineCreateInfo* pCreateInfos,
    const VkAllocationCallbacks* pAllocator,
    VkPipeline* pPipelines);
```

- `device` is the logical device that creates the graphics pipelines.
- `pipelineCache` is either VK_NULL_HANDLE, indicating that pipeline caching is disabled; or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.
- `createInfoCount` is the length of the `pCreateInfos` and `pPipelines` arrays.
- `pCreateInfos` is a pointer to an array of `VkGraphicsPipelineCreateInfo` structures.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
• \texttt{pPipelines} is a pointer to an array of VkPipeline handles in which the resulting graphics pipeline objects are returned.

The \texttt{VkGraphicsPipelineCreateInfo} structure includes an array of VkPipelineShaderStageCreateInfo structures for each of the desired active shader stages, as well as creation information for all relevant fixed-function stages, and a pipeline layout.

### Valid Usage

- **VUID-vkCreateGraphicsPipelines-flags-00720**
  If the flags member of any element of \texttt{pCreateInfos} contains the \texttt{VK_PIPELINE_CREATE_DERIVATIVE_BIT} flag, and the basePipelineIndex member of that same element is not -1, basePipelineIndex must be less than the index into \texttt{pCreateInfos} that corresponds to that element.

- **VUID-vkCreateGraphicsPipelines-flags-00721**
  If the flags member of any element of \texttt{pCreateInfos} contains the \texttt{VK_PIPELINE_CREATE_DERIVATIVE_BIT} flag, the base pipeline must have been created with the \texttt{VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT} flag set.

- **VUID-vkCreateGraphicsPipelines-pipelineCache-02876**
  If pipelineCache was created with \texttt{VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT}, host access to pipelineCache must be externally synchronized.

### Note

An implicit cache may be provided by the implementation or a layer. For this reason, it is still valid to set \texttt{VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT} on flags for any element of \texttt{pCreateInfos} while passing \texttt{VK_NULL_HANDLE} for pipelineCache.

### Valid Usage (Explicit)

- **VUID-vkCreateGraphicsPipelines-device-parameter**
  device must be a valid VkDevice handle.

- **VUID-vkCreateGraphicsPipelines-pipelineCache-parameter**
  If pipelineCache is not \texttt{VK_NULL_HANDLE}, pipelineCache must be a valid VkPipelineCache handle.

- **VUID-vkCreateGraphicsPipelines-pCreateInfos-parameter**
  pCreateInfos must be a valid pointer to an array of createInfoCount valid VkGraphicsPipelineCreateInfo structures.

- **VUID-vkCreateGraphicsPipelines-pAllocator-parameter**
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure.

- **VUID-vkCreateGraphicsPipelines-pPipelines-parameter**
  pPipelines must be a valid pointer to an array of createInfoCount VkPipeline handles.
• VUID-vkCreateGraphicsPipelines-createInfoCount-arraylength
  createInfoCount must be greater than 0

• VUID-vkCreateGraphicsPipelines-pipelineCache-parent
  If pipelineCache is a valid handle, it must have been created, allocated, or retrieved from device

Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkGraphicsPipelineCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkGraphicsPipelineCreateInfo {
    VkStructureType                     sType;
    const void*                         pNext;
    VkPipelineCreateFlags               flags;
    uint32_t                            stageCount;
    const VkPipelineShaderStageCreateInfo* pStages;
    const VkPipelineInputAssemblyStateCreateInfo* pInputAssemblyState;
    const VkPipelineTessellationStateCreateInfo* pTessellationState;
    const VkPipelineViewportStateCreateInfo* pViewportState;
    const VkPipelineRasterizationStateCreateInfo* pRasterizationState;
    const VkPipelineMultisampleStateCreateInfo* pMultisampleState;
    const VkPipelineDepthStencilStateCreateInfo* pDepthStencilState;
    const VkPipelineColorBlendStateCreateInfo* pColorBlendState;
    const VkPipelineDynamicStateCreateInfo* pDynamicState;
    VkPipelineLayout                      layout;
    VkRenderPass                         renderPass;
    uint32_t                             subpass;
    VkPipeline                           basePipelineHandle;
    int32_t                              basePipelineIndex;
} VkGraphicsPipelineCreateInfo;
```

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• flags is a bitmask of VkPipelineCreateFlagBits specifying how the pipeline will be generated.
• stageCount is the number of entries in the pStages array.
• `pStages` is a pointer to an array of `stageCount` `VkPipelineShaderStageCreateInfo` structures describing the set of the shader stages to be included in the graphics pipeline.

• `pVertexInputState` is a pointer to a `VkPipelineVertexInputStateCreateInfo` structure.

• `pInputAssemblyState` is a pointer to a `VkPipelineInputAssemblyStateCreateInfo` structure which determines input assembly behavior for vertex shading, as described in Drawing Commands.

• `pTessellationState` is a pointer to a `VkPipelineTessellationStateCreateInfo` structure defining tessellation state used by tessellation shaders.

• `pViewportState` is a pointer to a `VkPipelineViewportStateCreateInfo` structure defining viewport state used when rasterization is enabled.

• `pRasterizationState` is a pointer to a `VkPipelineRasterizationStateCreateInfo` structure defining rasterization state.

• `pMultisampleState` is a pointer to a `VkPipelineMultisampleStateCreateInfo` structure defining multisample state used when rasterization is enabled.

• `pDepthStencilState` is a pointer to a `VkPipelineDepthStencilStateCreateInfo` structure defining depth/stencil state used when rasterization is enabled for depth or stencil attachments accessed during rendering.

• `pColorBlendState` is a pointer to a `VkPipelineColorBlendStateCreateInfo` structure defining color blend state used when rasterization is enabled for any color attachments accessed during rendering.

• `pDynamicState` is a pointer to a `VkPipelineDynamicStateCreateInfo` structure defining which properties of the pipeline state object are dynamic and can be changed independently of the pipeline state. This can be `NULL`, which means no state in the pipeline is considered dynamic.

• `layout` is the description of binding locations used by both the pipeline and descriptor sets used with the pipeline.

• `renderPass` is a handle to a render pass object describing the environment in which the pipeline will be used. The pipeline must only be used with a render pass instance compatible with the one provided. See Render Pass Compatibility for more information.

• `subpass` is the index of the subpass in the render pass where this pipeline will be used.

• `basePipelineHandle` is a pipeline to derive from.

• `basePipelineIndex` is an index into the `pCreateInfos` parameter to use as a pipeline to derive from.

The parameters `basePipelineHandle` and `basePipelineIndex` are described in more detail in Pipeline Derivatives.

The state required for a graphics pipeline is divided into vertex input state, pre-rasterization shader state, fragment shader state, and fragment output state.

**Vertex Input State**

Vertex input state is defined by:

• `VkPipelineVertexInputStateCreateInfo`  
• `VkPipelineInputAssemblyStateCreateInfo`
This state **must** be specified to create a complete graphics pipeline.

**Pre-Rasterization Shader State**

Pre-rasterization shader state is defined by:

- **VkPipelineShaderStageCreateInfo** entries for:
  - Vertex shaders
  - Tessellation control shaders
  - Tessellation evaluation shaders
  - Geometry shaders
- Within the **VkPipelineLayout**, the full pipeline layout must be specified.
- **VkPipelineViewportStateCreateInfo**
- **VkPipelineRasterizationStateCreateInfo**
- **VkPipelineTessellationStateCreateInfo**
- **VkRenderPass** and **subpass** parameter
- The **viewMask** parameter of **VkPipelineRenderingCreateInfo** (formats are ignored)

This state **must** be specified to create a complete graphics pipeline.

**Fragment Shader State**

Fragment shader state is defined by:

- A **VkPipelineShaderStageCreateInfo** entry for the fragment shader
- Within the **VkPipelineLayout**, the full pipeline layout must be specified.
- **VkPipelineMultisampleStateCreateInfo** if **sample shading** is enabled or **renderpass** is not **VK_NULL_HANDLE**
- **VkPipelineDepthStencilStateCreateInfo**
- **VkRenderPass** and **subpass** parameter
- The **viewMask** parameter of **VkPipelineRenderingCreateInfo** (formats are ignored)

If **rasterizerDiscardEnable** is set to **VK_FALSE** or **VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE** is used, this state **must** be specified to create a complete graphics pipeline.

**Fragment Output State**

Fragment output state is defined by:

- **VkPipelineColorBlendStateCreateInfo**
- **VkRenderPass** and **subpass** parameter
- **VkPipelineMultisampleStateCreateInfo**
- **VkPipelineRenderingCreateInfo**

If **rasterizerDiscardEnable** is set to **VK_FALSE** or **VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE** is used,
this state **must** be specified to create a complete graphics pipeline.

**Dynamic State**

Dynamic state values set via **pDynamicState** **must** be ignored if the state they correspond to is not otherwise statically set by one of the state subsets used to create the pipeline. For example, if a pipeline only included pre-rasterization shader state, then any dynamic state value corresponding to depth or stencil testing has no effect.

**Complete Graphics Pipelines**

A complete graphics pipeline always includes pre-rasterization shader state, with other subsets included depending on that state as specified in the above sections.

### Valid Usage

- **VUID-VkGraphicsPipelineCreateInfo-flags-07984**
  If **flags** contains the **VK_PIPELINE_CREATE_DERIVATIVE_BIT** flag, and **basePipelineIndex** is -1, **basePipelineHandle** **must** be a valid handle to a graphics **VkPipeline**

- **VUID-VkGraphicsPipelineCreateInfo-flags-07985**
  If **flags** contains the **VK_PIPELINE_CREATE_DERIVATIVE_BIT** flag, and **basePipelineHandle** is **VK_NULL_HANDLE**, **basePipelineIndex** **must** be a valid index into the calling command's **pCreateInfos** parameter

- **VUID-VkGraphicsPipelineCreateInfo-flags-07986**
  If **flags** contains the **VK_PIPELINE_CREATE_DERIVATIVE_BIT** flag, **basePipelineIndex** **must** be -1 or **basePipelineHandle** **must** be **VK_NULL_HANDLE**

- **VUID-VkGraphicsPipelineCreateInfo-layout-07987**
  If a push constant block is declared in a shader, a push constant range in **layout** **must** match both the shader stage and range

- **VUID-VkGraphicsPipelineCreateInfo-layout-07988**
  If a **resource variables** is declared in a shader, a descriptor slot in **layout** **must** match the shader stage

- **VUID-VkGraphicsPipelineCreateInfo-layout-07989**
  If a **resource variables** is declared in a shader, a descriptor slot in **layout** **must** match the descriptor type

- **VUID-VkGraphicsPipelineCreateInfo-layout-07991**
  If a **resource variables** is declared in a shader as an array, a descriptor slot in **layout** **must** match the descriptor count

- **VUID-VkGraphicsPipelineCreateInfo-stage-00727**
  If the pipeline requires pre-rasterization shader state the **stage** member of one element of **pStages** **must** be **VK_SHADER_STAGE_VERTEX_BIT**

- **VUID-VkGraphicsPipelineCreateInfo-pStages-00729**
  If the pipeline requires pre-rasterization shader state and **pStages** includes a tessellation control shader stage, it **must** include a tessellation evaluation shader stage

- **VUID-VkGraphicsPipelineCreateInfo-pStages-00730**
  If the pipeline requires pre-rasterization shader state and **pStages** includes a tessellation
evaluation shader stage, it must include a tessellation control shader stage

- VUID-VkGraphicsPipelineCreateInfo-pStages-00731
  If the pipeline requires pre-rasterization shader state and pStages includes a tessellation control shader stage and a tessellation evaluation shader stage, pTessellationState must be a valid pointer to a valid VkPipelineTessellationStateCreateInfo structure

- VUID-VkGraphicsPipelineCreateInfo-pStages-00732
  If the pipeline requires pre-rasterization shader state and pStages includes tessellation shader stages, the shader code of at least one stage must contain an OpExecutionMode instruction specifying the type of subdivision in the pipeline

- VUID-VkGraphicsPipelineCreateInfo-pStages-00733
  If the pipeline requires pre-rasterization shader state and pStages includes tessellation shader stages, and the shader code of both stages contain an OpExecutionMode instruction specifying the type of subdivision in the pipeline, they must both specify the same subdivision mode

- VUID-VkGraphicsPipelineCreateInfo-pStages-00734
  If the pipeline requires pre-rasterization shader state and pStages includes tessellation shader stages, the shader code of at least one stage must contain an OpExecutionMode instruction specifying the output patch size in the pipeline

- VUID-VkGraphicsPipelineCreateInfo-pStages-00735
  If the pipeline requires pre-rasterization shader state and pStages includes tessellation shader stages, and the shader code of both contain an OpExecutionMode instruction specifying the output patch size in the pipeline, they must both specify the same patch size

- VUID-VkGraphicsPipelineCreateInfo-pStages-00736
  If the pipeline requires pre-rasterization shader state and vertex input state and pStages includes tessellation shader stages, the topology member of pInputAssembly must be VK_PRIMITIVE_TOPOLOGY_PATCH_LIST

- VUID-VkGraphicsPipelineCreateInfo-topology-00737
  If the pipeline requires pre-rasterization shader state and vertex input state and the topology member of pInputAssembly is VK_PRIMITIVE_TOPOLOGY_PATCH_LIST, pStages must include tessellation shader stages

- VUID-VkGraphicsPipelineCreateInfo-Vertex-07722
  If the pipeline is being created with a Vertex Execution Model and no TessellationEvaluation or Geometry Execution Model, and the topology member of pInputAssembly is VK_PRIMITIVE_TOPOLOGY_POINT_LIST, a PointSize decorated variable must be written to

- VUID-VkGraphicsPipelineCreateInfo-TessellationEvaluation-07723
  If the pipeline is being created with a TessellationEvaluation Execution Model, no Geometry Execution Model, uses the PointMode Execution Mode, and shaderTessellationAndGeometryPointSize is enabled, a PointSize decorated variable must be written to

- VUID-VkGraphicsPipelineCreateInfo-TessellationEvaluation-07724
  If the pipeline is being created with a TessellationEvaluation Execution Model, no Geometry Execution Model, uses the PointMode Execution Mode, and shaderTessellationAndGeometryPointSize is not enabled, a PointSize decorated variable
must not be written to

- VUID-VkGraphicsPipelineCreateInfo-Geometry-07725
  If the pipeline is being created with a Geometry Execution Model, uses the OutputPoints Execution Mode, and shaderTessellationAndGeometryPointSize is enabled, a PointSize decorated variable must be written to for every vertex emitted

- VUID-VkGraphicsPipelineCreateInfo-Geometry-07726
  If the pipeline is being created with a Geometry Execution Model, uses the OutputPoints Execution Mode, and shaderTessellationAndGeometryPointSize is not enabled, a PointSize decorated variable must not be written to

- VUID-VkGraphicsPipelineCreateInfo-pStages-00738
  If the pipeline requires pre-rasterization shader state and pStages includes a geometry shader stage, and does not include any tessellation shader stages, its shader code must contain an OpExecutionMode instruction specifying an input primitive type that is compatible with the primitive topology specified in pInputAssembly

- VUID-VkGraphicsPipelineCreateInfo-pStages-00739
  If the pipeline requires pre-rasterization shader state and pStages includes a geometry shader stage, and also includes tessellation shader stages, its shader code must contain an OpExecutionMode instruction specifying an input primitive type that is compatible with the primitive topology that is output by the tessellation stages

- VUID-VkGraphicsPipelineCreateInfo-pStages-00740
  If the pipeline requires pre-rasterization shader state and fragment shader state, it includes both a fragment shader and a geometry shader, and the fragment shader code reads from an input variable that is decorated with PrimitiveId, then the geometry shader code must write to a matching output variable, decorated with PrimitiveId, in all execution paths

- VUID-VkGraphicsPipelineCreateInfo-renderPass-06038
  If renderPass is not VK_NULL_HANDLE and the pipeline is being created with fragment shader state the fragment shader must not read from any input attachment that is defined as VK_ATTACHMENT_UNUSED in subpass

- VUID-VkGraphicsPipelineCreateInfo-pStages-00742
  If the pipeline requires pre-rasterization shader state and multiple pre-rasterization shader stages are included in pStages, the shader code for the entry points identified by those pStages and the rest of the state identified by this structure must adhere to the pipeline linking rules described in the Shader Interfaces chapter

- VUID-VkGraphicsPipelineCreateInfo-None-04889
  If the pipeline requires pre-rasterization shader state and fragment shader state, the fragment shader and last pre-rasterization shader stage and any relevant state must adhere to the pipeline linking rules described in the Shader Interfaces chapter

- VUID-VkGraphicsPipelineCreateInfo-renderPass-06041
  If renderPass is not VK_NULL_HANDLE, and the pipeline is being created with fragment output interface state, then for each color attachment in the subpass, if the potential format features of the format of the corresponding attachment description do not contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT, then the blendEnable member of the corresponding element of the pAttachments member of pColorBlendState must be VK_FALSE
If \(\text{renderPass}\) is not \(\text{VK_NULL_HANDLE}\), and the pipeline is being created with \text{fragment output interface state}, and the \(\text{pColorBlendState}\) pointer is not \text{NULL}, and the subpass uses color attachments, the \text{attachmentCount} member of \(\text{pColorBlendState}\) must be equal to the \text{colorAttachmentCount} used to create \text{subpass}.

If the pipeline requires \text{pre-rasterization shader state}, and \(\text{pViewportState->pViewports}\) is not dynamic, then \(\text{pViewportState->pViewports}\) must be a valid pointer to an array of \(\text{pViewportState->viewports}\) valid \text{VkViewport} structures.

If the pipeline requires \text{pre-rasterization shader state}, and \(\text{pViewportState->pScissors}\) is not dynamic, then \(\text{pViewportState->pScissors}\) must be a valid pointer to an array of \(\text{pViewportState->scissors}\) \text{VkRect2D} structures.

If the pipeline requires \text{pre-rasterization shader state}, and the \text{wideLines} feature is not enabled, and no element of the \(\text{pDynamicStates}\) member of \(\text{pDynamicState}\) is \(\text{VK_DYNAMIC_STATE_LINE_WIDTH}\), the \text{lineWidth} member of \(\text{pRasterizationState}\) must be \(1.0\).

If the pipeline requires \text{pre-rasterization shader state}, and the \text{rasterizerDiscardEnable} member of \(\text{pRasterizationState}\) is \(\text{VK_FALSE}\), \(\text{pViewportState}\) must be a valid pointer to a valid \text{VkPipelineViewportStateCreateInfo} structure.

If the pipeline requires \text{pre-rasterization shader state}, and the graphics pipeline state was created with the \(\text{VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE}\) dynamic state enabled, \(\text{pViewportState}\) must be a valid pointer to a valid \text{VkPipelineViewportStateCreateInfo} structure.

If the pipeline requires \text{fragment output interface state}, \(\text{pMultisampleState}\) must be a valid pointer to a valid \text{VkPipelineMultisampleStateCreateInfo} structure.

If the pipeline is being created with \text{fragment shader state}, the \text{VkPipelineMultisampleStateCreateInfo::alphaToCoverageEnable} is not ignored and is \text{VK_TRUE}, then the \text{Fragment Output Interface} must contain a variable for the alpha Component word in Location 0 at Index 0.

If \(\text{renderPass}\) is not \(\text{VK_NULL_HANDLE}\), the pipeline is being created with \text{fragment shader state}, and \text{subpass} uses a depth/stencil attachment, \(\text{pDepthStencilState}\) must be a valid pointer to a valid \text{VkPipelineDepthStencilStateCreateInfo} structure.

If \(\text{renderPass}\) is not \(\text{VK_NULL_HANDLE}\), the pipeline is being created with \text{fragment output interface state}, and \text{subpass} uses color attachments, \(\text{pColorBlendState}\) must be a valid pointer to a valid \text{VkPipelineColorBlendStateCreateInfo} structure.

If the pipeline requires \text{pre-rasterization shader state}, the \text{depthBiasClamp} feature is not
enabled, no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_DEPTH_BIAS`, and the `depthBiasEnable` member of `pRasterizationState` is `VK_TRUE`, the `depthBiasClamp` member of `pRasterizationState` must be 0.0.

- **VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-00755**
  If the pipeline requires fragment shader state, and no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_DEPTH_BOUNDS`, and the `depthBoundsTestEnable` member of `pDepthStencilState` is `VK_TRUE`, the `minDepthBounds` and `maxDepthBounds` members of `pDepthStencilState` must be between 0.0 and 1.0, inclusive.

- **VUID-VkGraphicsPipelineCreateInfo-subpass-00758**
  If the pipeline requires fragment output interface state, `rasterizationSamples` is not dynamic, and `subpass` does not use any color and/or depth/stencil attachments, then the `rasterizationSamples` member of `pMultisampleState` must follow the rules for a zero-attachment subpass.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06046**
  If `renderPass` is not `VK_NULL_HANDLE`, `subpass` must be a valid subpass within `renderPass`.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06047**
  If `renderPass` is not `VK_NULL_HANDLE`, the pipeline is being created with pre-rasterization shader state, `subpass` viewMask is not 0, and `multiviewTessellationShader` is not enabled, then `pStages` must not include tessellation shaders.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06048**
  If `renderPass` is not `VK_NULL_HANDLE`, the pipeline is being created with pre-rasterization shader state, `subpass` viewMask is not 0, and `multiviewGeometryShader` is not enabled, then `pStages` must not include a geometry shader.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06049**
  If `renderPass` is not `VK_NULL_HANDLE` and the pipeline is being created with pre-rasterization shader state, and `subpass` viewMask is not 0, all of the shaders in the pipeline must not write to the `Layer` built-in output.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06050**
  If `renderPass` is not `VK_NULL_HANDLE` and the pipeline is being created with pre-rasterization shader state, and `subpass` viewMask is not 0, then all of the shaders in the pipeline must not include variables decorated with the `Layer` built-in decoration in their interfaces.

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-07717**
  If `renderPass` is not `VK_NULL_HANDLE` and the pipeline is being created with pre-rasterization shader state, and `subpass` viewMask is not 0, then all of the shaders in the pipeline must not include variables decorated with the `ViewMask` built-in decoration in their interfaces.

- **VUID-VkGraphicsPipelineCreateInfo-flags-00764**
  `flags` must not contain the `VK_PIPELINE_CREATE_DISPATCH_BASE` flag.

- **VUID-VkGraphicsPipelineCreateInfo-pStages-01565**
  If the pipeline requires fragment shader state and an input attachment was referenced by an `aspectMask` at `renderPass` creation time, the fragment shader must only read from the aspects that were specified for that input attachment.
• VUID-VkGraphicsPipelineCreateInfo-layout-01688
  The number of resources in layout accessible to each shader stage that is used by the pipeline must be less than or equal to VkPhysicalDeviceLimits::maxPerStageResources.

• VUID-VkGraphicsPipelineCreateInfo-pStages-02097
  If the pipeline requires vertex input state, and pVertexInputState is not dynamic, then pVertexInputState must be a valid pointer to a valid VkPipelineVertexInputStateCreateInfo structure.

• VUID-VkGraphicsPipelineCreateInfo-Input-07904
  If the pipeline is being created with vertex input state and pVertexInputState is not dynamic, then all variables with the Input storage class decorated with Location in the Vertex Execution Model OpEntryPoint must contain a location in VkVertexInputAttributeDescription::location.

• VUID-VkGraphicsPipelineCreateInfo-Input-08733
  If the pipeline requires vertex input state and pVertexInputState is not dynamic, then the numeric type associated with all Input variables of the corresponding Location in the Vertex Execution Model OpEntryPoint must be the same as VkVertexInputAttributeDescription::format.

• VUID-VkGraphicsPipelineCreateInfo-pVertexInputState-08929
  If the pipeline is being created with vertex input state and pVertexInputState is not dynamic, and VkVertexInputAttributeDescription::format has a 64-bit component, then the scalar width associated with all Input variables of the corresponding Location in the Vertex Execution Model OpEntryPoint must be 64-bit.

• VUID-VkGraphicsPipelineCreateInfo-pVertexInputState-08930
  If the pipeline is being created with vertex input state and pVertexInputState is not dynamic, and the scalar width associated with a Location decorated Input variable in the Vertex Execution Model OpEntryPoint is 64-bit, then the corresponding VkVertexInputAttributeDescription::format must have a 64-bit component.

• VUID-VkGraphicsPipelineCreateInfo-pStages-02098
  If the pipeline requires vertex input state, pInputAssemblyState must be a valid pointer to a valid VkPipelineInputAssemblyStateCreateInfo structure.

• VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-03378
  If the value of VkApplicationInfo::apiVersion used to create the VkInstance is less than Version 1.3 there must be no element of the pDynamicStates member of pDynamicState set to VK_DYNAMIC_STATE_CULL_MODE, VK_DYNAMIC_STATE_FRONT_FACE, VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY, VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT, VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT, VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE, VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE, VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE, VK_DYNAMIC_STATE_DEPTH_COMPARE_OP, VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE, VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE, or VK_DYNAMIC_STATE_STENCIL_OP.

• VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-03379
  If the pipeline requires pre-rasterization shader state, and VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT is included in the pDynamicStates array then viewportCount must be zero.

• VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-03380
If the pipeline requires pre-rasterization shader state, and 
`VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` is included in the `pDynamicStates` array then
`scissorCount` must be zero

- VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-04132
  If the pipeline requires pre-rasterization shader state, and
  `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` is included in the `pDynamicStates` array then
  `VK_DYNAMIC_STATE_VIEWPORT` must not be present

- VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-04133
  If the pipeline requires pre-rasterization shader state, and
  `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` is included in the `pDynamicStates` array then
  `VK_DYNAMIC_STATE_SCISSOR` must not be present

- VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-04868
  If the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` is less than
  Version 1.3 there must be no element of the `pDynamicStates` member of `pDynamicState` set to
  `VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE`, `VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE`, or
  `VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE`

- VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-04869
  If the `extendedDynamicState2LogicOp` feature is not enabled, there must be no element of
  the `pDynamicStates` member of `pDynamicState` set to `VK_DYNAMIC_STATE_LOGIC_OP_EXT`

- VUID-VkGraphicsPipelineCreateInfo-pDynamicStates-04870
  If the `extendedDynamicState2PatchControlPoints` feature is not enabled, there must be no
  element of the `pDynamicStates` member of `pDynamicState` set to
  `VK_DYNAMIC_STATE_PATCH_CONTROL_POINTS_EXT`

- VUID-VkGraphicsPipelineCreateInfo-pipelineCreationCacheControl-02878
  If the `pipelineCreationCacheControl` feature is not enabled, flags must not include
  `VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT` or
  `VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT`

- VUID-VkGraphicsPipelineCreateInfo-renderPass-06575
  If the pipeline requires pre-rasterization shader state, fragment shader state, or fragment
  output interface state, `renderPass` must be `VK_NULL_HANDLE` or a valid render pass object

- VUID-VkGraphicsPipelineCreateInfo-dynamicRendering-06576
  If the `dynamicRendering` feature is not enabled and the pipeline requires pre-rasterization
  shader state, fragment shader state, or fragment output interface state, `renderPass` must
  not be `VK_NULL_HANDLE`

- VUID-VkGraphicsPipelineCreateInfo-multiview-06577
  If the `multiview` feature is not enabled, the pipeline requires pre-rasterization shader state,
  fragment shader state, or fragment output interface state, and `renderPass` is
  `VK_NULL_HANDLE`, `VkPipelineRenderingCreateInfo::viewMask` must be `0`

- VUID-VkGraphicsPipelineCreateInfo-renderPass-06578
  If the pipeline requires pre-rasterization shader state, fragment shader state, or fragment
  output interface state, and `renderPass` is `VK_NULL_HANDLE`, the index of the most
  significant bit in `VkPipelineRenderingCreateInfo::viewMask` must be less than
  `maxMultiviewViewCount`
• VUID-VkGraphicsPipelineCreateInfo-renderPass-06579
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::colorAttachmentCount is not 0, VkPipelineRenderingCreateInfo::pColorAttachmentFormats must be a valid pointer to an array of colorAttachmentCount valid VkFormat values

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06580
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::pColorAttachmentFormats must be a valid pointer to an array of colorAttachmentCount valid VkFormat values

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06581
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, each element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats must be a valid VkFormat value

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06582
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and any element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats is not VK_FORMAT_UNDEFINED, that format must be a format with potential format features that include VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06583
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, VkPipelineRenderingCreateInfo::depthAttachmentFormat must be a valid VkFormat value

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06584
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, VkPipelineRenderingCreateInfo::stencilAttachmentFormat must be a valid VkFormat value

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06585
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::depthAttachmentFormat is not VK_FORMAT_UNDEFINED, it must be a format with potential format features that include VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06586
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::stencilAttachmentFormat is not VK_FORMAT_UNDEFINED, it must be a format with potential format features that include VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06587
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::depthAttachmentFormat is not VK_FORMAT_UNDEFINED, it must be a format that includes a depth component

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06588
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, and VkPipelineRenderingCreateInfo::stencilAttachmentFormat is not VK_FORMAT_UNDEFINED, it must be a format that includes a stencil component

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06589
If the pipeline requires fragment output interface state, and renderPass is VK_NULL_HANDLE, VkPipelineRenderingCreateInfo::depthAttachmentFormat is not VK_FORMAT_UNDEFINED, and VkPipelineRenderingCreateInfo::stencilAttachmentFormat is not VK_FORMAT_UNDEFINED,
depthAttachmentFormat must equal stencilAttachmentFormat

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06053
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with fragment shader state and fragment output interface state, and either of VkPipelineRenderingCreateInfo::depthAttachmentFormat or VkPipelineRenderingCreateInfo::stencilAttachmentFormat are not VK_FORMAT_UNDEFINED, pDepthStencilState must be a valid pointer to a valid VkPipelineDepthStencilStateCreateInfo structure

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06054
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with fragment output interface state, and VkPipelineRenderingCreateInfo::colorAttachmentCount is not equal to 0, pColorBlendState must be a valid pointer to a valid VkPipelineColorBlendStateCreateInfo structure

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06055
  If renderPass is VK_NULL_HANDLE and the pipeline is being created with fragment output interface state, pColorBlendState->attachmentCount must be equal to VkPipelineRenderingCreateInfo::colorAttachmentCount

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06057
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with pre-rasterization shader state, VkPipelineRenderingCreateInfo::viewMask is not 0, and the multiviewTessellationShader feature is not enabled, then pStages must not include tessellation shaders

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06058
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with pre-rasterization shader state, VkPipelineRenderingCreateInfo::viewMask is not 0, and the multiviewGeometryShader feature is not enabled, then pStages must not include a geometry shader

• VUID-VkGraphicsPipelineCreateInfo-renderPass-07718
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with pre-rasterization shader state, and VkPipelineRenderingCreateInfo::viewMask is not 0, all of the shaders in the pipeline must not write to the Layer built-in output

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06059
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with pre-rasterization shader state, and VkPipelineRenderingCreateInfo::viewMask is not 0, all of the shaders in the pipeline must not include variables decorated with the Layer built-in decoration in their interfaces

• VUID-VkGraphicsPipelineCreateInfo-renderPass-07719
  If renderPass is VK_NULL_HANDLE, the pipeline is being created with pre-rasterization shader state, and VkPipelineRenderingCreateInfo::viewMask is not 0, all of the shaders in the pipeline must not include variables decorated with the ViewIndex built-in decoration in their interfaces

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06061
  If the pipeline requires fragment shader state and renderPass is VK_NULL_HANDLE, fragment shaders in pStages must not include the InputAttachment capability

• VUID-VkGraphicsPipelineCreateInfo-renderPass-06062
If the pipeline requires **fragment output interface state** and **renderPass** is **VK_NULL_HANDLE**, for each color attachment format defined by the **pColorAttachmentFormats** member of **VkPipelineRenderingCreateInfo**, if its potential format features do not contain **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT**, then the **blendEnable** member of the corresponding element of the **pAttachments** member of **pColorBlendState** must be **VK_FALSE**

- **VUID-VkGraphicsPipelineCreateInfo-pipelineStageCreationFeedbackCount-06594**
  If **VkPipelineCreationFeedbackCreateInfo**::**pipelineStageCreationFeedbackCount** is not 0, it must be equal to **stageCount**

- **VUID-VkGraphicsPipelineCreateInfo-pStages-06600**
  If the pipeline requires **pre-rasterization shader state** or **fragment shader state**, **pStages** must be a valid pointer to an array of **stageCount** valid **VkPipelineShaderStageCreateInfo** structures

- **VUID-VkGraphicsPipelineCreateInfo-pRasterizationState-06601**
  If the pipeline requires **pre-rasterization shader state**, **pRasterizationState** must be a valid pointer to a valid **VkPipelineRasterizationStateCreateInfo** structure

- **VUID-VkGraphicsPipelineCreateInfo-layout-06602**
  If the pipeline requires **fragment shader state** or **pre-rasterization shader state**, **layout** must be a valid **VkPipelineLayout** handle

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-06603**
  If **pre-rasterization shader state**, **fragment shader state**, or **fragment output state**, and **renderPass** is not **VK_NULL_HANDLE**, **renderPass** must be a valid **VkRenderPass** handle

- **VUID-VkGraphicsPipelineCreateInfo-stageCount-06604**
  If the pipeline requires **pre-rasterization shader state** or **fragment shader state**, **stageCount** must be greater than 0

- **VUID-VkGraphicsPipelineCreateInfo-pStages-06894**
  If the pipeline requires **pre-rasterization shader state** but not **fragment shader state**, elements of **pStages** must not have **stage** set to **VK_SHADER_STAGE_FRAGMENT_BIT**

- **VUID-VkGraphicsPipelineCreateInfo-pStages-06895**
  If the pipeline requires **fragment shader state** but not **pre-rasterization shader state**, elements of **pStages** must not have **stage** set to a shader stage which participates in pre-rasterization

- **VUID-VkGraphicsPipelineCreateInfo-pStages-06896**
  If the pipeline requires **pre-rasterization shader state**, all elements of **pStages** must have a **stage** set to a shader stage which participates in **fragment shader state** or **pre-rasterization shader state**

- **VUID-VkGraphicsPipelineCreateInfo-stage-06897**
  If the pipeline requires **fragment shader state** and/or **pre-rasterization shader state**, any value of **stage** must not be set in more than one element of **pStages**

- **VUID-VkGraphicsPipelineCreateInfo-renderPass-08744**
  If **renderPass** is **VK_NULL_HANDLE**, the pipeline requires **fragment output state** or **fragment shader state**, the pipeline enables **sample shading**, **rasterizationSamples** is not dynamic, and the **pNext** chain includes a **VkPipelineRenderingCreateInfo** structure,
rasterizationSamples must be a bit value that is set in imageCreateSampleCounts (as defined in Image Creation Limits) for every element of depthAttachmentFormat, stencilAttachmentFormat and the pColorAttachmentFormats array which is not VK_FORMAT_UNDEFINED

• VUID-VkGraphicsPipelineCreateInfo-None-08893
  The pipeline must be created with pre-rasterization shader state

• VUID-VkGraphicsPipelineCreateInfo-pStages-08894
  If pStages includes a vertex shader stage, the pipeline must be created with vertex input state

• VUID-VkGraphicsPipelineCreateInfo-pDynamicState-08896
  If pDynamicState->pDynamicStates includes VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE, or if it does not and pRasterizationState->rasterizerDiscardEnable is VK_FALSE, the pipeline must be created with fragment shader state and fragment output interface state

• VUID-VkGraphicsPipelineCreateInfo-None-09043
  If the format of any color attachment is VK_FORMAT_E5B9G9R9_UFLOAT_PACK32, the colorWriteMask member of the corresponding element of pColorBlendState->pAttachments must either include all of VK_COLOR_COMPONENT_R_BIT, VK_COLOR_COMPONENT_G_BIT, and VK_COLOR_COMPONENT_B_BIT, or none of them

Valid Usage (Implicit)

• VUID-VkGraphicsPipelineCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO

• VUID-VkGraphicsPipelineCreateInfo-pNext-pNext
  Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkPipelineCreationFeedbackCreateInfo or VkPipelineRenderingCreateInfo

• VUID-VkGraphicsPipelineCreateInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

• VUID-VkGraphicsPipelineCreateInfo-flags-parameter
  flags must be a valid combination of VkPipelineCreateFlagBits values

• VUID-VkGraphicsPipelineCreateInfo-pDynamicState-parameter
  If pDynamicState is not NULL, pDynamicState must be a valid pointer to a valid VkPipelineDynamicStateCreateInfo structure

• VUID-VkGraphicsPipelineCreateInfo-commonparent
  Each of basePipelineHandle, layout, and renderPass that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

The VkPipelineRenderingCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPipelineRenderingCreateInfo {
```
VkStructureType sType;
const void* pNext;
uint32_t viewMask;
uint32_t colorAttachmentCount;
const VkFormat* pColorAttachmentFormats;
VkFormat depthAttachmentFormat;
VkFormat stencilAttachmentFormat;

} VkPipelineRenderingCreateInfo;

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• viewMask is the viewMask used for rendering.
• colorAttachmentCount is the number of entries in pColorAttachmentFormats.
• pColorAttachmentFormats is a pointer to an array of VkFormat values defining the format of color attachments used in this pipeline.
• depthAttachmentFormat is a VkFormat value defining the format of the depth attachment used in this pipeline.
• stencilAttachmentFormat is a VkFormat value defining the format of the stencil attachment used in this pipeline.

When a pipeline is created without a VkRenderPass, if the pNext chain of VkGraphicsPipelineCreateInfo includes this structure, it specifies the view mask and format of attachments used for rendering. If this structure is not specified, and the pipeline does not include a VkRenderPass, viewMask and colorAttachmentCount are 0, and depthAttachmentFormat and stencilAttachmentFormat are VK_FORMAT_UNDEFINED. If a graphics pipeline is created with a valid VkRenderPass, parameters of this structure are ignored.

If depthAttachmentFormat, stencilAttachmentFormat, or any element of pColorAttachmentFormats is VK_FORMAT_UNDEFINED, it indicates that the corresponding attachment is unused within the render pass. Valid formats indicate that an attachment can be used - but it is still valid to set the attachment to NULL when beginning rendering.

Valid Usage (Implicit)

- VUID-VkPipelineRenderingCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_PIPELINE_RENDERING_CREATE_INFO

Bits which can be set in

- VkGraphicsPipelineCreateInfo::flags
- VkComputePipelineCreateInfo::flags

specify how a pipeline is created, and are:

// Provided by VK_VERSION_1_0
typedef enum VkPipelineCreateFlagBits {
    VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT = 0x00000001,
    VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT = 0x00000002,
    VK_PIPELINE_CREATE_DERIVATIVE_BIT = 0x00000004,
    // Provided by VK_VERSION_1_1
    VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT = 0x00000008,
    // Provided by VK_VERSION_1_1
    VK_PIPELINE_CREATE_DISPATCH_BASE_BIT = 0x00000010,
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT = 0x00000100,
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT = 0x00000200,
    // Provided by VK_VERSION_1_1
    VK_PIPELINE_CREATE_DISPATCH_BASE = VK_PIPELINE_CREATE_DISPATCH_BASE_BIT,
} VkPipelineCreateFlagBits;

• **VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT** specifies that the created pipeline will not be optimized. Using this flag may reduce the time taken to create the pipeline.

• **VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT** specifies that the pipeline to be created is allowed to be the parent of a pipeline that will be created in a subsequent pipeline creation call.

• **VK_PIPELINE_CREATE_DERIVATIVE_BIT** specifies that the pipeline to be created will be a child of a previously created parent pipeline.

• **VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT** specifies that any shader input variables decorated as `ViewIndex` will be assigned values as if they were decorated as `DeviceIndex`.

• **VK_PIPELINE_CREATE_DISPATCH_BASE** specifies that a compute pipeline can be used with `vkCmdDispatchBase` with a non-zero base workgroup.

• **VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT** specifies that pipeline creation will fail if a compile is required for creation of a valid `VkPipeline` object; `VK_PIPELINE_COMPILE_REQUIRED` will be returned by pipeline creation, and the `VkPipeline` will be set to `VK_NULL_HANDLE`.

• When creating multiple pipelines, **VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT** specifies that control will be returned to the application if any individual pipeline returns a result which is not `VK_SUCCESS` rather than continuing to create additional pipelines.

It is valid to set both **VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT** and **VK_PIPELINE_CREATE_DERIVATIVE_BIT**. This allows a pipeline to be both a parent and possibly a child in a pipeline hierarchy. See Pipeline Derivatives for more information.

// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineCreateFlags;

`VkPipelineCreateFlags` is a bitmask type for setting a mask of zero or more `VkPipelineCreateFlagBits`.

The `VkPipelineDynamicStateCreateInfo` structure is defined as:
typedef struct VkPipelineDynamicStateCreateInfo {
    VkStructureType sType;
    const void*pNext;
    VkPipelineDynamicStateCreateFlags flags;
    uint32_t dynamicStateCount;
    const VkDynamicState*pDynamicStates;
} VkPipelineDynamicStateCreateInfo;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is reserved for future use.
- **dynamicStateCount** is the number of elements in the **pDynamicStates** array.
- **pDynamicStates** is a pointer to an array of VkDynamicState values specifying which pieces of pipeline state will use the values from dynamic state commands rather than from pipeline state creation information.

### Valid Usage

- VUID-VkPipelineDynamicStateCreateInfo-pDynamicStates-01442
  Each element of **pDynamicStates** must be unique

### Valid Usage (Implicit)

- VUID-VkPipelineDynamicStateCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO
- VUID-VkPipelineDynamicStateCreateInfo-pNext-pNext
  pNext must be NULL
- VUID-VkPipelineDynamicStateCreateInfo-flags-zerobitmask
  flags must be 0
- VUID-VkPipelineDynamicStateCreateInfo-pDynamicStates-parameter
  If dynamicStateCount is not 0, pDynamicStates must be a valid pointer to an array of dynamicStateCount valid VkDynamicState values

// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineDynamicStateCreateFlags;

**VkPipelineDynamicStateCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

The source of different pieces of dynamic state is specified by the **VkPipelineDynamicStateCreateInfo::pDynamicStates** property of the currently active pipeline, each
of whose elements must be one of the values:

```c
typedef enum VkDynamicState {
    VK_DYNAMIC_STATE_VIEWPORT = 0,
    VK_DYNAMIC_STATE_SCISSOR = 1,
    VK_DYNAMIC_STATE_LINE_WIDTH = 2,
    VK_DYNAMIC_STATE_DEPTH_BIAS = 3,
    VK_DYNAMIC_STATE_BLEND_CONSTANTS = 4,
    VK_DYNAMIC_STATE_DEPTH_BOUNDS = 5,
    VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK = 6,
    VK_DYNAMIC_STATE_STENCIL_WRITE_MASK = 7,
    VK_DYNAMIC_STATE_STENCIL_REFERENCE = 8,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_CULL_MODE = 1000267000,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_FRONT_FACE = 1000267001,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY = 1000267002,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT = 1000267003,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT = 1000267004,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE = 1000267005,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE = 1000267006,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE = 1000267007,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_DEPTH_COMPARE_OP = 1000267008,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE = 1000267009,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE = 1000267010,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_STENCIL_OP = 1000267011,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE = 1000377001,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE = 1000377002,
    // Provided by VK_VERSION_1_3
    VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE = 1000377004,
} VkDynamicState;
```

- **VK_DYNAMIC_STATE_VIEWPORT** specifies that the `pViewports` state in `VkPipelineViewportStateCreateInfo` will be ignored and must be set dynamically with `vkCmdSetViewport` before any drawing commands. The number of viewports used by a pipeline is still specified by the `viewportCount` member of `VkPipelineViewportStateCreateInfo`. 
• **VK_DYNAMIC_STATE_SCISSOR** specifies that the `pScissors` state in `VkPipelineViewportStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetScissor` before any drawing commands. The number of scissor rectangles used by a pipeline is still specified by the `scissorCount` member of `VkPipelineViewportStateCreateInfo`.

• **VK_DYNAMIC_STATE_LINE_WIDTH** specifies that the `lineWidth` state in `VkPipelineRasterizationStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetLineWidth` before any drawing commands that generate line primitives for the rasterizer.

• **VK_DYNAMIC_STATE_DEPTH_BIAS** specifies that the `depthBiasConstantFactor`, `depthBiasClamp` and `depthBiasSlopeFactor` states in `VkPipelineRasterizationStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetDepthBias` before any draws are performed with depth bias enabled.

• **VK_DYNAMIC_STATE_BLEND_CONSTANTS** specifies that the `blendConstants` state in `VkPipelineColorBlendStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetBlendConstants` before any draws are performed with a pipeline state with `VkPipelineColorBlendAttachmentState` member `blendEnable` set to **VK_TRUE** and any of the blend functions using a constant blend color.

• **VK_DYNAMIC_STATE_DEPTH_BOUNDS** specifies that the `minDepthBounds` and `maxDepthBounds` states of `VkPipelineDepthStencilStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetDepthBounds` before any draws are performed with a pipeline state with `VkPipelineDepthStencilStateCreateInfo` member `depthBoundsTestEnable` set to **VK_TRUE**.

• **VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK** specifies that the `compareMask` state in `VkPipelineDepthStencilStateCreateInfo` for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilCompareMask` before any draws are performed with a pipeline state with `VkPipelineDepthStencilStateCreateInfo` member `stencilTestEnable` set to **VK_TRUE**.

• **VK_DYNAMIC_STATE_STENCIL_WRITE_MASK** specifies that the `writeMask` state in `VkPipelineDepthStencilStateCreateInfo` for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilWriteMask` before any draws are performed with a pipeline state with `VkPipelineDepthStencilStateCreateInfo` member `stencilTestEnable` set to **VK_TRUE**.

• **VK_DYNAMIC_STATE_STENCIL_REFERENCE** specifies that the `reference` state in `VkPipelineDepthStencilStateCreateInfo` for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilReference` before any draws are performed with a pipeline state with `VkPipelineDepthStencilStateCreateInfo` member `stencilTestEnable` set to **VK_TRUE**.

• **VK_DYNAMIC_STATE_CULL_MODE** specifies that the `cullMode` state in `VkPipelineRasterizationStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetCullMode` before any drawing commands.

• **VK_DYNAMIC_STATE_FRONT_FACE** specifies that the `frontFace` state in `VkPipelineRasterizationStateCreateInfo` will be ignored and **must** be set dynamically with `vkCmdSetFrontFace` before any drawing commands.

• **VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY** specifies that the `topology` state in `VkPipelineInputAssemblyStateCreateInfo` only specifies the topology class, and the specific topology order and adjacency **must** be set dynamically with `vkCmdSetPrimitiveTopology` before any drawing commands.
• **VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT** specifies that the *viewportCount* and *pViewports* state in *VkPipelineViewportStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetViewportWithCount* before any draw call.

• **VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT** specifies that the *scissorCount* and *pScissors* state in *VkPipelineViewportStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetScissorWithCount* before any draw call.

• **VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE** specifies that the *stride* state in *VkVertexInputBindingDescription* will be ignored and **must** be set dynamically with *vkCmdBindVertexBuffers2* before any draw call.

• **VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE** specifies that the *depthTestEnable* state in *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetDepthTestEnable* before any draw call.

• **VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE** specifies that the *depthWriteEnable* state in *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetDepthWriteEnable* before any draw call.

• **VK_DYNAMIC_STATE_DEPTH_COMPARE_OP** specifies that the *depthCompareOp* state in *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetDepthCompareOp* before any draw call.

• **VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE** specifies that the *depthBoundsTestEnable* state in *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetDepthBoundsTestEnable* before any draw call.

• **VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE** specifies that the *stencilTestEnable* state in *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetStencilTestEnable* before any draw call.

• **VK_DYNAMIC_STATE_STENCIL_OP** specifies that the *failOp*, *passOp*, *depthFailOp*, and *compareOp* states in *VkPipelineDepthStencilStateCreateInfo* for both *front* and *back* will be ignored and **must** be set dynamically with *vkCmdSetStencilOp* before any draws are performed with a pipeline state with *VkPipelineDepthStencilStateCreateInfo* member *stencilTestEnable* set to VK_TRUE.

• **VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE** specifies that the *rasterizerDiscardEnable* state in *VkPipelineRasterizationStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetRasterizerDiscardEnable* before any drawing commands.

• **VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE** specifies that the *depthBiasEnable* state in *VkPipelineRasterizationStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetDepthBiasEnable* before any drawing commands.

• **VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE** specifies that the *primitiveRestartEnable* state in *VkPipelineInputAssemblyStateCreateInfo* will be ignored and **must** be set dynamically with *vkCmdSetPrimitiveRestartEnable* before any drawing commands.

### 10.2.1. Valid Combinations of Stages for Graphics Pipelines

If tessellation shader stages are omitted, the tessellation shading and fixed-function stages of the pipeline are skipped.

If a geometry shader is omitted, the geometry shading stage is skipped.
If a fragment shader is omitted, fragment color outputs have undefined values, and the fragment depth value is determined by Fragment Operations state. This can be useful for depth-only rendering.

Presence of a shader stage in a pipeline is indicated by including a valid VkPipelineShaderStageCreateInfo with module and pName selecting an entry point from a shader module, where that entry point is valid for the stage specified by stage.

Presence of some of the fixed-function stages in the pipeline is implicitly derived from enabled shaders and provided state. For example, the fixed-function tessellator is always present when the pipeline has valid Tessellation Control and Tessellation Evaluation shaders.

For example:

• Depth/stencil-only rendering in a subpass with no color attachments
  
  ◦ Active Pipeline Shader Stages
    • Vertex Shader
  
  ◦ Required: Fixed-Function Pipeline Stages
    • VkPipelineVertexInputStateCreateInfo
    • VkPipelineInputAssemblyStateCreateInfo
    • VkPipelineViewportStateCreateInfo
    • VkPipelineRasterizationStateCreateInfo
    • VkPipelineMultisampleStateCreateInfo
    • VkPipelineDepthStencilStateCreateInfo

• Color-only rendering in a subpass with no depth/stencil attachment
  
  ◦ Active Pipeline Shader Stages
    • Vertex Shader
    • Fragment Shader
  
  ◦ Required: Fixed-Function Pipeline Stages
    • VkPipelineVertexInputStateCreateInfo
    • VkPipelineInputAssemblyStateCreateInfo
    • VkPipelineViewportStateCreateInfo
    • VkPipelineRasterizationStateCreateInfo
    • VkPipelineMultisampleStateCreateInfo
    • VkPipelineColorBlendStateCreateInfo

• Rendering pipeline with tessellation and geometry shaders
  
  ◦ Active Pipeline Shader Stages
    • Vertex Shader
    • Tessellation Control Shader
    • Tessellation Evaluation Shader
- Geometry Shader
- Fragment Shader

- **Required: Fixed-Function Pipeline Stages**
  - VkPipelineVertexInputStateCreateInfo
  - VkPipelineInputAssemblyStateCreateInfo
  - VkPipelineTessellationStateCreateInfo
  - VkPipelineViewportStateCreateInfo
  - VkPipelineRasterizationStateCreateInfo
  - VkPipelineMultisampleStateCreateInfo
  - VkPipelineDepthStencilStateCreateInfo
  - VkPipelineColorBlendStateCreateInfo

### 10.3. Pipeline Destruction

To destroy a pipeline, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyPipeline(
    VkDevice device,           // Provided by VK_VERSION_1_0
    VkPipeline pipeline,       // Provided by VK_VERSION_1_0
    const VkAllocationCallbacks* pAllocator);  // Provided by VK_VERSION_1_0
```

- **device** is the logical device that destroys the pipeline.
- **pipeline** is the handle of the pipeline to destroy.
- **pAllocator** controls host memory allocation as described in the **Memory Allocation** chapter.

### Valid Usage

- VUID-vkDestroyPipeline-pipeline-00765
  All submitted commands that refer to **pipeline** **must** have completed execution

- VUID-vkDestroyPipeline-pipeline-00766
  If **VkAllocationCallbacks** were provided when **pipeline** was created, a compatible set of callbacks **must** be provided here

- VUID-vkDestroyPipeline-pipeline-00767
  If no **VkAllocationCallbacks** were provided when **pipeline** was created, **pAllocator** **must** be **NULL**

### Valid Usage (Implicit)

- VUID-vkDestroyPipeline-device-parameter
device must be a valid VkDevice handle

• VUID-vkDestroyPipeline-pipeline-parameter
  If pipeline is not VK_NULL_HANDLE, pipeline must be a valid VkPipeline handle

• VUID-vkDestroyPipeline-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid
  VkAllocationCallbacks structure

• VUID-vkDestroyPipeline-pipeline-parent
  If pipeline is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to pipeline must be externally synchronized

10.4. Multiple Pipeline Creation

Multiple pipelines can be created simultaneously by passing an array of
VkGraphicsPipelineCreateInfo, or VkComputePipelineCreateInfo structures into the
vkCreateGraphicsPipelines, and vkCreateComputePipelines commands, respectively. Applications
can group together similar pipelines to be created in a single call, and implementations are
couraged to look for reuse opportunities within a group-create.

When an application attempts to create many pipelines in a single command, it is possible that
some subset may fail creation. In that case, the corresponding entries in the pPipelines output
array will be filled with VK_NULL_HANDLE values. If any pipeline fails creation despite valid
arguments (for example, due to out of memory errors), the VkResult code returned by
vkCreate*Pipelines will indicate why. The implementation will attempt to create all pipelines, and
only return VK_NULL_HANDLE values for those that actually failed.

If creation fails for a pipeline that had VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT set,
pipelines at an index in the pPipelines array greater than or equal to that of the failing pipeline
must be set to VK_NULL_HANDLE.

If multiple pipelines fail to be created, the VkResult must be the return value of any of the pipelines
which did not return VK_SUCCESS.

10.5. Pipeline Derivatives

A pipeline derivative is a child pipeline created from a parent pipeline, where the child and parent
are expected to have much commonality.

The goal of derivative pipelines is that they be cheaper to create using the parent as a starting
point, and that it be more efficient (on either host or device) to switch/bind between children of the
same parent.

A derivative pipeline is created by setting the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag in the
The base pipeline structure. If this is set, then exactly one of basePipelineHandle or basePipelineIndex members of the structure must have a valid handle/index, and specifies the parent pipeline. If basePipelineHandle is used, the parent pipeline must have already been created. If basePipelineIndex is used, then the parent is being created in the same command. VK_NULL_HANDLE acts as the invalid handle for basePipelineHandle, and -1 is the invalid index for basePipelineIndex. If basePipelineIndex is used, the base pipeline must appear earlier in the array. The base pipeline must have been created with the VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT flag set.

10.6. Pipeline Cache

Pipeline cache objects allow the result of pipeline construction to be reused between pipelines and between runs of an application. Reuse between pipelines is achieved by passing the same pipeline cache object when creating multiple related pipelines. Reuse across runs of an application is achieved by retrieving pipeline cache contents in one run of an application, saving the contents, and using them to preinitialize a pipeline cache on a subsequent run. The contents of the pipeline cache objects are managed by the implementation. Applications can manage the host memory consumed by a pipeline cache object and control the amount of data retrieved from a pipeline cache object.

Pipeline cache objects are represented by VkPipelineCache handles:

```
// Provided by VK_VERSION_1_0
Vk_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineCache)
```

10.6.1. Creating a Pipeline Cache

To create pipeline cache objects, call:

```
// Provided by VK_VERSION_1_0
VkResult vkCreatePipelineCache(
    VkDevice device,
    const VkPipelineCacheCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkPipelineCache* pPipelineCache);
```

- device is the logical device that creates the pipeline cache object.
- pCreateInfo is a pointer to a VkPipelineCacheCreateInfo structure containing initial parameters for the pipeline cache object.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pPipelineCache is a pointer to a VkPipelineCache handle in which the resulting pipeline cache object is returned.

Note
Applications can track and manage the total host memory size of a pipeline cache.
object using the pAllocators. Applications can limit the amount of data retrieved from a pipeline cache object in vkGetPipelineCacheData. Implementations should not internally limit the total number of entries added to a pipeline cache object or the total host memory consumed.

Once created, a pipeline cache can be passed to the vkCreateGraphicsPipelines and vkCreateComputePipelines commands. If the pipeline cache passed into these commands is not VK_NULL_HANDLE, the implementation will query it for possible reuse opportunities and update it with new content. The use of the pipeline cache object in these commands is internally synchronized, and the same pipeline cache object can be used in multiple threads simultaneously.

If flags of pCreateInfo includes VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT, all commands that modify the returned pipeline cache object must be externally synchronized.

Note
Implementations should make every effort to limit any critical sections to the actual accesses to the cache, which is expected to be significantly shorter than the duration of the vkCreate*Pipelines commands.

Valid Usage (Implicit)

- VUID-vkCreatePipelineCache-device-parameter
device must be a valid VkDevice handle

- VUID-vkCreatePipelineCache-pCreateInfo-parameter
pCreateInfo must be a valid pointer to a valid VkPipelineCacheCreateInfo structure

- VUID-vkCreatePipelineCache-pAllocator-parameter
If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkCreatePipelineCache-pPipelineCache-parameter
pPipelineCache must be a valid pointer to a VkPipelineCache handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkPipelineCacheCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineCacheCreateInfo {
```
VkStructureType sType;
const void* pNext;
VkPipelineCacheCreateFlags flags;
size_t initialDataSize;
const void* pInitialData;
}

VkPipelineCacheCreateInfo;

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is a bitmask of `VkPipelineCacheCreateFlagBits` specifying the behavior of the pipeline cache.
- `initialDataSize` is the number of bytes in `pInitialData`. If `initialDataSize` is zero, the pipeline cache will initially be empty.
- `pInitialData` is a pointer to previously retrieved pipeline cache data. If the pipeline cache data is incompatible (as defined below) with the device, the pipeline cache will be initially empty. If `initialDataSize` is zero, `pInitialData` is ignored.

### Valid Usage

- **VUID-VkPipelineCacheCreateInfo-initialDataSize-00768**
  If `initialDataSize` is not 0, it must be equal to the size of `pInitialData`, as returned by `vkGetPipelineCacheData` when `pInitialData` was originally retrieved.

- **VUID-VkPipelineCacheCreateInfo-initialDataSize-00769**
  If `initialDataSize` is not 0, `pInitialData` must have been retrieved from a previous call to `vkGetPipelineCacheData`.

- **VUID-VkPipelineCacheCreateInfo-pipelineCreationCacheControl-02892**
  If the `pipelineCreationCacheControl` feature is not enabled, `flags` must not include `VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT`.

### Valid Usage (Implicit)

- **VUID-VkPipelineCacheCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_CACHE_CREATE_INFO`.

- **VUID-VkPipelineCacheCreateInfo-pNext-pNext**
  `pNext` must be `NULL`.

- **VUID-VkPipelineCacheCreateInfo-flags-parameter**
  `flags` must be a valid combination of `VkPipelineCacheCreateFlagBits` values.

- **VUID-VkPipelineCacheCreateInfo-pInitialData-parameter**
  If `initialDataSize` is not 0, `pInitialData` must be a valid pointer to an array of `initialDataSize` bytes.

// Provided by VK_VERSION_1_0
**typedef** VkFlags VkPipelineCacheCreateFlags;

**VkPipelineCacheCreateFlags** is a bitmask type for setting a mask of zero or more **VkPipelineCacheCreateFlagBits**.

Bits which **can** be set in **VkPipelineCacheCreateInfo::flags**, specifying behavior of the pipeline cache, are:

```c
typedef enum VkPipelineCacheCreateFlagBits {
    // Provided by VK_VERSION_1_3
    VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT = 0x00000001,
} VkPipelineCacheCreateFlagBits;
```

- **VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT** specifies that all commands that modify the created **VkPipelineCache** will be externally synchronized. When set, the implementation **may** skip any unnecessary processing needed to support simultaneous modification from multiple threads where allowed.

### 10.6.2. Merging Pipeline Caches

Pipeline cache objects **can** be merged using the command:

```c
// Provided by VK_VERSION_1_0
VkResult vkMergePipelineCaches(VkDevice device,
                                VkPipelineCache dstCache,
                                uint32_t srcCacheCount,
                                const VkPipelineCache* pSrcCaches);
```

- **device** is the logical device that owns the pipeline cache objects.
- **dstCache** is the handle of the pipeline cache to merge results into.
- **srcCacheCount** is the length of the **pSrcCaches** array.
- **pSrcCaches** is a pointer to an array of pipeline cache handles, which will be merged into **dstCache**. The previous contents of **dstCache** are included after the merge.

**Note**

The details of the merge operation are implementation-dependent, but implementations **should** merge the contents of the specified pipelines and prune duplicate entries.

### Valid Usage

- **VUID-vkMergePipelineCaches-dstCache-00770**

  **dstCache** must not appear in the list of source caches
Valid Usage (Implicit)

- VUID-vkMergePipelineCaches-device-parameter
  
  device must be a valid VkDevice handle

- VUID-vkMergePipelineCaches-dstCache-parameter
  
  dstCache must be a valid VkPipelineCache handle

- VUID-vkMergePipelineCaches-pSrcCaches-parameter
  
  pSrcCaches must be a valid pointer to an array of srcCacheCount valid VkPipelineCache handles

- VUID-vkMergePipelineCaches-srcCacheCount-arraylength
  
  srcCacheCount must be greater than 0

- VUID-vkMergePipelineCaches-dstCache-parent
  
  dstCache must have been created, allocated, or retrieved from device

- VUID-vkMergePipelineCaches-pSrcCaches-parent
  
  Each element of pSrcCaches must have been created, allocated, or retrieved from device

Host Synchronization

- Host access to dstCache must be externally synchronized

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

10.6.3. Retrieving Pipeline Cache Data

Data can be retrieved from a pipeline cache object using the command:

```c
// Provided by VK_VERSION_1_0
VkResult vkGetPipelineCacheData(
    VkDevice device, 
    VkPipelineCache pipelineCache, 
    size_t* pDataSize, 
    void* pData);
```

- device is the logical device that owns the pipeline cache.
• **pipelineCache** is the pipeline cache to retrieve data from.

• **pDataSize** is a pointer to a `size_t` value related to the amount of data in the pipeline cache, as described below.

• **pData** is either `NULL` or a pointer to a buffer.

If **pData** is `NULL`, then the maximum size of the data that **can** be retrieved from the pipeline cache, in bytes, is returned in **pDataSize**. Otherwise, **pDataSize** must point to a variable set by the user to the size of the buffer, in bytes, pointed to by **pData**, and on return the variable is overwritten with the amount of data actually written to **pData**. If **pDataSize** is less than the maximum size that **can** be retrieved by the pipeline cache, at most **pDataSize** bytes will be written to **pData**, and **VK_INCOMPLETE** will be returned instead of **VK_SUCCESS**, to indicate that not all of the pipeline cache was returned.

Any data written to **pData** is valid and **can** be provided as the **pInitialData** member of the **VkPipelineCacheCreateInfo** structure passed to **vkCreatePipelineCache**.

Two calls to **vkGetPipelineCacheData** with the same parameters must retrieve the same data unless a command that modifies the contents of the cache is called between them.

The initial bytes written to **pData** must be a header as described in the **Pipeline Cache Header** section.

If **pDataSize** is less than what is necessary to store this header, nothing will be written to **pData** and zero will be written to **pDataSize**.

### Valid Usage (Implicit)

- VUID-vkGetPipelineCacheData-device-parameter
  - **device** must be a valid **VkDevice** handle

- VUID-vkGetPipelineCacheData-pipelineCache-parameter
  - **pipelineCache** must be a valid **VkPipelineCache** handle

- VUID-vkGetPipelineCacheData-pDataSize-parameter
  - **pDataSize** must be a valid pointer to a `size_t` value

- VUID-vkGetPipelineCacheData-pData-parameter
  - If the value referenced by **pDataSize** is not 0, and **pData** is not `NULL`, **pData** must be a valid pointer to an array of **pDataSize** bytes

- VUID-vkGetPipelineCacheData-pipelineCache-parent
  - **pipelineCache** must have been created, allocated, or retrieved from **device**

### Return Codes

**Success**

- **VK_SUCCESS**
- **VK_INCOMPLETE**
10.6.4. Pipeline Cache Header

Applications can store the data retrieved from the pipeline cache, and use these data, possibly in a future run of the application, to populate new pipeline cache objects. The results of pipeline compiles, however, may depend on the vendor ID, device ID, driver version, and other details of the device. To enable applications to detect when previously retrieved data is incompatible with the device, the pipeline cache data must begin with a valid pipeline cache header.

**Note**

Structures described in this section are not part of the Vulkan API and are only used to describe the representation of data elements in pipeline cache data. Accordingly, the valid usage clauses defined for structures defined in this section do not define valid usage conditions for APIs accepting pipeline cache data as input, as providing invalid pipeline cache data as input to any Vulkan API commands will result in the provided pipeline cache data being ignored.

Version one of the pipeline cache header is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineCacheHeaderVersionOne {
    uint32_t headerSize;
    VkPipelineCacheHeaderVersion headerVersion;
    uint32_t vendorID;
    uint32_t deviceID;
    uint8_t pipelineCacheUUID[VK_UUID_SIZE];
} VkPipelineCacheHeaderVersionOne;
```

- **headerSize** is the length in bytes of the pipeline cache header.
- **headerVersion** is a `VkPipelineCacheHeaderVersion` enum value specifying the version of the header. A consumer of the pipeline cache should use the cache version to interpret the remainder of the cache header.
- **vendorID** is the `VkPhysicalDeviceProperties::vendorID` of the implementation.
- **deviceID** is the `VkPhysicalDeviceProperties::deviceID` of the implementation.
- **pipelineCacheUUID** is the `VkPhysicalDeviceProperties::pipelineCacheUUID` of the implementation.

Unlike most structures declared by the Vulkan API, all fields of this structure are written with the least significant byte first, regardless of host byte-order.

The C language specification does not define the packing of structure members. This layout assumes tight structure member packing, with members laid out in the order listed in the structure, and the intended size of the structure is 32 bytes. If a compiler produces code that diverges from
that pattern, applications must employ another method to set values at the correct offsets.

### Valid Usage

- **VUID-VkPipelineCacheHeaderVersionOne-headerSize-04967**
  
  \( \text{headerSize must be 32} \)

- **VUID-VkPipelineCacheHeaderVersionOne-headerVersion-04968**
  
  \( \text{headerVersion must be \text{VK_PIPELINE_CACHE_HEADER_VERSION_ONE}} \)

- **VUID-VkPipelineCacheHeaderVersionOne-headerSize-08990**
  
  \( \text{headerSize must not exceed the size of the pipeline cache} \)

### Valid Usage (Implicit)

- **VUID-VkPipelineCacheHeaderVersionOne-headerVersion-parameter**
  
  \( \text{headerVersion must be a valid} \ \text{VkPipelineCacheHeaderVersion value} \)

Possible values of the \text{headerVersion} value of the pipeline cache header are:

```c
// Provided by \text{VK_VERSION_1_0}

typedef enum VkPipelineCacheHeaderVersion {
    VK_PIPELINE_CACHE_HEADER_VERSION_ONE = 1,
} VkPipelineCacheHeaderVersion;
```

- \text{VK_PIPELINE_CACHE_HEADER_VERSION_ONE} specifies version one of the pipeline cache, described by \text{VkPipelineCacheHeaderVersionOne}.

### 10.6.5. Destroying a Pipeline Cache

To destroy a pipeline cache, call:

```c
// Provided by \text{VK_VERSION_1_0}

\text{void} \text{vkDestroyPipelineCache(}
    \text{VkDevice} \ \text{device,}
    \text{VkPipelineCache} \ \text{pipelineCache,}
    \text{const} \ \text{VkAllocationCallbacks*} \ \text{pAllocator);}
```

- \text{device} is the logical device that destroys the pipeline cache object.
- \text{pipelineCache} is the handle of the pipeline cache to destroy.
- \text{pAllocator} controls host memory allocation as described in the \text{Memory Allocation} chapter.

### Valid Usage

- **VUID-vkDestroyPipelineCache-pipelineCache-00771**
If `VkAllocationCallbacks` were provided when `pipelineCache` was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyPipelineCache-pipelineCache-00772

If no `VkAllocationCallbacks` were provided when `pipelineCache` was created, `pAllocator` must be `NULL`

**Valid Usage (Implicit)**

- VUID-vkDestroyPipelineCache-device-parameter
  
  `device` must be a valid `VkDevice` handle

- VUID-vkDestroyPipelineCache-pipelineCache-parameter
  
  If `pipelineCache` is not `VK_NULL_HANDLE`, `pipelineCache` must be a valid `VkPipelineCache` handle

- VUID-vkDestroyPipelineCache-pAllocator-parameter
  
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- VUID-vkDestroyPipelineCache-pipelineCache-parent
  
  If `pipelineCache` is a valid handle, it must have been created, allocated, or retrieved from `device`

**Host Synchronization**

- Host access to `pipelineCache` must be externally synchronized

### 10.7. Specialization Constants

Specialization constants are a mechanism whereby constants in a SPIR-V module can have their constant value specified at the time the `VkPipeline` is created. This allows a SPIR-V module to have constants that can be modified while executing an application that uses the Vulkan API.

Note

Specialization constants are useful to allow a compute shader to have its local workgroup size changed at runtime by the user, for example.

Each `VkPipelineShaderStageCreateInfo` structure contains a `pSpecializationInfo` member, which can be `NULL` to indicate no specialization constants, or point to a `VkSpecializationInfo` structure.

The `VkSpecializationInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSpecializationInfo {
    uint32_t mapEntryCount;
    const VkSpecializationMapEntry* pMapEntries;
} VkSpecializationInfo;
```
size_t dataSize;
const void* pData;
} VkSpecializationInfo;

- `mapEntryCount` is the number of entries in the `pMapEntries` array.
- `pMapEntries` is a pointer to an array of `VkSpecializationMapEntry` structures, which map constant IDs to offsets in `pData`.
- `dataSize` is the byte size of the `pData` buffer.
- `pData` contains the actual constant values to specialize with.

### Valid Usage

- **VUID-VkSpecializationInfo-offset-00773**
  The `offset` member of each element of `pMapEntries` **must** be less than `dataSize`

- **VUID-VkSpecializationInfo-pMapEntries-00774**
  The `size` member of each element of `pMapEntries` **must** be less than or equal to `dataSize` minus `offset`

- **VUID-VkSpecializationInfo-constantID-04911**
  The `constantID` value of each element of `pMapEntries` **must** be unique within `pMapEntries`

### Valid Usage (Implicit)

- **VUID-VkSpecializationInfo-pMapEntries-parameter**
  If `mapEntryCount` is not 0, `pMapEntries` **must** be a valid pointer to an array of `mapEntryCount` valid `VkSpecializationMapEntry` structures

- **VUID-VkSpecializationInfo-pData-parameter**
  If `dataSize` is not 0, `pData` **must** be a valid pointer to an array of `dataSize` bytes

The `VkSpecializationMapEntry` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSpecializationMapEntry {
  uint32_t  constantID;
  uint32_t  offset;
  size_t    size;
} VkSpecializationMapEntry;
```

- `constantID` is the ID of the specialization constant in SPIR-V.
- `offset` is the byte offset of the specialization constant value within the supplied data buffer.
- `size` is the byte size of the specialization constant value within the supplied data buffer.

If a `constantID` value is not a specialization constant ID used in the shader, that map entry does not
affect the behavior of the pipeline.

---

**Valid Usage**

- [VUID-VkSpecializationMapEntry-constantID-00776](#)

For a `constantID` specialization constant declared in a shader, `size` **must** match the byte size of the `constantID`. If the specialization constant is of type `boolean`, `size` **must** be the byte size of `VkBool32`.

In human readable SPIR-V:

```glsl
OpDecorate %x SpecId 13 ; decorate .x component of WorkgroupSize with ID 13
OpDecorate %y SpecId 42 ; decorate .y component of WorkgroupSize with ID 42
OpDecorate %z SpecId 3 ; decorate .z component of WorkgroupSize with ID 3
OpDecorate %wgsiz BuiltIn WorkgroupSize ; decorate WorkgroupSize onto constant
%32 = OpTypeInt 32 0 ; declare an unsigned 32-bit type
%uvec3 = OpTypeVector %32 3 ; declare a 3 element vector type of unsigned 32-bit
%x = OpSpecConstant %32 1 ; declare the .x component of WorkgroupSize
%y = OpSpecConstant %32 1 ; declare the .y component of WorkgroupSize
%z = OpSpecConstant %32 1 ; declare the .z component of WorkgroupSize
%wgsiz = OpSpecConstantComposite %uvec3 %x %y %z ; declare WorkgroupSize
```

From the above we have three specialization constants, one for each of the x, y & z elements of the WorkgroupSize vector.

Now to specialize the above via the specialization constants mechanism:

```c
const VkSpecializationMapEntry entries[] =
{
    {
        .constantID = 13,
        .offset = 0 * sizeof(uint32_t),
        .size = sizeof(uint32_t)
    },
    {
        .constantID = 42,
        .offset = 1 * sizeof(uint32_t),
        .size = sizeof(uint32_t)
    },
    {
        .constantID = 3,
        .offset = 2 * sizeof(uint32_t),
        .size = sizeof(uint32_t)
    }
};

const uint32_t data[] = { 16, 8, 4 }; // our workgroup size is 16x8x4
```
const VkSpecializationInfo info =
{
    .mapEntryCount = 3,
    .pMapEntries = entries,
    .dataSize = 3 * sizeof(uint32_t),
    .pData = data,
};

Then when calling `vkCreateComputePipelines`, and passing the `VkSpecializationInfo` we defined as the `pSpecializationInfo` parameter of `VkPipelineShaderStageCreateInfo`, we will create a compute pipeline with the runtime specified local workgroup size.

Another example would be that an application has a SPIR-V module that has some platform-dependent constants they wish to use.

In human readable SPIR-V:

```text
OpDecorate %1 SpecId 0 ; decorate our signed 32-bit integer constant
OpDecorate %2 SpecId 12 ; decorate our 32-bit floating-point constant
%i32 = OpTypeInt 32 1 ; declare a signed 32-bit type
%f32 = OpTypeFloat 32 ; declare a 32-bit floating-point type
%i = OpSpecConstant %i32 -1 ; some signed 32-bit integer constant
%f2 = OpSpecConstant %f32 0.5 ; some 32-bit floating-point constant
```

From the above we have two specialization constants, one is a signed 32-bit integer and the second is a 32-bit floating-point value.

Now to specialize the above via the specialization constants mechanism:

```c
struct SpecializationData {
    int32_t data0;
    float data1;
};

const VkSpecializationMapEntry entries[] =
{
    {
        .constantID = 0,
        .offset = offsetof(SpecializationData, data0),
        .size = sizeof(SpecializationData::data0)
    },
    {
        .constantID = 12,
        .offset = offsetof(SpecializationData, data1),
        .size = sizeof(SpecializationData::data1)
    }
};

SpecializationData data;
```
data.data0 = -42;  // set the data for the 32-bit integer
data.data1 = 42.0f;  // set the data for the 32-bit floating-point

const VkSpecializationInfo info =
{
    .mapEntryCount = 2,
    .pMapEntries = entries,
    .dataSize = sizeof(data),
    .pdata = &data,
};

It is legal for a SPIR-V module with specializations to be compiled into a pipeline where no specialization information was provided. SPIR-V specialization constants contain default values such that if a specialization is not provided, the default value will be used. In the examples above, it would be valid for an application to only specialize some of the specialization constants within the SPIR-V module, and let the other constants use their default values encoded within the OpSpecConstant declarations.

10.8. Pipeline Binding

Once a pipeline has been created, it can be bound to the command buffer using the command:

```cpp
// Provided by VK_VERSION_1_0
void vkCmdBindPipeline(
    VkCommandBuffer commandBuffer,
    VkPipelineBindPoint pipelineBindPoint,
    VkPipeline pipeline);
```

- `commandBuffer` is the command buffer that the pipeline will be bound to.
- `pipelineBindPoint` is a `VkPipelineBindPoint` value specifying to which bind point the pipeline is bound. Binding one does not disturb the others.
- `pipeline` is the pipeline to be bound.

Once bound, a pipeline binding affects subsequent commands that interact with the given pipeline type in the command buffer until a different pipeline of the same type is bound to the bind point. Commands that do not interact with the given pipeline type must not be affected by the pipeline state.

Valid Usage

- VUID-vkCmdBindPipeline-pipelineBindPoint-00777
  If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, the `VkCommandPool` that `commandBuffer` was allocated from must support compute operations.

- VUID-vkCmdBindPipeline-pipelineBindPoint-00778
  If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, the `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.
• VUID-vkCmdBindPipeline-pipelineBindPoint-00779
  If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, `pipeline` must be a compute pipeline

• VUID-vkCmdBindPipeline-pipelineBindPoint-00780
  If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, `pipeline` must be a graphics pipeline

• VUID-vkCmdBindPipeline-pipeline-00781
  If the `variableMultisampleRate` feature is not supported, `pipeline` is a graphics pipeline, the current subpass uses no attachments, and this is not the first call to this function with a graphics pipeline after transitioning to the current subpass, then the sample count specified by this pipeline must match that set in the previous pipeline

### Valid Usage (Implicit)

• VUID-vkCmdBindPipeline-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

• VUID-vkCmdBindPipeline-pipelineBindPoint-parameter
  `pipelineBindPoint` must be a valid `VkPipelineBindPoint` value

• VUID-vkCmdBindPipeline-pipeline-parameter
  `pipeline` must be a valid `VkPipeline` handle

• VUID-vkCmdBindPipeline-commandBuffer-recording
  `commandBuffer` must be in the recording state

• VUID-vkCmdBindPipeline-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations

• VUID-vkCmdBindPipeline-commonparent
  Both of `commandBuffer`, and `pipeline` must have been created, allocated, or retrieved from the same `VkDevice`

### Host Synchronization

• Host access to `commandBuffer` must be externally synchronized

• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
Command Properties

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Possible values of `vkCmdBindPipeline::pipelineBindPoint`, specifying the bind point of a pipeline object, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPipelineBindPoint {
    VK_PIPELINE_BIND_POINT_GRAPHICS = 0,
    VK_PIPELINE_BIND_POINT_COMPUTE = 1,
} VkPipelineBindPoint;
```

- `VK_PIPELINE_BIND_POINT_COMPUTE` specifies binding as a compute pipeline.
- `VK_PIPELINE_BIND_POINT_GRAPHICS` specifies binding as a graphics pipeline.

10.9. Dynamic State

When a pipeline object is bound, any pipeline object state that is not specified as dynamic is applied to the command buffer state. Pipeline object state that is specified as dynamic is not applied to the command buffer state at this time. Instead, dynamic state can be modified at any time and persists for the lifetime of the command buffer, or until modified by another dynamic state setting command, or made invalid by another pipeline bind with that state specified as static.

When a pipeline object is bound, the following applies to each state parameter:

- If the state is not specified as dynamic in the new pipeline object, then that command buffer state is overwritten by the state in the new pipeline object. Before any draw or dispatch call with this pipeline there must not have been any calls to any of the corresponding dynamic state setting commands after this pipeline was bound.

- If the state is specified as dynamic in the new pipeline object, then that command buffer state is not disturbed. Before any draw or dispatch call with this pipeline there must have been at least one call to each of the corresponding dynamic state setting commands. The state-setting commands must be recorded after command buffer recording was begun, or after the last command binding a pipeline object with that state specified as static, whichever was the latter.

- If the state is not included (corresponding pointer in `VkGraphicsPipelineCreateInfo` was NULL or was ignored) in the new pipeline object, then that command buffer state is not disturbed.

Dynamic state that does not affect the result of operations can be left undefined.

**Note**
For example, if blending is disabled by the pipeline object state then the dynamic color blend constants do not need to be specified in the command buffer, even if this state is specified as dynamic in the pipeline object.

10.10. Pipeline Creation Feedback

Feedback about the creation of a particular pipeline object can be obtained by adding a VkPipelineCreationFeedbackCreateInfo structure to the pNext chain of VkGraphicsPipelineCreateInfo, or VkComputePipelineCreateInfo. The VkPipelineCreationFeedbackCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPipelineCreationFeedbackCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineCreationFeedback* pPipelineCreationFeedback;
    uint32_t pipelineStageCreationFeedbackCount;
    VkPipelineCreationFeedback* pPipelineStageCreationFeedbacks;
} VkPipelineCreationFeedbackCreateInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **pPipelineCreationFeedback** is a pointer to a VkPipelineCreationFeedback structure.
- **pipelineStageCreationFeedbackCount** is the number of elements in **pPipelineStageCreationFeedbacks**.
- **pPipelineStageCreationFeedbacks** is a pointer to an array of **pipelineStageCreationFeedbackCount** VkPipelineCreationFeedback structures.

An implementation should write pipeline creation feedback to **pPipelineCreationFeedback** and may write pipeline stage creation feedback to **pPipelineStageCreationFeedbacks**. An implementation must set or clear the VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT in **VkPipelineCreationFeedback**::flags for **pPipelineCreationFeedback** and every element of **pPipelineStageCreationFeedbacks**.

**Note**

One common scenario for an implementation to skip per-stage feedback is when VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT is set in **pPipelineCreationFeedback**.

When chained to VkGraphicsPipelineCreateInfo, the i element of **pPipelineStageCreationFeedbacks** corresponds to the i element of VkGraphicsPipelineCreateInfo::pStages. When chained to VkComputePipelineCreateInfo, the first element of **pPipelineStageCreationFeedbacks** corresponds to VkComputePipelineCreateInfo::stage.

**Valid Usage (Implicit)**

- VUID-VkPipelineCreationFeedbackCreateInfo-sType-sType
**sType** must be `VK_STRUCTURE_TYPE_PIPELINE_CREATION_FEEDBACK_CREATE_INFO`

- VUID-VkPipelineCreationFeedbackCreateInfo-pPipelineCreationFeedback-parameter
  
  **pPipelineCreationFeedback** must be a valid pointer to a `VkPipelineCreationFeedback` structure

- VUID-VkPipelineCreationFeedbackCreateInfo-pPipelineStageCreationFeedbacks-parameter
  
  If `pipelineStageCreationFeedbackCount` is not 0, **pPipelineStageCreationFeedbacks** must be a valid pointer to an array of `pipelineStageCreationFeedbackCount` `VkPipelineCreationFeedback` structures

The `VkPipelineCreationFeedback` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPipelineCreationFeedback {
    VkPipelineCreationFeedbackFlags flags;
    uint64_t duration;
} VkPipelineCreationFeedback;
```

- **flags** is a bitmask of `VkPipelineCreationFeedbackFlagBits` providing feedback about the creation of a pipeline or of a pipeline stage.
- **duration** is the duration spent creating a pipeline or pipeline stage in nanoseconds.

If the `VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT` is not set in **flags**, an implementation must not set any other bits in **flags**, and the values of all other `VkPipelineCreationFeedback` data members are undefined.

Possible values of the **flags** member of `VkPipelineCreationFeedback` are:

```c
// Provided by VK_VERSION_1_3
typedef enum VkPipelineCreationFeedbackFlagBits {
    VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT = 0x00000001,
    VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT = 0x00000002,
    VK_PIPELINE_CREATION_FEEDBACK_BASE_PIPELINE_ACCELERATION_BIT = 0x00000004,
    VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT_EXT = VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT,
    VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT_EXT = VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT,
    VK_PIPELINE_CREATION_FEEDBACK_BASE_PIPELINE_ACCELERATION_BIT_EXT = VK_PIPELINE_CREATION_FEEDBACK_BASE_PIPELINE_ACCELERATION_BIT,
} VkPipelineCreationFeedbackFlagBits;
```

- **VK_PIPELINE_CREATION_FEEDBACK_VALID_BIT** indicates that the feedback information is valid.
- **VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT** indicates that a readily usable pipeline or pipeline stage was found in the `pipelineCache` specified by the application in the pipeline creation command.
An implementation should set the `VK_PIPELINE_CREATION_FEEDBACK_APPLICATION_PIPELINE_CACHE_HIT_BIT` bit if it was able to avoid the large majority of pipeline or pipeline stage creation work by using the `pipelineCache` parameter of `vkCreateGraphicsPipelines`, or `vkCreateComputePipelines`. When an implementation sets this bit for the entire pipeline, it may leave it unset for any stage.

**Note**
Implementations are encouraged to provide a meaningful signal to applications using this bit. The intention is to communicate to the application that the pipeline or pipeline stage was created “as fast as it gets” using the pipeline cache provided by the application. If an implementation uses an internal cache, it is discouraged from setting this bit as the feedback would be unactionable.

- `VK_PIPELINE_CREATION_FEEDBACK_BASE_PIPELINE_ACCELERATION_BIT` indicates that the base pipeline specified by the `basePipelineHandle` or `basePipelineIndex` member of the `Vk*PipelineCreateInfo` structure was used to accelerate the creation of the pipeline.

An implementation should set the `VK_PIPELINE_CREATION_FEEDBACK_BASE_PIPELINE_ACCELERATION_BIT` bit if it was able to avoid a significant amount of work by using the base pipeline.

**Note**
While “significant amount of work” is subjective, implementations are encouraged to provide a meaningful signal to applications using this bit. For example, a 1% reduction in duration may not warrant setting this bit, while a 50% reduction would.

```c
// Provided by VK_VERSION_1_3
typedef VkFlags VkPipelineCreationFeedbackFlags;
```

`VkPipelineCreationFeedbackFlags` is a bitmask type for providing zero or more `VkPipelineCreationFeedbackFlagBits`. 

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Chapter 11. Memory Allocation

Vulkan memory is broken up into two categories, *host memory* and *device memory*.

### 11.1. Host Memory

Host memory is memory needed by the Vulkan implementation for non-device-visible storage.

**Note**

This memory *may* be used to store the implementation's representation and state of Vulkan objects.

Vulkan provides applications the opportunity to perform host memory allocations on behalf of the Vulkan implementation. If this feature is not used, the implementation will perform its own memory allocations. Since most memory allocations are off the critical path, this is not meant as a performance feature. Rather, this *can* be useful for certain embedded systems, for debugging purposes (e.g. putting a guard page after all host allocations), or for memory allocation logging.

Allocators are provided by the application as a pointer to a `VkAllocationCallbacks` structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkAllocationCallbacks {
    void* pUserData;
    PFN_vkAllocationFunction pfnAllocation;
    PFN_vkReallocationFunction pfnReallocation;
    PFN_vkFreeFunction pfnFree;
    PFN_vkInternalAllocationNotification pfnInternalAllocation;
    PFN_vkInternalFreeNotification pfnInternalFree;
} VkAllocationCallbacks;
```

- *pUserData* is a value to be interpreted by the implementation of the callbacks. When any of the callbacks in `VkAllocationCallbacks` are called, the Vulkan implementation will pass this value as the first parameter to the callback. This value *can* vary each time an allocator is passed into a command, even when the same object takes an allocator in multiple commands.

- *pfnAllocation* is a `PFN_vkAllocationFunction` pointer to an application-defined memory allocation function.

- *pfnReallocation* is a `PFN_vkReallocationFunction` pointer to an application-defined memory reallocation function.

- *pfnFree* is a `PFN_vkFreeFunction` pointer to an application-defined memory free function.

- *pfnInternalAllocation* is a `PFN_vkInternalAllocationNotification` pointer to an application-defined function that is called by the implementation when the implementation makes internal allocations.

- *pfnInternalFree* is a `PFN_vkInternalFreeNotification` pointer to an application-defined function that is called by the implementation when the implementation frees internal allocations.
Valid Usage

- VUID-VkAllocationCallbacks-pfnAllocation-00632
  
  `pfnAllocation` must be a valid pointer to a valid user-defined `PFN_vkAllocationFunction`

- VUID-VkAllocationCallbacks-pfnReallocation-00633
  
  `pfnReallocation` must be a valid pointer to a valid user-defined `PFN_vkReallocationFunction`

- VUID-VkAllocationCallbacks-pfnFree-00634
  
  `pfnFree` must be a valid pointer to a valid user-defined `PFN_vkFreeFunction`

- VUID-VkAllocationCallbacks-pfnInternalAllocation-00635
  
  If either of `pfnInternalAllocation` or `pfnInternalFree` is not NULL, both must be valid callbacks

The type of `pfnAllocation` is:

```c
// Provided by VK_VERSION_1_0
typedef void* (VKAPI_PTR *PFN_vkAllocationFunction)(
    void* pUserData,
    size_t size,
    size_t alignment,
    VkSystemAllocationScope allocationScope);
```

- `pUserData` is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- `size` is the size in bytes of the requested allocation.
- `alignment` is the requested alignment of the allocation in bytes and must be a power of two.
- `allocationScope` is a `VkSystemAllocationScope` value specifying the allocation scope of the lifetime of the allocation, as described here.

If `pfnAllocation` is unable to allocate the requested memory, it must return NULL. If the allocation was successful, it must return a valid pointer to memory allocation containing at least `size` bytes, and with the pointer value being a multiple of `alignment`.

**Note**

Correct Vulkan operation cannot be assumed if the application does not follow these rules.

For example, `pfnAllocation` (or `pfnReallocation`) could cause termination of running Vulkan instance(s) on a failed allocation for debugging purposes, either directly or indirectly. In these circumstances, it cannot be assumed that any part of any affected `VkInstance` objects are going to operate correctly (even `vkDestroyInstance`), and the application must ensure it cleans up properly via other means (e.g. process termination).
If `pfnAllocation` returns `NULL`, and if the implementation is unable to continue correct processing of the current command without the requested allocation, it **must** treat this as a runtime error, and generate `VK_ERROR_OUT_OF_HOST_MEMORY` at the appropriate time for the command in which the condition was detected, as described in **Return Codes**.

If the implementation is able to continue correct processing of the current command without the requested allocation, then it **may** do so, and **must** not generate `VK_ERROR_OUT_OF_HOST_MEMORY` as a result of this failed allocation.

The type of `pfnReallocation` is:

```
// Provided by VK_VERSION_1_0
typedef void* (VKAPI_PTR *PFN_vkReallocationFunction)(
    void* pUserData,
    void* pOriginal,
    size_t size,
    size_t alignment,
    VkSystemAllocationScope allocationScope);
```

- `pUserData` is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- `pOriginal` **must** be either `NULL` or a pointer previously returned by `pfnReallocation` or `pfnAllocation` of a compatible allocator.
- `size` is the size in bytes of the requested allocation.
- `alignment` is the requested alignment of the allocation in bytes and **must** be a power of two.
- `allocationScope` is a `VkSystemAllocationScope` value specifying the allocation scope of the lifetime of the allocation, as described [here](#).

If the reallocation was successful, `pfnReallocation` **must** return an allocation with enough space for `size` bytes, and the contents of the original allocation from bytes zero to `min(original size, new size) - 1` **must** be preserved in the returned allocation. If `size` is larger than the old size, the contents of the additional space are undefined. If satisfying these requirements involves creating a new allocation, then the old allocation **should** be freed.

If `pOriginal` is `NULL`, then `pfnReallocation` **must** behave equivalently to a call to `PFN_vkAllocationFunction` with the same parameter values (without `pOriginal`).

If `size` is zero, then `pfnReallocation` **must** behave equivalently to a call to `PFN_vkFreeFunction` with the same `pUserData` parameter value, and `pMemory` equal to `pOriginal`.

If `pOriginal` is non-`NULL`, the implementation **must** ensure that `alignment` is equal to the `alignment` used to originally allocate `pOriginal`.

If this function fails and `pOriginal` is non-`NULL` the application **must** not free the old allocation.

`pfnReallocation` **must** follow the same **rules for return values** as `PFN_vkAllocationFunction`.

The type of `pfnFree` is:
typedef void (VKAPI_PTR *PFN_vkFreeFunction)(
    void* pUserData,
    void* pMemory);

- **pUserData** is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- **pMemory** is the allocation to be freed.

`pMemory` **may** be `NULL`, which the callback **must** handle safely. **If** `pMemory` **is** non-`NULL`, it **must** be a pointer previously allocated by `PFN_allocation` or `PFN_reallocation`. The application **should** free this memory.

The type of `PFN_internalAllocation` is:

typedef void (VKAPI_PTR *PFN_vkInternalAllocationNotification)(
    void* pUserData,
    size_t size,
    VkInternalAllocationType allocationType,
    VkSystemAllocationScope allocationScope);

- **pUserData** is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- **size** is the requested size of an allocation.
- **allocationType** is a `VkInternalAllocationType` value specifying the requested type of an allocation.
- **allocationScope** is a `VkSystemAllocationScope` value specifying the allocation scope of the lifetime of the allocation, as described here.

This is a purely informational callback.

The type of `PFN_internalFree` is:

typedef void (VKAPI_PTR *PFN_vkInternalFreeNotification)(
    void* pUserData,
    size_t size,
    VkInternalAllocationType allocationType,
    VkSystemAllocationScope allocationScope);

- **pUserData** is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- **size** is the requested size of an allocation.
• **allocationType** is a *VkInternalAllocationType* value specifying the requested type of an allocation.

• **allocationScope** is a *VkSystemAllocationScope* value specifying the allocation scope of the lifetime of the allocation, as described here.

Each allocation has an allocation scope defining its lifetime and which object it is associated with. Possible values passed to the allocationScope parameter of the callback functions specified by *VkAllocationCallbacks*, indicating the allocation scope, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSystemAllocationScope {
    VK_SYSTEM_ALLOCATION_SCOPE_COMMAND = 0,
    VK_SYSTEM_ALLOCATION_SCOPE_OBJECT = 1,
    VK_SYSTEM_ALLOCATION_SCOPE_CACHE = 2,
    VK_SYSTEM_ALLOCATION_SCOPE_DEVICE = 3,
    VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE = 4,
} VkSystemAllocationScope;
```

• **VK_SYSTEM_ALLOCATION_SCOPE_COMMAND** specifies that the allocation is scoped to the duration of the Vulkan command.

• **VK_SYSTEM_ALLOCATION_SCOPE_OBJECT** specifies that the allocation is scoped to the lifetime of the Vulkan object that is being created or used.

• **VK_SYSTEM_ALLOCATION_SCOPE_CACHE** specifies that the allocation is scoped to the lifetime of a *VkPipelineCache* object.

• **VK_SYSTEM_ALLOCATION_SCOPE_DEVICE** specifies that the allocation is scoped to the lifetime of the Vulkan device.

• **VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE** specifies that the allocation is scoped to the lifetime of the Vulkan instance.

Most Vulkan commands operate on a single object, or there is a sole object that is being created or manipulated. When an allocation uses an allocation scope of **VK_SYSTEM_ALLOCATION_SCOPE_OBJECT** or **VK_SYSTEM_ALLOCATION_SCOPE_CACHE**, the allocation is scoped to the object being created or manipulated.

When an implementation requires host memory, it will make callbacks to the application using the most specific allocator and allocation scope available:

• If an allocation is scoped to the duration of a command, the allocator will use the **VK_SYSTEM_ALLOCATION_SCOPE_COMMAND** allocation scope. The most specific allocator available is used: if the object being created or manipulated has an allocator, that object's allocator will be used, else if the parent *VkDevice* has an allocator it will be used, else if the parent *VkInstance* has an allocator it will be used. Else,

• If an allocation is associated with a *VkPipelineCache* object, the allocator will use the **VK_SYSTEM_ALLOCATION_SCOPE_CACHE** allocation scope. The most specific allocator available is used (cache, else device, else instance). Else,
• If an allocation is scoped to the lifetime of an object, that object is being created or manipulated by the command, and that object’s type is not \texttt{VkDevice} or \texttt{VkInstance}, the allocator will use an allocation scope of \texttt{VK_SYSTEM_ALLOCATION_SCOPE_OBJECT}. The most specific allocator available is used (object, else device, else instance). Else,

• If an allocation is scoped to the lifetime of a device, the allocator will use an allocation scope of \texttt{VK_SYSTEM_ALLOCATION_SCOPE_DEVICE}. The most specific allocator available is used (device, else instance). Else,

• If the allocation is scoped to the lifetime of an instance and the instance has an allocator, its allocator will be used with an allocation scope of \texttt{VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE}.

• Otherwise an implementation will allocate memory through an alternative mechanism that is unspecified.

Objects that are allocated from pools do not specify their own allocator. When an implementation requires host memory for such an object, that memory is sourced from the object’s parent pool’s allocator.

The application is not expected to handle allocating memory that is intended for execution by the host due to the complexities of differing security implementations across multiple platforms. The implementation will allocate such memory internally and invoke an application provided informational callback when these \textit{internal allocations} are allocated and freed. Upon allocation of executable memory, \texttt{PFNInternalAllocation} will be called. Upon freeing executable memory, \texttt{PFNInternalFree} will be called. An implementation will only call an informational callback for executable memory allocations and frees.

The \texttt{allocationType} parameter to the \texttt{PFNInternalAllocation} and \texttt{PFNInternalFree} functions \textbf{may} be one of the following values:

```c
// Provided by VK_VERSION_1_0
typedef enum VkInternalAllocationType {
    VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE = 0,
} VkInternalAllocationType;
```

• \texttt{VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE} specifies that the allocation is intended for execution by the host.

An implementation \textbf{must} only make calls into an application-provided allocator during the execution of an API command. An implementation \textbf{must} only make calls into an application-provided allocator from the same thread that called the provoking API command. The implementation \textbf{should} not synchronize calls to any of the callbacks. If synchronization is needed, the callbacks \textbf{must} provide it themselves. The informational callbacks are subject to the same restrictions as the allocation callbacks.

If an implementation intends to make calls through a \texttt{VkAllocationCallbacks} structure between the time a \texttt{vkCreate*} command returns and the time a corresponding \texttt{vkDestroy*} command begins, that implementation \textbf{must} save a copy of the allocator before the \texttt{vkCreate*} command returns. The callback functions and any data structures they rely upon \textbf{must} remain valid for the lifetime of the object they are associated with.
If an allocator is provided to a \texttt{vkCreate*} command, a \textit{compatible} allocator \textbf{must} be provided to the corresponding \texttt{vkDestroy*} command. Two \texttt{VkAllocationCallbacks} structures are compatible if memory allocated with \texttt{pfnAllocation} or \texttt{pfnReallocation} in each \textbf{can} be freed with \texttt{pfnReallocation} or \texttt{pfnFree} in the other. An allocator \textbf{must} not be provided to a \texttt{vkDestroy*} command if an allocator was not provided to the corresponding \texttt{vkCreate*} command.

If a non-NULL allocator is used, the \texttt{pfnAllocation}, \texttt{pfnReallocation} and \texttt{pfnFree} members \textbf{must} be non-NULL and point to valid implementations of the callbacks. An application \textbf{can} choose to not provide informational callbacks by setting both \texttt{pfnInternalAllocation} and \texttt{pfnInternalFree} to NULL. \texttt{pfnInternalAllocation} and \texttt{pfnInternalFree} \textbf{must} either both be NULL or both be non-NULL.

If \texttt{pfnAllocation} or \texttt{pfnReallocation} fail, the implementation \textbf{may} fail object creation and/or generate a \texttt{VK_ERROR_OUT_OF_HOST_MEMORY} error, as appropriate.

Allocation callbacks \textbf{must} not call any Vulkan commands.

The following sets of rules define when an implementation is permitted to call the allocator callbacks.

\texttt{pfnAllocation} or \texttt{pfnReallocation} \textbf{may} be called in the following situations:

- Allocations scoped to a \texttt{VkDevice} or \texttt{VkInstance} \textbf{may} be allocated from any API command.
- Allocations scoped to a command \textbf{may} be allocated from any API command.
- Allocations scoped to a \texttt{VkPipelineCache} \textbf{may} only be allocated from:
  - \texttt{vkCreatePipelineCache}
  - \texttt{vkMergePipelineCaches} for \texttt{dstCache}
  - \texttt{vkCreateGraphicsPipelines} for \texttt{pipelineCache}
  - \texttt{vkCreateComputePipelines} for \texttt{pipelineCache}
- Allocations scoped to a \texttt{VkDescriptorPool} \textbf{may} only be allocated from:
  - any command that takes the pool as a direct argument
  - \texttt{vkAllocateDescriptorSets} for the \texttt{descriptorPool} member of its \texttt{pAllocateInfo} parameter
  - \texttt{vkCreateDescriptorPool}
- Allocations scoped to a \texttt{VkCommandPool} \textbf{may} only be allocated from:
  - any command that takes the pool as a direct argument
  - \texttt{vkCreateCommandPool}
  - \texttt{vkAllocateCommandBuffers} for the \texttt{commandPool} member of its \texttt{pAllocateInfo} parameter
  - any \texttt{vkCmd*} command whose \texttt{commandBuffer} was allocated from that \texttt{VkCommandPool}
- Allocations scoped to any other object \textbf{may} only be allocated in that object's \texttt{vkCreate*} command.

\texttt{pfnFree}, or \texttt{pfnReallocation} with zero \texttt{size}, \textbf{may} be called in the following situations:

- Allocations scoped to a \texttt{VkDevice} or \texttt{VkInstance} \textbf{may} be freed from any API command.
• Allocations scoped to a command must be freed by any API command which allocates such memory.

• Allocations scoped to a VkPipelineCache may be freed from vkDestroyPipelineCache.

• Allocations scoped to a VkDescriptorPool may be freed from:
  ◦ any command that takes the pool as a direct argument

• Allocations scoped to a VkCommandPool may be freed from:
  ◦ any command that takes the pool as a direct argument
  ◦ vkResetCommandBuffer whose commandBuffer was allocated from that VkCommandPool

• Allocations scoped to any other object may be freed in that object’s vkDestroy* command.

• Any command that allocates host memory may also free host memory of the same scope.

11.2. Device Memory

Device memory is memory that is visible to the device — for example the contents of the image or buffer objects, which can be natively used by the device.

11.2.1. Device Memory Properties

Memory properties of a physical device describe the memory heaps and memory types available.

To query memory properties, call:

```c
// Provided by VK_VERSION_1_0
void vkGetPhysicalDeviceMemoryProperties(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceMemoryProperties* pMemoryProperties);
```

• `physicalDevice` is the handle to the device to query.

• `pMemoryProperties` is a pointer to a `VkPhysicalDeviceMemoryProperties` structure in which the properties are returned.

Valid Usage (Implicit)

• VUID-vkGetPhysicalDeviceMemoryProperties-physicalDevice-parameter
  `physicalDevice` must be a valid `VkPhysicalDevice` handle

• VUID-vkGetPhysicalDeviceMemoryProperties-pMemoryProperties-parameter
  `pMemoryProperties` must be a valid pointer to a `VkPhysicalDeviceMemoryProperties` structure

The `VkPhysicalDeviceMemoryProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
```
typedef struct VkPhysicalDeviceMemoryProperties {
    uint32_t memoryTypeCount;
    VkMemoryType memoryTypes[VK_MAX_MEMORY_TYPES];
    uint32_t memoryHeapCount;
    VkMemoryHeap memoryHeaps[VK_MAX_MEMORY_HEAPS];
} VkPhysicalDeviceMemoryProperties;

- `memoryTypeCount` is the number of valid elements in the `memoryTypes` array.
- `memoryTypes` is an array of `VK_MAX_MEMORY_TYPES` `VkMemoryType` structures describing the `memory types` that can be used to access memory allocated from the heaps specified by `memoryHeaps`.
- `memoryHeapCount` is the number of valid elements in the `memoryHeaps` array.
- `memoryHeaps` is an array of `VK_MAX_MEMORY_HEAPS` `VkMemoryHeap` structures describing the `memory heaps` from which memory can be allocated.

The `VkPhysicalDeviceMemoryProperties` structure describes a number of `memory heaps` as well as a number of `memory types` that can be used to access memory allocated in those heaps. Each heap describes a memory resource of a particular size, and each memory type describes a set of memory properties (e.g. host cached vs. uncached) that can be used with a given memory heap. Allocations using a particular memory type will consume resources from the heap indicated by that memory type’s heap index. More than one memory type may share each heap, and the heaps and memory types provide a mechanism to advertise an accurate size of the physical memory resources while allowing the memory to be used with a variety of different properties.

The number of memory heaps is given by `memoryHeapCount` and is less than or equal to `VK_MAX_MEMORY_HEAPS`. Each heap is described by an element of the `memoryHeaps` array as a `VkMemoryHeap` structure. The number of memory types available across all memory heaps is given by `memoryTypeCount` and is less than or equal to `VK_MAX_MEMORY_TYPES`. Each memory type is described by an element of the `memoryTypes` array as a `VkMemoryType` structure.

At least one heap must include `VK_MEMORY_HEAP_DEVICE_LOCAL_BIT` in `VkMemoryHeap::flags`. If there are multiple heaps that all have similar performance characteristics, they may all include `VK_MEMORY_HEAP_DEVICE_LOCAL_BIT`. In a unified memory architecture (UMA) system there is often only a single memory heap which is considered to be equally “local” to the host and to the device, and such an implementation must advertise the heap as device-local.

Each memory type returned by `vkGetPhysicalDeviceMemoryProperties` must have its `propertyFlags` set to one of the following values:

- 0
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT`
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT |`
There must be at least one memory type with both the VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT and VK_MEMORY_PROPERTY_HOST_COHERENT_BIT bits set in its propertyFlags. There must be at least one memory type with the VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT bit set in its propertyFlags.

For each pair of elements X and Y returned in memoryTypes, X must be placed at a lower index position than Y if:

- the set of bit flags returned in the propertyFlags member of X is a strict subset of the set of bit flags returned in the propertyFlags member of Y; or
- the propertyFlags members of X and Y are equal, and X belongs to a memory heap with greater performance (as determined in an implementation-specific manner)

Note
There is no ordering requirement between X and Y elements for the case their propertyFlags members are not in a subset relation. That potentially allows more than one possible way to order the same set of memory types. Notice that the list of all allowed memory property flag combinations is written in a valid order. But if instead VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT was before VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT, the list would still be in a valid order.

This ordering requirement enables applications to use a simple search loop to select the desired memory type along the lines of:

```c
// Find a memory in 'memoryTypeBitsRequirement' that includes all of 'requiredProperties'
int32_t findProperties(const VkPhysicalDeviceMemoryProperties* pMemoryProperties,
                        uint32_t memoryTypeBitsRequirement,
```
VkMemoryPropertyFlags requiredProperties) {
    const uint32_t memoryCount = pMemoryProperties->memoryTypeCount;
    for (uint32_t memoryIndex = 0; memoryIndex < memoryCount; ++memoryIndex) {
        const uint32_t memoryTypeBits = (1 << memoryIndex);
        const bool isRequiredMemoryType = memoryTypeBitsRequirement & memoryTypeBits;
        const VkMemoryPropertyFlags properties = pMemoryProperties->memoryTypes[memoryIndex].propertyFlags;
        const bool hasRequiredProperties = (properties & requiredProperties) == requiredProperties;
        if (isRequiredMemoryType && hasRequiredProperties) {
            return static_cast<int32_t>(memoryIndex);
        }
    }
    // failed to find memory type
    return -1;
}

// Try to find an optimal memory type, or if it does not exist try fallback memory type
// 'device' is the VkDevice
// 'image' is the VkImage that requires memory to be bound
// 'memoryProperties' properties as returned by vkGetPhysicalDeviceMemoryProperties
// 'requiredProperties' are the property flags that must be present
// 'optimalProperties' are the property flags that are preferred by the application
VkMemoryRequirements memoryRequirements;
vkGetImageMemoryRequirements(device, image, &memoryRequirements);
int32_t memoryType = findProperties(&memoryProperties, memoryRequirements.memoryTypeBits, optimalProperties);
if (memoryType == -1) // not found; try fallback properties
    memoryType = findProperties(&memoryProperties, memoryRequirements.memoryTypeBits, requiredProperties);

VK_MAX_MEMORY_TYPES is the length of an array of VkMemoryType structures describing memory types, as returned in VkPhysicalDeviceMemoryProperties::memoryTypes.

#define VK_MAX_MEMORY_TYPES 32U

VK_MAX_MEMORY_HEAPS is the length of an array of VkMemoryHeap structures describing memory heaps, as returned in VkPhysicalDeviceMemoryProperties::memoryHeaps.

#define VK_MAX_MEMORY_HEAPS 16U

To query memory properties, call:
void vkGetPhysicalDeviceMemoryProperties2(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceMemoryProperties2* pMemoryProperties);

- `physicalDevice` is the handle to the device to query.
- `pMemoryProperties` is a pointer to a `VkPhysicalDeviceMemoryProperties2` structure in which the properties are returned.

`vkGetPhysicalDeviceMemoryProperties2` behaves similarly to `vkGetPhysicalDeviceMemoryProperties`, with the ability to return extended information in a `pNext` chain of output structures.

**Valid Usage (Implicit)**

- `VUID-vkGetPhysicalDeviceMemoryProperties2-physicalDevice-parameter physicalDevice` must be a valid `VkPhysicalDevice` handle
- `VUID-vkGetPhysicalDeviceMemoryProperties2-pMemoryProperties-parameter pMemoryProperties` must be a valid pointer to a `VkPhysicalDeviceMemoryProperties2` structure

The `VkPhysicalDeviceMemoryProperties2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceMemoryProperties2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceMemoryProperties memoryProperties;
} VkPhysicalDeviceMemoryProperties2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `memoryProperties` is a `VkPhysicalDeviceMemoryProperties` structure which is populated with the same values as in `vkGetPhysicalDeviceMemoryProperties`.

**Valid Usage (Implicit)**

- `VUID-VkPhysicalDeviceMemoryProperties2-sType-sType sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2`
- `VUID-VkPhysicalDeviceMemoryProperties2-pNext-pNext pNext` must be `NULL`

The `VkMemoryHeap` structure is defined as:
typedef struct VkMemoryHeap {
    VkDeviceSize size;
    VkMemoryHeapFlags flags;
} VkMemoryHeap;

- **size** is the total memory size in bytes in the heap.
- **flags** is a bitmask of VkMemoryHeapFlagBits specifying attribute flags for the heap.

Bits which **may** be set in VkMemoryHeap::flags, indicating attribute flags for the heap, are:

typedef enum VkMemoryHeapFlagBits {
    VK_MEMORY_HEAP_DEVICE_LOCAL_BIT = 0x00000001,
    VK_MEMORY_HEAP_MULTI_INSTANCE_BIT = 0x00000002,
} VkMemoryHeapFlagBits;

- **VK_MEMORY_HEAP_DEVICE_LOCAL_BIT** specifies that the heap corresponds to device-local memory. Device-local memory **may** have different performance characteristics than host-local memory, and **may** support different memory property flags.
- **VK_MEMORY_HEAP_MULTI_INSTANCE_BIT** specifies that in a logical device representing more than one physical device, there is a per-physical device instance of the heap memory. By default, an allocation from such a heap will be replicated to each physical device's instance of the heap.

typedef VkFlags VkMemoryHeapFlags;

VkMemoryHeapFlags is a bitmask type for setting a mask of zero or more VkMemoryHeapFlagBits.

The **VkMemoryType** structure is defined as:

typedef struct VkMemoryType {
    VkMemoryPropertyFlags propertyFlags;
    uint32_t heapIndex;
} VkMemoryType;

- **heapIndex** describes which memory heap this memory type corresponds to, and **must** be less than memoryHeapCount from the VkPhysicalDeviceMemoryProperties structure.
- **propertyFlags** is a bitmask of VkMemoryPropertyFlagBits of properties for this memory type.

Bits which **may** be set in VkMemoryType::propertyFlags, indicating properties of a memory type, are:
typedef enum VkMemoryPropertyFlagBits {
  VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT = 0x00000001,
  VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT = 0x00000002,
  VK_MEMORY_PROPERTY_HOST_COHERENT_BIT = 0x00000004,
  VK_MEMORY_PROPERTY_HOST_CACHED_BIT = 0x00000008,
  VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT = 0x00000010,
  VK_MEMORY_PROPERTY_PROTECTED_BIT = 0x00000020,
} VkMemoryPropertyFlagBits;

- **VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT** bit specifies that memory allocated with this type is the most efficient for device access. This property will be set if and only if the memory type belongs to a heap with the **VK_MEMORY_HEAP_DEVICE_LOCAL_BIT** set.

- **VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT** bit specifies that memory allocated with this type can be mapped for host access using `vkMapMemory`.

- **VK_MEMORY_PROPERTY_HOST_COHERENT_BIT** bit specifies that the host cache management commands `vkFlushMappedMemoryRanges` and `vkInvalidateMappedMemoryRanges` are not needed to flush host writes to the device or make device writes visible to the host, respectively.

- **VK_MEMORY_PROPERTY_HOST_CACHED_BIT** bit specifies that memory allocated with this type is cached on the host. Host memory accesses to uncached memory are slower than to cached memory, however uncached memory is always host coherent.

- **VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT** bit specifies that the memory type only allows device access to the memory. Memory types must not have both **VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT** and **VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT** set. Additionally, the object’s backing memory may be provided by the implementation lazily as specified in Lazily Allocated Memory.

- **VK_MEMORY_PROPERTY_PROTECTED_BIT** bit specifies that the memory type only allows device access to the memory, and allows protected queue operations to access the memory. Memory types must not have **VK_MEMORY_PROPERTY_PROTECTED_BIT** set and any of **VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT** set, or **VK_MEMORY_PROPERTY_HOST_COHERENT_BIT** set, or **VK_MEMORY_PROPERTY_HOST_CACHED_BIT** set.

typedef VkFlags VkMemoryPropertyFlags;

`VkMemoryPropertyFlags` is a bitmask type for setting a mask of zero or more `VkMemoryPropertyFlagBits`.

### 11.2.2. Device Memory Objects

A Vulkan device operates on data in device memory via memory objects that are represented in the API by a `VkDeviceMemory` handle:
11.2.3. Device Memory Allocation

To allocate memory objects, call:

```c
VkResult vkAllocateMemory(
    VkDevice device,
    const VkMemoryAllocateInfo* pAllocateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkDeviceMemory* pMemory);
```

- `device` is the logical device that owns the memory.
- `pAllocateInfo` is a pointer to a `VkMemoryAllocateInfo` structure describing parameters of the allocation. A successfully returned allocation must use the requested parameters—no substitution is permitted by the implementation.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pMemory` is a pointer to a `VkDeviceMemory` handle in which information about the allocated memory is returned.

Allocations returned by `vkAllocateMemory` are guaranteed to meet any alignment requirement of the implementation. For example, if an implementation requires 128 byte alignment for images and 64 byte alignment for buffers, the device memory returned through this mechanism would be 128-byte aligned. This ensures that applications can correctly suballocate objects of different types (with potentially different alignment requirements) in the same memory object.

When memory is allocated, its contents are undefined with the following constraint:

- The contents of unprotected memory must not be a function of the contents of data protected memory objects, even if those memory objects were previously freed.

Note
The contents of memory allocated by one application should not be a function of data from protected memory objects of another application, even if those memory objects were previously freed.

The maximum number of valid memory allocations that can exist simultaneously within a `VkDevice` may be restricted by implementation- or platform-dependent limits. The `maxMemoryAllocationCount` feature describes the number of allocations that can exist simultaneously before encountering these internal limits.

Note
For historical reasons, if `maxMemoryAllocationCount` is exceeded, some
implementations may return `VK_ERROR_TOO_MANY_OBJECTS`. Exceeding this limit will result in undefined behavior, and an application should not rely on the use of the returned error code in order to identify when the limit is reached.

Note

Many protected memory implementations involve complex hardware and system software support, and often have additional and much lower limits on the number of simultaneous protected memory allocations (from memory types with the `VK_MEMORY_PROPERTY_PROTECTED_BIT` property) than for non-protected memory allocations. These limits can be system-wide, and depend on a variety of factors outside of the Vulkan implementation, so they cannot be queried in Vulkan. Applications should use as few allocations as possible from such memory types by suballocating aggressively, and be prepared for allocation failure even when there is apparently plenty of capacity remaining in the memory heap. As a guideline, the Vulkan conformance test suite requires that at least 80 minimum-size allocations can exist concurrently when no other uses of protected memory are active in the system.

Some platforms may have a limit on the maximum size of a single allocation. For example, certain systems may fail to create allocations with a size greater than or equal to 4GB. Such a limit is implementation-dependent, and if such a failure occurs then the error `VK_ERROR_OUT_OF_DEVICE_MEMORY` must be returned.

Valid Usage

- VUID-vkAllocateMemory-pAllocateInfo-01713
  
  `pAllocateInfo->allocationSize` must be less than or equal to `VkPhysicalDeviceMemoryProperties::memoryHeaps[memindex].size` where `memindex = VkPhysicalDeviceMemoryProperties::memoryTypes[pAllocateInfo->memoryTypeIndex].heapIndex` as returned by `vkGetPhysicalDeviceMemoryProperties` for the `VkPhysicalDevice` that device was created from

- VUID-vkAllocateMemory-pAllocateInfo-01714
  
  `pAllocateInfo->memoryTypeIndex` must be less than `VkPhysicalDeviceMemoryProperties::memoryTypeCount` as returned by `vkGetPhysicalDeviceMemoryProperties` for the `VkPhysicalDevice` that device was created from

- VUID-vkAllocateMemory-maxMemoryAllocationCount-04101
  
  There must be less than `VkPhysicalDeviceLimits::maxMemoryAllocationCount` device memory allocations currently allocated on the device

Valid Usage (Implicit)

- VUID-vkAllocateMemory-device-parameter
  
  `device` must be a valid `VkDevice` handle

- VUID-vkAllocateMemory-pAllocateInfo-parameter
  
  `pAllocateInfo` must be a valid pointer to a valid `VkMemoryAllocateInfo` structure
If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.

*pMemory must be a valid pointer to a `VkDeviceMemory` handle.*

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`

The `VkMemoryAllocateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkMemoryAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDeviceSize allocationSize;
    uint32_t memoryTypeIndex;
} VkMemoryAllocateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `allocationSize` is the size of the allocation in bytes.
- `memoryTypeIndex` is an index identifying a memory type from the `memoryTypes` array of the `VkPhysicalDeviceMemoryProperties` structure.

The internal data of an allocated device memory object must include a reference to implementation-specific resources, referred to as the memory object's *payload.*

### Valid Usage

- `VK_SUCCESS`

- `allocationSize must be greater than 0` for non-`NULL` values
- If the `protectedMemory` feature is not enabled, `memoryTypeIndex must not indicate a memory type that reports VK_MEMORY_PROPERTY_PROTECTED_BIT`
- `opaqueCaptureAddress-03329`
If \( \text{VkMemoryOpaqueCaptureAddressAllocateInfo}::\text{opaqueCaptureAddress} \) is not zero, \( \text{VkMemoryAllocateFlagsInfo}::\text{flags} \) must include \( \text{VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT} \)

- VUID-VkMemoryAllocateInfo-flags-03330
  If \( \text{VkMemoryAllocateFlagsInfo}::\text{flags} \) includes \( \text{VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT} \), the bufferDeviceAddressCaptureReplay feature must be enabled

- VUID-VkMemoryAllocateInfo-flags-03331
  If \( \text{VkMemoryAllocateFlagsInfo}::\text{flags} \) includes \( \text{VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT} \), the bufferDeviceAddress feature must be enabled

- VUID-VkMemoryAllocateInfo-opaqueCaptureAddress-03333
  If the parameters define an import operation, \( \text{VkMemoryOpaqueCaptureAddressAllocateInfo}::\text{opaqueCaptureAddress} \) must be zero

**Valid Usage (Implicit)**

- VUID-VkMemoryAllocateInfo-sType-sType
  \( \text{sType} \) must be \( \text{VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO} \)

- VUID-VkMemoryAllocateInfo-pNext-pNext
  Each \( \text{pNext} \) member of any structure (including this one) in the \( \text{pNext} \) chain must be either \( \text{NULL} \) or a pointer to a valid instance of \( \text{VkExportMemoryAllocateInfo} \), \( \text{VkMemoryAllocateFlagsInfo} \), \( \text{VkMemoryDedicatedAllocateInfo} \), or \( \text{VkMemoryOpaqueCaptureAddressAllocateInfo} \)

- VUID-VkMemoryAllocateInfo-sType-unique
  The \( \text{sType} \) value of each struct in the \( \text{pNext} \) chain must be unique

If the \( \text{pNext} \) chain includes a \( \text{VkMemoryDedicatedAllocateInfo} \) structure, then that structure includes a handle of the sole buffer or image resource that the memory can be bound to.

The \( \text{VkMemoryDedicatedAllocateInfo} \) structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkMemoryDedicatedAllocateInfo {
    VkStructureType     sType;
    const void*        pNext;
    VkImage             image;
    VkBuffer            buffer;
} VkMemoryDedicatedAllocateInfo;
```

- \( \text{sType} \) is a \( \text{VkStructureType} \) value identifying this structure.
- \( \text{pNext} \) is \( \text{NULL} \) or a pointer to a structure extending this structure.
- \( \text{image} \) is \( \text{VK_NULL_HANDLE} \) or a handle of an image which this memory will be bound to.
- \( \text{buffer} \) is \( \text{VK_NULL_HANDLE} \) or a handle of a buffer which this memory will be bound to.
Valid Usage

- VUID-VkMemoryDedicatedAllocateInfo-image-01432
  At least one of `image` and `buffer` must be `VK_NULL_HANDLE`

- VUID-VkMemoryDedicatedAllocateInfo-image-01433
  If `image` is not `VK_NULL_HANDLE`, `VkMemoryAllocateInfo::allocationSize` must equal the `VkMemoryRequirements::size` of the image

- VUID-VkMemoryDedicatedAllocateInfo-image-01434
  If `image` is not `VK_NULL_HANDLE`, `image` must have been created without `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` set in `VkImageCreateInfo::flags`

- VUID-VkMemoryDedicatedAllocateInfo-buffer-01435
  If `buffer` is not `VK_NULL_HANDLE`, `VkMemoryAllocateInfo::allocationSize` must equal the `VkMemoryRequirements::size` of the buffer

- VUID-VkMemoryDedicatedAllocateInfo-buffer-01436
  If `buffer` is not `VK_NULL_HANDLE`, `buffer` must have been created without `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` set in `VkBufferCreateInfo::flags`

Valid Usage (Implicit)

- VUID-VkMemoryDedicatedAllocateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO`

- VUID-VkMemoryDedicatedAllocateInfo-image-parameter
  If `image` is not `VK_NULL_HANDLE`, `image` must be a valid `VkImage` handle

- VUID-VkMemoryDedicatedAllocateInfo-buffer-parameter
  If `buffer` is not `VK_NULL_HANDLE`, `buffer` must be a valid `VkBuffer` handle

- VUID-VkMemoryDedicatedAllocateInfo-commonparent
  Both of `buffer`, and `image` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

When allocating memory whose payload may be exported to another process or Vulkan instance, add a `VkExportMemoryAllocateInfo` structure to the `pNext` chain of the `VkMemoryAllocateInfo` structure, specifying the handle types that may be exported.

The `VkExportMemoryAllocateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkExportMemoryAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlags handleTypes;
} VkExportMemoryAllocateInfo;
```
• *sType* is a *VkStructureType* value identifying this structure.

• *pNext* is *NULL* or a pointer to a structure extending this structure.

• *handleTypes* is zero or a bitmask of *VkExternalMemoryHandleTypeFlagBits* specifying one or more memory handle types the application *can* export from the resulting allocation. The application *can* request multiple handle types for the same allocation.

### Valid Usage

- VUID-VkExportMemoryAllocateInfo-handleTypes-00656
  The bits in *handleTypes* *must* be supported and compatible, as reported by *VkExternalImageFormatProperties* or *VkExternalBufferProperties*

### Valid Usage (Implicit)

- VUID-VkExportMemoryAllocateInfo-sType-sType
  *sType* *must* be *VK_STRUCTURE_TYPE_EXPORT_MEMORY_ALLOCATE_INFO*

- VUID-VkExportMemoryAllocateInfo-handleTypes-parameter
  *handleTypes* *must* be a valid combination of *VkExternalMemoryHandleTypeFlagBits* values

### 11.2.4. Device Group Memory Allocations

If the *pNext* chain of *VkMemoryAllocateInfo* includes a *VkMemoryAllocateFlagsInfo* structure, then that structure includes flags and a device mask controlling how many instances of the memory will be allocated.

The *VkMemoryAllocateFlagsInfo* structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkMemoryAllocateFlagsInfo {
    VkStructureType sType;
    const void* pNext;
    VkMemoryAllocateFlags flags;
    uint32_t deviceMask;
} VkMemoryAllocateFlagsInfo;
```

• *sType* is a *VkStructureType* value identifying this structure.

• *pNext* is *NULL* or a pointer to a structure extending this structure.

• *flags* is a bitmask of *VkMemoryAllocateFlagBits* controlling the allocation.

• *deviceMask* is a mask of physical devices in the logical device, indicating that memory *must* be allocated on each device in the mask, if *VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT* is set in *flags*.

If *VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT* is not set, the number of instances allocated depends on
whether `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is set in the memory heap. If `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is set, then memory is allocated for every physical device in the logical device (as if `deviceMask` has bits set for all device indices). If `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is not set, then a single instance of memory is allocated (as if `deviceMask` is set to one).

On some implementations, allocations from a multi-instance heap may consume memory on all physical devices even if the `deviceMask` excludes some devices. If `VkPhysicalDeviceGroupProperties::subsetAllocation` is `VK_TRUE`, then memory is only consumed for the devices in the device mask.

Note

In practice, most allocations on a multi-instance heap will be allocated across all physical devices. Unicast allocation support is an optional optimization for a minority of allocations.

Valid Usage

- VUID-VkMemoryAllocateFlagsInfo-deviceMask-00675
  
  If `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is set, `deviceMask` must be a valid device mask

- VUID-VkMemoryAllocateFlagsInfo-deviceMask-00676
  
  If `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is set, `deviceMask` must not be zero

Valid Usage (Implicit)

- VUID-VkMemoryAllocateFlagsInfo-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO`

- VUID-VkMemoryAllocateFlagsInfo-flags-parameter
  
  `flags` must be a valid combination of `VkMemoryAllocateFlagBits` values

Bits which can be set in `VkMemoryAllocateFlagsInfo::flags`, controlling device memory allocation, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkMemoryAllocateFlagBits {
    VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT = 0x00000001,
    // Provided by VK_VERSION_1_2
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT = 0x00000002,
    // Provided by VK_VERSION_1_2
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT = 0x00000004,
} VkMemoryAllocateFlagBits;
```

- `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` specifies that memory will be allocated for the devices in `VkMemoryAllocateFlagsInfo::deviceMask`. 

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• **VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT** specifies that the memory can be attached to a buffer object created with the **VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT** bit set in usage, and that the memory handle can be used to retrieve an opaque address via 
\[\text{vkGetDeviceMemoryOpaqueCaptureAddress}\].

• **VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT** specifies that the memory’s address can be saved and reused on a subsequent run (e.g. for trace capture and replay), see **VkBufferOpaqueCaptureAddressCreateInfo** for more detail.

```cpp
// Provided by VK_VERSION_1_1
typedef VkFlags VkMemoryAllocateFlags;
```

**VkMemoryAllocateFlags** is a bitmask type for setting a mask of zero or more **VkMemoryAllocateFlagBits**.

### 11.2.5. Opaque Capture Address Allocation

To request a specific device address for a memory allocation, add a **VkMemoryOpaqueCaptureAddressAllocateInfo** structure to the **pNext** chain of the **VkMemoryAllocateInfo** structure. The **VkMemoryOpaqueCaptureAddressAllocateInfo** structure is defined as:

```cpp
// Provided by VK_VERSION_1_2
typedef struct VkMemoryOpaqueCaptureAddressAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    uint64_t opaqueCaptureAddress;
} VkMemoryOpaqueCaptureAddressAllocateInfo;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **opaqueCaptureAddress** is the opaque capture address requested for the memory allocation.

If **opaqueCaptureAddress** is zero, no specific address is requested.

If **opaqueCaptureAddress** is not zero, it should be an address retrieved from **vkGetDeviceMemoryOpaqueCaptureAddress** on an identically created memory allocation on the same implementation.

**Note**

In most cases, it is expected that a non-zero **opaqueAddress** is an address retrieved from **vkGetDeviceMemoryOpaqueCaptureAddress** on an identically created memory allocation. If this is not the case, it is likely that **VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS** errors will occur.

This is, however, not a strict requirement because trace capture/replay tools may
need to adjust memory allocation parameters for imported memory.

If this structure is not present, it is as if `opaqueCaptureAddress` is zero.

### Valid Usage (Implicit)

- **VUID-VkMemoryOpaqueCaptureAddressAllocateInfo-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_MEMORY_OPAQUE_CAPTURE_ADDRESS_ALLOCATE_INFO`

### 11.2.6. Freeing Device Memory

To free a memory object, call:

```c
// Provided by VK_VERSION_1_0
void vkFreeMemory(
    VkDevice device,
    VkDeviceMemory memory,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that owns the memory.
- `memory` is the `VkDeviceMemory` object to be freed.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

Before freeing a memory object, an application must ensure the memory object is no longer in use by the device—for example by command buffers in the pending state. Memory can be freed whilst still bound to resources, but those resources must not be used afterwards. Freeing a memory object releases the reference it held, if any, to its payload. If there are still any bound images or buffers, the memory object’s payload may not be immediately released by the implementation, but must be released by the time all bound images and buffers have been destroyed. Once all references to a payload are released, it is returned to the heap from which it was allocated.

How memory objects are bound to Images and Buffers is described in detail in the Resource Memory Association section.

If a memory object is mapped at the time it is freed, it is implicitly unmapped.

#### Note

As described below, host writes are not implicitly flushed when the memory object is unmapped, but the implementation must guarantee that writes that have not been flushed do not affect any other memory.

### Valid Usage

- **VUID-vkFreeMemory-memory-00677**
  - All submitted commands that refer to `memory` (via images or buffers) must have completed
Valid Usage (Implicit)

- **VUID-vkFreeMemory-device-parameter**
  
  *device* must be a valid [VkDevice](https://www.khronos.org/registry/vulkan/specs/1.3-extensions/man005.html#VkDevice) handle

- **VUID-vkFreeMemory-memory-parameter**
  
  If *memory* is not VK_NULL_HANDLE, *memory* must be a valid [VkDeviceMemory](https://www.khronos.org/registry/vulkan/specs/1.3-extensions/man005.html#VkDeviceMemory) handle

- **VUID-vkFreeMemory-pAllocator-parameter**
  
  If *pAllocator* is not NULL, *pAllocator* must be a valid pointer to a valid [VkAllocationCallbacks](https://www.khronos.org/registry/vulkan/specs/1.3-extensions/man005.html#VkAllocationCallbacks) structure

- **VUID-vkFreeMemory-memory-parent**
  
  If *memory* is a valid handle, it must have been created, allocated, or retrieved from *device*

Host Synchronization

- Host access to *memory* must be externally synchronized

11.2.7. Host Access to Device Memory Objects

Memory objects created with [vkAllocateMemory](https://www.khronos.org/registry/vulkan/specs/1.3-extensions/man005.html#vkAllocateMemory) are not directly host accessible.

Memory objects created with the memory property `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` are considered *mappable*. Memory objects must be mappable in order to be successfully mapped on the host.

To retrieve a host virtual address pointer to a region of a mappable memory object, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkMapMemory(
    VkDevice device,  // device is the logical device that owns the memory.
    VkDeviceMemory memory,  // memory is the VkDeviceMemory object to be mapped.
    VkDeviceSize offset,  // offset is a zero-based byte offset from the beginning of the memory object.
    VkDeviceSize size,  // size is the size of the memory range to map, or VK_WHOLE_SIZE to map from offset to the end of the allocation.
    VkMemoryMapFlags flags,  // flags
    void** ppData);  // ppData
```
• **flags** is reserved for future use.

• **pData** is a pointer to a *void* variable in which a host-accessible pointer to the beginning of the mapped range is returned. This pointer minus **offset** must be aligned to at least **VkPhysicalDeviceLimits::minMemoryMapAlignment**.

After a successful call to **vkMapMemory** the memory object **memory** is considered to be currently **host mapped**.

**Note**
It is an application error to call **vkMapMemory** on a memory object that is already **host mapped**.

**Note**
**vkMapMemory** will fail if the implementation is unable to allocate an appropriately sized contiguous virtual address range, e.g. due to virtual address space fragmentation or platform limits. In such cases, **vkMapMemory** must return **VK_ERROR_MEMORY_MAP_FAILED**. The application can improve the likelihood of success by reducing the size of the mapped range and/or removing unneeded mappings using **vkUnmapMemory**.

**vkMapMemory** does not check whether the device memory is currently in use before returning the host-accessible pointer. The application must guarantee that any previously submitted command that writes to this range has completed before the host reads from or writes to that range, and that any previously submitted command that reads from that range has completed before the host writes to that region (see here for details on fulfilling such a guarantee). If the device memory was allocated without the **VK_MEMORY_PROPERTY_HOST_COHERENT_BIT** set, these guarantees must be made for an extended range: the application must round down the start of the range to the nearest multiple of **VkPhysicalDeviceLimits::nonCoherentAtomSize**, and round the end of the range up to the nearest multiple of **VkPhysicalDeviceLimits::nonCoherentAtomSize**.

While a range of device memory is host mapped, the application is responsible for synchronizing both device and host access to that memory range.

**Note**
It is important for the application developer to become meticulously familiar with all of the mechanisms described in the chapter on **Synchronization and Cache Control** as they are crucial to maintaining memory access ordering.

**Valid Usage**

- **VUID-vkMapMemory-memory-00678**
  **memory** must not be currently host mapped

- **VUID-vkMapMemory-offset-00679**
  **offset** must be less than the size of **memory**

- **VUID-vkMapMemory-size-00680**
If size is not equal to VK_WHOLE_SIZE, size must be greater than 0

- VUID-vkMapMemory-size-00681
  If size is not equal to VK_WHOLE_SIZE, size must be less than or equal to the size of the memory minus offset

- VUID-vkMapMemory-memory-00682
  memory must have been created with a memory type that reports VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT

Valid Usage (Implicit)

- VUID-vkMapMemory-device-parameter
devicemustbe avalid VkDevice handle

- VUID-vkMapMemory-memory-parameter
memory must be a valid VkDeviceMemory handle

- VUID-vkMapMemory-flags-zerobitmask
flags must be 0

- VUID-vkMapMemory-ppData-parameter
ppData must be a valid pointer to a pointer value

- VUID-vkMapMemory-memory-parent
memory must have been created, allocated, or retrieved from device

Host Synchronization

- Host access to memory must be externally synchronized

Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY
  • VK_ERROR_MEMORY_MAP_FAILED

// Provided by VK_VERSION_1_0
typedef VkFlags VkMemoryMapFlags;

VkMemoryMapFlags is a bitmask type for setting a mask, but is currently reserved for future use.
Two commands are provided to enable applications to work with non-coherent memory allocations: `vkFlushMappedMemoryRanges` and `vkInvalidateMappedMemoryRanges`.

**Note**

If the memory object was created with the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` set, `vkFlushMappedMemoryRanges` and `vkInvalidateMappedMemoryRanges` are unnecessary and may have a performance cost. However, availability and visibility operations still need to be managed on the device. See the description of host access types for more information.

After a successful call to `vkMapMemory` the memory object memory is considered to be currently host mapped.

To flush ranges of non-coherent memory from the host caches, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkFlushMappedMemoryRanges(
    VkDevice device,
    uint32_t memoryRangeCount,
    const VkMappedMemoryRange* pMemoryRanges);
```

- `device` is the logical device that owns the memory ranges.
- `memoryRangeCount` is the length of the `pMemoryRanges` array.
- `pMemoryRanges` is a pointer to an array of `VkMappedMemoryRange` structures describing the memory ranges to flush.

`vkFlushMappedMemoryRanges` guarantees that host writes to the memory ranges described by `pMemoryRanges` are made available to the host memory domain, such that they can be made available to the device memory domain via memory domain operations using the `VK_ACCESS_HOST_WRITE_BIT` access type.

Within each range described by `pMemoryRanges`, each set of `nonCoherentAtomSize` bytes in that range is flushed if any byte in that set has been written by the host since it was first host mapped, or the last time it was flushed. If `pMemoryRanges` includes sets of `nonCoherentAtomSize` bytes where no bytes have been written by the host, those bytes must not be flushed.

Unmapping non-coherent memory does not implicitly flush the host mapped memory, and host writes that have not been flushed may not ever be visible to the device. However, implementations must ensure that writes that have not been flushed do not become visible to any other memory.

**Note**

The above guarantee avoids a potential memory corruption in scenarios where host writes to a mapped memory object have not been flushed before the memory is unmapped (or freed), and the virtual address range is subsequently reused for a different mapping (or memory allocation).
Valid Usage (Implicit)

- **VUID-vkFlushMappedMemoryRanges-device-parameter**
  - `device` must be a valid `VkDevice` handle

- **VUID-vkFlushMappedMemoryRanges-pMemoryRanges-parameter**
  - `pMemoryRanges` must be a valid pointer to an array of `memoryRangeCount` valid `VkMappedMemoryRange` structures

- **VUID-vkFlushMappedMemoryRanges-memoryRangeCount-arraylength**
  - `memoryRangeCount` must be greater than 0

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

To invalidate ranges of non-coherent memory from the host caches, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkInvalidateMappedMemoryRanges(
    VkDevice device, uint32_t memoryRangeCount,
    const VkMappedMemoryRange* pMemoryRanges);
```

- `device` is the logical device that owns the memory ranges.
- `memoryRangeCount` is the length of the `pMemoryRanges` array.
- `pMemoryRanges` is a pointer to an array of `VkMappedMemoryRange` structures describing the memory ranges to invalidate.

`vkInvalidateMappedMemoryRanges` guarantees that device writes to the memory ranges described by `pMemoryRanges`, which have been made available to the host memory domain using the `VK_ACCESS_HOST_WRITE_BIT` and `VK_ACCESS_HOST_READ_BIT` access types, are made visible to the host. If a range of non-coherent memory is written by the host and then invalidated without first being flushed, its contents are undefined.

Within each range described by `pMemoryRanges`, each set of `nonCoherentAtomSize` bytes in that range is invalidated if any byte in that set has been written by the device since it was first host mapped, or the last time it was invalidated.

Note
Mapping non-coherent memory does not implicitly invalidate that memory.

Valid Usage (Implicit)

- **VUID-vkInvalidateMappedMemoryRanges-device-parameter**
  device must be a valid VkDevice handle

- **VUID-vkInvalidateMappedMemoryRanges-pMemoryRanges-parameter**
  pMemoryRanges must be a valid pointer to an array of memoryRangeCount valid VkMappedMemoryRange structures

- **VUID-vkInvalidateMappedMemoryRanges-memoryRangeCount-arraylength**
  memoryRangeCount must be greater than 0

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkMappedMemoryRange structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkMappedMemoryRange {
    VkStructureType sType;
    const void*pNext;
    VkDeviceMemory memory;
    VkDeviceSize offset;
    VkDeviceSize size;
} VkMappedMemoryRange;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **memory** is the memory object to which this range belongs.
- **offset** is the zero-based byte offset from the beginning of the memory object.
- **size** is either the size of range, or VK_WHOLE_SIZE to affect the range from offset to the end of the current mapping of the allocation.

Valid Usage

- **VUID-VkMappedMemoryRange-memory-00684**
memory must be currently host mapped

- VUID-VkMappedMemoryRange-size-00685
  If size is not equal to VK_WHOLE_SIZE, offset and size must specify a range contained within the currently mapped range of memory

- VUID-VkMappedMemoryRange-size-00686
  If size is equal to VK_WHOLE_SIZE, offset must be within the currently mapped range of memory

- VUID-VkMappedMemoryRange-offset-00687
  offset must be a multiple of VkPhysicalDeviceLimits::nonCoherentAtomSize

- VUID-VkMappedMemoryRange-size-01389
  If size is equal to VK_WHOLE_SIZE, the end of the current mapping of memory must either be a multiple of VkPhysicalDeviceLimits::nonCoherentAtomSize bytes from the beginning of the memory object, or be equal to the end of the memory object

- VUID-VkMappedMemoryRange-size-01390
  If size is not equal to VK_WHOLE_SIZE, size must either be a multiple of VkPhysicalDeviceLimits::nonCoherentAtomSize, or offset plus size must equal the size of memory

Valid Usage (Implicit)

- VUID-VkMappedMemoryRange-sType-sType
  sType must be VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE

- VUID-VkMappedMemoryRange-pNext-pNext
  pNext must be NULL

- VUID-VkMappedMemoryRange-memory-parameter
  memory must be a valid VkDeviceMemory handle

To unmapped a memory object once host access to it is no longer needed by the application, call:

```c
// Provided by VK_VERSION_1_0
void vkUnmapMemory(
    VkDevice device,
    VkDeviceMemory memory);
```

- device is the logical device that owns the memory.
- memory is the memory object to be unmapped.

Valid Usage

- VUID-vkUnmapMemory-memory-00689
  memory must be currently host mapped
Valid Usage (Implicit)

- **VUID-vkUnmapMemory-device-parameter**
  
  `device` must be a valid `VkDevice` handle

- **VUID-vkUnmapMemory-memory-parameter**
  
  `memory` must be a valid `VkDeviceMemory` handle

- **VUID-vkUnmapMemory-memory-parent**
  
  `memory` must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `memory` must be externally synchronized

11.2.8. Lazily Allocated Memory

If the memory object is allocated from a heap with the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set, that object’s backing memory may be provided by the implementation lazily. The actual committed size of the memory may initially be as small as zero (or as large as the requested size), and monotonically increases as additional memory is needed.

A memory type with this flag set is only allowed to be bound to a `VkImage` whose usage flags include `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`.

**Note**

Using lazily allocated memory objects for framebuffer attachments that are not needed once a render pass instance has completed may allow some implementations to never allocate memory for such attachments.

To determine the amount of lazily-allocated memory that is currently committed for a memory object, call:

```c
// Provided by VK_VERSION_1_0
void vkGetDeviceMemoryCommitment(
    VkDevice device,
    VkDeviceMemory memory,
    VkDeviceSize* pCommittedMemoryInBytes);
```

- `device` is the logical device that owns the memory.
- `memory` is the memory object being queried.
- `pCommittedMemoryInBytes` is a pointer to a `VkDeviceSize` value in which the number of bytes currently committed is returned, on success.

The implementation may update the commitment at any time, and the value returned by this query...
The implementation guarantees to allocate any committed memory from the heapIndex indicated by the memory type that the memory object was created with.

11.2.9. Protected Memory

Protected memory divides device memory into protected device memory and unprotected device memory.

Protected memory adds the following concepts:

- **Memory:**
  - Unprotected device memory, which **can** be visible to the device and **can** be visible to the host
  - Protected device memory, which **can** be visible to the device but **must** not be visible to the host

- **Resources:**
  - Unprotected images and unprotected buffers, to which unprotected memory **can** be bound
  - Protected images and protected buffers, to which protected memory **can** be bound

- **Command buffers:**
  - Unprotected command buffers, which **can** be submitted to a device queue to execute unprotected queue operations
  - Protected command buffers, which **can** be submitted to a protected-capable device queue to execute protected queue operations
• Device queues:
  ◦ Unprotected device queues, to which unprotected command buffers can be submitted
  ◦ Protected-capable device queues, to which unprotected command buffers or protected command buffers can be submitted

• Queue submissions
  ◦ Unprotected queue submissions, through which unprotected command buffers can be submitted
  ◦ Protected queue submissions, through which protected command buffers can be submitted

• Queue operations
  ◦ Unprotected queue operations
  ◦ Protected queue operations

Protected Memory Access Rules

If `VkPhysicalDeviceProtectedMemoryProperties::protectedNoFault` is `VK_FALSE`, applications must not perform any of the following operations:

• Write to unprotected memory within protected queue operations.
• Access protected memory within protected queue operations other than in framebuffer-space pipeline stages, the compute shader stage, or the transfer stage.
• Perform a query within protected queue operations.

If `VkPhysicalDeviceProtectedMemoryProperties::protectedNoFault` is `VK_TRUE`, these operations are valid, but reads will return undefined values, and writes will either be dropped or store undefined values.

Additionally, indirect operations must not be performed within protected queue operations.

Whether these operations are valid or not, or if any other invalid usage is performed, the implementation must guarantee that:

• Protected device memory must never be visible to the host.
• Values written to unprotected device memory must not be a function of values from protected memory.

11.2.10. Peer Memory Features

Peer memory is memory that is allocated for a given physical device and then bound to a resource and accessed by a different physical device, in a logical device that represents multiple physical devices. Some ways of reading and writing peer memory may not be supported by a device.

To determine how peer memory can be accessed, call:

```c
// Provided by VK_VERSION_1_1
void vkGetDeviceGroupPeerMemoryFeatures(
```

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VkDevice device, uint32_t heapIndex, uint32_t localDeviceIndex, uint32_t remoteDeviceIndex, VkPeerMemoryFeatureFlags* pPeerMemoryFeatures);

- `device` is the logical device that owns the memory.
- `heapIndex` is the index of the memory heap from which the memory is allocated.
- `localDeviceIndex` is the device index of the physical device that performs the memory access.
- `remoteDeviceIndex` is the device index of the physical device that the memory is allocated for.
- `pPeerMemoryFeatures` is a pointer to a `VkPeerMemoryFeatureFlags` bitmask indicating which types of memory accesses are supported for the combination of heap, local, and remote devices.

### Valid Usage

- VUID-vkGetDeviceGroupPeerMemoryFeatures-heapIndex-00691  
  `heapIndex` must be less than `memoryHeapCount`

- VUID-vkGetDeviceGroupPeerMemoryFeatures-localDeviceIndex-00692  
  `localDeviceIndex` must be a valid device index

- VUID-vkGetDeviceGroupPeerMemoryFeatures-remoteDeviceIndex-00693  
  `remoteDeviceIndex` must be a valid device index

- VUID-vkGetDeviceGroupPeerMemoryFeatures-localDeviceIndex-00694  
  `localDeviceIndex` must not equal `remoteDeviceIndex`

### Valid Usage (Implicit)

- VUID-vkGetDeviceGroupPeerMemoryFeatures-device-parameter  
  `device` must be a valid `VkDevice` handle

- VUID-vkGetDeviceGroupPeerMemoryFeatures-pPeerMemoryFeatures-parameter  
  `pPeerMemoryFeatures` must be a valid pointer to a `VkPeerMemoryFeatureFlags` value

Bits which may be set in `vkGetDeviceGroupPeerMemoryFeatures::pPeerMemoryFeatures`, indicating supported peer memory features, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkPeerMemoryFeatureFlagBits {
    VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT = 0x00000001,
    VK_PEER_MEMORY_FEATURE_COPY_DST_BIT = 0x00000002,
    VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT = 0x00000004,
    VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT = 0x00000008,
} VkPeerMemoryFeatureFlagBits;
```
• **VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT** specifies that the memory can be accessed as the source of any vkCmdCopy* command.

• **VK_PEER_MEMORY_FEATURE_COPY_DST_BIT** specifies that the memory can be accessed as the destination of any vkCmdCopy* command.

• **VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT** specifies that the memory can be read as any memory access type.

• **VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT** specifies that the memory can be written as any memory access type. Shader atomics are considered to be writes.

**Note**
The peer memory features of a memory heap also apply to any accesses that may be performed during image layout transitions.

**VK_PEER_MEMORY_FEATURE_COPY_DST_BIT** must be supported for all host local heaps and for at least one device-local memory heap.

If a device does not support a peer memory feature, it is still valid to use a resource that includes both local and peer memory bindings with the corresponding access type as long as only the local bindings are actually accessed. For example, an application doing split-frame rendering would use framebuffer attachments that include both local and peer memory bindings, but would scissor the rendering to only update local memory.

```c
// Provided byVK_VERSION_1_1
typedef VkFlags VkPeerMemoryFeatureFlags;
```

**VkPeerMemoryFeatureFlags** is a bitmask type for setting a mask of zero or more **VkPeerMemoryFeatureFlagBits**.

### 11.2.11. Opaque Capture Address Query

To query a 64-bit opaque capture address value from a memory object, call:

```c
// Provided by VK_VERSION_1_2
uint64_t vkGetDeviceMemoryOpaqueCaptureAddress(
    VkDevice device,
    const VkDeviceMemoryOpaqueCaptureAddressInfo* pInfo);
```

• **device** is the logical device that the memory object was allocated on.

• **pInfo** is a pointer to a **VkDeviceMemoryOpaqueCaptureAddressInfo** structure specifying the memory object to retrieve an address for.

The 64-bit return value is an opaque address representing the start of pInfo->memory.

If the memory object was allocated with a non-zero value of **VkMemoryOpaqueCaptureAddressAllocateInfo::opaqueCaptureAddress**, the return value must be the
The expected usage for these opaque addresses is only for trace capture/replay tools to store these addresses in a trace and subsequently specify them during replay.

---

**Valid Usage**

- VUID-vkGetDeviceMemoryOpaqueCaptureAddress-None-03334
  
  The `bufferDeviceAddress` feature must be enabled

- VUID-vkGetDeviceMemoryOpaqueCaptureAddress-device-03335
  
  If `device` was created with multiple physical devices, then the `bufferDeviceAddressMultiDevice` feature must be enabled

---

**Valid Usage (Implicit)**

- VUID-vkGetDeviceMemoryOpaqueCaptureAddress-device-parameter
  
  `device` must be a valid `VkDevice` handle

- VUID-vkGetDeviceMemoryOpaqueCaptureAddress-pInfo-parameter
  
  `pInfo` must be a valid pointer to a valid `VkDeviceMemoryOpaqueCaptureAddressInfo` structure

---

The `VkDeviceMemoryOpaqueCaptureAddressInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkDeviceMemoryOpaqueCaptureAddressInfo {
    VkStructureType sType;
    const void* pNext;
    VkDeviceMemory memory;
} VkDeviceMemoryOpaqueCaptureAddressInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `memory` specifies the memory whose address is being queried.

---

**Valid Usage**

- VUID-VkDeviceMemoryOpaqueCaptureAddressInfo-memory-03336
  
  `memory` must have been allocated with `VK_MEMORY_ALLOCATEDEVICE_ADDRESS_BIT`
Valid Usage (Implicit)

- VUID-VkDeviceMemoryOpaqueCaptureAddressInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DEVICE_MEMORY_OPAQUE_CAPTURE_ADDRESS_INFO
- VUID-VkDeviceMemoryOpaqueCaptureAddressInfo-pNext-pNext
  pNext must be NULL
- VUID-VkDeviceMemoryOpaqueCaptureAddressInfo-memory-parameter
  memory must be a valid VkDeviceMemory handle
Chapter 12. Resource Creation

Vulkan supports two primary resource types: buffers and images. Resources are views of memory with associated formatting and dimensionality. Buffers provide access to raw arrays of bytes, whereas images can be multidimensional and may have associated metadata.

12.1. Buffers

Buffers represent linear arrays of data which are used for various purposes by binding them to a graphics or compute pipeline via descriptor sets or certain commands, or by directly specifying them as parameters to certain commands.

Buffers are represented by VkBuffer handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBuffer)
```

To create buffers, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateBuffer(   
    VkDevice device, 
    const VkBufferCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkBuffer* pBuffer);
```

- device is the logical device that creates the buffer object.
- pCreateInfo is a pointer to a VkBufferCreateInfo structure containing parameters affecting creation of the buffer.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pBuffer is a pointer to a VkBuffer handle in which the resulting buffer object is returned.

Valid Usage

- VUID-vkCreateBuffer-flags-00911
  If the flags member of pCreateInfo includes VK_BUFFER_CREATE_SPARSE_BINDING_BIT, creating this VkBuffer must not cause the total required sparse memory for all currently valid sparse resources on the device to exceed VkPhysicalDeviceLimits::sparseAddressSpaceSize

Valid Usage (Implicit)

- VUID-vkCreateBuffer-device-parameter

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device must be a valid VkDevice handle

- VUID-vkCreateBuffer-pCreateInfo-parameter
  pCreateInfo must be a valid pointer to a valid VkBufferCreateInfo structure

- VUID-vkCreateBuffer-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkCreateBuffer-pBuffer-parameter
  pBuffer must be a valid pointer to a VkBuffer handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkBufferCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBufferCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkBufferCreateFlags flags;
    VkDeviceSize size;
    VkBufferUsageFlags usage;
    VkSharingMode sharingMode;
    uint32_t queueFamilyIndexCount;
    const uint32_t* pQueueFamilyIndices;
} VkBufferCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- flags is a bitmask of VkBufferCreateFlagBits specifying additional parameters of the buffer.
- size is the size in bytes of the buffer to be created.
- usage is a bitmask of VkBufferUsageFlagBits specifying allowed usages of the buffer.
- sharingMode is a VkSharingMode value specifying the sharing mode of the buffer when it will be accessed by multiple queue families.
- queueFamilyIndexCount is the number of entries in the pQueueFamilyIndices array.
- pQueueFamilyIndices is a pointer to an array of queue families that will access this buffer. It is ignored if sharingMode is not VK_SHARING_MODE_CONCURRENT.
Valid Usage

- VUID-VkBufferCreateInfo-size-00912
  size must be greater than 0

- VUID-VkBufferCreateInfo-sharingMode-00913
  If sharingMode is VK_SHARING_MODE_CONCURRENT, pQueueFamilyIndices must be a valid pointer to an array of queueFamilyIndexCount uint32_t values

- VUID-VkBufferCreateInfo-sharingMode-00914
  If sharingMode is VK_SHARING_MODE_CONCURRENT, queueFamilyIndexCount must be greater than 1

- VUID-VkBufferCreateInfo-sharingMode-01419
  If sharingMode is VK_SHARING_MODE_CONCURRENT, each element of pQueueFamilyIndices must be unique and must be less than pQueueFamilyPropertyCount returned by either vkGetPhysicalDeviceQueueFamilyProperties or vkGetPhysicalDeviceQueueFamilyProperties2 for the physicalDevice that was used to create device

- VUID-VkBufferCreateInfo-flags-00915
  If the sparseBinding feature is not enabled, flags must not contain VK_BUFFER_CREATE_SPARSE_BINDING_BIT

- VUID-VkBufferCreateInfo-flags-00916
  If the sparseResidencyBuffer feature is not enabled, flags must not contain VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT

- VUID-VkBufferCreateInfo-flags-00917
  If the sparseResidencyAliased feature is not enabled, flags must not contain VK_BUFFER_CREATE_SPARSE_ALIASED_BIT

- VUID-VkBufferCreateInfo-flags-00918
  If flags contains VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT or VK_BUFFER_CREATE_SPARSE_ALIASED_BIT, it must also contain VK_BUFFER_CREATE_SPARSE_BINDING_BIT

- VUID-VkBufferCreateInfo-pNext-00920
  If the pNext chain includes a VkExternalMemoryBufferCreateInfo structure, its handleTypes member must only contain bits that are also in VkExternalBufferProperties::externalMemoryProperties.compatibleHandleTypes, as returned by vkGetPhysicalDeviceExternalBufferProperties with pExternalBufferInfo->handleType equal to any one of the handle types specified in VkExternalMemoryBufferCreateInfo::handleTypes

- VUID-VkBufferCreateInfo-flags-01887
  If the protectedMemory feature is not enabled, flags must not contain VK_BUFFER_CREATE_PROTECTED_BIT

- VUID-VkBufferCreateInfo-None-01888
  If any of the bits VK_BUFFER_CREATE_SPARSE_BINDING_BIT, VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT, or VK_BUFFER_CREATE_SPARSE_ALIASED_BIT are set, VK_BUFFER_CREATE_PROTECTED_BIT must not also be set
If `VkBufferOpaqueCaptureAddressCreateInfo::opaqueCaptureAddress` is not zero, flags must include `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`.

If flags includes `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`, the `bufferDeviceAddressCaptureReplay` feature must be enabled.

Size must be less than or equal to `VkPhysicalDeviceMaintenance4Properties::maxBufferSize`.

---

**Valid Usage (Implicit)**

- **VUID-VkBufferCreateInfo-sType-sType**
  
  `sType` must be `VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO`.

- **VUID-VkBufferCreateInfo-pNext-pNext**
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkBufferOpaqueCaptureAddressCreateInfo` or `VkExternalMemoryBufferCreateInfo`.

- **VUID-VkBufferCreateInfo-sType-unique**
  The `sType` value of each struct in the `pNext` chain must be unique.

- **VUID-VkBufferCreateInfo-flags-parameter**
  `flags` must be a valid combination of `VkBufferCreateFlagBits` values.

- **VUID-VkBufferCreateInfo-usage-parameter**
  `usage` must be a valid combination of `VkBufferUsageFlagBits` values.

- **VUID-VkBufferCreateInfo-usage-requiredbitsetmask**
  `usage` must not be `0`.

- **VUID-VkBufferCreateInfo-sharingMode-parameter**
  `sharingMode` must be a valid `VkSharingMode` value.

---

Bits which can be set in `VkBufferCreateInfo::usage`, specifying usage behavior of a buffer, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkBufferUsageFlagBits {
    VK_BUFFER_USAGE_TRANSFER_SRC_BIT = 0x00000001,
    VK_BUFFER_USAGE_TRANSFER_DST_BIT = 0x00000002,
    VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT = 0x00000004,
    VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT = 0x00000008,
    VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT = 0x00000010,
    VK_BUFFER_USAGE_STORAGE_BUFFER_BIT = 0x00000020,
    VK_BUFFER_USAGE_INDEX_BUFFER_BIT = 0x00000040,
    VK_BUFFER_USAGE_VERTEX_BUFFER_BIT = 0x00000080,
    VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT = 0x00000100,

// Provided by VK_VERSION_1_2
```
VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT = 0x00020000,
} VkBufferUsageFlagBits;

- VkBufferUsageFlagBits specifies that the buffer can be used as the source of a transfer command (see the definition of VK_PIPELINE_STAGE_TRANSFER_BIT).
- VkBufferUsageFlagBits specifies that the buffer can be used as the destination of a transfer command.
- VkBufferUsageFlagBits specifies that the buffer can be used to create a VkBufferView suitable for occupying a VkDescriptorSet slot of type VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER.
- VkBufferUsageFlagBits specifies that the buffer can be used to create a VkBufferView suitable for occupying a VkDescriptorSet slot of type VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER.
- VkBufferUsageFlagBits specifies that the buffer can be used in a VkDescriptorBufferInfo suitable for occupying a VkDescriptorSet slot either of type VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC.
- VkBufferUsageFlagBits specifies that the buffer can be used in a VkDescriptorBufferInfo suitable for occupying a VkDescriptorSet slot either of type VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC.
- VkBufferUsageFlagBits specifies that the buffer is suitable for passing as the buffer parameter to vkCmdBindIndexBuffer.
- VkBufferUsageFlagBits specifies that the buffer is suitable for passing as an element of the pBuffer array to vkCmdBindVertexBuffers.
- VkBufferUsageFlagBits specifies that the buffer is suitable for passing as the buffer parameter to vkCmdDrawIndirect, vkCmdDrawIndexedIndirect, or vkCmdDispatchIndirect.
- VkBufferUsageFlagBits specifies that the buffer can be used to retrieve a buffer device address via vkGetBufferDeviceAddress and use that address to access the buffer's memory from a shader.

// Provided by VK_VERSION_1_0
typedef VkFlags VkBufferUsageFlags;

VkBufferUsageFlags is a bitmask type for setting a mask of zero or more VkBufferUsageFlagBits.

Bits which can be set in VkBufferCreateInfo::flags, specifying additional parameters of a buffer, are:

// Provided by VK_VERSION_1_0
typedef enum VkBufferCreateFlagBits {
    VK_BUFFER_CREATE_SPARSE_BINDING_BIT = 0x00000001,
    VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
    VK_BUFFER_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
};
• **VK_BUFFER_CREATE_SPARSE_BINDING_BIT** specifies that the buffer will be backed using sparse memory binding.

• **VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT** specifies that the buffer can be partially backed using sparse memory binding. Buffers created with this flag must also be created with the **VK_BUFFER_CREATE_SPARSE_BINDING_BIT** flag.

• **VK_BUFFER_CREATE_SPARSE_ALIASED_BIT** specifies that the buffer will be backed using sparse memory binding with memory ranges that might also simultaneously be backing another buffer (or another portion of the same buffer). Buffers created with this flag must also be created with the **VK_BUFFER_CREATE_SPARSE_BINDING_BIT** flag.

• **VK_BUFFER_CREATE_PROTECTED_BIT** specifies that the buffer is a protected buffer.

• **VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT** specifies that the buffer’s address can be saved and reused on a subsequent run (e.g. for trace capture and replay), see **VkBufferOpaqueCaptureAddressCreateInfo** for more detail.

See [Sparse Resource Features](#) and [Physical Device Features](#) for details of the sparse memory features supported on a device.

#### Provided by VK_VERSION_1_0

```c
typedef VkFlags VkBufferCreateFlags;
```

**VkBufferCreateFlags** is a bitmask type for setting a mask of zero or more VkBufferCreateFlagBits.

To define a set of external memory handle types that may be used as backing store for a buffer, add a **VkExternalMemoryBufferCreateInfo** structure to the **pNext** chain of the **VkBufferCreateInfo** structure. The **VkExternalMemoryBufferCreateInfo** structure is defined as:

#### Provided by VK_VERSION_1_1

```c
typedef struct VkExternalMemoryBufferCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlags handleTypes;
} VkExternalMemoryBufferCreateInfo;
```

**Note**

A **VkExternalMemoryBufferCreateInfo** structure with a non-zero handleTypes field must be included in the creation parameters for a buffer that will be bound to memory that is either exported or imported.

- **sType** is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.

• handleTypes is zero or a bitmask of VkExternalMemoryHandleTypeFlagBits specifying one or more external memory handle types.

Valid Usage (Implicit)

• VUID-VkExternalMemoryBufferCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO

• VUID-VkExternalMemoryBufferCreateInfo-handleTypes-parameter
  handleTypes must be a valid combination of VkExternalMemoryHandleTypeFlagBits values

To request a specific device address for a buffer, add a VkBufferOpaqueCaptureAddressCreateInfo structure to the pNext chain of the VkBufferCreateInfo structure. The VkBufferOpaqueCaptureAddressCreateInfo structure is defined as:

```
// Provided by VK_VERSION_1_2
typedef struct VkBufferOpaqueCaptureAddressCreateInfo {
  VkStructureType sType;
  const void* pNext;
  uint64_t opaqueCaptureAddress;
} VkBufferOpaqueCaptureAddressCreateInfo;
```

• sType is a VkStructureType value identifying this structure.

• pNext is NULL or a pointer to a structure extending this structure.

• opaqueCaptureAddress is the opaque capture address requested for the buffer.

If opaqueCaptureAddress is zero, no specific address is requested.

If opaqueCaptureAddress is not zero, then it should be an address retrieved from vkGetBufferOpaqueCaptureAddress for an identically created buffer on the same implementation.

If this structure is not present, it is as if opaqueCaptureAddress is zero.

Apps should avoid creating buffers with app-provided addresses and implementation-provided addresses in the same process, to reduce the likelihood of VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS errors.

Note

The expected usage for this is that a trace capture/replay tool will add the VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT flag to all buffers that use VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT, and during capture will save the queried opaque device addresses in the trace. During replay, the buffers will be created specifying the original address so any address values stored in the trace data will remain valid.
Implementations are expected to separate such buffers in the GPU address space so normal allocations will avoid using these addresses. Apps/tools should avoid mixing app-provided and implementation-provided addresses for buffers created with `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`, to avoid address space allocation conflicts.

**Valid Usage (Implicit)**

- VUID-VkBufferOpaqueCaptureAddressCreateInfo-sType-sType
  
  *sType* must be `VK_STRUCTURE_TYPE_BUFFER_OPAQUE_CAPTURE_ADDRESS_CREATE_INFO`

To destroy a buffer, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyBuffer(
    VkDevice device,
    VkBuffer buffer,
    const VkAllocationCallbacks* pAllocator);
```

- *device* is the logical device that destroys the buffer.
- *buffer* is the buffer to destroy.
- *pAllocator* controls host memory allocation as described in the Memory Allocation chapter.

**Valid Usage**

- VUID-vkDestroyBuffer-buffer-00922
  
  All submitted commands that refer to *buffer*, either directly or via a `VkBufferView`, must have completed execution

- VUID-vkDestroyBuffer-buffer-00923
  
  If `VkAllocationCallbacks` were provided when *buffer* was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyBuffer-buffer-00924
  
  If no `VkAllocationCallbacks` were provided when *buffer* was created, *pAllocator* must be `NULL`

**Valid Usage (Implicit)**

- VUID-vkDestroyBuffer-device-parameter
  
  *device* must be a valid `VkDevice` handle

- VUID-vkDestroyBuffer-buffer-parameter
  
  If *buffer* is not `VK_NULL_HANDLE`, *buffer* must be a valid `VkBuffer` handle

- VUID-vkDestroyBuffer-pAllocator-parameter
If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- `VUID-vkDestroyBuffer-buffer-parent`

If `buffer` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- `Host access to buffer must be externally synchronized`

### 12.2. Buffer Views

A buffer view represents a contiguous range of a buffer and a specific format to be used to interpret the data. Buffer views are used to enable shaders to access buffer contents using image operations. In order to create a valid buffer view, the buffer must have been created with at least one of the following usage flags:

- `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT`
- `VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT`

Buffer views are represented by `VkBufferView` handles:

```cpp
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBufferView)
```

To create a buffer view, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkCreateBufferView(
    VkDevice device, 
    const VkBufferViewCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkBufferView* pView);
```

- `device` is the logical device that creates the buffer view.
- `pCreateInfo` is a pointer to a `VkBufferViewCreateInfo` structure containing parameters to be used to create the buffer view.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pView` is a pointer to a `VkBufferView` handle in which the resulting buffer view object is returned.
Valid Usage (Implicit)

- VUID-vkCreateBufferView-device-parameter
  The `device` must be a valid `VkDevice` handle.

- VUID-vkCreateBufferView-pCreateInfo-parameter
  The `pCreateInfo` must be a valid pointer to a valid `VkBufferViewCreateInfo` structure.

- VUID-vkCreateBufferView-pAllocator-parameter
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.

- VUID-vkCreateBufferView-pView-parameter
  The `pView` must be a valid pointer to a `VkBufferView` handle.

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkBufferViewCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBufferViewCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkBufferViewCreateFlags flags;
    VkBuffer buffer;
    VkFormat format;
    VkDeviceSize offset;
    VkDeviceSize range;
} VkBufferViewCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `buffer` is a `VkBuffer` on which the view will be created.
- `format` is a `VkFormat` describing the format of the data elements in the buffer.
- `offset` is an offset in bytes from the base address of the buffer. Accesses to the buffer view from shaders use addressing that is relative to this starting offset.
- `range` is a size in bytes of the buffer view. If `range` is equal to `VK_WHOLE_SIZE`, the range from...
offset to the end of the buffer is used. If VK_WHOLE_SIZE is used and the remaining size of the buffer is not a multiple of the texel block size of format, the nearest smaller multiple is used.

### Valid Usage

- **VUID-VkBufferViewCreateInfo-offset-00925**
  
  offset must be less than the size of buffer

- **VUID-VkBufferViewCreateInfo-range-00928**
  
  If range is not equal to VK_WHOLE_SIZE, range must be greater than \(0\)

- **VUID-VkBufferViewCreateInfo-range-00929**
  
  If range is not equal to VK_WHOLE_SIZE, range must be an integer multiple of the texel block size of format

- **VUID-VkBufferViewCreateInfo-range-00930**
  
  If range is not equal to VK_WHOLE_SIZE, the number of texel buffer elements given by \(\lfloor\frac{\text{range}}{\text{texel block size}}\rfloor \times \text{texels per block}\) where texel block size and texels per block are as defined in the Compatible Formats table for format, must be less than or equal to VkPhysicalDeviceLimits::maxTexelBufferElements

- **VUID-VkBufferViewCreateInfo-offset-00931**
  
  If range is not equal to VK_WHOLE_SIZE, the sum of offset and range must be less than or equal to the size of buffer

- **VUID-VkBufferViewCreateInfo-range-04059**
  
  If range is equal to VK_WHOLE_SIZE, the number of texel buffer elements given by \(\lfloor\frac{\text{size} - \text{offset}}{\text{texel block size}}\rfloor \times \text{texels per block}\) where size is the size of buffer, and texel block size and texels per block are as defined in the Compatible Formats table for format, must be less than or equal to VkPhysicalDeviceLimits::maxTexelBufferElements

- **VUID-VkBufferViewCreateInfo-buffer-00932**
  
  buffer must have been created with a usage value containing at least one of VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT or VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT

- **VUID-VkBufferViewCreateInfo-buffer-00933**
  
  If buffer was created with usage containing VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT, then format features of format must contain VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT

- **VUID-VkBufferViewCreateInfo-buffer-00934**
  
  If buffer was created with usage containing VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT, then format features of format must contain VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT

- **VUID-VkBufferViewCreateInfo-buffer-00935**
  
  If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- **VUID-VkBufferViewCreateInfo-offset-02749**
  
  If the texelBufferAlignment feature is not enabled, offset must be a multiple of VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment

- **VUID-VkBufferViewCreateInfo-offset-02750**
  
  If the texelBufferAlignment feature is enabled and if buffer was created with usage containing VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT, offset must be a multiple of the...
lesser of `VkPhysicalDeviceTexelBufferAlignmentProperties::storageTexelBufferOffsetAlignmentBytes` or, if `VkPhysicalDeviceTexelBufferAlignmentProperties::storageTexelBufferOffsetSingleTexelAlignment` is `VK_TRUE`, the size of a texel of the requested format. If the size of a texel is a multiple of three bytes, then the size of a single component of format is used instead.

- **VUID-VkBufferViewCreateInfo-buffer-02751**
  If the `texelBufferAlignment` feature is enabled and if buffer was created with usage containing `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT`, offset must be a multiple of the lesser of `VkPhysicalDeviceTexelBufferAlignmentProperties::uniformTexelBufferOffsetAlignmentBytes` or, if `VkPhysicalDeviceTexelBufferAlignmentProperties::uniformTexelBufferOffsetSingleTexelAlignment` is `VK_TRUE`, the size of a texel of the requested format. If the size of a texel is a multiple of three bytes, then the size of a single component of format is used instead.

### Valid Usage (Implicit)

- **VUID-VkBufferViewCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_BUFFER_VIEW_CREATE_INFO`

- **VUID-VkBufferViewCreateInfo-pNext-pNext**
  `pNext` must be `NULL`

- **VUID-VkBufferViewCreateInfo-flags-zerobitmask**
  `flags` must be `0`

- **VUID-VkBufferViewCreateInfo-buffer-parameter**
  `buffer` must be a valid `VkBuffer` handle

- **VUID-VkBufferViewCreateInfo-format-parameter**
  `format` must be a valid `VkFormat` value

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkBufferViewCreateFlags;
```

`VkBufferViewCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy a buffer view, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyBufferView(
    VkDevice device,
    VkBufferView bufferView,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the buffer view.
• bufferView is the buffer view to destroy.
• pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

• VUID-vkDestroyBufferView-bufferView-00936
  All submitted commands that refer to bufferView must have completed execution

• VUID-vkDestroyBufferView-bufferView-00937
  If VkAllocationCallbacks were provided when bufferView was created, a compatible set of callbacks must be provided here

• VUID-vkDestroyBufferView-bufferView-00938
  If no VkAllocationCallbacks were provided when bufferView was created, pAllocator must be NULL

Valid Usage (Implicit)

• VUID-vkDestroyBufferView-device-parameter
  device must be a valid VkDevice handle

• VUID-vkDestroyBufferView-bufferView-parameter
  If bufferView is not VK_NULL_HANDLE, bufferView must be a valid VkBufferView handle

• VUID-vkDestroyBufferView-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

• VUID-vkDestroyBufferView-bufferView-parent
  If bufferView is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to bufferView must be externally synchronized

12.2.1. Buffer View Format Features

Valid uses of a VkBufferView may depend on the buffer view's format features, defined below. Such constraints are documented in the affected valid usage statement.

• If Vulkan 1.3 is supported or the VK_KHR_format_feature_flags2 extension is supported, then the buffer view's set of format features is the value of VkFormatProperties3::bufferFeatures found by calling vkGetPhysicalDeviceFormatProperties2 on the same format as VkBufferViewCreateInfo::format.
12.3. Images

Images represent multidimensional - up to 3 - arrays of data which can be used for various purposes (e.g. attachments, textures), by binding them to a graphics or compute pipeline via descriptor sets, or by directly specifying them as parameters to certain commands.

Images are represented by VkImage handles:

```perl
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImage)
```

To create images, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkCreateImage(
    VkDevice device,
    const VkImageCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkImage* pImage);
```

- `device` is the logical device that creates the image.
- `pCreateInfo` is a pointer to a VkImageCreateInfo structure containing parameters to be used to create the image.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pImage` is a pointer to a VkImage handle in which the resulting image object is returned.

### Valid Usage

- VUID-vkCreateImage-flags-00939
  If the `flags` member of `pCreateInfo` includes VK_IMAGE_CREATE_SPARSE_BINDING_BIT, creating this VkImage must not cause the total required sparse memory for all currently valid sparse resources on the device to exceed VkPhysicalDeviceLimits::sparseAddressSpaceSize

### Valid Usage (Implicit)

- VUID-vkCreateImage-device-parameter
  `device` must be a valid VkDevice handle

- VUID-vkCreateImage-pCreateInfo-parameter
  `pCreateInfo` must be a valid pointer to a valid VkImageCreateInfo structure

- VUID-vkCreateImage-pAllocator-parameter
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkCreateImage-pImage-parameter
pImage must be a valid pointer to a VkImage handle

### Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkImageCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageCreateFlags flags;
    VkImageType imageType;
    VkFormat format;
    VkExtent3D extent;
    uint32_t mipLevels;
    uint32_t arrayLayers;
    VkSampleCountFlagBits samples;
    VkImageTiling tiling;
    VkImageUsageFlags usage;
    VkSharingMode sharingMode;
    uint32_t queueFamilyIndexCount;
    const uint32_t* pQueueFamilyIndices;
    VkImageLayout initialLayout;
} VkImageCreateInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is a bitmask of VkImageCreateFlagBits describing additional parameters of the image.
- **imageType** is a VkImageType value specifying the basic dimensionality of the image. Layers in array textures do not count as a dimension for the purposes of the image type.
- **format** is a VkFormat describing the format and type of the texel blocks that will be contained in the image.
- **extent** is a VkExtent3D describing the number of data elements in each dimension of the base level.
- **mipLevels** describes the number of levels of detail available for minified sampling of the image.
- **arrayLayers** is the number of layers in the image.
• **samples** is a `VkSampleCountFlagBits` value specifying the number of samples per texel.

• **tiling** is a `VkImageTiling` value specifying the tiling arrangement of the texel blocks in memory.

• **usage** is a bitmask of `VkImageUsageFlagBits` describing the intended usage of the image.

• **sharingMode** is a `VkSharingMode` value specifying the sharing mode of the image when it will be accessed by multiple queue families.

• **queueFamilyIndexCount** is the number of entries in the `pQueueFamilyIndices` array.

• **pQueueFamilyIndices** is a pointer to an array of queue families that will access this image. It is ignored if `sharingMode` is not `VK_SHARING_MODE_CONCURRENT`.

• **initialLayout** is a `VkImageLayout` value specifying the initial `VkImageLayout` of all image subresources of the image. See Image Layouts.

Images created with **tiling** equal to `VK_IMAGE_TILING_LINEAR` have further restrictions on their limits and capabilities compared to images created with **tiling** equal to `VK_IMAGE_TILING_OPTIMAL`. Creation of images with tiling `VK_IMAGE_TILING_LINEAR` may not be supported unless other parameters meet all of the constraints:

• **imageType** is `VK_IMAGE_TYPE_2D`

• **format** is not a depth/stencil format

• **mipLevels** is 1

• **arrayLayers** is 1

• **samples** is `VK_SAMPLE_COUNT_1_BIT`

• **usage** only includes `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` and/or `VK_IMAGE_USAGE_TRANSFER_DST_BIT`

Images created with one of the formats that require a sampler Y'CbCr conversion, have further restrictions on their limits and capabilities compared to images created with other formats. Creation of images with a format requiring Y'CbCr conversion may not be supported unless other parameters meet all of the constraints:

• **imageType** is `VK_IMAGE_TYPE_2D`

• **mipLevels** is 1

• **arrayLayers** is 1, unless otherwise indicated by `VkImageFormatProperties::maxArrayLayers`, as returned by `vkGetPhysicalDeviceImageFormatProperties`

• **samples** is `VK_SAMPLE_COUNT_1_BIT`

Implementations may support additional limits and capabilities beyond those listed above.

To determine the set of valid **usage** bits for a given format, call `vkGetPhysicalDeviceFormatProperties`.

If the size of the resultant image would exceed `maxResourceSize`, then `vkCreateImage` must fail and return `VK_ERROR_OUT_OF_DEVICE_MEMORY`. This failure may occur even when all image creation parameters satisfy their valid usage requirements.

---

**Note**
For images created without `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT` a `usage` bit is valid if it is supported for the format the image is created with.

For images created with `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT` a `usage` bit is valid if it is supported for at least one of the formats a `VkImageView` created from the image can have (see Image Views for more detail).

### Image Creation Limits

Valid values for some image creation parameters are limited by a numerical upper bound or by inclusion in a bitset. For example, `VkImageCreateInfo::arrayLayers` is limited by `imageCreateMaxArrayLayers`, defined below; and `VkImageCreateInfo::samples` is limited by `imageCreateSampleCounts`, also defined below.

Several limiting values are defined below, as well as assisting values from which the limiting values are derived. The limiting values are referenced by the relevant valid usage statements of `VkImageCreateInfo`.

- Let `VkBool32 imageCreateMaybeLinear` indicate if the resultant image may be linear. (The definition below is trivial because certain extensions are disabled in this build of the specification).
  - If tiling is `VK_IMAGE_TILING_LINEAR`, then `imageCreateMaybeLinear` is `VK_TRUE`.
  - If tiling is `VK_IMAGE_TILING_OPTIMAL`, then `imageCreateMaybeLinear` is `VK_FALSE`.

- Let `VkFormatFeatureFlags imageCreateFormatFeatures` be the set of valid `format features` available during image creation.
  - If tiling is `VK_IMAGE_TILING_LINEAR`, then `imageCreateFormatFeatures` is the value of `VkFormatProperties::linearTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` with parameter `format` equal to `VkImageCreateInfo::format`.
  - If tiling is `VK_IMAGE_TILING_OPTIMAL`, then `imageCreateFormatFeatures` is the value of `VkFormatProperties::optimalTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` with parameter `format` equal to `VkImageCreateInfo::format`.

- Let `VkImageFormatProperties2 imageCreateImageFormatPropertiesList[]` be the list of structures obtained by calling `vkGetPhysicalDeviceImageFormatProperties2`, possibly multiple times, as follows:
  - The parameters `VkPhysicalDeviceImageFormatInfo2::format`, `imageType`, `tiling`, `usage`, and `flags` must be equal to those in `VkImageCreateInfo`.
  - If `VkImageCreateInfo::pNext` contains a `VkExternalMemoryImageCreateInfo` structure whose `handleTypes` is not 0, then `VkPhysicalDeviceImageFormatInfo2::pNext` must contain a `VkPhysicalDeviceExternalImageFormatInfo` structure whose `handleType` is not 0; and `vkGetPhysicalDeviceImageFormatProperties2` must be called for each handle type in `VkExternalMemoryImageCreateInfo::handleTypes`, successively setting `VkPhysicalDeviceExternalImageFormatInfo::handleType` on each call.
If `VkImageCreateInfo::pNext` contains no `VkExternalMemoryImageCreateInfo` structure, or contains a structure whose `handleTypes` is `0`, then `VkPhysicalDeviceImageFormatInfo2::pNext` must either contain no `VkPhysicalDeviceExternalImageFormatInfo` structure, or contain a structure whose `handleType` is `0`.

If any call to `vkGetPhysicalDeviceImageFormatProperties2` returns an error, then `imageCreateImageFormatPropertiesList` is defined to be the empty list.

- Let `uint32_t imageCreateMaxMipLevels` be the minimum value of `VkImageFormatProperties::maxMipLevels` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

- Let `uint32_t imageCreateMaxArrayLayers` be the minimum value of `VkImageFormatProperties::maxArrayLayers` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

- Let `VkExtent3D imageCreateMaxExtent` be the component-wise minimum over all `VkImageFormatProperties::maxExtent` values in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

- Let `VkSampleCountFlags imageCreateSampleCounts` be the intersection of each `VkImageFormatProperties::sampleCounts` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

**Valid Usage**

- **VUID-VkImageCreateInfo-imageCreateMaxMipLevels-02251**
  Each of the following values (as described in Image Creation Limits) must not be undefined: `imageCreateMaxMipLevels`, `imageCreateMaxArrayLayers`, `imageCreateMaxExtent`, and `imageCreateSampleCounts`

- **VUID-VkImageCreateInfo-sharingMode-00941**
  If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, `pQueueFamilyIndices` must be a valid pointer to an array of `queueFamilyIndexCount uint32_t` values

- **VUID-VkImageCreateInfo-sharingMode-00942**
  If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, `queueFamilyIndexCount` must be greater than `1`

- **VUID-VkImageCreateInfo-sharingMode-01420**
  If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, each element of `pQueueFamilyIndices` must be unique and must be less than `pQueueFamilyPropertyCount` returned by either `vkGetPhysicalDeviceQueueFamilyProperties` or `vkGetPhysicalDeviceQueueFamilyProperties2` for the `physicalDevice` that was used to create `device`

- **VUID-VkImageCreateInfo-format-00943**
  `format` must not be `VK_FORMAT_UNDEFINED`

- **VUID-VkImageCreateInfo-extent-00944**
  `extent.width` must be greater than `0`
• VUID-VkImageCreateInfo-extent-00945
  extent.height must be greater than 0

• VUID-VkImageCreateInfo-extent-00946
  extent.depth must be greater than 0

• VUID-VkImageCreateInfo-mipLevels-00947
  mipLevels must be greater than 0

• VUID-VkImageCreateInfo-arrayLayers-00948
  arrayLayers must be greater than 0

• VUID-VkImageCreateInfo-flags-00949
  If flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, imageType must be VK_IMAGE_TYPE_2D

• VUID-VkImageCreateInfo-flags-08865
  If flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, extent.width and extent.height must be equal

• VUID-VkImageCreateInfo-flags-08866
  If flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, arrayLayers must be greater than or equal to 6

• VUID-VkImageCreateInfo-flags-00950
  If flags contains VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT, imageType must be VK_IMAGE_TYPE_3D

• VUID-VkImageCreateInfo-extent-02252
  extent.width must be less than or equal to imageCreateMaxExtent.width (as defined in Image Creation Limits)

• VUID-VkImageCreateInfo-extent-02253
  extent.height must be less than or equal to imageCreateMaxExtent.height (as defined in Image Creation Limits)

• VUID-VkImageCreateInfo-extent-02254
  extent.depth must be less than or equal to imageCreateMaxExtent.depth (as defined in Image Creation Limits)

• VUID-VkImageCreateInfo-imageType-00956
  If imageType is VK_IMAGE_TYPE_1D, both extent.height and extent.depth must be 1

• VUID-VkImageCreateInfo-imageType-00957
  If imageType is VK_IMAGE_TYPE_2D, extent.depth must be 1

• VUID-VkImageCreateInfo-mipLevels-00958
  mipLevels must be less than or equal to the number of levels in the complete mipmap chain based on extent.width, extent.height, and extent.depth

• VUID-VkImageCreateInfo-mipLevels-02255
  mipLevels must be less than or equal to imageCreateMaxMipLevels (as defined in Image Creation Limits)

• VUID-VkImageCreateInfo-arrayLayers-02256
  arrayLayers must be less than or equal to imageCreateMaxArrayLayers (as defined in Image Creation Limits)
• VUID-VkImageCreateInfo-imageType-00961
  If `imageType` is `VK_IMAGE_TYPE_3D`, `arrayLayers` must be 1

• VUID-VkImageCreateInfo-samples-02257
  If `samples` is not `VK_SAMPLE_COUNT_1_BIT`, then `imageType` must be `VK_IMAGE_TYPE_2D`, `flags` must not contain `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`, `mipLevels` must be equal to 1, and `imageCreateMaybeLinear` (as defined in `Image Creation Limits`) must be `VK_FALSE`.

• VUID-VkImageCreateInfo-usage-00963
  If `usage` includes `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, then bits other than `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, and `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` must not be set.

• VUID-VkImageCreateInfo-usage-00964
  If `usage` includes `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`, `extent.width` must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferWidth`.

• VUID-VkImageCreateInfo-usage-00965
  If `usage` includes `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`, `extent.height` must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferHeight`.

• VUID-VkImageCreateInfo-usage-00966
  If `usage` includes `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, usage must also contain at least one of `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`.

• VUID-VkImageCreateInfo-samples-02258
  `samples` must be a bit value that is set in `imageCreateSampleCounts` (as defined in `Image Creation Limits`).

• VUID-VkImageCreateInfo-usage-00968
  If the `shaderStorageImageMultisample` feature is not enabled, and `usage` contains `VK_IMAGE_USAGE_STORAGE_BIT`, `samples` must be `VK_SAMPLE_COUNT_1_BIT`.

• VUID-VkImageCreateInfo-flags-00969
  If the `sparseBinding` feature is not enabled, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`.

• VUID-VkImageCreateInfo-flags-01924
  If the `sparseResidencyAliased` feature is not enabled, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT`.

• VUID-VkImageCreateInfo-tiling-04121
  If `tiling` is `VK_IMAGE_TILING_LINEAR`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

• VUID-VkImageCreateInfo-imageType-00970
  If `imageType` is `VK_IMAGE_TYPE_1D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

• VUID-VkImageCreateInfo-imageType-00971
If the `sparseResidencyImage2D` feature is not enabled, and `imageType` is `VK_IMAGE_TYPE_2D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-imageType-00972
  If the `sparseResidencyImage3D` feature is not enabled, and `imageType` is `VK_IMAGE_TYPE_3D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-imageType-00973
  If the `sparseResidency2Samples` feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_2_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-imageType-00974
  If the `sparseResidency4Samples` feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_4_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-imageType-00975
  If the `sparseResidency8Samples` feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_8_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-imageType-00976
  If the `sparseResidency16Samples` feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_16_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`

- VUID-VkImageCreateInfo-flags-00987
  If `flags` contains `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` or `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT`, it must also contain `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`

- VUID-VkImageCreateInfo-flags-01890
  If any of the bits `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`, or `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` are set, `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT` must not also be set

- VUID-VkImageCreateInfo-None-01891
  If any of the bits `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`, or `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` are set, `VK_IMAGE_CREATE_PROTECTED_BIT` must not also be set

- VUID-VkImageCreateInfo-pNext-00990
  If the `pNext` chain includes a `VkExternalMemoryImageCreateInfo` structure, its `handleTypes` member must only contain bits that are also in `VkExternalImageFormatProperties::externalMemoryProperties.compatibleHandleTypes`, as returned by `vkGetPhysicalDeviceImageFormatProperties2` with `format`, `imageType`, `tiling`, `usage`, and `flags` equal to those in this structure, and with a `VkPhysicalDeviceExternalImageFormatInfo` structure included in the `pNext` chain, with a `handleType` equal to any one of the handle types specified in
 VkExternalMemoryImageCreateInfo::handleTypes

- VUID-VkImageCreateInfo-physicalDeviceCount-01421
  If the logical device was created with VkDeviceGroupDeviceCreateInfo::physicalDeviceCount equal to 1, flags must not contain VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT

- VUID-VkImageCreateInfo-flags-02259
  If flags contains VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT, then mipLevels must be one, arrayLayers must be one, imageType must be VK_IMAGE_TYPE_2D, and imageCreateMaybeLinear (as defined in Image Creation Limits) must be VK_FALSE

- VUID-VkImageCreateInfo-flags-01572
  If flags contains VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT, then format must be a compressed image format

- VUID-VkImageCreateInfo-flags-01573
  If flags contains VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT, then flags must also contain VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT

- VUID-VkImageCreateInfo-initialLayout-00993
  initialLayout must be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

- VUID-VkImageCreateInfo-pNext-01443
  If the pNext chain includes a VkExternalMemoryImageCreateInfo or VkExternalMemoryImageCreateInfoNV structure whose handleTypes member is not 0, initialLayout must be VK_IMAGE_LAYOUT_UNDEFINED

- VUID-VkImageCreateInfo-format-06410
  If the image format is one of the formats that require a sampler Y′CbCr conversion, mipLevels must be 1

- VUID-VkImageCreateInfo-format-06411
  If the image format is one of the formats that require a sampler Y′CbCr conversion, samples must be VK_SAMPLE_COUNT_1_BIT

- VUID-VkImageCreateInfo-format-06412
  If the image format is one of the formats that require a sampler Y′CbCr conversion, imageType must be VK_IMAGE_TYPE_2D

- VUID-VkImageCreateInfo-imageCreateFormatFeatures-02260
  If format is a multi-planar format, and if imageCreateFormatFeatures (as defined in Image Creation Limits) does not contain VK_FORMAT_FEATURE_DISJOINT_BIT, then flags must not contain VK_IMAGE_CREATE_DISJOINT_BIT

- VUID-VkImageCreateInfo-format-01577
  If format is not a multi-planar format, and flags does not include VK_IMAGE_CREATE_ALIAS_BIT, flags must not contain VK_IMAGE_CREATE_DISJOINT_BIT

- VUID-VkImageCreateInfo-format-04712
  If format has a _422 or _420 suffix, width must be a multiple of 2

- VUID-VkImageCreateInfo-format-04713
  If format has a _420 suffix, height must be a multiple of 2

- VUID-VkImageCreateInfo-format-02795
If format is a depth-stencil format, usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and the pNext chain includes a VkImageStencilUsageCreateInfo structure, then its VkImageStencilUsageCreateInfo::stencilUsage member must also include VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

• VUID-VkImageCreateInfo-format-02796
If format is a depth-stencil format, usage does not include VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and the pNext chain includes a VkImageStencilUsageCreateInfo structure, then its VkImageStencilUsageCreateInfo::stencilUsage member must also not include VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

• VUID-VkImageCreateInfo-format-02797
If format is a depth-stencil format, usage includes VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT, and the pNext chain includes a VkImageStencilUsageCreateInfo structure, then its VkImageStencilUsageCreateInfo::stencilUsage member must also include VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT.

• VUID-VkImageCreateInfo-format-02798
If format is a depth-stencil format, usage does not include VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT, and the pNext chain includes a VkImageStencilUsageCreateInfo structure, then its VkImageStencilUsageCreateInfo::stencilUsage member must also not include VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT.

• VUID-VkImageCreateInfo-Format-02536
If the shaderStorageImageMultisample feature is not enabled, format is a depth-stencil format and the pNext chain includes a VkImageStencilUsageCreateInfo structure with its stencilUsage including VK_IMAGE_USAGE_STORAGE_BIT, samples must be VK_SAMPLE_COUNT_1_BIT.

• VUID-VkImageCreateInfo-pNext-06722
If a VkImageFormatListCreateInfo structure was included in the pNext chain and VkImageFormatListCreateInfo::viewFormatCount is not zero, then each format in VkImageFormatListCreateInfo::pViewFormats must either be compatible with the format as described in the compatibility table or, if flags contains VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT, be an uncompressed format that is size-compatible with format.

• VUID-VkImageCreateInfo-flags-04738
If flags does not contain VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT and the pNext chain includes a VkImageFormatListCreateInfo structure, then VkImageFormatListCreateInfo::viewFormatCount must be zero.
::viewFormatCount must be 0 or 1

Valid Usage (Implicit)

- VUID-VkImageCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO

- VUID-VkImageCreateInfo-pNext-pNext
  Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkExternalMemoryImageCreateInfo, VkImageFormatListCreateInfo, or VkImageStencilUsageCreateInfo

- VUID-VkImageCreateInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

- VUID-VkImageCreateInfo(flags)-parameter
  flags must be a valid combination of VkImageCreateFlagBits values

- VUID-VkImageCreateInfo-imageType-parameter
  imageType must be a valid VkImageType value

- VUID-VkImageCreateInfo-format-parameter
  format must be a valid VkFormat value

- VUID-VkImageCreateInfo-samples-parameter
  samples must be a valid VkSampleCountFlagBits value

- VUID-VkImageCreateInfo-tiling-parameter
  tiling must be a valid VkImageTiling value

- VUID-VkImageCreateInfo-usage-parameter
  usage must be a valid combination of VkImageUsageFlagBits values

- VUID-VkImageCreateInfo-usage-requiredbitmask
  usage must not be 0

- VUID-VkImageCreateInfo-sharingMode-parameter
  sharingMode must be a valid VkSharingMode value

- VUID-VkImageCreateInfo-initialLayout-parameter
  initialLayout must be a valid VkImageLayout value

The VkImageStencilUsageCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkImageStencilUsageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageUsageFlags stencilUsage;
} VkImageStencilUsageCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
• **pNext** is **NULL** or a pointer to a structure extending this structure.

• **stencilUsage** is a bitmask of **VkImageUsageFlagBits** describing the intended usage of the stencil aspect of the image.

If the **pNext** chain of **VkImageCreateInfo** includes a **VkImageStencilUsageCreateInfo** structure, then that structure includes the usage flags specific to the stencil aspect of the image for an image with a depth-stencil format.

This structure specifies image usages which only apply to the stencil aspect of a depth/stencil format image. When this structure is included in the **pNext** chain of **VkImageCreateInfo**, the stencil aspect of the image **must** only be used as specified by **stencilUsage**. When this structure is not included in the **pNext** chain of **VkImageCreateInfo**, the stencil aspect of an image **must** only be used as specified by **VkImageCreateInfo::usage**. Use of other aspects of an image are unaffected by this structure.

This structure **can** also be included in the **pNext** chain of **VkPhysicalDeviceImageFormatInfo2** to query additional capabilities specific to image creation parameter combinations including a separate set of usage flags for the stencil aspect of the image using **vkGetPhysicalDeviceImageFormatProperties2**. When this structure is not included in the **pNext** chain of **VkPhysicalDeviceImageFormatInfo2** then the implicit value of **stencilUsage** matches that of **VkPhysicalDeviceImageFormatInfo2::usage**.

### Valid Usage

- **VUID-VkImageStencilUsageCreateInfo-stencilUsage-02539**
  
  If **stencilUsage** includes **VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT**, it **must** not include bits other than **VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT** or **VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT**

### Valid Usage (Implicit)

- **VUID-VkImageStencilUsageCreateInfo-sType-sType**
  
  **sType** **must** be **VK_STRUCTURE_TYPE_IMAGE_STENCIL_USAGE_CREATE_INFO**

- **VUID-VkImageStencilUsageCreateInfo-stencilUsage-parameter**
  
  **stencilUsage** **must** be a valid combination of **VkImageUsageFlagBits** values

- **VUID-VkImageStencilUsageCreateInfo-stencilUsage-required bitmask**
  
  **stencilUsage** **must** not be **0**

To define a set of external memory handle types that **may** be used as backing store for an image, add a **VkExternalMemoryImageCreateInfo** structure to the **pNext** chain of the **VkImageCreateInfo** structure. The **VkExternalMemoryImageCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkExternalMemoryImageCreateInfo {
    VkStructureType sType;
```
const void* pNext;
VkExternalMemoryHandleTypeFlags handleTypes;
} VkExternalMemoryImageCreateInfo;

\begin{itemize}
\item \texttt{pNext} is NULL or a pointer to a structure extending this structure.
\item \texttt{handleTypes} is zero or a bitmask of \texttt{VkExternalMemoryHandleTypeFlagBits} specifying one or more external memory handle types.
\end{itemize}

\noindent \textbf{Valid Usage (Implicit)}

\begin{itemize}
\item VUID-VkExternalMemoryImageCreateInfo-sType-sType \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO}
\item VUID-VkExternalMemoryImageCreateInfo-handleTypes-parameter \texttt{handleTypes} must be a valid combination of \texttt{VkExternalMemoryHandleTypeFlagBits} values
\end{itemize}

If the \texttt{pNext} chain of \texttt{VkImageCreateInfo} includes a \texttt{VkImageFormatListCreateInfo} structure, then that structure contains a list of all formats that can be used when creating views of this image.

The \texttt{VkImageFormatListCreateInfo} structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkImageFormatListCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t viewFormatCount;
    const VkFormat* pViewFormats;
} VkImageFormatListCreateInfo;
```

\begin{itemize}
\item \texttt{sType} is a \texttt{VkStructureType} value identifying this structure.
\item \texttt{pNext} is NULL or a pointer to a structure extending this structure.
\item \texttt{viewFormatCount} is the number of entries in the \texttt{pViewFormats} array.
\item \texttt{pViewFormats} is a pointer to an array of \texttt{VkFormat} values specifying all formats which can be used when creating views of this image.
\end{itemize}

If \texttt{viewFormatCount} is zero, \texttt{pViewFormats} is ignored and the image is created as if the \texttt{VkImageFormatListCreateInfo} structure were not included in the \texttt{pNext} chain of \texttt{VkImageCreateInfo}.

\noindent \textbf{Note}

A \texttt{VkExternalMemoryImageCreateInfo} structure with a non-zero \texttt{handleTypes} field must be included in the creation parameters for an image that will be bound to memory that is either exported or imported.
Valid Usage (Implicit)

- VUID-VkImageFormatListCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO

- VUID-VkImageFormatListCreateInfo-pViewFormats-parameter
  If viewFormatCount is not 0, pViewFormats must be a valid pointer to an array of
  viewFormatCount valid VkFormat values

Bits which can be set in

- VkImageViewUsageCreateInfo::usage
- VkImageStencilUsageCreateInfo::stencilUsage
- VkImageCreateInfo::usage

specify intended usage of an image, and are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageUsageFlagBits {
    VK_IMAGE_USAGE_TRANSFER_SRC_BIT = 0x00000001,
    VK_IMAGE_USAGE_TRANSFER_DST_BIT = 0x00000002,
    VK_IMAGE_USAGE_SAMPLED_BIT = 0x00000004,
    VK_IMAGE_USAGE_STORAGE_BIT = 0x00000008,
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT = 0x00000010,
    VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000020,
    VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT = 0x00000040,
    VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT = 0x00000080,
} VkImageUsageFlagBits;
```

- **VK_IMAGE_USAGE_TRANSFER_SRC_BIT** specifies that the image can be used as the source of a transfer command.
- **VK_IMAGE_USAGE_TRANSFER_DST_BIT** specifies that the image can be used as the destination of a transfer command.
- **VK_IMAGE_USAGE_SAMPLED_BIT** specifies that the image can be used to create a VkImageView suitable for occupying a VkDescriptorSet slot either of type VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and be sampled by a shader.
- **VK_IMAGE_USAGE_STORAGE_BIT** specifies that the image can be used to create a VkImageView suitable for occupying a VkDescriptorSet slot of type VK_DESCRIPTOR_TYPE_STORAGE_IMAGE.
- **VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT** specifies that the image can be used to create a VkImageView suitable for use as a color or resolve attachment in a VkFramebuffer.
- **VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT** specifies that the image can be used to create a VkImageView suitable for use as a depth/stencil or depth/stencil resolve attachment in a VkFramebuffer.
- **VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT** specifies that implementations may support using
memory allocations with the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` to back an image with this usage. This bit can be set for any image that can be used to create a `VkImageView` suitable for use as a color, resolve, depth/stencil, or input attachment.

- `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` specifies that the image can be used to create a `VkImageView` suitable for occupying `VkDescriptorSet` slot of type `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`; be read from a shader as an input attachment; and be used as an input attachment in a framebuffer.

```cpp
// Provided by VK_VERSION_1_0
typedef VkFlags VkImageUsageFlags;
```

`VkImageUsageFlags` is a bitmask type for setting a mask of zero or more `VkImageUsageFlagBits`.

When creating a `VkImageView` one of the following `VkImageUsageFlagBits` must be set:

- `VK_IMAGE_USAGE_SAMPLED_BIT`
- `VK_IMAGE_USAGE_STORAGE_BIT`
- `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`
- `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`
- `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`
- `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`

Bits which can be set in `VkImageCreateInfo::flags`, specifying additional parameters of an image, are:

```cpp
// Provided by VK_VERSION_1_0
typedef enum VkImageCreateFlagBits {
    VK_IMAGE_CREATE_SPARSE_BINDING_BIT = 0x00000001,
    VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
    VK_IMAGE_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
    VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT = 0x00000008,
    VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT = 0x00000010,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_ALIAS_BIT = 0x00000400,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT = 0x00000040,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT = 0x00000020,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT = 0x00000080,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_EXTENDED_USAGE_BIT = 0x00000100,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_PROTECTED_BIT = 0x00000800,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_CREATE_DISJOINT_BIT = 0x00000200,
}
```
- **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** specifies that the image will be backed using sparse memory binding.

- **VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT** specifies that the image can be partially backed using sparse memory binding. Images created with this flag must also be created with the **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** flag.

- **VK_IMAGE_CREATE_SPARSE_ALIASED_BIT** specifies that the image will be backed using sparse memory binding with memory ranges that might also simultaneously be backing another image (or another portion of the same image). Images created with this flag must also be created with the **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** flag.

- **VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT** specifies that the image can be used to create a VkImageView with a different format from the image. For multi-planar formats, **VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT** specifies that a VkImageView can be created of a plane of the image.

- **VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT** specifies that the image can be used to create a VkImageView of type **VK_IMAGE_VIEW_TYPE_CUBE** or **VK_IMAGE_VIEW_TYPE_CUBE_ARRAY**.

- **VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT** specifies that the image can be used to create a VkImageView of type **VK_IMAGE_VIEW_TYPE_2D** or **VK_IMAGE_VIEW_TYPE_2D_ARRAY**.

- **VK_IMAGE_CREATE_PROTECTED_BIT** specifies that the image is a protected image.

- **VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT** specifies that the image can be used with a non-zero value of the **splitInstanceBindRegionCount** member of a VkBindImageMemoryDeviceGroupInfo structure passed into vkBindImageMemory2. This flag also has the effect of making the image use the standard sparse image block dimensions.

- **VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT** specifies that the image having a compressed format can be used to create a VkImageView with an uncompressed format where each texel in the image view corresponds to a compressed texel block of the image.

- **VK_IMAGE_CREATE_EXTENDED_USAGE_BIT** specifies that the image can be created with usage flags that are not supported for the format the image is created with but are supported for at least one format a VkImageView created from the image can have.

- **VK_IMAGE_CREATE_DISJOINT_BIT** specifies that an image with a multi-planar format must have each plane separately bound to memory, rather than having a single memory binding for the whole image; the presence of this bit distinguishes a disjoint image from an image without this bit set.

- **VK_IMAGE_CREATE_ALIAS_BIT** specifies that two images created with the same creation parameters and aliased to the same memory can interpret the contents of the memory consistently with each other, subject to the rules described in the Memory Aliasing section. This flag further specifies that each plane of a disjoint image can share an in-memory non-linear representation with single-plane images, and that a single-plane image can share an in-memory non-linear representation with a plane of a multi-planar disjoint image, according to the rules in Compatible formats of planes of multi-planar formats. If the **pNext** chain includes a VkExternalMemoryImageCreateInfo structure whose **handleTypes** member is not 0, it is as if **VK_IMAGE_CREATE_ALIAS_BIT** is set.
See Sparse Resource Features and Sparse Physical Device Features for more details.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkImageCreateFlags;
```

`VkImageCreateFlags` is a bitmask type for setting a mask of zero or more `VkImageCreateFlagBits`.

Possible values of `VkImageCreateInfo::imageType`, specifying the basic dimensionality of an image, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageType {
    VK_IMAGE_TYPE_1D = 0,
    VK_IMAGE_TYPE_2D = 1,
    VK_IMAGE_TYPE_3D = 2,
} VkImageType;
```

- **VK_IMAGE_TYPE_1D** specifies a one-dimensional image.
- **VK_IMAGE_TYPE_2D** specifies a two-dimensional image.
- **VK_IMAGE_TYPE_3D** specifies a three-dimensional image.

Possible values of `VkImageCreateInfo::tiling`, specifying the tiling arrangement of texel blocks in an image, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageTiling {
    VK_IMAGE_TILING_OPTIMAL = 0,
    VK_IMAGE_TILING_LINEAR = 1,
} VkImageTiling;
```

- **VK_IMAGE_TILING_OPTIMAL** specifies optimal tiling (texels are laid out in an implementation-dependent arrangement, for more efficient memory access).
- **VK_IMAGE_TILING_LINEAR** specifies linear tiling (texels are laid out in memory in row-major order, possibly with some padding on each row).

To query the memory layout of an image subresource, call:

```c
// Provided by VK_VERSION_1_0
void vkGetImageSubresourceLayout(
    VkDevice device,
    VkImage image,
    const VkImageSubresource* pSubresource,
    VkSubresourceLayout* pLayout);
```

- **device** is the logical device that owns the image.
• **image** is the image whose layout is being queried.

• **pSubresource** is a pointer to a **VkImageSubresource** structure selecting a specific image subresource from the image.

• **pLayout** is a pointer to a **VkSubresourceLayout** structure in which the layout is returned.

The image must be linear. The returned layout is valid for host access.

If the image’s format is a multi-planar format, then *vkGetImageSubresourceLayout* describes one plane of the image.

*vkGetImageSubresourceLayout* is invariant for the lifetime of a single image.

---

### Valid Usage

- **VUID-vkGetImageSubresourceLayout-image-07789**
  image must have been created with **tiling** equal to **VK_IMAGE_TILING_LINEAR**

- **VUID-vkGetImageSubresourceLayout-aspectMask-00997**
  The **aspectMask** member of **pSubresource** must only have a single bit set

- **VUID-vkGetImageSubresourceLayout-mipLevel-01716**
  The **mipLevel** member of **pSubresource** must be less than the **mipLevels** specified in **VkImageCreateInfo** when **image** was created

- **VUID-vkGetImageSubresourceLayout-arrayLayer-01717**
  The **arrayLayer** member of **pSubresource** must be less than the **arrayLayers** specified in **VkImageCreateInfo** when **image** was created

- **VUID-vkGetImageSubresourceLayout-format-08886**
  If format of the **image** is a color format, **tiling** of the **image** is **VK_IMAGE_TILING_LINEAR** or **VK_IMAGE_TILING_OPTIMAL**, and does not have a multi-planar image format, the **aspectMask** member of **pSubresource** must be **VK_IMAGE_ASPECT_COLOR_BIT**

- **VUID-vkGetImageSubresourceLayout-format-04462**
  If format of the **image** has a depth component, the **aspectMask** member of **pSubresource** must contain **VK_IMAGE_ASPECT_DEPTH_BIT**

- **VUID-vkGetImageSubresourceLayout-format-04463**
  If format of the **image** has a stencil component, the **aspectMask** member of **pSubresource** must contain **VK_IMAGE_ASPECT_STENCIL_BIT**

- **VUID-vkGetImageSubresourceLayout-format-04464**
  If format of the **image** does not contain a stencil or depth component, the **aspectMask** member of **pSubresource** must not contain **VK_IMAGE_ASPECT_DEPTH_BIT** or **VK_IMAGE_ASPECT_STENCIL_BIT**

- **VUID-vkGetImageSubresourceLayout-tiling-08717**
  If the **tiling** of the **image** is **VK_IMAGE_TILING_LINEAR** and has a multi-planar image format, then the **aspectMask** member of **pSubresource** must be a single valid multi-planar aspect mask
Valid Usage (Implicit)

- VUID-vkGetImageSubresourceLayout-device-parameter
  
  device must be a valid VkDevice handle

- VUID-vkGetImageSubresourceLayout-image-parameter
  
  image must be a valid VkImage handle

- VUID-vkGetImageSubresourceLayout-pSubresource-parameter
  
  pSubresource must be a valid pointer to a valid VkImageSubresource structure

- VUID-vkGetImageSubresourceLayout-pLayout-parameter
  
  pLayout must be a valid pointer to a VkSubresourceLayout structure

- VUID-vkGetImageSubresourceLayout-image-parent
  
  image must have been created, allocated, or retrieved from device

The VkImageSubresource structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageSubresource {
    VkImageAspectFlags aspectMask;
    uint32_t mipLevel;
    uint32_t arrayLayer;
} VkImageSubresource;
```

- aspectMask is a VkImageAspectFlags value selecting the image aspect.
- mipLevel selects the mipmap level.
- arrayLayer selects the array layer.

Valid Usage (Implicit)

- VUID-VkImageSubresource-aspectMask-parameter
  
  aspectMask must be a valid combination of VkImageAspectFlagBits values

- VUID-VkImageSubresource-aspectMask-requiredbitmask
  
  aspectMask must not be 0

Information about the layout of the image subresource is returned in a VkSubresourceLayout structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSubresourceLayout {
    VkDeviceSize offset;
    VkDeviceSize size;
    VkDeviceSize rowPitch;
    VkDeviceSize arrayPitch;
} VkSubresourceLayout;
```
VkDeviceSize depthPitch;
} VkSubresourceLayout;

- **offset** is the byte offset from the start of the image or the plane where the image subresource begins.
- **size** is the size in bytes of the image subresource. **size** includes any extra memory that is required based on **rowPitch**.
- **rowPitch** describes the number of bytes between each row of texels in an image.
- **arrayPitch** describes the number of bytes between each array layer of an image.
- **depthPitch** describes the number of bytes between each slice of 3D image.

If the image is **linear**, then **rowPitch**, **arrayPitch** and **depthPitch** describe the layout of the image subresource in linear memory. For uncompressed formats, **rowPitch** is the number of bytes between texels with the same x coordinate in adjacent rows (y coordinates differ by one). **arrayPitch** is the number of bytes between texels with the same x and y coordinate in adjacent array layers of the image (array layer values differ by one). **depthPitch** is the number of bytes between texels with the same x and y coordinate in adjacent slices of a 3D image (z coordinates differ by one). Expressed as an addressing formula, the starting byte of a texel in the image subresource has address:

```plaintext
// (x,y,z,layer) are in texel coordinates
address(x,y,z,layer) = layer*arrayPitch + z*depthPitch + y*rowPitch + x*elementSize + offset
```

For compressed formats, the **rowPitch** is the number of bytes between compressed texel blocks in adjacent rows. **arrayPitch** is the number of bytes between compressed texel blocks in adjacent array layers. **depthPitch** is the number of bytes between compressed texel blocks in adjacent slices of a 3D image.

```plaintext
// (x,y,z,layer) are in compressed texel block coordinates
address(x,y,z,layer) = layer*arrayPitch + z*depthPitch + y*rowPitch + x
*compressedTexelBlockSize + offset;
```

The value of **arrayPitch** is undefined for images that were not created as arrays. **depthPitch** is defined only for 3D images.

If the image has a **single-plane** color format, then the **aspectMask** member of **VkImageSubresource** must be **VK_IMAGE_ASPECT_COLOR_BIT**.

If the image has a depth/stencil format, then **aspectMask** must be either **VK_IMAGE_ASPECT_DEPTH_BIT** or **VK_IMAGE_ASPECT_STENCIL_BIT**. On implementations that store depth and stencil aspects separately, querying each of these image subresource layouts will return a different **offset** and **size** representing the region of memory used for that aspect. On implementations that store depth and stencil aspects interleaved, the same **offset** and **size** are returned and represent the interleaved memory allocation.
If the image has a multi-planar format, then the aspectMask member of VkImageSubresource must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or (for 3-plane formats only) VK_IMAGE_ASPECT_PLANE_2_BIT. Querying each of these image subresource layouts will return a different offset and size representing the region of memory used for that plane. If the image is disjoint, then the offset is relative to the base address of the plane. If the image is non-disjoint, then the offset is relative to the base address of the image.

To destroy an image, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyImage(
    VkDevice device,
    VkImage image,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the image.
- `image` is the image to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- **VUID-vkDestroyImage-image-01000**
  All submitted commands that refer to `image`, either directly or via a VkImageView, must have completed execution.

- **VUID-vkDestroyImage-image-01001**
  If `VkAllocationCallbacks` were provided when `image` was created, a compatible set of callbacks must be provided here.

- **VUID-vkDestroyImage-image-01002**
  If no `VkAllocationCallbacks` were provided when `image` was created, `pAllocator` must be NULL.

### Valid Usage (Implicit)

- **VUID-vkDestroyImage-device-parameter**
  `device` must be a valid VkDevice handle.

- **VUID-vkDestroyImage-image-parameter**
  If `image` is not VK_NULL_HANDLE, `image` must be a valid VkImage handle.

- **VUID-vkDestroyImage-pAllocator-parameter**
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure.

- **VUID-vkDestroyImage-image-parent**
  If `image` is a valid handle, it must have been created, allocated, or retrieved from `device`.
Host Synchronization

- Host access to image must be externally synchronized

12.3.1. Image Format Features

Valid uses of a VkImage may depend on the image’s format features, defined below. Such constraints are documented in the affected valid usage statement.

- If the image was created with VK_IMAGE_TILING_LINEAR, then its set of format features is the value of VkFormatProperties::linearTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties on the same format as VkImageCreateInfo::format.

- If the image was created with VK_IMAGE_TILING_OPTIMAL, then its set of format features is the value of VkFormatProperties::optimalTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties on the same format as VkImageCreateInfo::format.

12.3.2. Image Mip Level Sizing

A complete mipmap chain is the full set of mip levels, from the largest mip level provided, down to the minimum mip level size.

Conventional Images

For conventional images, the dimensions of each successive mip level, n+1, are:

\[
\begin{align*}
\text{width}_{n+1} &= \max\left(\left\lfloor\frac{\text{width}_n}{2}\right\rfloor, 1\right) \\
\text{height}_{n+1} &= \max\left(\left\lfloor\frac{\text{height}_n}{2}\right\rfloor, 1\right) \\
\text{depth}_{n+1} &= \max\left(\left\lfloor\frac{\text{depth}_n}{2}\right\rfloor, 1\right)
\end{align*}
\]

where \(\text{width}_n\), \(\text{height}_n\), and \(\text{depth}_n\) are the dimensions of the next larger mip level, n.

The minimum mip level size is:

- 1 for one-dimensional images,
- 1x1 for two-dimensional images, and
- 1x1x1 for three-dimensional images.

The number of levels in a complete mipmap chain is:

\[
\left\lceil\log_2(\max(\text{width}_0, \text{height}_0, \text{depth}_0))\right\rceil + 1
\]
where $\text{width}_0$, $\text{height}_0$, and $\text{depth}_0$ are the dimensions of the largest (most detailed) mip level, 0.

## 12.4. Image Layouts

Images are stored in implementation-dependent opaque layouts in memory. Each layout has limitations on what kinds of operations are supported for image subresources using the layout. At any given time, the data representing an image subresource in memory exists in a particular layout which is determined by the most recent layout transition that was performed on that image subresource. Applications have control over which layout each image subresource uses, and can transition an image subresource from one layout to another. Transitions can happen with an image memory barrier, included as part of a `vkCmdPipelineBarrier` or a `vkCmdWaitEvents` command buffer command (see [Image Memory Barriers]), or as part of a subpass dependency within a render pass (see [VkSubpassDependency]).

Image layout is per-image subresource. Separate image subresources of the same image can be in different layouts at the same time, with the exception that depth and stencil aspects of a given image subresource can only be in different layouts if the `separateDepthStencilLayouts` feature is enabled.

### Note

Each layout may offer optimal performance for a specific usage of image memory. For example, an image with a layout of `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL` may provide optimal performance for use as a color attachment, but be unsupported for use in transfer commands. Applications can transition an image subresource from one layout to another in order to achieve optimal performance when the image subresource is used for multiple kinds of operations. After initialization, applications need not use any layout other than the general layout, though this may produce suboptimal performance on some implementations.

Upon creation, all image subresources of an image are initially in the same layout, where that layout is selected by the `VkImageCreateInfo::initialLayout` member. The `initialLayout` must be either `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`. If it is `VK_IMAGE_LAYOUT_PREINITIALIZED`, then the image data can be preinitialized by the host while using this layout, and the transition away from this layout will preserve that data. If it is `VK_IMAGE_LAYOUT_UNDEFINED`, then the contents of the data are considered to be undefined, and the transition away from this layout is not guaranteed to preserve that data. For either of these initial layouts, any image subresources must be transitioned to another layout before they are accessed by the device.

Host access to image memory is only well-defined for linear images and for image subresources of those images which are currently in either the `VK_IMAGE_LAYOUT_PREINITIALIZED` or `VK_IMAGE_LAYOUT_GENERAL` layout. Calling `vkGetImageSubresourceLayout` for a linear image returns a subresource layout mapping that is valid for either of those image layouts.

The set of image layouts consists of:

```c
// Provided by VK_VERSION_1_0
```
typedef enum VkImageLayout {
    VK_IMAGE_LAYOUT_UNDEFINED = 0,
    VK_IMAGE_LAYOUT_GENERAL = 1,
    VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL = 2,
    VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL = 3,
    VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL = 4,
    VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL = 5,
    VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL = 6,
    VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL = 7,
    VK_IMAGE_LAYOUT_PREINITIALIZED = 8,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL = 1000117000,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL = 1000117001,
    // Provided by VK_VERSION_1_2
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL = 1000241000,
    // Provided by VK_VERSION_1_2
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL = 1000241001,
    // Provided by VK_VERSION_1_2
    VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL = 1000241002,
    // Provided by VK_VERSION_1_2
    VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL = 1000241003,
    // Provided by VK_VERSION_1_3
    VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL = 1000314000,
    // Provided by VK_VERSION_1_3
    VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL = 1000314001
} VkImageLayout;

The type(s) of device access supported by each layout are:

- **VK_IMAGE_LAYOUT_UNDEFINED** specifies that the layout is unknown. Image memory cannot be transitioned into this layout. This layout can be used as the initialLayout member of VkImageCreateInfo. This layout can be used in place of the current image layout in a layout transition, but doing so will cause the contents of the image's memory to be undefined.

- **VK_IMAGE_LAYOUT_PREINITIALIZED** specifies that an image's memory is in a defined layout and can be populated by data, but that it has not yet been initialized by the driver. Image memory cannot be transitioned into this layout. This layout can be used as the initialLayout member of VkImageCreateInfo. This layout is intended to be used as the initial layout for an image whose contents are written by the host, and hence the data can be written to memory immediately, without first executing a layout transition. Currently, VK_IMAGE_LAYOUT_PREINITIALIZED is only useful with linear images because there is not a standard layout defined for VK_IMAGE_TILING_OPTIMAL images.

- **VK_IMAGE_LAYOUT_GENERAL** supports all types of device access.

- **VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL** specifies a layout that must only be used with attachment accesses in the graphics pipeline.

- **VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL** specifies a layout allowing read only access as an attachment, or in shaders as a sampled image, combined image/sampler, or input attachment.
• **VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL** **must** only be used as a color or resolve attachment in a VkFramebuffer. This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL** specifies a layout for both the depth and stencil aspects of a depth/stencil format image allowing read and write access as a depth/stencil attachment. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for both the depth and stencil aspects of a depth/stencil format image allowing read only access as a depth/stencil attachment or in shaders as a sampled image, combined image/sampler, or input attachment. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for depth/stencil format images allowing read and write access to the stencil aspect as a stencil attachment, and read only access to the depth aspect as a depth attachment or in shaders as a sampled image, combined image/sampler, or input attachment. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for depth/stencil format images allowing read and write access to the depth aspect as a depth attachment, and read only access to the stencil aspect as a stencil attachment or in shaders as a sampled image, combined image/sampler, or input attachment. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL** specifies a layout allowing read-only access in a shader as a sampled image, combined image/sampler, or input attachment. This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_SAMPLED_BIT** or **VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT** usage bits enabled.

• **VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL** **must** only be used as a source image of a transfer command (see the definition of **VK_PIPELINE_STAGE_TRANSFER_BIT**). This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_TRANSFER_SRC_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL** **must** only be used as a destination image of a transfer command. This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_TRANSFER_DST_BIT** usage bit enabled.
The layout of each image subresource is not a state of the image subresource itself, but is rather a property of how the data in memory is organized, and thus for each mechanism of accessing an image in the API the application must specify a parameter or structure member that indicates which image layout the image subresource(s) are considered to be in when the image will be accessed. For transfer commands, this is a parameter to the command (see Clear Commands and Copy Commands). For use as a framebuffer attachment, this is a member in the substructures of the VkRenderPassCreateInfo (see Render Pass). For use in a descriptor set, this is a member in the VkDescriptorImageInfo structure (see Descriptor Set Updates).

12.4.1. Image Layout Matching Rules

At the time that any command buffer command accessing an image executes on any queue, the layouts of the image subresources that are accessed must all match exactly the layout specified via the API controlling those accesses, except in case of accesses to an image with a depth/stencil format performed through descriptors referring to only a single aspect of the image, where the following relaxed matching rules apply:

- Descriptors referring just to the depth aspect of a depth/stencil image only need to match in the image layout of the depth aspect, thus VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL and VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL are considered to match.
- Descriptors referring just to the stencil aspect of a depth/stencil image only need to match in the image layout of the stencil aspect, thus VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL and VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL are considered to match.

When performing a layout transition on an image subresource, the old layout value must either equal the current layout of the image subresource (at the time the transition executes), or else be VK_IMAGE_LAYOUT_UNDEFINED (implying that the contents of the image subresource need not be preserved). The new layout used in a transition must not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

12.5. Image Views

Image objects are not directly accessed by pipeline shaders for reading or writing image data. Instead, image views representing contiguous ranges of the image subresources and containing additional metadata are used for that purpose. Views must be created on images of compatible types, and must represent a valid subset of image subresources.

Image views are represented by VkImageView handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImageView)
```

VK_REMAINING_ARRAY_LAYERS is a special constant value used for image views to indicate that all remaining array layers in an image after the base layer should be included in the view.

```c
#define VK_REMAINING_ARRAY_LAYERS (~0U)
```
VK_REMAINING_MIP_LEVELS is a special constant value used for image views to indicate that all remaining mipmap levels in an image after the base level should be included in the view.

```c
#define VK_REMAINING_MIP_LEVELS (~0U)
```

The types of image views that can be created are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageViewType {
    VK_IMAGE_VIEW_TYPE_1D = 0,
    VK_IMAGE_VIEW_TYPE_2D = 1,
    VK_IMAGE_VIEW_TYPE_3D = 2,
    VK_IMAGE_VIEW_TYPE_CUBE = 3,
    VK_IMAGE_VIEW_TYPE_1D_ARRAY = 4,
    VK_IMAGE_VIEW_TYPE_2D_ARRAY = 5,
    VK_IMAGE_VIEW_TYPE_CUBE_ARRAY = 6,
} VkImageViewType;
```

To create an image view, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateImageView(
    VkDevice device,
    const VkImageViewCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkImageView* pView);
```

- **device** is the logical device that creates the image view.
- **pCreateInfo** is a pointer to a VkImageViewCreateInfo structure containing parameters to be used to create the image view.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pView** is a pointer to a VkImageView handle in which the resulting image view object is returned.

## Valid Usage (Implicit)

- VUID-vkCreateImageView-device-parameter
  - **device** must be a valid VkDevice handle
- VUID-vkCreateImageView-pCreateInfo-parameter
  - **pCreateInfo** must be a valid pointer to a valid VkImageViewCreateInfo structure
- VUID-vkCreateImageView-pAllocator-parameter
  - If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure
**Return Codes**

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkImageViewCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageViewCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageViewCreateFlags flags;
    VkImage image;
    VkImageViewType viewType;
    VkFormat format;
    VkComponentMapping components;
    VkImageSubresourceRange subresourceRange;
} VkImageViewCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `flags` is a bitmask of `VkImageViewCreateFlagBits` specifying additional parameters of the image view.
- `image` is a `VkImage` on which the view will be created.
- `viewType` is a `VkImageViewType` value specifying the type of the image view.
- `format` is a `VkFormat` specifying the format and type used to interpret texel blocks of the image.
- `components` is a `VkComponentMapping` structure specifying a remapping of color components (or of depth or stencil components after they have been converted into color components).
- `subresourceRange` is a `VkImageSubresourceRange` structure selecting the set of mipmap levels and array layers to be accessible to the view.

Some of the `image` creation parameters are inherited by the view. In particular, image view creation inherits the implicit parameter `usage` specifying the allowed usages of the image view that, by default, takes the value of the corresponding `usage` parameter specified in `VkImageCreateInfo` at image creation time. The implicit `usage` can be overridden by adding a `VkImageViewUsageCreateInfo` structure to the `pNext` chain, but the view usage must be a subset of
If `image` has a depth-stencil format and was created with a `VkImageStencilUsageCreateInfo` structure included in the `pNext` chain of `VkImageCreateInfo`, the usage is calculated based on the `subresource.aspectMask` provided:

- If `aspectMask` includes only `VK_IMAGE_ASPECT_STENCIL_BIT`, the implicit *usage* is equal to `VkImageStencilUsageCreateInfo::stencilUsage`.
- If `aspectMask` includes only `VK_IMAGE_ASPECT_DEPTH_BIT`, the implicit *usage* is equal to `VkImageCreateInfo::usage`.
- If both aspects are included in `aspectMask`, the implicit *usage* is equal to the intersection of `VkImageCreateInfo::usage` and `VkImageStencilUsageCreateInfo::stencilUsage`.

If `image` was created with the `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` flag, and if the `format` of the image is not multi-planar, `format` can be different from the image’s format, but if `image` was created without the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag and they are not equal they must be compatible. Image format compatibility is defined in the Format Compatibility Classes section. Views of compatible formats will have the same mapping between texel coordinates and memory locations irrespective of the `format`, with only the interpretation of the bit pattern changing.

If `image` was created with a multi-planar format, and the image view’s `aspectMask` is one of `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT` or `VK_IMAGE_ASPECT_PLANE_2_BIT`, the view’s aspect mask is considered to be equivalent to `VK_IMAGE_ASPECT_COLOR_BIT` when used as a framebuffer attachment.

### Note

Values intended to be used with one view format may not be exactly preserved when written or read through a different format. For example, an integer value that happens to have the bit pattern of a floating point denorm or NaN may be flushed or canonicalized when written or read through a view with a floating point format. Similarly, a value written through a signed normalized format that has a bit pattern exactly equal to \(-2^b\) may be changed to \(-2^b + 1\) as described in Conversion from Normalized Fixed-Point to Floating-Point.

If `image` was created with the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag, `format` must be compatible with the image’s format as described above; or must be an uncompressed format, in which case it must be size-compatible with the image’s format. In this case, the resulting image view’s texel dimensions equal the dimensions of the selected mip level divided by the compressed texel block size and rounded up.

The `VkComponentMapping components` member describes a remapping from components of the image to components of the vector returned by shader image instructions. This remapping must be the identity swizzle for storage image descriptors, input attachment descriptors, framebuffer attachments, and any `VkImageView` used with a combined image sampler that enables sampler Y’C\(_b\)C\(_R\) conversion.

If the image view is to be used with a sampler which supports sampler Y’C\(_b\)C\(_R\) conversion, an *identically defined object* of type `VkSamplerYcbcrConversion` to that used to create the sampler must be passed to `vkCreateImageView` in a `VkSamplerYcbcrConversionInfo` included in the `pNext` chain of `VkImageViewCreateInfo`. Conversely, if a `VkSamplerYcbcrConversion` object is passed to
vkCreateImageView, an identically defined VkSamplerYcbcrConversion object must be used when sampling the image.

If the image has a multi-planar format, subresourceRange.aspectMask is VK_IMAGE_ASPECT_COLOR_BIT, and usage includes VK_IMAGE_USAGE_SAMPLED_BIT, then the format must be identical to the image format and the sampler to be used with the image view must enable sampler Y’CbCr conversion.

If image was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT and the image has a multi-planar format, and if subresourceRange.aspectMask is VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT, format must be compatible with the corresponding plane of the image, and the sampler to be used with the image view must not enable sampler Y’CbCr conversion. The width and height of the single-plane image view must be derived from the multi-planar image’s dimensions in the manner listed for plane compatibility for the plane.

Any view of an image plane will have the same mapping between texel coordinates and memory locations as used by the components of the color aspect, subject to the formulae relating texel coordinates to lower-resolution planes as described in Chroma Reconstruction. That is, if an R or B plane has a reduced resolution relative to the G plane of the multi-planar image, the image view operates using the \((u_{plane}, v_{plane})\) unnormalized coordinates of the reduced-resolution plane, and these coordinates access the same memory locations as the \((u_{color}, v_{color})\) unnormalized coordinates of the color aspect for which chroma reconstruction operations operate on the same \((u_{plane}, v_{plane})\) or \((i_{plane}, j_{plane})\) coordinates.

<table>
<thead>
<tr>
<th>Image View Type</th>
<th>Compatible Image Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_IMAGE_VIEW_TYPE_1D</td>
<td>VK_IMAGE_TYPE_1D</td>
</tr>
<tr>
<td>VK_IMAGE_VIEW_TYPE_1D_ARRAY</td>
<td>VK_IMAGE_TYPE_1D</td>
</tr>
<tr>
<td>VK_IMAGE_VIEW_TYPE_2D</td>
<td>VK_IMAGE_TYPE_2D, VK_IMAGE_TYPE_3D</td>
</tr>
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<td>VK_IMAGE_TYPE_2D, VK_IMAGE_TYPE_3D</td>
</tr>
<tr>
<td>VK_IMAGE_VIEW_TYPE_CUBE</td>
<td>VK_IMAGE_TYPE_2D</td>
</tr>
<tr>
<td>VK_IMAGE_VIEW_TYPE_CUBE_ARRAY</td>
<td>VK_IMAGE_TYPE_2D</td>
</tr>
<tr>
<td>VK_IMAGE_VIEW_TYPE_3D</td>
<td>VK_IMAGE_TYPE_3D</td>
</tr>
</tbody>
</table>

### Valid Usage

- **VUID-VkImageViewCreateInfo-image-01003**
  If image was not created with VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT then viewType must not be VK_IMAGE_VIEW_TYPE_CUBE or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY

- **VUID-VkImageViewCreateInfo-viewType-01004**
  If the imageCubeArray feature is not enabled, viewType must not be VK_IMAGE_VIEW_TYPE_CUBE_ARRAY

- **VUID-VkImageViewCreateInfo-image-06723**
  If image was created with VK_IMAGE_TYPE_3D but without VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set then viewType must not be
• VUID-VkImageViewCreateInfo-image-06727
  If image was created with VK_IMAGE_TYPE_3D but without
  VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set then viewType must not be
  VK_IMAGE_VIEW_TYPE_2D

• VUID-VkImageViewCreateInfo-image-04970
  If image was created with VK_IMAGE_TYPE_3D and viewType is VK_IMAGE_VIEW_TYPE_2D or
  VK_IMAGE_VIEW_TYPE_2D_ARRAY then subresourceRange.levelCount must be 1

• VUID-VkImageViewCreateInfo-image-04971
  If image was created with VK_IMAGE_TYPE_3D and viewType is VK_IMAGE_VIEW_TYPE_2D or
  VK_IMAGE_VIEW_TYPE_2D_ARRAY then VkImageCreateInfo::flags must not contain any of
  VK_IMAGE_CREATE_SPARSE_BINDING_BIT, VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT, and
  VK_IMAGE_CREATE_SPARSE_ALIASED_BIT

• VUID-VkImageViewCreateInfo-image-04972
  If image was created with a samples value not equal to VK_SAMPLE_COUNT_1_BIT then viewType
  must be either VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY

• VUID-VkImageViewCreateInfo-image-04441
  image must have been created with a usage value containing at least one of the usages
  defined in the valid image usage list for image views

• VUID-VkImageViewCreateInfo-None-02273
  The format features of the resultant image view must contain at least one bit

• VUID-VkImageViewCreateInfo-usage-02274
  If usage contains VK_IMAGE_USAGE_SAMPLED_BIT, then the format features of the resultant
  image view must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT

• VUID-VkImageViewCreateInfo-usage-02275
  If usage contains VK_IMAGE_USAGE_STORAGE_BIT, then the image view's format features must
  contain VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT

• VUID-VkImageViewCreateInfo-usage-02276
  If usage contains VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, then the image view's format
  features must contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT

• VUID-VkImageViewCreateInfo-usage-02277
  If usage contains VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, then the image view's
  format features must contain VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkImageViewCreateInfo-usage-02652
  If usage contains VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT, then the image view's format
  features must contain at least one of VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT or
  VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT

• VUID-VkImageViewCreateInfo-subresourceRange-01478
  subresourceRange.baseMipLevel must be less than the mipLevels specified in
  VkImageCreateInfo when image was created

• VUID-VkImageViewCreateInfo-subresourceRange-01718
  If subresourceRange.levelCount is not VK_REMAINING_MIP_LEVELS,
  subresourceRange.baseMipLevel + subresourceRange.levelCount must be less than or equal
to the `mipLevels` specified in `VkImageCreateInfo` when `image` was created

- **VUID-VkImageViewCreateInfo-image-01482**
  If `image` is not a 3D image created with `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT` set, or `viewType` is not `VK_IMAGE_VIEW_TYPE_2D` or `VK_IMAGE_VIEW_TYPE_2D_ARRAY`, `subresourceRange.baseArrayLayer` must be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

- **VUID-VkImageViewCreateInfo-subresourceRange-01483**
  If `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, `image` is not a 3D image created with `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT` set, or `viewType` is not `VK_IMAGE_VIEW_TYPE_2D` or `VK_IMAGE_VIEW_TYPE_2D_ARRAY`, `subresourceRange.layerCount` must be non-zero and `subresourceRange.baseArrayLayer + subresourceRange.layerCount` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

- **VUID-VkImageViewCreateInfo-image-02724**
  If `image` is a 3D image created with `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT` set, and `viewType` is `VK_IMAGE_VIEW_TYPE_2D` or `VK_IMAGE_VIEW_TYPE_2D_ARRAY`, `subresourceRange.baseArrayLayer` must be less than the depth computed from `baseMipLevel` and `extent.depth` specified in `VkImageCreateInfo` when `image` was created, according to the formula defined in `Image Mip Level Sizing`.

- **VUID-VkImageViewCreateInfo-subresourceRange-02725**
  If `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, `image` is a 3D image created with `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT` set, and `viewType` is `VK_IMAGE_VIEW_TYPE_2D` or `VK_IMAGE_VIEW_TYPE_2D_ARRAY`, `subresourceRange.layerCount` must be non-zero and `subresourceRange.baseArrayLayer + subresourceRange.layerCount` must be less than or equal to the depth computed from `baseMipLevel` and `extent.depth` specified in `VkImageCreateInfo` when `image` was created, according to the formula defined in `Image Mip Level Sizing`.

- **VUID-VkImageViewCreateInfo-image-01761**
  If `image` was created with the `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` flag, but without the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag, and if the `format` of the `image` is not a multi-planar format, `format` must be compatible with the `format` used to create `image`, as defined in `Format Compatibility Classes`.

- **VUID-VkImageViewCreateInfo-image-01583**
  If `image` was created with the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag, `format` must be compatible with, or must be an uncompressed format that is size-compatible with, the `format` used to create `image`.

- **VUID-VkImageViewCreateInfo-image-07072**
  If `image` was created with the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag and `format` is a non-compressed format, the `levelCount` and `layerCount` members of `subresourceRange` must both be 1.

- **VUID-VkImageViewCreateInfo-pNext-01585**
  If a `VkImageFormatListCreateInfo` structure was included in the `pNext` chain of the `VkImageCreateInfo` structure used when creating `image` and `VkImageFormatListCreateInfo::viewFormatCount` is not zero then `format` must be one of the formats in `VkImageFormatListCreateInfo::pViewFormats`.
If image was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, if the format of the image is a multi-planar format, and if subresourceRange.aspectMask is one of the multi-planar aspect masks, then format must be compatible with the VkFormat for the plane of the image format indicated by subresourceRange.aspectMask, as defined in Compatible formats of planes of multi-planar formats.

subresourceRange.aspectMask must only have at most 1 valid multi-planar aspect mask.

If image was not created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, or if the format of the image is a multi-planar format and if subresourceRange.aspectMask is VK_IMAGE_ASPECT_COLOR_BIT, format must be identical to the format used to create image.

If the image view requires a sampler Y’C₆C₈R conversion and usage contains VK_IMAGE_USAGE_SAMPLED_BIT, then the pNext chain must include a VkSamplerYcbcrConversionInfo structure with a conversion value other than VK_NULL_HANDLE.

If format has a _422 or _420 suffix then image must have been created with a width that is a multiple of 2.

If format has a _420 suffix then image must have been created with a height that is a multiple of 2.

If the pNext chain includes a VkSamplerYcbcrConversionInfo structure with a conversion value other than VK_NULL_HANDLE, all members of components must have the identity swizzle.

If the pNext chain includes a VkSamplerYcbcrConversionInfo structure with a conversion value other than VK_NULL_HANDLE, format must be the same used in VkSamplerYcbcrConversionCreateInfo::format.

If image is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

viewType must be compatible with the type of image as shown in the view type compatibility table.

If the pNext chain includes a VkImageViewUsageCreateInfo structure, and image was not created with a VkImageStencilUsageCreateInfo structure included in the pNext chain of VkImageCreateInfo, its usage member must not include any bits that were not set in the usage member of the VkImageCreateInfo structure used to create image.

If image is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.
If the `pNext` chain includes a `VkImageViewUsageCreateInfo` structure, `image` was created with a `VkImageStencilUsageCreateInfo` structure included in the `pNext` chain of `VkImageCreateInfo`, and `subresourceRange.aspectMask` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, the `usage` member of the `VkImageViewUsageCreateInfo` structure must not include any bits that were not set in the `usage` member of the `VkImageStencilUsageCreateInfo` structure used to create `image`.

- **VUID-VkImageViewCreateInfo-pNext-02664**
  If the `pNext` chain includes a `VkImageViewUsageCreateInfo` structure, `image` was created with a `VkImageStencilUsageCreateInfo` structure included in the `pNext` chain of `VkImageCreateInfo`, and `subresourceRange.aspectMask` includes bits other than `VK_IMAGE_ASPECT_STENCIL_BIT`, the `usage` member of the `VkImageViewUsageCreateInfo` structure must not include any bits that were not set in the `usage` member of the `VkImageCreateInfo` structure used to create `image`.

- **VUID-VkImageViewCreateInfo-imageViewType-04973**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_1D`, `VK_IMAGE_VIEW_TYPE_2D`, or `VK_IMAGE_VIEW_TYPE_3D`; and `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, then `subresourceRange.layerCount` must be 1.

- **VUID-VkImageViewCreateInfo-imageViewType-04974**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_1D`, `VK_IMAGE_VIEW_TYPE_2D`, or `VK_IMAGE_VIEW_TYPE_3D`; and `subresourceRange.layerCount` is `VK_REMAINING_ARRAY_LAYERS`, then the remaining number of layers must be 1.

- **VUID-VkImageViewCreateInfo-viewType-02960**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_CUBE` and `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, `subresourceRange.layerCount` must be 6.

- **VUID-VkImageViewCreateInfo-viewType-02961**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY` and `subresourceRange.layerCount` is `VK_REMAINING_ARRAY_LAYERS`, `subresourceRange.layerCount` must be a multiple of 6.

- **VUID-VkImageViewCreateInfo-viewType-02962**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_CUBE` and `subresourceRange.layerCount` is `VK_REMAINING_ARRAY_LAYERS`, the remaining number of layers must be 6.

- **VUID-VkImageViewCreateInfo-viewType-02963**
  If `viewType` is `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY` and `subresourceRange.layerCount` is `VK_REMAINING_ARRAY_LAYERS`, the remaining number of layers must be a multiple of 6.

**Valid Usage (Implicit)**

- **VUID-VkImageViewCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO`.

- **VUID-VkImageViewCreateInfo-pNext-pNext**
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkImageViewUsageCreateInfo` or `VkSamplerYcbcrConversionInfo`.

- **VUID-VkImageViewCreateInfo-sType-unique**
The **sType** value of each struct in the **pNext** chain **must** be unique

- **VUID-VkImageViewCreateInfo-flags-zerobitmask**
  - **flags** **must** be 0
- **VUID-VkImageViewCreateInfo-image-parameter**
  - **image** **must** be a valid **VkImage** handle
- **VUID-VkImageViewCreateInfo-viewType-parameter**
  - **viewType** **must** be a valid **VkImageViewType** value
- **VUID-VkImageViewCreateInfo-format-parameter**
  - **format** **must** be a valid **VkFormat** value
- **VUID-VkImageViewCreateInfo-components-parameter**
  - **components** **must** be a valid **VkComponentMapping** structure
- **VUID-VkImageViewCreateInfo-subresourceRange-parameter**
  - **subresourceRange** **must** be a valid **VkImageSubresourceRange** structure

Bits which **can** be set in **VkImageViewCreateInfo::flags**, specifying additional parameters of an image view, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageViewCreateFlagBits {
    } VkImageViewCreateFlagBits;
```

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkImageViewCreateFlags;
```

**VkImageViewCreateFlags** is a bitmask type for setting a mask of zero or more **VkImageViewCreateFlagBits**.

The set of usages for the created image view **can** be restricted compared to the parent image’s **usage flags** by adding a **VkImageViewUsageCreateInfo** structure to the **pNext** chain of **VkImageViewCreateInfo**.

The **VkImageViewUsageCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkImageViewUsageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageUsageFlags usage;
} VkImageViewUsageCreateInfo;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
• usage is a bitmask of VkImageUsageFlagBits specifying allowed usages of the image view.

When this structure is chained to VkImageViewCreateInfo the usage field overrides the implicit usage parameter inherited from image creation time and its value is used instead for the purposes of determining the valid usage conditions of VkImageViewCreateInfo.

Valid Usage (Implicit)

• VUID-VkImageViewUsageCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_IMAGE_VIEW_USAGE_CREATE_INFO

• VUID-VkImageViewUsageCreateInfo-usage-parameter
  usage must be a valid combination of VkImageUsageFlagBits values

• VUID-VkImageViewUsageCreateInfo-usage-requiredbitmask
  usage must not be 0

The VkImageSubresourceRange structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageSubresourceRange {
    VkImageAspectFlags aspectMask;
    uint32_t baseMipLevel;
    uint32_t levelCount;
    uint32_t baseArrayLayer;
    uint32_t layerCount;
} VkImageSubresourceRange;
```

• aspectMask is a bitmask of VkImageAspectFlagBits specifying which aspect(s) of the image are included in the view.

• baseMipLevel is the first mipmap level accessible to the view.

• levelCount is the number of mipmap levels (starting from baseMipLevel) accessible to the view.

• baseArrayLayer is the first array layer accessible to the view.

• layerCount is the number of array layers (starting from baseArrayLayer) accessible to the view.

The number of mipmap levels and array layers must be a subset of the image subresources in the image. If an application wants to use all mip levels or layers in an image after the baseMipLevel or baseArrayLayer, it can set levelCount and layerCount to the special values VK_REMAINING_MIP_LEVELS and VK_REMAINING_ARRAY_LAYERS without knowing the exact number of mip levels or layers.

For cube and cube array image views, the layers of the image view starting at baseArrayLayer correspond to faces in the order +X, -X, +Y, -Y, +Z, -Z. For cube arrays, each set of six sequential layers is a single cube, so the number of cube maps in a cube map array view is layerCount / 6, and image array layer (baseArrayLayer + i) is face index (i mod 6) of cube i / 6. If the number of layers in the view, whether set explicitly in layerCount or implied by VK_REMAINING_ARRAY_LAYERS, is not a multiple of 6, the last cube map in the array must not be accessed.
aspectMask must be only VK_IMAGE_ASPECT_COLOR_BIT, VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT if format is a color, depth-only or stencil-only format, respectively, except if format is a multi-planar format. If using a depth/stencil format with both depth and stencil components, aspectMask must include at least one of VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT, and can include both.

When the VkImageSubresourceRange structure is used to select a subset of the slices of a 3D image’s mip level in order to create a 2D or 2D array image view of a 3D image created with VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT, baseArrayLayer and layerCount specify the first slice index and the number of slices to include in the created image view. Such an image view can be used as a framebuffer attachment that refers only to the specified range of slices of the selected mip level. However, any layout transitions performed on such an attachment view during a render pass instance still apply to the entire subresource referenced which includes all the slices of the selected mip level.

When using an image view of a depth/stencil image to populate a descriptor set (e.g. for sampling in the shader, or for use as an input attachment), the aspectMask must only include one bit, which selects whether the image view is used for depth reads (i.e. using a floating-point sampler or input attachment in the shader) or stencil reads (i.e. using an unsigned integer sampler or input attachment in the shader). When an image view of a depth/stencil image is used as a depth/stencil framebuffer attachment, the aspectMask is ignored and both depth and stencil image subresources are used.

When creating a VkImageView, if sampler Y’C_bC_r conversion is enabled in the sampler, the aspectMask of a subresourceRange used by the VkImageView must be VK_IMAGE_ASPECT_COLOR_BIT.

When creating a VkImageView, if sampler Y’C_bC_r conversion is not enabled in the sampler and the image format is multi-planar, the image must have been created with VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT, and the aspectMask of the VkImageView’s subresourceRange must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT or VK_IMAGE_ASPECT_PLANE_2_BIT.

Valid Usage

- VUID-VkImageSubresourceRange-levelCount-01720
  If levelCount is not VK_REMAINING_MIP_LEVELS, it must be greater than 0
- VUID-VkImageSubresourceRange-layerCount-01721
  If layerCount is not VK_REMAINING_ARRAY_LAYERS, it must be greater than 0
- VUID-VkImageSubresourceRange-aspectMask-01670
  If aspectMask includes VK_IMAGE_ASPECT_COLOR_BIT, then it must not include any of VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT

Valid Usage (Implicit)

- VUID-VkImageSubresourceRange-aspectMask-parameter
  aspectMask must be a valid combination of VkImageAspectFlagBits values
- VUID-VkImageSubresourceRange-aspectMask-requiredbitmask
Bits which **can** be set in an aspect mask to specify aspects of an image for purposes such as identifying a subresource, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkImageAspectFlagBits {
    VK_IMAGE_ASPECT_COLOR_BIT = 0x00000001,
    VK_IMAGE_ASPECT_DEPTH_BIT = 0x00000002,
    VK_IMAGE_ASPECT_STENCIL_BIT = 0x00000004,
    VK_IMAGE_ASPECT_METADATA_BIT = 0x00000008,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_ASPECT_PLANE_0_BIT = 0x00000010,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_ASPECT_PLANE_1_BIT = 0x00000020,
    // Provided by VK_VERSION_1_1
    VK_IMAGE_ASPECT_PLANE_2_BIT = 0x00000040,
    // Provided by VK_VERSION_1_3
    VK_IMAGE_ASPECT_NONE = 0,
} VkImageAspectFlagBits;
```

- **VK_IMAGE_ASPECT_NONE** specifies no image aspect, or the image aspect is not applicable.
- **VK_IMAGE_ASPECT_COLOR_BIT** specifies the color aspect.
- **VK_IMAGE_ASPECT_DEPTH_BIT** specifies the depth aspect.
- **VK_IMAGE_ASPECT_STENCIL_BIT** specifies the stencil aspect.
- **VK_IMAGE_ASPECT_METADATA_BIT** specifies the metadata aspect used for **sparse resource** operations.
- **VK_IMAGE_ASPECT_PLANE_0_BIT** specifies plane 0 of a **multi-planar** image format.
- **VK_IMAGE_ASPECT_PLANE_1_BIT** specifies plane 1 of a **multi-planar** image format.
- **VK_IMAGE_ASPECT_PLANE_2_BIT** specifies plane 2 of a **multi-planar** image format.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkImageAspectFlags;
```

**VkImageAspectFlags** is a bitmask type for setting a mask of zero or more **VkImageAspectFlagBits**.

The **VkComponentMapping** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkComponentMapping {
    VkComponentSwizzle r;
    VkComponentSwizzle g;
    VkComponentSwizzle b;
    VkComponentSwizzle a;
} VkComponentMapping;
```
VkComponentMapping;

- \( r \) is a \texttt{VkComponentSwizzle} specifying the component value placed in the R component of the output vector.
- \( g \) is a \texttt{VkComponentSwizzle} specifying the component value placed in the G component of the output vector.
- \( b \) is a \texttt{VkComponentSwizzle} specifying the component value placed in the B component of the output vector.
- \( a \) is a \texttt{VkComponentSwizzle} specifying the component value placed in the A component of the output vector.

**Valid Usage (Implicit)**

- VUID-VkComponentMapping-r-parameter \( r \) must be a valid \texttt{VkComponentSwizzle} value
- VUID-VkComponentMapping-g-parameter \( g \) must be a valid \texttt{VkComponentSwizzle} value
- VUID-VkComponentMapping-b-parameter \( b \) must be a valid \texttt{VkComponentSwizzle} value
- VUID-VkComponentMapping-a-parameter \( a \) must be a valid \texttt{VkComponentSwizzle} value

Possible values of the members of \texttt{VkComponentMapping}, specifying the component values placed in each component of the output vector, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkComponentSwizzle {
    VK_COMPONENT_SWIZZLE_IDENTITY = 0,
    VK_COMPONENT_SWIZZLE_ZERO = 1,
    VK_COMPONENT_SWIZZLE_ONE = 2,
    VK_COMPONENT_SWIZZLE_R = 3,
    VK_COMPONENT_SWIZZLE_G = 4,
    VK_COMPONENT_SWIZZLE_B = 5,
    VK_COMPONENT_SWIZZLE_A = 6,
} VkComponentSwizzle;
```

- \texttt{VK_COMPONENT_SWIZZLE_IDENTITY} specifies that the component is set to the identity swizzle.
- \texttt{VK_COMPONENT_SWIZZLE_ZERO} specifies that the component is set to zero.
- \texttt{VK_COMPONENT_SWIZZLE_ONE} specifies that the component is set to either 1 or 1.0, depending on whether the type of the image view format is integer or floating-point respectively, as determined by the Format Definition section for each \texttt{VkFormat}.
- \texttt{VK_COMPONENT_SWIZZLE_R} specifies that the component is set to the value of the R component of the image.
• **VK_COMPONENT_SWIZZLE_G** specifies that the component is set to the value of the G component of the image.

• **VK_COMPONENT_SWIZZLE_B** specifies that the component is set to the value of the B component of the image.

• **VK_COMPONENT_SWIZZLE_A** specifies that the component is set to the value of the A component of the image.

Setting the identity swizzle on a component is equivalent to setting the identity mapping on that component. That is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Identity Mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>components.r</td>
<td>VK_COMPONENT_SWIZZLE_R</td>
</tr>
<tr>
<td>components.g</td>
<td>VK_COMPONENT_SWIZZLE_G</td>
</tr>
<tr>
<td>components.b</td>
<td>VK_COMPONENT_SWIZZLE_B</td>
</tr>
<tr>
<td>components.a</td>
<td>VK_COMPONENT_SWIZZLE_A</td>
</tr>
</tbody>
</table>

To destroy an image view, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyImageView(
    VkDevice device,
    VkImageView imageView,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the image view.
- **imageView** is the image view to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- **VUID-vkDestroyImageView-imageView-01026**
  All submitted commands that refer to **imageView** must have completed execution

- **VUID-vkDestroyImageView-imageView-01027**
  If **VkAllocationCallbacks** were provided when **imageView** was created, a compatible set of callbacks must be provided here

- **VUID-vkDestroyImageView-imageView-01028**
  If no **VkAllocationCallbacks** were provided when **imageView** was created, **pAllocator** must be **NULL**

### Valid Usage (Implicit)

- **VUID-vkDestroyImageView-device-parameter**
device must be a valid VkDevice handle

• VUID-vkDestroyImageView-imageView-parameter
  If imageView is not VK_NULL_HANDLE, imageView must be a valid VkImageView handle

• VUID-vkDestroyImageView-pAllocator-parameter
  If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure

• VUID-vkDestroyImageView-imageView-parent
  If imageView is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to imageView must be externally synchronized

12.5.1. Image View Format Features

Valid uses of a VkImageView may depend on the image view's format features, defined below. Such constraints are documented in the affected valid usage statement.

• If Vulkan 1.3 is supported or the VK_KHR_format_feature_flags2 extension is supported, and VkImageViewCreateInfo::image was created with VK_IMAGE_TILING_LINEAR, then the image view's set of format features is the value of VkFormatProperties3::linearTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties2 on the same format as VkImageViewCreateInfo::format.

• If Vulkan 1.3 is not supported and the VK_KHR_format_feature_flags2 extension is not supported, and VkImageViewCreateInfo::image was created with VK_IMAGE_TILING_LINEAR, then the image view's set of format features is the union of the value of VkFormatProperties::linearTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties on the same format as VkImageViewCreateInfo::format, with:
  ◦ VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT if the format is a depth/stencil format and the image view features also contain VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT.
  ◦ VK_FORMAT_FEATURE_2_STORAGE_READ WITHOUT_FORMAT_BIT if the format is one of the extended storage formats and shaderStorageImageReadWithoutFormat is enabled on the device.
  ◦ VK_FORMAT_FEATURE_2_STORAGE_WRITE WITHOUT_FORMAT_BIT if the format is one of the extended storage formats and shaderStorageImageWriteWithoutFormat is enabled on the device.

• If Vulkan 1.3 is supported or the VK_KHR_format_feature_flags2 extension is supported, and VkImageViewCreateInfo::image was created with VK_IMAGE_TILING_OPTIMAL, then the image view's set of format features is the value of VkFormatProperties::optimalTilingFeatures or VkFormatProperties3::optimalTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties or vkGetPhysicalDeviceImageFormatProperties2 on the same format as VkImageViewCreateInfo::format.

• If Vulkan 1.3 is not supported and the VK_KHR_format_feature_flags2 extension is not supported, and VkImageViewCreateInfo::image was created with VK_IMAGE_TILING_OPTIMAL, then the image
view’s set of format features is the union of the value of \texttt{VkFormatProperties::optimalTilingFeatures} found by calling \texttt{vkGetPhysicalDeviceFormatProperties} on the same format as \texttt{VkImageViewCreateInfo::format}, with:

- \texttt{VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT} if the format is a depth/stencil format and the image view features also contain \texttt{VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT}.
- \texttt{VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT} if the format is one of the extended storage formats and \texttt{shaderStorageImageReadWithoutFormat} is enabled on the device.
- \texttt{VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT} if the format is one of the extended storage formats and \texttt{shaderStorageImageWriteWithoutFormat} is enabled on the device.

### 12.6. Resource Memory Association

Resources are initially created as \textit{virtual allocations} with no backing memory. Device memory is allocated separately (see \textit{Device Memory}) and then associated with the resource. This association is done differently for sparse and non-sparse resources.

Resources created with any of the sparse creation flags are considered sparse resources. Resources created without these flags are non-sparse. The details on resource memory association for sparse resources is described in \textit{Sparse Resources}.

Non-sparse resources \textbf{must} be bound completely and contiguously to a single \texttt{VkDeviceMemory} object before the resource is passed as a parameter to any of the following operations:

- creating image or buffer views
- updating descriptor sets
- recording commands in a command buffer

Once bound, the memory binding is immutable for the lifetime of the resource.

In a logical device representing more than one physical device, buffer and image resources exist on all physical devices but \textbf{can} be bound to memory differently on each. Each such replicated resource is an \textit{instance} of the resource. For sparse resources, each instance \textbf{can} be bound to memory arbitrarily differently. For non-sparse resources, each instance \textbf{can} either be bound to the local or a peer instance of the memory, or for images \textbf{can} be bound to rectangular regions from the local and/or peer instances. When a resource is used in a descriptor set, each physical device interprets the descriptor according to its own instance’s binding to memory.

\begin{center}
\textbf{Note}
\end{center}

There are no new copy commands to transfer data between physical devices. Instead, an application \textbf{can} create a resource with a peer mapping and use it as the source or destination of a transfer command executed by a single physical device to copy the data from one physical device to another.

To determine the memory requirements for a buffer resource, call:

\begin{verbatim}
// Provided by VK_VERSION_1_0
\end{verbatim}
```c
void vkGetBufferMemoryRequirements(
    VkDevice device,  // device is the logical device that owns the buffer.
    VkBuffer buffer,  // buffer is the buffer to query.
    VkMemoryRequirements* pMemoryRequirements);  // pMemoryRequirements is a pointer to a VkMemoryRequirements structure in which the memory requirements of the buffer object are returned.
```

Valid Usage (Implicit)

- VUID-vkGetBufferMemoryRequirements-device-parameter
  ```
  device must be a valid VkDevice handle
  ```

- VUID-vkGetBufferMemoryRequirements-buffer-parameter
  ```
  buffer must be a valid VkBuffer handle
  ```

- VUID-vkGetBufferMemoryRequirements-pMemoryRequirements-parameter
  ```
  pMemoryRequirements must be a valid pointer to a VkMemoryRequirements structure
  ```

- VUID-vkGetBufferMemoryRequirements-buffer-parent
  ```
  buffer must have been created, allocated, or retrieved from device
  ```

To determine the memory requirements for an image resource which is not created with the VK_IMAGE_CREATE_DISJOINT_BIT flag set, call:

```c
// Provided by VK_VERSION_1_0
void vkGetImageMemoryRequirements(
    VkDevice device,  // device is the logical device that owns the image.
    VkImage image,   // image is the image to query.
    VkMemoryRequirements* pMemoryRequirements);  // pMemoryRequirements is a pointer to a VkMemoryRequirements structure in which the memory requirements of the image object are returned.
```

Valid Usage

- VUID-vkGetImageMemoryRequirements-image-01588
  ```
  image must not have been created with the VK_IMAGE_CREATE_DISJOINT_BIT flag set
  ```
Valid Usage (Implicit)

- **VUID-vkGetImageMemoryRequirements-device-parameter**
  
  `device` must be a valid `VkDevice` handle.

- **VUID-vkGetImageMemoryRequirements-image-parameter**

  `image` must be a valid `VkImage` handle.

- **VUID-vkGetImageMemoryRequirements-pMemoryRequirements-parameter**

  `pMemoryRequirements` must be a valid pointer to a `VkMemoryRequirements` structure.

- **VUID-vkGetImageMemoryRequirements-image-parent**

  `image` must have been created, allocated, or retrieved from `device`.

The `VkMemoryRequirements` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkMemoryRequirements {
    VkDeviceSize size;
    VkDeviceSize alignment;
    uint32_t memoryTypeBits;
} VkMemoryRequirements;
```

- **size** is the size, in bytes, of the memory allocation **required** for the resource.

- **alignment** is the alignment, in bytes, of the offset within the allocation **required** for the resource.

- **memoryTypeBits** is a bitmask and contains one bit set for every supported memory type for the resource. Bit \( i \) is set if and only if the memory type \( i \) in the `VkPhysicalDeviceMemoryProperties` structure for the physical device is supported for the resource.

The implementation guarantees certain properties about the memory requirements returned by `vkGetDeviceBufferMemoryRequirements`, `vkGetDeviceImageMemoryRequirements`, `vkGetBufferMemoryRequirements` and `vkGetImageMemoryRequirements`:

- The `memoryTypeBits` member always contains at least one bit set.

- If `buffer` is a `VkBuffer` not created with the `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` bit set, or if `image` is linear image, then the `memoryTypeBits` member always contains at least one bit set corresponding to a `VkMemoryType` with a `propertyFlags` that has both the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` bit and the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` bit set. In other words, mappable coherent memory can always be attached to these objects.

- If `buffer` was created with `VkExternalMemoryBufferCreateInfo::handleTypes` set to 0 or `image` was created with `VkExternalMemoryImageCreateInfo::handleTypes` set to 0, the `memoryTypeBits` member always contains at least one bit set corresponding to a `VkMemoryType` with a `propertyFlags` that has the `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` bit set.

- The `memoryTypeBits` member is identical for all `VkBuffer` objects created with the same value for the `flags` and `usage` members in the `VkBufferCreateInfo` structure and the `handleTypes` member.
of the VkExternalMemoryBufferCreateInfo structure passed to vkCreateBuffer. Further, if usage1 and usage2 of type VkBufferUsageFlags are such that the bits set in usage2 are a subset of the bits set in usage1, and they have the same flags and VkExternalMemoryBufferCreateInfo::handleTypes, then the bits set in memoryTypeBits returned for usage1 must be a subset of the bits set in memoryTypeBits returned for usage2, for all values of flags.

• The alignment member is a power of two.

• The alignment member is identical for all VkBuffer objects created with the same combination of values for the usage and flags members in the VkBufferCreateInfo structure passed to vkCreateBuffer.

• If the maintenance4 feature is enabled, then the alignment member is identical for all VkImage objects created with the same combination of values for the flags, imageType, format, extent, mipLevels, arrayLayers, samples, tiling and usage members in the VkImageCreateInfo structure passed to vkCreateImage.

• The alignment member satisfies the buffer descriptor offset alignment requirements associated with the VkBuffer’s usage:
  ◦ If usage included VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT or VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT, alignment must be an integer multiple of VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment.
  ◦ If usage included VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT, alignment must be an integer multiple of VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment.
  ◦ If usage included VK_BUFFER_USAGE_STORAGE_BUFFER_BIT, alignment must be an integer multiple of VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment.

• For images created with a color format, the memoryTypeBits member is identical for all VkImage objects created with the same combination of values for the tiling member, the VK_IMAGE_CREATE_SPARSE_BINDING_BIT bit of the flags member, the VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT bit of the flags member, handleTypes member of VkExternalMemoryImageCreateInfo, and the VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT of the usage member in the VkImageCreateInfo structure passed to vkCreateImage.

• For images created with a depth/stencil format, the memoryTypeBits member is identical for all VkImage objects created with the same combination of values for the format member, the tiling member, the VK_IMAGE_CREATE_SPARSE_BINDING_BIT bit of the flags member, the VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT bit of the flags member, handleTypes member of VkExternalMemoryImageCreateInfo, and the VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT of the usage member in the VkImageCreateInfo structure passed to vkCreateImage.

• If the memory requirements are for a VkImage, the memoryTypeBits member must not refer to a VkMemoryType with a propertyFlags that has the VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT bit set if the image did not have VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT bit set in the usage member of the VkImageCreateInfo structure passed to vkCreateImage.

• If the memory requirements are for a VkBuffer, the memoryTypeBits member must not refer to a VkMemoryType with a propertyFlags that has the VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT bit set.

Note
The implication of this requirement is that lazily allocated memory is
disallowed for buffers in all cases.

- The `size` member is identical for all `VkBuffer` objects created with the same combination of creation parameters specified in `VkBufferCreateInfo` and its `pNext` chain.

- The `size` member is identical for all `VkImage` objects created with the same combination of creation parameters specified in `VkImageCreateInfo` and its `pNext` chain.

**Note**
This, however, does not imply that they interpret the contents of the bound memory identically with each other. That additional guarantee, however, can be explicitly requested using `VK_IMAGE_CREATE_ALIAS_BIT`.

- If the `maintenance4` feature is enabled, these additional guarantees apply:
  
  - For a `VkBuffer`, the `size` memory requirement is never greater than that of another `VkBuffer` created with a greater or equal `size` specified in `VkBufferCreateInfo`, all other creation parameters being identical.
  
  - For a `VkBuffer`, the `size` memory requirement is never greater than the result of aligning `VkBufferCreateInfo::size` with the `alignment` memory requirement.
  
  - For a `VkImage`, the `size` memory requirement is never greater than that of another `VkImage` created with a greater or equal value in each of `extent.width`, `extent.height`, and `extent.depth`; all other creation parameters being identical.
  
  - The memory requirements returned by `vkGetDeviceBufferMemoryRequirements` are identical to those that would be returned by `vkGetBufferMemoryRequirements2` if it were called with a `VkBuffer` created with the same `VkBufferCreateInfo` values.
  
  - The memory requirements returned by `vkGetDeviceImageMemoryRequirements` are identical to those that would be returned by `vkGetImageMemoryRequirements2` if it were called with a `VkImage` created with the same `VkImageCreateInfo` values.

To determine the memory requirements for a buffer resource, call:

```c
// Provided by VK_VERSION_1_1
void vkGetBufferMemoryRequirements2(
    VkDevice device, 
    const VkBufferMemoryRequirementsInfo2* pInfo,  
    VkMemoryRequirements2* pMemoryRequirements);
```

- `device` is the logical device that owns the buffer.

- `pInfo` is a pointer to a `VkBufferMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.

- `pMemoryRequirements` is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the buffer object are returned.
Valid Usage (Implicit)

- VUID-vkGetBufferMemoryRequirements2-device-parameter
  `device` must be a valid `VkDevice` handle

- VUID-vkGetBufferMemoryRequirements2-pInfo-parameter
  `pInfo` must be a valid pointer to a valid `VkBufferMemoryRequirementsInfo2` structure

- VUID-vkGetBufferMemoryRequirements2-pMemoryRequirements-parameter
  `pMemoryRequirements` must be a valid pointer to a `VkMemoryRequirements2` structure

To determine the memory requirements for a buffer resource without creating an object, call:

```c
// Provided by VK_VERSION_1_3
void vkGetDeviceBufferMemoryRequirements(
    VkDevice device,
    const VkDeviceBufferMemoryRequirements* pInfo,
    VkMemoryRequirements2* pMemoryRequirements);
```

- `device` is the logical device intended to own the buffer.
- `pInfo` is a pointer to a `VkDeviceBufferMemoryRequirements` structure containing parameters required for the memory requirements query.
- `pMemoryRequirements` is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the buffer object are returned.

Valid Usage (Implicit)

- VUID-vkGetDeviceBufferMemoryRequirements-device-parameter
  `device` must be a valid `VkDevice` handle

- VUID-vkGetDeviceBufferMemoryRequirements-pInfo-parameter
  `pInfo` must be a valid pointer to a valid `VkDeviceBufferMemoryRequirements` structure

- VUID-vkGetDeviceBufferMemoryRequirements-pMemoryRequirements-parameter
  `pMemoryRequirements` must be a valid pointer to a `VkMemoryRequirements2` structure

The `VkBufferMemoryRequirementsInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkBufferMemoryRequirementsInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkBuffer buffer;
} VkBufferMemoryRequirementsInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `buffer` is the buffer to query.

#### Valid Usage (Implicit)

- VUID-VkBufferMemoryRequirementsInfo2-sType-sType
  - `sType` must be `VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2`
- VUID-VkBufferMemoryRequirementsInfo2-pNext-pNext
  - `pNext` must be `NULL`
- VUID-VkBufferMemoryRequirementsInfo2-buffer-parameter
  - `buffer` must be a valid `VkBuffer` handle

The `VkDeviceBufferMemoryRequirements` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkDeviceBufferMemoryRequirements {
    VkStructureType sType;
    const void* pNext;
    const VkBufferCreateInfo* pCreateInfo;
} VkDeviceBufferMemoryRequirements;
```

• `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `pCreateInfo` is a pointer to a `VkBufferCreateInfo` structure containing parameters affecting creation of the buffer to query.

#### Valid Usage (Implicit)

- VUID-VkDeviceBufferMemoryRequirements-sType-sType
  - `sType` must be `VK_STRUCTURE_TYPE_DEVICE_BUFFER_MEMORY_REQUIREMENTS`
- VUID-VkDeviceBufferMemoryRequirements-pNext-pNext
  - `pNext` must be `NULL`
- VUID-VkDeviceBufferMemoryRequirements-pCreateInfo-parameter
  - `pCreateInfo` must be a valid pointer to a valid `VkBufferCreateInfo` structure

To determine the memory requirements for an image resource, call:

```c
// Provided by VK_VERSION_1_1
void vkGetImageMemoryRequirements2(
    VkDevice device,
    const VkImageMemoryRequirementsInfo2* pInfo,
    VkMemoryRequirements2* pMemoryRequirements);
```
• **device** is the logical device that owns the image.

• **pInfo** is a pointer to a `VkImageMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.

• **pMemoryRequirements** is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the image object are returned.

---

**Valid Usage (Implicit)**

- VUID-vkGetImageMemoryRequirements2-device-parameter
  
  **device** must be a valid `VkDevice` handle

- VUID-vkGetImageMemoryRequirements2-pInfo-parameter
  
  **pInfo** must be a valid pointer to a valid `VkImageMemoryRequirementsInfo2` structure

- VUID-vkGetImageMemoryRequirements2-pMemoryRequirements-parameter
  
  **pMemoryRequirements** must be a valid pointer to a `VkMemoryRequirements2` structure

---

To determine the memory requirements for an image resource without creating an object, call:

```c
// Provided by VK_VERSION_1_3
void vkGetDeviceImageMemoryRequirements(
    VkDevice device,         // Provided by VK_VERSION_1_3
    const VkDeviceImageMemoryRequirements* pInfo,  // Provided by VK_VERSION_1_3
    VkMemoryRequirements2* pMemoryRequirements);   // Provided by VK_VERSION_1_3
```

• **device** is the logical device intended to own the image.

• **pInfo** is a pointer to a `VkDeviceImageMemoryRequirements` structure containing parameters required for the memory requirements query.

• **pMemoryRequirements** is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the image object are returned.

---

**Valid Usage (Implicit)**

- VUID-vkGetDeviceImageMemoryRequirements-device-parameter
  
  **device** must be a valid `VkDevice` handle

- VUID-vkGetDeviceImageMemoryRequirements-pInfo-parameter
  
  **pInfo** must be a valid pointer to a valid `VkDeviceImageMemoryRequirements` structure

- VUID-vkGetDeviceImageMemoryRequirements-pMemoryRequirements-parameter
  
  **pMemoryRequirements** must be a valid pointer to a `VkMemoryRequirements2` structure

---

The `VkImageMemoryRequirementsInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkImageMemoryRequirementsInfo2 {
```
VkDeviceImageMemoryRequirements structure is defined as:

```
// Provided by VK_VERSION_1_3
typedef struct VkDeviceImageMemoryRequirements {
    VkStructureType sType;
    const void* pNext;
    const VkImageCreateInfo* pCreateInfo;
} VkDeviceImageMemoryRequirements;
```
VkImageAspectFlagBits planeAspect;
} VkDeviceImageMemoryRequirements;

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **pCreateInfo** is a pointer to a **VkImageCreateInfo** structure containing parameters affecting creation of the image to query.
- **planeAspect** is a **VkImageAspectFlagBits** value specifying the aspect corresponding to the image plane to query. This parameter is ignored unless **pCreateInfo::flags** has **VK_IMAGE_CREATE_DISJOINT_BIT** set.

### Valid Usage

- VUID-VkDeviceImageMemoryRequirementsKHR-pCreateInfo-06416
  The **pCreateInfo::pNext** chain **must** not contain a **VkImageSwapchainCreateInfoKHR** structure

- VUID-VkDeviceImageMemoryRequirementsKHR-pCreateInfo-06417
  If **pCreateInfo::format** specifies a **multi-planar** format and **pCreateInfo::flags** has **VK_IMAGE_CREATE_DISJOINT_BIT** set then **planeAspect** **must** not be **VK_IMAGE_ASPECT_NONE_KHR**

- VUID-VkDeviceImageMemoryRequirementsKHR-pCreateInfo-06419
  If **pCreateInfo::flags** has **VK_IMAGE_CREATE_DISJOINT_BIT** set and if the **pCreateInfo::tiling** is **VK_IMAGE_TILING_LINEAR** or **VK_IMAGE_TILING_OPTIMAL**, then **planeAspect** **must** be a single valid **multi-planar aspect mask**

### Valid Usage (Implicit)

- VUID-VkDeviceImageMemoryRequirements-sType-sType
  **sType** **must** be **VK_STRUCTURE_TYPEDEVICE_IMAGE_MEMORY_REQUIREMENTS**

- VUID-VkDeviceImageMemoryRequirements-pNext-pNext
  **pNext** **must** be NULL

- VUID-VkDeviceImageMemoryRequirements-pCreateInfo-parameter
  **pCreateInfo** **must** be a valid pointer to a valid **VkImageCreateInfo** structure

- VUID-VkDeviceImageMemoryRequirements-planeAspect-parameter
  If **planeAspect** is not 0, **planeAspect must** be a valid **VkImageAspectFlagBits** value

To determine the memory requirements for a plane of a disjoint image, add a **VkImagePlaneMemoryRequirementsInfo** structure to the **pNext** chain of the **VkImageMemoryRequirementsInfo2** structure.

The **VkImagePlaneMemoryRequirementsInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkImagePlaneMemoryRequirementsInfo {
```
VkImagePlaneMemoryRequirementsInfo

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `planeAspect` is a `VkImageAspectFlagBits` value specifying the aspect corresponding to the image plane to query.

Valid Usage

- VUID-VkImagePlaneMemoryRequirementsInfo-planeAspect-02281
  If the image’s tiling is `VK_IMAGE_TILING_LINEAR` or `VK_IMAGE_TILING_OPTIMAL`, then `planeAspect` must be a single valid multi-planar aspect mask

Valid Usage (Implicit)

- VUID-VkImagePlaneMemoryRequirementsInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_IMAGE_PLANE_MEMORY_REQUIREMENTS_INFO`
- VUID-VkImagePlaneMemoryRequirementsInfo-planeAspect-parameter
  `planeAspect` must be a valid `VkImageAspectFlagBits` value

The `VkMemoryRequirements2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkMemoryRequirements2 {
    VkStructureType sType;
    const void* pNext;
    VkMemoryRequirements memoryRequirements;
} VkMemoryRequirements2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `memoryRequirements` is a `VkMemoryRequirements` structure describing the memory requirements of the resource.

Valid Usage (Implicit)

- VUID-VkMemoryRequirements2-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2`
- VUID-VkMemoryRequirements2-pNext-pNext
**pNext** must be **NULL** or a pointer to a valid instance of **VkMemoryDedicatedRequirements**

- VUID-VkMemoryRequirements2-sType-unique
  The sType value of each struct in the **pNext** chain must be unique

The **VkMemoryDedicatedRequirements** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkMemoryDedicatedRequirements {
    VkStructureType sType;
    void* pNext;
    VkBool32 prefersDedicatedAllocation;
    VkBool32 requiresDedicatedAllocation;
} VkMemoryDedicatedRequirements;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **prefersDedicatedAllocation** specifies that the implementation would prefer a dedicated allocation for this resource. The application is still free to suballocate the resource but it may get better performance if a dedicated allocation is used.
- **requiresDedicatedAllocation** specifies that a dedicated allocation is required for this resource.

To determine the dedicated allocation requirements of a buffer or image resource, add a **VkMemoryDedicatedRequirements** structure to the **pNext** chain of the **VkMemoryRequirements2** structure passed as the **pMemoryRequirements** parameter of **vkGetBufferMemoryRequirements2** or **vkGetImageMemoryRequirements2**, respectively.

Constraints on the values returned for buffer resources are:

- **requiresDedicatedAllocation** may be **VK_TRUE** if the **pNext** chain of **VkBufferCreateInfo** for the call to **vkCreateBuffer** used to create the buffer being queried included a **VkExternalMemoryBufferCreateInfo** structure, and any of the handle types specified in **VkExternalMemoryBufferCreateInfo::handleTypes** requires dedicated allocation, as reported by **vkGetPhysicalDeviceExternalBufferProperties** in **VkExternalBufferProperties::externalMemoryProperties.externalMemoryFeatures**. Otherwise, **requiresDedicatedAllocation** will be **VK_FALSE**.

- When the implementation sets **requiresDedicatedAllocation** to **VK_TRUE**, it must also set **prefersDedicatedAllocation** to **VK_TRUE**.

- If **VK_BUFFER_CREATE_SPARSE_BINDING_BIT** was set in **VkBufferCreateInfo::flags** when buffer was created, then both **prefersDedicatedAllocation** and **requiresDedicatedAllocation** will be **VK_FALSE**.

Constraints on the values returned for image resources are:

- **requiresDedicatedAllocation** may be **VK_TRUE** if the **pNext** chain of **VkImageCreateInfo** for the call to **vkCreateImage** used to create the image being queried included a **VkExternalMemoryImageCreateInfo** structure, and any of the handle types specified in **VkExternalMemoryImageCreateInfo::handleTypes** requires dedicated allocation, as reported by
vkGetPhysicalDeviceImageFormatProperties2

• requiresDedicatedAllocation will otherwise be VK_FALSE

• If VK_IMAGE_CREATE_SPARSE_BINDING_BIT was set in VkImageCreateInfo::flags when image was created, then both prefersDedicatedAllocation and requiresDedicatedAllocation will be VK_FALSE.

Valid Usage (Implicit)

• VUID-VkMemoryDedicatedRequirements-sType-sType
  sType must be VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS

To attach memory to a buffer object, call:

// Provided by VK_VERSION_1_0
void vkBindBufferMemory(
    VkDevice device,
    VkBuffer buffer,
    VkDeviceMemory memory,
    VkDeviceSize memoryOffset);

• device is the logical device that owns the buffer and memory.

• buffer is the buffer to be attached to memory.

• memory is a VkDeviceMemory object describing the device memory to attach.

• memoryOffset is the start offset of the region of memory which is to be bound to the buffer. The number of bytes returned in the VkMemoryRequirements::size member in memory, starting from memoryOffset bytes, will be bound to the specified buffer.

vkBindBufferMemory is equivalent to passing the same parameters through VkBindBufferMemoryInfo to vkBindBufferMemory2.

Valid Usage

• VUID-vkBindBufferMemory-buffer-07459
  buffer must not have been bound to a memory object

• VUID-vkBindBufferMemory-buffer-01030
  buffer must not have been created with any sparse memory binding flags

• VUID-vkBindBufferMemory-memoryOffset-01031
  memoryOffset must be less than the size of memory

• VUID-vkBindBufferMemory-memory-01035
  memory must have been allocated using one of the memory types allowed in the memoryTypeBits member of the VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer

• VUID-vkBindBufferMemory-memoryOffset-01036
memoryOffset must be an integer multiple of the alignment member of the VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer.

- VUID-vkBindBufferMemory-size-01037
  The size member of the VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer must be less than or equal to the size of memory minus memoryOffset.

- VUID-vkBindBufferMemory-buffer-01444
  If buffer requires a dedicated allocation (as reported by vkGetBufferMemoryRequirements2 in VkMemoryDedicatedRequirements::requiresDedicatedAllocation for buffer), memory must have been allocated with VkMemoryDedicatedAllocateInfo::buffer equal to buffer.

- VUID-vkBindBufferMemory-memory-01508
  If the VkMemoryAllocateInfo provided when memory was allocated included a VkMemoryDedicatedAllocateInfo structure in its pNext chain, and VkMemoryDedicatedAllocateInfo::buffer was not VK_NULL_HANDLE, then buffer must equal VkMemoryDedicatedAllocateInfo::buffer, and memoryOffset must be zero.

- VUID-vkBindBufferMemory-None-01898
  If buffer was created with the VK_BUFFER_CREATE_PROTECTED_BIT bit set, the buffer must be bound to a memory object allocated with a memory type that reports VK_MEMORY_PROPERTY_PROTECTED_BIT.

- VUID-vkBindBufferMemory-None-01899
  If buffer was created with the VK_BUFFER_CREATE_PROTECTED_BIT bit not set, the buffer must not be bound to a memory object allocated with a memory type that reports VK_MEMORY_PROPERTY_PROTECTED_BIT.

- VUID-vkBindBufferMemory-memory-02726
  If the value of VkExportMemoryAllocateInfo::handleTypes used to allocate memory is not 0, it must include at least one of the handles set in VkExternalMemoryBufferCreateInfo::handleTypes when buffer was created.

- VUID-vkBindBufferMemory-memory-02727
  If memory was allocated by a memory import operation, the external handle type of the imported memory must also have been set in VkExternalMemoryBufferCreateInfo::handleTypes when buffer was created.

- VUID-vkBindBufferMemory-bufferDeviceAddress-03339
  If the VkPhysicalDeviceBufferDeviceAddressFeatures::bufferDeviceAddress feature is enabled and buffer was created with the VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT bit set, memory must have been allocated with the VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT bit set.

### Valid Usage (Implicit)

- VUID-vkBindBufferMemory-device-parameter
  device must be a valid VkDevice handle.
• VUID-vkBindBufferMemory-buffer-parameter
  buffer must be a valid VkBuffer handle

• VUID-vkBindBufferMemory-memory-parameter
  memory must be a valid VkDeviceMemory handle

• VUID-vkBindBufferMemory-buffer-parent
  buffer must have been created, allocated, or retrieved from device

• VUID-vkBindBufferMemory-memory-parent
  memory must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to buffer must be externally synchronized

Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY

To attach memory to buffer objects for one or more buffers at a time, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkBindBufferMemory2(
  VkDevice device,               
  uint32_t bindInfoCount,       
  const VkBindBufferMemoryInfo* pBindInfos);  
```

• device is the logical device that owns the buffers and memory.

• bindInfoCount is the number of elements in pBindInfos.

• pBindInfos is a pointer to an array of bindInfoCount VkBindBufferMemoryInfo structures describing buffers and memory to bind.

On some implementations, it may be more efficient to batch memory bindings into a single command.

Note

If vkBindBufferMemory2 fails, and bindInfoCount was greater than one, then the buffers referenced by pBindInfos will be in an indeterminate state, and must not be used. Applications should destroy these buffers.
Valid Usage (Implicit)

- VUID-vkBindBufferMemory2-device-parameter
  device must be a valid VkDevice handle

- VUID-vkBindBufferMemory2-pBindInfos-parameter
  pBindInfos must be a valid pointer to an array of bindInfoCount valid VkBindBufferMemoryInfo structures

- VUID-vkBindBufferMemory2-bindInfoCount-arraylength
  bindInfoCount must be greater than 0

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

VkBindBufferMemoryInfo contains members corresponding to the parameters of vkBindBufferMemory.

The VkBindBufferMemoryInfo structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkBindBufferMemoryInfo {
    VkStructureType sType;
    const void*pNext;
    VkBuffer buffer;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
} VkBindBufferMemoryInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- buffer is the buffer to be attached to memory.
- memory is a VkDeviceMemory object describing the device memory to attach.
- memoryOffset is the start offset of the region of memory which is to be bound to the buffer. The number of bytes returned in the VkMemoryRequirements::size member in memory, starting from memoryOffset bytes, will be bound to the specified buffer.
Valid Usage

- VUID-VkBindBufferMemoryInfo-buffer-07459
  buffer must not have been bound to a memory object

- VUID-VkBindBufferMemoryInfo-buffer-01030
  buffer must not have been created with any sparse memory binding flags

- VUID-VkBindBufferMemoryInfo-memoryOffset-01031
  memoryOffset must be less than the size of memory

- VUID-VkBindBufferMemoryInfo-memory-01035
  memory must have been allocated using one of the memory types allowed in the
  memoryTypeBits member of the VkMemoryRequirements structure returned from a call to
  vkGetBufferMemoryRequirements with buffer

- VUID-VkBindBufferMemoryInfo-memoryOffset-01036
  memoryOffset must be an integer multiple of the alignment member of the
  VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer

- VUID-VkBindBufferMemoryInfo-size-01037
  The size member of the VkMemoryRequirements structure returned from a call to
  vkGetBufferMemoryRequirements with buffer must be less than or equal to the size of memory
  minus memoryOffset

- VUID-VkBindBufferMemoryInfo-buffer-01444
  If buffer requires a dedicated allocation (as reported by
  vkGetBufferMemoryRequirements2 in VkMemoryDedicatedRequirements
  ::requiresDedicatedAllocation for buffer), memory must have been allocated with
  VkMemoryDedicatedAllocateInfo::buffer equal to buffer

- VUID-VkBindBufferMemoryInfo-memory-01508
  If the VkMemoryAllocateInfo provided when memory was allocated included a
  VkMemoryDedicatedAllocateInfo structure in its pNext chain, and
  VkMemoryDedicatedAllocateInfo::buffer was not VK_NULL_HANDLE, then buffer must
  equal VkMemoryDedicatedAllocateInfo::buffer, and memoryOffset must be zero

- VUID-VkBindBufferMemoryInfo-None-01898
  If buffer was created with the VK_BUFFER_CREATE_PROTECTED_BIT bit set, the buffer must be
  bound to a memory object allocated with a memory type that reports
  VK_MEMORY_PROPERTY_PROTECTED_BIT

- VUID-VkBindBufferMemoryInfo-None-01899
  If buffer was created with the VK_BUFFER_CREATE_PROTECTED_BIT bit not set, the buffer must
  not be bound to a memory object allocated with a memory type that reports
  VK_MEMORY_PROPERTY_PROTECTED_BIT

- VUID-VkBindBufferMemoryInfo-memory-02726
  If the value of VkExportMemoryAllocateInfo::handleTypes used to allocate memory is not 0, it
  must include at least one of the handles set in VkExternalMemoryBufferCreateInfo
  ::handleTypes when buffer was created

- VUID-VkBindBufferMemoryInfo-memory-02727
If memory was allocated by a memory import operation, the external handle type of the imported memory must also have been set in VkExternalMemoryBufferCreateInfo::handleTypes when buffer was created.

- VUID-VkBindBufferMemoryInfo-bufferDeviceAddress-03339
  If the VkPhysicalDeviceBufferDeviceAddressFeatures::bufferDeviceAddress feature is enabled and buffer was created with the VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT bit set, memory must have been allocated with the VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT bit set.

- VUID-VkBindBufferMemoryInfo-pNext-01605
  If the pNext chain includes a VkBindBufferMemoryDeviceGroupInfo structure, all instances of memory specified by VkBindBufferMemoryDeviceGroupInfo::pDeviceIndices must have been allocated.

### Valid Usage (Implicit)

- VUID-VkBindBufferMemoryInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO

- VUID-VkBindBufferMemoryInfo-pNext-pNext
  pNext must be NULL or a pointer to a valid instance of VkBindBufferMemoryDeviceGroupInfo

- VUID-VkBindBufferMemoryInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

- VUID-VkBindBufferMemoryInfo-buffer-parameter
  buffer must be a valid VkBuffer handle

- VUID-VkBindBufferMemoryInfo-memory-parameter
  memory must be a valid VkDeviceMemory handle

- VUID-VkBindBufferMemoryInfo-commonparent
  Both of buffer, and memory must have been created, allocated, or retrieved from the same VkDevice

The VkBindBufferMemoryDeviceGroupInfo structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkBindBufferMemoryDeviceGroupInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t deviceIndexCount;
    const uint32_t* pDeviceIndices;
} VkBindBufferMemoryDeviceGroupInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
• deviceIndexCount is the number of elements in pDeviceIndices.
• pDeviceIndices is a pointer to an array of device indices.

If the pNext chain of VkBindBufferMemoryInfo includes a VkBindBufferMemoryDeviceGroupInfo structure, then that structure determines how memory is bound to buffers across multiple devices in a device group.

If deviceIndexCount is greater than zero, then on device index i the buffer is attached to the instance of memory on the physical device with device index pDeviceIndices[i].

If deviceIndexCount is zero and memory comes from a memory heap with the VK_MEMORY_HEAP_MULTI_INSTANCE_BIT bit set, then it is as if pDeviceIndices contains consecutive indices from zero to the number of physical devices in the logical device, minus one. In other words, by default each physical device attaches to its own instance of memory.

If deviceIndexCount is zero and memory comes from a memory heap without the VK_MEMORY_HEAP_MULTI_INSTANCE_BIT bit set, then it is as if pDeviceIndices contains an array of zeros. In other words, by default each physical device attaches to instance zero.

Valid Usage

• VUID-VkBindBufferMemoryDeviceGroupInfo-deviceIndexCount-01606 deviceIndexCount must either be zero or equal to the number of physical devices in the logical device
• VUID-VkBindBufferMemoryDeviceGroupInfo-pDeviceIndices-01607 All elements of pDeviceIndices must be valid device indices

Valid Usage (Implicit)

• VUID-VkBindBufferMemoryDeviceGroupInfo-sType-sType sType must be VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO
• VUID-VkBindBufferMemoryDeviceGroupInfo-pDeviceIndices-parameter If deviceIndexCount is not 0, pDeviceIndices must be a valid pointer to an array of deviceIndexCount uint32_t values

To attach memory to a VkImage object created without the VK_IMAGE_CREATE_DISJOINT_BIT set, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkBindImageMemory(
    VkDevice device,
    VkImage image,
    VkDeviceMemory memory,
    VkDeviceSize memoryOffset);
```

• device is the logical device that owns the image and memory.
• **image** is the image.

• **memory** is the VkDeviceMemory object describing the device memory to attach.

• **memoryOffset** is the start offset of the region of memory which is to be bound to the image. The number of bytes returned in the VkMemoryRequirements:size member in memory, starting from memoryOffset bytes, will be bound to the specified image.

`vkBindImageMemory` is equivalent to passing the same parameters through `VkBindImageMemoryInfo` to `vkBindImageMemory2`.

### Valid Usage

- **VUID-vkBindImageMemory-image-07460**
  - **image** must not have been bound to a memory object

- **VUID-vkBindImageMemory-image-01045**
  - **image** must not have been created with any sparse memory binding flags

- **VUID-vkBindImageMemory-memoryOffset-01046**
  - **memoryOffset** must be less than the size of **memory**

- **VUID-vkBindImageMemory-image-01445**
  - If **image** requires a dedicated allocation (as reported by `vkGetImageMemoryRequirements2` in `VkMemoryDedicatedRequirements::requiresDedicatedAllocation` for **image**), **memory** must have been created with `VkMemoryDedicatedAllocateInfo::image` equal to **image**

- **VUID-vkBindImageMemory-memory-01509**
  - If the `VkMemoryAllocateInfo` provided when **memory** was allocated included a `VkMemoryDedicatedAllocateInfo` structure in its pNext chain, and `VkMemoryDedicatedAllocateInfo::image` was not `VK_NULL_HANDLE`, then **image** must equal `VkMemoryDedicatedAllocateInfo::image` and **memoryOffset** must be zero

- **VUID-vkBindImageMemory-None-01901**
  - If **image** was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit set, the image must be bound to a memory object allocated with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`

- **VUID-vkBindImageMemory-None-01902**
  - If **image** was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit not set, the image must not be bound to a memory object created with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`

- **VUID-vkBindImageMemory-memory-02728**
  - If the value of `VkExportMemoryAllocateInfo::handleTypes` used to allocate **memory** is not 0, it must include at least one of the handles set in `VkExternalMemoryImageCreateInfo::handleTypes` when **image** was created

- **VUID-vkBindImageMemory-memory-02729**
  - If **memory** was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryImageCreateInfo::handleTypes` when **image** was created
• VUID-vkBindImageMemory-image-01608
  image must not have been created with the VK_IMAGE_CREATE_DISJOINT_BIT set

• VUID-vkBindImageMemory-memory-01047
  memory must have been allocated using one of the memory types allowed in the
  memoryTypeBits member of the VkMemoryRequirements structure returned from a call to
  vkGetImageMemoryRequirements with image

• VUID-vkBindImageMemory-memoryOffset-01048
  memoryOffset must be an integer multiple of the alignment member of the
  VkMemoryRequirements structure returned from a call to vkGetImageMemoryRequirements
  with image

• VUID-vkBindImageMemory-size-01049
  The difference of the size of memory and memoryOffset must be greater than or equal to the
  size member of the VkMemoryRequirements structure returned from a call to
  vkGetImageMemoryRequirements with the same image

Valid Usage (Implicit)

• VUID-vkBindImageMemory-device-parameter
  device must be a valid VkDevice handle

• VUID-vkBindImageMemory-image-parameter
  image must be a valid VkImage handle

• VUID-vkBindImageMemory-memory-parameter
  memory must be a valid VkDeviceMemory handle

• VUID-vkBindImageMemory-image-parent
  image must have been created, allocated, or retrieved from device

• VUID-vkBindImageMemory-memory-parent
  memory must have been created, allocated, or retrieved from device

Host Synchronization

• Host access to image must be externally synchronized

Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY
To attach memory to image objects for one or more images at a time, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkBindImageMemory2(
    VkDevice device,
    uint32_t bindInfoCount,
    const VkBindImageMemoryInfo* pBindInfos);
```

- `device` is the logical device that owns the images and memory.
- `bindInfoCount` is the number of elements in `pBindInfos`.
- `pBindInfos` is a pointer to an array of `VkBindImageMemoryInfo` structures, describing images and memory to bind.

On some implementations, it may be more efficient to batch memory bindings into a single command.

**Note**

If `vkBindImageMemory2` fails, and `bindInfoCount` was greater than one, then the images referenced by `pBindInfos` will be in an indeterminate state, and must not be used. Applications should destroy these images.

**Valid Usage**

- VUID-vkBindImageMemory2-pBindInfos-02858
  If any `VkBindImageMemoryInfo::image` was created with `VK_IMAGE_CREATE_DISJOINT_BIT` then all planes of `VkBindImageMemoryInfo::image` must be bound individually in separate `pBindInfos`

- VUID-vkBindImageMemory2-pBindInfos-04006
  `pBindInfos must not refer to the same image subresource more than once`

**Valid Usage (Implicit)**

- VUID-vkBindImageMemory2-device-parameter
  `device must be a valid VkDevice handle`

- VUID-vkBindImageMemory2-pBindInfos-parameter
  `pBindInfos must be a valid pointer to an array of bindInfoCount valid VkBindImageMemoryInfo structures`

- VUID-vkBindImageMemory2-bindInfoCount-arraylength
  `bindInfoCount must be greater than 0`
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

VkBindImageMemoryInfo contains members corresponding to the parameters of vkBindImageMemory.

The VkBindImageMemoryInfo structure is defined as:

```
// Provided by VK_VERSION_1_1
typedef struct VkBindImageMemoryInfo {
    VkStructureType sType;
    const void* pNext;
    VkImage image;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
} VkBindImageMemoryInfo;
```

• `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `image` is the image to be attached to memory.
• `memory` is a `VkDeviceMemory` object describing the device memory to attach.
• `memoryOffset` is the start offset of the region of `memory` which is to be bound to the image. The number of bytes returned in the `VkMemoryRequirements::size` member in `memory`, starting from `memoryOffset` bytes, will be bound to the specified image.

Valid Usage

• VUID-VkBindImageMemoryInfo-image-07460
  `image` must not have been bound to a memory object

• VUID-VkBindImageMemoryInfo-image-01045
  `image` must not have been created with any sparse memory binding flags

• VUID-VkBindImageMemoryInfo-memoryOffset-01046
  `memoryOffset` must be less than the size of `memory`

• VUID-VkBindImageMemoryInfo-image-01445
  If `image` requires a dedicated allocation (as reported by `vkGetImageMemoryRequirements2` in `VkMemoryDedicatedRequirements::requiresDedicatedAllocation` for `image`), `memory` must have been created with
If the `VkMemoryAllocateInfo` provided when `memory` was allocated included a `VkMemoryDedicatedAllocateInfo` structure in its `pNext` chain, and `VkMemoryDedicatedAllocateInfo::image` was not `VK_NULL_HANDLE`, then `image` must equal `VkMemoryDedicatedAllocateInfo::image` and `memoryOffset` must be zero.

If `image` was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit set, the image must be bound to a memory object allocated with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`.

If `image` was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit not set, the image must not be bound to a memory object created with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`.

If the value of `VkExportMemoryAllocateInfo::handleTypes` used to allocate `memory` is not 0, it must include at least one of the handles set in `VkExternalMemoryImageCreateInfo::handleTypes` when `image` was created.

If `memory` was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryImageCreateInfo::handleTypes` when `image` was created.

If the `pNext` chain does not include a `VkBindImagePlaneMemoryInfo` structure, `memory` must have been allocated using one of the memory types allowed in the `memoryTypeBits` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with `image`.

If the `pNext` chain does not include a `VkBindImagePlaneMemoryInfo` structure, `memoryOffset` must be an integer multiple of the `alignment` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with `image`.

If the `pNext` chain does not include a `VkBindImagePlaneMemoryInfo` structure, the difference of the size of `memory` and `memoryOffset` must be greater than or equal to the `size` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with the same `image`.

If the `pNext` chain includes a `VkBindImagePlaneMemoryInfo` structure, `image` must have been created with the `VK_IMAGE_CREATE_DISJOINT_BIT` bit set.

If `image` was created with the `VK_IMAGE_CREATE_DISJOINT_BIT` bit set, then the `pNext` chain must include a `VkBindImagePlaneMemoryInfo` structure.
If the `pNext` chain includes a `VkBindImagePlaneMemoryInfo` structure, memory must have been allocated using one of the memory types allowed in the `memoryTypeBits` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with `image` and where `VkBindImagePlaneMemoryInfo::planeAspect` corresponds to the `VkImagePlaneMemoryRequirementsInfo::planeAspect` in the `VkImageMemoryRequirementsInfo2` structure’s `pNext` chain.

If the `pNext` chain includes a `VkBindImagePlaneMemoryInfo` structure, `memoryOffset` must be an integer multiple of the `alignment` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with `image` and where `VkBindImagePlaneMemoryInfo::planeAspect` corresponds to the `VkImagePlaneMemoryRequirementsInfo::planeAspect` in the `VkImageMemoryRequirementsInfo2` structure’s `pNext` chain.

If the `pNext` chain includes a `VkBindImagePlaneMemoryInfo` structure, the difference of the size of `memory` and `memoryOffset` must be greater than or equal to the `size` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements2` with the same `image` and where `VkBindImagePlaneMemoryInfo::planeAspect` corresponds to the `VkImagePlaneMemoryRequirementsInfo::planeAspect` in the `VkImageMemoryRequirementsInfo2` structure’s `pNext` chain.

`memory` must be a valid `VkDeviceMemory` handle.

If the `pNext` chain includes a `VkBindImageMemoryDeviceGroupInfo` structure, all instances of `memory` specified by `VkBindImageMemoryDeviceGroupInfo::pDeviceIndices` must have been allocated.

If the `pNext` chain includes a `VkBindImageMemoryDeviceGroupInfo` structure, and `VkBindImageMemoryDeviceGroupInfo::splitInstanceBindRegionCount` is not zero, then `image` must have been created with the `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT` bit set.

If the `pNext` chain includes a `VkBindImageMemoryDeviceGroupInfo` structure, all elements of `VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions` must be valid rectangles contained within the dimensions of `image`.

If the `pNext` chain includes a `VkBindImageMemoryDeviceGroupInfo` structure, the union of the areas of all elements of `VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions` that correspond to the same instance of `image` must cover the entire image.
Valid Usage (Implicit)

- **VUID-VkBindImageMemoryInfo-sType-sType**
  
  sType must be **VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO**

- **VUID-VkBindImageMemoryInfo-pNext-pNext**
  
  Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of **VkBindImageMemoryDeviceGroupInfo** or **VkBindImagePlaneMemoryInfo**

- **VUID-VkBindImageMemoryInfo-sType-unique**
  
  The sType value of each struct in the pNext chain must be unique

- **VUID-VkBindImageMemoryInfo-image-parameter**
  
  image must be a valid VkImage handle

- **VUID-VkBindImageMemoryInfo-commonparent**
  
  Both of image, and memory that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

The **VkBindImageMemoryDeviceGroupInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkBindImageMemoryDeviceGroupInfo {
    VkStructureType   sType;
    const void*       pNext;
    uint32_t           deviceIndexCount;
    const uint32_t*    pDeviceIndices;
    uint32_t           splitInstanceBindRegionCount;
    const VkRect2D*    pSplitInstanceBindRegions;
} VkBindImageMemoryDeviceGroupInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **deviceIndexCount** is the number of elements in **pDeviceIndices**.
- **pDeviceIndices** is a pointer to an array of device indices.
- **splitInstanceBindRegionCount** is the number of elements in **pSplitInstanceBindRegions**.
- **pSplitInstanceBindRegions** is a pointer to an array of VkRect2D structures describing which regions of the image are attached to each instance of memory.

If the pNext chain of **VkBindImageMemoryInfo** includes a **VkBindImageMemoryDeviceGroupInfo** structure, then that structure determines how memory is bound to images across multiple devices in a device group.

If **deviceIndexCount** is greater than zero, then on device index i **image** is attached to the instance of the memory on the physical device with device index **pDeviceIndices[i]**.
Let N be the number of physical devices in the logical device. If \( \text{splitInstanceBindRegionCount} \) is greater than zero, then \( \text{pSplitInstanceBindRegions} \) is a pointer to an array of \( N^2 \) rectangles, where the image region specified by the rectangle at element \( i*N+j \) in resource instance \( i \) is bound to the memory instance \( j \). The blocks of the memory that are bound to each sparse image block region use an offset in memory, relative to \( \text{memoryOffset} \), computed as if the whole image was being bound to a contiguous range of memory. In other words, horizontally adjacent image blocks use consecutive blocks of memory, vertically adjacent image blocks are separated by the number of bytes per block multiplied by the width in blocks of \( \text{image} \), and the block at \((0,0)\) corresponds to memory starting at \( \text{memoryOffset} \).

If \( \text{splitInstanceBindRegionCount} \) and \( \text{deviceIndexCount} \) are zero and the memory comes from a memory heap with the \( \text{VK_MEMORY_HEAP_MULTI_INSTANCE_BIT} \) bit set, then it is as if \( \text{pDeviceIndices} \) contains consecutive indices from zero to the number of physical devices in the logical device, minus one. In other words, by default each physical device attaches to its own instance of the memory.

If \( \text{splitInstanceBindRegionCount} \) and \( \text{deviceIndexCount} \) are zero and the memory comes from a memory heap without the \( \text{VK_MEMORY_HEAP_MULTI_INSTANCE_BIT} \) bit set, then it is as if \( \text{pDeviceIndices} \) contains an array of zeros. In other words, by default each physical device attaches to instance zero.

### Valid Usage

- **VUID-VkBindImageMemoryDeviceGroupInfo-deviceIndexCount-01633**  
  At least one of \( \text{deviceIndexCount} \) and \( \text{splitInstanceBindRegionCount} \) must be zero

- **VUID-VkBindImageMemoryDeviceGroupInfo-deviceIndexCount-01634**  
  \( \text{deviceIndexCount} \) must either be zero or equal to the number of physical devices in the logical device

- **VUID-VkBindImageMemoryDeviceGroupInfo-pDeviceIndices-01635**  
  All elements of \( \text{pDeviceIndices} \) must be valid device indices

- **VUID-VkBindImageMemoryDeviceGroupInfo-splitInstanceBindRegionCount-01636**  
  \( \text{splitInstanceBindRegionCount} \) must either be zero or equal to the number of physical devices in the logical device squared

- **VUID-VkBindImageMemoryDeviceGroupInfo-pSplitInstanceBindRegions-01637**  
  Elements of \( \text{pSplitInstanceBindRegions} \) that correspond to the same instance of an image must not overlap

- **VUID-VkBindImageMemoryDeviceGroupInfo-offset-01638**  
  The \( \text{offset.x} \) member of any element of \( \text{pSplitInstanceBindRegions} \) must be a multiple of the sparse image block width (\( \text{VkSparseImageFormatProperties::imageGranularity.width} \)) of all non-metadata aspects of the image

- **VUID-VkBindImageMemoryDeviceGroupInfo-offset-01639**  
  The \( \text{offset.y} \) member of any element of \( \text{pSplitInstanceBindRegions} \) must be a multiple of the sparse image block height (\( \text{VkSparseImageFormatProperties::imageGranularity.height} \)) of all non-metadata aspects of the image

- **VUID-VkBindImageMemoryDeviceGroupInfo-extent-01640**  
  The \( \text{extent.width} \) member of any element of \( \text{pSplitInstanceBindRegions} \) must either be a
multiple of the sparse image block width of all non-metadata aspects of the image, or else 
\[ \text{extent.width + offset.x} \] must equal the width of the image subresource

- **VUID-VkBindImageMemoryDeviceGroupInfo-extent-01641**
The \[ \text{extent.height} \] member of any element of \[ p\text{SplitInstanceBindRegions} \] must either be a multiple of the sparse image block height of all non-metadata aspects of the image, or else \[ \text{extent.height + offset.y} \] must equal the height of the image subresource

### Valid Usage (Implicit)

- **VUID-VkBindImageMemoryDeviceGroupInfo-sType-sType**
  \[ s\text{Type} \] must be \[ VK\_STRUCTURE\_TYPE\_BIND\_IMAGE\_MEMORY\_DEVICE\_GROUP\_INFO \]

- **VUID-VkBindImageMemoryDeviceGroupInfo-pDeviceIndices-parameter**
  If \[ deviceIndexCount \] is not \[ 0 \], \[ p\text{DeviceIndices} \] must be a valid pointer to an array of \[ deviceIndexCount\_uint32\_t \] values

- **VUID-VkBindImageMemoryDeviceGroupInfo-pSplitInstanceBindRegions-parameter**
  If \[ splitInstanceBindRegionCount \] is not \[ 0 \], \[ p\text{SplitInstanceBindRegions} \] must be a valid pointer to an array of \[ splitInstanceBindRegionCount\_VkRect2D \] structures

In order to bind \[ \text{planes} \] of a disjoint image, add a \[ Vk\text{BindImagePlaneMemoryInfo} \] structure to the \[ p\text{Next} \] chain of \[ Vk\text{BindImageMemoryInfo} \].

The \[ Vk\text{BindImagePlaneMemoryInfo} \] structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkBindImagePlaneMemoryInfo {
    VkStructureType       sType;
    const void*           pNext;
    VkImageAspectFlagBits planeAspect;
} VkBindImagePlaneMemoryInfo;
```

- **sType** is a \[ Vk\text{StructureType} \] value identifying this structure.
- **pNext** is \[ NULL \] or a pointer to a structure extending this structure.
- **planeAspect** is a \[ Vk\text{ImageAspectFlagBits} \] value specifying the aspect of the disjoint image plane to bind.

### Valid Usage

- **VUID-VkBindImagePlaneMemoryInfo-planeAspect-02283**
  If the image’s \[ tiling \] is \[ VK\_IMAGE\_TILING\_LINEAR \] or \[ VK\_IMAGE\_TILING\_OPTIMAL \], then \[ planeAspect \] must be a single valid \[ multi-planar aspect mask \]
Valid Usage (Implicit)

- VUID-VkBindImagePlaneMemoryInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO
- VUID-VkBindImagePlaneMemoryInfo-planeAspect-parameter
  planeAspect must be a valid VkImageAspectFlagBits value

Buffer-Image Granularity

The implementation-dependent limit bufferImageGranularity specifies a page-like granularity at which linear and non-linear resources must be placed in adjacent memory locations to avoid aliasing. Two resources which do not satisfy this granularity requirement are said to alias. bufferImageGranularity is specified in bytes, and must be a power of two. Implementations which do not impose a granularity restriction may report a bufferImageGranularity value of one.

Note

Despite its name, bufferImageGranularity is really a granularity between “linear” and “non-linear” resources.

Given resourceA at the lower memory offset and resourceB at the higher memory offset in the same VkDeviceMemory object, where one resource is linear and the other is non-linear (as defined in the Glossary), and the following:

| resourceA.end       | = resourceA.memoryOffset + resourceA.size - 1 |
| resourceA.endPage   | = resourceA.end & ~(bufferImageGranularity-1) |
| resourceB.start     | = resourceB.memoryOffset |
| resourceB.startPage | = resourceB.start & ~(bufferImageGranularity-1) |

The following property must hold:

| resourceA.endPage   | < resourceB.startPage |

That is, the end of the first resource (A) and the beginning of the second resource (B) must be on separate “pages” of size bufferImageGranularity. bufferImageGranularity may be different than the physical page size of the memory heap. This restriction is only needed when a linear resource and a non-linear resource are adjacent in memory and will be used simultaneously. The memory ranges of adjacent resources can be closer than bufferImageGranularity, provided they meet the alignment requirement for the objects in question.

Sparse block size in bytes and sparse image and buffer memory alignments must all be multiples of the bufferImageGranularity. Therefore, memory bound to sparse resources naturally satisfies the bufferImageGranularity.
12.7. Resource Sharing Mode

Buffer and image objects are created with a sharing mode controlling how they can be accessed from queues. The supported sharing modes are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSharingMode {
    VK_SHARING_MODE_EXCLUSIVE = 0,
    VK_SHARING_MODE_CONCURRENT = 1,
} VkSharingMode;
```

- **VK_SHARING_MODE_EXCLUSIVE** specifies that access to any range or image subresource of the object will be exclusive to a single queue family at a time.
- **VK_SHARING_MODE_CONCURRENT** specifies that concurrent access to any range or image subresource of the object from multiple queue families is supported.

**Note**

**VK_SHARING_MODE_CONCURRENT** may result in lower performance access to the buffer or image than **VK_SHARING_MODE_EXCLUSIVE**.

Ranges of buffers and image subresources of image objects created using **VK_SHARING_MODE_EXCLUSIVE** must only be accessed by queues in the queue family that has ownership of the resource. Upon creation, such resources are not owned by any queue family; ownership is implicitly acquired upon first use within a queue. Once a resource using **VK_SHARING_MODE_EXCLUSIVE** is owned by some queue family, the application must perform a queue family ownership transfer to make the memory contents of a range or image subresource accessible to a different queue family.

**Note**

Images still require a layout transition from **VK_IMAGE_LAYOUT_UNDEFINED** or **VK_IMAGE_LAYOUT_PREINITIALIZED** before being used on the first queue.

A queue family can take ownership of an image subresource or buffer range of a resource created with **VK_SHARING_MODE_EXCLUSIVE**, without an ownership transfer, in the same way as for a resource that was just created; however, taking ownership in this way has the effect that the contents of the image subresource or buffer range are undefined.

Ranges of buffers and image subresources of image objects created using **VK_SHARING_MODE_CONCURRENT** must only be accessed by queues from the queue families specified through the `queueFamilyIndexCount` and `pQueueFamilyIndices` members of the corresponding create info structures.

### 12.7.1. External Resource Sharing

Resources should only be accessed in the Vulkan instance that has exclusive ownership of their underlying memory. Only one Vulkan instance has exclusive ownership of a resource’s underlying memory at a given time, regardless of whether the resource was created using
VK_SHARING_MODE_EXCLUSIVE or VK_SHARING_MODE_CONCURRENT. Applications can transfer ownership of a resource's underlying memory only if the memory has been imported from or exported to another instance or external API using external memory handles. The semantics for transferring ownership outside of the instance are similar to those used for transferring ownership of VK_SHARING_MODE_EXCLUSIVE resources between queues, and is also accomplished using VkBufferMemoryBarrier or VkImageMemoryBarrier operations. To make the contents of the underlying memory accessible in the destination instance or API, applications must

1. Release exclusive ownership from the source instance or API.
2. Ensure the release operation has completed using semaphores or fences.
3. Acquire exclusive ownership in the destination instance or API

Unlike queue ownership transfers, the destination instance or API is not specified explicitly when releasing ownership, nor is the source instance or API specified when acquiring ownership. Instead, the image or memory barrier's dstQueueFamilyIndex or srcQueueFamilyIndex parameters are set to the reserved queue family index VK_QUEUE_FAMILY_EXTERNAL to represent the external destination or source respectively.

Binding a resource to a memory object shared between multiple Vulkan instances or other APIs does not change the ownership of the underlying memory. The first entity to access the resource implicitly acquires ownership. An entity can also implicitly take ownership from another entity in the same way without an explicit ownership transfer. However, taking ownership in this way has the effect that the contents of the underlying memory are undefined.

Accessing a resource backed by memory that is owned by a particular instance or API has the same semantics as accessing a VK_SHARING_MODE_EXCLUSIVE resource, with one exception: Implementations must ensure layout transitions performed on one member of a set of identical subresources of identical images that alias the same range of an underlying memory object affect the layout of all the subresources in the set.

As a corollary, writes to any image subresources in such a set must not make the contents of memory used by other subresources in the set undefined. An application can define the content of a subresource of one image by performing device writes to an identical subresource of another image provided both images are bound to the same region of external memory. Applications may also add resources to such a set after the content of the existing set members has been defined without making the content undefined by creating a new image with the initial layout VK_IMAGE_LAYOUT_UNDEFINED and binding it to the same region of external memory as the existing images.

Note
Because layout transitions apply to all identical images aliasing the same region of external memory, the actual layout of the memory backing a new image as well as an existing image with defined content will not be undefined. Such an image is not usable until it acquires ownership of its memory from the existing owner. Therefore, the layout specified as part of this transition will be the true initial layout of the image. The undefined layout specified when creating it is a placeholder to simplify valid usage requirements.
12.8. Memory Aliasing

A range of a `VkDeviceMemory` allocation is *aliased* if it is bound to multiple resources simultaneously, as described below, via `vkBindImageMemory`, `vkBindBufferMemory`, via sparse memory bindings, or by binding the memory to resources in multiple Vulkan instances or external APIs using external memory handle export and import mechanisms.

Consider two resources, resource\(_A\) and resource\(_B\), bound respectively to memory range\(_A\) and range\(_B\). Let paddedRange\(_A\) and paddedRange\(_B\) be, respectively, range\(_A\) and range\(_B\) aligned to `bufferImageGranularity`. If the resources are both linear or both non-linear (as defined in the Glossary), then the resources alias the memory in the intersection of range\(_A\) and range\(_B\). If one resource is linear and the other is non-linear, then the resources alias the memory in the intersection of paddedRange\(_A\) and paddedRange\(_B\).

Applications can alias memory, but use of multiple aliases is subject to several constraints.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory aliasing can be useful to reduce the total device memory footprint of an application, if some large resources are used for disjoint periods of time.</td>
</tr>
</tbody>
</table>

When a non-linear, non-`VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` image is bound to an aliased range, all image subresources of the image overlap the range. When a linear image is bound to an aliased range, the image subresources that (according to the image’s advertised layout) include bytes from the aliased range overlap the range. When a `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` image has sparse image blocks bound to an aliased range, only image subresources including those sparse image blocks overlap the range, and when the memory bound to the image’s mip tail overlaps an aliased range all image subresources in the mip tail overlap the range.

Buffers, and linear image subresources in either the `VK_IMAGE_LAYOUT_PREINITIALIZED` or `VK_IMAGE_LAYOUT_GENERAL` layouts, are host-accessible subresources. That is, the host has a well-defined addressing scheme to interpret the contents, and thus the layout of the data in memory can be consistently interpreted across aliases if each of those aliases is a host-accessible subresource. Non-linear images, and linear image subresources in other layouts, are not host-accessible.

If two aliases are both host-accessible, then they interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

If two aliases are both images that were created with identical creation parameters, both were created with the `VK_IMAGE_CREATE_ALIAS_BIT` flag set, and both are bound identically to memory except for `VkBindImageMemoryDeviceGroupInfo::pDeviceIndices` and `VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions`, then they interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

Additionally, if an individual plane of a multi-planar image and a single-plane image alias the same memory, then they also interpret the contents of the memory in consistent ways under the same conditions, but with the following modifications:

- Both must have been created with the `VK_IMAGE_CREATE_DISJOINT_BIT` flag.
• The single-plane image **must** have a **VkFormat** that is **equivalent** to that of the multi-planar image’s individual plane.

• The single-plane image and the individual plane of the multi-planar image **must** be bound identically to memory except for **VkBindImageMemoryDeviceGroupInfo::pDeviceIndices** and **VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions**.

• The **width** and **height** of the single-plane image are derived from the multi-planar image’s dimensions in the manner listed for **plane compatibility** for the aliased plane.

• All other creation parameters **must** be identical

Aliases created by binding the same memory to resources in multiple Vulkan instances or external APIs using external memory handle export and import mechanisms interpret the contents of the memory in consistent ways, and data written to one alias **can** be read by the other alias.

Otherwise, the aliases interpret the contents of the memory differently, and writes via one alias make the contents of memory partially or completely undefined to the other alias. If the first alias is a host-accessible subresource, then the bytes affected are those written by the memory operations according to its addressing scheme. If the first alias is not host-accessible, then the bytes affected are those overlapped by the image subresources that were written. If the second alias is a host-accessible subresource, the affected bytes become undefined. If the second alias is not host-accessible, all sparse image blocks (for sparse partially-resident images) or all image subresources (for non-sparse image and fully resident sparse images) that overlap the affected bytes become undefined.

If any image subresources are made undefined due to writes to an alias, then each of those image subresources **must** have its layout transitioned from **VK_IMAGE_LAYOUT_UNDEFINED** to a valid layout before it is used, or from **VK_IMAGE_LAYOUT_PREINITIALIZED** if the memory has been written by the host. If any sparse blocks of a sparse image have been made undefined, then only the image subresources containing them **must** be transitioned.

Use of an overlapping range by two aliases **must** be separated by a memory dependency using the appropriate **access types** if at least one of those uses performs writes, whether the aliases interpret memory consistently or not. If buffer or image memory barriers are used, the scope of the barrier **must** contain the entire range and/or set of image subresources that overlap.

If two aliasing image views are used in the same framebuffer, then the render pass **must** declare the attachments using the **VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT**, and follow the other rules listed in that section.

**Note**

Memory recycled via an application suballocator (i.e. without freeing and reallocating the memory objects) is not substantially different from memory aliasing. However, a suballocator usually waits on a fence before recycling a region of memory, and signaling a fence involves sufficient implicit dependencies to satisfy all the above requirements.
12.8.1. Resource Memory Overlap

Applications can safely access a resource concurrently as long as the memory locations do not overlap as defined in Memory Location. This includes aliased resources if such aliasing is well-defined. It also includes access from different queues and/or queue families if such concurrent access is supported by the resource. Transfer commands only access memory locations specified by the range of the transfer command.

**Note**

The intent is that buffers (or linear images) can be accessed concurrently, even when they share cache lines, but otherwise do not access the same memory range. The concept of a device cache line size is not exposed in the memory model.
Chapter 13. Samplers

VkSampler objects represent the state of an image sampler which is used by the implementation to read image data and apply filtering and other transformations for the shader.

Samplers are represented by VkSampler handles:

```cpp
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSampler)
```

To create a sampler object, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkCreateSampler(
    VkDevice device,
    const VkSamplerCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkSampler* pSampler);
```

- **device** is the logical device that creates the sampler.
- **pCreateInfo** is a pointer to a VkSamplerCreateInfo structure specifying the state of the sampler object.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pSampler** is a pointer to a VkSampler handle in which the resulting sampler object is returned.

Valid Usage

- VUID-vkCreateSampler-maxSamplerAllocationCount-04110
  There **must** be less than VkPhysicalDeviceLimits::maxSamplerAllocationCount VkSampler objects currently created on the device

Valid Usage (Implicit)

- VUID-vkCreateSampler-device-parameter
device **must** be a valid VkDevice handle
- VUID-vkCreateSampler-pCreateInfo-parameter
  pCreateInfo **must** be a valid pointer to a valid VkSamplerCreateInfo structure
- VUID-vkCreateSampler-pAllocator-parameter
  If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- VUID-vkCreateSampler-pSampler-parameter
  pSampler **must** be a valid pointer to a VkSampler handle
Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkSamplerCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSamplerCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkSamplerCreateFlags flags;
    VkFilter magFilter;
    VkFilter minFilter;
    VkSamplerMipmapMode mipMapMode;
    VkSamplerAddressMode addressModeU;
    VkSamplerAddressMode addressModeV;
    VkSamplerAddressMode addressModeW;
    float mipLodBias;
    VkBool32 anisotropyEnable;
    float maxAnisotropy;
    VkBool32 compareEnable;
    VkCompareOp compareOp;
    float minLod;
    float maxLod;
    VkBorderColor borderColor;
    VkBool32 unnormalizedCoordinates;
} VkSamplerCreateInfo;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is a bitmask of `VkSamplerCreateFlagBits` describing additional parameters of the sampler.
- **magFilter** is a `VkFilter` value specifying the magnification filter to apply to lookups.
- **minFilter** is a `VkFilter` value specifying the minification filter to apply to lookups.
- **mipMapMode** is a `VkSamplerMipmapMode` value specifying the mipmap filter to apply to lookups.
- **addressModeU** is a `VkSamplerAddressMode` value specifying the addressing mode for U coordinates outside [0,1).
- **addressModeV** is a `VkSamplerAddressMode` value specifying the addressing mode for V coordinates outside [0,1).
- **addressModeW** is a `VkSamplerAddressMode` value specifying the addressing mode for W coordinates outside [0,1).
coordinates outside [0,1).

- **mipLodBias** is the bias to be added to mipmap LOD calculation and bias provided by image sampling functions in SPIR-V, as described in the LOD Operation section.

- **anisotropyEnable** is **VK_TRUE** to enable anisotropic filtering, as described in the Texel Anisotropic Filtering section, or **VK_FALSE** otherwise.

- **maxAnisotropy** is the anisotropy value clamp used by the sampler when **anisotropyEnable** is **VK_TRUE**. If **anisotropyEnable** is **VK_FALSE**, **maxAnisotropy** is ignored.

- **compareEnable** is **VK_TRUE** to enable comparison against a reference value during lookups, or **VK_FALSE** otherwise.
  - Note: Some implementations will default to shader state if this member does not match.

- **compareOp** is a **VkCompareOp** value specifying the comparison operator to apply to fetched data before filtering as described in the Depth Compare Operation section.

- **minLod** is used to clamp the minimum of the computed LOD value.

- **maxLod** is used to clamp the maximum of the computed LOD value. To avoid clamping the maximum value, set **maxLod** to the constant **VK_LOD_CLAMP_NONE**.

- **borderColor** is a **VkBorderColor** value specifying the predefined border color to use.

- **unnormalizedCoordinates** controls whether to use unnormalized or normalized texel coordinates to address texels of the image. When set to **VK_TRUE**, the range of the image coordinates used to lookup the texel is in the range of zero to the image size in each dimension. When set to **VK_FALSE** the range of image coordinates is zero to one.

When **unnormalizedCoordinates** is **VK_TRUE**, images the sampler is used with in the shader have the following requirements:

- The viewType **must** be either **VK_IMAGE_VIEW_TYPE_1D** or **VK_IMAGE_VIEW_TYPE_2D**.
- The image view **must** have a single layer and a single mip level.

When **unnormalizedCoordinates** is **VK_TRUE**, image built-in functions in the shader that use the sampler have the following requirements:

- The functions **must** not use projection.
- The functions **must** not use offsets.

---

**Mapping of OpenGL to Vulkan filter modes**

**magFilter** values of **VK_FILTER_NEAREST** and **VK_FILTER_LINEAR** directly correspond to **GL_NEAREST** and **GL_LINEAR** magnification filters. **minFilter** and **mipmapMode** combine to correspond to the similarly named OpenGL minification filter of **GL_minFilter_MIPMAP_mipmapMode** (e.g. **minFilter** of **VK_FILTER_LINEAR** and **mipmapMode** of **VK_SAMPLER_MIPMAP_MODE_NEAREST** correspond to **GL_LINEAR_MIPMAP_NEAREST**).

There are no Vulkan filter modes that directly correspond to OpenGL minification filters of **GL_LINEAR** or **GL_NEAREST**, but they can be emulated using **VK_SAMPLER_MIPMAP_MODE_NEAREST**, **minLod** = 0, and **maxLod** = 0.25, and using **minFilter** = **VK_FILTER_LINEAR** or **minFilter** = **VK_FILTER_NEAREST**, respectively.
Note that using a \texttt{maxLod} of zero would cause \texttt{magnification} to always be performed, and the \texttt{magFilter} to always be used. This is valid, just not an exact match for OpenGL behavior. Clamping the maximum LOD to 0.25 allows the \( \lambda \) value to be non-zero and minification to be performed, while still always rounding down to the base level. If the \texttt{minFilter} and \texttt{magFilter} are equal, then using a \texttt{maxLod} of zero also works.

The maximum number of sampler objects which \texttt{can} be simultaneously created on a device is implementation-dependent and specified by the \texttt{maxSamplerAllocationCount} member of the \texttt{VkPhysicalDeviceLimits} structure.

\begin{itemize}
  \item \texttt{VUID-VkSamplerCreateInfo-mipLodBias-01069} \\
    The absolute value of \texttt{mipLodBias} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxSamplerLodBias} \\
  \item \texttt{VUID-VkSamplerCreateInfo-maxLod-01973} \\
    \texttt{maxLod} must be greater than or equal to \texttt{minLod} \\
  \item \texttt{VUID-VkSamplerCreateInfo-anisotropyEnable-01070} \\
    If the \texttt{samplerAnisotropy} feature is not enabled, \texttt{anisotropyEnable} must be \texttt{VK_FALSE} \\
  \item \texttt{VUID-VkSamplerCreateInfo-anisotropyEnable-01071} \\
    If \texttt{anisotropyEnable} is \texttt{VK_TRUE}, \texttt{maxAnisotropy} must be between 1.0 and \texttt{VkPhysicalDeviceLimits::maxSamplerAnisotropy}, inclusive \\
  \item \texttt{VUID-VkSamplerCreateInfo-minFilter-01645} \\
    If \texttt{sampler \ Y'CbCr} conversion is enabled and the potential format features of the sampler \texttt{Y'CbCr} conversion do not support \texttt{VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT}, \texttt{minFilter} and \texttt{magFilter} must be equal to the sampler \texttt{Y'CbCr} conversion’s \texttt{chromaFilter} \\
  \item \texttt{VUID-VkSamplerCreateInfo-unnormalizedCoordinates-01072} \\
    If \texttt{unnormalizedCoordinates} is \texttt{VK_TRUE}, \texttt{minFilter} and \texttt{magFilter} must be equal \\
  \item \texttt{VUID-VkSamplerCreateInfo-unnormalizedCoordinates-01073} \\
    If \texttt{unnormalizedCoordinates} is \texttt{VK_TRUE}, \texttt{mipmapMode} must be \texttt{VK_SAMPLER_MIPMAP_MODE_NEAREST} \\
  \item \texttt{VUID-VkSamplerCreateInfo-unnormalizedCoordinates-01074} \\
    If \texttt{unnormalizedCoordinates} is \texttt{VK_TRUE}, \texttt{minLod} and \texttt{maxLod} must be zero
\end{itemize}
If unnormalizedCoordinates is VK_TRUE, addressModeU and addressModeV must each be either VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE or VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER.

If unnormalizedCoordinates is VK_TRUE, anisotropyEnable must be VK_FALSE.

If unnormalizedCoordinates is VK_TRUE, compareEnable must be VK_FALSE.

If any of addressModeU, addressModeV or addressModeW are VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER, borderColor must be a valid VkBorderColor value.

If sampler Y’CbCr conversion is enabled, addressModeU, addressModeV, and addressModeW must be VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE, anisotropyEnable must be VK_FALSE, and unnormalizedCoordinates must be VK_FALSE.

If sampler Y’CbCr conversion is enabled and the pNext chain includes a VkSamplerReductionModeCreateInfo structure, then the sampler reduction mode must be set to VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE.

If samplerFilterMinmax is not enabled and the pNext chain includes a VkSamplerReductionModeCreateInfo structure, then the sampler reduction mode must be set to VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE.

If samplerMirrorClampToEdge is not enabled, and if the VK_KHR_sampler_mirror_clamp_to_edge extension is not enabled, addressModeU, addressModeV and addressModeW must not be VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE.

If compareEnable is VK_TRUE, compareOp must be a valid VkCompareOp value.

If compareEnable is VK_TRUE, the reductionMode member of VkSamplerReductionModeCreateInfo must be VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE.

Valid Usage (Implicit)

sType must be VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO.

Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkSamplerReductionModeCreateInfo or VkSamplerYcbcrConversionInfo.
The `sType` value of each struct in the `pNext` chain must be unique.

flags must be 0

`magFilter` must be a valid `VkFilter` value.

`minFilter` must be a valid `VkFilter` value.

`mipmapMode` must be a valid `VkSamplerMipmapMode` value.

`addressModeU` must be a valid `VkSamplerAddressMode` value.

`addressModeV` must be a valid `VkSamplerAddressMode` value.

`addressModeW` must be a valid `VkSamplerAddressMode` value.

`VK_LOD_CLAMP_NONE` is a special constant value used for `VkSamplerCreateInfo::maxLod` to indicate that maximum LOD clamping should not be performed.

```c
#define VK_LOD_CLAMP_NONE 1000.0F
```

Bits which can be set in `VkSamplerCreateInfo::flags`, specifying additional parameters of a sampler, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSamplerCreateFlagBits {
} VkSamplerCreateFlagBits;
```

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkSamplerCreateFlags;
```

`VkSamplerCreateFlags` is a bitmask type for setting a mask of zero or more `VkSamplerCreateFlagBits`.

The `VkSamplerReductionModeCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkSamplerReductionModeCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkSamplerReductionMode reductionMode;
} VkSamplerReductionModeCreateInfo;
```
VkSamplerReductionModeCreateInfo

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **reductionMode** is a `VkSamplerReductionMode` value controlling how texture filtering combines texel values.

If the **pNext** chain of `VkSamplerCreateInfo` includes a `VkSamplerReductionModeCreateInfo` structure, then that structure includes a mode controlling how texture filtering combines texel values.

If this structure is not present, `reductionMode` is considered to be `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`.

### Valid Usage (Implicit)

- **VUID-VkSamplerReductionModeCreateInfo-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_SAMPLER_REDUCTION_MODE_CREATE_INFO`.
- **VUID-VkSamplerReductionModeCreateInfo-reductionMode-parameter**
  - `reductionMode` must be a valid `VkSamplerReductionMode` value.

Reduction modes are specified by `VkSamplerReductionMode`, which takes values:

```c
// Provided by VK_VERSION_1_2
typedef enum VkSamplerReductionMode {
    VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE = 0,
    VK_SAMPLER_REDUCTION_MODE_MIN = 1,
    VK_SAMPLER_REDUCTION_MODE_MAX = 2,
} VkSamplerReductionMode;
```

- **VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE** specifies that texel values are combined by computing a weighted average of values in the footprint, using weights as specified in the image operations chapter.
- **VK_SAMPLER_REDUCTION_MODE_MIN** specifies that texel values are combined by taking the component-wise minimum of values in the footprint with non-zero weights.
- **VK_SAMPLER_REDUCTION_MODE_MAX** specifies that texel values are combined by taking the component-wise maximum of values in the footprint with non-zero weights.

Possible values of the `VkSamplerCreateInfo::magFilter` and `minFilter` parameters, specifying filters used for texture lookups, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkFilter {
    VK_FILTER_NEAREST = 0,
    VK_FILTER_LINEAR = 1,
};
```
• **VK_FILTER_NEAREST** specifies nearest filtering.
• **VK_FILTER_LINEAR** specifies linear filtering.

These filters are described in detail in [Texel Filtering](#).

Possible values of the `VkSamplerCreateInfo::mipmapMode`, specifying the mipmap mode used for texture lookups, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSamplerMipmapMode {
    VK_SAMPLER_MIPMAP_MODE_NEAREST = 0,
    VK_SAMPLER_MIPMAP_MODE_LINEAR = 1,
} VkSamplerMipmapMode;
```

• **VK_SAMPLER_MIPMAP_MODE_NEAREST** specifies nearest filtering.
• **VK_SAMPLER_MIPMAP_MODE_LINEAR** specifies linear filtering.

These modes are described in detail in [Texel Filtering](#).

Possible values of the `VkSamplerCreateInfo::addressMode*` parameters, specifying the behavior of sampling with coordinates outside the range [0,1] for the respective u, v, or w coordinate as defined in the [Wrapping Operation](#) section, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSamplerAddressMode {
    VK_SAMPLER_ADDRESS_MODE_REPEAT = 0,
    VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT = 1,
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE = 2,
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER = 3,
    // Provided by VK_VERSION_1_2
    VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE = 4,
} VkSamplerAddressMode;
```

• **VK_SAMPLER_ADDRESS_MODE_REPEAT** specifies that the repeat wrap mode will be used.
• **VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT** specifies that the mirrored repeat wrap mode will be used.
• **VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE** specifies that the clamp to edge wrap mode will be used.
• **VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER** specifies that the clamp to border wrap mode will be used.
• **VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE** specifies that the mirror clamp to edge wrap mode will be used. This is only valid if `samplerMirrorClampToEdge` is enabled, or if the `VK_KHR_sampler_mirror_clamp_to_edge` extension is enabled.
Comparison operators compare a reference and a test value, and return a true ("passed") or false ("failed") value depending on the comparison operator chosen. The supported operators are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCompareOp {
    VK_COMPARE_OP_NEVER = 0,
    VK_COMPARE_OP_LESS = 1,
    VK_COMPARE_OP_EQUAL = 2,
    VK_COMPARE_OP_LESS_OR_EQUAL = 3,
    VK_COMPARE_OP_GREATER = 4,
    VK_COMPARE_OP_NOT_EQUAL = 5,
    VK_COMPARE_OP_GREATER_OR_EQUAL = 6,
    VK_COMPARE_OP_ALWAYS = 7,
} VkCompareOp;
```

- **VK_COMPARE_OP_NEVER** specifies that the comparison always evaluates false.
- **VK_COMPARE_OP_LESS** specifies that the comparison evaluates reference < test.
- **VK_COMPARE_OP_EQUAL** specifies that the comparison evaluates reference = test.
- **VK_COMPARE_OP_LESS_OR_EQUAL** specifies that the comparison evaluates reference ≤ test.
- **VK_COMPARE_OP_GREATER** specifies that the comparison evaluates reference > test.
- **VK_COMPARE_OP_NOT_EQUAL** specifies that the comparison evaluates reference ≠ test.
- **VKCOMPARE_OP_GREATER_OR_EQUAL** specifies that the comparison evaluates reference ≥ test.
- **VK_COMPARE_OP_ALWAYS** specifies that the comparison always evaluates true.

Comparison operators are used for:

- The **Depth Compare Operation** operator for a sampler, specified by `VkSamplerCreateInfo::compareOp`.
- The stencil comparison operator for the stencil test, specified by `vkCmdSetStencilOp::compareOp` or `VkStencilOpState::compareOp`.
- The **Depth Comparison** operator for the depth test, specified by `vkCmdSetDepthCompareOp::depthCompareOp` or `VkPipelineDepthStencilStateCreateInfo::depthCompareOp`.

Each such use describes how the reference and test values for that comparison are determined.

Possible values of `VkSamplerCreateInfo::borderColor`, specifying the border color used for texture lookups, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkBorderColor {
    VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK = 0,
    VK_BORDER_COLOR_INT_TRANSPARENT_BLACK = 1,
    VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK = 2,
    VK_BORDER_COLOR_INT_OPAQUE_BLACK = 3,
    VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE = 4,
} VkBorderColor;
```
These colors are described in detail in Texel Replacement.

To destroy a sampler, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroySampler(
    VkDevice device,
    VkSampler sampler,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the sampler.
- **sampler** is the sampler to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- **VUID-vkDestroySampler-sampler-01082**
  All submitted commands that refer to `sampler` must have completed execution.
- **VUID-vkDestroySampler-sampler-01083**
  If `VkAllocationCallbacks` were provided when `sampler` was created, a compatible set of callbacks must be provided here.
- **VUID-vkDestroySampler-sampler-01084**
  If no `VkAllocationCallbacks` were provided when `sampler` was created, `pAllocator` must be NULL.

### Valid Usage (Implicit)

- **VUID-vkDestroySampler-device-parameter**
  `device` must be a valid `VkDevice` handle.
- **VUID-vkDestroySampler-sampler-parameter**
  If `sampler` is not `VK_NULL_HANDLE`, `sampler` must be a valid `VkSampler` handle.
If \( p\text{Allocator} \) is not \( \text{NULL} \), \( p\text{Allocator} \) must be a valid pointer to a valid \( \text{VkAllocationCallbacks} \) structure.

If \( \text{sampler} \) is a valid handle, it must have been created, allocated, or retrieved from device.

### Host Synchronization

Host access to \( \text{sampler} \) must be externally synchronized.

### 13.1. Sampler \( Y'\text{C}_B\text{C}_R \) conversion

To create a sampler with \( Y'\text{C}_B\text{C}_R \) conversion enabled, add a \( \text{VkSamplerYcbcrConversionInfo} \) structure to the \( \text{pNext} \) chain of the \( \text{VkSamplerCreateInfo} \) structure. To create a sampler \( Y'\text{C}_B\text{C}_R \) conversion, the \( \text{samplerYcbcrConversion} \) feature must be enabled. Conversion must be fixed at pipeline creation time, through use of a combined image sampler with an immutable sampler in \( \text{VkDescriptorSetLayoutBinding} \).

A \( \text{VkSamplerYcbcrConversionInfo} \) must be provided for samplers to be used with image views that access \( \text{VK_IMAGE_ASPECT_COLOR_BIT} \) if the format is one of the formats that require a sampler \( Y'\text{C}_B\text{C}_R \) conversion.

The \( \text{VkSamplerYcbcrConversionInfo} \) structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkSamplerYcbcrConversionInfo {
    VkStructureType          sType;
    const void*               pNext;
    VkSamplerYcbcrConversion conversion;
} VkSamplerYcbcrConversionInfo;
```

- \( \text{sType} \) is a \( \text{VkStructureType} \) value identifying this structure.
- \( \text{pNext} \) is \( \text{NULL} \) or a pointer to a structure extending this structure.
- \( \text{conversion} \) is a \( \text{VkSamplerYcbcrConversion} \) handle created with \( \text{vkCreateSamplerYcbcrConversion} \).

### Valid Usage (Implicit)

- VUID-VkSamplerYcbcrConversionInfo-sType-sType
  \( \text{sType must be } \text{VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO} \)

- VUID-VkSamplerYcbcrConversionInfo-conversion-parameter
  \( \text{conversion must be a valid } \text{VkSamplerYcbcrConversion} \) handle.

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A sampler Y’CbCr conversion is an opaque representation of a device-specific sampler Y’CbCr conversion description, represented as a `VkSamplerYcbcrConversion` handle:

```c
// Provided by VK_VERSION_1_1
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSamplerYcbcrConversion)
```

To create a `VkSamplerYcbcrConversion`, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkCreateSamplerYcbcrConversion(
    VkDevice device,
    const VkSamplerYcbcrConversionCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkSamplerYcbcrConversion* pYcbcrConversion);
```

- `device` is the logical device that creates the sampler Y’CbCr conversion.
- `pCreateInfo` is a pointer to a `VkSamplerYcbcrConversionCreateInfo` structure specifying the requested sampler Y’CbCr conversion.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pYcbcrConversion` is a pointer to a `VkSamplerYcbcrConversion` handle in which the resulting sampler Y’CbCr conversion is returned.

The interpretation of the configured sampler Y’CbCr conversion is described in more detail in the description of sampler Y’CbCr conversion in the Image Operations chapter.

### Valid Usage

- VUID-vkCreateSamplerYcbcrConversion-None-01648
  The `samplerYcbcrConversion` feature must be enabled

### Valid Usage (Implicit)

- VUID-vkCreateSamplerYcbcrConversion-device-parameter
  `device` must be a valid `VkDevice` handle
- VUID-vkCreateSamplerYcbcrConversion-pCreateInfo-parameter
  `pCreateInfo` must be a valid pointer to a valid `VkSamplerYcbcrConversionCreateInfo` structure
- VUID-vkCreateSamplerYcbcrConversion-pAllocator-parameter
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- VUID-vkCreateSamplerYcbcrConversion-pYcbcrConversion-parameter
  `pYcbcrConversion` must be a valid pointer to a `VkSamplerYcbcrConversion` handle
Return Codes

Success
  • VK_SUCCESS

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkSamplerYcbcrConversionCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkSamplerYcbcrConversionCreateInfo {
  VkStructureType sType;
  const void* pNext;
  VkFormat format;
  VkSamplerYcbcrModelConversion ycbcrModel;
  VkSamplerYcbcrRange ycbcrRange;
  VkComponentMapping components;
  VkChromaLocation xChromaOffset;
  VkChromaLocation yChromaOffset;
  VkFilter chromaFilter;
  VkBool32 forceExplicitReconstruction;
} VkSamplerYcbcrConversionCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `format` is the format of the image from which color information will be retrieved.
- `ycbcrModel` describes the color matrix for conversion between color models.
- `ycbcrRange` describes whether the encoded values have headroom and footroom, or whether the encoding uses the full numerical range.
- `components` applies a swizzle based on `VkComponentSwizzle` enums prior to range expansion and color model conversion.
- `xChromaOffset` describes the sample location associated with downsamped chroma components in the x dimension. `xChromaOffset` has no effect for formats in which chroma components are not downsamped horizontally.
- `yChromaOffset` describes the sample location associated with downsamped chroma components in the y dimension. `yChromaOffset` has no effect for formats in which the chroma components are not downsamped vertically.
- `chromaFilter` is the filter for chroma reconstruction.
- `forceExplicitReconstruction` can be used to ensure that reconstruction is done explicitly, if supported.
Note

Setting `forceExplicitReconstruction` to `VK_TRUE` may have a performance penalty on implementations where explicit reconstruction is not the default mode of operation.

If `format` supports `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT` the `forceExplicitReconstruction` value behaves as if it was set to `VK_TRUE`.

Sampler \( Y'C_bC_r \) conversion objects do not support external format conversion without additional extensions defining external formats.

Valid Usage

- `VUID-VkSamplerYcbcrConversionCreateInfo-format-04060`
  
  `format` must represent unsigned normalized values (i.e. the format must be a `UNORM` format)

- `VUID-VkSamplerYcbcrConversionCreateInfo-format-01650`
  
  The potential format features of the sampler \( Y'C_bC_r \) conversion must support `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT` or `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT`

- `VUID-VkSamplerYcbcrConversionCreateInfo-xChromaOffset-01651`
  
  If the potential format features of the sampler \( Y'C_bC_r \) conversion do not support `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT`, `xChromaOffset` and `yChromaOffset` must not be `VK_CHROMA_LOCATION_COSITED_EVEN` if the corresponding components are downsampled

- `VUID-VkSamplerYcbcrConversionCreateInfo-xChromaOffset-01652`
  
  If the potential format features of the sampler \( Y'C_bC_r \) conversion do not support `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT`, `xChromaOffset` and `yChromaOffset` must not be `VK_CHROMA_LOCATION_MIDPOINT` if the corresponding components are downsampled

- `VUID-VkSamplerYcbcrConversionCreateInfo-components-02581`
  
  If the format has a `_422` or `_420` suffix, then `components.g` must be the identity swizzle

- `VUID-VkSamplerYcbcrConversionCreateInfo-components-02582`
  
  If the format has a `_422` or `_420` suffix, then `components.a` must be the identity swizzle, `VK_COMPONENT_SWIZZLE_ONE`, or `VK_COMPONENT_SWIZZLE_ZERO`

- `VUID-VkSamplerYcbcrConversionCreateInfo-components-02583`
  
  If the format has a `_422` or `_420` suffix, then `components.r` must be the identity swizzle or `VK_COMPONENT_SWIZZLE_B`

- `VUID-VkSamplerYcbcrConversionCreateInfo-components-02584`
  
  If the format has a `_422` or `_420` suffix, then `components.b` must be the identity swizzle or `VK_COMPONENT_SWIZZLE_R`

- `VUID-VkSamplerYcbcrConversionCreateInfo-components-02585`
  
  If the format has a `_422` or `_420` suffix, and if either `components.r` or `components.b` is the identity swizzle, both values must be the identity swizzle

- `VUID-VkSamplerYcbcrConversionCreateInfo-ycbcrModel-01655`
If `ycbcrModel` is not `VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY`, then `components.r`, `components.g`, and `components.b` must correspond to components of the format; that is, `components.r`, `components.g`, and `components.b` must not be `VK_COMPONENT_SWIZZLE_ZERO` or `VK_COMPONENT_SWIZZLE_ONE`, and must not correspond to a component containing zero or one as a consequence of conversion to RGBA.

- **VUID-VkSamplerYcbcrConversionCreateInfo-ycbcrRange-02748**
  If `ycbcrRange` is `VK_SAMPLER_YCBCR_RANGE_ITU_NARROW` then the R, G and B components obtained by applying the component swizzle to format must each have a bit-depth greater than or equal to 8.

- **VUID-VkSamplerYcbcrConversionCreateInfo-forceExplicitReconstruction-01656**
  If the potential format features of the sampler Y’C_bC_R conversion do not support `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCE` bit `forceExplicitReconstruction` must be `VK_FALSE`.

- **VUID-VkSamplerYcbcrConversionCreateInfo-chromaFilter-01657**
  If the potential format features of the sampler Y’C_bC_R conversion do not support `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT`, `chromaFilter` must not be `VK_FILTER_LINEAR`.

**Valid Usage (Implicit)**

- **VUID-VkSamplerYcbcrConversionCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO`.

- **VUID-VkSamplerYcbcrConversionCreateInfo-pNext-pNext**
  `pNext` must be `NULL`.

- **VUID-VkSamplerYcbcrConversionCreateInfo-format-parameter**
  `format` must be a valid `VkFormat` value.

- **VUID-VkSamplerYcbcrConversionCreateInfo-ycbcrModel-parameter**
  `ycbcrModel` must be a valid `VkSamplerYcbcrModelConversion` value.

- **VUID-VkSamplerYcbcrConversionCreateInfo-ycbcrRange-parameter**
  `ycbcrRange` must be a valid `VkSamplerYcbcrRange` value.

- **VUID-VkSamplerYcbcrConversionCreateInfo-components-parameter**
  `components` must be a valid `VkComponentMapping` structure.

- **VUID-VkSamplerYcbcrConversionCreateInfo-xChromaOffset-parameter**
  `xChromaOffset` must be a valid `VkChromaLocation` value.

- **VUID-VkSamplerYcbcrConversionCreateInfo-yChromaOffset-parameter**
  `yChromaOffset` must be a valid `VkChromaLocation` value.

- **VUID-VkSamplerYcbcrConversionCreateInfo-chromaFilter-parameter**
  `chromaFilter` must be a valid `VkFilter` value.

If `chromaFilter` is `VK_FILTER_NEAREST`, chroma samples are reconstructed to luma component resolution using nearest-neighbour sampling. Otherwise, chroma samples are reconstructed using interpolation. More details can be found in the description of sampler Y’C_bC_R conversion in the
**Image Operations** chapter.

**VkSamplerYcbcrModelConversion** defines the conversion from the source color model to the shader color model. Possible values are:

```cpp
// Provided by VK_VERSION_1_1
typedef enum VkSamplerYcbcrModelConversion {
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY = 0,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY = 1,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709 = 2,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601 = 3,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020 = 4,
} VkSamplerYcbcrModelConversion;
```

- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY** specifies that the input values to the conversion are unmodified.
- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY** specifies no model conversion but the inputs are range expanded as for Y′C_bC_r.
- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709** specifies the color model conversion from Y′C_bC_r to R′G′B′ defined in BT.709 and described in the “BT.709 Y′C_bC_r conversion” section of the Khronos Data Format Specification.
- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601** specifies the color model conversion from Y′C_bC_r to R′G′B′ defined in BT.601 and described in the “BT.601 Y′C_bC_r conversion” section of the Khronos Data Format Specification.
- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020** specifies the color model conversion from Y′C_bC_r to R′G′B′ defined in BT.2020 and described in the “BT.2020 Y′C_bC_r conversion” section of the Khronos Data Format Specification.

In the **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_*** color models, for the input to the sampler Y′C_bC_r range expansion and model conversion:

- the Y (Y' luma) component corresponds to the G component of an RGB image.
- the CB (C_b or “U” blue color difference) component corresponds to the B component of an RGB image.
- the CR (C_r or “V” red color difference) component corresponds to the R component of an RGB image.
- the alpha component, if present, is not modified by color model conversion.

These rules reflect the mapping of components after the component swizzle operation (controlled by **VkSamplerYcbcrConversionCreateInfo::components**).

**Note**

For example, an “YUVA” 32-bit format comprising four 8-bit components can be implemented as **VK_FORMAT_R8G8B8A8_UNORM** with a component mapping:
The \texttt{VkSamplerYcbcrRange} enum describes whether color components are encoded using the full range of numerical values or whether values are reserved for headroom and foot room. \texttt{VkSamplerYcbcrRange} is defined as:

\begin{verbatim}
// Provided by VK_VERSION_1_1
typedef enum VkSamplerYcbcrRange {
    VK_SAMPLER_YCBCR_RANGE_ITU_FULL = 0,
    VK_SAMPLER_YCBCR_RANGE_ITU_NARROW = 1,
} VkSamplerYcbcrRange;
\end{verbatim}

- \texttt{VK_SAMPLER_YCBCR_RANGE_ITU_FULL} specifies that the full range of the encoded values are valid and interpreted according to the ITU “full range” quantization rules.
- \texttt{VK_SAMPLER_YCBCR_RANGE_ITU_NARROW} specifies that headroom and foot room are reserved in the numerical range of encoded values, and the remaining values are expanded according to the ITU “narrow range” quantization rules.

The formulae for these conversions is described in the \texttt{Sampler Y'CbCr Range Expansion} section of the \texttt{Image Operations} chapter.

No range modification takes place if \texttt{ycbcrModel} is \texttt{VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY}; the \texttt{ycbcrRange} field of \texttt{VkSamplerYcbcrConversionCreateInfo} is ignored in this case.

The \texttt{VkChromaLocation} enum defines the location of downsampled chroma component samples relative to the luma samples, and is defined as:

\begin{verbatim}
// Provided by VK_VERSION_1_1
typedef enum VkChromaLocation {
    VK_CHROMA_LOCATION_COSITED_EVEN = 0,
    VK_CHROMA_LOCATION_MIDPOINT = 1,
} VkChromaLocation;
\end{verbatim}

- \texttt{VK_CHROMA_LOCATION_COSITED_EVEN} specifies that downsampled chroma samples are aligned with luma samples with even coordinates.
- \texttt{VK_CHROMA_LOCATION_MIDPOINT} specifies that downsampled chroma samples are located half way between each even luma sample and the nearest higher odd luma sample.

To destroy a sampler Y'CbCr conversion, call:

\begin{verbatim}
// Provided by VK_VERSION_1_1
void vkDestroySamplerYcbcrConversion(
\end{verbatim}
• **device** is the logical device that destroys the Y'CbCr conversion.

• **ycbcrConversion** is the conversion to destroy.

• **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

---

### Valid Usage (Implicit)

- VUID-vkDestroySamplerYcbcrConversion-device-parameter
  
  **device** must be a valid VkDevice handle

- VUID-vkDestroySamplerYcbcrConversion-ycbcrConversion-parameter
  
  If **ycbcrConversion** is not VK_NULL_HANDLE, **ycbcrConversion** must be a valid VkSamplerYcbcrConversion handle

- VUID-vkDestroySamplerYcbcrConversion-pAllocator-parameter
  
  If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure

- VUID-vkDestroySamplerYcbcrConversion-ycbcrConversion-parent
  
  If **ycbcrConversion** is a valid handle, it must have been created, allocated, or retrieved from **device**

---

### Host Synchronization

- Host access to **ycbcrConversion** must be externally synchronized
Chapter 14. Resource Descriptors

A *descriptor* is an opaque data structure representing a shader resource such as a buffer, buffer view, image view, sampler, or combined image sampler. Descriptors are organized into *descriptor sets*, which are bound during command recording for use in subsequent drawing commands. The arrangement of content in each descriptor set is determined by a *descriptor set layout*, which determines what descriptors can be stored within it. The sequence of descriptor set layouts that can be used by a pipeline is specified in a *pipeline layout*. Each pipeline object can use up to `maxBoundDescriptorSets` (see Limits) descriptor sets.

Shaders access resources via variables decorated with a descriptor set and binding number that link them to a descriptor in a descriptor set. The shader interface mapping to bound descriptor sets is described in the Shader Resource Interface section.

Shaders can also access buffers without going through descriptors by using Physical Storage Buffer Access to access them through 64-bit addresses.

14.1. Descriptor Types

There are a number of different types of descriptor supported by Vulkan, corresponding to different resources or usage. The following sections describe the API definitions of each descriptor type. The mapping of each type to SPIR-V is listed in the Shader Resource and Descriptor Type Correspondence and Shader Resource and Storage Class Correspondence tables in the Shader Interfaces chapter.

14.1.1. Storage Image

A *storage image* (VK_DESCRIPTOR_TYPE_STORAGE_IMAGE) is a descriptor type associated with an image resource via an image view that load, store, and atomic operations can be performed on.

Storage image loads are supported in all shader stages for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`.

Stores to storage images are supported in compute shaders for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`.

Atomic operations on storage images are supported in compute shaders for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

When the fragmentStoresAndAtomics feature is enabled, stores and atomic operations are also supported for storage images in fragment shaders with the same set of image formats as supported in compute shaders. When the vertexPipelineStoresAndAtomics feature is enabled, stores and atomic operations are also supported in vertex, tessellation, and geometry shaders with the same set of image formats as supported in compute shaders.

The image subresources for a storage image must be in the `VK_IMAGE_LAYOUT_GENERAL` layout in order to access its data in a shader.
14.1.2. Sampler

A sampler descriptor (VK_DESCRIPTOR_TYPE_SAMPLER) is a descriptor type associated with a sampler object, used to control the behavior of sampling operations performed on a sampled image.

14.1.3. Sampled Image

A sampled image (VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE) is a descriptor type associated with an image resource via an image view that sampling operations can be performed on.

Shaders combine a sampled image variable and a sampler variable to perform sampling operations.

Sampled images are supported in all shader stages for image views whose format features contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT.

An image subresources for a sampled image must be in one of the following layouts:

- VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_GENERAL
- VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL
- VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

14.1.4. Combined Image Sampler

A combined image sampler (VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER) is a single descriptor type associated with both a sampler and an image resource, combining both a sampler and sampled image descriptor into a single descriptor.

If the descriptor refers to a sampler that performs YC\textsubscript{b}C\textsubscript{r} conversion, the sampler must only be used to sample the image in the same descriptor. Otherwise, the sampler and image in this type of descriptor can be used freely with any other samplers and images.

An image subresources for a combined image sampler must be in one of the following layouts:

- VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_GENERAL
- VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL
- VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL
- VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL
Note
On some implementations, it may be more efficient to sample from an image using a combination of sampler and sampled image that are stored together in the descriptor set in a combined descriptor.

14.1.5. Uniform Texel Buffer

A uniform texel buffer (VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER) is a descriptor type associated with a buffer resource via a buffer view that image sampling operations can be performed on.

Uniform texel buffers define a tightly-packed 1-dimensional linear array of texels, with texels going through format conversion when read in a shader in the same way as they are for an image.

Load operations from uniform texel buffers are supported in all shader stages for buffer view formats which report format features support for VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT

14.1.6. Storage Texel Buffer

A storage texel buffer (VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER) is a descriptor type associated with a buffer resource via a buffer view that image load, store, and atomic operations can be performed on.

Storage texel buffers define a tightly-packed 1-dimensional linear array of texels, with texels going through format conversion when read in a shader in the same way as they are for an image. Unlike uniform texel buffers, these buffers can also be written to in the same way as for storage images.

Storage texel buffer loads are supported in all shader stages for texel buffer view formats which report format features support for VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT

Stores to storage texel buffers are supported in compute shaders for texel buffer formats which report format features support for VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT

Atomic operations on storage texel buffers are supported in compute shaders for texel buffer formats which report format features support for VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT

When the fragmentStoresAndAtomics feature is enabled, stores and atomic operations are also supported for storage texel buffers in fragment shaders with the same set of texel buffer formats as supported in compute shaders. When the vertexPipelineStoresAndAtomics feature is enabled, stores and atomic operations are also supported in vertex, tessellation, and geometry shaders with the same set of texel buffer formats as supported in compute shaders.

14.1.7. Storage Buffer

A storage buffer (VK_DESCRIPTOR_TYPE_STORAGE_BUFFER) is a descriptor type associated with a buffer resource directly, described in a shader as a structure with various members that load, store, and atomic operations can be performed on.

Note
Atomic operations can only be performed on members of certain types as defined in the SPIR-V environment appendix.

14.1.8. Uniform Buffer

A uniform buffer (VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER) is a descriptor type associated with a buffer resource directly, described in a shader as a structure with various members that load operations can be performed on.

14.1.9. Dynamic Uniform Buffer

A dynamic uniform buffer (VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC) is almost identical to a uniform buffer, and differs only in how the offset into the buffer is specified. The base offset calculated by the VkDescriptorBufferInfo when initially updating the descriptor set is added to a dynamic offset when binding the descriptor set.

14.1.10. Dynamic Storage Buffer

A dynamic storage buffer (VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC) is almost identical to a storage buffer, and differs only in how the offset into the buffer is specified. The base offset calculated by the VkDescriptorBufferInfo when initially updating the descriptor set is added to a dynamic offset when binding the descriptor set.

14.1.11. Inline Uniform Block

An inline uniform block (VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK) is almost identical to a uniform buffer, and differs only in taking its storage directly from the encompassing descriptor set instead of being backed by buffer memory. It is typically used to access a small set of constant data that does not require the additional flexibility provided by the indirection enabled when using a uniform buffer where the descriptor and the referenced buffer memory are decoupled. Compared to push constants, they allow reusing the same set of constant data across multiple disjoint sets of drawing and dispatching commands.

Inline uniform block descriptors cannot be aggregated into arrays. Instead, the array size specified for an inline uniform block descriptor binding specifies the binding’s capacity in bytes.

14.1.12. Input Attachment

An input attachment (VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT) is a descriptor type associated with an image resource via an image view that can be used for framebuffer local load operations in fragment shaders.

All image formats that are supported for color attachments (VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT) or depth/stencil attachments (VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT) for a given image tiling mode are also supported for input attachments.

An image view used as an input attachment must be in one of the following layouts:
• VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
• VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL
• VK_IMAGE_LAYOUT_GENERAL
• VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL
• VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL

14.2. Descriptor Sets

Descriptors are grouped together into descriptor set objects. A descriptor set object is an opaque object containing storage for a set of descriptors, where the types and number of descriptors is defined by a descriptor set layout. The layout object may be used to define the association of each descriptor binding with memory or other implementation resources. The layout is used both for determining the resources that need to be associated with the descriptor set, and determining the interface between shader stages and shader resources.

14.2.1. Descriptor Set Layout

A descriptor set layout object is defined by an array of zero or more descriptor bindings. Each individual descriptor binding is specified by a descriptor type, a count (array size) of the number of descriptors in the binding, a set of shader stages that can access the binding, and (if using immutable samplers) an array of sampler descriptors.

Descriptor set layout objects are represented by VkDescriptorSetLayout handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSetLayout)
```

To create descriptor set layout objects, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateDescriptorSetLayout( 
    VkDevice device, 
    const VkDescriptorSetLayoutCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkDescriptorSetLayout* pSetLayout); 
```

• **device** is the logical device that creates the descriptor set layout.
• **pCreateInfo** is a pointer to a VkDescriptorSetLayoutCreateInfo structure specifying the state of the descriptor set layout object.
• **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
• **pSetLayout** is a pointer to a VkDescriptorSetLayout handle in which the resulting descriptor set layout object is returned.
Valid Usage (Implicit)

- **VUID-vkCreateDescriptorSetLayout-device-parameter**
  
  `device` **must** be a valid `VkDevice` handle

- **VUID-vkCreateDescriptorSetLayout-pCreateInfo-parameter**
  
  `pCreateInfo` **must** be a valid pointer to a valid `VkDescriptorSetLayoutCreateInfo` structure

- **VUID-vkCreateDescriptorSetLayout-pAllocator-parameter**
  
  If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure

- **VUID-vkCreateDescriptorSetLayout-pSetLayout-parameter**
  
  `pSetLayout` **must** be a valid pointer to a `VkDescriptorSetLayout` handle

Return Codes

**Success**

- **VK_SUCCESS**

**Failure**

- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

Information about the descriptor set layout is passed in a `VkDescriptorSetLayoutCreateInfo` structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorSetLayoutCreateInfo {
    VkStructureType            sType;            
    const void*                pNext;            
    VkDescriptorSetLayoutCreateFlags flags;    
    uint32_t                    bindingCount;    
    const VkDescriptorSetLayoutBinding* pBindings; 
} VkDescriptorSetLayoutCreateInfo;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **flags** is a bitmask specifying options for descriptor set layout creation.
- **bindingCount** is the number of elements in `pBindings`.
- **pBindings** is a pointer to an array of `VkDescriptorSetLayoutBinding` structures.

Valid Usage

- **VUID-VkDescriptorSetLayoutCreateInfo-binding-00279**
The `VkDescriptorSetLayoutBinding::binding` members of the elements of the `pBindings` array must each have different values

- VUID-VkDescriptorSetLayoutCreateInfo-flags-03000
  If any binding has the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set, `flags` must include `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT`

- VUID-VkDescriptorSetLayoutCreateInfo-descriptorType-03001
  If any binding has the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set, then all bindings must not have `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`

---

**Valid Usage (Implicit)**

- VUID-VkDescriptorSetLayoutCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO`

- VUID-VkDescriptorSetLayoutCreateInfo-pNext-pNext
  `pNext` must be `NULL` or a pointer to a valid instance of `VkDescriptorSetLayoutBindingFlagsCreateInfo`

- VUID-VkDescriptorSetLayoutCreateInfo-sType-unique
  The `sType` value of each struct in the `pNext` chain must be unique

- VUID-VkDescriptorSetLayoutCreateInfo-flags-parameter
  `flags` must be a valid combination of `VkDescriptorSetLayoutCreateFlagBits` values

- VUID-VkDescriptorSetLayoutCreateInfo-pBindings-parameter
  If `bindingCount` is not 0, `pBindings` must be a valid pointer to an array of `bindingCount` valid `VkDescriptorSetLayoutBinding` structures

---

Bits which can be set in `VkDescriptorSetLayoutCreateInfo::flags`, specifying options for descriptor set layout, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkDescriptorSetLayoutCreateFlagBits {
    // Provided by VK_VERSION_1_2
    VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT = 0x00000002,
} VkDescriptorSetLayoutCreateFlagBits;
```

- `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` specifies that descriptor sets using this layout must be allocated from a descriptor pool created with the `VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT` bit set. Descriptor set layouts created with this bit set have alternate limits for the maximum number of descriptors per-stage and per-pipeline layout. The non-UpdateAfterBind limits only count descriptors in sets created without this flag. The UpdateAfterBind limits count all descriptors, but the limits may be higher than the non-UpdateAfterBind limits.

---

**Note**
All bits for this type are defined by extensions, and none of those extensions are enabled in this build of the specification.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkDescriptorSetLayoutCreateFlags;
```

The `VkDescriptorSetLayoutCreateFlags` is a bitmask type for setting a mask of zero or more `VkDescriptorSetLayoutCreateFlagBits`.

The `VkDescriptorSetLayoutBinding` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorSetLayoutBinding {
    uint32_t binding;
    VkDescriptorType descriptorType;
    uint32_t descriptorCount;
    VkShaderStageFlags stageFlags;
    const VkSampler* pImmutableSamplers;
} VkDescriptorSetLayoutBinding;
```

- `binding` is the binding number of this entry and corresponds to a resource of the same binding number in the shader stages.
- `descriptorType` is a `VkDescriptorType` specifying which type of resource descriptors are used for this binding.
- `descriptorCount` is the number of descriptors contained in the binding, accessed in a shader as an array, except if `descriptorType` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` in which case `descriptorCount` is the size in bytes of the inline uniform block. If `descriptorCount` is zero this binding entry is reserved and the resource must not be accessed from any stage via this binding within any pipeline using the set layout.
- `stageFlags` member is a bitmask of `VkShaderStageFlagBits` specifying which pipeline shader stages can access a resource for this binding. `VK_SHADER_STAGE_ALL` is a shorthand specifying that all defined shader stages, including any additional stages defined by extensions, can access the resource.

If a shader stage is not included in `stageFlags`, then a resource must not be accessed from that stage via this binding within any pipeline using the set layout. Other than input attachments which are limited to the fragment shader, there are no limitations on what combinations of stages can use a descriptor binding, and in particular a binding can be used by both graphics stages and the compute stage.

- `pImmutableSamplers` affects initialization of samplers. If `descriptorType` specifies a `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` type descriptor, then `pImmutableSamplers` can be used to initialize a set of immutable samplers. Immutable samplers are permanently bound into the set layout and must not be changed; updating a `VK_DESCRIPTOR_TYPE_SAMPLER` descriptor with immutable samplers is not allowed and updates to a `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` descriptor with immutable samplers does not
modify the samplers (the image views are updated, but the sampler updates are ignored). If `pImmutableSamplers` is not `NULL`, then it is a pointer to an array of sampler handles that will be copied into the set layout and used for the corresponding binding. Only the sampler handles are copied; the sampler objects must not be destroyed before the final use of the set layout and any descriptor pools and sets created using it. If `pImmutableSamplers` is `NULL`, then the sampler objects are dynamic and sampler handles must be bound into descriptor sets using this layout. If `descriptorType` is not one of these descriptor types, then `pImmutableSamplers` is ignored.

The above layout definition allows the descriptor bindings to be specified sparsely such that not all binding numbers between 0 and the maximum binding number need to be specified in the `pBindings` array. Bindings that are not specified have a `descriptorCount` and `stageFlags` of zero, and the value of `descriptorType` is undefined. However, all binding numbers between 0 and the maximum binding number in the `VkDescriptorSetLayoutCreateInfo::pBindings` array may consume memory in the descriptor set layout even if not all descriptor bindings are used, though it should not consume additional memory from the descriptor pool.

Note
The maximum binding number specified should be as compact as possible to avoid wasted memory.

Valid Usage

• VUID-VkDescriptorSetLayoutBinding-descriptorType-00282
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, and `descriptorCount` is not 0 and `pImmutableSamplers` is not `NULL`, `pImmutableSamplers` must be a valid pointer to an array of `descriptorCount` valid `VkSampler` handles

• VUID-VkDescriptorSetLayoutBinding-descriptorType-04604
  If the `inlineUniformBlock` feature is not enabled, `descriptorType` must not be `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`

• VUID-VkDescriptorSetLayoutBinding-descriptorType-02209
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` then `descriptorCount` must be a multiple of 4

• VUID-VkDescriptorSetLayoutBinding-descriptorType-02210
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` then `descriptorCount` must be less than or equal to `VkPhysicalDeviceInlineUniformBlockProperties::maxInlineUniformBlockSize`

• VUID-VkDescriptorSetLayoutBinding-descriptorCount-00283
  If `descriptorCount` is not 0, `stageFlags` must be a valid combination of `VkShaderStageFlagBits` values

• VUID-VkDescriptorSetLayoutBinding-descriptorType-01510
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` and `descriptorCount` is not 0, then `stageFlags` must be 0 or `VK_SHADER_STAGE_FRAGMENT_BIT`
Valid Usage (Implicit)

- VUID-VkDescriptorSetLayoutBinding-descriptorType-parameter
descriptorType must be a valid VkDescriptorType value

If the pNext chain of a VkDescriptorSetLayoutCreateInfo structure includes a VkDescriptorSetLayoutBindingFlagsCreateInfo structure, then that structure includes an array of flags, one for each descriptor set layout binding.

The VkDescriptorSetLayoutBindingFlagsCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkDescriptorSetLayoutBindingFlagsCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t bindingCount;
    const VkDescriptorBindingFlags* pBindingFlags;
} VkDescriptorSetLayoutBindingFlagsCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- bindingCount is zero or the number of elements in pBindingFlags.
- pBindingFlags is a pointer to an array of VkDescriptorBindingFlags bitfields, one for each descriptor set layout binding.

If bindingCount is zero or if this structure is not included in the pNext chain, the VkDescriptorBindingFlags for each descriptor set layout binding is considered to be zero. Otherwise, the descriptor set layout binding at VkDescriptorSetLayoutCreateInfo::pBindings[i] uses the flags in pBindingFlags[i].

Valid Usage

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-bindingCount-03002
  If bindingCount is not zero, bindingCount must equal VkDescriptorSetLayoutCreateInfo::bindingCount

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-pBindingFlags-03004
  If an element of pBindingFlags includes VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT, then all other elements of VkDescriptorSetLayoutCreateInfo::pBindings must have a smaller value of binding

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-descriptorBindingUniformBufferUpdateAfterBind-03005
  If VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingUniformBufferUpdateAfterBind is not enabled, all bindings with descriptor type VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER must not use
If \( \text{::} \text{descriptorBindingSampledImageUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_SAMPLER} \), \( \text{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER} \), or \( \text{VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingStorageImageUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_STORAGE_IMAGE} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingStorageBufferUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingUniformTexelBufferUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingStorageTexelBufferUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingInlineUniformBlockUpdateAfterBind} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

All bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT} \), \( \text{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC} \), or \( \text{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).

If \( \text{::} \text{descriptorBindingUpdateUnusedWhilePending} \) is not enabled, all bindings with descriptor type \( \text{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT} \), \( \text{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC} \), or \( \text{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC} \) must not use \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \).
::descriptorBindingUpdateUnusedWhilePending is not enabled, all elements of pBindingFlags must not include VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-descriptorBindingPartiallyBound-03013
  If VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingPartiallyBound is not enabled, all elements of pBindingFlags must not include VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-descriptorBindingVariableDescriptorCount-03014
  If VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingVariableDescriptorCount is not enabled, all elements of pBindingFlags must not include VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-pBindingFlags-03015
  If an element of pBindingFlags includes VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT, that element's descriptorType must not be VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC

Valid Usage (Implicit)

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_BINDING_FLAGS_CREATE_INFO

- VUID-VkDescriptorSetLayoutBindingFlagsCreateInfo-pBindingFlags-parameter
  If bindingCount is not 0, pBindingFlags must be a valid pointer to an array of bindingCount valid combinations of VkDescriptorBindingFlagBits values

Bits which can be set in each element of VkDescriptorSetLayoutBindingFlagsCreateInfo ::pBindingFlags, specifying options for the corresponding descriptor set layout binding, are:

```c
// Provided by VK_VERSION_1_2
typedef enum VkDescriptorBindingFlagBits {
  VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT = 0x00000001,
  VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT = 0x00000002,
  VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT = 0x00000004,
  VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT = 0x00000008,
} VkDescriptorBindingFlagBits;
```

- VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT indicates that if descriptors in this binding are updated between when the descriptor set is bound in a command buffer and when that command buffer is submitted to a queue, then the submission will use the most recently set descriptors for this binding and the updates do not invalidate the command buffer. Descriptor bindings created with this flag are also partially exempt from the external synchronization requirement in vkUpdateDescriptorSets. Multiple descriptors with this flag set can be updated concurrently in different threads, though the same descriptor must not be updated
concurrently by two threads. Descriptors with this flag set can be updated concurrently with the set being bound to a command buffer in another thread, but not concurrently with the set being reset or freed.

- **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** indicates that descriptors in this binding that are not dynamically used need not contain valid descriptors at the time the descriptors are consumed. A descriptor is dynamically used if any shader invocation executes an instruction that performs any memory access using the descriptor. If a descriptor is not dynamically used, any resource referenced by the descriptor is not considered to be referenced during command execution.

- **VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT** indicates that descriptors in this binding can be updated after a command buffer has bound this descriptor set, or while a command buffer that uses this descriptor set is pending execution, as long as the descriptors that are updated are not used by those command buffers. Descriptor bindings created with this flag are also partially exempt from the external synchronization requirement in `vkUpdateDescriptorSetWithTemplateKHR` and `vkUpdateDescriptorSets` in the same way as for **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT**. If **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** is also set, then descriptors can be updated as long as they are not dynamically used by any shader invocations. If **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** is not set, then descriptors can be updated as long as they are not statically used by any shader invocations.

- **VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT** indicates that this is a variable-sized descriptor binding whose size will be specified when a descriptor set is allocated using this layout. The value of `descriptorCount` is treated as an upper bound on the size of the binding. This must only be used for the last binding in the descriptor set layout (i.e. the binding with the largest value of `binding`). For the purposes of counting against limits such as `maxDescriptorSet*` and `maxPerStageDescriptor*`, the full value of `descriptorCount` is counted, except for descriptor bindings with a descriptor type of **VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK**. In this case, `descriptorCount` specifies the upper bound on the byte size of the binding; thus it counts against the `maxInlineUniformTotalSize` limit instead.

---

**Note**

Note that while **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** and **VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT** both involve updates to descriptor sets after they are bound, **VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT** is a weaker requirement since it is only about descriptors that are not used, whereas **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** requires the implementation to observe updates to descriptors that are used.

```c
// Provided by VK_VERSION_1_2
typedef VkFlags VkDescriptorBindingFlags;
```

**VkDescriptorBindingFlags** is a bitmask type for setting a mask of zero or more **VkDescriptorBindingFlagBits**.

To query information about whether a descriptor set layout can be created, call:
void vkGetDescriptorSetLayoutSupport(
    VkDevice device,
    const VkDescriptorSetLayoutCreateInfo* pCreateInfo,
    VkDescriptorSetLayoutSupport* pSupport);

• device is the logical device that would create the descriptor set layout.
• pCreateInfo is a pointer to a VkDescriptorSetLayoutCreateInfo structure specifying the state of the descriptor set layout object.
• pSupport is a pointer to a VkDescriptorSetLayoutSupport structure, in which information about support for the descriptor set layout object is returned.

Some implementations have limitations on what fits in a descriptor set which are not easily expressible in terms of existing limits like maxDescriptorSet*, for example if all descriptor types share a limited space in memory but each descriptor is a different size or alignment. This command returns information about whether a descriptor set satisfies this limit. If the descriptor set layout satisfies the VkPhysicalDeviceMaintenance3Properties::maxPerSetDescriptors limit, this command is guaranteed to return VK_TRUE in VkDescriptorSetLayoutSupport::supported. If the descriptor set layout exceeds the VkPhysicalDeviceMaintenance3Properties::maxPerSetDescriptors limit, whether the descriptor set layout is supported is implementation-dependent and may depend on whether the descriptor sizes and alignments cause the layout to exceed an internal limit.

This command does not consider other limits such as maxPerStageDescriptor*, and so a descriptor set layout that is supported according to this command must still satisfy the pipeline layout limits such as maxPerStageDescriptor* in order to be used in a pipeline layout.

**Valid Usage (Implicit)**

• VUID-vkGetDescriptorSetLayoutSupport-device-parameter
device must be a valid VkDevice handle

• VUID-vkGetDescriptorSetLayoutSupport-pCreateInfo-parameter
pCreateInfo must be a valid pointer to a valid VkDescriptorSetLayoutCreateInfo structure

• VUID-vkGetDescriptorSetLayoutSupport-pSupport-parameter
pSupport must be a valid pointer to a VkDescriptorSetLayoutSupport structure

Information about support for the descriptor set layout is returned in a VkDescriptorSetLayoutSupport structure:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDescriptorSetLayoutSupport {
```
VkStructureType sType;
void* pNext;
VkBool32 supported;
} VkDescriptorSetLayoutSupport;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **supported** specifies whether the descriptor set layout can be created.

Supported is set to VK_TRUE if the descriptor set can be created, or else is set to VK_FALSE.

**Valid Usage (Implicit)**

- VUID-VkDescriptorSetLayoutSupport-sType-sType
  sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT
- VUID-VkDescriptorSetLayoutSupport-pNext-pNext
  pNext must be NULL or a pointer to a valid instance of VkDescriptorSetVariableDescriptorCountLayoutSupport
- VUID-VkDescriptorSetLayoutSupport-sType-unique
  The sType value of each struct in the pNext chain must be unique

If the pNext chain of a VkDescriptorSetLayoutSupport structure includes a VkDescriptorSetVariableDescriptorCountLayoutSupport structure, then that structure returns additional information about whether the descriptor set layout is supported.

// Provided by VK_VERSION_1_2
typedef struct VkDescriptorSetVariableDescriptorCountLayoutSupport {
  VkStructureType sType;
  void* pNext;
  uint32_t maxVariableDescriptorCount;
} VkDescriptorSetVariableDescriptorCountLayoutSupport;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **maxVariableDescriptorCount** indicates the maximum number of descriptors supported in the highest numbered binding of the layout, if that binding is variable-sized. If the highest numbered binding of the layout has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then maxVariableDescriptorCount indicates the maximum byte size supported for the binding, if that binding is variable-sized.

If the VkDescriptorSetLayoutCreateInfo structure specified in vkGetDescriptorSetLayoutSupport::pCreateInfo includes a variable-sized descriptor, then supported is determined assuming the requested size of the variable-sized descriptor, and maxVariableDescriptorCount is set to the maximum size of that descriptor that can be successfully created (which is greater than or equal to
the requested size passed in). If the 

*VkDescriptorSetLayoutCreateInfo* structure does not include a variable-sized descriptor, or if the 

*VkPhysicalDeviceDescriptorIndexingFeatures* ::

*descriptorBindingVariableDescriptorCount* feature is not enabled, then 

*maxVariableDescriptorCount* is set to zero. For the purposes of this command, a variable-sized descriptor binding with a 

*descriptorCount* of zero is treated as having a 

*descriptorCount* of four if 

*descriptorType* is 

*VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK*, or one otherwise, and thus the binding is not ignored and 

the maximum descriptor count will be returned. If the layout is not supported, then the value 

written to 

*maxVariableDescriptorCount* is undefined.

### Valid Usage (Implicit)

- VUID-

*VkDescriptorSetVariableDescriptorCountLayoutSupport*-sType-sType

**sType** must be 

*VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_LAYOUT_SUPPORT*

The following examples show a shader snippet using two descriptor sets, and application code that creates corresponding descriptor set layouts.

**GLSL example**

```glsl
isValid

// binding to a single sampled image descriptor in set 0
//
layout (set=0, binding=0) uniform texture2D mySampledImage;

// binding to an array of sampled image descriptors in set 0
//
layout (set=0, binding=1) uniform texture2D myArrayOfSampledImages[12];

// binding to a single uniform buffer descriptor in set 1
//
layout (set=1, binding=0) uniform myUniformBuffer
{
  vec4 myElement[32];
};
```

**SPIR-V example**

```spirv
...%1 = OpExtInstImport "GLSL.std.450"
...
OpName %9 "mySampledImage"
OpName %14 "myArrayOfSampledImages"
OpName %18 "myUniformBuffer"
OpMemberName %18 0 "myElement"
OpName %20 ""
```
API example

VkResult myResult;

const VkDescriptorSetLayoutBinding myDescriptorSetLayoutBinding[] =
{
    // binding to a single image descriptor
    {
        .binding = 0,
        .descriptorType = VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,
        .descriptorCount = 1,
        .stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT,
        .pImmutableSamplers = NULL
    },

    // binding to an array of image descriptors
    {
        .binding = 1,
        .descriptorType = VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,
        .descriptorCount = 12,
        .stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT,
        .pImmutableSamplers = NULL
    }
};
// binding to a single uniform buffer descriptor
{
    .binding = 0,
    .descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER,
    .descriptorCount = 1,
    .stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT,
    .pImmutableSamplers = NULL
}
};

const VkDescriptorSetLayoutCreateInfo myDescriptorSetLayoutCreateInfo[] = {
    // Information for first descriptor set with two descriptor bindings
    { .sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO,
        .pNext = NULL,
        .flags = 0,
        .bindingCount = 2,
        .pBindings = &myDescriptorSetLayoutBinding[0]
    },

    // Information for second descriptor set with one descriptor binding
    { .sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO,
        .pNext = NULL,
        .flags = 0,
        .bindingCount = 1,
        .pBindings = &myDescriptorSetLayoutBinding[2]
    }
};

VkDescriptorSetLayout myDescriptorSetLayout[2];

// Create first descriptor set layout
myResult = vkCreateDescriptorSetLayout(
    myDevice,   // Device
    &myDescriptorSetLayoutCreateInfo[0],
    NULL,
    &myDescriptorSetLayout[0]);

// Create second descriptor set layout
myResult = vkCreateDescriptorSetLayout(
    myDevice,   // Device
    &myDescriptorSetLayoutCreateInfo[1],
    NULL,
To destroy a descriptor set layout, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyDescriptorSetLayout(
    VkDevice device,
    VkDescriptorSetLayout descriptorSetLayout,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the descriptor set layout.
- `descriptorSetLayout` is the descriptor set layout to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- **VUID-vkDestroyDescriptorSetLayout-descriptorSetLayout-00284**
  If `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, a compatible set of callbacks must be provided here.

- **VUID-vkDestroyDescriptorSetLayout-descriptorSetLayout-00285**
  If no `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, `pAllocator` must be NULL.

### Valid Usage (Implicit)

- **VUID-vkDestroyDescriptorSetLayout-device-parameter**
  `device` must be a valid `VkDevice` handle.

- **VUID-vkDestroyDescriptorSetLayout-descriptorSetLayout-parameter**
  If `descriptorSetLayout` is not `VK_NULL_HANDLE`, `descriptorSetLayout` must be a valid `VkDescriptorSetLayout` handle.

- **VUID-vkDestroyDescriptorSetLayout-pAllocator-parameter**
  If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.

- **VUID-vkDestroyDescriptorSetLayout-descriptorSetLayout-parent**
  If `descriptorSetLayout` is a valid handle, it must have been created, allocated, or retrieved from `device`.

### Host Synchronization

- Host access to `descriptorSetLayout` must be externally synchronized.
14.2.2. Pipeline Layouts

Access to descriptor sets from a pipeline is accomplished through a pipeline layout. Zero or more descriptor set layouts and zero or more push constant ranges are combined to form a pipeline layout object describing the complete set of resources that can be accessed by a pipeline. The pipeline layout represents a sequence of descriptor sets with each having a specific layout. This sequence of layouts is used to determine the interface between shader stages and shader resources. Each pipeline is created using a pipeline layout.

Pipeline layout objects are represented by VkPipelineLayout handles:

```cpp
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineLayout)
```

To create a pipeline layout, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkCreatePipelineLayout(
    VkDevice device,
    const VkPipelineLayoutCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkPipelineLayout* pPipelineLayout);
```

- `device` is the logical device that creates the pipeline layout.
- `pCreateInfo` is a pointer to a VkPipelineLayoutCreateInfo structure specifying the state of the pipeline layout object.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pPipelineLayout` is a pointer to a VkPipelineLayout handle in which the resulting pipeline layout object is returned.

**Valid Usage (Implicit)**

- VUID-vkCreatePipelineLayout-device-parameter `device` must be a valid VkDevice handle
- VUID-vkCreatePipelineLayout-pCreateInfo-parameter `pCreateInfo` must be a valid pointer to a valid VkPipelineLayoutCreateInfo structure
- VUID-vkCreatePipelineLayout-pAllocator-parameter If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure
- VUID-vkCreatePipelineLayout-pPipelineLayout-parameter `pPipelineLayout` must be a valid pointer to a VkPipelineLayout handle
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkPipelineLayoutCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineLayoutCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineLayoutCreateFlags flags;
    uint32_t setLayoutCount;
    const VkDescriptorSetLayout* pSetLayouts;
    uint32_t pushConstantRangeCount;
    const VkPushConstantRange* pPushConstantRanges;
} VkPipelineLayoutCreateInfo;
```

• `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `flags` is a bitmask of `VkPipelineLayoutCreateFlagBits` specifying options for pipeline layout creation.
• `setLayoutCount` is the number of descriptor sets included in the pipeline layout.
• `pSetLayouts` is a pointer to an array of `VkDescriptorSetLayout` objects.
• `pushConstantRangeCount` is the number of push constant ranges included in the pipeline layout.
• `pPushConstantRanges` is a pointer to an array of `VkPushConstantRange` structures defining a set of push constant ranges for use in a single pipeline layout. In addition to descriptor set layouts, a pipeline layout also describes how many push constants can be accessed by each stage of the pipeline.

Note
Push constants represent a high speed path to modify constant data in pipelines that is expected to outperform memory-backed resource updates.

Valid Usage

• VUID-VkPipelineLayoutCreateInfo-setLayoutCount-00286
  `setLayoutCount` must be less than or equal to `VkPhysicalDeviceLimits::maxBoundDescriptorSets`
The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_SAMPLER` and `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSamplers`.

The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` and `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorUniformBuffers`.

The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` and `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageBuffers`.

The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, and `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSampledImages`.

The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, and `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageImages`.

The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorInputAttachments`.

The total number of bindings in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceInlineUniformBlockProperties::maxPerStageDescriptorInlineUniformBlocks`.

The total number of descriptors with a `descriptorType` of `VK_DESCRIPTOR_TYPE_SAMPLER` and
VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindSamplers

• VUID-VkPipelineLayoutCreateInfo-descriptorType-03023
The total number of descriptors with a descriptorType of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER and VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindUniformBuffers
• VUID-VkPipelineLayoutCreateInfo-descriptorType-03024
The total number of descriptors with a descriptorType of VK_DESCRIPTOR_TYPE_STORAGE_BUFFER and VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindStorageBuffers
• VUID-VkPipelineLayoutCreateInfo-descriptorType-03025
The total number of descriptors with a descriptorType of VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, and VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindSampledImages
• VUID-VkPipelineLayoutCreateInfo-descriptorType-03026
The total number of descriptors with a descriptorType of VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, and VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindStorageImages
• VUID-VkPipelineLayoutCreateInfo-descriptorType-03027
The total number of bindings with a descriptorType of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK accessible to any given shader stage across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceInlineUniformBlockProperties::maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks
• VUID-VkPipelineLayoutCreateInfo-descriptorType-02215
The total number of bindings with a descriptorType of VK_DESCRIPTOR_TYPE_SAMPLER and VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER accessible
across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetSamplers}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03029}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffers}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03030}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffersDynamic}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03031}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffers}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03032}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffersDynamic}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03033}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER}, \texttt{VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE}, and \texttt{VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetSampledImages}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03034}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_STORAGE_IMAGE}, and \texttt{VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetStorageImages}

- \textbf{VUID-VkPipelineLayoutCreateInfo-descriptorType-03035}
  The total number of descriptors in descriptor set layouts created without the \texttt{VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT} bit set with a \texttt{descriptorType} of \texttt{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT} accessible across all shader stages and across all elements of \texttt{pSetLayouts} must be less than or equal to \texttt{VkPhysicalDeviceLimits::maxDescriptorSetInputAttachments}
• VUID-VkPipelineLayoutCreateInfo-descriptorType-02216
  The total number of bindings in descriptor set layouts created without the
  VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set with a descriptorType
  of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK accessible across all shader stages and across
  all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceInlineUniformBlockProperties::maxDescriptorSetInlineUniformBlocks

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03036
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_SAMPLER and
  VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER accessible across all shader stages and across
  all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindSamplers

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03037
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER accessible
  across all shader stages and across all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindUniformBuffers

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03038
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC accessible
  across all shader stages and across all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindUniformBuffersDynamic

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03039
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_STORAGE_BUFFER accessible
  across all shader stages and across all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageBuffers

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03040
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC accessible
  across all shader stages and across all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageBuffersDynamic

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03041
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and
  VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, and VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER accessible
  across all shader stages and across all elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindSampledImages

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03042
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, and
  VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER accessible across all shader stages and across all
  elements of pSetLayouts must be less than or equal to
  VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageImages

• VUID-VkPipelineLayoutCreateInfo-pSetLayouts-03043
  The total number of descriptors of the type VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT
accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindInputAttachments`

- **VUID-VkPipelineLayoutCreateInfo-descriptorType-02217**
  The total number of bindings with a descriptorType of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceInlineUniformBlockProperties::maxDescriptorSetUpdateAfterBindInlineUniformBlocks`

- **VUID-VkPipelineLayoutCreateInfo-descriptorType-06531**
  The total number of descriptors with a descriptorType of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceVulkan13Properties::maxInlineUniformTotalSize`

- **VUID-VkPipelineLayoutCreateInfo-pPushConstantRanges-00292**
  Any two elements of `pPushConstantRanges` must not include the same stage in `stageFlags`

- **VUID-VkPipelineLayoutCreateInfo-pSetLayouts-06561**
  Elements of `pSetLayouts` must be valid `VkDescriptorSetLayout` objects

---

**Valid Usage (Implicit)**

- **VUID-VkPipelineLayoutCreateInfo-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO`

- **VUID-VkPipelineLayoutCreateInfo-pNext-pNext**
  `pNext` must be `NULL`

- **VUID-VkPipelineLayoutCreateInfo-flags-zerobitmask**
  `flags` must be `0`

- **VUID-VkPipelineLayoutCreateInfo-pSetLayouts-parameter**
  If `setLayoutCount` is not `0`, `pSetLayouts` must be a valid pointer to an array of `setLayoutCount` valid or `VK_NULL_HANDLE` `VkDescriptorSetLayout` handles

- **VUID-VkPipelineLayoutCreateInfo-pPushConstantRanges-parameter**
  If `pushConstantRangeCount` is not `0`, `pPushConstantRanges` must be a valid pointer to an array of `pushConstantRangeCount` valid `VkPushConstantRange` structures

```c
typedef enum VkPipelineLayoutCreateFlagBits {
} VkPipelineLayoutCreateFlagBits;
```

All values for this enum are defined by extensions.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineLayoutCreateFlags;
```
VkPipelineLayoutCreateFlags is a bitmask type for setting a mask of VkPipelineLayoutCreateFlagBits.

The VkPushConstantRange structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPushConstantRange {
    VkShaderStageFlags stageFlags;
    uint32_t offset;
    uint32_t size;
} VkPushConstantRange;
```

- **stageFlags** is a set of stage flags describing the shader stages that will access a range of push constants. If a particular stage is not included in the range, then accessing members of that range of push constants from the corresponding shader stage will return undefined values.

- **offset** and **size** are the start offset and size, respectively, consumed by the range. Both **offset** and **size** are in units of bytes and **must** be a multiple of 4. The layout of the push constant variables is specified in the shader.

### Valid Usage

- VUID-VkPushConstantRange-offset-00294
  **offset** must be less than VkPhysicalDeviceLimits::maxPushConstantsSize

- VUID-VkPushConstantRange-offset-00295
  **offset** must be a multiple of 4

- VUID-VkPushConstantRange-size-00296
  **size** must be greater than 0

- VUID-VkPushConstantRange-size-00297
  **size** must be a multiple of 4

- VUID-VkPushConstantRange-size-00298
  **size** must be less than or equal to VkPhysicalDeviceLimits::maxPushConstantsSize minus **offset**

### Valid Usage (Implicit)

- VUID-VkPushConstantRange-stageFlags-parameter
  **stageFlags** must be a valid combination of VkShaderStageFlagBits values

- VUID-VkPushConstantRange-stageFlags-requiredbitmask
  **stageFlags** must not be 0

Once created, pipeline layouts are used as part of pipeline creation (see Pipelines), as part of binding descriptor sets (see Descriptor Set Binding), and as part of setting push constants (see Push Constant Updates). Pipeline creation accepts a pipeline layout as input, and the layout may be used to map (set, binding, arrayElement) tuples to implementation resources or memory locations within
a descriptor set. The assignment of implementation resources depends only on the bindings defined in the descriptor sets that comprise the pipeline layout, and not on any shader source.

All resource variables statically used in all shaders in a pipeline must be declared with a (set, binding, arrayElement) that exists in the corresponding descriptor set layout and is of an appropriate descriptor type and includes the set of shader stages it is used by in stageFlags. The pipeline layout can include entries that are not used by a particular pipeline. The pipeline layout allows the application to provide a consistent set of bindings across multiple pipeline compiles, which enables those pipelines to be compiled in a way that the implementation may cheaply switch pipelines without reprogramming the bindings.

Similarly, the push constant block declared in each shader (if present) must only place variables at offsets that are each included in a push constant range with stageFlags including the bit corresponding to the shader stage that uses it. The pipeline layout can include ranges or portions of ranges that are not used by a particular pipeline.

There is a limit on the total number of resources of each type that can be included in bindings in all descriptor set layouts in a pipeline layout as shown in Pipeline Layout Resource Limits. The “Total Resources Available” column gives the limit on the number of each type of resource that can be included in bindings in all descriptor sets in the pipeline layout. Some resource types count against multiple limits. Additionally, there are limits on the total number of each type of resource that can be used in any pipeline stage as described in Shader Resource Limits.

Table 9. Pipeline Layout Resource Limits

<table>
<thead>
<tr>
<th>Total Resources Available</th>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxDescriptorSetSamplers or maxDescriptorSetUpdateAfterBindSamplers</td>
<td>sampler</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td>maxDescriptorSetSampledImages or maxDescriptorSetUpdateAfterBindSampledImages</td>
<td>sampled image</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td></td>
<td>uniform texel buffer</td>
</tr>
<tr>
<td>maxDescriptorSetStorageImages or maxDescriptorSetUpdateAfterBindStorageImages</td>
<td>storage image</td>
</tr>
<tr>
<td></td>
<td>storage texel buffer</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffers or maxDescriptorSetUpdateAfterBindUniformBuffers</td>
<td>uniform buffer</td>
</tr>
<tr>
<td></td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffersDynamic or maxDescriptorSetUpdateAfterBindUniformBuffersDynamic</td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffers or maxDescriptorSetUpdateAfterBindStorageBuffers</td>
<td>storage buffer</td>
</tr>
<tr>
<td></td>
<td>storage buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffersDynamic or maxDescriptorSetUpdateAfterBindStorageBuffersDynamic</td>
<td>storage buffer dynamic</td>
</tr>
</tbody>
</table>
To destroy a pipeline layout, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyPipelineLayout(
    VkDevice device,
    VkPipelineLayout pipelineLayout,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the pipeline layout.
- `pipelineLayout` is the pipeline layout to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- VUID-vkDestroyPipelineLayout-pipelineLayout-00299
  If `VkAllocationCallbacks` were provided when `pipelineLayout` was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyPipelineLayout-pipelineLayout-00300
  If no `VkAllocationCallbacks` were provided when `pipelineLayout` was created, `pAllocator` must be `NULL`

- VUID-vkDestroyPipelineLayout-pipelineLayout-02004
  `pipelineLayout` must not have been passed to any `vkCmd*` command for any command buffers that are still in the recording state when `vkDestroyPipelineLayout` is called

### Valid Usage (Implicit)

- VUID-vkDestroyPipelineLayout-device-parameter
  `device` must be a valid `VkDevice` handle

- VUID-vkDestroyPipelineLayout-pipelineLayout-parameter
  If `pipelineLayout` is not `VK_NULL_HANDLE`, `pipelineLayout` must be a valid `VkPipelineLayout` handle

- VUID-vkDestroyPipelineLayout-pAllocator-parameter
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- VUID-vkDestroyPipelineLayout-pipelineLayout-parent
If `pipelineLayout` is a valid handle, it must have been created, allocated, or retrieved from device.

**Host Synchronization**

- Host access to `pipelineLayout` must be externally synchronized.

**Pipeline Layout Compatibility**

Two pipeline layouts are defined to be “compatible for push constants” if they were created with identical push constant ranges. Two pipeline layouts are defined to be “compatible for set N” if they were created with *identically defined* descriptor set layouts for sets zero through N, and if they were created with identical push constant ranges.

When binding a descriptor set (see Descriptor Set Binding) to set number N, a previously bound descriptor set bound with lower index M than N is disturbed if the pipeline layouts for set M and N are not compatible for set M. Otherwise, the bound descriptor set in M is not disturbed.

If, additionally, the previously bound descriptor set for set N was bound using a pipeline layout not compatible for set N, then all bindings in sets numbered greater than N are disturbed.

When binding a pipeline, the pipeline can correctly access any previously bound descriptor set N if it was bound with compatible pipeline layout for set N, and it was not disturbed.

Layout compatibility means that descriptor sets can be bound to a command buffer for use by any pipeline created with a compatible pipeline layout, and without having bound a particular pipeline first. It also means that descriptor sets can remain valid across a pipeline change, and the same resources will be accessible to the newly bound pipeline.

When a descriptor set is disturbed by binding descriptor sets, the disturbed set is considered to contain undefined descriptors bound with the same pipeline layout as the disturbing descriptor set.

**Implementor’s Note**

A consequence of layout compatibility is that when the implementation compiles a pipeline layout and maps pipeline resources to implementation resources, the mechanism for set N should only be a function of sets [0..N].

**Note**

Place the least frequently changing descriptor sets near the start of the pipeline layout, and place the descriptor sets representing the most frequently changing resources near the end. When pipelines are switched, only the descriptor set bindings that have been invalidated will need to be updated and the remainder of the descriptor set bindings will remain in place.

The maximum number of descriptor sets that can be bound to a pipeline layout is queried from
physical device properties (see `maxBoundDescriptorSets` in `Limits`).

API example

```c
const VkDescriptorSetLayout layouts[] = { layout1, layout2 };

const VkPushConstantRange ranges[] =
{
    {
        .stageFlags = VK_SHADER_STAGE_VERTEX_BIT,
        .offset = 0,
        .size = 4
    },
    {
        .stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT,
        .offset = 4,
        .size = 4
    }
};

const VkPipelineLayoutCreateInfo createInfo =
{
    .sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO,
    .pNext = NULL,
    .flags = 0,
    .setLayoutCount = 2,
    .pSetLayouts = layouts,
    .pushConstantRangeCount = 2,
    .pPushConstantRanges = ranges
};

VkPipelineLayout myPipelineLayout;
myResult = vkCreatePipelineLayout( myDevice, &createInfo, NULL, &myPipelineLayout);
```

14.2.3. Allocation of Descriptor Sets

A descriptor pool maintains a pool of descriptors, from which descriptor sets are allocated. Descriptor pools are externally synchronized, meaning that the application must not allocate and/or free descriptor sets from the same pool in multiple threads simultaneously.

Descriptor pools are represented by `VkDescriptorPool` handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorPool)
```
To create a descriptor pool object, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkCreateDescriptorPool(
    VkDevice device,
    const VkDescriptorPoolCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkDescriptorPool* pDescriptorPool);
```

- **device** is the logical device that creates the descriptor pool.
- **pCreateInfo** is a pointer to a `VkDescriptorPoolCreateInfo` structure specifying the state of the descriptor pool object.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pDescriptorPool** is a pointer to a `VkDescriptorPool` handle in which the resulting descriptor pool object is returned.

The created descriptor pool is returned in **pDescriptorPool**.

### Valid Usage (Implicit)

- VUID-vkCreateDescriptorPool-device-parameter
  - `device` must be a valid `VkDevice` handle
- VUID-vkCreateDescriptorPool-pCreateInfo-parameter
  - `pCreateInfo` must be a valid pointer to a valid `VkDescriptorPoolCreateInfo` structure
- VUID-vkCreateDescriptorPool-pAllocator-parameter
  - If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- VUID-vkCreateDescriptorPool-pDescriptorPool-parameter
  - `pDescriptorPool` must be a valid pointer to a `VkDescriptorPool` handle

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Additional information about the pool is passed in a `VkDescriptorPoolCreateInfo` structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorPoolCreateInfo {
```
• **sType** is a `VkStructureType` value identifying this structure.

• **pNext** is `NULL` or a pointer to a structure extending this structure.

• **flags** is a bitmask of `VkDescriptorPoolCreateFlagBits` specifying certain supported operations on the pool.

• **maxSets** is the maximum number of descriptor sets that can be allocated from the pool.

• **poolSizeCount** is the number of elements in `pPoolSizes`.

• **pPoolSizes** is a pointer to an array of `VkDescriptorPoolSize` structures, each containing a descriptor type and number of descriptors of that type to be allocated in the pool.

If multiple `VkDescriptorPoolSize` structures containing the same descriptor type appear in the `pPoolSizes` array then the pool will be created with enough storage for the total number of descriptors of each type.

Fragmentation of a descriptor pool is possible and may lead to descriptor set allocation failures. A failure due to fragmentation is defined as failing a descriptor set allocation despite the sum of all outstanding descriptor set allocations from the pool plus the requested allocation requiring no more than the total number of descriptors requested at pool creation. Implementations provide certain guarantees of when fragmentation must not cause allocation failure, as described below.

If a descriptor pool has not had any descriptor sets freed since it was created or most recently reset then fragmentation must not cause an allocation failure (note that this is always the case for a pool created without the `VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT` bit set). Additionally, if all sets allocated from the pool since it was created or most recently reset use the same number of descriptors (of each type) and the requested allocation also uses that same number of descriptors (of each type), then fragmentation must not cause an allocation failure.

If an allocation failure occurs due to fragmentation, an application can create an additional descriptor pool to perform further descriptor set allocations.

If **flags** has the `VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT` bit set, descriptor pool creation may fail with the error `VK_ERROR_FRAGMENTATION` if the total number of descriptors across all pools (including this one) created with this bit set exceeds `maxUpdateAfterBindDescriptorsInAllPools`, or if fragmentation of the underlying hardware resources occurs.

### Valid Usage

- **VUID-VkDescriptorPoolCreateInfo-maxSets-00301**

  maxSets **must** be greater than 0
Valid Usage (Implicit)

- VUID-VkDescriptorPoolCreateInfo-sType-sType
  
sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO

- VUID-VkDescriptorPoolCreateInfo-pNext-pNext
  
pNext must be NULL or a pointer to a valid instance of VkDescriptorPoolInlineUniformBlockCreateInfo

- VUID-VkDescriptorPoolCreateInfo-sType-unique
  
The sType value of each struct in the pNext chain must be unique

- VUID-VkDescriptorPoolCreateInfo-flags-parameter
  
flags must be a valid combination of VkDescriptorPoolCreateFlagBits values

- VUID-VkDescriptorPoolCreateInfo-pPoolSizes-parameter
  
If poolSizeCount is not 0, pPoolSizes must be a valid pointer to an array of poolSizeCount valid VkDescriptorPoolSize structures

In order to be able to allocate descriptor sets having inline uniform block bindings the descriptor pool must be created with specifying the inline uniform block binding capacity of the descriptor pool, in addition to the total inline uniform data capacity in bytes which is specified through a VkDescriptorPoolSize structure with a descriptorType value of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK. This can be done by adding a VkDescriptorPoolInlineUniformBlockCreateInfo structure to the pNext chain of VkDescriptorPoolCreateInfo.

The VkDescriptorPoolInlineUniformBlockCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkDescriptorPoolInlineUniformBlockCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t maxInlineUniformBlockBindings;
} VkDescriptorPoolInlineUniformBlockCreateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- maxInlineUniformBlockBindings is the number of inline uniform block bindings to allocate.

Valid Usage (Implicit)

- VUID-VkDescriptorPoolInlineUniformBlockCreateInfo-sType-sType
  
sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_INLINE_UNIFORM_BLOCK_CREATE_INFO

Bits which can be set in VkDescriptorPoolCreateInfo::flags, enabling operations on a descriptor pool, are:
• **VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT** specifies that descriptor sets can return their individual allocations to the pool, i.e. all of `vkAllocateDescriptorSets`, `vkFreeDescriptorSets`, and `vkResetDescriptorPool` are allowed. Otherwise, descriptor sets allocated from the pool **must** not be individually freed back to the pool, i.e. only `vkAllocateDescriptorSets` and `vkResetDescriptorPool` are allowed.

• **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** specifies that descriptor sets allocated from this pool can include bindings with the **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** bit set. It is valid to allocate descriptor sets that have bindings that do not set the **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** bit from a pool that has **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** set.

---

**Valid Usage**

- **VUID-VkDescriptorPoolCreateFlags-descriptorCount-00302**
  
  descriptorCount **must** be greater than 0

- **VUID-VkDescriptorPoolSize-type-02218**
  
  If `type` is **VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK** then descriptorCount **must** be a multiple of 4
To destroy a descriptor pool, call:

```c
// Provided by VK_VERSION_1_0
void vkDestroyDescriptorPool(
    VkDevice device,  // device is the logical device that destroys the descriptor pool.
    VkDescriptorPool descriptorPool,  // descriptorPool is the descriptor pool to destroy.
    const VkAllocationCallbacks* pAllocator  // pAllocator controls host memory allocation as described in the Memory Allocation chapter.
);
```

When a pool is destroyed, all descriptor sets allocated from the pool are implicitly freed and become invalid. Descriptor sets allocated from a given pool do not need to be freed before destroying that descriptor pool.

---

**Valid Usage**

- **VUID-vkDestroyDescriptorPool-descriptorPool-00303**
  - All submitted commands that refer to `descriptorPool` (via any allocated descriptor sets) must have completed execution

- **VUID-vkDestroyDescriptorPool-descriptorPool-00304**
  - If `VkAllocationCallbacks` were provided when `descriptorPool` was created, a compatible set of callbacks must be provided here

- **VUID-vkDestroyDescriptorPool-descriptorPool-00305**
  - If no `VkAllocationCallbacks` were provided when `descriptorPool` was created, `pAllocator` must be `NULL`
VkAllocationCallbacks structure

- VUID-vkDestroyDescriptorPool-descriptorPool-parent
  If descriptorPool is a valid handle, it **must** have been created, allocated, or retrieved from device

**Host Synchronization**

- Host access to descriptorPool **must** be externally synchronized

Descriptor sets are allocated from descriptor pool objects, and are represented by VkDescriptorSet handles:

```c
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSet)
```

To allocate descriptor sets from a descriptor pool, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkAllocateDescriptorSets(
    VkDevice device,
    const VkDescriptorSetAllocateInfo* pAllocateInfo,
    VkDescriptorSet* pDescriptorSets);
```

- `device` is the logical device that owns the descriptor pool.
- `pAllocateInfo` is a pointer to a VkDescriptorSetAllocateInfo structure describing parameters of the allocation.
- `pDescriptorSets` is a pointer to an array of VkDescriptorSet handles in which the resulting descriptor set objects are returned.

The allocated descriptor sets are returned in `pDescriptorSets`.

When a descriptor set is allocated, the initial state is largely uninitialized and all descriptors are undefined, with the exception that samplers with a non-null `pImmutableSamplers` are initialized on allocation. Descriptors also become undefined if the underlying resource or view object is destroyed. Descriptor sets containing undefined descriptors **can** still be bound and used, subject to the following conditions:

- For descriptor set bindings created with the `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` bit set, all descriptors in that binding that are dynamically used **must** have been populated before the descriptor set is **consumed**.
- For descriptor set bindings created without the `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` bit set, all descriptors in that binding that are statically used **must** have been populated before the descriptor set is **consumed**.
• Descriptor bindings with descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` can be undefined when the descriptor set is consumed; though values in that block will be undefined.

• Entries that are not used by a pipeline can have undefined descriptors.

If a call to `vkAllocateDescriptorSets` would cause the total number of descriptor sets allocated from the pool to exceed the value of `VkDescriptorPoolCreateInfo::maxSets` used to create `pAllocateInfo->descriptorPool`, then the allocation may fail due to lack of space in the descriptor pool. Similarly, the allocation may fail due to lack of space if the call to `vkAllocateDescriptorSets` would cause the number of any given descriptor type to exceed the sum of all the `descriptorCount` members of each element of `VkDescriptorPoolCreateInfo::pPoolSizes` with a type equal to that type.

Additionally, the allocation may also fail if a call to `vkAllocateDescriptorSets` would cause the total number of inline uniform block bindings allocated from the pool to exceed the value of `VkDescriptorPoolInlineUniformBlockCreateInfo::maxInlineUniformBlockBindings` used to create the descriptor pool.

If the allocation fails due to no more space in the descriptor pool, and not because of system or device memory exhaustion, then `VK_ERROR_OUT_OF_POOL_MEMORY` must be returned.

`vkAllocateDescriptorSets` can be used to create multiple descriptor sets. If the creation of any of those descriptor sets fails, then the implementation must destroy all successfully created descriptor set objects from this command, set all entries of the `pDescriptorSets` array to `VK_NULL_HANDLE` and return the error.

**Valid Usage (Implicit)**

- VUID-vkAllocateDescriptorSets-device-parameter
  device must be a valid `VkDevice` handle

- VUID-vkAllocateDescriptorSets-pAllocateInfo-parameter
  `pAllocateInfo` must be a valid pointer to a valid `VkDescriptorSetAllocateInfo` structure

- VUID-vkAllocateDescriptorSets-pDescriptorSets-parameter
  `pDescriptorSets` must be a valid pointer to an array of `pAllocateInfo->descriptorSetCount` `VkDescriptorSet` handles

- VUID-vkAllocateDescriptorSets-pAllocateInfo::descriptorSetCount-arraylength
  `pAllocateInfo->descriptorSetCount` must be greater than 0

**Host Synchronization**

- Host access to `pAllocateInfo->descriptorPool` must be externally synchronized

**Return Codes**

**Success**
- `VK_SUCCESS`
Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_FRAGMENTED_POOL
- VK_ERROR_OUT_OF_POOL_MEMORY

The `VkDescriptorSetAllocateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorSetAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorPool descriptorPool;
    uint32_t descriptorSetCount;
    const VkDescriptorSetLayout* pSetLayouts;
} VkDescriptorSetAllocateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `descriptorPool` is the pool which the sets will be allocated from.
- `descriptorSetCount` determines the number of descriptor sets to be allocated from the pool.
- `pSetLayouts` is a pointer to an array of descriptor set layouts, with each member specifying how the corresponding descriptor set is allocated.

Valid Usage

- VUID-VkDescriptorSetAllocateInfo-apiVersion-07895
  If the VK_KHR_maintenance1 extension is not enabled, `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, `descriptorSetCount` must not be greater than the number of sets that are currently available for allocation in `descriptorPool`

- VUID-VkDescriptorSetAllocateInfo-apiVersion-07896
  If the VK_KHR_maintenance1 extension is not enabled, `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, `descriptorPool` must have enough free descriptor capacity remaining to allocate the descriptor sets of the specified layouts

- VUID-VkDescriptorSetAllocateInfo-pSetLayouts-03044
  If any element of `pSetLayouts` was created with the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set, `descriptorPool` must have been created with the `VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT` flag set

Valid Usage (Implicit)

- VUID-VkDescriptorSetAllocateInfo-sType-sType
sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO

- VUID-VkDescriptorSetAllocateInfo-pNext-pNext
  pNext must be NULL or a pointer to a valid instance of VkDescriptorSetVariableDescriptorCountAllocateInfo

- VUID-VkDescriptorSetAllocateInfo-sType-unique
  The sType value of each struct in the pNext chain must be unique

- VUID-VkDescriptorSetAllocateInfo-descriptorPool-parameter
descriptorPool must be a valid VkDescriptorPool handle

- VUID-VkDescriptorSetAllocateInfo-pSetLayouts-parameter
  pSetLayouts must be a valid pointer to an array of descriptorSetCount valid VkDescriptorSetLayout handles

- VUID-VkDescriptorSetAllocateInfo-descriptorSetCount-arraylength
descriptorSetCount must be greater than 0

- VUID-VkDescriptorSetAllocateInfo-commonparent
  Both of descriptorPool, and the elements of pSetLayouts must have been created, allocated, or retrieved from the same VkDevice

If the pNext chain of a VkDescriptorSetAllocateInfo structure includes a VkDescriptorSetVariableDescriptorCountAllocateInfo structure, then that structure includes an array of descriptor counts for variable-sized descriptor bindings, one for each descriptor set being allocated.

The VkDescriptorSetVariableDescriptorCountAllocateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkDescriptorSetVariableDescriptorCountAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t descriptorSetCount;
    const uint32_t* pDescriptorCounts;
} VkDescriptorSetVariableDescriptorCountAllocateInfo;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- descriptorSetCount is zero or the number of elements in pDescriptorCounts.
- pDescriptorCounts is a pointer to an array of descriptor counts, with each member specifying the number of descriptors in a variable-sized descriptor binding in the corresponding descriptor set being allocated.

If descriptorSetCount is zero or this structure is not included in the pNext chain, then the variable lengths are considered to be zero. Otherwise, pDescriptorCounts[i] is the number of descriptors in the variable-sized descriptor binding in the corresponding descriptor set layout. If the variable-sized descriptor binding in the corresponding descriptor set layout has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then pDescriptorCounts[i] specifies the binding’s capacity.
in bytes. If VkDescriptorSetAllocateInfo::pSetLayouts[i] does not include a variable-sized descriptor binding, then pDescriptorCounts[i] is ignored.

Valid Usage

- VUID-VkDescriptorSetVariableDescriptorCountAllocateInfo-descriptorSetCount-03045
  If descriptorSetCount is not zero, descriptorSetCount must equal VkDescriptorSetAllocateInfo::descriptorSetCount

- VUID-VkDescriptorSetVariableDescriptorCountAllocateInfo-pSetLayouts-03046
  If VkDescriptorSetAllocateInfo::pSetLayouts[i] has a variable-sized descriptor binding, then pDescriptorCounts[i] must be less than or equal to the descriptor count specified for that binding when the descriptor set layout was created

Valid Usage (Implicit)

- VUID-VkDescriptorSetVariableDescriptorCountAllocateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_ALLOCATE_INFO

- VUID-VkDescriptorSetVariableDescriptorCountAllocateInfo-pDescriptorCounts-parameter
  If descriptorSetCount is not 0, pDescriptorCounts must be a valid pointer to an array of descriptorSetCount uint32_t values

To free allocated descriptor sets, call:

```
// Provided by VK_VERSION_1_0
VkResult vkFreeDescriptorSets(
    VkDevice device,
    VkDescriptorPool descriptorPool,
    uint32_t descriptorSetCount,
    const VkDescriptorSet* pDescriptorSets);
```

- device is the logical device that owns the descriptor pool.
- descriptorPool is the descriptor pool from which the descriptor sets were allocated.
- descriptorSetCount is the number of elements in the pDescriptorSets array.
- pDescriptorSets is a pointer to an array of handles to VkDescriptorSet objects.

After calling vkFreeDescriptorSets, all descriptor sets in pDescriptorSets are invalid.

Valid Usage

- VUID-vkFreeDescriptorSets-pDescriptorSets-00309
  All submitted commands that refer to any element of pDescriptorSets must have completed execution
VUID-vkFreeDescriptorSets-pDescriptorSets-00310

*pDescriptorSets must* be a valid pointer to an array of descriptorSetCount VkDescriptorSet handles, each element of which *must* either be a valid handle or VK_NULL_HANDLE

VUID-vkFreeDescriptorSets-descriptorPool-00312

descriptorPool *must* have been created with the VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT flag

**Valid Usage (Implicit)**

- VUID-vkFreeDescriptorSets-device-parameter
device *must* be a valid VkDevice handle
- VUID-vkFreeDescriptorSets-descriptorPool-parameter
descriptorPool *must* be a valid VkDescriptorPool handle
- VUID-vkFreeDescriptorSets-descriptorSetCount-arraylength
descriptorSetCount *must* be greater than 0
- VUID-vkFreeDescriptorSets-descriptorPool-parent
descriptorPool *must* have been created, allocated, or retrieved from device
- VUID-vkFreeDescriptorSets-pDescriptorSets-parent
Each element of pDescriptorSets that is a valid handle *must* have been created, allocated, or retrieved from descriptorPool

**Host Synchronization**

- Host access to descriptorPool *must* be externally synchronized
- Host access to each member of pDescriptorSets *must* be externally synchronized

**Return Codes**

**Success**

- VK_SUCCESS

To return all descriptor sets allocated from a given pool to the pool, rather than freeing individual descriptor sets, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkResetDescriptorPool(
    VkDevice device,    // Provided by VK_VERSION_1_0
    VkDescriptorPool descriptorPool,    // Provided by VK_VERSION_1_0
    VkDescriptorPoolResetFlags flags);
```

- *device* is the logical device that owns the descriptor pool.
• **descriptorPool** is the descriptor pool to be reset.

• **flags** is reserved for future use.

Resetting a descriptor pool recycles all of the resources from all of the descriptor sets allocated from the descriptor pool back to the descriptor pool, and the descriptor sets are implicitly freed.

### Valid Usage

- **VUID-vkResetDescriptorPool-descriptorPool-00313**
  
  All uses of **descriptorPool** (via any allocated descriptor sets) must have completed execution

### Valid Usage (Implicit)

- **VUID-vkResetDescriptorPool-device-parameter**
  
  device must be a valid VkDevice handle

- **VUID-vkResetDescriptorPool-descriptorPool-parameter**
  
  descriptorPool must be a valid VkDescriptorPool handle

- **VUID-vkResetDescriptorPool-flags-zerobitmask**
  
  flags must be 0

- **VUID-vkResetDescriptorPool-descriptorPool-parent**
  
  descriptorPool must have been created, allocated, or retrieved from device

### Host Synchronization

- Host access to **descriptorPool** must be externally synchronized

- Host access to any VkDescriptorSet objects allocated from **descriptorPool** must be externally synchronized

### Return Codes

**Success**

- VK_SUCCESS

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkDescriptorPoolResetFlags;
```

**VkDescriptorPoolResetFlags** is a bitmask type for setting a mask, but is currently reserved for future use.
14.2.4. Descriptor Set Updates

Once allocated, descriptor sets can be updated with a combination of write and copy operations. To update descriptor sets, call:

```c
// Provided by VK_VERSION_1_0
void vkUpdateDescriptorSets(
    VkDevice device, 
    uint32_t descriptorWriteCount, 
    const VkWriteDescriptorSet* pDescriptorWrites, 
    uint32_t descriptorCopyCount, 
    const VkCopyDescriptorSet* pDescriptorCopies);
```

- `device` is the logical device that updates the descriptor sets.
- `descriptorWriteCount` is the number of elements in the `pDescriptorWrites` array.
- `pDescriptorWrites` is a pointer to an array of `VkWriteDescriptorSet` structures describing the descriptor sets to write to.
- `descriptorCopyCount` is the number of elements in the `pDescriptorCopies` array.
- `pDescriptorCopies` is a pointer to an array of `VkCopyDescriptorSet` structures describing the descriptor sets to copy between.

The operations described by `pDescriptorWrites` are performed first, followed by the operations described by `pDescriptorCopies`. Within each array, the operations are performed in the order they appear in the array.

Each element in the `pDescriptorWrites` array describes an operation updating the descriptor set using descriptors for resources specified in the structure.

Each element in the `pDescriptorCopies` array is a `VkCopyDescriptorSet` structure describing an operation copying descriptors between sets.

If the `dstSet` member of any element of `pDescriptorWrites` or `pDescriptorCopies` is bound, accessed, or modified by any command that was recorded to a command buffer which is currently in the recording or executable state, and any of the descriptor bindings that are updated were not created with the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` or `VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT` bits set, that command buffer becomes invalid.

### Valid Usage

- VUID-vkUpdateDescriptorSets-pDescriptorWrites-06236
  For each element `i` where `pDescriptorWrites[i].descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, elements of the `pTexelBufferView` member of `pDescriptorWrites[i]` must have been created on `device`

- VUID-vkUpdateDescriptorSets-pDescriptorWrites-06237
For each element \( i \) where \( p\text{Descriptor Writes}[i].\text{descriptorType} \) is \( \text{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER} \), \( \text{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER} \), \( \text{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC} \), or \( \text{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC} \), the buffer member of any element of the \( pBufferInfo \) member of \( p\text{Descriptor Writes}[i] \) must have been created on device

- **VUID-vkUpdateDescriptorSets-pDescriptorWrites-06238**
  For each element \( i \) where \( p\text{Descriptor Writes}[i].\text{descriptorType} \) is \( \text{VK_DESCRIPTOR_TYPE_SAMPLER} \) or \( \text{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER} \), and \( dst\text{Set} \) was not allocated with a layout that included immutable samplers for \( dst\text{Binding} \) with \( \text{descriptorType} \), the sampler member of any element of the \( p\text{ImageInfo} \) member of \( p\text{Descriptor Writes}[i] \) must have been created on device

- **VUID-vkUpdateDescriptorSets-pDescriptorWrites-06239**
  For each element \( i \) where \( p\text{Descriptor Writes}[i].\text{descriptorType} \) is \( \text{VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE} \), \( \text{VK_DESCRIPTOR_TYPE_STORAGE_IMAGE} \), \( \text{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT} \), or \( \text{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER} \) the imageView member of any element of \( p\text{Descriptor Writes}[i] \) must have been created on device

- **VUID-vkUpdateDescriptorSets-pDescriptorWrites-06493**
  For each element \( i \) where \( p\text{Descriptor Writes}[i].\text{descriptorType} \) is \( \text{VK_DESCRIPTOR_TYPE_SAMPLER} \), \( \text{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER} \), \( \text{VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE} \), \( \text{VK_DESCRIPTOR_TYPE_STORAGE_IMAGE} \), or \( \text{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT} \), \( p\text{Descriptor Writes}[i].p\text{ImageInfo} \) must be a valid pointer to an array of \( p\text{Descriptor Writes}[i].\text{descriptorCount} \) valid VkDescriptorImageInfo structures

- **VUID-vkUpdateDescriptorSets-None-03047**
  Descriptor bindings updated by this command which were created without the \( \text{VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT} \) or \( \text{VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT} \) bits set must not be used by any command that was recorded to a command buffer which is in the pending state

- **VUID-vkUpdateDescriptorSets-pDescriptorWrites-06993**
  Host access to \( p\text{Descriptor Writes}[i].dst\text{Set} \) and \( p\text{DescriptorCopies}[i].dst\text{Set} \) must be externally synchronized unless explicitly denoted otherwise for specific flags

---

**Valid Usage (Implicit)**

- **VUID-vkUpdateDescriptorSets-device-parameter**
  device must be a valid VkDevice handle

- **VUID-vkUpdateDescriptorSets-pDescriptorWrites-parameter**
  If \( descriptor\text{WriteCount} \) is not 0, \( p\text{Descriptor Writes} \) must be a valid pointer to an array of \( descriptor\text{WriteCount} \) valid VkWriteDescriptorSet structures

- **VUID-vkUpdateDescriptorSets-pDescriptorCopies-parameter**
  If \( descriptor\text{CopyCount} \) is not 0, \( p\text{DescriptorCopies} \) must be a valid pointer to an array of \( descriptor\text{CopyCount} \) valid VkCopyDescriptorSet structures
The `VkWriteDescriptorSet` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkWriteDescriptorSet {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorSet dstSet;
    uint32_t dstBinding;
    uint32_t dstArrayElement;
    uint32_t descriptorCount;
    VkDescriptorType descriptorType;
    const VkDescriptorImageInfo* pImageInfo;
    const VkDescriptorBufferInfo* pBufferInfo;
    const VkBufferView* pTexelBufferView;
} VkWriteDescriptorSet;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `dstSet` is the destination descriptor set to update.
- `dstBinding` is the descriptor binding within that set.
- `dstArrayElement` is the starting element in that array. If the descriptor binding identified by `dstSet` and `dstBinding` has a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` then `dstArrayElement` specifies the starting byte offset within the binding.
- `descriptorCount` is the number of descriptors to update. If the descriptor binding identified by `dstSet` and `dstBinding` has a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`, then `descriptorCount` specifies the number of bytes to update. Otherwise, `descriptorCount` is one of:
  - the number of elements in `pImageInfo`
  - the number of elements in `pBufferInfo`
  - the number of elements in `pTexelBufferView`
  - a value matching the `dataSize` member of a `VkWriteDescriptorSetInlineUniformBlock` structure in the `pNext` chain
- `descriptorType` is a `VkDescriptorType` specifying the type of each descriptor in `pImageInfo`, `pBufferInfo`, or `pTexelBufferView`, as described below. It must be the same type as the `descriptorType` specified in `VkDescriptorSetLayoutBinding` for `dstSet` at `dstBinding`. The type of the descriptor also controls which array the descriptors are taken from.
- `pImageInfo` is a pointer to an array of `VkDescriptorImageInfo` structures or is ignored, as described below.
- `pBufferInfo` is a pointer to an array of `VkDescriptorBufferInfo` structures or is ignored, as described below.
- `pTexelBufferView` is a pointer to an array of `VkBufferView` handles as described in the Buffer Views section or is ignored, as described below.

Only one of `pImageInfo`, `pBufferInfo`, or `pTexelBufferView` members is used according to the
descriptor type specified in the descriptorType member of the containing VkWriteDescriptorSet structure, or none of them in case descriptorType is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, in which case the source data for the descriptor writes is taken from the VkWriteDescriptorSetInlineUniformBlock structure included in the pNext chain of VkWriteDescriptorSet, as specified below.

If the dstBinding has fewer than descriptorCount array elements remaining starting from dstArrayElement, then the remainder will be used to update the subsequent binding - dstBinding+1 starting at array element zero. If a binding has a descriptorCount of zero, it is skipped. This behavior applies recursively, with the update affecting consecutive bindings as needed to update all descriptorCount descriptors. Consecutive bindings must have identical VkDescriptorType, VkShaderStageFlags, VkDescriptorBindingFlagBits, and immutable samplers references.

Note

The same behavior applies to bindings with a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK where descriptorCount specifies the number of bytes to update while dstArrayElement specifies the starting byte offset, thus in this case if the dstArrayElement has a smaller byte size than the sum of dstArrayElement and descriptorCount, then the remainder will be used to update the subsequent binding - dstBinding+1 starting at offset zero. This falls out as a special case of the above rule.

Valid Usage

- VUID-VkWriteDescriptorSet-dstBinding-00315
dstBinding must be less than or equal to the maximum value of binding of all VkDescriptorSetLayoutBinding structures specified when dstSet's descriptor set layout was created.

- VUID-VkWriteDescriptorSet-dstBinding-00316
dstBinding must be a binding with a non-zero descriptorCount.

- VUID-VkWriteDescriptorSet-descriptorCount-00317
All consecutive bindings updated via a single VkWriteDescriptorSet structure, except those with a descriptorCount of zero, must have identical descriptorType and stageFlags.

- VUID-VkWriteDescriptorSet-descriptorCount-00318
All consecutive bindings updated via a single VkWriteDescriptorSet structure, except those with a descriptorCount of zero, must all either use immutable samplers or must all not use immutable samplers.

- VUID-VkWriteDescriptorSet-descriptorType-00319
descriptorType must match the type of dstBinding within dstSet.

- VUID-VkWriteDescriptorSet-dstSet-00320
dstSet must be a valid VkDescriptorSet handle.

- VUID-VkWriteDescriptorSet-dstArrayElement-00321
The sum of dstArrayElement and descriptorCount must be less than or equal to the number of array elements in the descriptor set binding specified by dstBinding, and all applicable consecutive bindings, as described by consecutive binding updates.
• VUID-VkWriteDescriptorSet-descriptorType-02219
  If descriptorType is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, dstArrayElement must be an integer multiple of 4

• VUID-VkWriteDescriptorSet-descriptorType-02220
  If descriptorType is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, descriptorCount must be an integer multiple of 4

• VUID-VkWriteDescriptorSet-descriptorType-02994
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, each element of pTexelBufferView must be either a valid VkBufferView handle or VK_NULL_HANDLE

• VUID-VkWriteDescriptorSet-descriptorType-02995
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER and the nullDescriptor feature is not enabled, each element of pTexelBufferView must not be VK_NULL_HANDLE

• VUID-VkWriteDescriptorSet-descriptorType-00324
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, VK_DESCRIPTOR_TYPE_STORAGE_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, pBufferInfo must be a valid pointer to an array of descriptorCount valid VkDescriptorBufferInfo structures

• VUID-VkWriteDescriptorSet-descriptorType-00325
  If descriptorType is VK_DESCRIPTOR_TYPE_SAMPLER or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and dstSet was not allocated with a layout that included immutable samplers for dstBinding with descriptorType, the sampler member of each element of pImageInfo must be a valid VkSampler object

• VUID-VkWriteDescriptorSet-descriptorType-02996
  If descriptorType is VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, or VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, the imageView member of each element of pImageInfo must be either a valid VkImageView handle or VK_NULL_HANDLE

• VUID-VkWriteDescriptorSet-descriptorType-02997
  If descriptorType is VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, or VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, and the nullDescriptor feature is not enabled, the imageView member of each element of pImageInfo must not be VK_NULL_HANDLE

• VUID-VkWriteDescriptorSet-descriptorType-07683
  If descriptorType is VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, the imageView member of each element of pImageInfo must not be VK_NULL_HANDLE

• VUID-VkWriteDescriptorSet-descriptorType-02221
  If descriptorType is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, the pNext chain must include a VkWriteDescriptorSetInlineUniformBlock structure whose dataSize member equals descriptorCount

• VUID-VkWriteDescriptorSet-descriptorType-00327
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, the offset member of each element of
pBufferInfo must be a multiple of VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment

- **VUID-VkWriteDescriptorSet-descriptorType-00328**
  If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, the offset member of each element of pBufferInfo must be a multiple of VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment

- **VUID-VkWriteDescriptorSet-descriptorType-00329**
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, VK_DESCRIPTOR_TYPE_STORAGE_BUFFER, or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, and the buffer member of any element of pBufferInfo is the handle of a non-sparse buffer, then that buffer must be bound completely and contiguously to a single VkDeviceMemory object

- **VUID-VkWriteDescriptorSet-descriptorType-00330**
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, the buffer member of each element of pBufferInfo must have been created with VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT set

- **VUID-VkWriteDescriptorSet-descriptorType-00331**
  If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, the buffer member of each element of pBufferInfo must have been created with VK_BUFFER_USAGE_STORAGE_BUFFER_BIT set

- **VUID-VkWriteDescriptorSet-descriptorType-00332**
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, the range member of each element of pBufferInfo, or the effective range if range is VK_WHOLE_SIZE, must be less than or equal to VkPhysicalDeviceLimits::maxUniformBufferRange

- **VUID-VkWriteDescriptorSet-descriptorType-00333**
  If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, the range member of each element of pBufferInfo, or the effective range if range is VK_WHOLE_SIZE, must be less than or equal to VkPhysicalDeviceLimits::maxStorageBufferRange

- **VUID-VkWriteDescriptorSet-descriptorType-00334**
  If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER, the VkBuffer that each element of pTexelBufferView was created from must have been created with VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT set

- **VUID-VkWriteDescriptorSet-descriptorType-00335**
  If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, the VkBuffer that each element of pTexelBufferView was created from must have been created with VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT set

- **VUID-VkWriteDescriptorSet-descriptorType-00336**
  If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_IMAGE or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, the imageView member of each element of pImageInfo must have been created with the identity swizzle

- **VUID-VkWriteDescriptorSet-descriptorType-00337**
If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_SAMPLED_BIT` set.

- VUID-VkWriteDescriptorSet-descriptorType-04149
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` the `imageLayout` member of each element of `pImageInfo` must be a member of the list given in Sampled Image.

- VUID-VkWriteDescriptorSet-descriptorType-04150
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` the `imageLayout` member of each element of `pImageInfo` must be a member of the list given in Combined Image Sampler.

- VUID-VkWriteDescriptorSet-descriptorType-04151
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` the `imageLayout` member of each element of `pImageInfo` must be a member of the list given in Input Attachment.

- VUID-VkWriteDescriptorSet-descriptorType-04152
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` the `imageLayout` member of each element of `pImageInfo` must be a member of the list given in Storage Image.

- VUID-VkWriteDescriptorSet-descriptorType-00338
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` set.

- VUID-VkWriteDescriptorSet-descriptorType-00339
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_STORAGE_BIT` set.

- VUID-VkWriteDescriptorSet-descriptorType-02752
  If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLER`, then `dstSet` must not have been allocated with a layout that included immutable samplers for `dstBinding`.

### Valid Usage (Implicit)

- VUID-VkWriteDescriptorSet-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET`.

- VUID-VkWriteDescriptorSet-pNext-pNext
  `pNext` must be `NULL` or a pointer to a valid instance of `VkWriteDescriptorSetInlineUniformBlock`.

- VUID-VkWriteDescriptorSet-sType-unique
  The `sType` value of each struct in the `pNext` chain must be unique.

- VUID-VkWriteDescriptorSet-descriptorType-parameter
  `descriptorType` must be a valid `VkDescriptorType` value.

- VUID-VkWriteDescriptorSet-descriptorCount-arraylength
  `descriptorCount` must be greater than 0.

- VUID-VkWriteDescriptorSet-commonparent
  Both of `dstSet`, and the elements of `pTexelBufferView` that are valid handles of non-ignored
parameters **must** have been created, allocated, or retrieved from the same **VkDevice**

The type of descriptors in a descriptor set is specified by **VkWriteDescriptorSet**:descriptorType, which **must** be one of the values:

```cpp
// Provided by VK_VERSION_1_0
typedef enum VkDescriptorType {
    VK_DESCRIPTOR_TYPE_SAMPLER = 0,
    VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER = 1,
    VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE = 2,
    VK_DESCRIPTOR_TYPE_STORAGE_IMAGE = 3,
    VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER = 4,
    VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER = 5,
    VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER = 6,
    VK_DESCRIPTOR_TYPE_STORAGE_BUFFER = 7,
    VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC = 8,
    VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC = 9,
    VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT = 10,
    // Provided by VK_VERSION_1_3
    VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK = 1000138000,
} VkDescriptorType;
```

- **VK_DESCRIPTOR_TYPE_SAMPLER** specifies a sampler descriptor.
- **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER** specifies a combined image sampler descriptor.
- **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE** specifies a sampled image descriptor.
- **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE** specifies a storage image descriptor.
- **VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER** specifies a uniform texel buffer descriptor.
- **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** specifies a storage texel buffer descriptor.
- **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER** specifies a uniform buffer descriptor.
- **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER** specifies a storage buffer descriptor.
- **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC** specifies a dynamic uniform buffer descriptor.
- **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC** specifies a dynamic storage buffer descriptor.
- **VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT** specifies an input attachment descriptor.
- **VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK** specifies an inline uniform block.

When a descriptor set is updated via elements of **VkWriteDescriptorSet**, members of **pImageInfo**, **pBufferInfo** and **pTexelBufferView** are only accessed by the implementation when they correspond to descriptor type being defined - otherwise they are ignored. The members accessed are as follows for each descriptor type:

- **For** **VK_DESCRIPTOR_TYPE_SAMPLER**, only the **sampler** member of each element of **VkWriteDescriptorSet**:pImageInfo is accessed.
- **For** **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**, **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE**, or
VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, only the imageView and imageLayout members of each element of VkWriteDescriptorSet::pImageInfo are accessed.

- For VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, all members of each element of VkWriteDescriptorSet::pImageInfo are accessed.

- For VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, VK_DESCRIPTOR_TYPE_STORAGE_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, all members of each element of VkWriteDescriptorSet::pBufferInfo are accessed.

- For VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, each element of VkWriteDescriptorSet::pTexelBufferView is accessed.

When updating descriptors with a descriptorType of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, none of the pImageInfo, pBufferInfo, or pTexelBufferView members are accessed, instead the source data of the descriptor update operation is taken from the VkWriteDescriptorSetInlineUniformBlock structure in the pNext chain of VkWriteDescriptorSet.

The VkDescriptorBufferInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorBufferInfo {
    VkBuffer buffer;
    VkDeviceSize offset;
   VkDeviceSize range;
} VkDescriptorBufferInfo;
```

- buffer is the buffer resource.
- offset is the offset in bytes from the start of buffer. Access to buffer memory via this descriptor uses addressing that is relative to this starting offset.
- range is the size in bytes that is used for this descriptor update, or VK_WHOLE_SIZE to use the range from offset to the end of the buffer.

**Note**

When setting range to VK_WHOLE_SIZE, the effective range must not be larger than the maximum range for the descriptor type (maxUniformBufferRange or maxStorageBufferRange). This means that VK_WHOLE_SIZE is not typically useful in the common case where uniform buffer descriptors are suballocated from a buffer that is much larger than maxUniformBufferRange.

For VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC and VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC descriptor types, offset is the base offset from which the dynamic offset is applied and range is the static size used for all dynamic offsets.

When range is VK_WHOLE_SIZE the effective range is calculated at vkUpdateDescriptorSets is by taking the size of buffer minus the offset.
Valid Usage

- **VUID-VkDescriptorBufferInfo-offset-00340**
  offset must be less than the size of buffer

- **VUID-VkDescriptorBufferInfo-range-00341**
  If range is not equal to VK_WHOLE_SIZE, range must be greater than 0

- **VUID-VkDescriptorBufferInfo-range-00342**
  If range is not equal to VK_WHOLE_SIZE, range must be less than or equal to the size of buffer minus offset

- **VUID-VkDescriptorBufferInfo-buffer-02998**
  If the nullDescriptor feature is not enabled, buffer must not be VK_NULL_HANDLE

Valid Usage (Implicit)

- **VUID-VkDescriptorBufferInfo-buffer-parameter**
  If buffer is not VK_NULL_HANDLE, buffer must be a valid VkBuffer handle

The *VkDescriptorImageInfo* structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDescriptorImageInfo {
  VkSampler sampler;
  VkImageView imageView;
  VkImageLayout imageLayout;
} VkDescriptorImageInfo;
```

- **sampler** is a sampler handle, and is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLER and VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER if the binding being updated does not use immutable samplers.

- **imageView** is an image view handle, and is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT.

- **imageLayout** is the layout that the image subresources accessible from imageView will be in at the time this descriptor is accessed. imageLayout is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT.

Members of VkDescriptorImageInfo that are not used in an update (as described above) are ignored.

Valid Usage

- **VUID-VkDescriptorImageInfo-imageView-06712**
  imageView must not be a 2D array image view created from a 3D image
- VUID-VkDescriptorImageInfo-descriptorType-06713
  `imageView` must not be a 2D view created from a 3D image

- VUID-VkDescriptorImageInfo-descriptorType-06714
  `imageView` must not be a 2D view created from a 3D image

- VUID-VkDescriptorImageInfo-imageView-01976
  If `imageView` is created from a depth/stencil image, the `aspectMask` used to create the `imageView` must include either `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT` but not both

- VUID-VkDescriptorImageInfo-imageView-01976
  `imageLayout` must match the actual `VkImageLayout` of each subresource accessible from `imageView` at the time this descriptor is accessed as defined by the image layout matching rules

- VUID-VkDescriptorImageInfo-imageView-01976
  If `sampler` is used and the `VkFormat` of the image is a multi-planar format, the image must have been created with `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT`, and the `aspectMask` of the `imageView` must be a valid multi-planar aspect mask

---

**Valid Usage (Implicit)**

- VUID-VkDescriptorImageInfo-commonparent
  Both of `imageView`, and `sampler` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

---

If the `descriptorType` member of `VkWriteDescriptorSet` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` then the data to write to the descriptor set is specified through a `VkWriteDescriptorSetInlineUniformBlock` structure included in the `pNext` chain of `VkWriteDescriptorSet`.

The `VkWriteDescriptorSetInlineUniformBlock` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkWriteDescriptorSetInlineUniformBlock {
    VkStructureType sType;
    const void* pNext;
    uint32_t dataSize;
    const void* pData;
} VkWriteDescriptorSetInlineUniformBlock;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `dataSize` is the number of bytes of inline uniform block data pointed to by `pData`.
- `pData` is a pointer to `dataSize` number of bytes of data to write to the inline uniform block.
Valid Usage

- VUID-VkWriteDescriptorSetInlineUniformBlock-dataSize-02222
dataSize must be an integer multiple of 4

Valid Usage (Implicit)

- VUID-VkWriteDescriptorSetInlineUniformBlock-sType-sType
  sType must be VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET_INLINE_UNIFORM_BLOCK
- VUID-VkWriteDescriptorSetInlineUniformBlock-pData-parameter
  pData must be a valid pointer to an array of dataSize bytes
- VUID-VkWriteDescriptorSetInlineUniformBlock-dataSize-arraylength
dataSize must be greater than 0

The VkCopyDescriptorSet structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkCopyDescriptorSet {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorSet srcSet;
    uint32_t srcBinding;
    uint32_t srcArrayElement;
    VkDescriptorSet dstSet;
    uint32_t dstBinding;
    uint32_t dstArrayElement;
    uint32_t descriptorCount;
} VkCopyDescriptorSet;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- srcSet, srcBinding, and srcArrayElement are the source set, binding, and array element, respectively. If the descriptor binding identified by srcSet and srcBinding has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then srcArrayElement specifies the starting byte offset within the binding to copy from.
- dstSet, dstBinding, and dstArrayElement are the destination set, binding, and array element, respectively. If the descriptor binding identified by dstSet and dstBinding has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then dstArrayElement specifies the starting byte offset within the binding to copy to.
- descriptorCount is the number of descriptors to copy from the source to destination. If descriptorCount is greater than the number of remaining array elements in the source or destination binding, those affect consecutive bindings in a manner similar to VkWriteDescriptorSet above. If the descriptor binding identified by srcSet and srcBinding has a
descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` then `descriptorCount` specifies the number of bytes to copy and the remaining array elements in the source or destination binding refer to the remaining number of bytes in those.

**Valid Usage**

- **VUID-VkCopyDescriptorSet-srcBinding-00345**
  
  `srcBinding` **must** be a valid binding within `srcSet`

- **VUID-VkCopyDescriptorSet-srcArrayElement-00346**
  
  The sum of `srcArrayElement` and `descriptorCount` **must** be less than or equal to the number of array elements in the descriptor set binding specified by `srcBinding`, and all applicable consecutive bindings, as described by consecutive binding updates

- **VUID-VkCopyDescriptorSet-dstBinding-00347**
  
  `dstBinding` **must** be a valid binding within `dstSet`

- **VUID-VkCopyDescriptorSet-dstArrayElement-00348**
  
  The sum of `dstArrayElement` and `descriptorCount` **must** be less than or equal to the number of array elements in the descriptor set binding specified by `dstBinding`, and all applicable consecutive bindings, as described by consecutive binding updates

- **VUID-VkCopyDescriptorSet-dstBinding-02632**
  
  The type of `dstBinding` within `dstSet` **must** be equal to the type of `srcBinding` within `srcSet`

- **VUID-VkCopyDescriptorSet-srcSet-00349**
  
  If `srcSet` is equal to `dstSet`, then the source and destination ranges of descriptors **must** not overlap, where the ranges **may** include array elements from consecutive bindings as described by consecutive binding updates

- **VUID-VkCopyDescriptorSet-srcBinding-02223**
  
  If the descriptor type of the descriptor set binding specified by `srcBinding` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`, `srcArrayElement` **must** be an integer multiple of 4

- **VUID-VkCopyDescriptorSet-dstBinding-02224**
  
  If the descriptor type of the descriptor set binding specified by `dstBinding` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`, `dstArrayElement` **must** be an integer multiple of 4

- **VUID-VkCopyDescriptorSet-srcBinding-02225**
  
  If the descriptor type of the descriptor set binding specified by either `srcBinding` or `dstBinding` is `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`, `descriptorCount` **must** be an integer multiple of 4

- **VUID-VkCopyDescriptorSet-srcSet-01918**
  
  If `srcSet`'s layout was created with the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` flag set, then `dstSet`'s layout **must** also have been created with the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` flag set

- **VUID-VkCopyDescriptorSet-srcSet-04886**
  
  If `srcSet`'s layout was created without the
VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT flag set, then dstSet’s layout must also have been created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT flag set

- VUID-VkCopyDescriptorSet-srcSet-01920
  If the descriptor pool from which srcSet was allocated was created with the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT flag set, then the descriptor pool from which dstSet was allocated must also have been created with the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT flag set

- VUID-VkCopyDescriptorSet-srcSet-04888
  If the descriptor pool from which srcSet was allocated was created without the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT flag set, then the descriptor pool from which dstSet was allocated must also have been created without the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT flag set

- VUID-VkCopyDescriptorSet-dstBinding-02753
  If the descriptor type of the descriptor set binding specified by dstBinding is VK_DESCRIPTOR_TYPE_SAMPLER, then dstSet must not have been allocated with a layout that included immutable samplers for dstBinding

Valid Usage (Implicit)

- VUID-VkCopyDescriptorSet-sType-sType
  sType must be VK_STRUCTURE_TYPE_COPY_DESCRIPTOR_SET

- VUID-VkCopyDescriptorSet-pNext-pNext
  pNext must be NULL

- VUID-VkCopyDescriptorSet-srcSet-parameter
  srcSet must be a valid VkDescriptorSet handle

- VUID-VkCopyDescriptorSet-dstSet-parameter
  dstSet must be a valid VkDescriptorSet handle

- VUID-VkCopyDescriptorSet-commonparent
  Both of dstSet, and srcSet must have been created, allocated, or retrieved from the same VkDevice

14.2.5. Descriptor Update Templates

A descriptor update template specifies a mapping from descriptor update information in host memory to descriptors in a descriptor set. It is designed to avoid passing redundant information to the driver when frequently updating the same set of descriptors in descriptor sets.

Descriptor update template objects are represented by VkDescriptorUpdateTemplate handles:

```c
// Provided by VK_VERSION_1_1
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorUpdateTemplate)
```
14.2.6. Descriptor Set Updates with Templates

Updating a large VkDescriptorSet array can be an expensive operation since an application must specify one VkWriteDescriptorSet structure for each descriptor or descriptor array to update, each of which re-specifies the same state when updating the same descriptor in multiple descriptor sets. For cases when an application wishes to update the same set of descriptors in multiple descriptor sets allocated using the same VkDescriptorSetLayout, vkUpdateDescriptorSetWithTemplate can be used as a replacement for vkUpdateDescriptorSets.

VkDescriptorUpdateTemplate allows implementations to convert a set of descriptor update operations on a single descriptor set to an internal format that, in conjunction with vkUpdateDescriptorSetWithTemplate, can be more efficient compared to calling vkUpdateDescriptorSets. The descriptors themselves are not specified in the VkDescriptorUpdateTemplate, rather, offsets into an application provided pointer to host memory are specified, which are combined with a pointer passed to vkUpdateDescriptorSetWithTemplate. This allows large batches of updates to be executed without having to convert application data structures into a strictly-defined Vulkan data structure.

To create a descriptor update template, call:

```c
// Provided by VK_VERSION_1_1
VkResult vkCreateDescriptorUpdateTemplate(
    VkDevice device,
    const VkDescriptorUpdateTemplateCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkDescriptorUpdateTemplate* pDescriptorUpdateTemplate);
```

- `device` is the logical device that creates the descriptor update template.
- `pCreateInfo` is a pointer to a VkDescriptorUpdateTemplateCreateInfo structure specifying the set of descriptors to update with a single call to vkUpdateDescriptorSetWithTemplate.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pDescriptorUpdateTemplate` is a pointer to a VkDescriptorUpdateTemplate handle in which the resulting descriptor update template object is returned.

**Valid Usage (Implicit)**

- VUID-vkCreateDescriptorUpdateTemplate-device-parameter `device` must be a valid VkDevice handle
- VUID-vkCreateDescriptorUpdateTemplate-pCreateInfo-parameter `pCreateInfo` must be a valid pointer to a valid VkDescriptorUpdateTemplateCreateInfo structure
- VUID-vkCreateDescriptorUpdateTemplate-pAllocator-parameter If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure
- VUID-vkCreateDescriptorUpdateTemplate-pDescriptorUpdateTemplate-parameter
The `VkDescriptorUpdateTemplateCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDescriptorUpdateTemplateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorUpdateTemplateCreateFlags flags;
    uint32_t descriptorUpdateEntryCount;
    const VkDescriptorUpdateTemplateEntry* pDescriptorUpdateEntries;
    VkDescriptorUpdateTemplateType templateType;
    VkDescriptorSetLayout descriptorSetLayout;
    VkPipelineBindPoint pipelineBindPoint;
    VkPipelineLayout pipelineLayout;
    uint32_t set;
} VkDescriptorUpdateTemplateCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `descriptorUpdateEntryCount` is the number of elements in the `pDescriptorUpdateEntries` array.
- `pDescriptorUpdateEntries` is a pointer to an array of `VkDescriptorUpdateTemplateEntry` structures describing the descriptors to be updated by the descriptor update template.
- `templateType` Specifies the type of the descriptor update template. If set to `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET` it **can** only be used to update descriptor sets with a fixed descriptorSetLayout.
- `descriptorSetLayout` is the descriptor set layout used to build the descriptor update template. All descriptor sets which are going to be updated through the newly created descriptor update template **must** be created with a layout that matches (is the same as, or defined identically to) this layout. This parameter is ignored if `templateType` is not `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET`.
- `pipelineBindPoint` is reserved for future use and is ignored.
• `pipelineLayout` is reserved for future use and is ignored
• `set` is reserved for future use and is ignored

**Valid Usage**

- VUID-VkDescriptorUpdateTemplateCreateInfo-templateType-00350
  If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET`, `descriptorSetLayout` must be a valid `VkDescriptorSetLayout` handle

**Valid Usage (Implicit)**

- VUID-VkDescriptorUpdateTemplateCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO`
- VUID-VkDescriptorUpdateTemplateCreateInfo-pNext-pNext
  `pNext` must be `NULL`
- VUID-VkDescriptorUpdateTemplateCreateInfo-flags-zeroBitmask
  `flags` must be `0`
- VUID-VkDescriptorUpdateTemplateCreateInfo-pDescriptorUpdateEntries-parameter
  `pDescriptorUpdateEntries` must be a valid pointer to an array of `descriptorUpdateEntryCount` valid `VkDescriptorUpdateTemplateEntry` structures
- VUID-VkDescriptorUpdateTemplateCreateInfo-templateType-parameter
  `templateType` must be a valid `VkDescriptorUpdateTemplateType` value
- VUID-VkDescriptorUpdateTemplateCreateInfo-descriptorUpdateEntryCount-arraylength
  `descriptorUpdateEntryCount` must be greater than `0`
- VUID-VkDescriptorUpdateTemplateCreateInfo-commonparent
  Both of `descriptorSetLayout`, and `pipelineLayout` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkDescriptorUpdateTemplateCreateFlags;
```

`VkDescriptorUpdateTemplateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The descriptor update template type is determined by the `VkDescriptorUpdateTemplateCreateInfo::templateType` property, which takes the following values:

```c
// Provided by VK_VERSION_1_1
typedef enum VkDescriptorUpdateTemplateType {
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET = 0,
} VkDescriptorUpdateTemplateType;
```
VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET specifies that the descriptor update template will be used for descriptor set updates only.

The VkDescriptorUpdateTemplateEntry structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDescriptorUpdateTemplateEntry {
    uint32_t dstBinding;
    uint32_t dstArrayElement;
    uint32_t descriptorCount;
    VkDescriptorType descriptorType;
    size_t offset;
    size_t stride;
} VkDescriptorUpdateTemplateEntry;
```

- **dstBinding** is the descriptor binding to update when using this descriptor update template.
- **dstArrayElement** is the starting element in the array belonging to **dstBinding**. If the descriptor binding identified by **dstBinding** has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then **dstArrayElement** specifies the starting byte offset to update.
- **descriptorCount** is the number of descriptors to update. If **descriptorCount** is greater than the number of remaining array elements in the destination binding, those affect consecutive bindings in a manner similar to VkWriteDescriptorSet above. If the descriptor binding identified by **dstBinding** has a descriptor type of VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then **descriptorCount** specifies the number of bytes to update and the remaining array elements in the destination binding refer to the remaining number of bytes in it.
- **descriptorType** is a VkDescriptorType specifying the type of the descriptor.
- **offset** is the offset in bytes of the first binding in the raw data structure.
- **stride** is the stride in bytes between two consecutive array elements of the descriptor update information in the raw data structure. The actual pointer **ptr** for each array element **j** of update entry **i** is computed using the following formula:

```c
const char *ptr = (const char *)pData + pDescriptorUpdateEntries[i].offset + j * pDescriptorUpdateEntries[i].stride
```

The stride is useful in case the bindings are stored in structs along with other data. If **descriptorType** is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK then the value of **stride** is ignored and the stride is assumed to be 1, i.e. the descriptor update information for them is always specified as a contiguous range.

**Valid Usage**

- VUID-VkDescriptorUpdateTemplateEntry-dstBinding-00354
  dstBinding must be a valid binding in the descriptor set layout implicitly specified when
using a descriptor update template to update descriptors

- VUID-VkDescriptorUpdateTemplateEntry-dstArrayElement-00355
dstArrayElement and descriptorCount must be less than or equal to the number of array elements in the descriptor set binding implicitly specified when using a descriptor update template to update descriptors, and all applicable consecutive bindings, as described by consecutive binding updates

- VUID-VkDescriptorUpdateTemplateEntry-descriptor-02226
If descriptor type is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, dstArrayElement must be an integer multiple of 4

- VUID-VkDescriptorUpdateTemplateEntry-descriptor-02227
If descriptor type is VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK, descriptorCount must be an integer multiple of 4

Valid Usage (Implicit)

- VUID-VkDescriptorUpdateTemplateEntry-descriptorType-parameter
descriptorType must be a valid VkDescriptorType value

To destroy a descriptor update template, call:

```c
// Provided by VK_VERSION_1_1
void vkDestroyDescriptorUpdateTemplate(
    VkDevice device,
    VkDescriptorUpdateTemplate descriptorUpdateTemplate,
    const VkAllocationCallbacks* pAllocator);
```

- device is the logical device that has been used to create the descriptor update template
- descriptorUpdateTemplate is the descriptor update template to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- VUID-vkDestroyDescriptorUpdateTemplate-descriptorSetLayout-00356
If VkAllocationCallbacks were provided when descriptorUpdateTemplate was created, a compatible set of callbacks must be provided here

- VUID-vkDestroyDescriptorUpdateTemplate-descriptorSetLayout-00357
If no VkAllocationCallbacks were provided when descriptorUpdateTemplate was created, pAllocator must be NULL

Valid Usage (Implicit)

- VUID-vkDestroyDescriptorUpdateTemplate-device-parameter
**device** must be a valid `VkDevice` handle

- [VUID-vkDestroyDescriptorUpdateTemplate-descriptorUpdateTemplate-parameter]
  If `descriptorUpdateTemplate` is not `VK_NULL_HANDLE`, `descriptorUpdateTemplate` must be a valid `VkDescriptorUpdateTemplate` handle

- [VUID-vkDestroyDescriptorUpdateTemplate-pAllocator-parameter]
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- [VUID-vkDestroyDescriptorUpdateTemplate-descriptorUpdateTemplate-parent]
  If `descriptorUpdateTemplate` is a valid handle, it must have been created, allocated, or retrieved from `device`

---

**Host Synchronization**

- Host access to `descriptorUpdateTemplate` must be externally synchronized

Once a `VkDescriptorUpdateTemplate` has been created, descriptor sets can be updated by calling:

```c
// Provided by VK_VERSION_1_1
void vkUpdateDescriptorSetWithTemplate(
    VkDevice device,
    VkDescriptorSet descriptorSet,
    VkDescriptorUpdateTemplate descriptorUpdateTemplate,
    const void* pData);
```

- `device` is the logical device that updates the descriptor set.
- `descriptorSet` is the descriptor set to update
- `descriptorUpdateTemplate` is a `VkDescriptorUpdateTemplate` object specifying the update mapping between `pData` and the descriptor set to update.
- `pData` is a pointer to memory containing one or more `VkDescriptorImageInfo`, `VkDescriptorBufferInfo`, or `VkBufferView` structures used to write the descriptors.

---

**Valid Usage**

- [VUID-vkUpdateDescriptorSetWithTemplate-pData-01685]
  `pData` must be a valid pointer to a memory containing one or more valid instances of `VkDescriptorImageInfo`, `VkDescriptorBufferInfo`, or `VkBufferView` in a layout defined by `descriptorUpdateTemplate` when it was created with `vkCreateDescriptorUpdateTemplate`

- [VUID-vkUpdateDescriptorSetWithTemplate-descriptorSet-06995]
  Host access to `descriptorSet` must be externally synchronized unless explicitly denoted otherwise for specific flags
Valid Usage (Implicit)

- VUID-vkUpdateDescriptorSetWithTemplate-device-parameter
  
  The **device** must be a valid **VkDevice** handle.

- VUID-vkUpdateDescriptorSetWithTemplate-descriptorSet-parameter
  
  The **descriptorSet** must be a valid **VkDescriptorSet** handle.

- VUID-vkUpdateDescriptorSetWithTemplate-descriptorUpdateTemplate-parameter
  
  The **descriptorUpdateTemplate** must be a valid **VkDescriptorUpdateTemplate** handle.

- VUID-vkUpdateDescriptorSetWithTemplate-descriptorUpdateTemplate-parent
  
  The **descriptorUpdateTemplate** must have been created, allocated, or retrieved from **device**.

API example

```c
struct AppBufferView {
    VkBufferView bufferView;
    uint32_t applicationRelatedInformation;
};

struct AppDataStructure {
    VkDescriptorImageInfo imageInfo;  // a single image info
    VkDescriptorBufferInfo bufferInfoArray[3];  // 3 buffer infos in an array
    AppBufferView bufferView[2];  // An application defined structure containing a bufferView
    // ... some more application related data
};

const VkDescriptorUpdateTemplateEntry descriptorUpdateTemplateEntries[] = {
    // binding to a single image descriptor
    {
        .binding = 0,
        .dstArrayElement = 0,
        .descriptorCount = 1,
        .descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER,
        .offset = offsetof(AppDataStructure, imageInfo),
        .stride = 0  // stride not required if descriptorCount is 1
    },

    // binding to an array of buffer descriptors
    {
        .binding = 1,
        .dstArrayElement = 0,
        .descriptorCount = 3,
        .descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER,
        .offset = offsetof(AppDataStructure, bufferInfoArray),
        .stride = sizeof(VkDescriptorBufferInfo)  // descriptor buffer infos are compact
    }
};
```
14.2.7. Descriptor Set Binding

To bind one or more descriptor sets to a command buffer, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdBindDescriptorSets(
    VkCommandBuffer commandBuffer,
    VkPipelineLayout layout, // ignored by given templateType
    VkDescriptorSet set,     // ignored by given templateType
    VkDescriptorUpdateTemplate template, // ignored by given templateType
    VkDescriptorUpdateTemplateCreateInfo createInfo, // ignored by given templateType
);
```
VkPipelineBindPoint
VkPipelineLayout
uint32_t
uint32_t
const VkDescriptorSet*
uint32_t
const uint32_t

vkCmdBindDescriptorSets

commandBuffer
pipelineBindPoint
layout
firstSet
descriptorSetCount
pDescriptorSets
dynamicOffsetCount
pDynamicOffsets);

• commandBuffer is the command buffer that the descriptor sets will be bound to.

• pipelineBindPoint is a VkPipelineBindPoint indicating the type of the pipeline that will use the descriptors. There is a separate set of bind points for each pipeline type, so binding one does not disturb the others.

• layout is a VkPipelineLayout object used to program the bindings.

• firstSet is the set number of the first descriptor set to be bound.

• descriptorSetCount is the number of elements in the pDescriptorSets array.

• pDescriptorSets is a pointer to an array of handles to VkDescriptorSet objects describing the descriptor sets to bind to.

• dynamicOffsetCount is the number of dynamic offsets in the pDynamicOffsets array.

• pDynamicOffsets is a pointer to an array of uint32_t values specifying dynamic offsets.

vkCmdBindDescriptorSets binds descriptor sets pDescriptorSets[0..descriptorSetCount-1] to set numbers [firstSet..firstSet+descriptorSetCount-1] for subsequent bound pipeline commands set by pipelineBindPoint. Any bindings that were previously applied via these sets are no longer valid.

Once bound, a descriptor set affects rendering of subsequent commands that interact with the given pipeline type in the command buffer until either a different set is bound to the same set number, or the set is disturbed as described in Pipeline Layout Compatibility.

A compatible descriptor set must be bound for all set numbers that any shaders in a pipeline access, at the time that a drawing or dispatching command is recorded to execute using that pipeline. However, if none of the shaders in a pipeline statically use any bindings with a particular set number, then no descriptor set need be bound for that set number, even if the pipeline layout includes a non-trivial descriptor set layout for that set number.

When consuming a descriptor, a descriptor is considered valid if the descriptor is not undefined as described by descriptor set allocation. A descriptor that was disturbed by Pipeline Layout Compatibility, or was never bound by vkCmdBindDescriptorSets is not considered valid. If a pipeline accesses a descriptor either statically or dynamically depending on the VkDescriptorBindingFlagBits, the consuming descriptor type in the pipeline must match the VkDescriptorType in VkDescriptorSetLayoutCreateInfo for the descriptor to be considered valid.

Note
Further validation may be carried out beyond validation for descriptor types, e.g. Texel Input Validation.

If any of the sets being bound include dynamic uniform or storage buffers, then pDynamicOffsets
includes one element for each array element in each dynamic descriptor type binding in each set. Values are taken from `pDynamicOffsets` in an order such that all entries for set N come before set N+1; within a set, entries are ordered by the binding numbers in the descriptor set layouts; and within a binding array, elements are in order. `dynamicOffsetCount` must equal the total number of dynamic descriptors in the sets being bound.

The effective offset used for dynamic uniform and storage buffer bindings is the sum of the relative offset taken from `pDynamicOffsets`, and the base address of the buffer plus base offset in the descriptor set. The range of the dynamic uniform and storage buffer bindings is the buffer range as specified in the descriptor set.

Each of the `pDescriptorSets` must be compatible with the pipeline layout specified by `layout`. The layout used to program the bindings must also be compatible with the pipeline used in subsequent bound pipeline commands with that pipeline type, as defined in the Pipeline Layout Compatibility section.

The descriptor set contents bound by a call to `vkCmdBindDescriptorSets` may be consumed at the following times:

- For descriptor bindings created with the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set, the contents may be consumed when the command buffer is submitted to a queue, or during shader execution of the resulting draws and dispatches, or any time in between. Otherwise,
- during host execution of the command, or during shader execution of the resulting draws and dispatches, or any time in between.

Thus, the contents of a descriptor set binding must not be altered (overwritten by an update command, or freed) between the first point in time that it may be consumed, and when the command completes executing on the queue.

The contents of `pDynamicOffsets` are consumed immediately during execution of `vkCmdBindDescriptorSets`. Once all pending uses have completed, it is legal to update and reuse a descriptor set.

---

**Valid Usage**

- **VUID-vkCmdBindDescriptorSets-pDescriptorSets-00358**
  Each element of `pDescriptorSets` must have been allocated with a `VkDescriptorSetLayout` that matches (is the same as, or identically defined as) the `VkDescriptorSetLayout` at set n in `layout`, where n is the sum of `firstSet` and the index into `pDescriptorSets`

- **VUID-vkCmdBindDescriptorSets-dynamicOffsetCount-00359**
  `dynamicOffsetCount` must be equal to the total number of dynamic descriptors in `pDescriptorSets`

- **VUID-vkCmdBindDescriptorSets-firstSet-00360**
  The sum of `firstSet` and `descriptorSetCount` must be less than or equal to `VkPipelineLayoutCreateInfo::setLayoutCount` provided when `layout` was created

- **VUID-vkCmdBindDescriptorSets-pipelineBindPoint-00361**
  `pipelineBindPoint` must be supported by the `commandBuffer`’s parent `VkCommandPool`’s queue
family

- **VUID-vkCmdBindDescriptorSets-pDynamicOffsets-01971**
  Each element of `pDynamicOffsets` which corresponds to a descriptor binding with type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` must be a multiple of `VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment`

- **VUID-vkCmdBindDescriptorSets-pDynamicOffsets-01972**
  Each element of `pDynamicOffsets` which corresponds to a descriptor binding with type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` must be a multiple of `VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment`

- **VUID-vkCmdBindDescriptorSets-pDescriptorSets-01979**
  For each dynamic uniform or storage buffer binding in `pDescriptorSets`, the sum of the effective offset and the range of the binding must be less than or equal to the size of the buffer

- **VUID-vkCmdBindDescriptorSets-pDescriptorSets-06715**
  For each dynamic uniform or storage buffer binding in `pDescriptorSets`, if the range was set with `VK_WHOLE_SIZE` then `pDynamicOffsets` which corresponds to the descriptor binding must be 0

- **VUID-vkCmdBindDescriptorSets-pDescriptorSets-06563**
  Each element of `pDescriptorSets` must be a valid `VkDescriptorSet`

---

**Valid Usage (Implicit)**

- **VUID-vkCmdBindDescriptorSets-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- **VUID-vkCmdBindDescriptorSets-pipelineBindPoint-parameter**
  `pipelineBindPoint` must be a valid `VkPipelineBindPoint` value

- **VUID-vkCmdBindDescriptorSets-layout-parameter**
  `layout` must be a valid `VkPipelineLayout` handle

- **VUID-vkCmdBindDescriptorSets-pDescriptorSets-parameter**
  `pDescriptorSets` must be a valid pointer to an array of `descriptorSetCount` valid or `VK_NULL_HANDLE` `VkDescriptorSet` handles

- **VUID-vkCmdBindDescriptorSets-pDynamicOffsets-parameter**
  If `dynamicOffsetCount` is not 0, `pDynamicOffsets` must be a valid pointer to an array of `dynamicOffsetCount` `uint32_t` values

- **VUID-vkCmdBindDescriptorSets-commandBuffer-recording**
  `commandBuffer` must be in the recording state

- **VUID-vkCmdBindDescriptorSets-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations

- **VUID-vkCmdBindDescriptorSets-descriptorSetCount-arraylength**
  `descriptorSetCount` must be greater than 0

- **VUID-vkCmdBindDescriptorSets-commonparent**

---

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Each of `commandBuffer`, `layout`, and the elements of `pDescriptorSets` that are valid handles of non-ignored parameters **must** have been created, allocated, or retrieved from the same `VkDevice`.

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized.

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

**14.2.8. Push Constant Updates**

As described above in section *Pipeline Layouts*, the pipeline layout defines shader push constants which are updated via Vulkan commands rather than via writes to memory or copy commands.

**Note**

Push constants represent a high speed path to modify constant data in pipelines that is expected to outperform memory-backed resource updates.

To update push constants, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdPushConstants(
    VkCommandBuffer commandBuffer,
    VkPipelineLayout layout,
    VkShaderStageFlags stageFlags,
    uint32_t offset,
    uint32_t size,
    const void* pValues);
```

- `commandBuffer` is the command buffer in which the push constant update will be recorded.
- `layout` is the pipeline layout used to program the push constant updates.
- `stageFlags` is a bitmask of `VkShaderStageFlagBits` specifying the shader stages that will use the push constants in the updated range.
- `offset` is the start offset of the push constant range to update, in units of bytes.
• **size** is the size of the push constant range to update, in units of bytes.

• **pValues** is a pointer to an array of **size** bytes containing the new push constant values.

When a command buffer begins recording, all push constant values are undefined. Reads of undefined push constant values by the executing shader return undefined values.

Push constant values can be updated incrementally, causing shader stages in **stageFlags** to read the new data from **pValues** for push constants modified by this command, while still reading the previous data for push constants not modified by this command. When a **bound pipeline command** is issued, the bound pipeline's layout must be compatible with the layouts used to set the values of all push constants in the pipeline layout's push constant ranges, as described in **Pipeline Layout Compatibility**. Binding a pipeline with a layout that is not compatible with the push constant layout does not disturb the push constant values.

**Note**

As **stageFlags** needs to include all flags the relevant push constant ranges were created with, any flags that are not supported by the queue family that the **VkCommandPool** used to allocate **commandBuffer** was created on are ignored.

---

### Valid Usage

- **VUID-vkCmdPushConstants-offset-01795**
  For each byte in the range specified by **offset** and **size** and for each shader stage in **stageFlags**, there must be a push constant range in **layout** that includes that byte and that stage.

- **VUID-vkCmdPushConstants-offset-01796**
  For each byte in the range specified by **offset** and **size** and for each push constant range that overlaps that byte, **stageFlags** must include all stages in that push constant range's **VkPushConstantRange::stageFlags**.

- **VUID-vkCmdPushConstants-offset-00368**
  **offset** must be a multiple of 4.

- **VUID-vkCmdPushConstants-size-00369**
  **size** must be a multiple of 4.

- **VUID-vkCmdPushConstants-offset-00370**
  **offset** must be less than **VkPhysicalDeviceLimits::maxPushConstantsSize**.

- **VUID-vkCmdPushConstants-size-00371**
  **size** must be less than or equal to **VkPhysicalDeviceLimits::maxPushConstantsSize** minus **offset**.

### Valid Usage (Implicit)

- **VUID-vkCmdPushConstants-commandBuffer-parameter**
  **commandBuffer** must be a valid **VkCommandBuffer** handle.
• VUID-vkCmdPushConstants-layout-parameter
  layout must be a valid VkPipelineLayout handle

• VUID-vkCmdPushConstants-stageFlags-parameter
  stageFlags must be a valid combination of VkShaderStageFlagBits values

• VUID-vkCmdPushConstants-stageFlags-requiredbitmask
  stageFlags must not be 0

• VUID-vkCmdPushConstants-pValues-parameter
  pValues must be a valid pointer to an array of size bytes

• VUID-vkCmdPushConstants-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdPushConstants-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

• VUID-vkCmdPushConstants-size-arraylength
  size must be greater than 0

• VUID-vkCmdPushConstants-commonparent
  Both of commandBuffer, and layout must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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<td>State</td>
</tr>
</tbody>
</table>

14.3. Physical Storage Buffer Access

To query a 64-bit buffer device address value through which buffer memory can be accessed in a shader, call:

```c
// Provided by VK_VERSION_1_2
VkDeviceAddress vkGetBufferDeviceAddress(VkDevice device,
```
const VkBufferDeviceAddressInfo* pInfo);

- `device` is the logical device that the buffer was created on.
- `pInfo` is a pointer to a VkBufferDeviceAddressInfo structure specifying the buffer to retrieve an address for.

The 64-bit return value is an address of the start of `pInfo->buffer`. The address range starting at this value and whose size is the size of the buffer can be used in a shader to access the memory bound to that buffer, using the SPV_KHR_physical_storage_buffer extension and the PhysicalStorageBuffer storage class. For example, this value can be stored in a uniform buffer, and the shader can read the value from the uniform buffer and use it to do a dependent read/write to this buffer. A value of zero is reserved as a “null” pointer and must not be returned as a valid buffer device address. All loads, stores, and atomics in a shader through PhysicalStorageBuffer pointers must access addresses in the address range of some buffer.

If the buffer was created with a non-zero value of VkBufferOpaqueCaptureAddressCreateInfo::opaqueCaptureAddress, the return value will be the same address that was returned at capture time.

The returned address must satisfy the alignment requirement specified by VkMemoryRequirements::alignment for the buffer in VkBufferDeviceAddressInfo::buffer.

If multiple VkBuffer objects are bound to overlapping ranges of VkDeviceMemory, implementations may return address ranges which overlap. In this case, it is ambiguous which VkBuffer is associated with any given device address. For purposes of valid usage, if multiple VkBuffer objects can be attributed to a device address, a VkBuffer is selected such that valid usage passes, if it exists.

### Valid Usage

- VUID-vkGetBufferDeviceAddress-None-06542
  The bufferDeviceAddress feature must be enabled

- VUID-vkGetBufferDeviceAddress-device-06543
  If `device` was created with multiple physical devices, then the bufferDeviceAddressMultiDevice feature must be enabled

### Valid Usage (Implicit)

- VUID-vkGetBufferDeviceAddress-address-device-parameter
  `device` must be a valid VkDevice handle

- VUID-vkGetBufferDeviceAddress-address-pInfo-parameter
  `pInfo` must be a valid pointer to a valid VkBufferDeviceAddressInfo structure

The VkBufferDeviceAddressInfo structure is defined as:

```c
// Provided by VK_VERSION_1_2
```
typedef struct VkBufferDeviceAddressInfo {
    VkStructureType sType;
    const void* pNext;
    VkBuffer buffer;
} VkBufferDeviceAddressInfo;

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- buffer specifies the buffer whose address is being queried.

**Valid Usage**

- VUID-VkBufferDeviceAddressInfo-buffer-02600
  If buffer is non-sparse and was not created with the
  VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT flag, then it must be bound
  completely and contiguously to a single VkDeviceMemory object

- VUID-VkBufferDeviceAddressInfo-buffer-02601
  buffer must have been created with VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT

**Valid Usage (Implicit)**

- VUID-VkBufferDeviceAddressInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_BUFFERDEVICE_ADDRESS_INFO

- VUID-VkBufferDeviceAddressInfo-pNext-pNext
  pNext must be NULL

- VUID-VkBufferDeviceAddressInfo-buffer-parameter
  buffer must be a valid VkBuffer handle

To query a 64-bit buffer opaque capture address, call:

```c
// Provided by VK_VERSION_1_2
uint64_t vkGetBufferOpaqueCaptureAddress(
    VkDevice device,
    const VkBufferDeviceAddressInfo* pInfo);
```

- device is the logical device that the buffer was created on.
- pInfo is a pointer to a VkBufferDeviceAddressInfo structure specifying the buffer to retrieve an
  address for.

The 64-bit return value is an opaque capture address of the start of pInfo->buffer.

If the buffer was created with a non-zero value of VkBufferOpaqueCaptureAddressCreateInfo
::opaqueCaptureAddress the return value must be the same address.
Valid Usage

• VUID-vkGetBufferOpaqueCaptureAddress-None-03326
  The bufferDeviceAddress feature must be enabled

• VUID-vkGetBufferOpaqueCaptureAddress-device-03327
  If device was created with multiple physical devices, then the bufferDeviceAddressMultiDevice feature must be enabled

Valid Usage (Implicit)

• VUID-vkGetBufferOpaqueCaptureAddress-device-parameter
  device must be a valid VkDevice handle

• VUID-vkGetBufferOpaqueCaptureAddress-pInfo-parameter
  pInfo must be a valid pointer to a valid VkBufferDeviceAddressInfo structure
Chapter 15. Shader Interfaces

When a pipeline is created, the set of shaders specified in the corresponding VkPipelineCreateInfo structure are implicitly linked at a number of different interfaces.

- Shader Input and Output Interface
- Vertex Input Interface
- Fragment Output Interface
- Fragment Input Attachment Interface
- Shader Resource Interface

This chapter describes valid uses for a set of SPIR-V decorations. Any other use of one of these decorations is invalid, with the exception that, when using SPIR-V versions 1.4 and earlier: Block, BufferBlock, Offset, ArrayStride, and MatrixStride can also decorate types and type members used by variables in the Private and Function storage classes.

\[\text{Note}\]

In this chapter, there are references to SPIR-V terms such as the MeshNV execution model. These terms will appear even in a build of the specification which does not support any extensions. This is as intended, since these terms appear in the unified SPIR-V specification without such qualifiers.

15.1. Shader Input and Output Interfaces

When multiple stages are present in a pipeline, the outputs of one stage form an interface with the inputs of the next stage. When such an interface involves a shader, shader outputs are matched against the inputs of the next stage, and shader inputs are matched against the outputs of the previous stage.

All the variables forming the shader input and output interfaces are listed as operands to the OpEntryPoint instruction and are declared with the Input or Output storage classes, respectively, in the SPIR-V module. These generally form the interfaces between consecutive shader stages, regardless of any non-shader stages between the consecutive shader stages.

There are two classes of variables that can be matched between shader stages, built-in variables and user-defined variables. Each class has a different set of matching criteria.

Output variables of a shader stage have undefined values until the shader writes to them or uses the Initializer operand when declaring the variable.

15.1.1. Built-in Interface Block

Shader built-in variables meeting the following requirements define the built-in interface block. They must

- be explicitly declared (there are no implicit built-ins),
• be identified with a **BuiltIn** decoration,
• form object types as described in the **Built-in Variables** section, and
• be declared in a block whose top-level members are the built-ins.

There **must** be no more than one built-in interface block per shader per interface.

Built-ins **must** not have any **Location** or **Component** decorations.

### 15.1.2. User-defined Variable Interface

The non-built-in variables listed by **OpEntryPoint** with the **Input** or **Output** storage class form the **user-defined variable interface**. These **must** have numeric type or, recursively, composite types of such types. By default, the components of such types have a width of 32 or 64 bits. If an implementation supports **storageInputOutput16**, components **can** also have a width of 16 bits. These variables **must** be identified with a **Location** decoration and **can** also be identified with a **Component** decoration.

### 15.1.3. Interface Matching

An output variable, block, or structure member in a given shader stage has an interface match with an input variable, block, or structure member in a subsequent shader stage if they both adhere to the following conditions:

• They have equivalent decorations, other than:
  • one is not decorated with **Component** and the other is declared with a **Component** of 0
  • **Interpolation** decorations
  • **RelaxedPrecision** if one is an input variable and the other an output variable

• Their types match as follows:
  • if the input is declared in a tessellation control or geometry shader as an **OpTypeArray** with an **Element Type** equivalent to the **OpType** declaration of the output, and neither is a structure member; or
  • if the **maintenance4** feature is enabled, they are declared as **OpTypeVector** variables, and the output has a **Component Count** value higher than that of the input but the same **Component Type**; or
  • if in any other case they are declared with an equivalent **OpType** declaration.

• If both are structures and every member has an interface match.

---

**Note**
The word “structure” above refers to both variables that have an **OpTypeStruct** type and interface blocks (which are also declared as **OpTypeStruct**).

All input variables and blocks **must** have an interface match in the preceding shader stage, except for built-in variables in fragment shaders. Shaders **can** declare and write to output variables that are not declared or read by the subsequent stage.
The value of an input variable is undefined if the preceding stage does not write to a matching output variable, as described above.

15.1.4. Location Assignment

This section describes Location assignments for user-defined variables and how many Location slots are consumed by a given user-variable type. As mentioned above, some inputs and outputs have an additional level of arrayness relative to other shader inputs and outputs. This outer array level is removed from the type before considering how many Location slots the type consumes.

The Location value specifies an interface slot comprised of a 32-bit four-component vector conveyed between stages. The Component specifies word components within these vector Location slots. Only types with widths of 16, 32 or 64 are supported in shader interfaces.

Inputs and outputs of the following types consume a single interface Location:

- 16-bit scalar and vector types, and
- 32-bit scalar and vector types, and
- 64-bit scalar and 2-component vector types.

64-bit three- and four-component vectors consume two consecutive Location slots.

If a declared input or output is an array of size $n$ and each element takes $m$ Location slots, it will be assigned $m \times n$ consecutive Location slots starting with the specified Location.

If the declared input or output is an $n \times m$ 16-, 32- or 64-bit matrix, it will be assigned multiple Location slots starting with the specified Location. The number of Location slots assigned for each matrix will be the same as for an $n$-element array of $m$-component vectors.

An OpVariable with a structure type that is not a block must be decorated with a Location.

When an OpVariable with a structure type (either block or non-block) is decorated with a Location, the members in the structure type must not be decorated with a Location. The OpVariable's members are assigned consecutive Location slots in declaration order, starting from the first member, which is assigned the Location decoration from the OpVariable.

When a block-type OpVariable is declared without a Location decoration, each member in its structure type must be decorated with a Location. Types nested deeper than the top-level members must not have Location decorations.

The Location slots consumed by block and structure members are determined by applying the rules above in a depth-first traversal of the instantiated members as though the structure or block member were declared as an input or output variable of the same type.

Any two inputs listed as operands on the same OpEntryPoint must not be assigned the same Location slot and Component word, either explicitly or implicitly. Any two outputs listed as operands on the same OpEntryPoint must not be assigned the same Location slot and Component word, either explicitly or implicitly.

The number of input and output Location slots available for a shader input or output interface is
limited, and dependent on the shader stage as described in Shader Input and Output Locations. All variables in both the built-in interface block and the user-defined variable interface count against these limits. Each effective Location must have a value less than the number of Location slots available for the given interface, as specified in the “Locations Available” column in Shader Input and Output Locations.

Table 10. Shader Input and Output Locations

<table>
<thead>
<tr>
<th>Shader Interface</th>
<th>Locations Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex input</td>
<td>maxVertexInputAttributes</td>
</tr>
<tr>
<td>vertex output</td>
<td>maxVertexOutputComponents / 4</td>
</tr>
<tr>
<td>tessellation control input</td>
<td>maxTessellationControlPerVertexInputComponents / 4</td>
</tr>
<tr>
<td>tessellation control output</td>
<td>maxTessellationControlPerVertexOutputComponents / 4</td>
</tr>
<tr>
<td>tessellation evaluation input</td>
<td>maxTessellationEvaluationInputComponents / 4</td>
</tr>
<tr>
<td>tessellation evaluation output</td>
<td>maxTessellationEvaluationOutputComponents / 4</td>
</tr>
<tr>
<td>geometry input</td>
<td>maxGeometryInputComponents / 4</td>
</tr>
<tr>
<td>geometry output</td>
<td>maxGeometryOutputComponents / 4</td>
</tr>
<tr>
<td>fragment input</td>
<td>maxFragmentInputComponents / 4</td>
</tr>
<tr>
<td>fragment output</td>
<td>maxFragmentOutputAttachments</td>
</tr>
</tbody>
</table>

15.1.5. Component Assignment

The Component decoration allows the Location to be more finely specified for scalars and vectors, down to the individual Component word within a Location slot that are consumed. The Component word within a Location are 0, 1, 2, and 3. A variable or block member starting at Component N will consume Component words N, N+1, N+2, ... up through its size. For 16-, and 32-bit types, it is invalid if this sequence of Component words gets larger than 3. A scalar 64-bit type will consume two of these Component words in sequence, and a two-component 64-bit vector type will consume all four Component words available within a Location. A three- or four-component 64-bit vector type must not specify a non-zero Component decoration. A three-component 64-bit vector type will consume all four Component words of the first Location and Component 0 and 1 of the second Location. This leaves Component 2 and 3 available for other component-qualified declarations.

A scalar or two-component 64-bit data type must not specify a Component decoration of 1 or 3. A Component decoration must not be specified for any type that is not a scalar or vector.

A four-component 64-bit data type will consume all four Component words of the first Location and all four Component words of the second Location.

15.2. Vertex Input Interface

When the vertex stage is present in a pipeline, the vertex shader input variables form an interface with the vertex input attributes. The vertex shader input variables are matched by the Location and
Component decorations to the vertex input attributes specified in the pVertexInputState member of the VkGraphicsPipelineCreateInfo structure.

The vertex shader input variables listed by OpEntryPoint with the Input storage class form the vertex input interface. These variables must be identified with a Location decoration and can also be identified with a Component decoration.

For the purposes of interface matching: variables declared without a Component decoration are considered to have a Component decoration of zero. The number of available vertex input Location slots is given by the maxVertexInputAttributes member of the VkPhysicalDeviceLimits structure.

See Attribute Location and Component Assignment for details.

All vertex shader inputs declared as above must have a corresponding attribute and binding in the pipeline.

15.3. Fragment Output Interface

When the fragment stage is present in a pipeline, the fragment shader outputs form an interface with the output attachments defined by a render pass instance. The fragment shader output variables are matched by the Location and Component decorations to specified color attachments.

The fragment shader output variables listed by OpEntryPoint with the Output storage class form the fragment output interface. These variables must be identified with a Location decoration. They can also be identified with a Component decoration and/or an Index decoration. For the purposes of interface matching: variables declared without a Component decoration are considered to have a Component decoration of zero, and variables declared without an Index decoration are considered to have an Index decoration of zero.

A fragment shader output variable identified with a Location decoration of i is associated with the color attachment indicated by VkRenderingInfo::pColorAttachments[i]. When using render pass objects, it is associated with the color attachment indicated by VkSubpassDescription::pColorAttachments[i]. Values are written to those attachments after passing through the blending unit as described in Blending, if enabled. Locations are consumed as described in Location Assignment. The number of available fragment output Location slots is given by the maxFragmentOutputAttachments member of the VkPhysicalDeviceLimits structure.

When an active fragment shader invocation finishes, the values of all fragment shader outputs are copied out and used as blend inputs or color attachments writes. If the invocation does not set a value for them, the input values to those blending or color attachment writes are undefined.

Components of the output variables are assigned as described in Component Assignment. Output Component words identified as 0, 1, 2, and 3 will be directed to the R, G, B, and A inputs to the blending unit, respectively, or to the output attachment if blending is disabled. If two variables are placed within the same Location, they must have the same underlying type (floating-point or integer). Component words which do not correspond to any fragment shader output will also result in undefined values for blending or color attachment writes.

Fragment outputs identified with an Index of zero are directed to the first input of the blending unit.
associated with the corresponding Location. Outputs identified with an Index of one are directed to the second input of the corresponding blending unit.

There must be no output variable which has the same Location, Component, and Index as any other, either explicitly declared or implied.

Output values written by a fragment shader must be declared with either OpTypeFloat or OpTypeInt, and a Width of 32. If storageInputOutput16 is supported, output values written by a fragment shader can be also declared with either OpTypeFloat or OpTypeInt and a Width of 16. Composites of these types are also permitted. If the color attachment has a signed or unsigned normalized fixed-point format, color values are assumed to be floating-point and are converted to fixed-point as described in Conversion from Floating-Point to Normalized Fixed-Point; If the color attachment has an integer format, color values are assumed to be integers and converted to the bit-depth of the target. Any value that cannot be represented in the attachment’s format is undefined. For any other attachment format no conversion is performed. If the type of the values written by the fragment shader do not match the format of the corresponding color attachment, the resulting values are undefined for those components.

15.4. Fragment Input Attachment Interface

When a fragment stage is present in a pipeline, the fragment shader subpass inputs form an interface with the input attachments of the current subpass. The fragment shader subpass input variables are matched by InputAttachmentIndex decorations to the input attachments specified in the pInputAttachments array of the VkSubpassDescription structure describing the subpass that the fragment shader is executed in.

The fragment shader subpass input variables with the UniformConstant storage class and a decoration of InputAttachmentIndex that are statically used by OpEntryPoint form the fragment input attachment interface. These variables must be declared with a type of OpTypeImage, a Dim operand of SubpassData, an Arrayed operand of 0, and a Sampled operand of 2. The MS operand of the OpTypeImage must be 0 if the samples field of the corresponding VkAttachmentDescription is VK_SAMPLE_COUNT_1_BIT and 1 otherwise.

A subpass input variable identified with an InputAttachmentIndex decoration of i reads from the input attachment indicated by pInputAttachments[i] member of VkSubpassDescription. If the subpass input variable is declared as an array of size N, it consumes N consecutive input attachments, starting with the index specified. There must not be more than one input variable with the same InputAttachmentIndex whether explicitly declared or implied by an array declaration per image aspect. A multi-aspect image (e.g. a depth/stencil format) can use the same input variable. The number of available input attachment indices is given by the maxPerStageDescriptorInputAttachments member of the VkPhysicalDeviceLimits structure.

Variables identified with the InputAttachmentIndex must only be used by a fragment stage. The numeric format of the subpass input must match the format of the corresponding input attachment, or the values of subpass loads from these variables are undefined. If the framebuffer attachment contains both depth and stencil aspects, the numeric format of the subpass input determines if depth or stencil aspect is accessed by the shader.

See Input Attachment for more details.
15.4.1. Fragment Input Attachment Compatibility

An input attachment that is statically accessed by a fragment shader must be backed by a descriptor that is equivalent to the VkImageView in the VkFramebuffer, except for subresourceRange.aspectMask. The aspectMask must be equal to the aspect accessed by the shader.

15.5. Shader Resource Interface

When a shader stage accesses buffer or image resources, as described in the Resource Descriptors section, the shader resource variables must be matched with the pipeline layout that is provided at pipeline creation time.

The set of shader variables that form the shader resource interface for a stage are the variables statically used by that stage's OpEntryPoint with a storage class of Uniform, UniformConstant, StorageBuffer, or PushConstant. For the fragment shader, this includes the fragment input attachment interface.

The shader resource interface consists of two sub-interfaces: the push constant interface and the descriptor set interface.

15.5.1. Push Constant Interface

The shader variables defined with a storage class of PushConstant that are statically used by the shader entry points for the pipeline define the push constant interface. They must be:

- typed as OpTypeStruct,
- identified with a Block decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

There must be no more than one push constant block statically used per shader entry point.

Each statically used member of a push constant block must be placed at an Offset such that the entire member is entirely contained within the VkPushConstantRange for each OpEntryPoint that uses it, and the stageFlags for that range must specify the appropriate VkShaderStageFlagBits for that stage. The Offset decoration for any member of a push constant block must not cause the space required for that member to extend outside the range [0, maxPushConstantsSize).

Any member of a push constant block that is declared as an array must only be accessed with dynamically uniform indices.

15.5.2. Descriptor Set Interface

The descriptor set interface is comprised of the shader variables with the storage class of StorageBuffer, Uniform or UniformConstant (including the variables in the fragment input attachment interface) that are statically used by the shader entry points for the pipeline.

These variables must have DescriptorSet and Binding decorations specified, which are assigned and matched with the VkDescriptorsetLayout objects in the pipeline layout as described in DescriptorSet.
and Binding Assignment.

The Image Format of an OpTypeImage declaration must not be Unknown, for variables which are used for OpImageRead, OpImageSparseRead, or OpImageWrite operations, except under the following conditions:

- For OpImageWrite, if the image format is listed in the storage without format list and if the shaderStorageImageWriteWithoutFormat feature is enabled and the shader module declares the StorageImageWriteWithoutFormat capability.

- For OpImageWrite, if the image format supports VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT and the shader module declares the StorageImageWriteWithoutFormat capability.

- For OpImageRead or OpImageSparseRead, if the image format is listed in the storage without format list and if the shaderStorageImageReadWithoutFormat feature is enabled and the shader module declares the StorageImageReadWithoutFormat capability.

- For OpImageRead or OpImageSparseRead, if the image format supports VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT and the shader module declares the StorageImageReadWithoutFormat capability.

- For OpImageRead, if Dim is SubpassData (indicating a read from an input attachment).

The Image Format of an OpTypeImage declaration must not be Unknown, for variables which are used for OpAtomic* operations.

Variables identified with the Uniform storage class are used to access transparent buffer backed resources. Such variables must be:

- typed as OpTypeStruct, or an array of this type,
- identified with a Block or BufferBlock decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

Variables identified with the StorageBuffer storage class are used to access transparent buffer backed resources. Such variables must be:

- typed as OpTypeStruct, or an array of this type,
- identified with a Block decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

The Offset decoration for any member of a Block-decorated variable in the Uniform storage class must not cause the space required for that variable to extend outside the range [0, maxUniformBufferRange). The Offset decoration for any member of a Block-decorated variable in the StorageBuffer storage class must not cause the space required for that variable to extend outside the range [0, maxStorageBufferRange).

Variables identified with the Uniform storage class can also be used to access transparent descriptor set backed resources when the variable is assigned to a descriptor set layout binding with a
The descriptorType of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`. In this case the variable **must** be typed as `OpTypeStruct` and **cannot** be aggregated into arrays of that type. Further, the Offset decoration for any member of such a variable **must** not cause the space required for that variable to extend outside the range `[0, maxInlineUniformBlockSize)`.

Variables identified with a storage class of `UniformConstant` and a decoration of `InputAttachmentIndex` **must** be declared as described in Fragment Input Attachment Interface.

SPIR-V variables decorated with a descriptor set and binding that identify a combined image sampler descriptor **can** have a type of `OpTypeImage`, `OpTypeSampler (Sampled=1)`, or `OpTypeSampledImage`.

Arrays of any of these types **can** be indexed with *constant integral expressions*. The following features **must** be enabled and capabilities **must** be declared in order to index such arrays with dynamically uniform or non-uniform indices:

- **Storage images (except storage texel buffers and input attachments):**
  - Dynamically uniform: `shaderStorageImageArrayDynamicIndexing` and `StorageImageArrayDynamicIndexing`
  - Non-uniform: `shaderStorageImageArrayNonUniformIndexing` and `StorageImageArrayNonUniformIndexing`

- **Storage texel buffers:**
  - Dynamically uniform: `shaderStorageTexelBufferArrayDynamicIndexing` and `StorageTexelBufferArrayDynamicIndexing`
  - Non-uniform: `shaderStorageTexelBufferArrayNonUniformIndexing` and `StorageTexelBufferArrayNonUniformIndexing`

- **Input attachments:**
  - Dynamically uniform: `shaderInputAttachmentArrayDynamicIndexing` and `InputAttachmentArrayDynamicIndexing`
  - Non-uniform: `shaderInputAttachmentArrayNonUniformIndexing` and `InputAttachmentArrayNonUniformIndexing`

- **Sampled images (except uniform texel buffers), samplers and combined image samplers:**
  - Dynamically uniform: `shaderSampledImageArrayDynamicIndexing` and `SampledImageArrayDynamicIndexing`
  - Non-uniform: `shaderSampledImageArrayNonUniformIndexing` and `SampledImageArrayNonUniformIndexing`

- **Uniform texel buffers:**
  - Dynamically uniform: `shaderUniformTexelBufferArrayDynamicIndexing` and `UniformTexelBufferArrayDynamicIndexing`
  - Non-uniform: `shaderUniformTexelBufferArrayNonUniformIndexing` and `UniformTexelBufferArrayNonUniformIndexing`

- **Uniform buffers:**
  - Dynamically uniform: `shaderUniformBufferArrayDynamicIndexing` and
UniformBufferArrayDynamicIndexing

- Non-uniform: shaderUniformBufferArrayNonUniformIndexing and UniformBufferArrayNonUniformIndexing

- Storage buffers:
  - Dynamically uniform: shaderStorageBufferArrayDynamicIndexing and StorageBufferArrayDynamicIndexing
  - Non-uniform: shaderStorageBufferArrayNonUniformIndexing and StorageBufferArrayNonUniformIndexing

If an instruction loads from or stores to a resource (including atomics and image instructions) and the resource descriptor being accessed is not dynamically uniform, then the corresponding non-uniform indexing feature **must** be enabled and the capability **must** be declared. If an instruction loads from or stores to a resource (including atomics and image instructions) and the resource descriptor being accessed is loaded from an array element with a non-constant index, then the corresponding dynamic or non-uniform indexing feature **must** be enabled and the capability **must** be declared.

If the combined image sampler enables sampler $Y'CbCr$ conversion, it **must** be indexed only by constant integral expressions when aggregated into arrays in shader code, irrespective of the shaderSampledImageArrayDynamicIndexing feature.

**Table 11. Shader Resource and Descriptor Type Correspondence**

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Descriptor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>sampler</td>
<td>VK_DESCRIPTOR_TYPE_SAMPLER or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>sampled image</td>
<td>VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>storage image</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_IMAGE</td>
</tr>
<tr>
<td>combined image sampler</td>
<td>VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>uniform texel buffer</td>
<td>VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER</td>
</tr>
<tr>
<td>storage texel buffer</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER</td>
</tr>
<tr>
<td>uniform buffer</td>
<td>VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC</td>
</tr>
<tr>
<td>storage buffer</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC</td>
</tr>
<tr>
<td>input attachment</td>
<td>VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT</td>
</tr>
<tr>
<td>inline uniform block</td>
<td>VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK</td>
</tr>
</tbody>
</table>

**Table 12. Shader Resource and Storage Class Correspondence**

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Storage Class</th>
<th>Type(^1)</th>
<th>Decoration(s)(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sampler</td>
<td>UniformConstant</td>
<td>OpTypeSampler</td>
<td></td>
</tr>
<tr>
<td>sampled image</td>
<td>UniformConstant</td>
<td>OpTypeImage (Sampled=1)</td>
<td></td>
</tr>
<tr>
<td>Resource type</td>
<td>Storage Class</td>
<td>Type$^1$</td>
<td>Decoration(s)$^2$</td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------</td>
<td>--------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>storage image</td>
<td>UniformConstant</td>
<td>OpTypeImage (Sampled=2)</td>
<td></td>
</tr>
<tr>
<td>combined image</td>
<td>UniformConstant</td>
<td>OpTypeSampler, OpTypeImage (Sampled=1)</td>
<td></td>
</tr>
<tr>
<td>sampler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uniform texel</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=Buffer, Sampled=1)</td>
<td></td>
</tr>
<tr>
<td>buffer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>storage texel buffer</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=Buffer, Sampled=2)</td>
<td></td>
</tr>
<tr>
<td>uniform buffer</td>
<td>Uniform</td>
<td>OpTypeStruct</td>
<td>Block, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>storage buffer</td>
<td>Uniform</td>
<td>OpTypeStruct</td>
<td>BufferBlock, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>StorageBuffer</td>
<td></td>
<td></td>
<td>Block, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>input attachment</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=SubpassData, Sampled=2)</td>
<td>InputAttachmentIndex</td>
</tr>
<tr>
<td>inline uniform</td>
<td>Uniform</td>
<td>OpTypeStruct</td>
<td>Block, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>block</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1
Where OpTypeImage is referenced, the Dim values Buffer and SubpassData are only accepted where they are specifically referenced. They do not correspond to resource types where a generic OpTypeImage is specified.

2
In addition to DescriptorSet and Binding.

### 15.5.3. DescriptorSet and Binding Assignment

A variable decorated with a DescriptorSet decoration of \(s\) and a Binding decoration of \(b\) indicates that this variable is associated with the VkDescriptorSetLayoutBinding that has a binding equal to \(b\) in \(pSetLayouts[s]\) that was specified in VkPipelineLayoutCreateInfo.

DescriptorSet decoration values **must** be between zero and maxBoundDescriptorSets minus one, inclusive. Binding decoration values **can** be any 32-bit unsigned integer value, as described in Descriptor Set Layout. Each descriptor set has its own binding name space.

If the Binding decoration is used with an array, the entire array is assigned that binding value. The array **must** be a single-dimensional array and size of the array **must** be no larger than the number of descriptors in the binding. If the array is runtime-sized, then array elements greater than or equal to the size of that binding in the bound descriptor set **must** not be used. If the array is runtime-sized, the runtimeDescriptorArray feature **must** be enabled and the RuntimeDescriptorArray capability **must** be declared. The index of each element of the array is referred to as the
arrayElement. For the purposes of interface matching and descriptor set operations, if a resource variable is not an array, it is treated as if it has an arrayElement of zero.

There is a limit on the number of resources of each type that can be accessed by a pipeline stage as shown in Shader Resource Limits. The “Resources Per Stage” column gives the limit on the number each type of resource that can be statically used for an entry point in any given stage in a pipeline. The “Resource Types” column lists which resource types are counted against the limit. Some resource types count against multiple limits.

The pipeline layout may include descriptor sets and bindings which are not referenced by any variables statically used by the entry points for the shader stages in the binding’s stageFlags.

However, if a variable assigned to a given DescriptorSet and Binding is statically used by the entry point for a shader stage, the pipeline layout must contain a descriptor set layout binding in that descriptor set layout and for that binding number, and that binding’s stageFlags must include the appropriate VkShaderStageFlagBits for that stage. The variable must be of a valid resource type determined by its SPIR-V type and storage class, as defined in Shader Resource and Storage Class Correspondence. The descriptor set layout binding must be of a corresponding descriptor type, as defined in Shader Resource and Descriptor Type Correspondence.

Note
There are no limits on the number of shader variables that can have overlapping set and binding values in a shader; but which resources are statically used has an impact. If any shader variable identifying a resource is statically used in a shader, then the underlying descriptor bound at the declared set and binding must support the declared type in the shader when the shader executes.

If multiple shader variables are declared with the same set and binding values, and with the same underlying descriptor type, they can all be statically used within the same shader. However, accesses are not automatically synchronized, and Aliased decorations should be used to avoid data hazards (see section 2.18.2 Aliasing in the SPIR-V specification).

If multiple shader variables with the same set and binding values are declared in a single shader, but with different declared types, where any of those are not supported by the relevant bound descriptor, that shader can only be executed if the variables with the unsupported type are not statically used.

A noteworthy example of using multiple statically-used shader variables sharing the same descriptor set and binding values is a descriptor of type VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER that has multiple corresponding shader variables in the UniformConstant storage class, where some could be OpTypeImage (Sampled=1), some could be OpTypeSampler, and some could be OpTypeSampledImage.

Table 13. Shader Resource Limits
### Resources per Stage

<table>
<thead>
<tr>
<th>Description</th>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxPerStageDescriptorSamplers or maxPerStageDescriptorUpdateAfterBindSamplers</td>
<td>sampler</td>
</tr>
<tr>
<td>maxPerStageDescriptorSampledImages or maxPerStageDescriptorUpdateAfterBindSampledImages</td>
<td>combined image sampler</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageImages or maxPerStageDescriptorUpdateAfterBindStorageImages</td>
<td>sampled image</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageImages or maxPerStageDescriptorUpdateAfterBindStorageImages</td>
<td>combined image sampler</td>
</tr>
<tr>
<td>maxPerStageDescriptorSampledImages or maxPerStageDescriptorUpdateAfterBindSampledImages</td>
<td>uniform texel buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorUniformBuffers or maxPerStageDescriptorUpdateAfterBindUniformBuffers</td>
<td>storage image</td>
</tr>
<tr>
<td>maxPerStageDescriptorUniformBuffers or maxPerStageDescriptorUpdateAfterBindUniformBuffers</td>
<td>uniform buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageBuffers or maxPerStageDescriptorUpdateAfterBindStorageBuffers</td>
<td>storage texel buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageBuffers or maxPerStageDescriptorUpdateAfterBindStorageBuffers</td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td>maxPerStageDescriptorInputAttachments or maxPerStageDescriptorUpdateAfterBindInputAttachments</td>
<td>storage buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorInputAttachments or maxPerStageDescriptorUpdateAfterBindInputAttachments</td>
<td>storage buffer dynamic</td>
</tr>
<tr>
<td>maxPerStageDescriptorInlineUniformBlocks or maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks</td>
<td>input attachment</td>
</tr>
<tr>
<td>maxPerStageDescriptorInlineUniformBlocks or maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks</td>
<td>inline uniform block</td>
</tr>
</tbody>
</table>

1

Input attachments **can** only be used in the fragment shader stage

### 15.5.4. Offset and Stride Assignment

Certain objects **must** be explicitly laid out using the Offset, ArrayStride, and MatrixStride, as described in SPIR-V explicit layout validation rules. All such layouts also **must** conform to the following requirements.

#### Note

The numeric order of Offset decorations does not need to follow member declaration order.

#### Alignment Requirements

There are different alignment requirements depending on the specific resources and on the features enabled on the device.

Matrix types are defined in terms of arrays as follows:

- A column-major matrix with C columns and R rows is equivalent to a C element array of vectors with R components.
- A row-major matrix with C columns and R rows is equivalent to an R element array of vectors with C components.
The scalar alignment of the type of an OpTypeStruct member is defined recursively as follows:

- A scalar of size N has a scalar alignment of N.
- A vector type has a scalar alignment equal to that of its component type.
- An array type has a scalar alignment equal to that of its element type.
- A structure has a scalar alignment equal to the largest scalar alignment of any of its members.
- A matrix type inherits scalar alignment from the equivalent array declaration.

The base alignment of the type of an OpTypeStruct member is defined recursively as follows:

- A scalar has a base alignment equal to its scalar alignment.
- A two-component vector has a base alignment equal to twice its scalar alignment.
- A three- or four-component vector has a base alignment equal to four times its scalar alignment.
- An array has a base alignment equal to the base alignment of its element type.
- A structure has a base alignment equal to the largest base alignment of any of its members. An empty structure has a base alignment equal to the size of the smallest scalar type permitted by the capabilities declared in the SPIR-V module. (e.g., for a 1 byte aligned empty struct in the StorageBuffer storage class, StorageBuffer8BitAccess or UniformAndStorageBuffer8BitAccess must be declared in the SPIR-V module.)
- A matrix type inherits base alignment from the equivalent array declaration.

The extended alignment of the type of an OpTypeStruct member is similarly defined as follows:

- A scalar or vector type has an extended alignment equal to its base alignment.
- An array or structure type has an extended alignment equal to the largest extended alignment of any of its members, rounded up to a multiple of 16.
- A matrix type inherits extended alignment from the equivalent array declaration.

A member is defined to improperly straddle if either of the following are true:

- It is a vector with total size less than or equal to 16 bytes, and has Offset decorations placing its first byte at F and its last byte at L, where floor(F / 16) ! = floor(L / 16).
- It is a vector with total size greater than 16 bytes and has its Offset decorations placing its first byte at a non-integer multiple of 16.

Standard Buffer Layout

Every member of an OpTypeStruct that is required to be explicitly laid out must be aligned according to the first matching rule as follows. If the struct is contained in pointer types of multiple storage classes, it must satisfy the requirements for every storage class used to reference it.

1. If the scalarBlockLayout feature is enabled on the device and the storage class is Uniform, StorageBuffer, PhysicalStorageBuffer, or PushConstant then every member must be aligned according to its scalar alignment.
2. All vectors must be aligned according to their scalar alignment.
3. If the `uniformBufferStandardLayout` feature is not enabled on the device, then any member of an `OpTypeStruct` with a storage class of `Uniform` and a decoration of `Block` **must** be aligned according to its extended alignment.

4. Every other member **must** be aligned according to its base alignment.

   **Note**

   Even if scalar alignment is supported, it is generally more performant to use the base alignment.

The memory layout **must** obey the following rules:

- The `Offset` decoration of any member **must** be a multiple of its alignment.
- Any `ArrayStride` or `MatrixStride` decoration **must** be a multiple of the alignment of the array or matrix as defined above.

If one of the conditions below applies

- The storage class is `Uniform`, `StorageBuffer`, `PhysicalStorageBuffer`, or `PushConstant`, and the `scalarBlockLayout` feature is not enabled on the device.
- The storage class is any other storage class.

the memory layout **must** also obey the following rules:

- Vectors **must** not improperly straddle, as defined above.
- The `Offset` decoration of a member **must** not place it between the end of a structure, an array or a matrix and the next multiple of the alignment of that structure, array or matrix.

   **Note**

   The `std430 layout` in GLSL satisfies these rules for types using the base alignment. The `std140 layout` satisfies the rules for types using the extended alignment.

### 15.6. Built-In Variables

Built-in variables are accessed in shaders by declaring a variable decorated with a `BuiltIn` SPIR-V decoration. The meaning of each `BuiltIn` decoration is as follows. In the remainder of this section, the name of a built-in is used interchangeably with a term equivalent to a variable decorated with that particular built-in. Built-ins that represent integer values **can** be declared as either signed or unsigned 32-bit integers.

As mentioned above, some inputs and outputs have an additional level of arrayness relative to other shader inputs and outputs. This level of arrayness is not included in the type descriptions below, but must be included when declaring the built-in.

**BaseInstance**

Decorating a variable with the `BaseInstance` built-in will make that variable contain the integer value corresponding to the first instance that was passed to the command that invoked the current vertex shader invocation. `BaseInstance` is the `firstInstance` parameter to a `direct`
drawing command or the firstInstance member of a structure consumed by an indirect drawing command.

Valid Usage

- VUID-BaseInstance-BaseInstance-04181
  The BaseInstance decoration must be used only within the Vertex Execution Model

- VUID-BaseInstance-BaseInstance-04182
  The variable decorated with BaseInstance must be declared using the Input Storage Class

- VUID-BaseInstance-BaseInstance-04183
  The variable decorated with BaseInstance must be declared as a scalar 32-bit integer value

BaseVertex

Decorating a variable with the BaseVertex built-in will make that variable contain the integer value corresponding to the first vertex or vertex offset that was passed to the command that invoked the current vertex shader invocation. For non-indexed drawing commands, this variable is the firstVertex parameter to a direct drawing command or the firstVertex member of the structure consumed by an indirect drawing command. For indexed drawing commands, this variable is the vertexOffset parameter to a direct drawing command or the vertexOffset member of the structure consumed by an indirect drawing command.

Valid Usage

- VUID-BaseVertex-BaseVertex-04184
  The BaseVertex decoration must be used only within the Vertex Execution Model

- VUID-BaseVertex-BaseVertex-04185
  The variable decorated with BaseVertex must be declared using the Input Storage Class

- VUID-BaseVertex-BaseVertex-04186
  The variable decorated with BaseVertex must be declared as a scalar 32-bit integer value

ClipDistance

Decorating a variable with the ClipDistance built-in decoration will make that variable contain the mechanism for controlling user clipping. ClipDistance is an array such that the i\(^{th}\) element of the array specifies the clip distance for plane i. A clip distance of 0 means the vertex is on the plane, a positive distance means the vertex is inside the clip half-space, and a negative distance means the vertex is outside the clip half-space.

Note

The array variable decorated with ClipDistance is explicitly sized by the shader.

Note

In the last pre-rasterization shader stage, these values will be linearly interpolated
across the primitive and the portion of the primitive with interpolated distances less than 0 will be considered outside the clip volume. If \texttt{ClipDistance} is then used by a fragment shader, \texttt{ClipDistance} contains these linearly interpolated values.

### Valid Usage

- **VUID-ClipDistance-ClipDistance-04187**
  The \texttt{ClipDistance} decoration \textbf{must} be used only within the \texttt{MeshEXT}, \texttt{MeshNV}, \texttt{Vertex}, \texttt{Fragment}, \texttt{TessellationControl}, \texttt{TessellationEvaluation}, or \texttt{Geometry Execution Model}.

- **VUID-ClipDistance-ClipDistance-04188**
  The variable decorated with \texttt{ClipDistance} within the \texttt{MeshEXT}, \texttt{MeshNV}, or \texttt{Vertex Execution Model} \textbf{must} be declared using the \texttt{Output Storage Class}.

- **VUID-ClipDistance-ClipDistance-04189**
  The variable decorated with \texttt{ClipDistance} within the \texttt{Fragment Execution Model} \textbf{must} be declared using the \texttt{Input Storage Class}.

- **VUID-ClipDistance-ClipDistance-04190**
  The variable decorated with \texttt{ClipDistance} within the \texttt{TessellationControl}, \texttt{TessellationEvaluation}, or \texttt{Geometry Execution Model} \textbf{must} not be declared in a \texttt{Storage Class} other than \texttt{Input} or \texttt{Output}.

- **VUID-ClipDistance-ClipDistance-04191**
  The variable decorated with \texttt{ClipDistance} \textbf{must} be declared as an array of 32-bit floating-point values.

### CullDistance

Decorating a variable with the \texttt{CullDistance} built-in decoration will make that variable contain the mechanism for controlling user culling. If any member of this array is assigned a negative value for all vertices belonging to a primitive, then the primitive is discarded before rasterization.

\textbf{Note}

In fragment shaders, the values of the \texttt{CullDistance} array are linearly interpolated across each primitive.

\textbf{Note}

If \texttt{CullDistance} decorates an input variable, that variable will contain the corresponding value from the \texttt{CullDistance} decorated output variable from the previous shader stage.

### Valid Usage

- **VUID-CullDistance-CullDistance-04196**
  The \texttt{CullDistance} decoration \textbf{must} be used only within the \texttt{MeshEXT}, \texttt{MeshNV}, \texttt{Vertex}, \texttt{Fragment}, \texttt{TessellationControl}, \texttt{TessellationEvaluation}, or \texttt{Geometry Execution Model}.
The variable decorated with `CullDistance` within the `MeshEXT, MeshNV` or `Vertex Execution Model` must be declared using the `Output Storage Class`.

The variable decorated with `CullDistance` within the `Fragment Execution Model` must be declared using the `Input Storage Class`.

The variable decorated with `CullDistance` within the `TessellationControl, TessellationEvaluation, or Geometry Execution Model` must not be declared using a `Storage Class` other than `Input` or `Output`.

The variable decorated with `CullDistance` must be declared as an array of 32-bit floating-point values.

---

**DeviceIndex**

The `DeviceIndex` decoration can be applied to a shader input which will be filled with the device index of the physical device that is executing the current shader invocation. This value will be in the range \([0, \max(1, \text{physicalDeviceCount})]\), where `physicalDeviceCount` is the `physicalDeviceCount` member of `VkDeviceGroupDeviceCreateInfo`.

---

**Valid Usage**

The variable decorated with `DeviceIndex` must be declared using the `Input Storage Class`.

The variable decorated with `DeviceIndex` must be declared as a scalar 32-bit integer value.

---

**DrawIndex**

Decorating a variable with the `DrawIndex` built-in will make that variable contain the integer value corresponding to the zero-based index of the drawing command that invoked the current vertex shader invocation. For *indirect drawing commands*, `DrawIndex` begins at zero and increments by one for each drawing command executed. The number of drawing commands is given by the `drawCount` parameter. For *direct drawing commands*, `DrawIndex` is always zero. `DrawIndex` is dynamically uniform.

---

**Valid Usage**

The `DrawIndex` decoration must be used only within the `Vertex, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model`.

The variable decorated with `DrawIndex` must be declared using the `Input Storage Class`.

The variable decorated with `DrawIndex` must be declared using the `Input Storage Class`.
The variable decorated with DrawIndex must be declared as a scalar 32-bit integer value

**FragCoord**

Decorating a variable with the FragCoord built-in decoration will make that variable contain the framebuffer coordinate \((x, y, z, \frac{1}{w})\) of the fragment being processed. The \((x,y)\) coordinate \((0,0)\) is the upper left corner of the upper left pixel in the framebuffer.

When Sample Shading is enabled, the \(x\) and \(y\) components of FragCoord reflect the location of one of the samples corresponding to the shader invocation.

Otherwise, the \(x\) and \(y\) components of FragCoord reflect the location of the center of the fragment.

The \(z\) component of FragCoord is the interpolated depth value of the primitive.

The \(w\) component is the interpolated \(\frac{1}{w}\).

The Centroid interpolation decoration is ignored, but allowed, on FragCoord.

**Valid Usage**

- VUID-FragCoord-FragCoord-04210
  The FragCoord decoration must be used only within the Fragment Execution Model

- VUID-FragCoord-FragCoord-04211
  The variable decorated with FragCoord must be declared using the Input Storage Class

- VUID-FragCoord-FragCoord-04212
  The variable decorated with FragCoord must be declared as a four-component vector of 32-bit floating-point values

**FragDepth**

To have a shader supply a fragment-depth value, the shader must declare the DepthReplacing execution mode. Such a shader's fragment-depth value will come from the variable decorated with the FragDepth built-in decoration.

This value will be used for any subsequent depth testing performed by the implementation or writes to the depth attachment. See fragment shader depth replacement for details.

**Valid Usage**

- VUID-FragDepth-FragDepth-04213
  The FragDepth decoration must be used only within the Fragment Execution Model

- VUID-FragDepth-FragDepth-04214
  The variable decorated with FragDepth must be declared using the Output Storage Class

- VUID-FragDepth-FragDepth-04215
  The variable decorated with FragDepth must be declared as a scalar 32-bit floating-point
If the shader dynamically writes to the variable decorated with `FragDepth`, the `DepthReplacing Execution Mode` must be declared.

**FrontFacing**

Decorating a variable with the `FrontFacing` built-in decoration will make that variable contain whether the fragment is front or back facing. This variable is non-zero if the current fragment is considered to be part of a `front-facing` polygon primitive or of a non-polygon primitive and is zero if the fragment is considered to be part of a back-facing polygon primitive.

**Valid Usage**

- VUID-FrontFacing-FrontFacing-04229
  The `FrontFacing` decoration must be used only within the `Fragment Execution Model`
- VUID-FrontFacing-FrontFacing-04230
  The variable decorated with `FrontFacing` must be declared using the `Input Storage Class`
- VUID-FrontFacing-FrontFacing-04231
  The variable decorated with `FrontFacing` must be declared as a boolean value

**GlobalInvocationId**

Decorating a variable with the `GlobalInvocationId` built-in decoration will make that variable contain the location of the current invocation within the global workgroup. Each component is equal to the index of the local workgroup multiplied by the size of the local workgroup plus `LocalInvocationId`.

**Valid Usage**

- VUID-GlobalInvocationId-GlobalInvocationId-04236
  The `GlobalInvocationId` decoration must be used only within the `GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model`
- VUID-GlobalInvocationId-GlobalInvocationId-04237
  The variable decorated with `GlobalInvocationId` must be declared using the `Input Storage Class`
- VUID-GlobalInvocationId-GlobalInvocationId-04238
  The variable decorated with `GlobalInvocationId` must be declared as a three-component vector of 32-bit integer values

**HelperInvocation**

Decorating a variable with the `HelperInvocation` built-in decoration will make that variable contain whether the current invocation is a helper invocation. This variable is non-zero if the current fragment being shaded is a helper invocation and zero otherwise. A helper invocation is an invocation of the shader that is produced to satisfy internal requirements such as the
Note

It is very likely that a helper invocation will have a value of SampleMask fragment shader input value that is zero.

Valid Usage

- VUID-HelperInvocation-HelperInvocation-04239
  The HelperInvocation decoration must be used only within the Fragment Execution Model

- VUID-HelperInvocation-HelperInvocation-04240
  The variable decorated with HelperInvocation must be declared using the Input Storage Class

- VUID-HelperInvocation-HelperInvocation-04241
  The variable decorated with HelperInvocation must be declared as a boolean value

InvocationId

Decorating a variable with the InvocationId built-in decoration will make that variable contain the index of the current shader invocation in a geometry shader, or the index of the output patch vertex in a tessellation control shader.

In a geometry shader, the index of the current shader invocation ranges from zero to the number of instances declared in the shader minus one. If the instance count of the geometry shader is one or is not specified, then InvocationId will be zero.

Valid Usage

- VUID-InvocationId-InvocationId-04257
  The InvocationId decoration must be used only within the TessellationControl or Geometry Execution Model

- VUID-InvocationId-InvocationId-04258
  The variable decorated with InvocationId must be declared using the Input Storage Class

- VUID-InvocationId-InvocationId-04259
  The variable decorated with InvocationId must be declared as a scalar 32-bit integer value

InstanceIndex

Decorating a variable in a vertex shader with the InstanceIndex built-in decoration will make that variable contain the index of the instance that is being processed by the current vertex shader invocation. InstanceIndex begins at the firstInstance parameter to vkCmdDraw or vkCmdDrawIndexed or at the firstInstance member of a structure consumed by vkCmdDrawIndirect or vkCmdDrawIndexedIndirect.
Valid Usage

- VUID-InstanceIndex-InstanceIndex-04263
  The InstanceIndex decoration must be used only within the Vertex Execution Model

- VUID-InstanceIndex-InstanceIndex-04264
  The variable decorated with InstanceIndex must be declared using the Input Storage Class

- VUID-InstanceIndex-InstanceIndex-04265
  The variable decorated with InstanceIndex must be declared as a scalar 32-bit integer value

Layer

Decorating a variable with the Layer built-in decoration will make that variable contain the select layer of a multi-layer framebuffer attachment.

In a vertex, tessellation evaluation, or geometry shader, any variable decorated with Layer can be written with the framebuffer layer index to which the primitive produced by that shader will be directed.

The last active pre-rasterization shader stage (in pipeline order) controls the Layer that is used. Outputs in previous shader stages are not used, even if the last stage fails to write the Layer.

If the last active pre-rasterization shader stage shader entry point's interface does not include a variable decorated with Layer, then the first layer is used. If a pre-rasterization shader stage shader entry point's interface includes a variable decorated with Layer, it must write the same value to Layer for all output vertices of a given primitive. If the Layer value is less than 0 or greater than or equal to the number of layers in the framebuffer, then primitives may still be rasterized, fragment shaders may be executed, and the framebuffer values for all layers are undefined.

In a fragment shader, a variable decorated with Layer contains the layer index of the primitive that the fragment invocation belongs to.

Valid Usage

- VUID-Layer-Layer-04272
  The Layer decoration must be used only within the MeshEXT, MeshNV, Vertex, TessellationEvaluation, Geometry, or Fragment Execution Model

- VUID-Layer-Layer-04273
  If the shaderOutputLayer feature is not enabled then the Layer decoration must be used only within the Geometry or Fragment Execution Model

- VUID-Layer-Layer-04274
  The variable decorated with Layer within the MeshEXT, MeshNV, Vertex, TessellationEvaluation, or Geometry Execution Model must be declared using the Output Storage Class

- VUID-Layer-Layer-04275
The variable decorated with `Layer` within the Fragment Execution Model **must** be declared using the Input Storage Class

- VUID-Layer-Layer-04276  
  The variable decorated with `Layer` **must** be declared as a scalar 32-bit integer value

- VUID-Layer-Layer-07039  
  The variable decorated with `Layer` within the MeshEXT Execution Model **must** also be decorated with the `PerPrimitiveEXT` decoration

**LocalInvocationId**

Decorating a variable with the `LocalInvocationId` built-in decoration will make that variable contain the location of the current compute shader invocation within the local workgroup. Each component ranges from zero through to the size of the workgroup in that dimension minus one.

*Note*

If the size of the workgroup in a particular dimension is one, then the `LocalInvocationId` in that dimension will be zero. If the workgroup is effectively two-dimensional, then `LocalInvocationId.z` will be zero. If the workgroup is effectively one-dimensional, then both `LocalInvocationId.y` and `LocalInvocationId.z` will be zero.

**Valid Usage**

- VUID-LocalInvocationId-LocalInvocationId-04281  
  The `LocalInvocationId` decoration **must** be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

- VUID-LocalInvocationId-LocalInvocationId-04282  
  The variable decorated with `LocalInvocationId` **must** be declared using the Input Storage Class

- VUID-LocalInvocationId-LocalInvocationId-04283  
  The variable decorated with `LocalInvocationId` **must** be declared as a three-component vector of 32-bit integer values

**LocalInvocationIndex**

Decorating a variable with the `LocalInvocationIndex` built-in decoration will make that variable contain a one-dimensional representation of `LocalInvocationId`. This is computed as:

```plaintext
LocalInvocationIndex =  
LocalInvocationId.z * WorkgroupSize.x * WorkgroupSize.y +  
LocalInvocationId.y * WorkgroupSize.x +  
LocalInvocationId.x;
```
Valid Usage

• VUID-LocalInvocationIndex-LocalInvocationIndex-04284
  The LocalInvocationIndex decoration must be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

• VUID-LocalInvocationIndex-LocalInvocationIndex-04285
  The variable decorated with LocalInvocationIndex must be declared using the Input Storage Class

• VUID-LocalInvocationIndex-LocalInvocationIndex-04286
  The variable decorated with LocalInvocationIndex must be declared as a scalar 32-bit integer value

NumSubgroups

Decorating a variable with the NumSubgroups built-in decoration will make that variable contain the number of subgroups in the local workgroup.

Valid Usage

• VUID-NumSubgroups-NumSubgroups-04293
  The NumSubgroups decoration must be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

• VUID-NumSubgroups-NumSubgroups-04294
  The variable decorated with NumSubgroups must be declared using the Input Storage Class

• VUID-NumSubgroups-NumSubgroups-04295
  The variable decorated with NumSubgroups must be declared as a scalar 32-bit integer value

NumWorkgroups

Decorating a variable with the NumWorkgroups built-in decoration will make that variable contain the number of local workgroups that are part of the dispatch that the invocation belongs to. Each component is equal to the values of the workgroup count parameters passed into the dispatching commands.

Valid Usage

• VUID-NumWorkgroups-NumWorkgroups-04296
  The NumWorkgroups decoration must be used only within the GLCompute, MeshEXT, or TaskEXT Execution Model

• VUID-NumWorkgroups-NumWorkgroups-04297
  The variable decorated with NumWorkgroups must be declared using the Input Storage Class

• VUID-NumWorkgroups-NumWorkgroups-04298
  The variable decorated with NumWorkgroups must be declared as a three-component vector of 32-bit integer values
**PatchVertices**

Decorating a variable with the `PatchVertices` built-in decoration will make that variable contain the number of vertices in the input patch being processed by the shader. In a Tessellation Control Shader, this is the same as the name:patchControlPoints member of `VkPipelineTessellationStateCreateInfo`. In a Tessellation Evaluation Shader, `PatchVertices` is equal to the tessellation control output patch size. When the same shader is used in different pipelines where the patch sizes are configured differently, the value of the `PatchVertices` variable will also differ.

**Valid Usage**

- **VUID-PatchVertices-PatchVertices-04308** The `PatchVertices` decoration **must** be used only within the `TessellationControl` or `TessellationEvaluation` Execution Model
- **VUID-PatchVertices-PatchVertices-04309** The variable decorated with `PatchVertices` **must** be declared using the `Input Storage Class`
- **VUID-PatchVertices-PatchVertices-04310** The variable decorated with `PatchVertices` **must** be declared as a scalar 32-bit integer value

**PointCoord**

Decorating a variable with the `PointCoord` built-in decoration will make that variable contain the coordinate of the current fragment within the point being rasterized, normalized to the size of the point with origin in the upper left corner of the point, as described in Basic Point Rasterization. If the primitive the fragment shader invocation belongs to is not a point, then the variable decorated with `PointCoord` contains an undefined value.

**Note**

Depending on how the point is rasterized, `PointCoord` may never reach (0,0) or (1,1).

**Valid Usage**

- **VUID-PointCoord-PointCoord-04311** The `PointCoord` decoration **must** be used only within the `Fragment` Execution Model
- **VUID-PointCoord-PointCoord-04312** The variable decorated with `PointCoord` **must** be declared using the `Input Storage Class`
- **VUID-PointCoord-PointCoord-04313** The variable decorated with `PointCoord` **must** be declared as a two-component vector of 32-bit floating-point values

**PointSize**

Decorating a variable with the `PointSize` built-in decoration will make that variable contain the 
size of point primitives. The value written to the variable decorated with \texttt{PointSize} by the last pre-rasterization shader stage in the pipeline is used as the framebuffer-space size of points produced by rasterization.

\begin{quote}
\textbf{Note}
When \texttt{PointSize} decorates a variable in the Input Storage Class, it contains the data written to the output variable decorated with \texttt{PointSize} from the previous shader stage.
\end{quote}

\begin{table}
\centering
\begin{tabular}{|l|}
\hline
\textbf{Valid Usage} \\
\hline
\textbullet{} VUID-PointSize-PointSize-04314 \\
The \texttt{PointSize} decoration \textbf{must} be used only within the \texttt{MeshEXT, MeshNV, Vertex, TessellationControl, TessellationEvaluation, or Geometry Execution Model} \\
\hline
\textbullet{} VUID-PointSize-PointSize-04315 \\
The variable decorated with \texttt{PointSize} within the \texttt{MeshEXT, MeshNV, or Vertex Execution Model} \textbf{must} be declared using the Output Storage Class \\
\hline
\textbullet{} VUID-PointSize-PointSize-04316 \\
The variable decorated with \texttt{PointSize} within the \texttt{TessellationControl, TessellationEvaluation, or Geometry Execution Model} \textbf{must} not be declared using a Storage Class other than Input or Output \\
\hline
\textbullet{} VUID-PointSize-PointSize-04317 \\
The variable decorated with \texttt{PointSize} \textbf{must} be declared as a scalar 32-bit floating-point value \\
\hline
\end{tabular}
\end{table}

\begin{quote}
\textbf{Position}
Decorating a variable with the \texttt{Position} built-in decoration will make that variable contain the position of the current vertex. In the last pre-rasterization shader stage, the value of the variable decorated with \texttt{Position} is used in subsequent primitive assembly, clipping, and rasterization operations.
\end{quote}

\begin{quote}
\textbf{Note}
When \texttt{Position} decorates a variable in the Input Storage Class, it contains the data written to the output variable decorated with \texttt{Position} from the previous shader stage.
\end{quote}

\begin{table}
\centering
\begin{tabular}{|l|}
\hline
\textbf{Valid Usage} \\
\hline
\textbullet{} VUID-Position-Position-04318 \\
The \texttt{Position} decoration \textbf{must} be used only within the \texttt{MeshEXT, MeshNV, Vertex, TessellationControl, TessellationEvaluation, or Geometry Execution Model} \\
\hline
\textbullet{} VUID-Position-Position-04319 \\
The variable decorated with \texttt{Position} within the \texttt{MeshEXT, MeshNV, or Vertex Execution Model} \textbf{must} be declared using the Output Storage Class \\
\hline
\end{tabular}
\end{table}
The variable decorated with `Position` within the `TessellationControl`, `TessellationEvaluation`, or `Geometry Execution Model` must not be declared using a `Storage Class` other than `Input` or `Output`.

The variable decorated with `Position` must be declared as a four-component vector of 32-bit floating-point values.

**PrimitiveId**

Decorating a variable with the `PrimitiveId` built-in decoration will make that variable contain the index of the current primitive.

The index of the first primitive generated by a drawing command is zero, and the index is incremented after every individual point, line, or triangle primitive is processed.

For triangles drawn as points or line segments (see `Polygon Mode`), the primitive index is incremented only once, even if multiple points or lines are eventually drawn.

Variables decorated with `PrimitiveId` are reset to zero between each instance drawn.

Restarting a primitive topology using primitive restart has no effect on the value of variables decorated with `PrimitiveId`.

In tessellation control and tessellation evaluation shaders, it will contain the index of the patch within the current set of rendering primitives that corresponds to the shader invocation.

In a geometry shader, it will contain the number of primitives presented as input to the shader since the current set of rendering primitives was started.

In a fragment shader, it will contain the primitive index written by the geometry shader if a geometry shader is present, or with the value that would have been presented as input to the geometry shader had it been present.

**Note**

When the `PrimitiveId` decoration is applied to an output variable in the geometry shader, the resulting value is seen through the `PrimitiveId` decorated input variable in the fragment shader.

The fragment shader using `PrimitiveId` will need to declare either the `Geometry` or `Tessellation` capability to satisfy the requirement SPIR-V has to use `PrimitiveId`.

**Valid Usage**

The `PrimitiveId` decoration must be used only within the `MeshEXT`, `MeshNV`, `IntersectionKHR`, `AnyHitKHR`, `ClosestHitKHR`, `TessellationControl`, `TessellationEvaluation`, `Geometry`, or `Fragment Execution Model`.
If pipeline contains both the Fragment and Geometry Execution Model and a variable decorated with PrimitiveId is read from Fragment shader, then the Geometry shader must write to the output variables decorated with PrimitiveId in all execution paths.

If pipeline contains both the Fragment and MeshEXT or MeshNV Execution Model and a variable decorated with PrimitiveId is read from Fragment shader, then the MeshEXT or MeshNV shader must write to the output variables decorated with PrimitiveId in all execution paths.

If Fragment Execution Model contains a variable decorated with PrimitiveId, then either the MeshShadingEXT, MeshShadingNV, Geometry or Tessellation capability must also be declared.

The variable decorated with PrimitiveId within the TessellationControl, TessellationEvaluation, Fragment, IntersectionKHR, AnyHitKHR, or ClosestHitKHR Execution Model must be declared using the Input Storage Class.

The variable decorated with PrimitiveId within the Geometry Execution Model must be declared using the Input or Output Storage Class.

The variable decorated with PrimitiveId within the MeshEXT or MeshNV Execution Model must be declared using the Output Storage Class.

The variable decorated with PrimitiveId must be declared as a scalar 32-bit integer value.

The variable decorated with PrimitiveId within the MeshEXT Execution Model must also be decorated with the PerPrimitiveEXT decoration.

**SampleId**

Decorating a variable with the SampleId built-in decoration will make that variable contain the coverage index for the current fragment shader invocation. SampleId ranges from zero to the number of samples in the framebuffer minus one. If a fragment shader entry point's interface includes an input variable decorated with SampleId, Sample Shading is considered enabled with a minSampleShading value of 1.0.

**Valid Usage**

- VUID-SampleId-SampleId-04354
  The SampleId decoration must be used only within the Fragment Execution Model.

- VUID-SampleId-SampleId-04355
  The variable decorated with SampleId must be declared using the Input Storage Class.

- VUID-SampleId-SampleId-04356
  The variable decorated with SampleId must be declared as a scalar 32-bit integer value.
SampleMask

Decorating a variable with the SampleMask built-in decoration will make any variable contain the sample mask for the current fragment shader invocation.

A variable in the Input storage class decorated with SampleMask will contain a bitmask of the set of samples covered by the primitive generating the fragment during rasterization. It has a sample bit set if and only if the sample is considered covered for this fragment shader invocation. SampleMask[] is an array of integers. Bits are mapped to samples in a manner where bit B of mask M (SampleMask[M]) corresponds to sample \(32 \times M + B\).

A variable in the Output storage class decorated with SampleMask is an array of integers forming a bit array in a manner similar to an input variable decorated with SampleMask, but where each bit represents coverage as computed by the shader. This computed SampleMask is combined with the generated coverage mask in the multisample coverage operation.

Variables decorated with SampleMask must be either an unsized array, or explicitly sized to be no larger than the implementation-dependent maximum sample-mask (as an array of 32-bit elements), determined by the maximum number of samples.

If a fragment shader entry point's interface includes an output variable decorated with SampleMask, the sample mask will be undefined for any array elements of any fragment shader invocations that fail to assign a value. If a fragment shader entry point's interface does not include an output variable decorated with SampleMask, the sample mask has no effect on the processing of a fragment.

Valid Usage

- VUID-SampleMask-SampleMask-04357
  The SampleMask decoration must be used only within the Fragment Execution Model

- VUID-SampleMask-SampleMask-04358
  The variable decorated with SampleMask must be declared using the Input or Output Storage Class

- VUID-SampleMask-SampleMask-04359
  The variable decorated with SampleMask must be declared as an array of 32-bit integer values

SamplePosition

Decorating a variable with the SamplePosition built-in decoration will make that variable contain the sub-pixel position of the sample being shaded. The top left of the pixel is considered to be at coordinate \((0,0)\) and the bottom right of the pixel is considered to be at coordinate \((1,1)\).

If a fragment shader entry point's interface includes an input variable decorated with SamplePosition, Sample Shading is considered enabled with a minSampleShading value of 1.0.
Valid Usage

- VUID-SamplePosition-SamplePosition-04360
  The SamplePosition decoration must be used only within the Fragment Execution Model

- VUID-SamplePosition-SamplePosition-04361
  The variable decorated with SamplePosition must be declared using the Input Storage Class

- VUID-SamplePosition-SamplePosition-04362
  The variable decorated with SamplePosition must be declared as a two-component vector of 32-bit floating-point values

SubgroupId
Decorating a variable with the SubgroupId built-in decoration will make that variable contain the index of the subgroup within the local workgroup. This variable is in range [0, NumSubgroups-1].

Valid Usage

- VUID-SubgroupId-SubgroupId-04367
  The SubgroupId decoration must be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

- VUID-SubgroupId-SubgroupId-04368
  The variable decorated with SubgroupId must be declared using the Input Storage Class

- VUID-SubgroupId-SubgroupId-04369
  The variable decorated with SubgroupId must be declared as a scalar 32-bit integer value

SubgroupEqMask
Decorating a variable with the SubgroupEqMask built-in decoration will make that variable contain the subgroup mask of the current subgroup invocation. The bit corresponding to the SubgroupLocalInvocationId is set in the variable decorated with SubgroupEqMask. All other bits are set to zero.

SubgroupEqMaskKHR is an alias of SubgroupEqMask.

Valid Usage

- VUID-SubgroupEqMask-SubgroupEqMask-04370
  The variable decorated with SubgroupEqMask must be declared using the Input Storage Class

- VUID-SubgroupEqMask-SubgroupEqMask-04371
  The variable decorated with SubgroupEqMask must be declared as a four-component vector of 32-bit integer values
SubgroupGeMask

Decorating a variable with the `SubgroupGeMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations greater than or equal to `SubgroupLocalInvocationId` through `SubgroupSize-1` are set in the variable decorated with `SubgroupGeMask`. All other bits are set to zero.

`SubgroupGeMaskKHR` is an alias of `SubgroupGeMask`.

Valid Usage

- **VUID-SubgroupGeMask-SubgroupGeMask-04372**
  The variable decorated with `SubgroupGeMask` must be declared using the Input Storage Class

- **VUID-SubgroupGeMask-SubgroupGeMask-04373**
  The variable decorated with `SubgroupGeMask` must be declared as a four-component vector of 32-bit integer values

SubgroupGtMask

Decorating a variable with the `SubgroupGtMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations greater than `SubgroupLocalInvocationId` through `SubgroupSize-1` are set in the variable decorated with `SubgroupGtMask`. All other bits are set to zero.

`SubgroupGtMaskKHR` is an alias of `SubgroupGtMask`.

Valid Usage

- **VUID-SubgroupGtMask-SubgroupGtMask-04374**
  The variable decorated with `SubgroupGtMask` must be declared using the Input Storage Class

- **VUID-SubgroupGtMask-SubgroupGtMask-04375**
  The variable decorated with `SubgroupGtMask` must be declared as a four-component vector of 32-bit integer values

SubgroupLeMask

Decorating a variable with the `SubgroupLeMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations less than or equal to `SubgroupLocalInvocationId` are set in the variable decorated with `SubgroupLeMask`. All other bits are set to zero.

`SubgroupLeMaskKHR` is an alias of `SubgroupLeMask`.

Valid Usage

- **VUID-SubgroupLeMask-SubgroupLeMask-04376**
The variable decorated with `SubgroupLeMask` **must** be declared using the `Input Storage Class`:

- VUID-SubgroupLeMask-SubgroupLeMask-04377  
The variable decorated with `SubgroupLeMask` **must** be declared as a four-component vector of 32-bit integer values.

### SubgroupLtMask

Decorating a variable with the `SubgroupLtMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations less than `SubgroupLocalInvocationId` are set in the variable decorated with `SubgroupLtMask`. All other bits are set to zero.

`SubgroupLtMaskKHR` is an alias of `SubgroupLtMask`.

### Valid Usage

- VUID-SubgroupLtMask-SubgroupLtMask-04378  
The variable decorated with `SubgroupLtMask` **must** be declared using the `Input Storage Class`.

- VUID-SubgroupLtMask-SubgroupLtMask-04379  
The variable decorated with `SubgroupLtMask` **must** be declared as a four-component vector of 32-bit integer values.

### SubgroupLocalInvocationId

Decorating a variable with the `SubgroupLocalInvocationId` builtin decoration will make that variable contain the index of the invocation within the subgroup. This variable is in range `[0, SubgroupSize-1]`.

If `VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT` is specified, or if module declares SPIR-V version 1.6 or higher, and the local workgroup size in the X dimension of the stage is a multiple of `SubgroupSize`, full subgroups are enabled for that pipeline stage. When full subgroups are enabled, subgroups **must** be launched with all invocations active, i.e., there is an active invocation with `SubgroupLocalInvocationId` for each value in range `[0, SubgroupSize-1]`.

#### Note

There is no direct relationship between `SubgroupLocalInvocationId` and `LocalInvocationId` or `LocalInvocationIndex`. If the pipeline was created with full subgroups applications can compute their own local invocation index to serve the same purpose:

\[
\text{index} = \text{SubgroupLocalInvocationId} + \text{SubgroupId} \times \text{SubgroupSize}
\]

If full subgroups are not enabled, some subgroups may be dispatched with inactive invocations that do not correspond to a local workgroup invocation, making the value of `index` unreliable.
Note

VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT is effectively deprecated when compiling SPIR-V 1.6 shaders, as this behavior is the default for Vulkan with SPIR-V 1.6. This is more aligned with developer expectations, and avoids applications unexpectedly breaking in the future.

Valid Usage

- VUID-SubgroupLocalInvocationId-SubgroupLocalInvocationId-04380
  The variable decorated with SubgroupLocalInvocationId must be declared using the Input Storage Class

- VUID-SubgroupLocalInvocationId-SubgroupLocalInvocationId-04381
  The variable decorated with SubgroupLocalInvocationId must be declared as a scalar 32-bit integer value

SubgroupSize

Decorating a variable with the SubgroupSize builtin decoration will make that variable contain the implementation-dependent number of invocations in a subgroup. This value must be a power-of-two integer.

If the pipeline was created with the VK_PIPELINE_SHADER_STAGE_CREATE.Allow_Varying_Subgroup_Size_BIT flag set, or the SPIR-V module is at least version 1.6, the SubgroupSize decorated variable will contain the subgroup size for each subgroup that gets dispatched. This value must be between minSubgroupSize and maxSubgroupSize and must be uniform with subgroup scope. The value may vary across a single draw call, and for fragment shaders may vary across a single primitive. In compute dispatches, SubgroupSize must be uniform with command scope.

If the pipeline was created with a chained VkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure, the SubgroupSize decorated variable will match requiredSubgroupSize.

If SPIR-V module is less than version 1.6 and the pipeline was not created with the VK_PIPELINE_SHADER_STAGE_CREATE.Allow_Varying_Subgroup_Size_BIT flag set and noVkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure was chained, the variable decorated with SubgroupSize will match subgroupSize.

The maximum number of invocations that an implementation can support per subgroup is 128.

Note

The old behavior for SubgroupSize is considered deprecated as certain compute algorithms cannot be easily implemented without the guarantees of VK_PIPELINE_SHADER_STAGE.Create.Allow_Varying_Subgroup_Size_BIT and VK_PIPELINE_SHADER_STAGE.Create.Require_Full_Subgroups_BIT.
Valid Usage

• VUID-SubgroupSize-SubgroupSize-04382
  The variable decorated with SubgroupSize must be declared using the Input Storage Class

• VUID-SubgroupSize-SubgroupSize-04383
  The variable decorated with SubgroupSize must be declared as a scalar 32-bit integer value

TessCoord

Decorating a variable with the TessCoord built-in decoration will make that variable contain the three-dimensional (u,v,w) barycentric coordinate of the tessellated vertex within the patch. u, v, and w are in the range [0,1] and vary linearly across the primitive being subdivided. For the tessellation modes of Quads or IsoLines, the third component is always zero.

Valid Usage

• VUID-TessCoord-TessCoord-04387
  The TessCoord decoration must be used only within the TessellationEvaluation Execution Model

• VUID-TessCoord-TessCoord-04388
  The variable decorated with TessCoord must be declared using the Input Storage Class

• VUID-TessCoord-TessCoord-04389
  The variable decorated with TessCoord must be declared as a three-component vector of 32-bit floating-point values

TessLevelOuter

Decorating a variable with the TessLevelOuter built-in decoration will make that variable contain the outer tessellation levels for the current patch.

In tessellation control shaders, the variable decorated with TessLevelOuter can be written to, controlling the tessellation factors for the resulting patch. These values are used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders.

In tessellation evaluation shaders, the variable decorated with TessLevelOuter can read the values written by the tessellation control shader.

Valid Usage

• VUID-TessLevelOuter-TessLevelOuter-04390
  The TessLevelOuter decoration must be used only within the TessellationControl or TessellationEvaluation Execution Model

• VUID-TessLevelOuter-TessLevelOuter-04391
  The variable decorated with TessLevelOuter within the TessellationControl Execution Model must be declared using the Output Storage Class
The variable decorated with `TessLevelOuter` within the `TessellationEvaluation Execution Model` must be declared using the `Input Storage Class`

The variable decorated with `TessLevelOuter` must be declared as an array of size four, containing 32-bit floating-point values.

---

**TessLevelInner**

Decorating a variable with the `TessLevelInner` built-in decoration will make that variable contain the inner tessellation levels for the current patch.

In tessellation control shaders, the variable decorated with `TessLevelInner` can be written to, controlling the tessellation factors for the resulting patch. These values are used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders.

In tessellation evaluation shaders, the variable decorated with `TessLevelInner` can read the values written by the tessellation control shader.

---

**Valid Usage**

The `TessLevelInner` decoration must be used only within the `TessellationControl` or `TessellationEvaluation Execution Model`

The variable decorated with `TessLevelInner` within the `TessellationControl Execution Model` must be declared using the `Output Storage Class`

The variable decorated with `TessLevelInner` within the `TessellationEvaluation Execution Model` must be declared using the `Input Storage Class`

The variable decorated with `TessLevelInner` must be declared as an array of size two, containing 32-bit floating-point values.

---

**VertexIndex**

Decorating a variable with the `VertexIndex` built-in decoration will make that variable contain the index of the vertex that is being processed by the current vertex shader invocation. For non-indexed draws, this variable begins at the `firstVertex` parameter to `vkCmdDraw` or the `firstVertex` member of a structure consumed by `vkCmdDrawIndirect` and increments by one for each vertex in the draw. For indexed draws, its value is the content of the index buffer for the vertex plus the `vertexOffset` parameter to `vkCmdDrawIndexed` or the `vertexOffset` member of the structure consumed by `vkCmdDrawIndexedIndirect`.

*Note*

`VertexIndex` starts at the same starting value for each instance.
Valid Usage

• VUID-VertexIndex-VertexIndex-04398
  The VertexIndex decoration **must** be used only within the Vertex Execution Model

• VUID-VertexIndex-VertexIndex-04399
  The variable decorated with VertexIndex **must** be declared using the Input Storage Class

• VUID-VertexIndex-VertexIndex-04400
  The variable decorated with VertexIndex **must** be declared as a scalar 32-bit integer value

**ViewIndex**

The ViewIndex decoration **can** be applied to a shader input which will be filled with the index of the view that is being processed by the current shader invocation.

If multiview is enabled in the render pass, this value will be one of the bits set in the view mask of the subpass the pipeline is compiled against. If multiview is not enabled in the render pass, this value will be zero.

Valid Usage

• VUID-ViewIndex-ViewIndex-04401
  The ViewIndex decoration **must** be used only within the MeshEXT, Vertex, Geometry, TessellationControl, TessellationEvaluation or Fragment Execution Model

• VUID-ViewIndex-ViewIndex-04402
  The variable decorated with ViewIndex **must** be declared using the Input Storage Class

• VUID-ViewIndex-ViewIndex-04403
  The variable decorated with ViewIndex **must** be declared as a scalar 32-bit integer value

**ViewportIndex**

Decorating a variable with the ViewportIndex built-in decoration will make that variable contain the index of the viewport.

In a vertex, tessellation evaluation, or geometry shader, the variable decorated with ViewportIndex can be written to with the viewport index to which the primitive produced by that shader will be directed.

The selected viewport index is used to select the viewport transform and scissor rectangle.

The last active pre-rasterization shader stage (in pipeline order) controls the ViewportIndex that is used. Outputs in previous shader stages are not used, even if the last stage fails to write the ViewportIndex.

If the last active pre-rasterization shader stage shader entry point’s interface does not include a variable decorated with ViewportIndex then the first viewport is used. If a pre-rasterization shader stage shader entry point’s interface includes a variable decorated with ViewportIndex, it **must** write the same value to ViewportIndex for all output vertices of a given primitive.
In a fragment shader, the variable decorated with `ViewportIndex` contains the viewport index of the primitive that the fragment invocation belongs to.

### Valid Usage

- **VUID-ViewportIndex-ViewportIndex-04404**
  The `ViewportIndex` decoration **must** be used only within the MeshEXT, MeshNV, Vertex, TessellationEvaluation, Geometry, or Fragment Execution Model

- **VUID-ViewportIndex-ViewportIndex-04405**
  If the shaderOutputViewportIndex feature is not enabled then the `ViewportIndex` decoration **must** be used only within the Geometry or Fragment Execution Model

- **VUID-ViewportIndex-ViewportIndex-04406**
  The variable decorated with `ViewportIndex` within the MeshEXT, MeshNV, Vertex, TessellationEvaluation, or Geometry Execution Model **must** be declared using the Output Storage Class

- **VUID-ViewportIndex-ViewportIndex-04407**
  The variable decorated with `ViewportIndex` within the Fragment Execution Model **must** be declared using the Input Storage Class

- **VUID-ViewportIndex-ViewportIndex-04408**
  The variable decorated with `ViewportIndex` **must** be declared as a scalar 32-bit integer value

- **VUID-ViewportIndex-ViewportIndex-07060**
  The variable decorated with `ViewportIndex` within the MeshEXT Execution Model **must** also be decorated with the PerPrimitiveEXT decoration

**WorkgroupId**

Decorating a variable with the `WorkgroupId` built-in decoration will make that variable contain the global workgroup that the current invocation is a member of. Each component ranges from a base value to a base + count value, based on the parameters passed into the dispatching commands.

### Valid Usage

- **VUID-WorkgroupId-WorkgroupId-04422**
  The `WorkgroupId` decoration **must** be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

- **VUID-WorkgroupId-WorkgroupId-04423**
  The variable decorated with `WorkgroupId` **must** be declared using the Input Storage Class

- **VUID-WorkgroupId-WorkgroupId-04424**
  The variable decorated with `WorkgroupId` **must** be declared as a three-component vector of 32-bit integer values

**WorkgroupSize**
Note
SPIR-V 1.6 deprecated WorkgroupSize in favor of using the LocalSizeId Execution Mode instead. Support for LocalSizeId was added with VK_KHR_maintenance4 and promoted to core in Version 1.3.

Decorating an object with the WorkgroupSize built-in decoration will make that object contain the dimensions of a local workgroup. If an object is decorated with the WorkgroupSize decoration, this takes precedence over any LocalSize or LocalSizeId execution mode.

Valid Usage

- VUID-WorkgroupSize-WorkgroupSize-04425
  The WorkgroupSize decoration must be used only within the GLCompute, MeshEXT, TaskEXT, MeshNV, or TaskNV Execution Model

- VUID-WorkgroupSize-WorkgroupSize-04426
  The variable decorated with WorkgroupSize must be a specialization constant or a constant

- VUID-WorkgroupSize-WorkgroupSize-04427
  The variable decorated with WorkgroupSize must be declared as a three-component vector of 32-bit integer values
Chapter 16. Image Operations

16.1. Image Operations Overview

Vulkan Image Operations are operations performed by those SPIR-V Image Instructions which take an OpTypeImage (representing a VkImageView) or OpTypeSampledImage (representing a (VkImageView, VkSampler) pair). Read, write, and atomic operations also take texel coordinates as operands, and return a value based on a neighborhood of texture elements (texels) within the image. Query operations return properties of the bound image or of the lookup itself. The “Depth” operand of OpTypeImage is ignored.

Note
Texel is a term which is a combination of the words texture and element. Early interactive computer graphics supported texture operations on textures, a small subset of the image operations on images described here. The discrete samples remain essentially equivalent, however, so we retain the historical term texel to refer to them.

Image Operations include the functionality of the following SPIR-V Image Instructions:

- OpImageSample* and OpImageSparseSample* read one or more neighboring texels of the image, and filter the texel values based on the state of the sampler.
  - Instructions with ImplicitLod in the name determine the LOD used in the sampling operation based on the coordinates used in neighboring fragments.
  - Instructions with ExplicitLod in the name determine the LOD used in the sampling operation based on additional coordinates.
  - Instructions with Proj in the name apply homogeneous projection to the coordinates.
- OpImageFetch and OpImageSparseFetch return a single texel of the image. No sampler is used.
- OpImage*Gather and OpImageSparse*Gather read neighboring texels and return a single component of each.
- OpImageRead (and OpImageSparseRead) and OpImageWrite read and write, respectively, a texel in the image. No sampler is used.
- OpImage*Dref* instructions apply depth comparison on the texel values.
- OpImageSparse* instructions additionally return a sparse residency code.
- OpImageQueryLod returns the LOD parameters that would be used in a sample operation. The actual operation is not performed.

16.1.1. Texel Coordinate Systems

Images are addressed by texel coordinates. There are three texel coordinate systems:
• normalized texel coordinates [0.0, 1.0]
• unnormalized texel coordinates [0.0, width / height / depth]
• integer texel coordinates [0, width / height / depth]


Other image instructions can use either normalized or unnormalized texel coordinates (selected by the `unnormalizedCoordinates` state of the sampler used in the instruction), but there are limitations on what operations, image state, and sampler state is supported. Normalized coordinates are logically converted to unnormalized as part of image operations, and certain steps are only performed on normalized coordinates. The array layer coordinate is always treated as unnormalized even when other coordinates are normalized.

Normalized texel coordinates are referred to as \((s,t,r,q,a)\), with the coordinates having the following meanings:

- **s**: Coordinate in the first dimension of an image.
- **t**: Coordinate in the second dimension of an image.
- **r**: Coordinate in the third dimension of an image.
  - \((s,t,r)\) are interpreted as a direction vector for Cube images.
- **q**: Fourth coordinate, for homogeneous (projective) coordinates.
- **a**: Coordinate for array layer.

The coordinates are extracted from the SPIR-V operand based on the dimensionality of the image variable and type of instruction. For Proj instructions, the components are in order \((s, [t], [r], q)\), with \(t\) and \(r\) being conditionally present based on the Dim of the image. For non-Proj instructions, the coordinates are \((s [,t] [,r] [,a])\), with \(t\) and \(r\) being conditionally present based on the Dim of the image and \(a\) being conditionally present based on the Arrayed property of the image. Projective image instructions are not supported on Arrayed images.

Unnormalized texel coordinates are referred to as \((u,v,w,a)\), with the coordinates having the following meanings:

- **u**: Coordinate in the first dimension of an image.
- **v**: Coordinate in the second dimension of an image.
- **w**: Coordinate in the third dimension of an image.
- **a**: Coordinate for array layer.

Only the \(u\) and \(v\) coordinates are directly extracted from the SPIR-V operand, because only 1D and 2D (non-Arrayed) dimensionalities support unnormalized coordinates. The components are in order \((u [,v])\), with \(v\) being conditionally present when the dimensionality is 2D. When normalized coordinates are converted to unnormalized coordinates, all four coordinates are used.

Integer texel coordinates are referred to as \((i,j,k,l,n)\), with the coordinates having the following meanings:
• i: Coordinate in the first dimension of an image.
• j: Coordinate in the second dimension of an image.
• k: Coordinate in the third dimension of an image.
• l: Coordinate for array layer.
• n: Index of the sample within the texel.

They are extracted from the SPIR-V operand in order (i [,j] [,k] [,l] [,n]), with j and k conditionally present based on the Dim of the image, and l conditionally present based on the Arrayed property of the image. n is conditionally present and is taken from the Sample image operand.

For all coordinate types, unused coordinates are assigned a value of zero.

![Texel Coordinate Systems, Linear Filtering](image)

The Texel Coordinate Systems - For the example shown of an 8×4 texel two dimensional image.

- Normalized texel coordinates:
  - The s coordinate goes from 0.0 to 1.0.
  - The t coordinate goes from 0.0 to 1.0.

- Unnormalized texel coordinates:
  - The u coordinate within the range 0.0 to 8.0 is within the image, otherwise it is outside the image.
  - The v coordinate within the range 0.0 to 4.0 is within the image, otherwise it is outside the image.

- Integer texel coordinates:
  - The i coordinate within the range 0 to 7 addresses texels within the image, otherwise it is outside the image.
• The j coordinate within the range 0 to 3 addresses texels within the image, otherwise it is outside the image.

• Also shown for linear filtering:
  • Given the unnormalized coordinates (u,v), the four texels selected are \( i_{j0}, i_{j0}, i_{j1}, \) and \( i_{j1} \).
  • The fractions \( \alpha \) and \( \beta \).
  • Given the offset \( \Delta_i \) and \( \Delta_j \), the four texels selected by the offset are \( i_{j0}, i_{j0}, i_{j1}, \) and \( i_{j1} \).

\[\text{Note}\]
For formats with reduced-resolution components, \( \Delta_i \) and \( \Delta_j \) are relative to the resolution of the highest-resolution component, and therefore may be divided by two relative to the unnormalized coordinate space of the lower-resolution components.

\[\text{Figure 4. Texel Coordinate Systems, Nearest Filtering}\]

The Texel Coordinate Systems - For the example shown of an 8×4 texel two dimensional image.

• Texel coordinates as above. Also shown for nearest filtering:
  • Given the unnormalized coordinates (u,v), the texel selected is \( ij \).
  • Given the offset \( \Delta_i \) and \( \Delta_j \), the texel selected by the offset is \( ij' \).

### 16.2. Conversion Formulas

#### 16.2.1. RGB to Shared Exponent Conversion

An RGB color (red, green, blue) is transformed to a shared exponent color \((\text{red}_{\text{shared}}, \text{green}_{\text{shared}}, \text{blue}_{\text{shared}}, \text{exp}_{\text{shared}})\) as follows:
First, the components (red, green, blue) are clamped to \( \text{red}_\text{clamped}, \text{green}_\text{clamped}, \text{blue}_\text{clamped} \) as:

\[
\text{red}_\text{clamped} = \max(0, \min(\text{sharedexp}_\text{max}, \text{red}))
\]

\[
\text{green}_\text{clamped} = \max(0, \min(\text{sharedexp}_\text{max}, \text{green}))
\]

\[
\text{blue}_\text{clamped} = \max(0, \min(\text{sharedexp}_\text{max}, \text{blue}))
\]

where:

\[
N = 9 \quad \text{number of mantissa bits per component}
\]

\[
B = 15 \quad \text{exponent bias}
\]

\[
E_{\text{max}} = 31 \quad \text{maximum possible biased exponent value}
\]

\[
\text{sharedexp}_\text{max} = \frac{2^N - 1}{2^N} \times 2^{(E_{\text{max}} - B)}
\]

**Note**

NaN, if supported, is handled as in IEEE 754-2008 \( \text{minNum}() \) and \( \text{maxNum}() \). This results in any NaN being mapped to zero.

The largest clamped component, \( \text{max}_\text{clamped} \) is determined:

\[
\text{max}_\text{clamped} = \max(\text{red}_\text{clamped}, \text{green}_\text{clamped}, \text{blue}_\text{clamped})
\]

A preliminary shared exponent \( \text{exp}' \) is computed:

\[
\text{exp}' = \begin{cases} 
[\log_2(\text{max}_\text{clamped})] + (B + 1) & \text{for } \text{max}_\text{clamped} > 2^{-(B + 1)} \\
0 & \text{for } \text{max}_\text{clamped} \leq 2^{-(B + 1)} 
\end{cases}
\]

The shared exponent \( \text{exp}_{\text{shared}} \) is computed:

\[
\text{max}_\text{shared} = \left\lfloor \frac{\text{max}_\text{clamped}}{2^{(\text{exp}' - B - N)}} + \frac{1}{2} \right\rfloor 
\]

\[
\text{exp}_{\text{shared}} = \begin{cases} 
\text{exp}' & \text{for } 0 \leq \text{max}_\text{shared} < 2^N \\
\text{exp}' + 1 & \text{for } \text{max}_\text{shared} = 2^N 
\end{cases}
\]

Finally, three integer values in the range 0 to \( 2^N \) are computed:
16.2.2. Shared Exponent to RGB

A shared exponent color \((\text{red}_{\text{shared}}, \text{green}_{\text{shared}}, \text{blue}_{\text{shared}}, \text{exp}_{\text{shared}})\) is transformed to an RGB color \((\text{red}, \text{green}, \text{blue})\) as follows:

\[
\text{red}_{\text{shared}} = \left\lfloor \frac{\text{red}_{\text{clamped}}}{2^{(\text{exp}_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor
\]

\[
\text{green}_{\text{shared}} = \left\lfloor \frac{\text{green}_{\text{clamped}}}{2^{(\text{exp}_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor
\]

\[
\text{blue}_{\text{shared}} = \left\lfloor \frac{\text{blue}_{\text{clamped}}}{2^{(\text{exp}_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor
\]

\[
\text{red} = \text{red}_{\text{shared}} \times 2^{(\text{exp}_{\text{shared}} - B - N)}
\]

\[
\text{green} = \text{green}_{\text{shared}} \times 2^{(\text{exp}_{\text{shared}} - B - N)}
\]

\[
\text{blue} = \text{blue}_{\text{shared}} \times 2^{(\text{exp}_{\text{shared}} - B - N)}
\]

where:

\(N = 9\) (number of mantissa bits per component)

\(B = 15\) (exponent bias)

16.3. Texel Input Operations

Texel input instructions are SPIR-V image instructions that read from an image. Texel input operations are a set of steps that are performed on state, coordinates, and texel values while processing a texel input instruction, and which are common to some or all texel input instructions. They include the following steps, which are performed in the listed order:

- Validation operations
  - Instruction/Sampler/Image validation
  - Coordinate validation
  - Sparse validation
  - Layout validation
- Format conversion
- Texel replacement
- Depth comparison
Conversion to RGBA
Component swizzle
Chroma reconstruction
Y′C_bC_r conversion

For texel input instructions involving multiple texels (for sampling or gathering), these steps are applied for each texel that is used in the instruction. Depending on the type of image instruction, other steps are conditionally performed between these steps or involving multiple coordinate or texel values.

If Chroma Reconstruction is implicit, Texel Filtering instead takes place during chroma reconstruction, before sampler Y′C_bC_r conversion occurs.

16.3.1. Texel Input Validation Operations

Texel input validation operations inspect instruction/image/sampler state or coordinates, and in certain circumstances cause the texel value to be replaced or become undefined. There are a series of validations that the texel undergoes.

Instruction/Sampler/Image View Validation

There are a number of cases where a SPIR-V instruction can mismatch with the sampler, the image view, or both, and a number of further cases where the sampler can mismatch with the image view. In such cases the value of the texel returned is undefined.

These cases include:

- The sampler borderColor is an integer type and the image view format is not one of the VkFormat integer types or a stencil component of a depth/stencil format.
- The sampler borderColor is a float type and the image view format is not one of the VkFormat float types or a depth component of a depth/stencil format.
- The sampler borderColor is one of the opaque black colors (VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK or VK_BORDER_COLOR_INT_OPAQUE_BLACK) and the image view VkComponentSwizzle for any of the VkComponentMapping components is not the identity swizzle.
- The VkImageLayout of any subresource in the image view does not match the VkDescriptorImageInfo::imageLayout used to write the image descriptor.
- The SPIR-V Image Format is not compatible with the image view’s format.
- The sampler unnormalizedCoordinates is VK_TRUE and any of the limitations of unnormalized coordinates are violated.
- The SPIR-V instruction is one of the OpImage*Dref* instructions and the sampler compareEnable is VK_FALSE.
- The SPIR-V instruction is not one of the OpImage*Dref* instructions and the sampler compareEnable is VK_TRUE.
- The SPIR-V instruction is one of the OpImage*Dref* instructions, the image view format is one of the depth/stencil formats, and the image view aspect is not VK_IMAGE_ASPECT_DEPTH_BIT.
The SPIR-V instruction’s image variable’s properties are not compatible with the image view:

- Rules for viewType:
  - **VK_IMAGE_VIEW_TYPE_1D** must have Dim = 1D, Arrayed = 0, MS = 0.
  - **VK_IMAGE_VIEW_TYPE_2D** must have Dim = 2D, Arrayed = 0.
  - **VK_IMAGE_VIEW_TYPE_3D** must have Dim = 3D, Arrayed = 0, MS = 0.
  - **VK_IMAGE_VIEW_TYPE_CUBE** must have Dim = Cube, Arrayed = 0, MS = 0.
  - **VK_IMAGE_VIEW_TYPE_1D_ARRAY** must have Dim = 1D, Arrayed = 1, MS = 0.
  - **VK_IMAGE_VIEW_TYPE_2D_ARRAY** must have Dim = 2D, Arrayed = 1.
  - **VK_IMAGE_VIEW_TYPE_CUBE_ARRAY** must have Dim = Cube, Arrayed = 1, MS = 0.

- If the image was created with `VkImageCreateInfo::samples` equal to `VK_SAMPLE_COUNT_1_BIT`, the instruction must have MS = 0.

- If the image was created with `VkImageCreateInfo::samples` not equal to `VK_SAMPLE_COUNT_1_BIT`, the instruction must have MS = 1.

- If the Sampled Type of the OpTypeImage does not match the SPIR-V Type.

- If the signedness of any read or sample operation does not match the signedness of the image’s format.

Only **OpImageSample** and **OpImageSparseSample** can be used with a sampler or image view that enables sampler Y’CbCr conversion.

**OpImageFetch, OpImageSparseFetch, OpImageGather, and OpImageSparseGather** must not be used with a sampler or image view that enables sampler Y’CbCr conversion.

The **ConstOffset** and **Offset** operands must not be used with a sampler or image view that enables sampler Y’CbCr conversion.

### Integer Texel Coordinate Validation

Integer texel coordinates are validated against the size of the image level, and the number of layers and number of samples in the image. For SPIR-V instructions that use integer texel coordinates, this is performed directly on the integer coordinates. For instructions that use normalized or unnormalized texel coordinates, this is performed on the coordinates that result after conversion to integer texel coordinates.

If the integer texel coordinates do not satisfy all of the conditions

\[
0 \leq i < w_s
\]

\[
0 \leq j < h_s
\]

\[
0 \leq k < d_s
\]
\[ 0 \leq l < \text{layers} \]
\[ 0 \leq n < \text{samples} \]

where:

\[ w_s = \text{width of the image level} \]
\[ h_s = \text{height of the image level} \]
\[ d_s = \text{depth of the image level} \]

\[ \text{layers} = \text{number of layers in the image} \]
\[ \text{samples} = \text{number of samples per texel in the image} \]

then the texel fails integer texel coordinate validation.

There are four cases to consider:

1. Valid Texel Coordinates
   - If the texel coordinates pass validation (that is, the coordinates lie within the image),
   then the texel value comes from the value in image memory.

2. Border Texel
   - If the texel coordinates fail validation, and
   - If the read is the result of an image sample instruction or image gather instruction, and
   - If the image is not a cube image,
   then the texel is a border texel and texel replacement is performed.

3. Invalid Texel
   - If the texel coordinates fail validation, and
   - If the read is the result of an image fetch instruction, image read instruction, or atomic instruction,
   then the texel is an invalid texel and texel replacement is performed.

4. Cube Map Edge or Corner
Otherwise the texel coordinates lie beyond the edges or corners of the selected cube map face, and **Cube map edge handling** is performed.

**Cube Map Edge Handling**

If the texel coordinates lie beyond the edges or corners of the selected cube map face (as described in the prior section), the following steps are performed. Note that this does not occur when using **VK_FILTER_NEAREST** filtering within a mip level, since **VK_FILTER_NEAREST** is treated as using **VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE**.

- **Cube Map Edge Texel**
  - If the texel lies beyond the selected cube map face in either only \textit{i} or only \textit{j}, then the coordinates \((i,j)\) and the array layer \(l\) are transformed to select the adjacent texel from the appropriate neighboring face.

- **Cube Map Corner Texel**
  - If the texel lies beyond the selected cube map face in both \textit{i} and \textit{j}, then there is no unique neighboring face from which to read that texel. The texel **should** be replaced by the average of the three values of the adjacent texels in each incident face. However, implementations **may** replace the cube map corner texel by other methods. The methods are subject to the constraint that if the three available texels have the same value, the resulting filtered texel **must** have that value.

**Sparse Validation**

If the texel reads from an unbound region of a sparse image, the texel is a **sparse unbound texel**, and processing continues with **texel replacement**.

**Layout Validation**

If all planes of a **disjoint multi-planar** image are not in the same **image layout**, the image **must** not be sampled with **sampler YC_aC_b conversion** enabled.

**16.3.2. Format Conversion**

Texels undergo a format conversion from the **VkFormat** of the image view to a vector of either floating point or signed or unsigned integer components, with the number of components based on the number of components present in the format.

- **Color formats** have one, two, three, or four components, according to the format.

- **Depth/stencil formats** are one component. The depth or stencil component is selected by the **aspectMask** of the image view.

Each component is converted based on its type and size (as defined in the **Format Definition** section for each **VkFormat**), using the appropriate equations in **16-Bit Floating-Point Numbers**, **Unsigned 11-Bit Floating-Point Numbers**, **Unsigned 10-Bit Floating-Point Numbers**, **Fixed-Point Data Conversion**, and **Shared Exponent to RGB**. Signed integer components smaller than 32 bits are sign-extended.
If the image view format is sRGB, the color components are first converted as if they are UNORM, and then sRGB to linear conversion is applied to the R, G, and B components as described in the “sRGB EOTF” section of the Khronos Data Format Specification. The A component, if present, is unchanged.

If the image view format is block-compressed, then the texel value is first decoded, then converted based on the type and number of components defined by the compressed format.

16.3.3. Texel Replacement

A texel is replaced if it is one (and only one) of:

- a border texel,
- an invalid texel, or
- a sparse unbound texel.

Border texels are replaced with a value based on the image format and the `borderColor` of the sampler. The border color is:

**Table 14. Border Color**

<table>
<thead>
<tr>
<th>Sampler</th>
<th>borderColor</th>
<th>Corresponding Border Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK</td>
<td>[B_r, B_g, B_b, B_a] = [0.0, 0.0, 0.0, 0.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK</td>
<td>[B_r, B_g, B_b, B_a] = [0.0, 0.0, 0.0, 1.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE</td>
<td>[B_r, B_g, B_b, B_a] = [1.0, 1.0, 1.0, 1.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_TRANSPARENT_BLACK</td>
<td>[B_r, B_g, B_b, B_a] = [0, 0, 0, 0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_BLACK</td>
<td>[B_r, B_g, B_b, B_a] = [0, 0, 0, 1]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_WHITE</td>
<td>[B_r, B_g, B_b, B_a] = [1, 1, 1, 1]</td>
<td></td>
</tr>
</tbody>
</table>

**Note**
The names `VK_BORDER_COLOR_*_TRANSPARENT_BLACK`, `VK_BORDER_COLOR_*_OPAQUE_BLACK`, and `VK_BORDER_COLOR_*_OPAQUE_WHITE` are meant to describe which components are zeros and ones in the vocabulary of compositing, and are not meant to imply that the numerical value of `VK_BORDER_COLOR_INT_OPAQUE_WHITE` is a saturating value for integers.

This is substituted for the texel value by replacing the number of components in the image format.

**Table 15. Border Texel Components After Replacement**

<table>
<thead>
<tr>
<th>Texel Aspect or Format</th>
<th>Component Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth aspect</td>
<td>D = B_r</td>
</tr>
<tr>
<td>Stencil aspect</td>
<td>S = B_r</td>
</tr>
<tr>
<td>One component color format</td>
<td>Color_r = B_r</td>
</tr>
<tr>
<td>Two component color format</td>
<td>[Color_r, Color_g] = [B_r, B_g]</td>
</tr>
</tbody>
</table>
The value returned by a read of an invalid texel is undefined, unless that read operation is from a buffer resource and the `robustBufferAccess` feature is enabled. In that case, an invalid texel is replaced as described by the `robustBufferAccess` feature. If the access is to an image resource and the x, y, z, or layer coordinate validation fails and the `robustImageAccess` feature is enabled, then zero **must** be returned for the R, G, and B components, if present. Either zero or one **must** be returned for the A component, if present. If only the sample index was invalid, the values returned are undefined.

Additionally, if the `robustImageAccess` feature is enabled, any invalid texels **may** be expanded to four components prior to texel replacement. This means that components not present in the image format may be replaced with 0 or may undergo conversion to RGBA as normal.

If the `VkPhysicalDeviceSparseProperties::residencyNonResidentStrict` property is `VK_TRUE`, a sparse unbound texel is replaced with 0 or 0.0 values for integer and floating-point components of the image format, respectively.

If `residencyNonResidentStrict` is `VK_FALSE`, the value of the sparse unbound texel is undefined.

### 16.3.4. Depth Compare Operation

If the image view has a depth/stencil format, the depth component is selected by the `aspectMask`, and the operation is an `OpImage*Dref*` instruction, a depth comparison is performed. The result is 1.0 if the comparison evaluates to true, and 0.0 otherwise. This value replaces the depth component \( D \).

The compare operation is selected by the `VkCompareOp` value set by `VkSamplerCreateInfo::compareOp`. The reference value from the SPIR-V operand \( D_{\text{ref}} \) and the texel depth value \( D_{\text{tex}} \) are used as the *reference* and *test* values, respectively, in that operation.

If the image being sampled has an unsigned normalized fixed-point format, then \( D_{\text{ref}} \) is clamped to \([0,1]\) before the compare operation.

### 16.3.5. Conversion to RGBA

The texel is expanded from one, two, or three components to four components based on the image base color:

<table>
<thead>
<tr>
<th>Texel Aspect or Format</th>
<th>RGBA Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth aspect</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b, \text{Color}_a] = [D,0,0,one])</td>
</tr>
<tr>
<td>Stencil aspect</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b, \text{Color}_a] = [S,0,0,one])</td>
</tr>
<tr>
<td>One component color format</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b, \text{Color}_a] = [\text{Color}_r,0,0,one])</td>
</tr>
<tr>
<td>Two component color format</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b, \text{Color}_a] = [\text{Color}_r,\text{Color}_g,0,one])</td>
</tr>
</tbody>
</table>
where one = 1.0f for floating-point formats and depth aspects, and one = 1 for integer formats and stencil aspects.

### 16.3.6. Component Swizzle

All texel input instructions apply a swizzle based on:

- the `VkComponentSwizzle` enums in the `components` member of the `VkImageViewCreateInfo` structure for the image being read if sampler Y’C_bC_r conversion is not enabled, and
- the `VkComponentSwizzle` enums in the `components` member of the `VkSamplerYcbcrConversionCreateInfo` structure for the sampler Y’C_bC_r conversion if sampler Y’C_bC_r conversion is enabled.

The swizzle can rearrange the components of the texel, or substitute zero or one for any components. It is defined as follows for each color component:

\[
\text{Color}_{	ext{component}} = \begin{cases} 
\text{Color}_r & \text{for RED swizzle} \\
\text{Color}_g & \text{for GREEN swizzle} \\
\text{Color}_b & \text{for BLUE swizzle} \\
\text{Color}_a & \text{for ALPHA swizzle} \\
0 & \text{for ZERO swizzle} \\
\text{one} & \text{for ONE swizzle} \\
\text{identity} & \text{for IDENTITY swizzle}
\end{cases}
\]

where:

\[
\text{one} = \begin{cases} 
1.0f & \text{for floating point components} \\
1 & \text{for integer components}
\end{cases}
\]

\[
\text{identity} = \begin{cases} 
\text{Color}_r & \text{for component = r} \\
\text{Color}_g & \text{for component = g} \\
\text{Color}_b & \text{for component = b} \\
\text{Color}_a & \text{for component = a}
\end{cases}
\]

If the border color is one of the `VK_BORDER_COLOR_*_OPAQUE_BLACK` enums and the `VkComponentSwizzle` is not the identity swizzle for all components, the value of the texel after swizzle is undefined.

### 16.3.7. Sparse Residency

`OpImageSparse*` instructions return a structure which includes a residency code indicating whether any texels accessed by the instruction are sparse unbound texels. This code can be interpreted by
the `OpImageSparseTexelsResident` instruction which converts the residency code to a boolean value.

### 16.3.8. Chroma Reconstruction

In some color models, the color representation is defined in terms of monochromatic light intensity (often called “luma”) and color differences relative to this intensity, often called “chroma”. It is common for color models other than RGB to represent the chroma components at lower spatial resolution than the luma component. This approach is used to take advantage of the eye’s lower spatial sensitivity to color compared with its sensitivity to brightness. Less commonly, the same approach is used with additive color, since the green component dominates the eye’s sensitivity to light intensity and the spatial sensitivity to color introduced by red and blue is lower.

Lower-resolution components are “downsampled” by resizing them to a lower spatial resolution than the component representing luminance. This process is also commonly known as “chroma subsampling”. There is one luminance sample in each texture texel, but each chrominance sample may be shared among several texels in one or both texture dimensions.

- **“_444”** formats do not spatially downsample chroma values compared with luma: there are unique chroma samples for each texel.
- **“_422”** formats have downsampling in the x dimension (corresponding to u or s coordinates): they are sampled at half the resolution of luma in that dimension.
- **“_420”** formats have downsampling in the x dimension (corresponding to u or s coordinates) and the y dimension (corresponding to v or t coordinates): they are sampled at half the resolution of luma in both dimensions.

The process of reconstructing a full color value for texture access involves accessing both chroma and luma values at the same location. To generate the color accurately, the values of the lower-resolution components at the location of the luma samples must be reconstructed from the lower-resolution sample locations, an operation known here as “chroma reconstruction” irrespective of the actual color model.

The location of the chroma samples relative to the luma coordinates is determined by the `xChromaOffset` and `yChromaOffset` members of the `VkSamplerYcbcrConversionCreateInfo` structure used to create the sampler Y’C₉B₉R conversion.

The following diagrams show the relationship between unnormalized (u, v) coordinates and (i, j) integer texel positions in the luma component (shown in black, with circles showing integer sample positions) and the texel coordinates of reduced-resolution chroma components, shown as crosses in red.

**Note**

If the chroma values are reconstructed at the locations of the luma samples by means of interpolation, chroma samples from outside the image bounds are needed; these are determined according to Wrapping Operation. These diagrams represent this by showing the bounds of the “chroma texel” extending beyond the image bounds, and including additional chroma sample positions where required for interpolation. The limits of a sample for NEAREST sampling is shown as a grid.
Figure 5. 422 downsampling, $xChromaOffset=COSITED\_EVEN$

Figure 6. 422 downsampling, $xChromaOffset=MIDPOINT$
Figure 7. 420 downsampling, xChromaOffset=COSITED_EVEN, yChromaOffset=COSITED_EVEN

Figure 8. 420 downsampling, xChromaOffset=MIDPOINT, yChromaOffset=COSITED_EVEN
Reconstruction is implemented in one of two ways:

If the format of the image that is to be sampled sets `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT`, or the `VkSamplerYcbcrConversionCreateInfo`'s `forceExplicitReconstruction` is set to `VK_TRUE`, reconstruction is performed as an explicit step independent of filtering, described in the *Explicit Reconstruction* section.

If the format of the image that is to be sampled does not set `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT` and if the
VkSamplerYcbcrConversionCreateInfo’s `forceExplicitReconstruction` is set to `VK_FALSE`, reconstruction is performed as an implicit part of filtering prior to color model conversion, with no separate post-conversion texel filtering step, as described in the Implicit Reconstruction section.

**Explicit Reconstruction**

- If the `chromaFilter` member of the `VkSamplerYcbcrConversionCreateInfo` structure is `VK_FILTER_NEAREST`:
  - If the format’s R and B components are reduced in resolution in just width by a factor of two relative to the G component (i.e. this is a “422” format), the \( \tau_{ij}[\text{level}] \) values accessed by texel filtering are reconstructed as follows:
    \[
    \begin{align*}
    \tau_R'(i, j) &= \tau_R([i \times 0.5], j)[\text{level}] \\
    \tau_B'(i, j) &= \tau_B([i \times 0.5], j)[\text{level}]
    \end{align*}
    \]
  - If the format’s R and B components are reduced in resolution in width and height by a factor of two relative to the G component (i.e. this is a “420” format), the \( \tau_{ij}[\text{level}] \) values accessed by texel filtering are reconstructed as follows:
    \[
    \begin{align*}
    \tau_R'(i, j) &= \tau_R([i \times 0.5], [j \times 0.5])[\text{level}] \\
    \tau_B'(i, j) &= \tau_B([i \times 0.5], [j \times 0.5])[\text{level}]
    \end{align*}
    \]

  *Note:* `xChromaOffset` and `yChromaOffset` have no effect if `chromaFilter` is `VK_FILTER_NEAREST` for explicit reconstruction.

- If the `chromaFilter` member of the `VkSamplerYcbcrConversionCreateInfo` structure is `VK_FILTER_LINEAR`:
  - If the format’s R and B components are reduced in resolution in just width by a factor of two relative to the G component (i.e. this is a “422” format):
    - If `xChromaOffset` is `VK_CHROMA_LOCATION_COSITED_EVEN`:
      \[
      \begin{align*}
      \tau_{RB}'(i, j) &= \begin{cases} \\
      \tau_{RB}([i \times 0.5], [j])[\text{level}], & 0.5 \times i = [0.5 \times i] \\
      0.5 \times \tau_{RB}([i \times 0.5], [j])[\text{level}] + 0.5 \times \tau_{RB}([i \times 0.5] + 1, [j])[\text{level}], & 0.5 \times i \neq [0.5 \times i]
      \end{cases}
      \]
    - If `xChromaOffset` is `VK_CHROMA_LOCATION_MIDPOINT`:
      \[
      \begin{align*}
      \tau_{RB}'(i, j) &= \begin{cases} \\
      0.25 \times \tau_{RB}([i \times 0.5] - 1, [j])[\text{level}] + 0.75 \times \tau_{RB}([i \times 0.5], [j])[\text{level}], & 0.5 \times i = [0.5 \times i] \\
      0.75 \times \tau_{RB}([i \times 0.5], [j])[\text{level}] + 0.25 \times \tau_{RB}([i \times 0.5] + 1, [j])[\text{level}], & 0.5 \times i \neq [0.5 \times i]
      \end{cases}
      \]
  - If the format’s R and B components are reduced in resolution in width and height by a factor of two relative to the G component (i.e. this is a “420” format), a similar relationship applies. Due to the number of options, these formulae are expressed more concisely as follows:
\[ i_{RB} = \begin{cases} 
0.5 \times (i) & \text{xChromaOffset=COSITED_EVEN} \\
0.5 \times (i - 0.5) & \text{xChromaOffset=MIDPOINT} 
\end{cases} \]
\[ j_{RB} = \begin{cases} 
0.5 \times (j) & \text{yChromaOffset=COSITED_EVEN} \\
0.5 \times (j - 0.5) & \text{yChromaOffset=MIDPOINT} 
\end{cases} \]
\[
\begin{align*}
    i_{floor} & = \lfloor i_{RB} \rfloor \\
    j_{floor} & = \lfloor j_{RB} \rfloor \\
    i_{frac} & = i_{RB} - i_{floor} \\
    j_{frac} & = j_{RB} - j_{floor}
\end{align*}
\]
\[
\begin{align*}
    \tau_{RB}^\prime(i, j) & = \tau_{RB}(i_{floor}, j_{floor}, level) \times (1 - i_{frac}) \times (1 - j_{frac}) + \\
    \tau_{RB}(i_{floor} + 1, j_{floor}, level) & \times (i_{frac}) \times (1 - j_{frac}) + \\
    \tau_{RB}(i_{floor}, j_{floor} + 1, level) & \times (1 - i_{frac}) \times (j_{frac}) + \\
    \tau_{RB}(i_{floor} + 1, j_{floor} + 1, level) & \times (i_{frac}) \times (j_{frac})
\end{align*}
\]

**Implicit Reconstruction**

Implicit reconstruction takes place by the samples being interpolated, as required by the filter settings of the sampler, except that \text{chromaFilter} takes precedence for the chroma samples.

If \text{chromaFilter} is \text{VK_FILTER_NEAREST}, an implementation \text{may} behave as if \text{xChromaOffset} and \text{yChromaOffset} were both \text{VK_CHROMA_LOCATION_MIDPOINT}, irrespective of the values set.

**Note**

This will not have any visible effect if the locations of the luma samples coincide with the location of the samples used for rasterization.

The sample coordinates are adjusted by the downsample factor of the component (such that, for example, the sample coordinates are divided by two if the component has a downsample factor of two relative to the luma component):

\[
\begin{align*}
    u_{RB}^\prime(422 / 420) & = \begin{cases} 
0.5 \times (u + 0.5), & \text{xChromaOffset=COSITED_EVEN} \\
0.5 \times u, & \text{xChromaOffset=MIDPOINT} 
\end{cases} \\
    v_{RB}^\prime(420) & = \begin{cases} 
0.5 \times (v + 0.5), & \text{yChromaOffset=COSITED_EVEN} \\
0.5 \times v, & \text{yChromaOffset=MIDPOINT} 
\end{cases}
\end{align*}
\]

**16.3.9. Sampler Y'CbCr Conversion**

Sampler Y’CbCr conversion performs the following operations, which an implementation \text{may}
combine into a single mathematical operation:

- **Sampler Y’C_bC_r Range Expansion**
- **Sampler Y’C_bC_r Model Conversion**

**Sampler Y’C_bC_r Range Expansion**

Sampler Y’C_bC_r range expansion is applied to color component values after all texel input operations which are not specific to sampler Y’C_bC_r conversion. For example, the input values to this stage have been converted using the normal format conversion rules.

Sampler Y’C_bC_r range expansion is not applied if `ycbcrModel` is `VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY`. That is, the shader receives the vector C’rgba as output by the Component Swizzle stage without further modification.

For other values of `ycbcrModel`, range expansion is applied to the texel component values output by the Component Swizzle defined by the `components` member of `VkSamplerYcbcrConversionCreateInfo`. Range expansion applies independently to each component of the image. For the purposes of range expansion and Y’C_bC_r model conversion, the R and B components contain color difference (chroma) values and the G component contains luma. The A component is not modified by sampler Y’C_bC_r range expansion.

The range expansion to be applied is defined by the `ycbcrRange` member of the `VkSamplerYcbcrConversionCreateInfo` structure:

- If `ycbcrRange` is `VK_SAMPLER_YCBCR_RANGE_ITU_FULL`, the following transformations are applied:

\[
Y' = C' \cdot [G] \\
C_B = C' \cdot [B] - \frac{2^{n-1}}{(2^n - 1)} \\
C_R = C' \cdot [R] - \frac{2^{n-1}}{(2^n - 1)}
\]

*Note*

These formulae correspond to the “full range” encoding in the “Quantization schemes” chapter of the Khronos Data Format Specification.

Should any future amendments be made to the ITU specifications from which these equations are derived, the formulae used by Vulkan may also be updated to maintain parity.

- If `ycbcrRange` is `VK_SAMPLER_YCBCR_RANGE_ITU_NARROW`, the following transformations are applied:
\[
Y' = \frac{C'_{rgb} \lbrack G \rbrack \times (2^n - 1) - 16 \times 2^n - 8}{219 \times 2^n - 8}
\]
\[
C_B = \frac{C'_{rgb} \lbrack B \rbrack \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8}
\]
\[
C_R = \frac{C'_{rgb} \lbrack R \rbrack \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8}
\]

**Note**

These formulae correspond to the “narrow range” encoding in the “Quantization schemes” chapter of the Khronos Data Format Specification.

* n is the bit-depth of the components in the format.

The precision of the operations performed during range expansion must be at least that of the source format.

An implementation may clamp the results of these range expansion operations such that \( Y' \) falls in the range \([0,1]\), and/or such that \( C_B \) and \( C_R \) fall in the range \([-0.5,0.5]\).

**Sampler Y'CbCr Model Conversion**

The range-expanded values are converted between color models, according to the color model conversion specified in the `ycbcrModel` member:

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY**

The color components are not modified by the color model conversion since they are assumed already to represent the desired color model in which the shader is operating; \( Y' \)\( C_B \)\( C_R \) range expansion is also ignored.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY**

The color components are not modified by the color model conversion and are assumed to be treated as though in \( Y' \)\( C_B \)\( C_R \) form both in memory and in the shader; \( Y' \)\( C_B \)\( C_R \) range expansion is applied to the components as for other \( Y' \)\( C_B \)\( C_R \) models, with the vector \((C_B,Y',C_B,A)\) provided to the shader.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709**

The color components are transformed from a \( Y' \)\( C_B \)\( C_R \) representation to an \( R'G'B' \) representation as described in the “BT.709 \( Y' \)\( C_B \)\( C_R \) conversion” section of the Khronos Data Format Specification.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601**

The color components are transformed from a \( Y' \)\( C_B \)\( C_R \) representation to an \( R'G'B' \) representation as described in the “BT.601 \( Y' \)\( C_B \)\( C_R \) conversion” section of the Khronos Data Format Specification.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020**

The color components are transformed from a \( Y' \)\( C_B \)\( C_R \) representation to an \( R'G'B' \) representation as described in the “BT.2020 \( Y' \)\( C_B \)\( C_R \) conversion” section of the Khronos Data Format Specification.
In this operation, each output component is dependent on each input component.

An implementation may clamp the R'G'B' results of these conversions to the range [0,1].

The precision of the operations performed during model conversion must be at least that of the source format.

The alpha component is not modified by these model conversions.

**Note**

Sampling operations in a non-linear color space can introduce color and intensity shifts at sharp transition boundaries. To avoid this issue, the technically precise color correction sequence described in the “Introduction to Color Conversions” chapter of the Khronos Data Format Specification may be performed as follows:

- Calculate the unnormalized texel coordinates corresponding to the desired sample position.
- For a `minFilter` or `magFilter` of `VK_FILTER_NEAREST`:
  1. Calculate \((i, j)\) for the sample location as described under the “nearest filtering” formulae in (\(u, v, w, a\)) to \((i, j, k, l, n)\) Transformation And Array Layer Selection
  2. Calculate the normalized texel coordinates corresponding to these integer coordinates.
  3. Sample using sampler Y'CbCr conversion at this location.
- For a `minFilter` or `magFilter` of `VK_FILTER_LINEAR`:
  1. Calculate \((i_{[0,1]}, j_{[0,1]}\)) for the sample location as described under the “linear filtering” formulae in (\(u, v, w, a\)) to \((i, j, k, l, n)\) Transformation And Array Layer Selection
  2. Calculate the normalized texel coordinates corresponding to these integer coordinates.
  3. Sample using sampler Y'CbCr conversion at each of these locations.
  4. Convert the non-linear A'R'G'B' outputs of the Y'CbCr conversions to linear ARGB values as described in the “Transfer Functions” chapter of the Khronos Data Format Specification.
  5. Interpolate the linear ARGB values using the \(\alpha\) and \(\beta\) values described in the “linear filtering” section of (\(u, v, w, a\)) to \((i, j, k, l, n)\) Transformation And Array Layer Selection and the equations in Texel Filtering.

The additional calculations and, especially, additional number of sampling operations in the `VK_FILTER_LINEAR` case can be expected to have a performance impact compared with using the outputs directly. Since the variations from “correct” results are subtle for most content, the application author should determine whether a more costly implementation is strictly necessary.

If `chromaFilter`, and `minFilter` or `magFilter` are both `VK_FILTER_NEAREST`, these
operations are redundant and sampling using sampler Y'CbCr conversion at the desired sample coordinates will produce the “correct” results without further processing.

16.4. Texel Output Operations

Texel output instructions are SPIR-V image instructions that write to an image. Texel output operations are a set of steps that are performed on state, coordinates, and texel values while processing a texel output instruction, and which are common to some or all texel output instructions. They include the following steps, which are performed in the listed order:

- Validation operations
  - Format validation
  - Type validation
  - Coordinate validation
  - Sparse validation
- Texel output format conversion

16.4.1. Texel Output Validation Operations

Texel output validation operations inspect instruction/image state or coordinates, and in certain circumstances cause the write to have no effect. There are a series of validations that the texel undergoes.

Texel Format Validation

If the image format of the OpTypeImage is not compatible with the VkImageView’s format, the write causes the contents of the image’s memory to become undefined.

Texel Type Validation

If the Sampled Type of the OpTypeImage does not match the SPIR-V Type, the write causes the value of the texel to become undefined. For integer types, if the signedness of the access does not match the signedness of the accessed resource, the write causes the value of the texel to become undefined.

16.4.2. Integer Texel Coordinate Validation

The integer texel coordinates are validated according to the same rules as for texel input coordinate validation.

If the texel fails integer texel coordinate validation, then the write has no effect.

16.4.3. Sparse Texel Operation

If the texel attempts to write to an unbound region of a sparse image, the texel is a sparse unbound texel. In such a case, if the VkPhysicalDeviceSparseProperties::residencyNonResidentStrict property is VK_TRUE, the sparse unbound texel write has no effect. If residencyNonResidentStrict is VK_FALSE,
the write may have a side effect that becomes visible to other accesses to unbound texels in any resource, but will not be visible to any device memory allocated by the application.

### 16.4.4. Texel Output Format Conversion

If the image format is sRGB, a linear to sRGB conversion is applied to the R, G, and B components as described in the “sRGB EOTF” section of the Khronos Data Format Specification. The A component, if present, is unchanged.

Texels then undergo a format conversion from the floating point, signed, or unsigned integer type of the texel data to the VkFormat of the image view. If the number of components in the texel data is larger than the number of components in the format, additional components are discarded.

Each component is converted based on its type and size (as defined in the Format Definition section for each VkFormat). Floating-point outputs are converted as described in Floating-Point Format Conversions and Fixed-Point Data Conversion. Integer outputs are converted such that their value is preserved. The converted value of any integer that cannot be represented in the target format is undefined.

### 16.5. Normalized Texel Coordinate Operations

If the image sampler instruction provides normalized texel coordinates, some of the following operations are performed.

#### 16.5.1. Projection Operation

For Proj image operations, the normalized texel coordinates \((s, t, r, q, a)\) and (if present) the \(D_{ref}\) coordinate are transformed as follows:

\[
\begin{align*}
    s &= \frac{s}{q}, & \text{for 1D, 2D, or 3D image} \\
    t &= \frac{t}{q}, & \text{for 2D or 3D image} \\
    r &= \frac{r}{q}, & \text{for 3D image} \\
    D_{ref} &= \frac{D_{ref}}{q}, & \text{if provided}
\end{align*}
\]

#### 16.5.2. Derivative Image Operations

Derivatives are used for LOD selection. These derivatives are either implicit (in an ImplicitLod image instruction in a fragment shader) or explicit (provided explicitly by shader to the image instruction in any shader).

For implicit derivatives image instructions, the derivatives of texel coordinates are calculated in the same manner as derivative operations. That is:
\[ \frac{\partial s}{\partial x} = dPd x(s), \quad \frac{\partial s}{\partial y} = dPd y(s), \quad \text{for 1D, 2D, Cube, or 3D image} \\
\frac{\partial t}{\partial x} = dPd x(t), \quad \frac{\partial t}{\partial y} = dPd y(t), \quad \text{for 2D, Cube, or 3D image} \\
\frac{\partial r}{\partial x} = dPd x(r), \quad \frac{\partial r}{\partial y} = dPd y(r), \quad \text{for Cube or 3D image} \]

Partial derivatives not defined above for certain image dimensionalities are set to zero.

For explicit LOD image instructions, if the \textbf{optional} SPIR-V operand \texttt{Grad} is provided, then the operand values are used for the derivatives. The number of components present in each derivative for a given image dimensionality matches the number of partial derivatives computed above.

If the \textbf{optional} SPIR-V operand \texttt{Lod} is provided, then derivatives are set to zero, the cube map derivative transformation is skipped, and the scale factor operation is skipped. Instead, the floating point scalar coordinate is directly assigned to $\lambda_{\text{base}}$ as described in LOD Operation.

If the image or sampler object used by an implicit derivative image instruction is not uniform across the quad and \texttt{quadDivergentImplicitLod} is not supported, then the derivative and LOD values are undefined. Implicit derivatives are well-defined when the image and sampler and control flow are uniform across the quad, even if they diverge between different quads.

If \texttt{quadDivergentImplicitLod} is supported, then derivatives and implicit LOD values are well-defined even if the image or sampler object are not uniform within a quad. The derivatives are computed as specified above, and the implicit LOD calculation proceeds for each shader invocation using its respective image and sampler object.

\subsection*{16.5.3. Cube Map Face Selection and Transformations}

For cube map image instructions, the \((s,t,r)\) coordinates are treated as a direction vector \((r_x, r_y, r_z)\). The direction vector is used to select a cube map face. The direction vector is transformed to a per-face texel coordinate system \((s_{\text{face}}, t_{\text{face}})\). The direction vector is also used to transform the derivatives to per-face derivatives.

\subsection*{16.5.4. Cube Map Face Selection}

The direction vector selects one of the cube map’s faces based on the largest magnitude coordinate direction (the major axis direction). Since two or more coordinates can have identical magnitude, the implementation \textbf{must} have rules to disambiguate this situation.

The rules \textbf{should} have as the first rule that $r_z$ wins over $r_y$ and $r_x$, and the second rule that $r_y$ wins over $r_x$. An implementation \textbf{may} choose other rules, but the rules \textbf{must} be deterministic and depend only on \((r_x, r_y, r_z)\).

The layer number (corresponding to a cube map face), the coordinate selections for $s_x$, $t_x$, $r_x$, and the selection of derivatives, are determined by the major axis direction as specified in the following two tables.

\textit{Table 17. Cube map face and coordinate selection}
<table>
<thead>
<tr>
<th>Major Axis Direction</th>
<th>Layer Number</th>
<th>Cube Map Face</th>
<th>( s_c )</th>
<th>( t_c )</th>
<th>( r_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>0</td>
<td>Positive X</td>
<td>-r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;x&lt;/sub&gt;</td>
</tr>
<tr>
<td>-r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>1</td>
<td>Negative X</td>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;x&lt;/sub&gt;</td>
</tr>
<tr>
<td>+r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>2</td>
<td>Positive Y</td>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>+r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;y&lt;/sub&gt;</td>
</tr>
<tr>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>3</td>
<td>Negative Y</td>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;y&lt;/sub&gt;</td>
</tr>
<tr>
<td>+r&lt;sub&gt;z&lt;/sub&gt;</td>
<td>4</td>
<td>Positive Z</td>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;z&lt;/sub&gt;</td>
</tr>
<tr>
<td>-r&lt;sub&gt;z&lt;/sub&gt;</td>
<td>5</td>
<td>Negative Z</td>
<td>-r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>r&lt;sub&gt;z&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Table 18. Cube map derivative selection

<table>
<thead>
<tr>
<th>Major Axis Direction</th>
<th>( \partial s_c / \partial x )</th>
<th>( \partial s_c / \partial y )</th>
<th>( \partial t_c / \partial x )</th>
<th>( \partial t_c / \partial y )</th>
<th>( \partial r_c / \partial x )</th>
<th>( \partial r_c / \partial y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>-( \partial r_x / \partial x )</td>
<td>-( \partial r_x / \partial y )</td>
<td>-( \partial r_y / \partial x )</td>
<td>-( \partial r_y / \partial y )</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
</tr>
<tr>
<td>-r&lt;sub&gt;x&lt;/sub&gt;</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
<td>-( \partial r_y / \partial x )</td>
<td>-( \partial r_y / \partial y )</td>
<td>-( \partial r_x / \partial x )</td>
<td>-( \partial r_x / \partial y )</td>
</tr>
<tr>
<td>+r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
<td>+( \partial r_z / \partial x )</td>
<td>+( \partial r_z / \partial y )</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
</tr>
<tr>
<td>-r&lt;sub&gt;y&lt;/sub&gt;</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
<td>-( \partial r_z / \partial x )</td>
<td>-( \partial r_z / \partial y )</td>
<td>-( \partial r_x / \partial x )</td>
<td>-( \partial r_x / \partial y )</td>
</tr>
<tr>
<td>+r&lt;sub&gt;z&lt;/sub&gt;</td>
<td>+( \partial r_x / \partial x )</td>
<td>+( \partial r_x / \partial y )</td>
<td>-( \partial r_y / \partial x )</td>
<td>-( \partial r_y / \partial y )</td>
<td>+( \partial r_z / \partial x )</td>
<td>+( \partial r_z / \partial y )</td>
</tr>
<tr>
<td>-r&lt;sub&gt;z&lt;/sub&gt;</td>
<td>-( \partial r_x / \partial x )</td>
<td>-( \partial r_x / \partial y )</td>
<td>-( \partial r_y / \partial x )</td>
<td>-( \partial r_y / \partial y )</td>
<td>-( \partial r_z / \partial x )</td>
<td>-( \partial r_z / \partial y )</td>
</tr>
</tbody>
</table>

16.5.5. Cube Map Coordinate Transformation

\[
\begin{align*}
    s_{face} &= \frac{1}{2} \times s_c + \frac{1}{\frac{r_c}{2}} \\
    t_{face} &= \frac{1}{2} \times t_c + \frac{1}{\frac{r_c}{2}}
\end{align*}
\]

16.5.6. Cube Map Derivative Transformation

\[
\begin{align*}
    \frac{\partial s_{face}}{\partial x} &= \frac{\partial}{\partial x} \left( \frac{1}{2} \times s_c + \frac{1}{\frac{r_c}{2}} \right) \\
    \frac{\partial s_{face}}{\partial x} &= \frac{1}{2} \times \frac{\partial}{\partial x} \left( s_c \right) \\
    \frac{\partial s_{face}}{\partial x} &= \frac{1}{\frac{r_c}{2}} \times \left( \frac{\partial s_c / \partial x - s_c \times \partial r_c / \partial x}{(r_c)^2} \right)
\end{align*}
\]
16.5.7. Scale Factor Operation, LOD Operation and Image Level(s) Selection

LOD selection can be either explicit (provided explicitly by the image instruction) or implicit (determined from a scale factor calculated from the derivatives). The LOD must be computed with `mipmapPrecisionBits` of accuracy.

**Scale Factor Operation**

The magnitude of the derivatives are calculated by:

\[
\frac{\partial s_{face}}{\partial y} = \frac{1}{2} \times \left( \frac{|r_c| \times \partial s_c / \partial y - s_c \times \partial r_c / \partial y}{(r_c)^2} \right)
\]

\[
\frac{\partial t_{face}}{\partial x} = \frac{1}{2} \times \left( \frac{|r_c| \times \partial t_c / \partial x - t_c \times \partial r_c / \partial x}{(r_c)^2} \right)
\]

\[
\frac{\partial t_{face}}{\partial y} = \frac{1}{2} \times \left( \frac{|r_c| \times \partial t_c / \partial y - t_c \times \partial r_c / \partial y}{(r_c)^2} \right)
\]

where:

\[
\frac{\partial t}{\partial x} = \frac{\partial t}{\partial y} = 0 \text{ (for 1D images)}
\]

\[
\frac{\partial r}{\partial x} = \frac{\partial r}{\partial y} = 0 \text{ (for 1D, 2D or Cube images)}
\]

and:

\[
w_{base} = \text{image.w}
\]
A point sampled in screen space has an elliptical footprint in texture space. The minimum and maximum scale factors ($\rho_{\text{min}}$, $\rho_{\text{max}}$) should be the minor and major axes of this ellipse.

The scale factors $\rho_x$ and $\rho_y$, calculated from the magnitude of the derivatives in x and y, are used to compute the minimum and maximum scale factors.

$\rho_x$ and $\rho_y$ may be approximated with functions $f_x$ and $f_y$, subject to the following constraints:

- $f_x$ is continuous and monotonically increasing in each of $m_{ux}$, $m_{vx}$, and $m_{wx}$
- $f_y$ is continuous and monotonically increasing in each of $m_{uy}$, $m_{vy}$, and $m_{wy}$

\[
\begin{align*}
\max(|m_{ux}|, |m_{vx}|, |m_{wx}|) & \leq f_x \leq \sqrt{2(|m_{ux}| + |m_{vx}| + |m_{wx}|)} \\
\max(|m_{uy}|, |m_{vy}|, |m_{wy}|) & \leq f_y \leq \sqrt{2(|m_{uy}| + |m_{vy}| + |m_{wy}|)}
\end{align*}
\]

The minimum and maximum scale factors ($\rho_{\text{min}}, \rho_{\text{max}}$) are determined by:

- $\rho_{\text{max}} = \max(\rho_x, \rho_y)$
- $\rho_{\text{min}} = \min(\rho_x, \rho_y)$

The ratio of anisotropy is determined by:

\[
\eta = \min(\rho_{\text{max}}/\rho_{\text{min}}, \text{maxAniso})
\]

where:

- $\text{sampler.maxAniso} = \text{maxAnisotropy}$ (from sampler descriptor)
- $\text{limits.maxAniso} = \text{maxSamplerAnisotropy}$ (from physical device limits)
- $\text{maxAniso} = \min(\text{sampler.maxAniso}, \text{limits.maxAniso})$

If $\rho_{\text{max}} = \rho_{\text{min}} = 0$, then all the partial derivatives are zero, the fragment's footprint in texel space is a point, and $\eta$ should be treated as 1. If $\rho_{\text{max}} \neq 0$ and $\rho_{\text{min}} = 0$ then all partial derivatives along one axis are zero, the fragment’s footprint in texel space is a line segment, and $\eta$ should be treated as
Aniso. However, anytime the footprint is small in texel space the implementation may use a smaller value of $\eta$, even when $\rho_{\text{min}}$ is zero or close to zero. If either $\text{VkPhysicalDeviceFeatures::samplerAnisotropy}$ or $\text{VkSamplerCreateInfo::anisotropyEnable}$ are $\text{VK_FALSE}$, $\text{maxAniso}$ is set to 1.

If $\eta = 1$, sampling is isotropic. If $\eta > 1$, sampling is anisotropic.

The sampling rate ($N$) is derived as:

$$ N = \lceil \eta \rceil $$

An implementation may round $N$ up to the nearest supported sampling rate. An implementation may use the value of $N$ as an approximation of $\eta$.

**LOD Operation**

The LOD parameter $\lambda$ is computed as follows:

$$ \lambda_{\text{base}}(x, y) = \begin{cases} \text{shaderOp.Lod} & \text{from optional SPIR-V operand} \\ \log_2 \left( \frac{\rho_{\text{max}}}{\eta} \right) & \text{otherwise} \end{cases} $$

$$ \lambda'(x, y) = \lambda_{\text{base}} + \text{clamp}(\text{sampler.bias} + \text{shaderOp.bias}, -\text{maxSamplerLodBias}, \text{maxSamplerLodBias}) $$

$$ \lambda = \begin{cases} \text{lod}_{\text{max}}, & \lambda' > \text{lod}_{\text{max}} \\ \lambda', & \text{lod}_{\text{min}} < \lambda' \leq \text{lod}_{\text{max}} \\ \text{lod}_{\text{min}}, & \lambda' < \text{lod}_{\text{min}} \\ \text{undefined}, & \text{lod}_{\text{min}} > \text{lod}_{\text{max}} \end{cases} $$

where:

$$ \text{sampler.bias} = \text{mipLodBias} $$

(from sampler descriptor)

$$ \text{shaderOp.bias} = \begin{cases} \text{Bias} & \text{from optional SPIR-V operand} \\ 0 & \text{otherwise} \end{cases} $$

(from sampler descriptor)

$$ \text{sampler.lod}_{\text{min}} = \text{minLod} $$

(from sampler descriptor)

$$ \text{shaderOp.lod}_{\text{min}} = \begin{cases} \text{MinLod} & \text{from optional SPIR-V operand} \\ 0 & \text{otherwise} \end{cases} $$

and $\text{maxSamplerLodBias}$ is the value of the $\text{VkPhysicalDeviceLimits}$ feature $\text{maxSamplerLodBias}$.

**Image Level(s) Selection**

The image level(s) $d$, $d_{\text{hi}}$, and $d_{\text{lo}}$ which texels are read from are determined by an image-level parameter $d_0$, which is computed based on the LOD parameter, as follows:

$$ d_j = \begin{cases} \text{nearest}(d'), & \text{mipmapMode is VK_SAMPLER_MIPMAP_MODE_NEAREST} \\ d', & \text{otherwise} \end{cases} $$

where:

$$ d' = \text{level}_{\text{base}} + \text{clamp}(\lambda, 0, q) $$
\[
\text{nearest}(d') = \begin{cases} 
[d' + 0.5] - 1, & \text{preferred} \\
[d' + 0.5], & \text{alternative}
\end{cases}
\]

and:

\[
\begin{align*}
\text{level}_\text{base} &= \text{baseMipLevel} \\
q &= \text{levelCount} - 1
\end{align*}
\]

\text{baseMipLevel} and \text{levelCount} are taken from the \text{subresourceRange} of the image view.

If the sampler’s \text{mipmapMode} is \text{VK_SAMPLER_MIPMAP_MODE_NEAREST}, then the level selected is \(d = d\).

If the sampler’s \text{mipmapMode} is \text{VK_SAMPLER_MIPMAP_MODE_LINEAR}, two neighboring levels are selected:

\[
\begin{align*}
d_{hi} &= \lfloor d \rfloor \\
d_{lo} &= \min(d_{hi} + 1, \text{level}_\text{base} + q) \\
\delta &= d - d_{hi}
\end{align*}
\]

\(\delta\) is the fractional value, quantized to the number of \text{mipmap precision bits}, used for linear filtering between levels.

### 16.5.8. \((s,t,r,q,a)\) to \((u,v,w,a)\) Transformation

The normalized texel coordinates are scaled by the image level dimensions and the array layer is selected.

This transformation is performed once for each level used in filtering (either \(d\), or \(d_{hi}\) and \(d_{lo}\)).

\[
\begin{align*}
\mathbf{u}(x, y) &= s(x, y) \times \text{width}_\text{scale} + \Delta_l \\
\mathbf{v}(x, y) &= \begin{cases} 
0 & \text{for 1D images} \\
t(x, y) \times \text{height}_\text{scale} + \Delta_l & \text{otherwise}
\end{cases} \\
\mathbf{w}(x, y) &= \begin{cases} 
0 & \text{for 2D or Cube images} \\
r(x, y) \times \text{depth}_\text{scale} + \Delta_k & \text{otherwise}
\end{cases} \\
\mathbf{a}(x, y) &= \begin{cases} 
a(x, y) & \text{for array images} \\
0 & \text{otherwise}
\end{cases}
\end{align*}
\]

where:

\[
\text{width}_\text{scale} = \text{width}_\text{level}
\]

\[
\text{height}_\text{scale} = \text{height}_\text{level}
\]

\[
\text{depth}_\text{scale} = \text{depth}_\text{level}
\]
and where \((\Delta_i, \Delta_j, \Delta_k)\) are taken from the image instruction if it includes a `ConstOffset` or `Offset` operand, otherwise they are taken to be zero.

Operations then proceed to Unnormalized Texel Coordinate Operations.

### 16.6. Unnormalized Texel Coordinate Operations

#### 16.6.1. \((u,v,w,a)\) to \((i,j,k,l,n)\) Transformation And Array Layer Selection

The unnormalized texel coordinates are transformed to integer texel coordinates relative to the selected mipmap level.

The layer index \(l\) is computed as:

\[
l = \text{clamp}(\text{RNE}(a), 0, \text{layerCount} - 1) + \text{baseArrayLayer}
\]

where \(\text{layerCount}\) is the number of layers in the image subresource range of the image view, \(\text{baseArrayLayer}\) is the first layer from the subresource range, and where:

\[
\text{RNE}(a) = \begin{cases} 
\text{roundTiesToEven}(a) & \text{preferred, from IEEE Std 754-2008 Floating-Point Arithmetic} \\
\lfloor a + 0.5 \rfloor & \text{alternative}
\end{cases}
\]

The sample index \(n\) is assigned the value 0.

Nearest filtering (VK_FILTER_NEAREST) computes the integer texel coordinates that the unnormalized coordinates lie within:

\[
i = \lfloor u + \text{shift} \rfloor \\
j = \lfloor v + \text{shift} \rfloor \\
k = \lfloor w + \text{shift} \rfloor
\]

where:

\[
\text{shift} = 0.0
\]

Linear filtering (VK_FILTER_LINEAR) computes a set of neighboring coordinates which bound the unnormalized coordinates. The integer texel coordinates are combinations of \(i_0\) or \(i_1\), \(j_0\) or \(j_1\), \(k_0\) or \(k_1\), as well as weights \(\alpha\), \(\beta\), and \(\gamma\).

\[
i_0 = \lfloor u - \text{shift} \rfloor \\
i_1 = i_0 + 1 \\
j_0 = \lfloor v - \text{shift} \rfloor \\
j_1 = j_0 + 1 \\
k_0 = \lfloor w - \text{shift} \rfloor \\
k_1 = k_0 + 1
\]
\[ \alpha = \text{frac}(u - \text{shift}) \]
\[ \beta = \text{frac}(v - \text{shift}) \]
\[ \gamma = \text{frac}(w - \text{shift}) \]

where:

\[ \text{shift} = 0.5 \]

and where:

\[ \text{frac}(x) = x - \lfloor x \rfloor \]

where the number of fraction bits retained is specified by \text{VkPhysicalDeviceLimits} \cdot \text{subTexelPrecisionBits}.

16.7. Integer Texel Coordinate Operations

The \text{OpImageFetch} and \text{OpImageFetchSparse} SPIR-V instructions may supply a LOD from which texels are to be fetched using the optional SPIR-V operand \text{Lod}. Other integer-coordinate operations must not. If the \text{Lod} is provided then it must be an integer.

The image level selected is:

\[ d = \text{level}_\text{base} + \begin{cases} \text{Lod} & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases} \]

If \(d\) does not lie in the range \([\text{baseMipLevel}, \text{baseMipLevel} + \text{levelCount})\) then any values fetched are undefined, and any writes (if supported) are discarded.

16.8. Image Sample Operations

16.8.1. Wrapping Operation

\text{Cube} images ignore the wrap modes specified in the sampler. Instead, if \text{VK_FILTER_NEAREST} is used within a mip level then \text{VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE} is used, and if \text{VK_FILTER_LINEAR} is used within a mip level then sampling at the edges is performed as described earlier in the \text{Cube map edge handling} section.

The first integer texel coordinate \(i\) is transformed based on the \text{addressModeU} parameter of the sampler.
\[
    i = \begin{cases} 
        i \mod \text{size} & \text{for repeat} \\
        (\text{size} - 1) - \text{mirror} ((i \mod (2 \times \text{size})) - \text{size}) & \text{for mirrored repeat} \\
        \text{clamp}(i, 0, \text{size} - 1) & \text{for clamp to edge} \\
        \text{clamp}(i, -1, \text{size}) & \text{for clamp to border} \\
        \text{clamp}(\text{mirror}(i), 0, \text{size} - 1) & \text{for mirror clamp to edge}
    \end{cases}
\]

where:

\[
    \text{mirror}(n) = \begin{cases} 
        n & \text{for } n \geq 0 \\
        -(1 + n) & \text{otherwise}
    \end{cases}
\]

\(j\) (for 2D and Cube image) and \(k\) (for 3D image) are similarly transformed based on the \(\text{addressModeV}\) and \(\text{addressModeW}\) parameters of the sampler, respectively.

### 16.8.2. Texel Gathering

SPIR-V instructions with \texttt{Gather} in the name return a vector derived from 4 texels in the base level of the image view. The rules for the \texttt{VK\_FILTER\_LINEAR} minification filter are applied to identify the four selected texels. Each texel is then converted to an RGBA value according to conversion to RGBA and then swizzled. A four-component vector is then assembled by taking the component indicated by the \texttt{Component} value in the instruction from the swizzled color value of the four texels. If the operation does not use the \texttt{ConstOffsets} image operand then the four texels form the \(2 \times 2\) rectangle used for texture filtering:

\[
\begin{align*}
    \tau[R] &= \tau_{i0j1}[\text{level}_\text{base}, \text{comp}] \\
    \tau[G] &= \tau_{i1j1}[\text{level}_\text{base}, \text{comp}] \\
    \tau[B] &= \tau_{i1j0}[\text{level}_\text{base}, \text{comp}] \\
    \tau[A] &= \tau_{i0j0}[\text{level}_\text{base}, \text{comp}]
\end{align*}
\]

If the operation does use the \texttt{ConstOffsets} image operand then the offsets allow a custom filter to be defined:

\[
\begin{align*}
    \tau[R] &= \tau_{i0j0} + \Delta_0[\text{level}_\text{base}, \text{comp}] \\
    \tau[G] &= \tau_{i0j0} + \Delta_1[\text{level}_\text{base}, \text{comp}] \\
    \tau[B] &= \tau_{i0j0} + \Delta_2[\text{level}_\text{base}, \text{comp}] \\
    \tau[A] &= \tau_{i0j0} + \Delta_3[\text{level}_\text{base}, \text{comp}]
\end{align*}
\]

where:

\[
\tau[\text{level}_\text{base}, \text{comp}] = \begin{cases} 
    \tau[\text{level}_\text{base}, R], & \text{for } \text{comp} = 0 \\
    \tau[\text{level}_\text{base}, G], & \text{for } \text{comp} = 1 \\
    \tau[\text{level}_\text{base}, B], & \text{for } \text{comp} = 2 \\
    \tau[\text{level}_\text{base}, A], & \text{for } \text{comp} = 3
\end{cases}
\]

\(\text{comp}\) from SPIR-V operand Component
OpImage*Gather must not be used on a sampled image with sampler Y’C_bC_r conversion enabled.

16.8.3. Texel Filtering

Texel filtering is first performed for each level (either d or d_hi and d_lo).

If \( \lambda \) is less than or equal to zero, the texture is said to be *magnified*, and the filter mode within a mip level is selected by the `magFilter` in the sampler. If \( \lambda \) is greater than zero, the texture is said to be *minified*, and the filter mode within a mip level is selected by the `minFilter` in the sampler.

**Texel Nearest Filtering**

Within a mip level, `VK_FILTER_NEAREST` filtering selects a single value using the \((i, j, k)\) texel coordinates, with all texels taken from layer \( l \).

\[
\tau_{level}[level] = \begin{cases} 
\tau_{ijk}[level], & \text{for 3D image} \\
\tau_{ijl}[level], & \text{for 2D or Cube image} \\
\tau_{il}[level], & \text{for 1D image}
\end{cases}
\]

**Texel Linear Filtering**

Within a mip level, `VK_FILTER_LINEAR` filtering combines 8 (for 3D), 4 (for 2D or Cube), or 2 (for 1D) texel values, together with their linear weights. The linear weights are derived from the fractions computed earlier:

\[
w_{i_0} = (1 - \alpha) \\
w_{i_1} = (\alpha) \\
w_{j_0} = (1 - \beta) \\
w_{j_1} = (\beta) \\
w_{k_0} = (1 - \gamma) \\
w_{k_1} = (\gamma)
\]

The values of multiple texels, together with their weights, are combined to produce a filtered value.

The `VkSamplerReductionModeCreateInfo::reductionMode` can control the process by which multiple texels, together with their weights, are combined to produce a filtered texture value.

When the `reductionMode` is set (explicitly or implicitly) to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, a weighted average is computed:
However, if the reduction mode is `VK_SAMPLER_REDUCTION_MODE_MIN` or `VK_SAMPLER_REDUCTION_MODE_MAX`, the process operates on the above set of multiple texels, together with their weights, computing a component-wise minimum or maximum, respectively, of the components of the set of texels with non-zero weights.

**Texel Mipmap Filtering**

`VK_SAMPLER_MIPMAP_MODE_NEAREST` filtering returns the value of a single mipmap level, $\tau = \tau[d]$.

`VK_SAMPLER_MIPMAP_MODE_LINEAR` filtering combines the values of multiple mipmap levels ($\tau[hi]$ and $\tau[lo]$), together with their linear weights.

The linear weights are derived from the fraction computed earlier:

$$w_{hi} = (1 - \delta)$$
$$w_{lo} = (\delta)$$

The values of multiple mipmap levels, together with their weights, are combined to produce a final filtered value.

The `VkSamplerReductionModeCreateInfo::reductionMode` can control the process by which multiple texels, together with their weights, are combined to produce a filtered texture value.

When the `reductionMode` is set (explicitly or implicitly) to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, a weighted average is computed:

$$\tau = (w_{hi})\tau[hi] + (w_{lo})\tau[lo]$$

However, if the reduction mode is `VK_SAMPLER_REDUCTION_MODE_MIN` or `VK_SAMPLER_REDUCTION_MODE_MAX`, the process operates on the above values, together with their weights, computing a component-wise minimum or maximum, respectively, of the components of the values with non-zero weights.

**Texel Anisotropic Filtering**

Anisotropic filtering is enabled by the `anisotropyEnable` in the sampler. When enabled, the image filtering scheme accounts for a degree of anisotropy.

The particular scheme for anisotropic texture filtering is implementation-dependent.
Implementations should consider the `magFilter`, `minFilter` and `mipmapMode` of the sampler to control the specifics of the anisotropic filtering scheme used. In addition, implementations should consider `minLod` and `maxLod` of the sampler.

**Note**

For historical reasons, vendor implementations of anisotropic filtering interpret these sampler parameters in different ways, particularly in corner cases such as `magFilter`, `minFilter` of NEAREST or `maxAnisotropy` equal to 1.0. Applications should not expect consistent behavior in such cases, and should use anisotropic filtering only with parameters which are expected to give a quality improvement relative to LINEAR filtering.

The following describes one particular approach to implementing anisotropic filtering for the 2D Image case; implementations may choose other methods:

Given a `magFilter`, `minFilter` of `VK_FILTER_LINEAR` and a `mipmapMode` of `VK_SAMPLER_MIPMAP_MODE_NEAREST`:

Instead of a single isotropic sample, N isotropic samples are sampled within the image footprint of the image level d to approximate an anisotropic filter. The sum τ_{2Daniso} is defined using the single isotropic τ_{2D}(u,v) at level d.

\[
τ_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} τ_{2D} \left( u \left( x - \frac{1}{2} + \frac{j}{N+1}, y \right), v \left( x - \frac{1}{2} + \frac{j}{N+1}, y \right) \right), \quad \text{when } ρ_x > ρ_y
\]

\[
τ_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} τ_{2D} \left( u \left( x, y - \frac{1}{2} + \frac{i}{N+1}, \right), v \left( x, y - \frac{1}{2} + \frac{i}{N+1}, \right) \right), \quad \text{when } ρ_y ≥ ρ_x
\]

When `VkSamplerReductionModeCreateInfo::reductionMode` is set to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, the above summation is used. However, if the reduction mode is `VK_SAMPLER_REDUCTION_MODE_MIN` or `VK_SAMPLER_REDUCTION_MODE_MAX`, the process operates on the above values, together with their weights, computing a component-wise minimum or maximum, respectively, of the components of the values with non-zero weights.

### 16.9. Image Operation Steps

Each step described in this chapter is performed by a subset of the image instructions:

- Texel Input Validation Operations, Format Conversion, Texel Replacement, Conversion to RGBA, and Component Swizzle: Performed by all instructions except `OpImageWrite`.
- Depth Comparison: Performed by `OpImage*Dref` instructions.
- All Texel output operations: Performed by `OpImageWrite`.
- Projection: Performed by all `OpImage*Proj` instructions.
- Derivative Image Operations, Cube Map Operations, Scale Factor Operation, LOD Operation and Image Level(s) Selection, and Texel Anisotropic Filtering: Performed by all `OpImageSample*` and `OpImageSparseSample*` instructions.
• (s,t,r,q,a) to (u,v,w,a) Transformation, Wrapping, and (u,v,w,a) to (i,j,k,l,n) Transformation And Array Layer Selection: Performed by all OpImageSample, OpImageSparseSample, and OpImage*Gather instructions.

• Texel Gathering: Performed by OpImage*Gather instructions.

• Texel Filtering: Performed by all OpImageSample* and OpImageSparseSample* instructions.

• Sparse Residency: Performed by all OpImageSparse* instructions.

### 16.10. Image Query Instructions

#### 16.10.1. Image Property Queries

OpImageQuerySize, OpImageQuerySizeLod, OpImageQueryLevels, and OpImageQuerySamples query properties of the image descriptor that would be accessed by a shader image operation.

OpImageQuerySizeLod returns the size of the image level identified by the Level of Detail operand. If that level does not exist in the image, then the value returned is undefined.

#### 16.10.2. Lod Query

OpImageQueryLod returns the Lod parameters that would be used in an image operation with the given image and coordinates. The steps described in this chapter are performed as if for OpImageSampleImplicitLod, up to Scale Factor Operation, LOD Operation and Image Level(s) Selection. The return value is the vector (\( \lambda' \), d). These values may be subject to implementation-specific maxima and minima for very large, out-of-range values.
Chapter 17. Queries

Queries provide a mechanism to return information about the processing of a sequence of Vulkan commands. Query operations are asynchronous, and as such, their results are not returned immediately. Instead, their results, and their availability status are stored in a Query Pool. The state of these queries can be read back on the host, or copied to a buffer object on the device.

The supported query types are Occlusion Queries, Pipeline Statistics Queries, and Timestamp Queries.

17.1. Query Pools

Queries are managed using query pool objects. Each query pool is a collection of a specific number of queries of a particular type.

Query pools are represented by VkQueryPool handles:

```cpp
// Provided by VK_VERSION_1_0
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkQueryPool)
```

To create a query pool, call:

```cpp
// Provided by VK_VERSION_1_0
VkResult vkCreateQueryPool(
    VkDevice device,
    const VkQueryPoolCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkQueryPool* pQueryPool);
```

- `device` is the logical device that creates the query pool.
- `pCreateInfo` is a pointer to a VkQueryPoolCreateInfo structure containing the number and type of queries to be managed by the pool.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pQueryPool` is a pointer to a VkQueryPool handle in which the resulting query pool object is returned.

Valid Usage (Implicit)

- VUID-vkCreateQueryPool-device-parameter `device` must be a valid VkDevice handle
- VUID-vkCreateQueryPool-pCreateInfo-parameter `pCreateInfo` must be a valid pointer to a valid VkQueryPoolCreateInfo structure
- If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid
VkAllocationCallbacks structure

- VUID-vkCreateQueryPool-pQueryPool-parameter
  pQueryPool must be a valid pointer to a VkQueryPool handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkQueryPoolCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkQueryPoolCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkQueryPoolCreateFlags flags;
    VkQueryType queryType;
    uint32_t queryCount;
    VkQueryPipelineStatisticFlags pipelineStatistics;
} VkQueryPoolCreateInfo;
```

- `sType` is a VkStructureType value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `queryType` is a VkQueryType value specifying the type of queries managed by the pool.
- `queryCount` is the number of queries managed by the pool.
- `pipelineStatistics` is a bitmask of VkQueryPipelineStatisticFlagBits specifying which counters will be returned in queries on the new pool, as described below in Pipeline Statistics Queries.

`pipelineStatistics` is ignored if `queryType` is not VK_QUERY_TYPE_PIPELINE_STATISTICS.

Valid Usage

- VUID-VkQueryPoolCreateInfo-queryType-00791
  If the pipelineStatisticsQuery feature is not enabled, `queryType` must not be VK_QUERY_TYPE_PIPELINE_STATISTICS

- VUID-VkQueryPoolCreateInfo-queryType-00792
  If `queryType` is VK_QUERY_TYPE_PIPELINE_STATISTICS, `pipelineStatistics` must be a valid combination of VkQueryPipelineStatisticFlagBits values
• VUID-VkQueryPoolCreateInfo-queryCount-02763
  queryCount must be greater than 0

Valid Usage (Implicit)

• VUID-VkQueryPoolCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO

• VUID-VkQueryPoolCreateInfo-pNext-pNext
  pNext must be NULL

• VUID-VkQueryPoolCreateInfo-flags-zerobitmask
  flags must be 0

• VUID-VkQueryPoolCreateInfo-queryType-parameter
  queryType must be a valid VkQueryType value

// Provided by VK_VERSION_1_0
typedef VkFlags VkQueryPoolCreateFlags;

VkQueryPoolCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy a query pool, call:

// Provided by VK_VERSION_1_0
void vkDestroyQueryPool(
  VkDevice device,
  VkQueryPool queryPool,
  const VkAllocationCallbacks* pAllocator);

• device is the logical device that destroys the query pool.
• queryPool is the query pool to destroy.
• pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

• VUID-vkDestroyQueryPool-queryPool-00793
  All submitted commands that refer to queryPool must have completed execution

• VUID-vkDestroyQueryPool-queryPool-00794
  If VkAllocationCallbacks were provided when queryPool was created, a compatible set of callbacks must be provided here

• VUID-vkDestroyQueryPool-queryPool-00795
  If no VkAllocationCallbacks were provided when queryPool was created, pAllocator must be NULL
Applications can verify that queryPool can be destroyed by checking that `vkGetQueryPoolResults()` without the `VK_QUERY_RESULT_PARTIAL_BIT` flag returns `VK_SUCCESS` for all queries that are used in command buffers submitted for execution.

### Valid Usage (Implicit)

- **VUID-vkDestroyQueryPool-device-parameter**
  - `device` must be a valid `VkDevice` handle

- **VUID-vkDestroyQueryPool-queryPool-parameter**
  - If `queryPool` is not `VK_NULL_HANDLE`, `queryPool` must be a valid `VkQueryPool` handle

- **VUID-vkDestroyQueryPool-pAllocator-parameter**
  - If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- **VUID-vkDestroyQueryPool-queryPool-parent**
  - If `queryPool` is a valid handle, it must have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to `queryPool` must be externally synchronized

Possible values of `VkQueryPoolCreateInfo::queryType`, specifying the type of queries managed by the pool, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkQueryType {
    VK_QUERY_TYPE_OCCLUSION = 0,
    VK_QUERY_TYPE_PIPELINE_STATISTICS = 1,
    VK_QUERY_TYPE_TIMESTAMP = 2,
} VkQueryType;
```

- `VK_QUERY_TYPE_OCCLUSION` specifies an occlusion query.
- `VK_QUERY_TYPE_PIPELINE_STATISTICS` specifies a pipeline statistics query.
- `VK_QUERY_TYPE_TIMESTAMP` specifies a timestamp query.

### 17.2. Query Operation

The operation of queries is controlled by the commands `vkCmdBeginQuery`, `vkCmdEndQuery`, `vkCmdResetQueryPool`, `vkCmdCopyQueryPoolResults`, `vkCmdWriteTimestamp2`, and `vkCmdWriteTimestamp`.  

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In order for a VkCommandBuffer to record query management commands, the queue family for which its VkCommandPool was created must support the appropriate type of operations (graphics, compute) suitable for the query type of a given query pool.

Each query in a query pool has a status that is either unavailable or available, and also has state to store the numerical results of a query operation of the type requested when the query pool was created. Resetting a query via vkCmdResetQueryPool or vkResetQueryPool sets the status to unavailable and makes the numerical results undefined. A query is made available by the operation of vkCmdEndQuery, vkCmdWriteTimestamp2, or vkCmdWriteTimestamp. Both the availability status and numerical results can be retrieved by calling either vkGetQueryPoolResults or vkCmdCopyQueryPoolResults.

After query pool creation, each query must be reset before it is used. Queries must also be reset between uses.

If a logical device includes multiple physical devices, then each command that writes a query must execute on a single physical device, and any call to vkCmdBeginQuery must execute the corresponding vkCmdEndQuery command on the same physical device.

To reset a range of queries in a query pool on a queue, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdResetQueryPool(
    VkCommandBuffer commandBuffer,  // Provided by VK_VERSION_1_0
    VkQueryPool queryPool,   // Provided by VK_VERSION_1_0
    uint32_t firstQuery,     // Provided by VK_VERSION_1_0
    uint32_t queryCount);    // Provided by VK_VERSION_1_0
```

- commandBuffer is the command buffer into which this command will be recorded.
- queryPool is the handle of the query pool managing the queries being reset.
- firstQuery is the initial query index to reset.
- queryCount is the number of queries to reset.

When executed on a queue, this command sets the status of query indices \([\text{firstQuery}, \text{firstQuery} + \text{queryCount} - 1]\) to unavailable.

This command defines an execution dependency between other query commands that reference the same query.

The first synchronization scope includes all commands which reference the queries in queryPool indicated by firstQuery and queryCount that occur earlier in submission order.

The second synchronization scope includes all commands which reference the queries in queryPool indicated by firstQuery and queryCount that occur later in submission order.

The operation of this command happens after the first scope and happens before the second scope.
Valid Usage

- VUID-vkCmdResetQueryPool-firstQuery-00796
  'firstQuery' must be less than the number of queries in 'queryPool'

- VUID-vkCmdResetQueryPool-firstQuery-00797
  The sum of 'firstQuery' and 'queryCount' must be less than or equal to the number of queries in 'queryPool'

- VUID-vkCmdResetQueryPool-None-02841
  All queries used by the command must not be active

Valid Usage (Implicit)

- VUID-vkCmdResetQueryPool-commandBuffer-parameter
  'commandBuffer' must be a valid VkCommandBuffer handle

- VUID-vkCmdResetQueryPool-queryPool-parameter
  'queryPool' must be a valid VkQueryPool handle

- VUID-vkCmdResetQueryPool-commandBuffer-recording
  'commandBuffer' must be in the recording state

- VUID-vkCmdResetQueryPool-commandBuffer-cmdpool
  The VkCommandPool that 'commandBuffer' was allocated from must support graphics, or compute operations

- VUID-vkCmdResetQueryPool-renderpass
  This command must only be called outside of a render pass instance

- VUID-vkCmdResetQueryPool-commonparent
  Both of 'commandBuffer', and 'queryPool' must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to 'commandBuffer' must be externally synchronized

- Host access to the VkCommandPool that 'commandBuffer' was allocated from must be externally synchronized

Command Properties

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<td></td>
</tr>
</tbody>
</table>
To reset a range of queries in a query pool on the host, call:

```c
// Provided by VK_VERSION_1_2
void vkResetQueryPool(
    VkDevice device,
    VkQueryPool queryPool,
    uint32_t firstQuery,
    uint32_t queryCount);
```

- `device` is the logical device that owns the query pool.
- `queryPool` is the handle of the query pool managing the queries being reset.
- `firstQuery` is the initial query index to reset.
- `queryCount` is the number of queries to reset.

This command sets the status of query indices \([firstQuery, firstQuery + queryCount - 1]\) to unavailable.

### Valid Usage

- **VUID-vkResetQueryPool-None-02665**
  The `hostQueryReset` feature **must** be enabled

- **VUID-vkResetQueryPool-firstQuery-02666**
  `firstQuery` **must** be less than the number of queries in `queryPool`

- **VUID-vkResetQueryPool-firstQuery-02667**
  The sum of `firstQuery` and `queryCount` **must** be less than or equal to the number of queries in `queryPool`

- **VUID-vkResetQueryPool-firstQuery-02741**
  Submitted commands that refer to the range specified by `firstQuery` and `queryCount` in `queryPool` **must** have completed execution

- **VUID-vkResetQueryPool-firstQuery-02742**
  The range of queries specified by `firstQuery` and `queryCount` in `queryPool` **must** not be in use by calls to `vkGetQueryPoolResults` or `vkResetQueryPool` in other threads

### Valid Usage (Implicit)

- **VUID-vkResetQueryPool-device-parameter**
  `device` **must** be a valid `VkDevice` handle

- **VUID-vkResetQueryPool-queryPool-parameter**
  `queryPool` **must** be a valid `VkQueryPool` handle

- **VUID-vkResetQueryPool-queryPool-parent**
  `queryPool` **must** have been created, allocated, or retrieved from `device`
Once queries are reset and ready for use, query commands can be issued to a command buffer. Occlusion queries and pipeline statistics queries count events - drawn samples and pipeline stage invocations, respectively - resulting from commands that are recorded between a \texttt{vkCmdBeginQuery} command and a \texttt{vkCmdEndQuery} command within a specified command buffer, effectively scoping a set of drawing and/or dispatching commands. Timestamp queries write timestamps to a query pool.

A query must begin and end in the same command buffer, although if it is a primary command buffer, and the \texttt{inheritedQueries} feature is enabled, it can execute secondary command buffers during the query operation. For a secondary command buffer to be executed while a query is active, it must set the \texttt{occlusionQueryEnable}, \texttt{queryFlags}, and/or \texttt{pipelineStatistics} members of \texttt{VkCommandBufferInheritanceInfo} to conservative values, as described in the Command Buffer Recording section. A query must either begin and end inside the same subpass of a render pass instance, or must both begin and end outside of a render pass instance (i.e. contain entire render pass instances).

If queries are used while executing a render pass instance that has multiview enabled, the query uses \(N\) consecutive query indices in the query pool (starting at \texttt{query}) where \(N\) is the number of bits set in the view mask in the subpass the query is used in. How the numerical results of the query are distributed among the queries is implementation-dependent. For example, some implementations may write each view's results to a distinct query, while other implementations may write the total result to the first query and write zero to the other queries. However, the sum of the results in all the queries must accurately reflect the total result of the query summed over all views. Applications can sum the results from all the queries to compute the total result.

Queries used with multiview rendering must not span subpasses, i.e. they must begin and end in the same subpass.

To begin a query, call:

```c
// Provided by VK_VERSION_1_0
define void vkCmdBeginQuery(  
    VkCommandBuffer commandBuffer,  
    VkQueryPool queryPool,  
    uint32_t query,  
    VkQueryControlFlags flags);
```

- \texttt{commandBuffer} is the command buffer into which this command will be recorded.
- \texttt{queryPool} is the query pool that will manage the results of the query.
- \texttt{query} is the query index within the query pool that will contain the results.
- \texttt{flags} is a bitmask of \texttt{VkQueryControlFlagBits} specifying constraints on the types of queries that can be performed.

If the \texttt{queryType} of the pool is \texttt{VK_QUERY_TYPE_OCCLUSION} and \texttt{flags} contains \texttt{VK_QUERY_CONTROL_PRECISE_BIT}, an implementation must return a result that matches the actual number of samples passed. This is described in more detail in Occlusion Queries.
After beginning a query, that query is considered active within the command buffer it was called in until that same query is ended. Queries active in a primary command buffer when secondary command buffers are executed are considered active for those secondary command buffers.

This command defines an execution dependency between other query commands that reference the same query.

The first synchronization scope includes all commands which reference the queries in `queryPool` indicated by `query` that occur earlier in submission order.

The second synchronization scope includes all commands which reference the queries in `queryPool` indicated by `query` that occur later in submission order.

The operation of this command happens after the first scope and happens before the second scope.

### Valid Usage

- **VUID-vkCmdBeginQuery-None-00807**
  All queries used by the command **must** be unavailable

- **VUID-vkCmdBeginQuery-queryType-02804**
  The `queryType` used to create `queryPool` **must** not be `VK_QUERY_TYPE_TIMESTAMP`

- **VUID-vkCmdBeginQuery-queryType-00800**
  If the `occlusionQueryPrecise` feature is not enabled, or the `queryType` used to create `queryPool` was not `VK_QUERY_TYPE_OCCLUSION`, flags **must** not contain `VK_QUERY_CONTROL_PRECISE_BIT`

- **VUID-vkCmdBeginQuery-query-00802**
  `query` **must** be less than the number of queries in `queryPool`

- **VUID-vkCmdBeginQuery-queryType-00803**
  If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_OCCLUSION`, the `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

- **VUID-vkCmdBeginQuery-queryType-00804**
  If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_PIPELINE_STATISTICS` and any of the `pipelineStatistics` indicate graphics operations, the `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

- **VUID-vkCmdBeginQuery-queryType-00805**
  If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_PIPELINE_STATISTICS` and any of the `pipelineStatistics` indicate compute operations, the `VkCommandPool` that `commandBuffer` was allocated from **must** support compute operations

- **VUID-vkCmdBeginQuery-commandBuffer-01885**
  `commandBuffer` **must** not be a protected command buffer

- **VUID-vkCmdBeginQuery-query-00808**
  If called within a render pass instance, the sum of `query` and the number of bits set in the current subpass’s view mask **must** be less than or equal to the number of queries in `queryPool`

- **VUID-vkCmdBeginQuery-queryPool-01922**
queryPool must have been created with a queryType that differs from that of any queries that are active within commandBuffer.

Valid Usage (Implicit)

- VUID-vkCmdBeginQuery-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle
- VUID-vkCmdBeginQuery-queryPool-parameter
  queryPool must be a valid VkQueryPool handle
- VUID-vkCmdBeginQuery-flags-parameter
  flags must be a valid combination of VkQueryControlFlagBits values
- VUID-vkCmdBeginQuery-commandBuffer-recording
  commandBuffer must be in the recording state
- VUID-vkCmdBeginQuery-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations
- VUID-vkCmdBeginQuery-commonparent
  Both of commandBuffer, and queryPool must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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</tbody>
</table>

Bits which can be set in vkCmdBeginQuery::flags, specifying constraints on the types of queries that can be performed, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkQueryControlFlagBits {
    VK_QUERY_CONTROL_PRECISE_BIT = 0x00000001,
} VkQueryControlFlagBits;
```
• **VK_QUERY_CONTROL_PRECISE_BIT** specifies the precision of occlusion queries.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkQueryControlFlags;
```

*VkQueryControlFlags* is a bitmask type for setting a mask of zero or more *VkQueryControlFlagBits*.

To end a query after the set of desired drawing or dispatching commands is executed, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdEndQuery(
    VkCommandBuffer commandBuffer,
    VkQueryPool queryPool,
    uint32_t query);
```

• *commandBuffer* is the command buffer into which this command will be recorded.
• *queryPool* is the query pool that is managing the results of the query.
• *query* is the query index within the query pool where the result is stored.

The command completes the query in *queryPool* identified by *query*, and marks it as available.

This command defines an execution dependency between other query commands that reference the same query.

The first synchronization scope includes all commands which reference the queries in *queryPool* indicated by *query* that occur earlier in submission order.

The second synchronization scope includes only the operation of this command.

### Valid Usage

- **VUID-vkCmdEndQuery-None-01923**
  All queries used by the command must be active

- **VUID-vkCmdEndQuery-query-00810**
  *query* must be less than the number of queries in *queryPool*

- **VUID-vkCmdEndQuery-commandBuffer-01886**
  *commandBuffer* must not be a protected command buffer

- **VUID-vkCmdEndQuery-query-00812**
  If *vkCmdEndQuery* is called within a render pass instance, the sum of *query* and the number of bits set in the current subpass's view mask must be less than or equal to the number of queries in *queryPool*

- **VUID-vkCmdEndQuery-None-07007**
  If called within a subpass of a render pass instance, the corresponding *vkCmdBeginQuery* command must have been called previously within the same subpass
If called outside of a render pass instance, the corresponding \texttt{vkCmdBeginQuery} command must have been called outside of a render pass instance.

**Valid Usage (Implicit)**

- VUID-vkCmdEndQuery-commandBuffer-parameter \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- VUID-vkCmdEndQuery-queryPool-parameter \texttt{queryPool} must be a valid \texttt{VkQueryPool} handle
- VUID-vkCmdEndQuery-commandBuffer-recording \texttt{commandBuffer} must be in the recording state
- VUID-vkCmdEndQuery-commandBuffer-cmdpool The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must support graphics, or compute operations
- VUID-vkCmdEndQuery-commonparent Both of \texttt{commandBuffer}, and \texttt{queryPool} must have been created, allocated, or retrieved from the same \texttt{VkDevice}

**Host Synchronization**

- Host access to \texttt{commandBuffer} must be externally synchronized
- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must be externally synchronized

**Command Properties**

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An application can retrieve results either by requesting they be written into application-provided memory, or by requesting they be copied into a \texttt{VkBuffer}. In either case, the layout in memory is defined as follows:

- The first query’s result is written starting at the first byte requested by the command, and each subsequent query’s result begins \texttt{stride} bytes later.
- Occlusion queries, pipeline statistics queries, and timestamp queries store results in a tightly packed array of unsigned integers, either 32- or 64-bits as requested by the command, storing the numerical results and, if requested, the availability status.
• If `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT` is used, the final element of each query’s result is an integer indicating whether the query’s result is available, with any non-zero value indicating that it is available.

• Occlusion queries write one integer value - the number of samples passed. Pipeline statistics queries write one integer value for each bit that is enabled in the `pipelineStatistics` when the pool is created, and the statistics values are written in bit order starting from the least significant bit. Timestamp queries write one integer value.

• If more than one query is retrieved and `stride` is not at least as large as the size of the array of values corresponding to a single query, the values written to memory are undefined.

To retrieve status and results for a set of queries, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkGetQueryPoolResults(
    VkDevice device,
    VkQueryPool queryPool,
    uint32_t firstQuery,
    uint32_t queryCount,
    size_t dataSize,
    void* pData,
    VkDeviceSize stride,
    VkQueryResultFlags flags);
```

• `device` is the logical device that owns the query pool.

• `queryPool` is the query pool managing the queries containing the desired results.

• `firstQuery` is the initial query index.

• `queryCount` is the number of queries to read.

• `dataSize` is the size in bytes of the buffer pointed to by `pData`.

• `pData` is a pointer to a user-allocated buffer where the results will be written.

• `stride` is the stride in bytes between results for individual queries within `pData`.

• `flags` is a bitmask of `VkQueryResultFlagBits` specifying how and when results are returned.

Any results written for a query are written according to a **layout dependent on the query type**.

If no bits are set in `flags`, and all requested queries are in the available state, results are written as an array of 32-bit unsigned integer values. Behavior when not all queries are available is described **below**.

If `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT` is set, results for all queries in `queryPool` identified by `firstQuery` and `queryCount` are copied to `pData`, along with an extra availability value written directly after the results of each query and interpreted as an unsigned integer. A value of zero indicates that the results are not yet available, otherwise the query is complete and results are available. The size of the availability values is 64 bits if `VK_QUERY_RESULT_64_BIT` is set in `flags`. Otherwise, it is 32 bits.
If `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT` is set, the layout of data in the buffer is a `(result, availability)` pair for each query returned, and `stride` is the stride between each pair.

Results for any available query written by this command are final and represent the final result of the query. If `VK_QUERY_RESULT_PARTIAL_BIT` is set, then for any query that is unavailable, an intermediate result between zero and the final result value is written for that query. Otherwise, any result written by this command is undefined.

If `VK_QUERY_RESULT_64_BIT` is set, results and, if returned, availability values for all queries are written as an array of 64-bit values. Otherwise, results and availability values are written as an array of 32-bit values. If an unsigned integer query’s value overflows the result type, the value may either wrap or saturate.

If `VK_QUERY_RESULT_WAIT_BIT` is set, this command defines an execution dependency with any earlier commands that writes one of the identified queries. The first synchronization scope includes all instances of `vkCmdEndQuery`, `vkCmdWriteTimestamp2`, and `vkCmdWriteTimestamp` that reference any query in `queryPool` indicated by `firstQuery` and `queryCount`. The second synchronization scope includes the host operations of this command.

If `VK_QUERY_RESULT_WAIT_BIT` is not set, `vkGetQueryPoolResults` may return `VK_NOT_READY` if there are queries in the unavailable state.

Applications must take care to ensure that use of the `VK_QUERY_RESULT_WAIT_BIT` bit has the desired effect.

For example, if a query has been used previously and a command buffer records the commands `vkCmdResetQueryPool`, `vkCmdBeginQuery`, and `vkCmdEndQuery` for that query, then the query will remain in the available state until `vkResetQueryPool` is called or the `vkCmdResetQueryPool` command executes on a queue. Applications can use fences or events to ensure that a query has already been reset before checking for its results or availability status. Otherwise, a stale value could be returned from a previous use of the query.

The above also applies when `VK_QUERY_RESULT_WAIT_BIT` is used in combination with `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT`. In this case, the returned availability status may reflect the result of a previous use of the query unless `vkResetQueryPool` is called or the `vkCmdResetQueryPool` command has been executed since the last use of the query.

Applications can double-buffer query pool usage, with a pool per frame, and reset queries at the end of the frame in which they are read.
Valid Usage

- VUID-vkGetQueryPoolResults-firstQuery-00813
  `firstQuery` must be less than the number of queries in `queryPool`

- VUID-vkGetQueryPoolResults-flags-02827
  If `VK_QUERY_RESULT_64_BIT` is not set in `flags`, then `pData` and `stride` must be multiples of 4

- VUID-vkGetQueryPoolResults-flags-00815
  If `VK_QUERY_RESULT_64_BIT` is set in `flags` then `pData` and `stride` must be multiples of 8

- VUID-vkGetQueryPoolResults-stride-08993
  If `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT` is set, `stride` must be large enough to contain the unsigned integer representing availability in addition to the query result.

- VUID-vkGetQueryPoolResults-firstQuery-00816
  The sum of `firstQuery` and `queryCount` must be less than or equal to the number of queries in `queryPool`

- VUID-vkGetQueryPoolResults-dataSize-00817
  `dataSize` must be large enough to contain the result of each query, as described here

- VUID-vkGetQueryPoolResults-queryType-00818
  If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_TIMESTAMP`, `flags` must not contain `VK_QUERY_RESULT_PARTIAL_BIT`

Valid Usage (Implicit)

- VUID-vkGetQueryPoolResults-device-parameter
  `device` must be a valid `VkDevice` handle

- VUID-vkGetQueryPoolResults-queryPool-parameter
  `queryPool` must be a valid `VkQueryPool` handle

- VUID-vkGetQueryPoolResults-pData-parameter
  `pData` must be a valid pointer to an array of `dataSize` bytes

- VUID-vkGetQueryPoolResults-flags-parameter
  `flags` must be a valid combination of `VkQueryResultFlagBits` values

- VUID-vkGetQueryPoolResults-dataSize-arraylength
  `dataSize` must be greater than 0

- VUID-vkGetQueryPoolResults-queryPool-parent
  `queryPool` must have been created, allocated, or retrieved from `device`

Return Codes

**Success**
- `VK_SUCCESS`
- `VK_NOT_READY`
Bits which can be set in `vkGetQueryPoolResults::flags` and `vkCmdCopyQueryPoolResults::flags`, specifying how and when results are returned, are:

```cpp
// Provided by VK_VERSION_1_0
typedef enum VkQueryResultFlagBits {
    VK_QUERY_RESULT_64_BIT = 0x00000001,
    VK_QUERY_RESULT_WAIT_BIT = 0x00000002,
    VK_QUERY_RESULT_WITH_AVAILABILITY_BIT = 0x00000004,
    VK_QUERY_RESULT_PARTIAL_BIT = 0x00000008,
} VkQueryResultFlagBits;
```

- **VK_QUERY_RESULT_64_BIT** specifies the results will be written as an array of 64-bit unsigned integer values. If this bit is not set, the results will be written as an array of 32-bit unsigned integer values.
- **VK_QUERY_RESULT_WAIT_BIT** specifies that Vulkan will wait for each query’s status to become available before retrieving its results.
- **VK_QUERY_RESULT_WITH_AVAILABILITY_BIT** specifies that the availability status accompanies the results.
- **VK_QUERY_RESULT_PARTIAL_BIT** specifies that returning partial results is acceptable.

```cpp
// Provided by VK_VERSION_1_0
typedef VkFlags VkQueryResultFlags;
```

`VkQueryResultFlags` is a bitmask type for setting a mask of zero or more `VkQueryResultFlagBits`.

To copy query statuses and numerical results directly to buffer memory, call:

```cpp
// Provided by VK_VERSION_1_0
void vkCmdCopyQueryPoolResults(  
    VkCommandBuffer commandBuffer,  
    VkQueryPool queryPool,  
    uint32_t firstQuery,  
    uint32_t queryCount,  
    VkBuffer dstBuffer,  
    VkDeviceSize dstOffset,  
    VkDeviceSize stride,  
    VkQueryResultFlags flags);
```

- **commandBuffer** is the command buffer into which this command will be recorded.
• **queryPool** is the query pool managing the queries containing the desired results.

• **firstQuery** is the initial query index.

• **queryCount** is the number of queries. **firstQuery** and **queryCount** together define a range of queries.

• **dstBuffer** is a **VkBuffer** object that will receive the results of the copy command.

• **dstOffset** is an offset into **dstBuffer**.

• **stride** is the stride in bytes between results for individual queries within **dstBuffer**. The required size of the backing memory for **dstBuffer** is determined as described above for **vkGetQueryPoolResults**.

• **flags** is a bitmask of **VkQueryResultFlagBits** specifying how and when results are returned.

Any results written for a query are written according to a layout dependent on the query type.

Results for any query in **queryPool** identified by **firstQuery** and **queryCount** that is available are copied to **dstBuffer**.

If **VK_QUERY_RESULT_WITH_AVAILABILITY_BIT** is set, results for all queries in **queryPool** identified by **firstQuery** and **queryCount** are copied to **dstBuffer**, along with an extra availability value written directly after the results of each query and interpreted as an unsigned integer. A value of zero indicates that the results are not yet available, otherwise the query is complete and results are available.

Results for any available query written by this command are final and represent the final result of the query. If **VK_QUERY_RESULT_PARTIAL_BIT** is set, then for any query that is unavailable, an intermediate result between zero and the final result value is written for that query. Otherwise, any result written by this command is undefined.

If **VK_QUERY_RESULT_64_BIT** is set, results and availability values for all queries are written as an array of 64-bit values. Otherwise, results and availability values are written as an array of 32-bit values. If an unsigned integer query's value overflows the result type, the value may either wrap or saturate.

This command defines an execution dependency between other query commands that reference the same query.

The first synchronization scope includes all commands which reference the queries in **queryPool** indicated by **query** that occur earlier in submission order. If **flags** does not include **VK_QUERY_RESULT_WAIT_BIT**, **vkCmdWriteTimestamp2**, **vkCmdEndQuery**, and **vkCmdWriteTimestamp** are excluded from this scope.

The second synchronization scope includes all commands which reference the queries in **queryPool** indicated by **query** that occur later in submission order.

The operation of this command happens after the first scope and happens before the second scope. **vkCmdCopyQueryPoolResults** is considered to be a transfer operation, and its writes to buffer memory must be synchronized using **VK_PIPELINE_STAGE_TRANSFER_BIT** and **VK_ACCESS_TRANSFER_WRITE_BIT** before using the results.
Valid Usage

- VUID-vkCmdCopyQueryPoolResults-dstOffset-00819
dstOffset must be less than the size of dstBuffer

- VUID-vkCmdCopyQueryPoolResults-firstQuery-00820
firstQuery must be less than the number of queries in queryPool

- VUID-vkCmdCopyQueryPoolResults-firstQuery-00821
The sum of firstQuery and queryCount must be less than or equal to the number of queries in queryPool

- VUID-vkCmdCopyQueryPoolResults-flags-00822
If VK_QUERY_RESULT_64_BIT is not set in flags then dstOffset and stride must be multiples of 4

- VUID-vkCmdCopyQueryPoolResults-flags-00823
If VK_QUERY_RESULT_64_BIT is set in flags then dstOffset and stride must be multiples of 8

- VUID-vkCmdCopyQueryPoolResults-dstBuffer-00824
dstBuffer must have enough storage, from dstOffset, to contain the result of each query, as described here

- VUID-vkCmdCopyQueryPoolResults-dstBuffer-00825
dstBuffer must have been created with VK_BUFFER_USAGE_TRANSFER_DST_BIT usage flag

- VUID-vkCmdCopyQueryPoolResults-dstBuffer-00826
If dstBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- VUID-vkCmdCopyQueryPoolResults-queryType-00827
If the queryType used to create queryPool was VK_QUERY_TYPE_TIMESTAMP, flags must not contain VK_QUERY_RESULT_PARTIAL_BIT

- VUID-vkCmdCopyQueryPoolResults-None-07429
All queries used by the command must not be active

- VUID-vkCmdCopyQueryPoolResults-None-08752
All queries used by the command must have been made available by prior executed commands

Valid Usage (Implicit)

- VUID-vkCmdCopyQueryPoolResults-commandBuffer-parameter
commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdCopyQueryPoolResults-queryPool-parameter
queryPool must be a valid VkQueryPool handle

- VUID-vkCmdCopyQueryPoolResults-dstBuffer-parameter
dstBuffer must be a valid VkBuffer handle

- VUID-vkCmdCopyQueryPoolResults-flags-parameter
flags must be a valid combination of VkQueryResultFlagBits values
• VUID-vkCmdCopyQueryPoolResults-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdCopyQueryPoolResults-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

• VUID-vkCmdCopyQueryPoolResults-renderpass
  This command must only be called outside of a render pass instance

• VUID-vkCmdCopyQueryPoolResults-commonparent
  Each of commandBuffer, dstBuffer, and queryPool must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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<tr>
<td>Secondary</td>
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</tbody>
</table>

Rendering operations such as clears, MSAA resolves, attachment load/store operations, and blits may count towards the results of queries. This behavior is implementation-dependent and may vary depending on the path used within an implementation. For example, some implementations have several types of clears, some of which may include vertices and some not.

17.3. Occlusion Queries

Occlusion queries track the number of samples that pass the per-fragment tests for a set of drawing commands. As such, occlusion queries are only available on queue families supporting graphics operations. The application can then use these results to inform future rendering decisions. An occlusion query is begun and ended by calling vkCmdBeginQuery and vkCmdEndQuery, respectively. When an occlusion query begins, the count of passing samples always starts at zero. For each drawing command, the count is incremented as described in Sample Counting. If flags does not contain VK_QUERY_CONTROL_PRECISE_BIT an implementation may generate any non-zero result value for the query if the count of passing samples is non-zero.

Note
Not setting VK_QUERY_CONTROL_PRECISE_BIT mode may be more efficient on some
implementations, and **should** be used where it is sufficient to know a boolean result on whether any samples passed the per-fragment tests. In this case, some implementations **may** only return zero or one, indifferent to the actual number of samples passing the per-fragment tests.

Setting `VK_QUERY_CONTROL_PRECISE_BIT` does not guarantee that different implementations return the same number of samples in an occlusion query. Some implementations may kill fragments in the **pre-rasterization shader stage**, and these killed fragments do not contribute to the final result of the query. It is possible that some implementations generate a zero result value for the query, while others generate a non-zero value.

When an occlusion query finishes, the result for that query is marked as available. The application **can** then either copy the result to a buffer (via `vkCmdCopyQueryPoolResults`) or request it be put into host memory (via `vkGetQueryPoolResults`).

*Note*

If occluding geometry is not drawn first, samples **can** pass the depth test, but still not be visible in a final image.

### 17.4. Pipeline Statistics Queries

Pipeline statistics queries allow the application to sample a specified set of `VkPipeline` counters. These counters are accumulated by Vulkan for a set of either drawing or dispatching commands while a pipeline statistics query is active. As such, pipeline statistics queries are available on queue families supporting either graphics or compute operations. The availability of pipeline statistics queries is indicated by the `pipelineStatisticsQuery` member of the `VkPhysicalDeviceFeatures` object (see `vkGetPhysicalDeviceFeatures` and `vkCreateDevice` for detecting and requesting this query type on a `VkDevice`).

A pipeline statistics query is begun and ended by calling `vkCmdBeginQuery` and `vkCmdEndQuery`, respectively. When a pipeline statistics query begins, all statistics counters are set to zero. While the query is active, the pipeline type determines which set of statistics are available, but these **must** be configured on the query pool when it is created. If a statistic counter is issued on a command buffer that does not support the corresponding operation, the value of that counter is undefined after the query has been made available. At least one statistic counter relevant to the operations supported on the recording command buffer **must** be enabled.

Bits which **can** be set in `VkQueryPoolCreateInfo::pipelineStatistics` for query pools and in `VkCommandBufferInheritanceInfo::pipelineStatistics` for secondary command buffers, individually enabling pipeline statistics counters, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkQueryPipelineStatisticFlagBits {
    VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT = 0x00000001,
    VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT = 0x00000002,
    VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT = 0x00000004,
};
```
• **VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT** specifies that queries managed by the pool will count the number of vertices processed by the **input assembly** stage. Vertices corresponding to incomplete primitives may contribute to the count.

• **VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives processed by the **input assembly** stage. If primitive restart is enabled, restarting the primitive topology has no effect on the count. Incomplete primitives may be counted.

• **VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of vertex shader invocations. This counter's value is incremented each time a vertex shader is **invoked**.

• **VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of geometry shader invocations. This counter's value is incremented each time a geometry shader is **invoked**. In the case of **instanced geometry shaders**, the geometry shader invocations count is incremented for each separate instanced invocation.

• **VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives generated by geometry shader invocations. The counter's value is incremented each time the geometry shader emits a primitive. Restarting primitive topology using the SPIR-V instructions `OpEndPrimitive` or `OpEndStreamPrimitive` has no effect on the geometry shader output primitives count.

• **VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of primitives processed by the **Primitive Clipping** stage of the pipeline. The counter's value is incremented each time a primitive reaches the primitive clipping stage.

• **VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives output by the **Primitive Clipping** stage of the pipeline. The actual number of primitives output by the primitive clipping stage for a particular input primitive is implementation-dependent but **must** satisfy the following conditions:
  ◦ If at least one vertex of the input primitive lies inside the clipping volume, the counter is incremented by one or more.
  ◦ Otherwise, the counter is incremented by zero or more.

• **VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT** specifies that queries managed
by the pool will count the number of fragment shader invocations. The counter’s value is incremented each time the fragment shader is invoked.

- `VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT` specifies that queries managed by the pool will count the number of patches processed by the tessellation control shader. The counter’s value is incremented once for each patch for which a tessellation control shader is invoked.

- `VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT` specifies that queries managed by the pool will count the number of invocations of the tessellation evaluation shader. The counter’s value is incremented each time the tessellation evaluation shader is invoked.

- `VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT` specifies that queries managed by the pool will count the number of compute shader invocations. The counter’s value is incremented every time the compute shader is invoked. Implementations may skip the execution of certain compute shader invocations or execute additional compute shader invocations for implementation-dependent reasons as long as the results of rendering otherwise remain unchanged.

These values are intended to measure relative statistics on one implementation. Various device architectures will count these values differently. Any or all counters may be affected by the issues described in Query Operation.

Note

For example, tile-based rendering devices may need to replay the scene multiple times, affecting some of the counts.

If a pipeline has `rasterizerDiscardEnable` enabled, implementations may discard primitives after the final pre-rasterization shader stage. As a result, if `rasterizerDiscardEnable` is enabled, the clipping input and output primitives counters may not be incremented.

When a pipeline statistics query finishes, the result for that query is marked as available. The application can copy the result to a buffer (via `vkCmdCopyQueryPoolResults`), or request it be put into host memory (via `vkGetQueryPoolResults`).

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkQueryPipelineStatisticFlags;
```

`VkQueryPipelineStatisticFlags` is a bitmask type for setting a mask of zero or more `VkQueryPipelineStatisticFlagBits`.

### 17.5. Timestamp Queries

Timestamps provide applications with a mechanism for timing the execution of commands. A timestamp is an integer value generated by the `VkPhysicalDevice`. Unlike other queries, timestamps do not operate over a range, and so do not use `vkCmdBeginQuery` or `vkCmdEndQuery`. The mechanism is built around a set of commands that allow the application to tell the `VkPhysicalDevice` to write timestamp values to a query pool and then either read timestamp values on the host (using
vkGetQueryPoolResults) or copy timestamp values to a VkBuffer (using vkCmdCopyQueryPoolResults). The application can then compute differences between timestamps to determine execution time.

The number of valid bits in a timestamp value is determined by the VkQueueFamilyProperties::timestampValidBits property of the queue on which the timestamp is written. Timestamps are supported on any queue which reports a non-zero value for timestampValidBits via vkGetPhysicalDeviceQueueFamilyProperties. If the timestampComputeAndGraphics limit is VK_TRUE, timestamps are supported by every queue family that supports either graphics or compute operations (see VkQueueFamilyProperties).

The number of nanoseconds it takes for a timestamp value to be incremented by 1 can be obtained from VkPhysicalDeviceLimits::timestampPeriod after a call to vkGetPhysicalDeviceProperties.

To request a timestamp and write the value to memory, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdWriteTimestamp2(
    VkCommandBuffer commandBuffer,
    VkPipelineStageFlags2 stage,
    VkQueryPool queryPool,
    uint32_t query);
```

- commandBuffer is the command buffer into which the command will be recorded.
- stage specifies a stage of the pipeline.
- queryPool is the query pool that will manage the timestamp.
- query is the query within the query pool that will contain the timestamp.

When vkCmdWriteTimestamp2 is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and writes a timestamp to a query pool.

The first synchronization scope includes all commands that occur earlier in submission order. The synchronization scope is limited to operations on the pipeline stage specified by stage.

The second synchronization scope includes only the timestamp write operation.

**Note**

Implementations may write the timestamp at any stage that is logically later than stage.

Any timestamp write that happens-after another timestamp write in the same submission must not have a lower value unless its value overflows the maximum supported integer bit width of the query. If an overflow occurs, the timestamp value must wrap back to zero.

**Note**

Comparisons between timestamps should be done between timestamps where they are guaranteed to not decrease. For example, subtracting an older timestamp
from a newer one to determine the execution time of a sequence of commands is only a reliable measurement if the two timestamp writes were performed in the same submission.

If `vkCmdWriteTimestamp2` is called while executing a render pass instance that has multiview enabled, the timestamp uses \( N \) consecutive query indices in the query pool (starting at `query`) where \( N \) is the number of bits set in the view mask of the subpass the command is executed in. The resulting query values are determined by an implementation-dependent choice of one of the following behaviors:

- The first query is a timestamp value and (if more than one bit is set in the view mask) zero is written to the remaining queries. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the difference between the first query written by each command.

- All \( N \) queries are timestamp values. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the sum of the difference between corresponding queries written by each command. The difference between corresponding queries may be the execution time of a single view.

In either case, the application can sum the differences between all \( N \) queries to determine the total execution time.

---

**Valid Usage**

- **VUID-vkCmdWriteTimestamp2-stage-03929**
  If the `geometryShader` feature is not enabled, `stage` must not contain `VK_PIPELINE_STAGE_2_GEOMETRY_SHADER_BIT`

- **VUID-vkCmdWriteTimestamp2-stage-03930**
  If the `tessellationShader` feature is not enabled, `stage` must not contain `VK_PIPELINE_STAGE_2_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_2_TESSELLATION_EVALUATION_SHADER_BIT`

- **VUID-vkCmdWriteTimestamp2-synchronization2-03858**
  The `synchronization2` feature must be enabled

- **VUID-vkCmdWriteTimestamp2-stage-03859**
  `stage` must only include a single pipeline stage

- **VUID-vkCmdWriteTimestamp2-stage-03860**
  `stage` must only include stages valid for the queue family that was used to create the command pool that `commandBuffer` was allocated from

- **VUID-vkCmdWriteTimestamp2-queryPool-03861**
  `queryPool` must have been created with a `queryType` of `VK_QUERY_TYPE_TIMESTAMP`

- **VUID-vkCmdWriteTimestamp2-queryPool-03862**
  The query identified by `queryPool` and `query` must be unavailable

- **VUID-vkCmdWriteTimestamp2-timestampValidBits-03863**
  The command pool's queue family must support a non-zero `timestampValidBits`

- **VUID-vkCmdWriteTimestamp2-query-04903**
query must be less than the number of queries in queryPool

- VUID-vkCmdWriteTimestamp2-None-03864
  All queries used by the command must be unavailable

- VUID-vkCmdWriteTimestamp2-query-03865
  If vkCmdWriteTimestamp2 is called within a render pass instance, the sum of query and the number of bits set in the current subpass's view mask must be less than or equal to the number of queries in queryPool

Valid Usage (Implicit)

- VUID-vkCmdWriteTimestamp2-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdWriteTimestamp2-stage-parameter
  stage must be a valid combination of VkPipelineStageFlagBits2 values

- VUID-vkCmdWriteTimestamp2-queryPool-parameter
  queryPool must be a valid VkQueryPool handle

- VUID-vkCmdWriteTimestamp2-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdWriteTimestamp2-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support transfer, graphics, or compute operations

- VUID-vkCmdWriteTimestamp2-commonparent
  Both of commandBuffer, and queryPool must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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<td>Compute</td>
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</tbody>
</table>

To request a timestamp and write the value to memory, call:
void vkCmdWriteTimestamp(
    VkCommandBuffer commandBuffer,
    VkPipelineStageFlagBits pipelineStage,
    VkQueryPool queryPool,
    uint32_t query);

- **commandBuffer** is the command buffer into which the command will be recorded.
- **pipelineStage** is a `VkPipelineStageFlagBits` value, specifying a stage of the pipeline.
- **queryPool** is the query pool that will manage the timestamp.
- **query** is the query within the query pool that will contain the timestamp.

When `vkCmdWriteTimestamp` is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and writes a timestamp to a query pool.

The first **synchronization scope** includes all commands that occur earlier in submission order. The synchronization scope is limited to operations on the pipeline stage specified by **pipelineStage**.

The second **synchronization scope** includes only the timestamp write operation.

**Note**
Implementations may write the timestamp at any stage that is **logically later** than stage.

Any timestamp write that happens-after another timestamp write in the same submission **must** not have a lower value unless its value overflows the maximum supported integer bit width of the query. If an overflow occurs, the timestamp value **must** wrap back to zero.

**Note**
Comparisons between timestamps should be done between timestamps where they are guaranteed to not decrease. For example, subtracting an older timestamp from a newer one to determine the execution time of a sequence of commands is only a reliable measurement if the two timestamp writes were performed in the same submission.

If `vkCmdWriteTimestamp` is called while executing a render pass instance that has multiview enabled, the timestamp uses N consecutive query indices in the query pool (starting at **query**) where N is the number of bits set in the view mask of the subpass the command is executed in. The resulting query values are determined by an implementation-dependent choice of one of the following behaviors:

- The first query is a timestamp value and (if more than one bit is set in the view mask) zero is written to the remaining queries. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the difference between the first query written by each command.
- All N queries are timestamp values. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the sum of the difference
between corresponding queries written by each command. The difference between corresponding queries may be the execution time of a single view.

In either case, the application can sum the differences between all N queries to determine the total execution time.

### Valid Usage

- **VUID-vkCmdWriteTimestamp-pipelineStage-04074**  
  `pipelineStage` must be a valid stage for the queue family that was used to create the command pool that `commandBuffer` was allocated from.

- **VUID-vkCmdWriteTimestamp-pipelineStage-04075**  
  If the `geometryShader` feature is not enabled, `pipelineStage` must not be `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.

- **VUID-vkCmdWriteTimestamp-pipelineStage-04076**  
  If the `tessellationShader` feature is not enabled, `pipelineStage` must not be `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.

- **VUID-vkCmdWriteTimestamp-synchronization2-06489**  
  If the `synchronization2` feature is not enabled, `pipelineStage` must not be `VK_PIPELINE_STAGE_NONE`.

- **VUID-vkCmdWriteTimestamp-queryPool-01416**  
  `queryPool` must have been created with a `queryType` of `VK_QUERY_TYPE_TIMESTAMP`.

- **VUID-vkCmdWriteTimestamp-queryPool-00828**  
  The query identified by `queryPool` and `query` must be unavailable.

- **VUID-vkCmdWriteTimestamp-timestampValidBits-00829**  
  The command pool's queue family must support a non-zero `timestampValidBits`.

- **VUID-vkCmdWriteTimestamp-query-04904**  
  `query` must be less than the number of queries in `queryPool`.

- **VUID-vkCmdWriteTimestamp-None-00830**  
  All queries used by the command must be unavailable.

- **VUID-vkCmdWriteTimestamp-query-00831**  
  If `vkCmdWriteTimestamp` is called within a render pass instance, the sum of `query` and the number of bits set in the current subpass's view mask must be less than or equal to the number of queries in `queryPool`.

### Valid Usage ( Implicit )

- **VUID-vkCmdWriteTimestamp-commandBuffer-parameter**  
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- **VUID-vkCmdWriteTimestamp-pipelineStage-parameter**  
  `pipelineStage` must be a valid `VkPipelineStageFlagBits` value.
• VUID-vkCmdWriteTimestamp-queryPool-parameter
  queryPool must be a valid VkQueryPool handle

• VUID-vkCmdWriteTimestamp-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdWriteTimestamp-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support transfer, graphics, or compute operations

• VUID-vkCmdWriteTimestamp-commonparent
  Both of commandBuffer, and queryPool must have been created, allocated, or retrieved from the same VkDevice

---

**Host Synchronization**

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

---

**Command Properties**

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<td></td>
<td></td>
<td>Graphics Compute</td>
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</tr>
</tbody>
</table>

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Chapter 18. Clear Commands

18.1. Clearing Images Outside A Render Pass Instance

Color and depth/stencil images can be cleared outside a render pass instance using `vkCmdClearColorImage` or `vkCmdClearDepthStencilImage`, respectively. These commands are only allowed outside of a render pass instance.

To clear one or more subranges of a color image, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdClearColorImage(
    VkCommandBuffer commandBuffer,  // Provided by VK_VERSION_1_0
    VkImage image,                  // Provided by VK_VERSION_1_0
    VkImageLayout imageLayout,      // Provided by VK_VERSION_1_0
    const VkClearColorValue* pColor,  // Provided by VK_VERSION_1_0
    uint32_t rangeCount,            // Provided by VK_VERSION_1_0
    const VkImageSubresourceRange* pRanges);  // Provided by VK_VERSION_1_0
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `image` is the image to be cleared.
- `imageLayout` specifies the current layout of the image subresource ranges to be cleared, and must be `VK_IMAGE_LAYOUT_GENERAL` or `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL`.
- `pColor` is a pointer to a `VkClearColorValue` structure containing the values that the image subresource ranges will be cleared to (see Clear Values below).
- `rangeCount` is the number of image subresource range structures in `pRanges`.
- `pRanges` is a pointer to an array of `VkImageSubresourceRange` structures describing a range of mipmap levels, array layers, and aspects to be cleared, as described in Image Views.

Each specified range in `pRanges` is cleared to the value specified by `pColor`.

Valid Usage

- VUID-vkCmdClearColorImage-image-01993
  The format features of `image` must contain `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`
- VUID-vkCmdClearColorImage-image-00002
  `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag
- VUID-vkCmdClearColorImage-image-01545
  `image` must not use any of the formats that require a sampler Y'CbCr conversion
- VUID-vkCmdClearColorImage-image-00003
  If `image` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object
- VUID-vkCmdClearColorImage-imageLayout-00004
imageLayout must specify the layout of the image subresource ranges of image specified in pRanges at the time this command is executed on a VkDevice

- VUID-vkCmdClearColorImage-imageLayout-00005
  imageLayout must be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL

- VUID-vkCmdClearColorImage-aspectMask-02498
  The VkImageSubresourceRange::aspectMask members of the elements of the pRanges array must each only include VK_IMAGE_ASPECT_COLOR_BIT

- VUID-vkCmdClearColorImage-baseMipLevel-01470
  The VkImageSubresourceRange::baseMipLevel members of the elements of the pRanges array must each be less than the mipLevels specified in VkImageCreateInfo when image was created

- VUID-vkCmdClearColorImage-pRanges-01692
  For each VkImageSubresourceRange element of pRanges, if the levelCount member is not VK_REMAINING_MIP_LEVELS, then baseMipLevel + levelCount must be less than or equal to the mipLevels specified in VkImageCreateInfo when image was created

- VUID-vkCmdClearColorImage-baseArrayLayer-01472
  The VkImageSubresourceRange::baseArrayLayer members of the elements of the pRanges array must each be less than the arrayLayers specified in VkImageCreateInfo when image was created

- VUID-vkCmdClearColorImage-pRanges-01693
  For each VkImageSubresourceRange element of pRanges, if the layerCount member is not VK_REMAINING_ARRAY_LAYERS, then baseArrayLayer + layerCount must be less than or equal to the arrayLayers specified in VkImageCreateInfo when image was created

- VUID-vkCmdClearColorImage-image-00007
  image must not have a compressed or depth/stencil format

- VUID-vkCmdClearColorImage-pColor-04961
  pColor must be a valid pointer to a VkClearColorValue union

- VUID-vkCmdClearColorImage-commandBuffer-01805
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, image must not be a protected image

- VUID-vkCmdClearColorImage-commandBuffer-01806
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, must not be an unprotected image

Valid Usage (Implicit)

- VUID-vkCmdClearColorImage-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdClearColorImage-image-parameter
  image must be a valid VkImage handle

- VUID-vkCmdClearColorImage-imageLayout-parameter
  imageLayout must be a valid VkImageLayout value
• VUID-vkCmdClearColorImage-pRanges-parameter
   pRanges must be a valid pointer to an array of rangeCount valid VkImageSubresourceRange structures

• VUID-vkCmdClearColorImage-commandBuffer-recording
   commandBuffer must be in the recording state

• VUID-vkCmdClearColorImage-commandBuffer-cmdpool
   The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

• VUID-vkCmdClearColorImage-renderpass
   This command must only be called outside of a render pass instance

• VUID-vkCmdClearColorImage-rangeCount-arraylength
   rangeCount must be greater than 0

• VUID-vkCmdClearColorImage-commonparent
   Both of commandBuffer, and image must have been created, allocated, or retrieved from the same VkDevice

---

**Host Synchronization**

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

---

**Command Properties**

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</tr>
</tbody>
</table>

To clear one or more subranges of a depth/stencil image, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdClearColorDepthStencilImage(
    VkCommandBuffer commandBuffer,
    VkImage image,
    VkImageLayout imageLayout,
    const VkClearDepthStencilValue* pDepthStencil,
    uint32_t rangeCount,
    const VkImageSubresourceRange* pRanges);
```

• commandBuffer is the command buffer into which the command will be recorded.
• **image** is the image to be cleared.

• **imageLayout** specifies the current layout of the image subresource ranges to be cleared, and **must** be **VK_IMAGE_LAYOUT_GENERAL** or **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL**.

• **pDepthStencil** is a pointer to a **VkClearColorValue** structure containing the values that the depth and stencil image subresource ranges will be cleared to (see **Clear Values** below).

• **rangeCount** is the number of image subresource range structures in **pRanges**.

• **pRanges** is a pointer to an array of **VkImageSubresourceRange** structures describing a range of mipmap levels, array layers, and aspects to be cleared, as described in **Image Views**.

---

**Valid Usage**

• VUID-vkCmdClearDepthStencilImage-image-01994
  The **format features** of **image** **must** contain **VK_FORMAT_FEATURE_TRANSFER_DST_BIT**

• VUID-vkCmdClearDepthStencilImage-pRanges-02658
  If the **aspect** member of any element of **pRanges** includes **VK_IMAGE_ASPECT_STENCIL_BIT**, and **image** was created with separate stencil usage, **VK_IMAGE_USAGE_TRANSFER_DST_BIT** **must** have been included in the **VkImageStagingCreateInfo::stencilUsage** used to create **image**

• VUID-vkCmdClearDepthStencilImage-pRanges-02659
  If the **aspect** member of any element of **pRanges** includes **VK_IMAGE_ASPECT_STENCIL_BIT**, and **image** was not created with separate stencil usage, **VK_IMAGE_USAGE_TRANSFER_DST_BIT** **must** have been included in the **VkImageCreateInfo::usage** used to create **image**

• VUID-vkCmdClearDepthStencilImage-pRanges-02660
  If the **aspect** member of any element of **pRanges** includes **VK_IMAGE_ASPECT_DEPTH_BIT**, **VK_IMAGE_USAGE_TRANSFER_DST_BIT** **must** have been included in the **VkImageCreateInfo::usage** used to create **image**

• VUID-vkCmdClearDepthStencilImage-image-00010
  If **image** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object

• VUID-vkCmdClearDepthStencilImage-imageLayout-00011
  **imageLayout** **must** specify the layout of the image subresource ranges of **image** specified in **pRanges** at the time this command is executed on a **VkDevice**

• VUID-vkCmdClearDepthStencilImage-imageLayout-00012
  **imageLayout** **must** be either of **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL** or **VK_IMAGE_LAYOUT_GENERAL**

• VUID-vkCmdClearDepthStencilImage-aspectMask-02824
  The **VkImageSubresourceRange::aspectMask** member of each element of the **pRanges** array **must** not include bits other than **VK_IMAGE_ASPECT_DEPTH_BIT** or **VK_IMAGE_ASPECT_STENCIL_BIT**

• VUID-vkCmdClearDepthStencilImage-aspectMask-02825
  If the **image**'s format does not have a stencil component, then the **VkImageSubresourceRange::aspectMask** member of each element of the **pRanges** array **must** not include the **VK_IMAGE_ASPECT_STENCIL_BIT** bit
If the image's format does not have a depth component, then the `VkImageSubresourceRange::aspectMask` member of each element of the `pRanges` array must not include the `VK_IMAGE_ASPECTDEPTH_BIT` bit.

The `VkImageSubresourceRange::baseMipLevel` members of the elements of the `pRanges` array must each be less than the `mipLevels` specified in `VkImageCreateInfo` when image was created.

For each `VkImageSubresourceRange` element of `pRanges`, if the `levelCount` member is not `VK_REMAINING_MIP_LEVELS`, then `baseMipLevel + levelCount` must be less than or equal to the `mipLevels` specified in `VkImageCreateInfo` when image was created.

The `VkImageSubresourceRange::baseArrayLayer` members of the elements of the `pRanges` array must each be less than the `arrayLayers` specified in `VkImageCreateInfo` when image was created.

For each `VkImageSubresourceRange` element of `pRanges`, if the `layerCount` member is not `VK_REMAINING_ARRAY_LAYERS`, then `baseArrayLayer + layerCount` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when image was created.

`image` must have a depth/stencil format.

If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `image` must not be a protected image.

If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `image` must not be an unprotected image.

Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle.
- `image` must be a valid `VkImage` handle.
- `imageLayout` must be a valid `VkImageLayout` value.
- `pDepthStencil` must be a valid pointer to a valid `VkClearDepthStencilValue` structure.
- `pRanges` must be a valid pointer to an array of `rangeCount` valid `VkImageSubresourceRange` structures.
18.2. Clearing Images Inside A Render Pass Instance

To clear one or more regions of color and depth/stencil attachments inside a render pass instance, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdClearAttachments(
    VkCommandBuffer commandBuffer, // Provided by VK_VERSION_1_0
    uint32_t attachmentCount, // Provided by VK_VERSION_1_0
    const VkClearAttachment* pAttachments, // Provided by VK_VERSION_1_0
    uint32_t rectCount, // Provided by VK_VERSION_1_0
    const VkClearRect* pRects); // Provided by VK_VERSION_1_0
```
• **commandBuffer** is the command buffer into which the command will be recorded.

• **attachmentCount** is the number of entries in the **pAttachments** array.

• **pAttachments** is a pointer to an array of **VkClearAttachment** structures defining the attachments to clear and the clear values to use.

• **rectCount** is the number of entries in the **pRects** array.

• **pRects** is a pointer to an array of **VkClearRect** structures defining regions within each selected attachment to clear.

Unlike other clear commands, **vkCmdClearAttachments** is not a transfer command. It performs its operations in rasterization order. For color attachments, the operations are executed as color attachment writes, by the **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** stage. For depth/stencil attachments, the operations are executed as depth writes and stencil writes by the **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT** and **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT** stages.

**vkCmdClearAttachments** is not affected by the bound pipeline state.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is generally preferable to clear attachments by using the <strong>VK_ATTACHMENT_LOAD_OP_CLEAR</strong> load operation at the start of rendering, as it is more efficient on some implementations.</td>
</tr>
</tbody>
</table>

If any attachment's **aspectMask** to be cleared is not backed by an image view, the clear has no effect on that aspect.

If an attachment being cleared refers to an image view created with an **aspectMask** equal to one of **VK_IMAGE_ASPECT_PLANE_0_BIT**, **VK_IMAGE_ASPECT_PLANE_1_BIT** or **VK_IMAGE_ASPECT_PLANE_2_BIT**, it is considered to be **VK_IMAGE_ASPECT_COLOR_BIT** for purposes of this command, and **must** be cleared with the **VK_IMAGE_ASPECT_COLOR_BIT** aspect as specified by image view creation.

### Valid Usage

- **VUID-vkCmdClearAttachments-aspectMask-07884**
  If the current render pass instance does not use dynamic rendering, and the **aspectMask** member of any element of **pAttachments** contains **VK_IMAGE_ASPECT_DEPTH_BIT**, the current subpass instance's depth-stencil attachment **must** be either **VK_ATTACHMENT_UNUSED** or the attachment **format** must contain a depth component.

- **VUID-vkCmdClearAttachments-aspectMask-07885**
  If the current render pass instance does not use dynamic rendering, and the **aspectMask** member of any element of **pAttachments** contains **VK_IMAGE_ASPECT_STENCIL_BIT**, the current subpass instance's depth-stencil attachment **must** be either **VK_ATTACHMENT_UNUSED** or the attachment **format** must contain a stencil component.

- **VUID-vkCmdClearAttachments-aspectMask-07271**
  If the **aspectMask** member of any element of **pAttachments** contains **VK_IMAGE_ASPECT_COLOR_BIT**, the **colorAttachment** must be a valid color attachment index in the current render pass instance.
The `rect` member of each element of `pRects` must have an `extent.width` greater than 0.

The `rect` member of each element of `pRects` must have an `extent.height` greater than 0.

The rectangular region specified by each element of `pRects` must be contained within the render area of the current render pass instance.

The layers specified by each element of `pRects` must be contained within every attachment that `pAttachments` refers to, i.e. for each element of `pRects`, `VkClearRect::baseArrayLayer + VkClearRect::layerCount` must be less than or equal to the number of layers rendered to in the current render pass instance.

The `layerCount` member of each element of `pRects` must not be 0.

If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, each attachment to be cleared must not be a protected image.

If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, each attachment to be cleared must not be an unprotected image.

If the render pass instance this is recorded in uses multiview, then `baseArrayLayer` must be zero and `layerCount` must be one.

---

**Valid Usage (Implicit)**

- `commandBuffer` must be a valid `VkCommandBuffer` handle

- `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkClearAttachment` structures

- `pRects` must be a valid pointer to an array of `rectCount` `VkClearRect` structures

- `commandBuffer` must be in the recording state

- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

- This command must only be called inside of a render pass instance

- `attachmentCount` must be greater than 0
Host Synchronization

• Host access to commandBuffer must be externally synchronized.
• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
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<tbody>
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<td>Inside</td>
<td>Graphics</td>
<td>Action</td>
</tr>
<tr>
<td>Secondary</td>
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<td></td>
</tr>
</tbody>
</table>

The VkClearRect structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkClearRect {
    VkRect2D rect;
    uint32_t baseArrayLayer;
    uint32_t layerCount;
} VkClearRect;
```

• rect is the two-dimensional region to be cleared.
• baseArrayLayer is the first layer to be cleared.
• layerCount is the number of layers to clear.

The layers \([\text{baseArrayLayer}, \text{baseArrayLayer} + \text{layerCount}]\) counting from the base layer of the attachment image view are cleared.

The VkClearAttachment structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkClearAttachment {
    VkImageAspectFlags aspectMask;
    uint32_t colorAttachment;
    VkClearValue clearValue;
} VkClearAttachment;
```

• aspectMask is a mask selecting the color, depth and/or stencil aspects of the attachment to be
cleared.

- **colorAttachment** is only meaningful if `VK_IMAGE_ASPECT_COLOR_BIT` is set in `aspectMask`, in which case it is an index into the currently bound color attachments.
- **clearValue** is the color or depth/stencil value to clear the attachment to, as described in **Clear Values** below.

### Valid Usage

- **VUID-VkClearAttachment-aspectMask-00019**
  If `aspectMask` includes `VK_IMAGE_ASPECT_COLOR_BIT`, it **must** not include `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`
- **VUID-VkClearAttachment-aspectMask-00020**
  `aspectMask` **must** not include `VK_IMAGE_ASPECT_METADATA_BIT`
- **VUID-VkClearAttachment-clearValue-00021**
  `clearValue` **must** be a valid `VkClearColorValue` union

### Valid Usage (Implicit)

- **VUID-VkClearAttachment-aspectMask-parameter**
  `aspectMask` **must** be a valid combination of `VkImageAspectFlagBits` values
- **VUID-VkClearAttachment-aspectMask-requiredbitmask**
  `aspectMask` **must** not be 0

### 18.3. Clear Values

The `VkClearColorValue` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef union VkClearColorValue {
    float  float32[4];
    int32_t int32[4];
    uint32_t uint32[4];
} VkClearColorValue;
```

- **float32** are the color clear values when the format of the image or attachment is one of the numeric formats with a numeric type that is floating-point. Floating point values are automatically converted to the format of the image, with the clear value being treated as linear if the image is sRGB.
- **int32** are the color clear values when the format of the image or attachment has a numeric type that is signed integer (**SINT**). Signed integer values are converted to the format of the image by casting to the smaller type (with negative 32-bit values mapping to negative values in the smaller type). If the integer clear value is not representable in the target type (e.g. would
overflow in conversion to that type), the clear value is undefined.

- `uint32` are the color clear values when the format of the image or attachment has a numeric type that is unsigned integer (`UINT`). Unsigned integer values are converted to the format of the image by casting to the integer type with fewer bits.

The four array elements of the clear color map to R, G, B, and A components of image formats, in order.

If the image has more than one sample, the same value is written to all samples for any pixels being cleared.

The `VkClearDepthStencilValue` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkClearDepthStencilValue {
    float depth;
    uint32_t stencil;
} VkClearDepthStencilValue;
```

- `depth` is the clear value for the depth aspect of the depth/stencil attachment. It is a floating-point value which is automatically converted to the attachment’s format.

- `stencil` is the clear value for the stencil aspect of the depth/stencil attachment. It is a 32-bit integer value which is converted to the attachment’s format by taking the appropriate number of LSBs.

**Valid Usage**

- VUID-VkClearDepthStencilValue-depth-02506
  
  `depth` must be between 0.0 and 1.0, inclusive

The `VkClearValue` union is defined as:

```c
// Provided by VK_VERSION_1_0
typedef union VkClearValue {
    VkClearColorValue color;
    VkClearDepthStencilValue depthStencil;
} VkClearValue;
```

- `color` specifies the color image clear values to use when clearing a color image or attachment.

- `depthStencil` specifies the depth and stencil clear values to use when clearing a depth/stencil image or attachment.

This union is used where part of the API requires either color or depth/stencil clear values, depending on the attachment, and defines the initial clear values in the `VkRenderPassBeginInfo` structure.
18.4. Filling Buffers

To clear buffer data, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdFillBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer dstBuffer,
    VkDeviceSize dstOffset,
    VkDeviceSize size,
    uint32_t data);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `dstBuffer` is the buffer to be filled.
- `dstOffset` is the byte offset into the buffer at which to start filling, and must be a multiple of 4.
- `size` is the number of bytes to fill, and must be either a multiple of 4, or `VK_WHOLE_SIZE` to fill the range from `offset` to the end of the buffer. If `VK_WHOLE_SIZE` is used and the remaining size of the buffer is not a multiple of 4, then the nearest smaller multiple is used.
- `data` is the 4-byte word written repeatedly to the buffer to fill `size` bytes of data. The data word is written to memory according to the host endianness.

`vkCmdFillBuffer` is treated as a “transfer” operation for the purposes of synchronization barriers. The `VK_BUFFER_USAGE_TRANSFER_DST_BIT` must be specified in `usage` of `VkBufferCreateInfo` in order for the buffer to be compatible with `vkCmdFillBuffer`.

### Valid Usage

- VUID-vkCmdFillBuffer-dstOffset-00024
  `dstOffset` must be less than the size of `dstBuffer`

- VUID-vkCmdFillBuffer-dstOffset-00025
  `dstOffset` must be a multiple of 4

- VUID-vkCmdFillBuffer-size-00026
  If `size` is not equal to `VK_WHOLE_SIZE`, `size` must be greater than 0

- VUID-vkCmdFillBuffer-size-00027
  If `size` is not equal to `VK_WHOLE_SIZE`, `size` must be less than or equal to the size of `dstBuffer` minus `dstOffset`

- VUID-vkCmdFillBuffer-size-00028
  If `size` is not equal to `VK_WHOLE_SIZE`, `size` must be a multiple of 4

- VUID-vkCmdFillBuffer-dstBuffer-00029
  `dstBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag

- VUID-vkCmdFillBuffer-apiVersion-07894
  If the `VK_KHR_maintenance1` extension is not enabled and `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, the `VkCommandPool` that `commandBuffer` was allocated
from **must** support graphics or compute operations

- **VUID-vkCmdFillBuffer-dstBuffer-00031**
  If `dstBuffer` is non-sparse then it **must** be bound completely and contiguously to a single `VkDeviceMemory` object.

- **VUID-vkCmdFillBuffer-commandBuffer-01811**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstBuffer` **must** not be a protected buffer.

- **VUID-vkCmdFillBuffer-commandBuffer-01812**
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstBuffer` **must** not be an unprotected buffer.

### Valid Usage (Implicit)

- **VUID-vkCmdFillBuffer-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle.

- **VUID-vkCmdFillBuffer-dstBuffer-parameter**
  `dstBuffer` **must** be a valid `VkBuffer` handle.

- **VUID-vkCmdFillBuffer-commandBuffer-recording**
  `commandBuffer` **must** be in the `recording state`.

- **VUID-vkCmdFillBuffer-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics or compute operations.

- **VUID-vkCmdFillBuffer-renderpass**
  This command **must** only be called outside of a render pass instance.

- **VUID-vkCmdFillBuffer-commonparent**
  Both of `commandBuffer`, and `dstBuffer` **must** have been created, allocated, or retrieved from the same `VkDevice`.

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized.

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized.
### Command Properties

<table>
<thead>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

### 18.5. Updating Buffers

To update buffer data inline in a command buffer, call:

```c
void vkCmdUpdateBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer dstBuffer,
    VkDeviceSize dstOffset,
    VkDeviceSize dataSize,
    const void* pData);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `dstBuffer` is a handle to the buffer to be updated.
- `dstOffset` is the byte offset into the buffer to start updating, and **must** be a multiple of 4.
- `dataSize` is the number of bytes to update, and **must** be a multiple of 4.
- `pData` is a pointer to the source data for the buffer update, and **must** be at least `dataSize` bytes in size.

`dataSize` **must** be less than or equal to 65536 bytes. For larger updates, applications can use buffer to buffer copies.

**Note**

Buffer updates performed with `vkCmdUpdateBuffer` first copy the data into command buffer memory when the command is recorded (which requires additional storage and may incur an additional allocation), and then copy the data from the command buffer into `dstBuffer` when the command is executed on a device.

The additional cost of this functionality compared to buffer to buffer copies means it is only recommended for very small amounts of data, and is why it is limited to only 65536 bytes.

Applications **can** work around this by issuing multiple `vkCmdUpdateBuffer` commands to different ranges of the same buffer, but it is strongly recommended...
The source data is copied from the user pointer to the command buffer when the command is called.

`vkCmdUpdateBuffer` is only allowed outside of a render pass. This command is treated as a “transfer” operation for the purposes of synchronization barriers. The `VK_BUFFER_USAGE_TRANSFER_DST_BIT` must be specified in `usage` of `VkBufferCreateInfo` in order for the buffer to be compatible with `vkCmdUpdateBuffer`.

**Valid Usage**

- `VUID-vkCmdUpdateBuffer-dstOffset-00032`
  `dstOffset` must be less than the size of `dstBuffer`

- `VUID-vkCmdUpdateBuffer-dataSize-00033`
  `dataSize` must be less than or equal to the size of `dstBuffer` minus `dstOffset`

- `VUID-vkCmdUpdateBuffer-dstBuffer-00034`
  `dstBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag

- `VUID-vkCmdUpdateBuffer-dstBuffer-00035`
  If `dstBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object

- `VUID-vkCmdUpdateBuffer-dstOffset-00036`
  `dstOffset` must be a multiple of 4

- `VUID-vkCmdUpdateBuffer-dataSize-00037`
  `dataSize` must be less than or equal to 65536

- `VUID-vkCmdUpdateBuffer-dataSize-00038`
  `dataSize` must be a multiple of 4

- `VUID-vkCmdUpdateBuffer-commandBuffer-01813`
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be a protected buffer

- `VUID-vkCmdUpdateBuffer-commandBuffer-01814`
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be an unprotected buffer

**Valid Usage (Implicit)**

- `VUID-vkCmdUpdateBuffer-commandBuffer-parameter`
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- `VUID-vkCmdUpdateBuffer-dstBuffer-parameter`
  `dstBuffer` must be a valid `VkBuffer` handle

- `VUID-vkCmdUpdateBuffer-pData-parameter`
  `pData` must be a valid pointer to an array of `dataSize` bytes
• VUID-vkCmdUpdateBuffer-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdUpdateBuffer-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support transfer, graphics, or compute operations

• VUID-vkCmdUpdateBuffer-renderpass
  This command must only be called outside of a render pass instance

• VUID-vkCmdUpdateBuffer-dataSize-arraylength
  dataSize must be greater than 0

• VUID-vkCmdUpdateBuffer-commonparent
  Both of commandBuffer, and dstBuffer must have been created, allocated, or retrieved from the same VkDevice

---

**Host Synchronization**

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

---

**Command Properties**

<table>
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<tr>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

---

*Note*

The pData parameter was of type uint32_t* instead of void* prior to version 1.0.19 of the Specification and VK_HEADER_VERSION 19 of the Vulkan Header Files. This was a historical anomaly, as the source data may be of other types.
Chapter 19. Copy Commands

An application can copy buffer and image data using several methods described in this chapter, depending on the type of data transfer.

All copy commands are treated as “transfer” operations for the purposes of synchronization barriers.

All copy commands that have a source format with an X component in its format description read undefined values from those bits.

All copy commands that have a destination format with an X component in its format description write undefined values to those bits.

19.1. Copying Data Between Buffers

To copy data between buffer objects, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdCopyBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer srcBuffer,
    VkBuffer dstBuffer,
    uint32_t regionCount,
    const VkBufferCopy* pRegions);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcBuffer` is the source buffer.
- `dstBuffer` is the destination buffer.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferCopy` structures specifying the regions to copy.

Each source region specified by `pRegions` is copied from the source buffer to the destination region of the destination buffer. If any of the specified regions in `srcBuffer` overlaps in memory with any of the specified regions in `dstBuffer`, values read from those overlapping regions are undefined.

Valid Usage

- VUID-vkCmdCopyBuffer-commandBuffer-01822
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcBuffer` must not be a protected buffer
- VUID-vkCmdCopyBuffer-commandBuffer-01823
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be a protected buffer
- VUID-vkCmdCopyBuffer-commandBuffer-01824
If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be an unprotected buffer.

- VUID-vkCmdCopyBuffer-srcOffset-00113
  The `srcOffset` member of each element of `pRegions` must be less than the size of `srcBuffer`.

- VUID-vkCmdCopyBuffer-dstOffset-00114
  The `dstOffset` member of each element of `pRegions` must be less than the size of `dstBuffer`.

- VUID-vkCmdCopyBuffer-size-00115
  The `size` member of each element of `pRegions` must be less than or equal to the size of `srcBuffer` minus `srcOffset`.

- VUID-vkCmdCopyBuffer-size-00116
  The `size` member of each element of `pRegions` must be less than or equal to the size of `dstBuffer` minus `dstOffset`.

- VUID-vkCmdCopyBuffer-pRegions-00117
  The union of the source regions, and the union of the destination regions, specified by the elements of `pRegions`, must not overlap in memory.

- VUID-vkCmdCopyBuffer-srcBuffer-00118
  `srcBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage flag.

- VUID-vkCmdCopyBuffer-srcBuffer-00119
  If `srcBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

- VUID-vkCmdCopyBuffer-dstBuffer-00120
  `dstBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag.

- VUID-vkCmdCopyBuffer-dstBuffer-00121
  If `dstBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

**Valid Usage (Implicit)**

- VUID-vkCmdCopyBuffer-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- VUID-vkCmdCopyBuffer-srcBuffer-parameter
  `srcBuffer` must be a valid `VkBuffer` handle.

- VUID-vkCmdCopyBuffer-dstBuffer-parameter
  `dstBuffer` must be a valid `VkBuffer` handle.

- VUID-vkCmdCopyBuffer-pRegions-parameter
  `pRegions` must be a valid pointer to an array of `regionCount` valid `VkBufferCopy` structures.

- VUID-vkCmdCopyBuffer-commandBuffer-recording
  `commandBuffer` must be in the `recording state`.

- VUID-vkCmdCopyBuffer-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations.
• VUID-vkCmdCopyBuffer-renderpass
  This command **must** only be called outside of a render pass instance

• VUID-vkCmdCopyBuffer-regionCount-arraylength
  **regionCount** **must** be greater than 0

• VUID-vkCmdCopyBuffer-commonparent
  Each of **commandBuffer**, **dstBuffer**, and **srcBuffer** **must** have been created, allocated, or retrieved from the same **VkDevice**

### Host Synchronization

• Host access to **commandBuffer** **must** be externally synchronized

• Host access to the **VkCommandPool** that **commandBuffer** was allocated from **must** be externally synchronized

### Command Properties

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</table>

The **VkBufferCopy** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBufferCopy {
    VkDeviceSize srcOffset;
    VkDeviceSize dstOffset;
    VkDeviceSize size;
} VkBufferCopy;
```

• **srcOffset** is the starting offset in bytes from the start of **srcBuffer**.

• **dstOffset** is the starting offset in bytes from the start of **dstBuffer**.

• **size** is the number of bytes to copy.

### Valid Usage

• VUID-VkBufferCopy-size-01988
  The **size** **must** be greater than 0

A more extensible version of the copy buffer command is defined below.
To copy data between buffer objects, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdCopyBuffer2(
    VkCommandBuffer commandBuffer,  // Provided by VK_VERSION_1_3
    const VkCopyBufferInfo2* pCopyBufferInfo);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pCopyBufferInfo` is a pointer to a `VkCopyBufferInfo2` structure describing the copy parameters.

Each source region specified by `pCopyBufferInfo->pRegions` is copied from the source buffer to the destination region of the destination buffer. If any of the specified regions in `pCopyBufferInfo-srcBuffer` overlaps in memory with any of the specified regions in `pCopyBufferInfo-dstBuffer`, values read from those overlapping regions are undefined.

### Valid Usage

- **VUID-vkCmdCopyBuffer2-commandBuffer-01822**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcBuffer` must not be a protected buffer.

- **VUID-vkCmdCopyBuffer2-commandBuffer-01823**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be a protected buffer.

- **VUID-vkCmdCopyBuffer2-commandBuffer-01824**
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstBuffer` must not be an unprotected buffer.

### Valid Usage (Implicit)

- **VUID-vkCmdCopyBuffer2-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- **VUID-vkCmdCopyBuffer2-pCopyBufferInfo-parameter**
  `pCopyBufferInfo` must be a valid pointer to a valid `VkCopyBufferInfo2` structure.

- **VUID-vkCmdCopyBuffer2-commandBuffer-recording**
  `commandBuffer` must be in the recording state.

- **VUID-vkCmdCopyBuffer2-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations.

- **VUID-vkCmdCopyBuffer2-renderpass**
  This command must only be called outside of a render pass instance.
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

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<td></td>
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<td></td>
</tr>
</tbody>
</table>

The `VkCopyBufferInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkCopyBufferInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkBuffer srcBuffer;
    VkBuffer dstBuffer;
    uint32_t regionCount;
    const VkBufferCopy2* pRegions;
} VkCopyBufferInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcBuffer` is the source buffer.
- `dstBuffer` is the destination buffer.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferCopy2` structures specifying the regions to copy.

Valid Usage

- VUID-VkCopyBufferInfo2-srcOffset-00113
  The `srcOffset` member of each element of `pRegions` must be less than the size of `srcBuffer`.

- VUID-VkCopyBufferInfo2-dstOffset-00114
  The `dstOffset` member of each element of `pRegions` must be less than the size of `dstBuffer`.

- VUID-VkCopyBufferInfo2-size-00115
  The `size` member of each element of `pRegions` must be less than or equal to the size of...
The size member of each element of `pRegions` must be less than or equal to the size of `dstBuffer` minus `dstOffset`.

The union of the source regions, and the union of the destination regions, specified by the elements of `pRegions`, must not overlap in memory.

`srcBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage flag.

If `srcBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

`dstBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag.

If `dstBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

Valid Usage (Implicit)

- **VUID-VkCopyBufferInfo2-sType-sType**
  
  `sType` must be `VK_STRUCTURE_TYPE_COPY_BUFFER_INFO_2`.

- **VUID-VkCopyBufferInfo2-pNext-pNext**
  
  `pNext` must be NULL.

- **VUID-VkCopyBufferInfo2-srcBuffer-parameter**
  
  `srcBuffer` must be a valid `VkBuffer` handle.

- **VUID-VkCopyBufferInfo2-dstBuffer-parameter**
  
  `dstBuffer` must be a valid `VkBuffer` handle.

- **VUID-VkCopyBufferInfo2-pRegions-parameter**
  
  `pRegions` must be a valid pointer to an array of `regionCount` valid `VkBufferCopy2` structures.

- **VUID-VkCopyBufferInfo2-regionCount-arraylength**
  
  `regionCount` must be greater than 0.

- **VUID-VkCopyBufferInfo2-commonparent**
  
  Both of `dstBuffer`, and `srcBuffer` must have been created, allocated, or retrieved from the same `VkDevice`.

The `VkBufferCopy2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkBufferCopy2 {
```
VkStructureType sType;
const void* pNext;
VkDeviceSize srcOffset;
VkDeviceSize dstOffset;
VkDeviceSize size;
} VkBufferCopy2;

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **srcOffset** is the starting offset in bytes from the start of `srcBuffer`.
- **dstOffset** is the starting offset in bytes from the start of `dstBuffer`.
- **size** is the number of bytes to copy.

### Valid Usage

- VUID-VkBufferCopy2-size-01988
  The **size** must be greater than 0

### Valid Usage (Implicit)

- VUID-VkBufferCopy2-sType-sType
  **sType** must be `VK_STRUCTURE_TYPE_BUFFER_COPY_2`
- VUID-VkBufferCopy2-pNext-pNext
  **pNext** must be `NULL`

### 19.2. Copying Data Between Images

To copy data between image objects, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdCopyImage(
    VkCommandBuffer commandBuffer,
    VkImage srcImage,
    VkImageLayout srcImageLayout,
    VkImage dstImage,
    VkImageLayout dstImageLayout,
    uint32_t regionCount,
    const VkImageCopy* pRegions);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **srcImage** is the source image.
- **srcImageLayout** is the current layout of the source image subresource.
• **dstImage** is the destination image.
• **dstImageLayout** is the current layout of the destination image subresource.
• **regionCount** is the number of regions to copy.
• **pRegions** is a pointer to an array of **VkImageCopy** structures specifying the regions to copy.

Each source region specified by **pRegions** is copied from the source image to the destination region of the destination image. If any of the specified regions in **srcImage** overlaps in memory with any of the specified regions in **dstImage**, values read from those overlapping regions are undefined.

**Multi-planar images** can only be copied on a per-plane basis, and the subresources used in each region when copying to or from such images must specify only one plane, though different regions can specify different planes. When copying planes of multi-planar images, the format considered is the compatible format for that plane, rather than the format of the multi-planar image.

If the format of the destination image has a different **block extent** than the source image (e.g., one is a compressed format), the offset and extent for each of the regions specified is scaled according to the block extents of each format to match in size. Copy regions for each image must be aligned to a multiple of the texel block extent in each dimension, except at the edges of the image, where region extents must match the edge of the image.

Image data can be copied between images with different image types. If one image is **VK_IMAGE_TYPE_3D** and the other image is **VK_IMAGE_TYPE_2D** with multiple layers, then each slice is copied to or from a different layer; depth slices in the 3D image correspond to **layerCount** layers in the 2D image, with an effective depth of 1 used for the 2D image.

### Valid Usage

- **VUID-vkCmdCopyImage-commandBuffer-01825**
  If **commandBuffer** is an unprotected command buffer and **protectedNoFault** is not supported, **srcImage** must not be a protected image

- **VUID-vkCmdCopyImage-commandBuffer-01826**
  If **commandBuffer** is an unprotected command buffer and **protectedNoFault** is not supported, **dstImage** must not be a protected image

- **VUID-vkCmdCopyImage-commandBuffer-01827**
  If **commandBuffer** is a protected command buffer and **protectedNoFault** is not supported, **dstImage** must not be an unprotected image

- **VUID-vkCmdCopyImage-pRegions-00124**
  The union of all source regions, and the union of all destination regions, specified by the elements of **pRegions**, must not overlap in memory

- **VUID-vkCmdCopyImage-srcImage-01995**
  The format features of **srcImage** must contain **VK_FORMAT_FEATURE_TRANSFER_SRC_BIT**

- **VUID-vkCmdCopyImage-srcImageLayout-00128**
  **srcImageLayout** must specify the layout of the image subresources of **srcImage** specified in **pRegions** at the time this command is executed on a **VkDevice**
• VUID-vkCmdCopyImage-srcImageLayout-00129
  
  srcImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL

• VUID-vkCmdCopyImage-dstImage-01996
  
  The format features of dstImage must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT

• VUID-vkCmdCopyImage-dstImageLayout-00133
  
  dstImageLayout must specify the layout of the image subresources of dstImage specified in pRegions at the time this command is executed on a VkDevice

• VUID-vkCmdCopyImage-dstImageLayout-00134
  
  dstImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL

• VUID-vkCmdCopyImage-srcImage-01548
  
  If the VkFormat of each of srcImage and dstImage is not a multi-planar format, the VkFormat of each of srcImage and dstImage must be size-compatible

• VUID-vkCmdCopyImage-None-01549
  
  In a copy to or from a plane of a multi-planar image, the VkFormat of the image and plane must be compatible according to the description of compatible planes for the plane being copied

• VUID-vkCmdCopyImage-srcImage-00136
  
  The sample count of srcImage and dstImage must match

• VUID-vkCmdCopyImage-srcOffset-01783
  
  The srcOffset and extent members of each element of pRegions must respect the image transfer granularity requirements of commandBuffer's command pool's queue family, as described in VkQueueFamilyProperties

• VUID-vkCmdCopyImage-dstOffset-01784
  
  The dstOffset and extent members of each element of pRegions must respect the image transfer granularity requirements of commandBuffer's command pool's queue family, as described in VkQueueFamilyProperties

• VUID-vkCmdCopyImage-srcImage-01551
  
  If neither srcImage nor dstImage has a multi-planar image format then for each element of pRegions, srcSubresource.aspectMask and dstSubresource.aspectMask must match

• VUID-vkCmdCopyImage-srcImage-01556
  
  If srcImage has a multi-planar image format, then for each element of pRegions, srcSubresource.aspectMask must be a single valid multi-planar aspect mask

• VUID-vkCmdCopyImage-dstImage-08714
  
  If dstImage has a multi-planar image format, then for each element of pRegions, dstSubresource.aspectMask must be a single valid multi-planar aspect mask

• VUID-vkCmdCopyImage-srcImage-01557
  
  If srcImage has a multi-planar image format and the dstImage does not have a multi-planar image format, then for each element of pRegions, dstSubresource.aspectMask must be VK_IMAGE_ASPECT_COLOR_BIT

• VUID-vkCmdCopyImage-dstImage-01557
  
  If dstImage has a multi-planar image format and the srcImage does not have a multi-planar image format, then for each element of pRegions, srcSubresource.aspectMask must be VK_IMAGE_ASPECT_COLOR_BIT
If the VK_KHR_maintenance1 extension is not enabled, VkPhysicalDeviceProperties::apiVersion is less than Vulkan 1.1, and either srcImage or dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcSubresource.baseArrayLayer and dstSubresource.baseArrayLayer must each be 0, and srcSubresource.layerCount and dstSubresource.layerCount must each be 1.

If srcImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcSubresource.baseArrayLayer must be 0 and srcSubresource.layerCount must be 1.

If dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, dstSubresource.baseArrayLayer must be 0 and dstSubresource.layerCount must be 1.

For each element of pRegions, srcSubresource.aspectMask must specify aspects present in srcImage.

For each element of pRegions, dstSubresource.aspectMask must specify aspects present in dstImage.

For each element of pRegions, srcOffset.x and (extent.width + srcOffset.x) must both be greater than or equal to 0 and less than or equal to the width of the specified srcSubresource of srcImage.

For each element of pRegions, srcOffset.y and (extent.height + srcOffset.y) must both be greater than or equal to 0 and less than or equal to the height of the specified srcSubresource of srcImage.

If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, srcOffset.y must be 0 and extent.height must be 1.

If srcImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcOffset.z and (extent.depth + srcOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified srcSubresource of srcImage.

If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, srcOffset.z must be 0 and extent.depth must be 1.

If dstImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, dstOffset.z must be 0 and extent.depth must be 1.

If srcImage is of type VK_IMAGE_TYPE_2D, then for each element of pRegions, srcOffset.z must be 0.

If srcImage is of type VK_IMAGE_TYPE_2D, then for each element of pRegions, srcOffset.z must be 0.

If dstImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, dstOffset.z must be 0.
If \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_2D}, then for each element of \( \text{pRegions} \), \( \text{dstOffset.z} \) must be 0.

- VUID-vkCmdCopyImage-apiVersion-07933
  If the \text{VK_KHR_maintenance1} extension is not enabled, \( \text{VkPhysicalDeviceProperties::apiVersion} \) is less than Vulkan 1.1, \( \text{srcImage} \) and \( \text{dstImage} \) must have the same \text{VkImageType}.

- VUID-vkCmdCopyImage-apiVersion-08969
  If the \text{VK_KHR_maintenance1} extension is not enabled, \( \text{VkPhysicalDeviceProperties::apiVersion} \) is less than Vulkan 1.1, and \( \text{srcImage} \) or \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_2D}, then for each element of \( \text{pRegions} \), \( \text{extent.depth} \) must be 1.

- VUID-vkCmdCopyImage-srcImage-07743
  If \( \text{srcImage} \) and \( \text{dstImage} \) have a different \text{VkImageType}, one must be \text{VK_IMAGE_TYPE_3D} and the other must be \text{VK_IMAGE_TYPE_2D}.

- VUID-vkCmdCopyImage-srcImage-07744
  If \( \text{srcImage} \) and \( \text{dstImage} \) have the same \text{VkImageType}, the \text{layerCount} member of \( \text{srcSubresource} \) and \( \text{dstSubresource} \) in each element of \( \text{pRegions} \) must match.

- VUID-vkCmdCopyImage-srcImage-01790
  If \( \text{srcImage} \) and \( \text{dstImage} \) are both of type \text{VK_IMAGE_TYPE_2D}, then for each element of \( \text{pRegions} \), \( \text{extent.depth} \) must be 1.

- VUID-vkCmdCopyImage-srcImage-01791
  If \( \text{srcImage} \) is of type \text{VK_IMAGE_TYPE_2D}, and \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_3D}, then for each element of \( \text{pRegions} \), \( \text{extent.depth} \) must equal \( \text{srcSubresource.layerCount} \).

- VUID-vkCmdCopyImage-dstImage-01792
  If \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_2D}, and \( \text{srcImage} \) is of type \text{VK_IMAGE_TYPE_3D}, then for each element of \( \text{pRegions} \), \( \text{extent.depth} \) must equal \( \text{dstSubresource.layerCount} \).

- VUID-vkCmdCopyImage-dstOffset-00150
  For each element of \( \text{pRegions} \), \( \text{dstOffset.x} \) and \( (\text{extent.width} + \text{dstOffset.x}) \) must both be greater than or equal to 0 and less than or equal to the width of the specified \( \text{dstSubresource} \) of \( \text{dstImage} \).

- VUID-vkCmdCopyImage-dstOffset-00151
  For each element of \( \text{pRegions} \), \( \text{dstOffset.y} \) and \( (\text{extent.height} + \text{dstOffset.y}) \) must both be greater than or equal to 0 and less than or equal to the height of the specified \( \text{dstSubresource} \) of \( \text{dstImage} \).

- VUID-vkCmdCopyImage-dstImage-00152
  If \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_1D}, then for each element of \( \text{pRegions} \), \( \text{dstOffset.y} \) must be 0 and \( \text{extent.height} \) must be 1.

- VUID-vkCmdCopyImage-dstImage-00153
  If \( \text{dstImage} \) is of type \text{VK_IMAGE_TYPE_3D}, then for each element of \( \text{pRegions} \), \( \text{dstOffset.z} \) and \( (\text{extent.depth} + \text{dstOffset.z}) \) must both be greater than or equal to 0 and less than or equal to the depth of the specified \( \text{dstSubresource} \) of \( \text{dstImage} \).

- VUID-vkCmdCopyImage-pRegions-07278
  For each element of \( \text{pRegions} \), \( \text{srcOffset.x} \) must be a multiple of the \text{texel block extent width} of the \text{VkFormat} of \( \text{srcImage} \).
For each element of `pRegions`, `srcOffset.y` must be a multiple of the texel block extent height of the `VkFormat` of `srcImage`.

For each element of `pRegions`, `srcOffset.z` must be a multiple of the texel block extent depth of the `VkFormat` of `srcImage`.

For each element of `pRegions`, `dstOffset.x` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`.

For each element of `pRegions`, `dstOffset.y` must be a multiple of the texel block extent height of the `VkFormat` of `dstImage`.

For each element of `pRegions`, `dstOffset.z` must be a multiple of the texel block extent depth of the `VkFormat` of `dstImage`.

For each element of `pRegions`, if the sum of `srcOffset.x` and `extent.width` does not equal the width of the subresource specified by `srcSubresource`, `extent.width` must be a multiple of the texel block extent width of the `VkFormat` of `srcImage`.

For each element of `pRegions`, if the sum of `srcOffset.y` and `extent.height` does not equal the height of the subresource specified by `srcSubresource`, `extent.height` must be a multiple of the texel block extent height of the `VkFormat` of `srcImage`.

For each element of `pRegions`, if the sum of `srcOffset.z` and `extent.depth` does not equal the depth of the subresource specified by `srcSubresource`, `extent.depth` must be a multiple of the texel block extent depth of the `VkFormat` of `srcImage`.

For each element of `pRegions`, if the sum of `dstOffset.x` and `extent.width` does not equal the width of the subresource specified by `dstSubresource`, `extent.width` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`.

For each element of `pRegions`, if the sum of `dstOffset.y` and `extent.height` does not equal the height of the subresource specified by `dstSubresource`, `extent.height` must be a multiple of the texel block extent height of the `VkFormat` of `dstImage`.

For each element of `pRegions`, if the sum of `dstOffset.z` and `extent.depth` does not equal the depth of the subresource specified by `dstSubresource`, `extent.depth` must be a multiple of the texel block extent depth of the `VkFormat` of `dstImage`.

If the `aspect` member of any element of `pRegions` includes any flag other than `VK_IMAGE_ASPECT_STENCIL_BIT` or `srcImage` was not created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` must have been included in the `VkImageCreateInfo`.
::usage used to create srcImage

- VUID-vkCmdCopyImage-aspect-06663
  If the `aspect` member of any element of `pRegions` includes any flag other than `VK_IMAGE_ASPECT_STENCIL_BIT` or `dstImage` was not created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_DST_BIT` must have been included in the `VkImageCreateInfo`.

- VUID-vkCmdCopyImage-aspect-06664
  If the `aspect` member of any element of `pRegions` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, and `srcImage` was created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` must have been included in the `VkImageStencilUsageCreateInfo`.

- VUID-vkCmdCopyImage-aspect-06665
  If the `aspect` member of any element of `pRegions` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, and `dstImage` was created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_DST_BIT` must have been included in the `VkImageStencilUsageCreateInfo`.

- VUID-vkCmdCopyImage-srcImage-07966
  If `srcImage` is non-sparse then the image or the specified disjoint plane must be bound completely and contiguously to a single `VkDeviceMemory` object.

- VUID-vkCmdCopyImage-srcSubresource-07967
  The `srcSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `srcImage` was created.

- VUID-vkCmdCopyImage-srcSubresource-07968
  The `srcSubresource.baseArrayLayer + srcSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `srcImage` was created.

- VUID-vkCmdCopyImage-dstImage-07966
  If `dstImage` is non-sparse then the image or the specified disjoint plane must be bound completely and contiguously to a single `VkDeviceMemory` object.

- VUID-vkCmdCopyImage-dstSubresource-07967
  The `dstSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `dstImage` was created.

- VUID-vkCmdCopyImage-dstSubresource-07968
  The `dstSubresource.baseArrayLayer + dstSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.

**Valid Usage (Implicit)**

- VUID-vkCmdCopyImage-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- VUID-vkCmdCopyImage-srcImage-parameter
**srcImage** **must** be a valid **VkImage** handle

- VUID-vkCmdCopyImage-srcImageLayout-parameter
  **srcImageLayout** **must** be a valid **VkImageLayout** value

- VUID-vkCmdCopyImage-dstImage-parameter
  **dstImage** **must** be a valid **VkImage** handle

- VUID-vkCmdCopyImage-dstImageLayout-parameter
  **dstImageLayout** **must** be a valid **VkImageLayout** value

- VUID-vkCmdCopyImage-pRegions-parameter
  **pRegions** **must** be a valid pointer to an array of **regionCount** valid **VkImageCopy** structures

- VUID-vkCmdCopyImage-commandBuffer-recording
  **commandBuffer** **must** be in the **recording state**

- VUID-vkCmdCopyImage-commandBuffer-cmdpool
  The **VkCommandPool** that **commandBuffer** was allocated from **must** support transfer, graphics, or compute operations

- VUID-vkCmdCopyImage-renderpass
  This command **must** only be called outside of a render pass instance

- VUID-vkCmdCopyImage-regionCount-arraylength
  **regionCount** **must** be greater than 0

- VUID-vkCmdCopyImage-commonparent
  Each of **commandBuffer**, **dstImage**, and **srcImage** **must** have been created, allocated, or retrieved from the same **VkDevice**

### Host Synchronization

- Host access to **commandBuffer** **must** be externally synchronized
- Host access to the **VkCommandPool** that **commandBuffer** was allocated from **must** be externally synchronized

### Command Properties

<table>
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</tbody>
</table>

The **VkImageCopy** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageCopy {
```
VkImageSubresourceLayers srcSubresource;
VkOffset3D srcOffset;
VkImageSubresourceLayers dstSubresource;
VkOffset3D dstOffset;
VkExtent3D extent;}

VkImageCopy;

- `srcSubresource` and `dstSubresource` are `VkImageSubresourceLayers` structures specifying the image subresources of the images used for the source and destination image data, respectively.
- `srcOffset` and `dstOffset` select the initial x, y, and z offsets in texels of the sub-regions of the source and destination image data.
- `extent` is the size in texels of the image to copy in width, height and depth.

### Valid Usage

- **VUID-VkImageCopy-apiVersion-07940**
  If the `VK_KHR_sampler_ycbcr_conversion` extension is not enabled and `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, the `aspectMask` member of `srcSubresource` and `dstSubresource` must match.

- **VUID-VkImageCopy-apiVersion-07941**
  If the `VK_KHR_maintenance1` extension is not enabled and `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, the `layerCount` member of `srcSubresource` and `dstSubresource` must match.

- **VUID-VkImageCopy-extent-06668**
  `extent.width` must not be 0

- **VUID-VkImageCopy-extent-06669**
  `extent.height` must not be 0

- **VUID-VkImageCopy-extent-06670**
  `extent.depth` must not be 0

### Valid Usage (Implicit)

- **VUID-VkImageCopy-srcSubresource-parameter**
  `srcSubresource` must be a valid `VkImageSubresourceLayers` structure

- **VUID-VkImageCopy-dstSubresource-parameter**
  `dstSubresource` must be a valid `VkImageSubresourceLayers` structure

The `VkImageSubresourceLayers` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageSubresourceLayers {
    VkImageAspectFlags aspectMask;
    uint32_t mipLevel;
} VkImageSubresourceLayers;
```
uint32_t baseArrayLayer;
uint32_t layerCount;
} VkImageSubresourceLayers;

• aspectMask is a combination of VkImageAspectFlagBits, selecting the color, depth and/or stencil aspects to be copied.
• mipLevel is the mipmap level to copy.
• baseArrayLayer and layerCount are the starting layer and number of layers to copy.

Valid Usage

• VUID-VkImageSubresourceLayers-aspectMask-00167
  If aspectMask contains VK_IMAGE_ASPECT_COLOR_BIT, it must not contain either of VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT
• VUID-VkImageSubresourceLayers-aspectMask-00168
  aspectMask must not contain VK_IMAGE_ASPECT_METADATA_BIT
• VUID-VkImageSubresourceLayers-layerCount-01700
  layerCount must be greater than 0

Valid Usage (Implicit)

• VUID-VkImageSubresourceLayers-aspectMask-parameter
  aspectMask must be a valid combination of VkImageAspectFlagBits values
• VUID-VkImageSubresourceLayers-aspectMask-requiredbitmask
  aspectMask must not be 0

A more extensible version of the copy image command is defined below.

To copy data between image objects, call:

```
// Provided by VK_VERSION_1_3
void vkCmdCopyImage2(
    VkCommandBuffer commandBuffer,
    const VkCopyImageInfo2* pCopyImageInfo);
```

• commandBuffer is the command buffer into which the command will be recorded.
• pCopyImageInfo is a pointer to a VkCopyImageInfo2 structure describing the copy parameters.

This command is functionally identical to vkCmdCopyImage, but includes extensible sub-structures that include sType and pNext parameters, allowing them to be more easily extended.
Valid Usage

- VUID-vkCmdCopyImage2-commandBuffer-01825
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcImage` must not be a protected image

- VUID-vkCmdCopyImage2-commandBuffer-01826
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image

- VUID-vkCmdCopyImage2-commandBuffer-01827
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image

Valid Usage (Implicit)

- VUID-vkCmdCopyImage2-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- VUID-vkCmdCopyImage2-pCopyImageInfo-parameter
  `pCopyImageInfo` must be a valid pointer to a valid `VkCopyImageInfo2` structure

- VUID-vkCmdCopyImage2-commandBuffer-recording
  `commandBuffer` must be in the recording state

- VUID-vkCmdCopyImage2-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations

- VUID-vkCmdCopyImage2-renderpass
  This command must only be called outside of a render pass instance

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>
The `VkCopyImageInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkCopyImageInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkImage srcImage;
    VkImageLayout srcImageLayout;
    VkImage dstImage;
    VkImageLayout dstImageLayout;
    uint32_t regionCount;
    const VkImageCopy2* pRegions;
} VkCopyImageInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcImage` is the source image.
- `srcImageLayout` is the current layout of the source image subresource.
- `dstImage` is the destination image.
- `dstImageLayout` is the current layout of the destination image subresource.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkImageCopy2` structures specifying the regions to copy.

### Valid Usage

- **VUID-VkCopyImageInfo2-pRegions-00124**
  The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, **must** not overlap in memory

- **VUID-VkCopyImageInfo2-srcImage-01995**
  The **format features** of `srcImage` **must** contain `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`

- **VUID-VkCopyImageInfo2-srcImageLayout-00128**
  `srcImageLayout` **must** specify the layout of the image subresources of `srcImage` specified in `pRegions` at the time this command is executed on a `VkDevice`

- **VUID-VkCopyImageInfo2-srcImageLayout-00129**
  `srcImageLayout` **must** be `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`

- **VUID-VkCopyImageInfo2-dstImage-01996**
  The **format features** of `dstImage` **must** contain `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`

- **VUID-VkCopyImageInfo2-dstImageLayout-00133**
  `dstImageLayout` **must** specify the layout of the image subresources of `dstImage` specified in `pRegions` at the time this command is executed on a `VkDevice`

- **VUID-VkCopyImageInfo2-dstImageLayout-00134**
  `dstImageLayout` **must** be `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`
If the `VkFormat` of each of `srcImage` and `dstImage` is not a **multi-planar format**, the `VkFormat` of each of `srcImage` and `dstImage` must be **size-compatible**.

In a copy to or from a plane of a **multi-planar image**, the `VkFormat` of the image and plane must be compatible according to the description of compatible planes for the plane being copied.

The sample count of `srcImage` and `dstImage` must match.

The `srcOffset` and `extent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

The `dstOffset` and `extent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

If neither `srcImage` nor `dstImage` has a **multi-planar image format** then for each element of `pRegions`, `srcSubresource.aspectMask` and `dstSubresource.aspectMask` must match.

If `srcImage` has a **multi-planar image format**, then for each element of `pRegions`, `srcSubresource.aspectMask` must be a single valid **multi-planar aspect mask**.

If `dstImage` has a **multi-planar image format**, then for each element of `pRegions`, `dstSubresource.aspectMask` must be a single valid **multi-planar aspect mask**.

If `srcImage` has a **multi-planar image format** and the `dstImage` does not have a multi-planar image format, then for each element of `pRegions`, `dstSubresource.aspectMask` must be `VK_IMAGE_ASPECT_COLOR_BIT`.

If `dstImage` has a **multi-planar image format** and the `srcImage` does not have a multi-planar image format, then for each element of `pRegions`, `srcSubresource.aspectMask` must be `VK_IMAGE_ASPECT_COLOR_BIT`.

If the `VK_KHR_maintenance1` extension is not enabled, `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, and either `srcImage` or `dstImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `srcSubresource.baseArrayLayer` and `dstSubresource.baseArrayLayer` must each be 0, and `srcSubresource.layerCount` and `dstSubresource.layerCount` must each be 1.

If `srcImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `srcSubresource.baseArrayLayer` must be 0 and `srcSubresource.layerCount` must be 1.
• VUID-VkCopyImageInfo2-dstImage-04444
  If `dstImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `dstSubresource.baseArrayLayer` must be 0 and `dstSubresource.layerCount` must be 1

• VUID-VkCopyImageInfo2-aspectMask-00142
  For each element of `pRegions`, `srcSubresource.aspectMask` must specify aspects present in `srcImage`

• VUID-VkCopyImageInfo2-aspectMask-00143
  For each element of `pRegions`, `dstSubresource.aspectMask` must specify aspects present in `dstImage`

• VUID-VkCopyImageInfo2-srcOffset-00144
  For each element of `pRegions`, `srcOffset.x` and `(extent.width + srcOffset.x)` must both be greater than or equal to 0 and less than or equal to the width of the specified `srcSubresource` of `srcImage`

• VUID-VkCopyImageInfo2-srcOffset-00145
  For each element of `pRegions`, `srcOffset.y` and `(extent.height + srcOffset.y)` must both be greater than or equal to 0 and less than or equal to the height of the specified `srcSubresource` of `srcImage`

• VUID-VkCopyImageInfo2-srcImage-00146
  If `srcImage` is of type `VK_IMAGE_TYPE_1D`, then for each element of `pRegions`, `srcOffset.y` must be 0 and `extent.height` must be 1

• VUID-VkCopyImageInfo2-srcOffset-00147
  If `srcImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `srcOffset.z` and `(extent.depth + srcOffset.z)` must both be greater than or equal to 0 and less than or equal to the depth of the specified `srcSubresource` of `srcImage`

• VUID-VkCopyImageInfo2-srcImage-01785
  If `srcImage` is of type `VK_IMAGE_TYPE_1D`, then for each element of `pRegions`, `srcOffset.z` must be 0

• VUID-VkCopyImageInfo2-dstImage-01786
  If `dstImage` is of type `VK_IMAGE_TYPE_1D`, then for each element of `pRegions`, `dstOffset.z` must be 0

• VUID-VkCopyImageInfo2-srcImage-01787
  If `srcImage` is of type `VK_IMAGE_TYPE_2D`, then for each element of `pRegions`, `srcOffset.z` must be 0

• VUID-VkCopyImageInfo2-dstImage-01788
  If `dstImage` is of type `VK_IMAGE_TYPE_2D`, then for each element of `pRegions`, `dstOffset.z` must be 0

• VUID-VkCopyImageInfo2-apiVersion-07933
  If the `VK_KHR_maintenance1` extension is not enabled, `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, `srcImage` and `dstImage` must have the same `VkImageType`

• VUID-VkCopyImageInfo2-apiVersion-08969
  If the `VK_KHR_maintenance1` extension is not enabled, `VkPhysicalDeviceProperties::apiVersion` is less than Vulkan 1.1, and `srcImage` or `dstImage` is of type `VK_IMAGE_TYPE_2D`,
then for each element of `pRegions`, `extent.depth` must be 1

- **VUID-VkCopyImageInfo2-srcImage-07743**
  
  If `srcImage` and `dstImage` have a different `VkImageType`, one must be `VK_IMAGE_TYPE_3D` and the other must be `VK_IMAGE_TYPE_2D`

- **VUID-VkCopyImageInfo2-srcImage-07744**
  
  If `srcImage` and `dstImage` have the same `VkImageType`, the `layerCount` member of `srcSubresource` and `dstSubresource` in each element of `pRegions` must match.

- **VUID-VkCopyImageInfo2-srcImage-01790**
  
  If `srcImage` and `dstImage` are both of type `VK_IMAGE_TYPE_2D`, then for each element of `pRegions`, `extent.depth` must be 1

- **VUID-VkCopyImageInfo2-srcImage-01791**
  
  If `srcImage` is of type `VK_IMAGE_TYPE_2D`, and `dstImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `extent.depth` must equal `srcSubresource.layerCount`

- **VUID-VkCopyImageInfo2-dstImage-00150**
  
  For each element of `pRegions`, `dstOffset.x` and `(extent.width + dstOffset.x)` must both be greater than or equal to 0 and less than or equal to the width of the specified `dstSubresource` of `dstImage`

- **VUID-VkCopyImageInfo2-dstImage-00151**
  
  For each element of `pRegions`, `dstOffset.y` and `(extent.height + dstOffset.y)` must both be greater than or equal to 0 and less than or equal to the height of the specified `dstSubresource` of `dstImage`

- **VUID-VkCopyImageInfo2-dstImage-00152**
  
  If `dstImage` is of type `VK_IMAGE_TYPE_1D`, then for each element of `pRegions`, `dstOffset.y` must be 0 and `extent.height` must be 1

- **VUID-VkCopyImageInfo2-dstImage-00153**
  
  If `dstImage` is of type `VK_IMAGE_TYPE_3D`, then for each element of `pRegions`, `dstOffset.z` and `(extent.depth + dstOffset.z)` must both be greater than or equal to 0 and less than or equal to the depth of the specified `dstSubresource` of `dstImage`

- **VUID-VkCopyImageInfo2-pRegions-07278**
  
  For each element of `pRegions`, `srcOffset.x` must be a multiple of the texel block extent width of the `VkFormat` of `srcImage`

- **VUID-VkCopyImageInfo2-pRegions-07279**
  
  For each element of `pRegions`, `srcOffset.y` must be a multiple of the texel block extent height of the `VkFormat` of `srcImage`

- **VUID-VkCopyImageInfo2-pRegions-07280**
  
  For each element of `pRegions`, `srcOffset.z` must be a multiple of the texel block extent depth of the `VkFormat` of `srcImage`

- **VUID-VkCopyImageInfo2-pRegions-07281**
  
  For each element of `pRegions`, `dstOffset.x` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`
• VUID-VkCopyImageInfo2-pRegions-07282
  For each element of pRegions, dstOffset.y must be a multiple of the texel block extent height of the VkFormat of dstImage

• VUID-VkCopyImageInfo2-pRegions-07283
  For each element of pRegions, dstOffset.z must be a multiple of the texel block extent depth of the VkFormat of dstImage

• VUID-VkCopyImageInfo2-srcImage-01728
  For each element of pRegions, if the sum of srcOffset.x and extent.width does not equal the width of the subresource specified by srcSubresource, extent.width must be a multiple of the texel block extent width of the VkFormat of srcImage

• VUID-VkCopyImageInfo2-srcImage-01729
  For each element of pRegions, if the sum of srcOffset.y and extent.height does not equal the height of the subresource specified by srcSubresource, extent.height must be a multiple of the texel block extent height of the VkFormat of srcImage

• VUID-VkCopyImageInfo2-srcImage-01730
  For each element of pRegions, if the sum of srcOffset.z and extent.depth does not equal the depth of the subresource specified by srcSubresource, extent.depth must be a multiple of the texel block extent depth of the VkFormat of srcImage

• VUID-VkCopyImageInfo2-dstImage-01732
  For each element of pRegions, if the sum of dstOffset.x and extent.width does not equal the width of the subresource specified by dstSubresource, extent.width must be a multiple of the texel block extent width of the VkFormat of dstImage

• VUID-VkCopyImageInfo2-dstImage-01733
  For each element of pRegions, if the sum of dstOffset.y and extent.height does not equal the height of the subresource specified by dstSubresource, extent.height must be a multiple of the texel block extent height of the VkFormat of dstImage

• VUID-VkCopyImageInfo2-dstImage-01734
  For each element of pRegions, if the sum of dstOffset.z and extent.depth does not equal the depth of the subresource specified by dstSubresource, extent.depth must be a multiple of the texel block extent depth of the VkFormat of dstImage

• VUID-VkCopyImageInfo2-aspect-06662
  If the aspect member of any element of pRegions includes any flag other than VK_IMAGE_ASPECT_STENCIL_BIT or srcImage was not created with separate stencil usage, VK_IMAGE_USAGE_TRANSFER_SRC_BIT must have been included in the VkImageCreateInfo::usage used to create srcImage

• VUID-VkCopyImageInfo2-aspect-06663
  If the aspect member of any element of pRegions includes any flag other than VK_IMAGE_ASPECT_STENCIL_BIT or dstImage was not created with separate stencil usage, VK_IMAGE_USAGE_TRANSFER_DST_BIT must have been included in the VkImageCreateInfo::usage used to create dstImage

• VUID-VkCopyImageInfo2-aspect-06664
  If the aspect member of any element of pRegions includes VK_IMAGE_ASPECT_STENCIL_BIT, and srcImage was created with separate stencil usage, VK_IMAGE_USAGE_TRANSFER_SRC_BIT must have been included in the VkImageStencilUsageCreateInfo::stencilUsage used to
create srcImage

- VUID-VkCopyImageInfo2-aspect-06665
  If the aspect member of any element of pRegions includes VK_IMAGE_ASPECT_STENCIL_BIT, and dstImage was created with separate stencil usage, VK_IMAGE_USAGE_TRANSFER_DST_BIT must have been included in the VkImageStencilUsageCreateInfo::stencilUsage used to create dstImage

- VUID-VkCopyImageInfo2-srcImage-07966
  If srcImage is non-sparse then the image or the specified disjoint plane must be bound completely and contiguously to a single VkDeviceMemory object

- VUID-VkCopyImageInfo2-srcSubresource-07967
  The srcSubresource.mipLevel member of each element of pRegions must be less than the mipLevels specified in VkImageCreateInfo when srcImage was created

- VUID-VkCopyImageInfo2-srcSubresource-07968
  The srcSubresource.baseArrayLayer + srcSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when srcImage was created

- VUID-VkCopyImageInfo2-dstImage-07966
  If dstImage is non-sparse then the image or the specified disjoint plane must be bound completely and contiguously to a single VkDeviceMemory object

- VUID-VkCopyImageInfo2-dstSubresource-07967
  The dstSubresource.mipLevel member of each element of pRegions must be less than the mipLevels specified in VkImageCreateInfo when dstImage was created

- VUID-VkCopyImageInfo2-dstSubresource-07968
  The dstSubresource.baseArrayLayer + dstSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when dstImage was created

Valid Usage (Implicit)

- VUID-VkCopyImageInfo2-sType-sType
  sType must be VK_STRUCTURE_TYPE_COPY_IMAGE_INFO_2

- VUID-VkCopyImageInfo2-pNext-pNext
  pNext must be NULL

- VUID-VkCopyImageInfo2-srcImage-parameter
  srcImage must be a valid VkImage handle

- VUID-VkCopyImageInfo2-srcImageLayout-parameter
  srcImageLayout must be a valid VkImageLayout value

- VUID-VkCopyImageInfo2-dstImage-parameter
  dstImage must be a valid VkImage handle

- VUID-VkCopyImageInfo2-dstImageLayout-parameter
  dstImageLayout must be a valid VkImageLayout value
- **VUID-VkCopyImageInfo2-pRegions-parameter**
  \( \text{pRegions} \text{ must} \) be a valid pointer to an array of \( \text{regionCount} \) valid \( \text{VkImageCopy2} \) structures

- **VUID-VkCopyImageInfo2-regionCount-arraylength**
  \( \text{regionCount} \text{ must} \) be greater than 0

- **VUID-VkCopyImageInfo2-commonparent**
  Both of \( \text{dstImage} \), and \( \text{srcImage} \) \text{must have been created, allocated, or retrieved from the same} \( \text{VkDevice} \)

The \( \text{VkImageCopy2} \) structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkImageCopy2 {
    VkStructureType sType;
    const void* pNext;
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffset;
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffset;
    VkExtent3D extent;
} VkImageCopy2;
```

- **sType** is a \( \text{VkStructureType} \) value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **srcSubresource** and **dstSubresource** are \( \text{VkImageSubresourceLayers} \) structures specifying the image subresources of the images used for the source and destination image data, respectively.
- **srcOffset** and **dstOffset** select the initial \( x \), \( y \), and \( z \) offsets in texels of the sub-regions of the source and destination image data.
- **extent** is the size in texels of the image to copy in \( \text{width} \), \( \text{height} \) and \( \text{depth} \).

**Valid Usage**

- **VUID-VkImageCopy2-apiVersion-07940**
  If the \( \text{VK_KHR_sampler_ycbcr_conversion} \) extension is not enabled and \( \text{VkPhysicalDeviceProperties}::\text{apiVersion} \) is less than Vulkan 1.1, the \( \text{aspectMask} \) member of \( \text{srcSubresource} \) and \( \text{dstSubresource} \) \text{must} match

- **VUID-VkImageCopy2-apiVersion-07941**
  If the \( \text{VK_KHR_maintenance1} \) extension is not enabled and \( \text{VkPhysicalDeviceProperties}::\text{apiVersion} \) is less than Vulkan 1.1, the \( \text{layerCount} \) member of \( \text{srcSubresource} \) and \( \text{dstSubresource} \) \text{must} match

- **VUID-VkImageCopy2-extent-06668**
  \( \text{extent.width} \text{ must} \) not be 0

- **VUID-VkImageCopy2-extent-06669**
**Valid Usage (Implicit)**

- VUID-VkImageCopy2-sType-sType
  
  **sType** must be **VK_STRUCTURE_TYPE_IMAGE_COPY_2**

- VUID-VkImageCopy2-pNext-pNext
  
  **pNext** must be **NULL**

- VUID-VkImageCopy2-srcSubresource-parameter
  
  **srcSubresource** must be a valid **VkImageSubresourceLayers** structure

- VUID-VkImageCopy2-dstSubresource-parameter
  
  **dstSubresource** must be a valid **VkImageSubresourceLayers** structure

---

### 19.3. Copying Data Between Buffers and Images

Data can be copied between buffers and images, enabling applications to load and store data between images and user-defined offsets in buffer memory.

When copying between a buffer and an image, whole texel blocks are always copied; each texel block in the specified extent in the image to be copied will be written to a region in the buffer, specified according to the position of the texel block, and the texel block extent and size of the format being copied.

For a set of coordinates \((x,y,z,\text{layer})\), where:

- \(x\) is in the range \([\text{imageOffset.x} / \text{blockWidth}, \lceil(\text{imageOffset.x} + \text{imageExtent.width}) / \text{blockWidth}\rceil)\),

- \(y\) is in the range \([\text{imageOffset.y} / \text{blockHeight}, \lceil(\text{imageOffset.y} + \text{imageExtent.height}) / \text{blockHeight}\rceil)\),

- \(z\) is in the range \([\text{imageOffset.z} / \text{blockDepth}, \lceil(\text{imageOffset.z} + \text{imageExtent.depth}) / \text{blockDepth}\rceil)\),

- \(\text{layer}\) is in the range \([\text{imageSubresource.baseArrayLayer}, \text{imageSubresource.baseArrayLayer} + \text{imageSubresource.layerCount})\),

and where blockWidth, blockHeight, and blockDepth are the dimensions of the texel block extent of the image's format.
For each \((x,y,z,\text{layer})\) coordinate, texels in the image layer selected by \(\text{layer}\) are accessed in the following ranges:

\[
[x \times \text{blockWidth}, \max( (x \times \text{blockWidth}) + \text{blockWidth}, \text{imageWidth}) )
\]

\[
[y \times \text{blockHeight}, \max( (y \times \text{blockHeight}) + \text{blockHeight}, \text{imageHeight}) )
\]

\[
[z \times \text{blockDepth}, \max( (z \times \text{blockDepth}) + \text{blockDepth}, \text{imageDepth}) )
\]

where \(\text{imageWidth}\), \(\text{imageHeight}\), and \(\text{imageDepth}\) are the dimensions of the image subresource.

For each \((x,y,z,\text{layer})\) coordinate, bytes in the buffer are accessed at offsets in the range \([\text{texelOffset}, \text{texelOffset} + \text{blockSize})\], where:

\[
\text{texelOffset} = \text{bufferOffset} + (x \times \text{blockSize}) + (y \times \text{rowExtent}) + (z \times \text{sliceExtent}) + (\text{layer} \times \text{layerExtent})
\]

\(\text{blockSize}\) is the size of the block in bytes for the format

\[
\text{rowExtent} = \max(\text{bufferRowLength}, \lceil \text{imageExtent.width} / \text{blockWidth} \rceil \times \text{blockSize})
\]

\[
\text{sliceExtent} = \max(\text{bufferImageHeight}, \text{imageExtent.height} \times \text{rowExtent})
\]

\[
\text{layerExtent} = \text{imageExtent.depth} \times \text{sliceExtent}
\]

When copying between a buffer and the depth or stencil aspect of an image, data in the buffer is assumed to be laid out as separate planes rather than interleaved. Addressing calculations are thus performed for a different format than the base image, according to the aspect, as described in the following table:

**Table 19. Depth/Stencil Aspect Copy Table**

<table>
<thead>
<tr>
<th>Base Format</th>
<th>Depth Aspect Format</th>
<th>Stencil Aspect Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_D16_UNORM</td>
<td>VK_FORMAT_D16_UNORM</td>
<td>-</td>
</tr>
<tr>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
<td>-</td>
</tr>
<tr>
<td>VK_FORMAT_D32_SFLOAT</td>
<td>VK_FORMAT_D32_SFLOAT</td>
<td>-</td>
</tr>
<tr>
<td>VK_FORMAT_S8_UINT</td>
<td>-</td>
<td>VK_FORMAT_S8_UINT</td>
</tr>
<tr>
<td>VK_FORMAT_D16_UNORM_S8_UINT</td>
<td>VK_FORMAT_D16_UNORM</td>
<td>VK_FORMAT_S8_UINT</td>
</tr>
<tr>
<td>VK_FORMAT_D24_UNORM_S8_UINT</td>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
<td>VK_FORMAT_S8_UINT</td>
</tr>
</tbody>
</table>
When copying between a buffer and any plane of a multi-planar image, addressing calculations are performed using the compatible format for that plane, rather than the format of the multi-planar image.

Each texel block is copied from one resource to the other according to the above addressing equations.

To copy data from a buffer object to an image object, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdCopyBufferToImage(
    VkCommandBuffer commandBuffer,
    VkBuffer srcBuffer,
    VkImage dstImage,
    VkImageLayout dstImageLayout,
    uint32_t regionCount,
    const VkBufferImageCopy* pRegions);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcBuffer` is the source buffer.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the copy.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferImageCopy` structures specifying the regions to copy.

Each source region specified by `pRegions` is copied from the source buffer to the destination region of the destination image according to the addressing calculations for each resource. If any of the specified regions in `srcBuffer` overlaps in memory with any of the specified regions in `dstImage`, values read from those overlapping regions are undefined. If any region accesses a depth aspect in `dstImage` values copied from `srcBuffer` outside of the range $[0,1]$ will be be written as undefined values to the destination image.

Copy regions for the image **must** be aligned to a multiple of the texel block extent in each dimension, except at the edges of the image, where region extents **must** match the edge of the image.

### Valid Usage

- VUID-vkCmdCopyBufferToImage-dstImage-07966
  If `dstImage` is non-sparse then the image or the specified disjoint plane **must** be bound completely and contiguously to a single `VkDeviceMemory` object

- VUID-vkCmdCopyBufferToImage-imageSubresource-07967
The `imageSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `dstImage` was created.

- **VUID-vkCmdCopyBufferToImage-imageSubresource-07968**
  The `imageSubresource.baseArrayLayer + imageSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.

- **VUID-vkCmdCopyBufferToImage-imageSubresource-07970**
  The image region specified by each element of `pRegions` must be contained within the specified `imageSubresource` of `dstImage`.

- **VUID-vkCmdCopyBufferToImage-imageSubresource-07971**
  For each element of `pRegions`, `imageOffset.x` and `(imageExtent.width + imageOffset.x)` must both be greater than or equal to 0 and less than or equal to the width of the specified `imageSubresource` of `dstImage`.

- **VUID-vkCmdCopyBufferToImage-imageSubresource-07972**
  For each element of `pRegions`, `imageOffset.y` and `(imageExtent.height + imageOffset.y)` must both be greater than or equal to 0 and less than or equal to the height of the specified `imageSubresource` of `dstImage`.

- **VUID-vkCmdCopyBufferToImage-dstImage-07973**
  `dstImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`.

- **VUID-vkCmdCopyBufferToImage-commandBuffer-01828**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcBuffer` must not be a protected buffer.

- **VUID-vkCmdCopyBufferToImage-commandBuffer-01829**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image.

- **VUID-vkCmdCopyBufferToImage-commandBuffer-01830**
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image.

- **VUID-vkCmdCopyBufferToImage-commandBuffer-07737**
  If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`, the `bufferOffset` member of any element of `pRegions` must be a multiple of 4.

- **VUID-vkCmdCopyBufferToImage-imageOffset-07738**
  The `imageOffset` and `imageExtent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`’s command pool’s queue family, as described in `VkQueueFamilyProperties`.

- **VUID-vkCmdCopyBufferToImage-commandBuffer-07739**
  If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT`, for each element of `pRegions`, the `aspectMask` member of `imageSubresource` must not be `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`.
srcBuffer must be large enough to contain all buffer locations that are accessed according to Buffer and Image Addressing, for each element of pRegions.

The union of all source regions, and the union of all destination regions, specified by the elements of pRegions, must not overlap in memory.

srcBuffer must have been created with VK_BUFFER_USAGE_TRANSFER_SRC_BIT usage flag.

The format features of dstImage must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT.

If srcBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

dstImage must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag.

dstImageLayout must specify the layout of the image subresources of dstImage specified in pRegions at the time this command is executed on a VkDevice.

dstImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL.

For each element of pRegions whose imageSubresource contains a depth aspect, the data in srcBuffer must be in the range [0,1].

If dstImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, imageOffset.y must be 0 and imageExtent.height must be 1.

For each element of pRegions, imageOffset.z and (imageExtent.depth + imageOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified imageSubresource of dstImage.

If dstImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, imageOffset.z must be 0 and imageExtent.depth must be 1.

For each element of pRegions, imageOffset.x must be a multiple of the texel block extent width of the VkFormat of dstImage.

For each element of pRegions, imageOffset.y must be a multiple of the texel block extent height of the VkFormat of dstImage.

For each element of pRegions, imageOffset.z must be a multiple of the texel block extent depth of the VkFormat of dstImage.
For each element of `pRegions`, if the sum of `imageOffset.x` and `extent.width` does not equal
the width of the subresource specified by `srcSubresource`, `extent.width` must be a multiple
of the texel block extent width of the VkFormat of `dstImage`.

For each element of `pRegions`, if the sum of `imageOffset.y` and `extent.height` does not equal
the height of the subresource specified by `srcSubresource`, `extent.height` must be a multiple
of the texel block extent height of the VkFormat of `dstImage`.

For each element of `pRegions`, if the sum of `imageOffset.z` and `extent.depth` does not equal
the depth of the subresource specified by `srcSubresource`, `extent.depth` must be a multiple
of the texel block extent depth of the VkFormat of `dstImage`.

For each element of `pRegions`, `imageSubresource.aspectMask` must specify aspects present in `dstImage`.

If `dstImage` has a VkFormat with two planes then for each element of `pRegions`,
`imageSubresource.aspectMask` must be `VK_IMAGE_ASPECT_PLANE_0_BIT` or `VK_IMAGE_ASPECT_PLANE_1_BIT`.

If `dstImage` has a VkFormat with three planes then for each element of `pRegions`,
`imageSubresource.aspectMask` must be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`.

If `dstImage` is of type `VK_IMAGE_TYPE_3D`, for each element of `pRegions`,
`imageSubresource.baseArrayLayer` must be 0 and `imageSubresource.layerCount` must be 1.

For each element of `pRegions`, `bufferRowLength` must be a multiple of the texel block extent width of the VkFormat of `dstImage`.

For each element of `pRegions`, `bufferImageHeight` must be a multiple of the texel block extent height of the VkFormat of `dstImage`.

For each element of `pRegions`, `bufferRowLength` divided by the texel block extent width and then multiplied by the texel block size of `dstImage` must be less than or equal to $2^{31}-1$.

If `dstImage` does not have either a depth/stencil or a multi-planar format, then for each element of `pRegions`, `bufferOffset` must be a multiple of the texel block size.

If `dstImage` has a multi-planar format, then for each element of `pRegions`, `bufferOffset` must be a multiple of the element size of the compatible format for the format and the `aspectMask` of the `imageSubresource` as defined in Compatible formats of planes of multi-planar formats.
VUID-vkCmdCopyBufferToImage-dstImage-07978
If `dstImage` has a depth/stencil format, the `bufferOffset` member of any element of `pRegions` must be a multiple of 4.

**Valid Usage (Implicit)**

- VUID-vkCmdCopyBufferToImage-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- VUID-vkCmdCopyBufferToImage-srcBuffer-parameter
  `srcBuffer` must be a valid `VkBuffer` handle
- VUID-vkCmdCopyBufferToImage-dstImage-parameter
  `dstImage` must be a valid `VkImage` handle
- VUID-vkCmdCopyBufferToImage-dstImageLayout-parameter
  `dstImageLayout` must be a valid `VkImageLayout` value
- VUID-vkCmdCopyBufferToImage-pRegions-parameter
  `pRegions` must be a valid pointer to an array of `regionCount` valid `VkBufferImageCopy` structures
- VUID-vkCmdCopyBufferToImage-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdCopyBufferToImage-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations
- VUID-vkCmdCopyBufferToImage-renderpass
  This command must only be called outside of a render pass instance
- VUID-vkCmdCopyBufferToImage-regionCount-arraylength
  `regionCount` must be greater than 0
- VUID-vkCmdCopyBufferToImage-commonparent
  Each of `commandBuffer`, `dstImage`, and `srcBuffer` must have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
To copy data from an image object to a buffer object, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdCopyImageToBuffer(  
    VkCommandBuffer commandBuffer,  
    VkImage srcImage,  
    VkImageLayout srcImageLayout,  
    VkBuffer dstBuffer,  
    uint32_t regionCount,  
    const VkBufferImageCopy* pRegions);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcImage` is the source image.
- `srcImageLayout` is the layout of the source image subresources for the copy.
- `dstBuffer` is the destination buffer.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferImageCopy` structures specifying the regions to copy.

Each source region specified by `pRegions` is copied from the source image to the destination region of the destination buffer according to the addressing calculations for each resource. If any of the specified regions in `srcImage` overlaps in memory with any of the specified regions in `dstBuffer`, values read from those overlapping regions are undefined.

Copy regions for the image **must** be aligned to a multiple of the texel block extent in each dimension, except at the edges of the image, where region extents **must** match the edge of the image.

### Valid Usage

- **VUID-vkCmdCopyImageToBuffer-srcImage-07966**
  - If `srcImage` is non-sparse then the image or the specified disjoint plane **must** be bound completely and contiguously to a single `VkDeviceMemory` object

- **VUID-vkCmdCopyImageToBuffer-imageSubresource-07967**
  - The `imageSubresource.mipLevel` member of each element of `pRegions` **must** be less than the `mipLevels` specified in `VkImageCreateInfo` when `srcImage` was created
The `imageSubresource.baseArrayLayer + imageSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `srcImage` was created.

The image region specified by each element of `pRegions` must be contained within the specified `imageSubresource` of `srcImage`.

For each element of `pRegions, imageOffset.x` and `(imageExtent.width + imageOffset.x)` must both be greater than or equal to 0 and less than or equal to the width of the specified `imageSubresource` of `srcImage`.

For each element of `pRegions, imageOffset.y` and `(imageExtent.height + imageOffset.y)` must both be greater than or equal to 0 and less than or equal to the height of the specified `imageSubresource` of `srcImage`.

`srcImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`.

If `commandBuffer` is an unprotected command buffer and protectedNoFault is not supported, `srcImage` must not be a protected image.

If `commandBuffer` is an unprotected command buffer and protectedNoFault is not supported, `dstBuffer` must not be a protected buffer.

If `commandBuffer` is a protected command buffer and protectedNoFault is not supported, `dstBuffer` must not be an unprotected buffer.

If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`, the `bufferOffset` member of any element of `pRegions` must be a multiple of 4.

The `imageOffset` and `imageExtent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`’s command pool’s queue family, as described in `VkQueueFamilyProperties`.

`dstBuffer` must be large enough to contain all buffer locations that are accessed according to `Buffer and Image Addressing`, for each element of `pRegions`.

The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory.

`srcImage` must be large enough to contain all buffer locations that are accessed according to `Buffer and Image Addressing`, for each element of `pRegions`.
srcImage must have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag

- VUID-vkCmdCopyImageToBuffer-srcImage-01998
  The format features of srcImage must contain VK_FORMAT_FEATURE_TRANSFER_SRC_BIT

- VUID-vkCmdCopyImageToBuffer-dstBuffer-00191
  dstBuffer must have been created with VK_BUFFER_USAGE_TRANSFER_DST_BIT usage flag

- VUID-vkCmdCopyImageToBuffer-dstBuffer-00192
  If dstBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- VUID-vkCmdCopyImageToBuffer-srcImageLayout-00189
  srcImageLayout must specify the layout of the image subresources of srcImage specified in pRegions at the time this command is executed on a VkDevice

- VUID-vkCmdCopyImageToBuffer-srcImageLayout-00190
  srcImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL

- VUID-vkCmdCopyImageToBuffer-srcImage-07979
  If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, imageOffset.y must be 0 and imageExtent.height must be 1

- VUID-vkCmdCopyImageToBuffer-imageOffset-09104
  For each element of pRegions, imageOffset.z and (imageExtent.depth + imageOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified imageSubresource of srcImage

- VUID-vkCmdCopyImageToBuffer-srcImage-07980
  If srcImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, imageOffset.z must be 0 and imageExtent.depth must be 1

- VUID-vkCmdCopyImageToBuffer-pRegions-07274
  For each element of pRegions, imageOffset.x must be a multiple of the texel block extent width of the VkFormat of srcImage

- VUID-vkCmdCopyImageToBuffer-pRegions-07275
  For each element of pRegions, imageOffset.y must be a multiple of the texel block extent height of the VkFormat of srcImage

- VUID-vkCmdCopyImageToBuffer-pRegions-07276
  For each element of pRegions, imageOffset.z must be a multiple of the texel block extent depth of the VkFormat of srcImage

- VUID-vkCmdCopyImageToBuffer-imageExtent-00207
  For each element of pRegions, if the sum of imageOffset.x and extent.width does not equal the width of the subresource specified by srcSubresource, extent.width must be a multiple of the texel block extent width of the VkFormat of srcImage

- VUID-vkCmdCopyImageToBuffer-imageExtent-00208
  For each element of pRegions, if the sum of imageOffset.y and extent.height does not equal the height of the subresource specified by srcSubresource, extent.height must be a multiple of the texel block extent height of the VkFormat of srcImage

- VUID-vkCmdCopyImageToBuffer-imageExtent-00209
  For each element of pRegions, if the sum of imageOffset.z and extent.depth does not equal
the depth of the subresource specified by \texttt{srcSubresource}, \texttt{extent.depth} must be a multiple of the texel block extent depth of the \texttt{VkFormat} of \texttt{srcImage}

- VUID-vkCmdCopyImageToBuffer-imageSubresource-09105
  For each element of \texttt{pRegions}, \texttt{imageSubresource.aspectMask} must specify aspects present in \texttt{srcImage}

- VUID-vkCmdCopyImageToBuffer-srcImage-07981
  If \texttt{srcImage} has a \texttt{VkFormat} with two planes then for each element of \texttt{pRegions}, \texttt{imageSubresource.aspectMask} must be \texttt{VK_IMAGE_ASPECT_PLANE_0_BIT} or \texttt{VK_IMAGE_ASPECT_PLANE_1_BIT}

- VUID-vkCmdCopyImageToBuffer-srcImage-07982
  If \texttt{srcImage} has a \texttt{VkFormat} with three planes then for each element of \texttt{pRegions}, \texttt{imageSubresource.aspectMask} must be \texttt{VK_IMAGE_ASPECT_PLANE_0_BIT}, \texttt{VK_IMAGE_ASPECT_PLANE_1_BIT}, or \texttt{VK_IMAGE_ASPECT_PLANE_2_BIT}

- VUID-vkCmdCopyImageToBuffer-srcImage-07983
  If \texttt{srcImage} is of type \texttt{VK_IMAGE_TYPE_3D}, for each element of \texttt{pRegions}, \texttt{imageSubresource.baseArrayLayer} must be 0 and \texttt{imageSubresource.layerCount} must be 1

- VUID-vkCmdCopyImageToBuffer-bufferRowLength-09106
  For each element of \texttt{pRegions}, \texttt{bufferRowLength} must be a multiple of the texel block extent width of the \texttt{VkFormat} of \texttt{srcImage}

- VUID-vkCmdCopyImageToBuffer-bufferImageHeight-09107
  For each element of \texttt{pRegions}, \texttt{bufferImageHeight} must be a multiple of the texel block extent height of the \texttt{VkFormat} of \texttt{srcImage}

- VUID-vkCmdCopyImageToBuffer-bufferRowLength-09108
  For each element of \texttt{pRegions}, \texttt{bufferRowLength} divided by the texel block extent width and then multiplied by the texel block size of \texttt{srcImage} must be less than or equal to \(2^{31}-1\)

- VUID-vkCmdCopyImageToBuffer-srcImage-07975
  If \texttt{srcImage} does not have either a depth/stencil or a multi-planar format, then for each element of \texttt{pRegions}, \texttt{bufferOffset} must be a multiple of the texel block size

- VUID-vkCmdCopyImageToBuffer-srcImage-07976
  If \texttt{srcImage} has a multi-planar format, then for each element of \texttt{pRegions}, \texttt{bufferOffset} must be a multiple of the element size of the compatible format for the format and the aspectMask of the \texttt{imageSubresource} as defined in \texttt{Compatible formats of planes of multi-planar formats}

- VUID-vkCmdCopyImageToBuffer-srcImage-07978
  If \texttt{srcImage} has a depth/stencil format, the \texttt{bufferOffset} member of any element of \texttt{pRegions} must be a multiple of 4

### Valid Usage (Implicit)

- VUID-vkCmdCopyImageToBuffer-commandBuffer-parameter
  \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle

- VUID-vkCmdCopyImageToBuffer-srcImage-parameter
**srcImage** must be a valid *VkImage* handle

- **VUID-vkCmdCopyImageToBuffer-srcImageLayout-parameter**
  **srcImageLayout** must be a valid *VkImageLayout* value

- **VUID-vkCmdCopyImageToBuffer-dstBuffer-parameter**
  **dstBuffer** must be a valid *VkBuffer* handle

- **VUID-vkCmdCopyImageToBuffer-pRegions-parameter**
  **pRegions** must be a valid pointer to an array of **regionCount** valid *VkBufferImageCopy* structures

- **VUID-vkCmdCopyImageToBuffer-commandBuffer-recording**
  **commandBuffer** must be in the recording state

- **VUID-vkCmdCopyImageToBuffer-commandBuffer-cmdpool**
  The *VkCommandPool* that **commandBuffer** was allocated from must support transfer, graphics, or compute operations

- **VUID-vkCmdCopyImageToBuffer-renderpass**
  This command must only be called outside of a render pass instance

- **VUID-vkCmdCopyImageToBuffer-regionCount-arraylength**
  **regionCount** must be greater than 0

- **VUID-vkCmdCopyImageToBuffer-commonparent**
  Each of **commandBuffer**, **dstBuffer**, and **srcImage** must have been created, allocated, or retrieved from the same *VkDevice*

---

**Host Synchronization**

- Host access to **commandBuffer** must be externally synchronized
- Host access to the *VkCommandPool* that **commandBuffer** was allocated from must be externally synchronized

---

**Command Properties**

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<td></td>
</tr>
</tbody>
</table>

For both *vkCmdCopyBufferToImage* and *vkCmdCopyImageToBuffer*, each element of **pRegions** is a structure defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBufferImageCopy {
```
VkDeviceSize bufferOffset;
uint32_t bufferRowLength;
uint32_t bufferImageHeight;
VkImageSubresourceLayers imageSubresource;
VkOffset3D imageOffset;
VkExtent3D imageExtent;
}
VkBufferImageCopy;

- **bufferOffset** is the offset in bytes from the start of the buffer object where the image data is copied from or to.

- **bufferRowLength** and **bufferImageHeight** specify in texels a subregion of a larger two- or threedimensional image in buffer memory, and control the addressing calculations. If either of these values is zero, that aspect of the buffer memory is considered to be tightly packed according to the **imageExtent**.

- **imageSubresource** is a **VkImageSubresourceLayers** used to specify the specific image subresources of the image used for the source or destination image data.

- **imageOffset** selects the initial x, y, z offsets in texels of the sub-region of the source or destination image data.

- **imageExtent** is the size in texels of the image to copy in width, height and depth.

### Valid Usage

- VUID-VkBufferImageCopy-bufferRowLength-09101
  bufferRowLength must be 0, or greater than or equal to the width member of imageExtent

- VUID-VkBufferImageCopy-bufferImageHeight-09102
  bufferImageHeight must be 0, or greater than or equal to the height member of imageExtent

- VUID-VkBufferImageCopy-aspectMask-09103
  The aspectMask member of imageSubresource must only have a single bit set

- VUID-VkBufferImageCopy-imageExtent-06659
  imageExtent.width must not be 0

- VUID-VkBufferImageCopy-imageExtent-06660
  imageExtent.height must not be 0

- VUID-VkBufferImageCopy-imageExtent-06661
  imageExtent.depth must not be 0

### Valid Usage (Implicit)

- VUID-VkBufferImageCopy-imageSubresource-parameter
  imageSubresource must be a valid VkImageSubresourceLayers structure

More extensible versions of the commands to copy between buffers and images are defined below.
To copy data from a buffer object to an image object, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdCopyBufferToImage2(
    VkCommandBuffer commandBuffer,
    const VkCopyBufferToImageInfo2* pCopyBufferToImageInfo);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pCopyBufferToImageInfo` is a pointer to a `VkCopyBufferToImageInfo2` structure describing the copy parameters.

This command is functionally identical to `vkCmdCopyBufferToImage`, but includes extensible substructures that include `sType` and `pNext` parameters, allowing them to be more easily extended.

### Valid Usage

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-01828**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcBuffer` must not be a protected buffer

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-01829**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-01829**
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-07737**
  If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`, the `bufferOffset` member of any element of `pCopyBufferToImageInfo->pRegions` must be a multiple of 4

- **VUID-vkCmdCopyBufferToImage2-imageOffset-07738**
  The `imageOffset` and `imageExtent` members of each element of `pCopyBufferToImageInfo->pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-07739**
  If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT`, for each element of `pCopyBufferToImageInfo->pRegions`, the `aspectMask` member of `imageSubresource` must not be `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`

### Valid Usage (Implicit)

- **VUID-vkCmdCopyBufferToImage2-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle
The **VkCopyBufferToImageInfo2** structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkCopyBufferToImageInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkBuffer srcBuffer;
    VkImage dstImage;
    VkImageLayout dstImageLayout;
    uint32_t regionCount;
    const VkBufferImageCopy2* pRegions;
} VkCopyBufferToImageInfo2;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **srcBuffer** is the source buffer.
• `dstImage` is the destination image.
• `dstImageLayout` is the layout of the destination image subresources for the copy.
• `regionCount` is the number of regions to copy.
• `pRegions` is a pointer to an array of `VkBufferImageCopy2` structures specifying the regions to copy.

**Valid Usage**

• VUID-VkCopyBufferToImageInfo2-pRegions-00172
  The image region specified by each element of `pRegions` must be contained within the specified `imageSubresource` of `dstImage`

• VUID-VkCopyBufferToImageInfo2-pRegions-00171
  `srcBuffer` must be large enough to contain all buffer locations that are accessed according to Buffer and Image Addressing, for each element of `pRegions`

• VUID-VkCopyBufferToImageInfo2-pRegions-00173
  The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory

• VUID-VkCopyBufferToImageInfo2-srcBuffer-00174
  `srcBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage flag

• VUID-VkCopyBufferToImageInfo2-dstImage-01997
  The `format features` of `dstImage` must contain `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`

• VUID-VkCopyBufferToImageInfo2-srcBuffer-00176
  If `srcBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object

• VUID-VkCopyBufferToImageInfo2-dstImage-00177
  `dstImage` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag

• VUID-VkCopyBufferToImageInfo2-dstImageLayout-00180
  `dstImageLayout` must specify the layout of the image subresources of `dstImage` specified in `pRegions` at the time this command is executed on a `VkDevice`

• VUID-VkCopyBufferToImageInfo2-dstImageLayout-00181
  `dstImageLayout` must be `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`

• VUID-VkCopyBufferToImageInfo2-None-00214
  For each element of `pRegions` whose `imageSubresource` contains a depth aspect, the data in `srcBuffer` must be in the range [0,1]

• VUID-VkCopyBufferToImageInfo2-dstImage-07966
  If `dstImage` is non-sparse then the image or the specified disjoint plane must be bound completely and contiguously to a single `VkDeviceMemory` object

• VUID-VkCopyBufferToImageInfo2-imageSubresource-07967
  The `imageSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `dstImage` was created

• VUID-VkCopyBufferToImageInfo2-imageSubresource-07968
The `imageSubresource.baseArrayLayer + imageSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.

- **VUID-VkCopyBufferToImageInfo2-dstImage-07973**
  `dstImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`

- **VUID-VkCopyBufferToImageInfo2-dstImage-07979**
  If `dstImage` is of type `VK_IMAGE_TYPE_1D`, then for each element of `pRegions`, `imageOffset.y` must be 0 and `imageExtent.height` must be 1.

- **VUID-VkCopyBufferToImageInfo2-imageOffset-09104**
  For each element of `pRegions`, `imageOffset.z` and `(imageExtent.depth + imageOffset.z)` must both be greater than or equal to 0 and less than or equal to the depth of the specified `imageSubresource` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-dstImage-07980**
  If `dstImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then for each element of `pRegions`, `imageOffset.z` must be 0 and `imageExtent.depth` must be 1.

- **VUID-VkCopyBufferToImageInfo2-pRegions-07274**
  For each element of `pRegions`, `imageOffset.x` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-pRegions-07275**
  For each element of `pRegions`, `imageOffset.y` must be a multiple of the texel block extent height of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-pRegions-07276**
  For each element of `pRegions`, `imageOffset.z` must be a multiple of the texel block extent depth of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-imageExtent-00207**
  For each element of `pRegions`, if the sum of `imageOffset.x` and `extent.width` does not equal the width of the subresource specified by `srcSubresource`, `extent.width` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-imageExtent-00208**
  For each element of `pRegions`, if the sum of `imageOffset.y` and `extent.height` does not equal the height of the subresource specified by `srcSubresource`, `extent.height` must be a multiple of the texel block extent height of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-imageExtent-00209**
  For each element of `pRegions`, if the sum of `imageOffset.z` and `extent.depth` does not equal the depth of the subresource specified by `srcSubresource`, `extent.depth` must be a multiple of the texel block extent depth of the `VkFormat` of `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-imageSubresource-09105**
  For each element of `pRegions`, `imageSubresource.aspectMask` must specify aspects present in `dstImage`.

- **VUID-VkCopyBufferToImageInfo2-dstImage-07981**
  If `dstImage` has a `VkFormat` with two planes then for each element of `pRegions`, `imageSubresource.aspectMask` must be `VK_IMAGE_ASPECT_PLANE_0_BIT` or...
If `dstImage` has a `VkFormat` with **three planes** then for each element of `pRegions`, `imageSubresource.aspectMask` must be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`.

If `dstImage` is of type `VK_IMAGE_TYPE_3D`, for each element of `pRegions`, `imageSubresource.baseArrayLayer` must be 0 and `imageSubresource.layerCount` must be 1.

For each element of `pRegions`, `bufferRowLength` must be a multiple of the texel block extent width of the `VkFormat` of `dstImage`.

For each element of `pRegions`, `bufferImageHeight` must be a multiple of the texel block extent height of the `VkFormat` of `dstImage`.

For each element of `pRegions`, `bufferRowLength` divided by the texel block extent width and then multiplied by the texel block size of `dstImage` must be less than or equal to $2^{31} - 1$.

If `dstImage` does not have either a depth/stencil or a **multi-planar format**, then for each element of `pRegions`, `bufferOffset` must be a multiple of the texel block size.

If `dstImage` has a **multi-planar format**, then for each element of `pRegions`, `bufferOffset` must be a multiple of the element size of the compatible format for the format and the `aspectMask` of the `imageSubresource` as defined in **Compatible formats of planes of multi-planar formats**.

If `dstImage` has a depth/stencil format, the `bufferOffset` member of any element of `pRegions` must be a multiple of 4.

For each element of `pRegions` not containing `VkCopyCommandTransformInfoQCOM` in its `pNext` chain, `imageOffset.x` and ($imageExtent.width + imageOffset.x$) must both be greater than or equal to 0 and less than or equal to the width of the specified `imageSubresource` of `dstImage`.

For each element of `pRegions` not containing `VkCopyCommandTransformInfoQCOM` in its `pNext` chain, `imageOffset.y` and ($imageExtent.height + imageOffset.y$) must both be greater than or equal to 0 and less than or equal to the height of the specified `imageSubresource` of `dstImage`.

Valid Usage (Implicit)

- **VUID-VkCopyBufferToImageInfo2-sType-sType**
  
sType must be `VK_STRUCTURE_TYPE_COPY_BUFFER_TO_IMAGE_INFO_2`.
• VUID-VkCopyBufferToImageInfo2-pNext-pNext
  pNext must be NULL

• VUID-VkCopyBufferToImageInfo2-srcBuffer-parameter
  srcBuffer must be a valid VkBuffer handle

• VUID-VkCopyBufferToImageInfo2-dstImage-parameter
  dstImage must be a valid VkImage handle

• VUID-VkCopyBufferToImageInfo2-dstImageLayout-parameter
  dstImageLayout must be a valid VkImageLayout value

• VUID-VkCopyBufferToImageInfo2-pRegions-parameter
  pRegions must be a valid pointer to an array of regionCount valid VkBufferImageCopy2 structures

• VUID-VkCopyBufferToImageInfo2-regionCount-arraylength
  regionCount must be greater than 0

• VUID-VkCopyBufferToImageInfo2-commonparent
  Both of dstImage, and srcBuffer must have been created, allocated, or retrieved from the same VkDevice

To copy data from an image object to a buffer object, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdCopyImageToBuffer2(
    VkCommandBuffer commandBuffer,
    const VkCopyImageToBufferInfo2* pCopyImageToBufferInfo);
```

• commandBuffer is the command buffer into which the command will be recorded.

• pCopyImageToBufferInfo is a pointer to a VkCopyImageToBufferInfo2 structure describing the copy parameters.

This command is functionally identical to vkCmdCopyImageToBuffer, but includes extensible substructures that include sType and pNext parameters, allowing them to be more easily extended.

**Valid Usage**

• VUID-vkCmdCopyImageToBuffer2-commandBuffer-01831
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, srcImage must not be a protected image

• VUID-vkCmdCopyImageToBuffer2-commandBuffer-01832
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, dstBuffer must not be a protected buffer

• VUID-vkCmdCopyImageToBuffer2-commandBuffer-01833
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, dstBuffer must not be an unprotected buffer

• VUID-vkCmdCopyImageToBuffer2-commandBuffer-07746
If the queue family used to create the `VkCommandPool` which `commandBuffer` was allocated from does not support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`, the `bufferOffset` member of any element of `pCopyImageToBufferInfo->pRegions` must be a multiple of 4.

- VUID-vkCmdCopyImageToBuffer2-imageOffset-07747
  The `imageOffset` and `imageExtent` members of each element of `pCopyImageToBufferInfo->pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

---

**Valid Usage (Implicit)**

- VUID-vkCmdCopyImageToBuffer2-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- VUID-vkCmdCopyImageToBuffer2-pCopyImageToBufferInfo-parameter
  `pCopyImageToBufferInfo` must be a valid pointer to a valid `VkCopyImageToBufferInfo2` structure.

- VUID-vkCmdCopyImageToBuffer2-commandBuffer-recording
  `commandBuffer` must be in the `recording` state.

- VUID-vkCmdCopyImageToBuffer2-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations.

- VUID-vkCmdCopyImageToBuffer2-renderpass
  This command must only be called outside of a render pass instance.

---

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized.

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

---

**Command Properties**

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The `VkCopyImageToBufferInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
```
typedef struct VkCopyImageToBufferInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkImage srcImage;
    VkImageLayout srcImageLayout;
    VkBuffer dstBuffer;
    uint32_t regionCount;
    const VkBufferImageCopy2* pRegions;
} VkCopyImageToBufferInfo2;

• **sType** is a **VkStructureType** value identifying this structure.
• **pNext** is **NULL** or a pointer to a structure extending this structure.
• **srcImage** is the source image.
• **srcImageLayout** is the layout of the source image subresources for the copy.
• **dstBuffer** is the destination buffer.
• **regionCount** is the number of regions to copy.
• **pRegions** is a pointer to an array of **VkBufferImageCopy2** structures specifying the regions to copy.

**Valid Usage**

• **VUID-VkCopyImageToBufferInfo2-pRegions-00182**
  The image region specified by each element of **pRegions** **must** be contained within the specified **imageSubresource** of **srcImage**

• **VUID-VkCopyImageToBufferInfo2-pRegions-00183**
  **dstBuffer** **must** be large enough to contain all buffer locations that are accessed according to **Buffer and Image Addressing**, for each element of **pRegions**

• **VUID-VkCopyImageToBufferInfo2-pRegions-00184**
  The union of all source regions, and the union of all destination regions, specified by the elements of **pRegions**, **must** not overlap in memory

• **VUID-VkCopyImageToBufferInfo2-srcImage-00186**
  **srcImage** **must** have been created with **VK_IMAGE_USAGE_TRANSFER_SRC_BIT** usage flag

• **VUID-VkCopyImageToBufferInfo2-srcImage-01998**
  The **format features** of **srcImage** **must** contain **VK_FORMAT_FEATURE_TRANSFER_SRC_BIT**

• **VUID-VkCopyImageToBufferInfo2-dstBuffer-00191**
  **dstBuffer** **must** have been created with **VK_BUFFER_USAGE_TRANSFER_DST_BIT** usage flag

• **VUID-VkCopyImageToBufferInfo2-dstBuffer-00192**
  If **dstBuffer** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object

• **VUID-VkCopyImageToBufferInfo2-srcImageLayout-00189**
  **srcImageLayout** **must** specify the layout of the image subresources of **srcImage** specified in **pRegions** at the time this command is executed on a **VkDevice**
• **VUID-VkCopyImageToBufferInfo2-srcImageLayout-00190**
  
  *srcImageLayout* must be *VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL* or *VK_IMAGE_LAYOUT_GENERAL*

• **VUID-VkCopyImageToBufferInfo2-srcImage-07966**
  
  If *srcImage* is non-sparse then the image or the specified *disjoint* plane must be bound completely and contiguously to a single *VkDeviceMemory* object.

• **VUID-VkCopyImageToBufferInfo2-imageSubresource-07967**
  
  The *imageSubresource.mipLevel* member of each element of *pRegions* must be less than the *mipLevels* specified in *VkImageCreateInfo* when *srcImage* was created.

• **VUID-VkCopyImageToBufferInfo2-imageSubresource-07968**
  
  The *imageSubresource.baseArrayLayer* + *imageSubresource.layerCount* of each element of *pRegions* must be less than or equal to the *arrayLayers* specified in *VkImageCreateInfo* when *srcImage* was created.

• **VUID-VkCopyImageToBufferInfo2-srcImage-07973**
  
  *srcImage* must have a sample count equal to *VK_SAMPLE_COUNT_1_BIT*.

• **VUID-VkCopyImageToBufferInfo2-srcImage-07979**
  
  If *srcImage* is of type *VK_IMAGE_TYPE_1D*, then for each element of *pRegions*, *imageOffset.y* must be 0 and *imageExtent.height* must be 1.

• **VUID-VkCopyImageToBufferInfo2-imageOffset-09104**
  
  For each element of *pRegions*, *imageOffset.z* and (*imageExtent.depth* + *imageOffset.z*) must both be greater than or equal to 0 and less than or equal to the depth of the specified *imageSubresource* of *srcImage*.

• **VUID-VkCopyImageToBufferInfo2-srcImage-07980**
  
  If *srcImage* is of type *VK_IMAGE_TYPE_1D* or *VK_IMAGE_TYPE_2D*, then for each element of *pRegions*, *imageOffset.z* must be 0 and *imageExtent.depth* must be 1.

• **VUID-VkCopyImageToBufferInfo2-pRegions-07274**
  
  For each element of *pRegions*, *imageOffset.x* must be a multiple of the texel block extent width of the *VkFormat* of *srcImage*.

• **VUID-VkCopyImageToBufferInfo2-pRegions-07275**
  
  For each element of *pRegions*, *imageOffset.y* must be a multiple of the texel block extent height of the *VkFormat* of *srcImage*.

• **VUID-VkCopyImageToBufferInfo2-pRegions-07276**
  
  For each element of *pRegions*, *imageOffset.z* must be a multiple of the texel block extent depth of the *VkFormat* of *srcImage*.

• **VUID-VkCopyImageToBufferInfo2-imageExtent-00207**
  
  For each element of *pRegions*, if the sum of *imageOffset.x* and *extent.width* does not equal the width of the subresource specified by *srcSubresource*, *extent.width* must be a multiple of the texel block extent width of the *VkFormat* of *srcImage*.

• **VUID-VkCopyImageToBufferInfo2-imageExtent-00208**
  
  For each element of *pRegions*, if the sum of *imageOffset.y* and *extent.height* does not equal the height of the subresource specified by *srcSubresource*, *extent.height* must be a multiple of the texel block extent height of the *VkFormat* of *srcImage*.
For each element of `pRegions`, if the sum of `imageOffset.z` and `extent.depth` does not equal the depth of the subresource specified by `srcSubresource`, `extent.depth` **must** be a multiple of the **texel block extent depth** of the `VkFormat` of `srcImage`.

For each element of `pRegions`, `imageSubresource.aspectMask` **must** specify aspects present in `srcImage`.

If `srcImage` has a `VkFormat` with **two planes**, then for each element of `pRegions`, `imageSubresource.aspectMask` **must** be `VK_IMAGE_ASPECT_PLANE_0_BIT` or `VK_IMAGE_ASPECT_PLANE_1_BIT`.

If `srcImage` has a `VkFormat` with **three planes**, then for each element of `pRegions`, `imageSubresource.aspectMask` **must** be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`.

If `srcImage` is of type `VK_IMAGE_TYPE_3D`, for each element of `pRegions`, `imageSubresource.baseArrayLayer` **must** be 0 and `imageSubresource.layerCount` **must** be 1.

For each element of `pRegions`, `bufferRowLength` **must** be a multiple of the **texel block extent width** of the `VkFormat` of `srcImage`.

For each element of `pRegions`, `bufferImageHeight` **must** be a multiple of the **texel block extent height** of the `VkFormat` of `srcImage`.

For each element of `pRegions`, `bufferRowLength` divided by the **texel block extent width** and then multiplied by the texel block size of `srcImage` **must** be less than or equal to $2^{31}-1$.

If `srcImage` does not have either a depth/stencil or a **multi-planar format**, then for each element of `pRegions`, `bufferOffset` **must** be a multiple of the **texel block size**.

If `srcImage` has a **multi-planar format**, then for each element of `pRegions`, `bufferOffset` must be a multiple of the element size of the compatible format for the format and the `aspectMask` of the `imageSubresource` as defined in **Compatible formats of planes of multi-planar formats**.

If `srcImage` has a depth/stencil format, the `bufferOffset` member of any element of `pRegions` **must** be a multiple of 4.

For each element of `pRegions` not containing `VkCopyCommandTransformInfoQCOM` in its `pNext` chain, `imageOffset.x` and $(imageExtent.width + imageOffset.x)$ **must** both be greater than or equal to 0 and less than or equal to the width of the specified `imageSubresource` of `srcImage`.
For each element of \( pRegions \) not containing \( \text{VkCopyCommandTransformInfoQCOM} \) in its \( pNext \) chain, \( \text{imageOffset.y} \) and \((\text{imageExtent.height} + \text{imageOffset.y})\) must both be greater than or equal to \( 0 \) and less than or equal to the height of the specified \( \text{imageSubresource} \) of \( \text{srcImage} \)

### Valid Usage (Implicit)

- **VUID-VkCopyImageToBufferInfo2-sType-sType**  
  \( sType \) must be \( \text{VK_STRUCTURE_TYPE_COPY_IMAGE_TO_BUFFER_INFO_2} \)

- **VUID-VkCopyImageToBufferInfo2-pNext-pNext**  
  \( pNext \) must be \( \text{NULL} \)

- **VUID-VkCopyImageToBufferInfo2-srcImage-parameter**  
  \( \text{srcImage} \) must be a valid \( \text{VkImage} \) handle

- **VUID-VkCopyImageToBufferInfo2-srcImageLayout-parameter**  
  \( \text{srcImageLayout} \) must be a valid \( \text{VkImageLayout} \) value

- **VUID-VkCopyImageToBufferInfo2-dstBuffer-parameter**  
  \( \text{dstBuffer} \) must be a valid \( \text{VkBuffer} \) handle

- **VUID-VkCopyImageToBufferInfo2-pRegions-parameter**  
  \( \text{pRegions} \) must be a valid pointer to an array of \( \text{regionCount} \) valid \( \text{VkBufferImageCopy2} \) structures

- **VUID-VkCopyImageToBufferInfo2-regionCount-arraylength**  
  \( \text{regionCount} \) must be greater than \( 0 \)

- **VUID-VkCopyImageToBufferInfo2-commonparent**  
  Both of \( \text{dstBuffer} \), and \( \text{srcImage} \) must have been created, allocated, or retrieved from the same \( \text{VkDevice} \)

For both \( \text{vkCmdCopyBufferToImage2} \) and \( \text{vkCmdCopyImageToBuffer2} \), each element of \( pRegions \) is a structure defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkBufferImageCopy2 {
    VkStructureType sType;
    const void* pNext;
    VkDeviceSize bufferOffset;
    uint32_t bufferRowLength;
    uint32_t bufferImageHeight;
    VkImageSubresourceLayers imageSubresource;
    VkOffset3D imageOffset;
    VkExtent3D imageExtent;
} VkBufferImageCopy2;
```

- \( sType \) is a \( \text{VkStructureType} \) value identifying this structure.
• `pNext` is `NULL` or a pointer to a structure extending this structure.
• `bufferOffset` is the offset in bytes from the start of the buffer object where the image data is copied from or to.
• `bufferRowLength` and `bufferImageHeight` specify in texels a subregion of a larger two- or three-dimensional image in buffer memory, and control the addressing calculations. If either of these values is zero, that aspect of the buffer memory is considered to be tightly packed according to the `imageExtent`.
• `imageSubresource` is a `VkImageSubresourceLayers` used to specify the specific image subresources of the image used for the source or destination image data.
• `imageOffset` selects the initial `x`, `y`, `z` offsets in texels of the sub-region of the source or destination image data.
• `imageExtent` is the size in texels of the image to copy in `width`, `height` and `depth`.

This structure is functionally identical to `VkBufferImageCopy`, but adds `sType` and `pNext` parameters, allowing it to be more easily extended.

---

**Valid Usage**

- VUID-VkBufferImageCopy2-bufferRowLength-09101
  `bufferRowLength` must be 0, or greater than or equal to the `width` member of `imageExtent`

- VUID-VkBufferImageCopy2-bufferImageHeight-09102
  `bufferImageHeight` must be 0, or greater than or equal to the `height` member of `imageExtent`

- VUID-VkBufferImageCopy2-aspectMask-09103
  The `aspectMask` member of `imageSubresource` must only have a single bit set

- VUID-VkBufferImageCopy2-imageExtent-06659
  `imageExtent.width` must not be 0

- VUID-VkBufferImageCopy2-imageExtent-06660
  `imageExtent.height` must not be 0

- VUID-VkBufferImageCopy2-imageExtent-06661
  `imageExtent.depth` must not be 0

---

**Valid Usage (Implicit)**

- VUID-VkBufferImageCopy2-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_BUFFER_IMAGE_COPY_2`

- VUID-VkBufferImageCopy2-pNext-pNext
  `pNext` must be `NULL`

- VUID-VkBufferImageCopy2-imageSubresource-parameter
  `imageSubresource` must be a valid `VkImageSubresourceLayers` structure
19.4. Image Copies with Scaling

To copy regions of a source image into a destination image, potentially performing format conversion, arbitrary scaling, and filtering, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdBlitImage(
    VkCommandBuffer commandBuffer,
    VkImage srcImage,
    VkImageLayout srcImageLayout,
    VkImage dstImage,
    VkImageLayout dstImageLayout,
    uint32_t regionCount,
    const VkImageBlit* pRegions,
    VkFilter filter);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcImage` is the source image.
- `srcImageLayout` is the layout of the source image subresources for the blit.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the blit.
- `regionCount` is the number of regions to blit.
- `pRegions` is a pointer to an array of `VkImageBlit` structures specifying the regions to blit.
- `filter` is a `VkFilter` specifying the filter to apply if the blits require scaling.

`vkCmdBlitImage` must not be used for multisampled source or destination images. Use `vkCmdResolveImage` for this purpose.

As the sizes of the source and destination extents can differ in any dimension, texels in the source extent are scaled and filtered to the destination extent. Scaling occurs via the following operations:

- For each destination texel, the integer coordinate of that texel is converted to an unnormalized texture coordinate, using the effective inverse of the equations described in [unnormalized to integer conversion]:

  \[
  u_{\text{base}} = i + \frac{1}{2} \\
  v_{\text{base}} = j + \frac{1}{2} \\
  w_{\text{base}} = k + \frac{1}{2}
  \]

- These base coordinates are then offset by the first destination offset:
\[ u_{\text{offset}} = u_{\text{base}} - x_{\text{dst0}} \]

\[ v_{\text{offset}} = v_{\text{base}} - y_{\text{dst0}} \]

\[ w_{\text{offset}} = w_{\text{base}} - z_{\text{dst0}} \]

\[ a_{\text{offset}} = a - \text{baseArrayCount}_{\text{dst}} \]

- The scale is determined from the source and destination regions, and applied to the offset coordinates:

\[ \text{scale}_u = \frac{(x_{\text{src1}} - x_{\text{src0}})}{(x_{\text{dst1}} - x_{\text{dst0}})} \]

\[ \text{scale}_v = \frac{(y_{\text{src1}} - y_{\text{src0}})}{(y_{\text{dst1}} - y_{\text{dst0}})} \]

\[ \text{scale}_w = \frac{(z_{\text{src1}} - z_{\text{src0}})}{(z_{\text{dst1}} - z_{\text{dst0}})} \]

\[ u_{\text{scaled}} = u_{\text{offset}} \times \text{scale}_u \]

\[ v_{\text{scaled}} = v_{\text{offset}} \times \text{scale}_v \]

\[ w_{\text{scaled}} = w_{\text{offset}} \times \text{scale}_w \]

- Finally the source offset is added to the scaled coordinates, to determine the final unnormalized coordinates used to sample from \text{srcImage}:

\[ u = u_{\text{scaled}} + x_{\text{src0}} \]

\[ v = v_{\text{scaled}} + y_{\text{src0}} \]

\[ w = w_{\text{scaled}} + z_{\text{src0}} \]

\[ q = \text{mipLevel} \]
These coordinates are used to sample from the source image, as described in Image Operations chapter, with the filter mode equal to that of filter, a mipmap mode of VK_SAMPLER_MIPMAP_MODE_NEAREST and an address mode of VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE. Implementations must clamp at the edge of the source image, and may additionally clamp to the edge of the source region.

Note

Due to allowable rounding errors in the generation of the source texture coordinates, it is not always possible to guarantee exactly which source texels will be sampled for a given blit. As rounding errors are implementation-dependent, the exact results of a blitting operation are also implementation-dependent.

Blits are done layer by layer starting with the baseArrayLayer member of srcSubresource for the source and dstSubresource for the destination. layerCount layers are blitted to the destination image.

When blitting 3D textures, slices in the destination region bounded by dstOffsets[0].z and dstOffsets[1].z are sampled from slices in the source region bounded by srcOffsets[0].z and srcOffsets[1].z. If the filter parameter is VK_FILTER_LINEAR then the value sampled from the source image is taken by doing linear filtering using the interpolated \( z \) coordinate represented by \( w \) in the previous equations. If the filter parameter is VK_FILTER_NEAREST then the value sampled from the source image is taken from the single nearest slice, with an implementation-dependent arithmetic rounding mode.

The following filtering and conversion rules apply:

- Integer formats can only be converted to other integer formats with the same signedness.
- No format conversion is supported between depth/stencil images. The formats must match.
- Format conversions on unorm, snorm, scaled and packed float formats of the copied aspect of the image are performed by first converting the pixels to float values.
- For sRGB source formats, nonlinear RGB values are converted to linear representation prior to filtering.
- After filtering, the float values are first clamped and then cast to the destination image format. In case of sRGB destination format, linear RGB values are converted to nonlinear representation before writing the pixel to the image.

Signed and unsigned integers are converted by first clamping to the representable range of the destination format, then casting the value.

Valid Usage

- VUID-vkCmdBlitImage-commandBuffer-01834
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, srcImage must not be a protected image
VUID-vkCmdBlitImage-commandBuffer-01835
If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image.

VUID-vkCmdBlitImage-commandBuffer-01836
If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image.

VUID-vkCmdBlitImage-pRegions-00215
The source region specified by each element of `pRegions` must be a region that is contained within `srcImage`.

VUID-vkCmdBlitImage-pRegions-00216
The destination region specified by each element of `pRegions` must be a region that is contained within `dstImage`.

VUID-vkCmdBlitImage-pRegions-00217
The union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory with any texel that may be sampled during the blit operation.

VUID-vkCmdBlitImage-srcImage-01999
The format features of `srcImage` must contain `VK_FORMAT_FEATURE_BLIT_SRC_BIT`.

VUID-vkCmdBlitImage-srcImage-06421
`srcImage` must not use a format that requires a sampler Y'CbCr conversion.

VUID-vkCmdBlitImage-srcImage-00219
`srcImage` must have been created with `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` usage flag.

VUID-vkCmdBlitImage-srcImage-00220
If `srcImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

VUID-vkCmdBlitImage-srcImageLayout-00221
`srcImageLayout` must specify the layout of the image subresources of `srcImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.

VUID-vkCmdBlitImage-srcImageLayout-00222
`srcImageLayout` must be `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.

VUID-vkCmdBlitImage-dstImage-02000
The format features of `dstImage` must contain `VK_FORMAT_FEATURE_BLIT_DST_BIT`.

VUID-vkCmdBlitImage-dstImage-06422
`dstImage` must not use a format that requires a sampler Y'CbCr conversion.

VUID-vkCmdBlitImage-dstImage-00224
`dstImage` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag.

VUID-vkCmdBlitImage-dstImage-00225
If `dstImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

VUID-vkCmdBlitImage-dstImageLayout-00226
`dstImageLayout` must specify the layout of the image subresources of `dstImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.
• VUID-vkCmdBlitImage-dstImageLayout-00227
dstImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL

• VUID-vkCmdBlitImage-srcImage-00229
If either of srcImage or dstImage was created with a signed integer VkFormat, the other must also have been created with a signed integer VkFormat

• VUID-vkCmdBlitImage-srcImage-00230
If either of srcImage or dstImage was created with an unsigned integer VkFormat, the other must also have been created with an unsigned integer VkFormat

• VUID-vkCmdBlitImage-srcImage-00231
If either of srcImage or dstImage was created with a depth/stencil format, the other must have exactly the same format

• VUID-vkCmdBlitImage-srcImage-00232
If srcImage was created with a depth/stencil format, filter must be VK_FILTER_NEAREST

• VUID-vkCmdBlitImage-srcImage-00240
If either srcImage or dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcSubresource.baseArrayLayer and dstSubresource.baseArrayLayer must each be 0, and srcSubresource.layerCount and dstSubresource.layerCount must each be 1

• VUID-vkCmdBlitImage-aspectMask-00241
For each element of pRegions, srcSubresource.aspectMask must specify aspects present in srcImage

• VUID-vkCmdBlitImage-aspectMask-00242
For each element of \( pRegions \), \( dstSubresource.aspectMask \) must specify aspects present in \( dstImage \)

- **VUID-vkCmdBlitImage-srcOffset-00243**
  For each element of \( pRegions, srcOffsets[0].x \) and \( srcOffsets[1].x \) must both be greater than or equal to \( 0 \) and less than or equal to the width of the specified \( srcSubresource \) of \( srcImage \)

- **VUID-vkCmdBlitImage-srcOffset-00244**
  For each element of \( pRegions, srcOffsets[0].y \) and \( srcOffsets[1].y \) must both be greater than or equal to \( 0 \) and less than or equal to the height of the specified \( srcSubresource \) of \( srcImage \)

- **VUID-vkCmdBlitImage-srcImage-00245**
  If \( srcImage \) is of type \( VK_IMAGE_TYPE_1D \), then for each element of \( pRegions, srcOffsets[0].y \) must be \( 0 \) and \( srcOffsets[1].y \) must be \( 1 \)

- **VUID-vkCmdBlitImage-srcOffset-00246**
  For each element of \( pRegions, srcOffsets[0].z \) and \( srcOffsets[1].z \) must both be greater than or equal to \( 0 \) and less than or equal to the depth of the specified \( srcSubresource \) of \( srcImage \)

- **VUID-vkCmdBlitImage-srcImage-00247**
  If \( srcImage \) is of type \( VK_IMAGE_TYPE_1D \) or \( VK_IMAGE_TYPE_2D \), then for each element of \( pRegions, srcOffsets[0].z \) must be \( 0 \) and \( srcOffsets[1].z \) must be \( 1 \)

- **VUID-vkCmdBlitImage-dstOffset-00248**
  For each element of \( pRegions, dstOffsets[0].x \) and \( dstOffsets[1].x \) must both be greater than or equal to \( 0 \) and less than or equal to the width of the specified \( dstSubresource \) of \( dstImage \)

- **VUID-vkCmdBlitImage-dstOffset-00249**
  For each element of \( pRegions, dstOffsets[0].y \) and \( dstOffsets[1].y \) must both be greater than or equal to \( 0 \) and less than or equal to the height of the specified \( dstSubresource \) of \( dstImage \)

- **VUID-vkCmdBlitImage-dstImage-00250**
  If \( dstImage \) is of type \( VK_IMAGE_TYPE_1D \), then for each element of \( pRegions, dstOffsets[0].y \) must be \( 0 \) and \( dstOffsets[1].y \) must be \( 1 \)

- **VUID-vkCmdBlitImage-dstOffset-00251**
  For each element of \( pRegions, dstOffsets[0].z \) and \( dstOffsets[1].z \) must both be greater than or equal to \( 0 \) and less than or equal to the depth of the specified \( dstSubresource \) of \( dstImage \)

- **VUID-vkCmdBlitImage-dstImage-00252**
  If \( dstImage \) is of type \( VK_IMAGE_TYPE_1D \) or \( VK_IMAGE_TYPE_2D \), then for each element of \( pRegions, dstOffsets[0].z \) must be \( 0 \) and \( dstOffsets[1].z \) must be \( 1 \)

---

**Valid Usage (Implicit)**

- **VUID-vkCmdBlitImage-commandBuffer-parameter**
  \( commandBuffer \) must be a valid \( VkCommandBuffer \) handle
• VUID-vkCmdBlitImage-srcImage-parameter
  srcImage must be a valid VkImage handle
• VUID-vkCmdBlitImage-srcImageLayout-parameter
  srcImageLayout must be a valid VkImageLayout value
• VUID-vkCmdBlitImage-dstImage-parameter
  dstImage must be a valid VkImage handle
• VUID-vkCmdBlitImage-dstImageLayout-parameter
  dstImageLayout must be a valid VkImageLayout value
• VUID-vkCmdBlitImage-pRegions-parameter
  pRegions must be a valid pointer to an array of regionCount valid VkImageBlit structures
• VUID-vkCmdBlitImage-filter-parameter
  filter must be a valid VkFilter value
• VUID-vkCmdBlitImage-commandBuffer-recording
  commandBuffer must be in the recording state
• VUID-vkCmdBlitImage-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations
• VUID-vkCmdBlitImage-renderpass
  This command must only be called outside of a render pass instance
• VUID-vkCmdBlitImage-regionCount-arraylength
  regionCount must be greater than 0
• VUID-vkCmdBlitImage-commonparent
  Each of commandBuffer, dstImage, and srcImage must have been created, allocated, or retrieved from the same VkDevice

**Host Synchronization**

• Host access to commandBuffer must be externally synchronized
• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

**Command Properties**

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The VkImageBlit structure is defined as:
typedef struct VkImageBlit {
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffsets[2];
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffsets[2];
} VkImageBlit;

• srcSubresource is the subresource to blit from.
• srcOffsets is a pointer to an array of two VkOffset3D structures specifying the bounds of the source region within srcSubresource.
• dstSubresource is the subresource to blit into.
• dstOffsets is a pointer to an array of two VkOffset3D structures specifying the bounds of the destination region within dstSubresource.

For each element of the pRegions array, a blit operation is performed for the specified source and destination regions.

Valid Usage

• VUID-VkImageBlit-aspectMask-00238
  The aspectMask member of srcSubresource and dstSubresource must match

• VUID-VkImageBlit-layerCount-00239
  The layerCount member of srcSubresource and dstSubresource must match

Valid Usage (Implicit)

• VUID-VkImageBlit-srcSubresource-parameter
  srcSubresource must be a valid VkImageSubresourceLayers structure

• VUID-VkImageBlit-dstSubresource-parameter
  dstSubresource must be a valid VkImageSubresourceLayers structure

A more extensible version of the blit image command is defined below.

To copy regions of a source image into a destination image, potentially performing format conversion, arbitrary scaling, and filtering, call:

// Provided by VK_VERSION_1_3
void vkCmdBlitImage2(
    VkCommandBuffer commandBuffer,
    const VkBlitImageInfo2* pBlitImageInfo);

• commandBuffer is the command buffer into which the command will be recorded.
• `pBlitImageInfo` is a pointer to a `VkBlitImageInfo2` structure describing the blit parameters.

This command is functionally identical to `vkCmdBlitImage`, but includes extensible sub-structures that include `sType` and `pNext` parameters, allowing them to be more easily extended.

### Valid Usage

- **VUID-vkCmdBlitImage2-commandBuffer-01834**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcImage` must not be a protected image

- **VUID-vkCmdBlitImage2-commandBuffer-01835**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image

- **VUID-vkCmdBlitImage2-commandBuffer-01836**
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image

### Valid Usage (Implicit)

- **VUID-vkCmdBlitImage2-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- **VUID-vkCmdBlitImage2-pBlitImageInfo-parameter**
  `pBlitImageInfo` must be a valid pointer to a valid `VkBlitImageInfo2` structure

- **VUID-vkCmdBlitImage2-commandBuffer-recording**
  `commandBuffer` must be in the recording state

- **VUID-vkCmdBlitImage2-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

- **VUID-vkCmdBlitImage2-renderpass**
  This command must only be called outside of a render pass instance

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
The `VkBlitImageInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkBlitImageInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkImage srcImage;
    VkImageLayout srcImageLayout;
    VkImage dstImage;
    VkImageLayout dstImageLayout;
    uint32_t regionCount;
    const VkImageBlit2* pRegions;
    VkFilter filter;
} VkBlitImageInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcImage` is the source image.
- `srcImageLayout` is the layout of the source image subresources for the blit.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the blit.
- `regionCount` is the number of regions to blit.
- `pRegions` is a pointer to an array of `VkImageBlit2` structures specifying the regions to blit.
- `filter` is a `VkFilter` specifying the filter to apply if the blits require scaling.

**Valid Usage**

- VUID-VkBlitImageInfo2-pRegions-00215
  The source region specified by each element of `pRegions` must be a region that is contained within `srcImage`
- VUID-VkBlitImageInfo2-pRegions-00216
  The destination region specified by each element of `pRegions` must be a region that is contained within `dstImage`
- VUID-VkBlitImageInfo2-pRegions-00217
The union of all destination regions, specified by the elements of \( p\text{Regions} \), **need** not overlap in memory with any texel that **may** be sampled during the blit operation

- VUID-VkBlitImageInfo2-srcImage-01999
  The **format features** of \( \text{srcImage} \) **need** contain \( \text{VK_FORMAT_FEATURE_BLIT_SRC_BIT} \)

- VUID-VkBlitImageInfo2-srcImage-06421
  \( \text{srcImage} \) **need** not use a **format** that requires a sampler \( \text{Y'C'_C_R'} \) **conversion**

- VUID-VkBlitImageInfo2-srcImage-00219
  \( \text{srcImage} \) **need** have been created with \( \text{VK_IMAGE_USAGE_TRANSFER_SRC_BIT} \) usage flag

- VUID-VkBlitImageInfo2-srcImage-00220
  If \( \text{srcImage} \) is non-sparse then it **need** be bound completely and contiguously to a single \( \text{VkDeviceMemory} \) object

- VUID-VkBlitImageInfo2-srcImageLayout-00221
  \( \text{srcImageLayout} \) **need** specify the layout of the image subresources of \( \text{srcImage} \) specified in \( p\text{Regions} \) at the time this command is executed on a \( \text{VkDevice} \)

- VUID-VkBlitImageInfo2-srcImageLayout-00222
  \( \text{srcImageLayout} \) **need** be \( \text{VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL} \) or \( \text{VK_IMAGE_LAYOUT_GENERAL} \)

- VUID-VkBlitImageInfo2-dstImage-02000
  The **format features** of \( \text{dstImage} \) **need** contain \( \text{VK_FORMAT_FEATURE_BLIT_DST_BIT} \)

- VUID-VkBlitImageInfo2-dstImage-06422
  \( \text{dstImage} \) **need** not use a **format** that requires a sampler \( \text{Y'C'_C_R'} \) **conversion**

- VUID-VkBlitImageInfo2-dstImage-00224
  \( \text{dstImage} \) **need** have been created with \( \text{VK_IMAGE_USAGE_TRANSFER_DST_BIT} \) usage flag

- VUID-VkBlitImageInfo2-dstImage-00225
  If \( \text{dstImage} \) is non-sparse then it **need** be bound completely and contiguously to a single \( \text{VkDeviceMemory} \) object

- VUID-VkBlitImageInfo2-dstImageLayout-00226
  \( \text{dstImageLayout} \) **need** specify the layout of the image subresources of \( \text{dstImage} \) specified in \( p\text{Regions} \) at the time this command is executed on a \( \text{VkDevice} \)

- VUID-VkBlitImageInfo2-dstImageLayout-00227
  \( \text{dstImageLayout} \) **need** be \( \text{VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL} \) or \( \text{VK_IMAGE_LAYOUT_GENERAL} \)

- VUID-VkBlitImageInfo2-srcImage-00229
  If either of \( \text{srcImage} \) or \( \text{dstImage} \) was created with a signed integer \( \text{VkFormat} \), the other **must** also have been created with a signed integer \( \text{VkFormat} \)

- VUID-VkBlitImageInfo2-srcImage-00230
  If either of \( \text{srcImage} \) or \( \text{dstImage} \) was created with an unsigned integer \( \text{VkFormat} \), the other **must** also have been created with an unsigned integer \( \text{VkFormat} \)

- VUID-VkBlitImageInfo2-srcImage-00231
  If either of \( \text{srcImage} \) or \( \text{dstImage} \) was created with a depth/stencil format, the other **must** have exactly the same format

- VUID-VkBlitImageInfo2-srcImage-00232
  If \( \text{srcImage} \) was created with a depth/stencil format, **filter** **must** be \( \text{VK_FILTER_NEAREST} \)
• VUID-VkBlitImageInfo2-srcImage-00233
  srcImage must have been created with a samples value of VK_SAMPLE_COUNT_1_BIT

• VUID-VkBlitImageInfo2-dstImage-00234
dstImage must have been created with a samples value of VK_SAMPLE_COUNT_1_BIT

• VUID-VkBlitImageInfo2-filter-02001
  If filter is VK_FILTER_LINEAR, then the format features of srcImage must contain
  VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

• VUID-VkBlitImageInfo2-srcSubresource-01705
  The srcSubresource.mipLevel member of each element of pRegions must be less than the
  mipLevels specified in VkImageCreateInfo when srcImage was created

• VUID-VkBlitImageInfo2-dstSubresource-01706
  The dstSubresource.mipLevel member of each element of pRegions must be less than the
  mipLevels specified in VkImageCreateInfo when dstImage was created

• VUID-VkBlitImageInfo2-srcSubresource-01707
  The srcSubresource.baseArrayLayer + srcSubresource.layerCount of each element of
  pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo
  when srcImage was created

• VUID-VkBlitImageInfo2-dstSubresource-01708
  The dstSubresource.baseArrayLayer + dstSubresource.layerCount of each element of
  pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo
  when dstImage was created

• VUID-VkBlitImageInfo2-srcImage-00240
  If either srcImage or dstImage is of type VK_IMAGE_TYPE_3D, then for each element of
  pRegions, srcSubresource.baseArrayLayer and dstSubresource.baseArrayLayer must each be
  0, and srcSubresource.layerCount and dstSubresource.layerCount must each be 1

• VUID-VkBlitImageInfo2-aspectMask-00241
  For each element of pRegions, srcSubresource.aspectMask must specify aspects present in
  srcImage

• VUID-VkBlitImageInfo2-aspectMask-00242
  For each element of pRegions, dstSubresource.aspectMask must specify aspects present in
dstImage

• VUID-VkBlitImageInfo2-srcOffset-00243
  For each element of pRegions, srcOffsets[0].x and srcOffsets[1].x must both be greater
  than or equal to 0 and less than or equal to the width of the specified srcSubresource of
  srcImage

• VUID-VkBlitImageInfo2-srcOffset-00244
  For each element of pRegions, srcOffsets[0].y and srcOffsets[1].y must both be greater
  than or equal to 0 and less than or equal to the height of the specified srcSubresource of
  srcImage

• VUID-VkBlitImageInfo2-srcImage-00245
  If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, srcOffsets[0].y
  must be 0 and srcOffsets[1].y must be 1

• VUID-VkBlitImageInfo2-srcOffset-00246
For each element of \texttt{pRegions}, \texttt{srcOffsets[0].z} and \texttt{srcOffsets[1].z} \textbf{must} both be greater than or equal to 0 and less than or equal to the depth of the specified \texttt{srcSubresource} of \texttt{srcImage}

- **VUID-VkBlitImageInfo2-srcImage-00247**
  If \texttt{srcImage} is of type \texttt{VK_IMAGE_TYPE_1D} or \texttt{VK_IMAGE_TYPE_2D}, then for each element of \texttt{pRegions}, \texttt{srcOffsets[0].z} \textbf{must} be 0 and \texttt{srcOffsets[1].z} \textbf{must} be 1

- **VUID-VkBlitImageInfo2-dstOffset-00248**
  For each element of \texttt{pRegions}, \texttt{dstOffsets[0].x} and \texttt{dstOffsets[1].x} \textbf{must} both be greater than or equal to 0 and less than or equal to the width of the specified \texttt{dstSubresource} of \texttt{dstImage}

- **VUID-VkBlitImageInfo2-dstOffset-00249**
  For each element of \texttt{pRegions}, \texttt{dstOffsets[0].y} and \texttt{dstOffsets[1].y} \textbf{must} both be greater than or equal to 0 and less than or equal to the height of the specified \texttt{dstSubresource} of \texttt{dstImage}

- **VUID-VkBlitImageInfo2-dstOffset-00250**
  If \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_1D}, then for each element of \texttt{pRegions}, \texttt{dstOffsets[0].y} \textbf{must} be 0 and \texttt{dstOffsets[1].y} \textbf{must} be 1

- **VUID-VkBlitImageInfo2-dstOffset-00251**
  For each element of \texttt{pRegions}, \texttt{dstOffsets[0].z} and \texttt{dstOffsets[1].z} \textbf{must} both be greater than or equal to 0 and less than or equal to the depth of the specified \texttt{dstSubresource} of \texttt{dstImage}

- **VUID-VkBlitImageInfo2-dstOffset-00252**
  If \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_1D} or \texttt{VK_IMAGE_TYPE_2D}, then for each element of \texttt{pRegions}, \texttt{dstOffsets[0].z} \textbf{must} be 0 and \texttt{dstOffsets[1].z} \textbf{must} be 1

---

**Valid Usage (Implicit)**

- **VUID-VkBlitImageInfo2-sType-sType**
  \texttt{sType} \textbf{must} be \texttt{VK_STRUCTURE_TYPE_BLIT_IMAGE_INFO_2}

- **VUID-VkBlitImageInfo2-pNext-pNext**
  \texttt{pNext} \textbf{must} be \texttt{NULL}

- **VUID-VkBlitImageInfo2-srcImage-parameter**
  \texttt{srcImage} \textbf{must} be a valid \texttt{VkImage} handle

- **VUID-VkBlitImageInfo2-srcImageLayout-parameter**
  \texttt{srcImageLayout} \textbf{must} be a valid \texttt{VkImageLayout} value

- **VUID-VkBlitImageInfo2-dstImage-parameter**
  \texttt{dstImage} \textbf{must} be a valid \texttt{VkImage} handle

- **VUID-VkBlitImageInfo2-dstImageLayout-parameter**
  \texttt{dstImageLayout} \textbf{must} be a valid \texttt{VkImageLayout} value

- **VUID-VkBlitImageInfo2-pRegions-parameter**
  \texttt{pRegions} \textbf{must} be a valid pointer to an array of \texttt{regionCount} valid \texttt{VkImageBlit2} structures

- **VUID-VkBlitImageInfo2-filter-parameter**
filter must be a valid VkFilter value

- VUID-VkBlitImageInfo2-regionCount-arraylength
  regionCount must be greater than 0
- VUID-VkBlitImageInfo2-commonparent
  Both of dstImage, and srcImage must have been created, allocated, or retrieved from the same VkDevice

The VkImageBlit2 structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkImageBlit2 {
    VkStructureType sType;
    const void* pNext;
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffsets[2];
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffsets[2];
} VkImageBlit2;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- srcSubresource is the subresource to blit from.
- srcOffsets is a pointer to an array of two VkOffset3D structures specifying the bounds of the source region within srcSubresource.
- dstSubresource is the subresource to blit into.
- dstOffsets is a pointer to an array of two VkOffset3D structures specifying the bounds of the destination region within dstSubresource.

For each element of the pRegions array, a blit operation is performed for the specified source and destination regions.

**Valid Usage**

- VUID-VkImageBlit2-aspectMask-00238
  The aspectMask member of srcSubresource and dstSubresource must match
- VUID-VkImageBlit2-layerCount-00239
  The layerCount member of srcSubresource and dstSubresource must match

**Valid Usage (Implicit)**

- VUID-VkImageBlit2-sType-sType
  sType must be VK_STRUCTURE_TYPE_IMAGE_BLIT_2
19.5. Resolving Multisample Images

To resolve a multisample color image to a non-multisample color image, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdResolveImage(
    VkCommandBuffer commandBuffer,
    VkImage srcImage,
    VkImageLayout srcImageLayout,
    VkImage dstImage,
    VkImageLayout dstImageLayout,
    uint32_t regionCount,
    const VkImageResolve* pRegions);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **srcImage** is the source image.
- **srcImageLayout** is the layout of the source image subresources for the resolve.
- **dstImage** is the destination image.
- **dstImageLayout** is the layout of the destination image subresources for the resolve.
- **regionCount** is the number of regions to resolve.
- **pRegions** is a pointer to an array of VkImageResolve structures specifying the regions to resolve.

During the resolve the samples corresponding to each pixel location in the source are converted to a single sample before being written to the destination. If the source formats are floating-point or normalized types, the sample values for each pixel are resolved in an implementation-dependent manner. If the source formats are integer types, a single sample’s value is selected for each pixel.

**srcOffset** and **dstOffset** select the initial x, y, and z offsets in texels of the sub-regions of the source and destination image data. **extent** is the size in texels of the source image to resolve in width, height and depth. Each element of **pRegions** must be a region that is contained within its corresponding image.

Resolves are done layer by layer starting with **baseArrayLayer** member of **srcSubresource** for the source and **dstSubresource** for the destination. **layerCount** layers are resolved to the destination image.
Valid Usage

- VUID-vkCmdResolveImage-commandBuffer-01837
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `srcImage` must not be a protected image.

- VUID-vkCmdResolveImage-commandBuffer-01838
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, `dstImage` must not be a protected image.

- VUID-vkCmdResolveImage-commandBuffer-01839
  If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, `dstImage` must not be an unprotected image.

- VUID-vkCmdResolveImage-pRegions-00255
  The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory.

- VUID-vkCmdResolveImage-srcImage-00256
  If `srcImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

- VUID-vkCmdResolveImage-srcImage-00257
  `srcImage` must have a sample count equal to any valid sample count value other than `VK_SAMPLE_COUNT_1_BIT`.

- VUID-vkCmdResolveImage-dstImage-00258
  If `dstImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

- VUID-vkCmdResolveImage-dstImage-00259
  `dstImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`.

- VUID-vkCmdResolveImage-srcImageLayout-00260
  The `srcImageLayout` must specify the layout of the image subresources of `srcImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.

- VUID-vkCmdResolveImage-dstImageLayout-00261
  The `dstImageLayout` must specify the layout of the image subresources of `dstImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.

- VUID-vkCmdResolveImage-dstImage-02003
  The format features of `dstImage` must contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.

- VUID-vkCmdResolveImage-srcImage-01386
  `srcImage` and `dstImage` must have been created with the same image format.

- VUID-vkCmdResolveImage-srcSubresource-01709
  The `srcSubresource.mipLevel` member of each element of `pRegions` must be less than the
• VUID-vkCmdResolveImage-dstSubresource-01710
  The dstSubresource.mipLevel member of each element of pRegions must be less than the mipLevels specified in VkImageCreateInfo when dstImage was created

• VUID-vkCmdResolveImage-srcSubresource-01711
  The srcSubresource.baseArrayLayer + srcSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when srcImage was created

• VUID-vkCmdResolveImage-dstSubresource-01712
  The dstSubresource.baseArrayLayer + dstSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when dstImage was created

• VUID-vkCmdResolveImage-srcImage-04446
  If dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcSubresource.layerCount must be 1

• VUID-vkCmdResolveImage-srcImage-04447
  If dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, dstSubresource.baseArrayLayer must be 0 and dstSubresource.layerCount must be 1

• VUID-vkCmdResolveImage-srcOffset-00269
  For each element of pRegions, srcOffset.x and (extent.width + srcOffset.x) must both be greater than or equal to 0 and less than or equal to the width of the specified srcSubresource of srcImage

• VUID-vkCmdResolveImage-srcOffset-00270
  For each element of pRegions, srcOffset.y and (extent.height + srcOffset.y) must both be greater than or equal to 0 and less than or equal to the height of the specified srcSubresource of srcImage

• VUID-vkCmdResolveImage-srcImage-00271
  If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, srcOffset.y must be 0 and extent.height must be 1

• VUID-vkCmdResolveImage-srcOffset-00272
  For each element of pRegions, srcOffset.z and (extent.depth + srcOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified srcSubresource of srcImage

• VUID-vkCmdResolveImage-srcImage-00273
  If srcImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, srcOffset.z must be 0 and extent.depth must be 1

• VUID-vkCmdResolveImage-dstOffset-00274
  For each element of pRegions, dstOffset.x and (extent.width + dstOffset.x) must both be greater than or equal to 0 and less than or equal to the width of the specified dstSubresource of dstImage

• VUID-vkCmdResolveImage-dstOffset-00275
  For each element of pRegions, dstOffset.y and (extent.height + dstOffset.y) must both be greater than or equal to 0 and less than or equal to the height of the specified
**dstSubresource of dstImage**

- VUID-vkCmdResolveImage-dstImage-00276
  
  If dstImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, dstOffset.y must be 0 and extent.height must be 1

- VUID-vkCmdResolveImage-dstOffset-00277
  
  For each element of pRegions, dstOffset.z and (extent.depth + dstOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified dstSubresource of dstImage

- VUID-vkCmdResolveImage-dstImage-00278
  
  If dstImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, dstOffset.z must be 0 and extent.depth must be 1

- VUID-vkCmdResolveImage-srcImage-06762
  
  srcImage must have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag

- VUID-vkCmdResolveImage-srcImage-06763
  
  The format features of srcImage must contain VK_FORMAT_FEATURE_TRANSFER_SRC_BIT

- VUID-vkCmdResolveImage-dstImage-06764
  
  dstImage must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag

- VUID-vkCmdResolveImage-dstImage-06765
  
  The format features of dstImage must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT

---

**Valid Usage (Implicit)**

- VUID-vkCmdResolveImage-commandBuffer-parameter
  
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdResolveImage-srcImage-parameter
  
  srcImage must be a valid VkImage handle

- VUID-vkCmdResolveImage-srcImageLayout-parameter
  
  srcImageLayout must be a valid VkImageLayout value

- VUID-vkCmdResolveImage-dstImage-parameter
  
  dstImage must be a valid VkImage handle

- VUID-vkCmdResolveImage-dstImageLayout-parameter
  
  dstImageLayout must be a valid VkImageLayout value

- VUID-vkCmdResolveImage-pRegions-parameter
  
  pRegions must be a valid pointer to an array of regionCount valid VkImageResolve structures

- VUID-vkCmdResolveImage-commandBuffer-recording
  
  commandBuffer must be in the recording state

- VUID-vkCmdResolveImage-commandBuffer-cmdpool
  
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

- VUID-vkCmdResolveImage-renderpass
This command **must** only be called outside of a render pass instance

- **VUID-vkCmdResolveImage-regionCount-arraylength**
  - `regionCount` **must** be greater than 0
- **VUID-vkCmdResolveImage-commonparent**
  - Each of `commandBuffer`, `dstImage`, and `srcImage` **must** have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

**Command Properties**

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<td>Secondary</td>
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</tbody>
</table>

The `VkImageResolve` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkImageResolve {
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffset;
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffset;
    VkExtent3D extent;
} VkImageResolve;
```

- `srcSubresource` and `dstSubresource` are `VkImageSubresourceLayers` structures specifying the image subresources of the images used for the source and destination image data, respectively. Resolve of depth/stencil images is not supported.
- `srcOffset` and `dstOffset` select the initial x, y, and z offsets in texels of the sub-regions of the source and destination image data.
- `extent` is the size in texels of the source image to resolve in width, height and depth.

**Valid Usage**

- **VUID-VkImageResolve-aspectMask-00266**
The aspectMask member of srcSubresource and dstSubresource must only contain VK_IMAGE_ASPECT_COLOR_BIT

- VUID-VkImageResolve-layerCount-00267
  The layerCount member of srcSubresource and dstSubresource must match

Valid Usage (Implicit)

- VUID-VkImageResolve-srcSubresource-parameter
  srcSubresource must be a valid VkImageSubresourceLayers structure

- VUID-VkImageResolve-dstSubresource-parameter
  dstSubresource must be a valid VkImageSubresourceLayers structure

A more extensible version of the resolve image command is defined below.

To resolve a multisample image to a non-multisample image, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdResolveImage2(
    VkCommandBuffer commandBuffer,
    const VkResolveImageInfo2* pResolveImageInfo);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pResolveImageInfo` is a pointer to a VkResolveImageInfo2 structure describing the resolve parameters.

This command is functionally identical to vkCmdResolveImage, but includes extensible sub-structures that include sType and pNext parameters, allowing them to be more easily extended.

Valid Usage

- VUID-vkCmdResolveImage2-commandBuffer-01837
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, srcImage must not be a protected image

- VUID-vkCmdResolveImage2-commandBuffer-01838
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, dstImage must not be a protected image

- VUID-vkCmdResolveImage2-commandBuffer-01839
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, dstImage must not be an unprotected image

Valid Usage (Implicit)
• VUID-vkCmdResolveImage2-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

• VUID-vkCmdResolveImage2-pResolveImageInfo-parameter
  pResolveImageInfo must be a valid pointer to a valid VkResolveImageInfo2 structure

• VUID-vkCmdResolveImage2-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdResolveImage2-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

• VUID-vkCmdResolveImage2-renderpass
  This command must only be called outside of a render pass instance

---

**Host Synchronization**

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

---

**Command Properties**

<table>
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<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkResolveImageInfo2 structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkResolveImageInfo2 {
    VkStructureType   sType;
    const void*       pNext;
    VkImage           srcImage;
    VkImageLayout     srcImageLayout;
    VkImage           dstImage;
    VkImageLayout     dstImageLayout;
    uint32_t          regionCount;
    const VkImageResolve2* pRegions;
} VkResolveImageInfo2;
```

• sType is a VkStructureType value identifying this structure.

• pNext is NULL or a pointer to a structure extending this structure.
• **srcImage** is the source image.
• **srcImageLayout** is the layout of the source image subresources for the resolve.
• **dstImage** is the destination image.
• **dstImageLayout** is the layout of the destination image subresources for the resolve.
• **regionCount** is the number of regions to resolve.
• **pRegions** is a pointer to an array of **VkImageResolve2** structures specifying the regions to resolve.

### Valid Usage

- **VUID-VkResolveImageInfo2-pRegions-00255**
  The union of all source regions, and the union of all destination regions, specified by the elements of **pRegions**, **must** not overlap in memory

- **VUID-VkResolveImageInfo2-srcImage-00256**
  If **srcImage** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object

- **VUID-VkResolveImageInfo2-srcImage-00257**
  **srcImage** **must** have a sample count equal to any valid sample count value other than **VK_SAMPLE_COUNT_1_BIT**

- **VUID-VkResolveImageInfo2-dstImage-00258**
  If **dstImage** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object

- **VUID-VkResolveImageInfo2-dstImage-00259**
  **dstImage** **must** have a sample count equal to **VK_SAMPLE_COUNT_1_BIT**

- **VUID-VkResolveImageInfo2-srcImageLayout-00260**
  **srcImageLayout** **must** specify the layout of the image subresources of **srcImage** specified in **pRegions** at the time this command is executed on a **VkDevice**

- **VUID-VkResolveImageInfo2-srcImageLayout-00261**
  **srcImageLayout** **must** be **VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL** or **VK_IMAGE_LAYOUT_GENERAL**

- **VUID-VkResolveImageInfo2-dstImageLayout-00262**
  **dstImageLayout** **must** specify the layout of the image subresources of **dstImage** specified in **pRegions** at the time this command is executed on a **VkDevice**

- **VUID-VkResolveImageInfo2-dstImageLayout-00263**
  **dstImageLayout** **must** be **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL** or **VK_IMAGE_LAYOUT_GENERAL**

- **VUID-VkResolveImageInfo2-dstImage-02003**
  The **format features** of **dstImage** **must** contain **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT**

- **VUID-VkResolveImageInfo2-srcImage-01386**
  **srcImage** and **dstImage** **must** have been created with the same image format

- **VUID-VkResolveImageInfo2-srcSubresource-01709**
  The **srcSubresource.mipLevel** member of each element of **pRegions** **must** be less than the **mipLevels** specified in **VkImageCreateInfo** when **srcImage** was created
• VUID-VkResolveImageInfo2-dstSubresource-01710
The dstSubresource.mipLevel member of each element of pRegions must be less than the mipLevels specified in VkImageCreateInfo when dstImage was created.

• VUID-VkResolveImageInfo2-srcSubresource-01711
The srcSubresource.baseArrayLayer + srcSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when srcImage was created.

• VUID-VkResolveImageInfo2-dstSubresource-01712
The dstSubresource.baseArrayLayer + dstSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when dstImage was created.

• VUID-VkResolveImageInfo2-srcImage-04446
If dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, srcSubresource.layerCount must be 1.

• VUID-VkResolveImageInfo2-srcImage-04447
If dstImage is of type VK_IMAGE_TYPE_3D, then for each element of pRegions, dstSubresource.baseArrayLayer must be 0 and dstSubresource.layerCount must be 1.

• VUID-VkResolveImageInfo2-srcOffset-00269
For each element of pRegions, srcOffset.x and (extent.width + srcOffset.x) must both be greater than or equal to 0 and less than or equal to the width of the specified srcSubresource of srcImage.

• VUID-VkResolveImageInfo2-srcOffset-00270
For each element of pRegions, srcOffset.y and (extent.height + srcOffset.y) must both be greater than or equal to 0 and less than or equal to the height of the specified srcSubresource of srcImage.

• VUID-VkResolveImageInfo2-srcImage-00271
If srcImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, srcOffset.y must be 0 and extent.height must be 1.

• VUID-VkResolveImageInfo2-srcOffset-00272
For each element of pRegions, srcOffset.z and (extent.depth + srcOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified srcSubresource of srcImage.

• VUID-VkResolveImageInfo2-srcImage-00273
If srcImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, srcOffset.z must be 0 and extent.depth must be 1.

• VUID-VkResolveImageInfo2-dstOffset-00274
For each element of pRegions, dstOffset.x and (extent.width + dstOffset.x) must both be greater than or equal to 0 and less than or equal to the width of the specified dstSubresource of dstImage.

• VUID-VkResolveImageInfo2-dstOffset-00275
For each element of pRegions, dstOffset.y and (extent.height + dstOffset.y) must both be greater than or equal to 0 and less than or equal to the height of the specified dstSubresource of dstImage.
• VUID-VkResolveImageInfo2-dstImage-00276
  If dstImage is of type VK_IMAGE_TYPE_1D, then for each element of pRegions, dstOffset.y must be 0 and extent.height must be 1

• VUID-VkResolveImageInfo2-dstOffset-00277
  For each element of pRegions, dstOffset.z and (extent.depth + dstOffset.z) must both be greater than or equal to 0 and less than or equal to the depth of the specified dstSubresource of dstImage

• VUID-VkResolveImageInfo2-dstImage-00278
  If dstImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then for each element of pRegions, dstOffset.z must be 0 and extent.depth must be 1

• VUID-VkResolveImageInfo2-srcImage-06762
  srcImage must have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag

• VUID-VkResolveImageInfo2-srcImage-06763
  The format features of srcImage must contain VK_FORMAT_FEATURE_TRANSFER_SRC_BIT

• VUID-VkResolveImageInfo2-dstImage-06764
  dstImage must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag

• VUID-VkResolveImageInfo2-dstImage-06765
  The format features of dstImage must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT

Valid Usage (Implicit)

• VUID-VkResolveImageInfo2-sType-sType
  sType must be VK_STRUCTURE_TYPE_RESOLVE_IMAGE_INFO_2

• VUID-VkResolveImageInfo2-pNext-pNext
  pNext must be NULL

• VUID-VkResolveImageInfo2-srcImage-parameter
  srcImage must be a valid VkImage handle

• VUID-VkResolveImageInfo2-srcImageLayout-parameter
  srcImageLayout must be a valid VkImageLayout value

• VUID-VkResolveImageInfo2-dstImage-parameter
  dstImage must be a valid VkImage handle

• VUID-VkResolveImageInfo2-dstImageLayout-parameter
  dstImageLayout must be a valid VkImageLayout value

• VUID-VkResolveImageInfo2-pRegions-parameter
  pRegions must be a valid pointer to an array of regionCount valid VkImageResolve2 structures

• VUID-VkResolveImageInfo2-regionCount-arraylength
  regionCount must be greater than 0

• VUID-VkResolveImageInfo2-commonparent
  Both of dstImage, and srcImage must have been created, allocated, or retrieved from the same VkDevice
The `VkImageResolve2` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkImageResolve2 {
    VkStructureType sType;
    const void* pNext;
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffset;
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffset;
    VkExtent3D extent;
} VkImageResolve2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `srcSubresource` and `dstSubresource` are `VkImageSubresourceLayers` structures specifying the image subresources of the images used for the source and destination image data, respectively. Resolve of depth/stencil images is not supported.
- `srcOffset` and `dstOffset` select the initial x, y, and z offsets in texels of the sub-regions of the source and destination image data.
- `extent` is the size in texels of the source image to resolve in width, height and depth.

### Valid Usage

- **VUID-VkImageResolve2-aspectMask-00266**
The `aspectMask` member of `srcSubresource` and `dstSubresource` must only contain `VK_IMAGE_ASPECT_COLOR_BIT`

- **VUID-VkImageResolve2-layerCount-00267**
The `layerCount` member of `srcSubresource` and `dstSubresource` must match

### Valid Usage (Implicit)

- **VUID-VkImageResolve2-sType-sType**
  `sType` must be `VK_STRUCTURE_TYPE_IMAGE_RESOLVE_2`

- **VUID-VkImageResolve2-pNext-pNext**
  `pNext` must be `NULL`

- **VUID-VkImageResolve2-srcSubresource-parameter**
  `srcSubresource` must be a valid `VkImageSubresourceLayers` structure

- **VUID-VkImageResolve2-dstSubresource-parameter**
  `dstSubresource` must be a valid `VkImageSubresourceLayers` structure
Chapter 20. Drawing Commands

Drawing commands (commands with Draw in the name) provoke work in a graphics pipeline. Drawing commands are recorded into a command buffer and when executed by a queue, will produce work which executes according to the bound graphics pipeline. A graphics pipeline must be bound to a command buffer before any drawing commands are recorded in that command buffer.

Each draw is made up of zero or more vertices and zero or more instances, which are processed by the device and result in the assembly of primitives. Primitives are assembled according to the pInputAssemblyState member of the VkGraphicsPipelineCreateInfo structure, which is of type VkPipelineInputAssemblyStateCreateInfo:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineInputAssemblyStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineInputAssemblyStateCreateFlags flags;
    VkPrimitiveTopology topology;
    VkBool32 primitiveRestartEnable;
} VkPipelineInputAssemblyStateCreateInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is reserved for future use.
- **topology** is a VkPrimitiveTopology defining the primitive topology, as described below.
- **primitiveRestartEnable** controls whether a special vertex index value is treated as restarting the assembly of primitives. This enable only applies to indexed draws (vkCmdDrawIndexed, and vkCmdDrawIndexedIndirect), and the special index value is either 0xFFFFFFFF when the indexType parameter of vkCmdBindIndexBuffer is equal to VK_INDEX_TYPE_UINT32, or 0xFFFF when indexType is equal to VK_INDEX_TYPE_UINT16. Primitive restart is not allowed for “list” topologies.

Restarting the assembly of primitives discards the most recent index values if those elements formed an incomplete primitive, and restarts the primitive assembly using the subsequent indices, but only assembling the immediately following element through the end of the originally specified elements. The primitive restart index value comparison is performed before adding the vertexOffset value to the index value.

**Valid Usage**

- VUID-VkPipelineInputAssemblyStateCreateInfo-topology-06252
  
  If topology is VK_PRIMITIVE_TOPOLOGY_POINT_LIST, VK_PRIMITIVE_TOPOLOGY_LINE_LIST, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY, or VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY, primitiveRestartEnable must be VK_FALSE
• VUID-VkPipelineInputAssemblyStateCreateInfo-topology-06253
  If topology is VK_PRIMITIVE_TOPOLOGY_PATCH_LIST, primitiveRestartEnable must be VK_FALSE

• VUID-VkPipelineInputAssemblyStateCreateInfo-topology-00429
  If the geometryShader feature is not enabled, topology must not be any of
  VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY,
  VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY,
  VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY
  or
  VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY

• VUID-VkPipelineInputAssemblyStateCreateInfo-topology-00430
  If the tessellationShader feature is not enabled, topology must not be
  VK_PRIMITIVE_TOPOLOGY_PATCH_LIST

Valid Usage (Implicit)

• VUID-VkPipelineInputAssemblyStateCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO

• VUID-VkPipelineInputAssemblyStateCreateInfo-pNext-pNext
  pNext must be NULL

• VUID-VkPipelineInputAssemblyStateCreateInfo-flags-zerobitmask
  flags must be 0

• VUID-VkPipelineInputAssemblyStateCreateInfo-topology-parameter
  topology must be a valid VkPrimitiveTopology value

// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineInputAssemblyStateCreateFlags;

VkPipelineInputAssemblyStateCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

To dynamically control whether a special vertex index value is treated as restarting the assembly of primitives, call:

// Provided by VK_VERSION_1_3
void vkCmdSetPrimitiveRestartEnable(
    VkCommandBuffer commandBuffer,
    VkBool32 primitiveRestartEnable);

• commandBuffer is the command buffer into which the command will be recorded.

• primitiveRestartEnable controls whether a special vertex index value is treated as restarting the assembly of primitives. It behaves in the same way as VkPipelineInputAssemblyStateCreateInfo::primitiveRestartEnable
This command sets the primitive restart enable for subsequent drawing commands when the graphics pipeline is created with \texttt{VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE} set in \texttt{VkPipelineDynamicStateCreateInfo::pDynamicStates}. Otherwise, this state is specified by the \texttt{VkPipelineInputAssemblyStateCreateInfo::primitiveRestartEnable} value used to create the currently active pipeline.

### Valid Usage

- \texttt{VUID-vkCmdSetPrimitiveRestartEnable-None-08970}
  - At least one of the following \textbf{must} be true:
    - the value of \texttt{VkApplicationInfo::apiVersion} used to create the \texttt{VkInstance} parent of \texttt{commandBuffer} is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- \texttt{VUID-vkCmdSetPrimitiveRestartEnable-commandBuffer-parameter commandBuffer} \textbf{must} be a valid \texttt{VkCommandBuffer} handle
- \texttt{VUID-vkCmdSetPrimitiveRestartEnable-commandBuffer-recording commandBuffer} \textbf{must} be in the \texttt{recording} state
- \texttt{VUID-vkCmdSetPrimitiveRestartEnable-commandBuffer-cmdpool}
  - The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} support graphics operations

### Host Synchronization

- Host access to \texttt{commandBuffer} \textbf{must} be externally synchronized
- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary, Secondary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
</tbody>
</table>

### 20.1. Primitive Topologies

\textit{Primitive topology} determines how consecutive vertices are organized into primitives, and determines the type of primitive that is used at the beginning of the graphics pipeline. The effective topology for later stages of the pipeline is altered by tessellation or geometry shading (if either is in
The primitive topologies defined by `VkPrimitiveTopology` are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPrimitiveTopology {
    VK_PRIMITIVE_TOPOLOGY_POINT_LIST = 0,
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST = 1,
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP = 2,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST = 3,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP = 4,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN = 5,
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY = 6,
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY = 7,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY = 8,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY = 9,
    VK_PRIMITIVE_TOPOLOGY_PATCH_LIST = 10,
} VkPrimitiveTopology;
```

- `VK_PRIMITIVE_TOPOLOGY_POINT_LIST` specifies a series of separate point primitives.
- `VK_PRIMITIVE_TOPOLOGY_LINE_LIST` specifies a series of separate line primitives.
- `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP` specifies a series of connected line primitives with consecutive lines sharing a vertex.
- `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST` specifies a series of separate triangle primitives.
- `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP` specifies a series of connected triangle primitives with consecutive triangles sharing an edge.
- `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN` specifies a series of connected triangle primitives with all triangles sharing a common vertex.
- `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY` specifies a series of separate line primitives with adjacency.
- `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY` specifies a series of connected line primitives with adjacency, with consecutive primitives sharing three vertices.
- `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` specifies a series of separate triangle primitives with adjacency.
- `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY` specifies connected triangle primitives with adjacency, with consecutive triangles sharing an edge.
- `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST` specifies separate patch primitives.

Each primitive topology, and its construction from a list of vertices, is described in detail below with a supporting diagram, according to the following key:

<table>
<thead>
<tr>
<th>Vertex</th>
<th>A point in 3-dimensional space. Positions chosen within the diagrams are arbitrary and for illustration only.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Sequence position of a vertex within the provided vertex data.</td>
</tr>
</tbody>
</table>
Provoking Vertex | Provoking vertex within the main primitive. The tail is angled towards the relevant primitive. Used in flat shading.
---|---
Primitive Edge | An edge connecting the points of a main primitive.
Adjacency Edge | Points connected by these lines do not contribute to a main primitive, and are only accessible in a geometry shader.
Winding Order | The relative order in which vertices are defined within a primitive, used in the facing determination. This ordering has no specific start or end point.

The diagrams are supported with mathematical definitions where the vertices (v) and primitives (p) are numbered starting from 0; v₀ is the first vertex in the provided data and p₀ is the first primitive in the set of primitives defined by the vertices and topology.

To dynamically set primitive topology, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetPrimitiveTopology(
    VkCommandBuffer commandBuffer, 
    VkPrimitiveTopology primitiveTopology);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `primitiveTopology` specifies the primitive topology to use for drawing.

This command sets the primitive topology for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineInputAssemblyStateCreateInfo::topology` value used to create the currently active pipeline.

### Valid Usage

- **VUID-vkCmdSetPrimitiveTopology-None-08971**
  At least one of the following must be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- **VUID-vkCmdSetPrimitiveTopology-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- **VUID-vkCmdSetPrimitiveTopology-primitiveTopology-parameter**
  `primitiveTopology` must be a valid `VkPrimitiveTopology` value
- **VUID-vkCmdSetPrimitiveTopology-commandBuffer-recording**

commandBuffer must be in the recording state

- VUID-vkCmdSetPrimitiveTopology-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
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<td>Graphics</td>
<td>State</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20.1.1. Topology Class

The primitive topologies are grouped into the following topology classes:

Table 20. Topology classes

<table>
<thead>
<tr>
<th>Topology Class</th>
<th>Primitive Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>VK_PRIMITIVE_TOPOLOGY_POINT_LIST</td>
</tr>
<tr>
<td>Line</td>
<td>VK_PRIMITIVE_TOPOLOGY_LINE_LIST, VK_PRIMITIVE_TOPOLOGY_LINE_STRIP, VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY, VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY</td>
</tr>
<tr>
<td>Triangle</td>
<td>VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY</td>
</tr>
<tr>
<td>Patch</td>
<td>VK_PRIMITIVE_TOPOLOGY_PATCH_LIST</td>
</tr>
</tbody>
</table>

20.1.2. Point Lists

When the topology is VK_PRIMITIVE_TOPOLOGY_POINT_LIST, each consecutive vertex defines a single
point primitive, according to the equation:

\[ p_i = \{v_i\} \]

As there is only one vertex, that vertex is the provoking vertex. The number of primitives generated is equal to `vertexCount`.

### 20.1.3. Line Lists

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_LINE_LIST`, each consecutive pair of vertices defines a single line primitive, according to the equation:

\[ p_i = \{v_{2i}, v_{2i+1}\} \]

The number of primitives generated is equal to \(\left\lfloor \frac{\text{vertexCount}}{2} \right\rfloor\).

The provoking vertex for \(p_i\) is \(v_{2i}\).

### 20.1.4. Line Strips

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP`, one line primitive is defined by each vertex and the following vertex, according to the equation:

\[ p_i = \{v_i, v_{i+1}\} \]

The number of primitives generated is equal to \(\max(0, \text{vertexCount}-1)\).

The provoking vertex for \(p_i\) is \(v_i\).
20.1.5. Triangle Lists

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, each consecutive set of three vertices defines a single triangle primitive, according to the equation:

\[ p_i = \{v_{3i}, v_{3i+1}, v_{3i+2}\} \]

The number of primitives generated is equal to \(\lfloor \text{vertexCount}/3 \rfloor\).

The provoking vertex for \(p_i\) is \(v_{3i}\).

20.1.6. Triangle Strips

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`, one triangle primitive is defined by each vertex and the two vertices that follow it, according to the equation:

\[ p_i = \{v_i, v_{i+(1+i\%2)}, v_{i+(2-i\%2)}\} \]

The number of primitives generated is equal to \(\max(0, \text{vertexCount}-2)\).

The provoking vertex for \(p_i\) is \(v_i\).

Note

The ordering of the vertices in each successive triangle is reversed, so that the winding order is consistent throughout the strip.

20.1.7. Triangle Fans

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`, triangle primitives are defined
around a shared common vertex, according to the equation:

\[ p_i = \{v_{i+1}, v_{i+2}, v_0\} \]

The number of primitives generated is equal to \( \max(0, \text{vertexCount}-2) \).

The provoking vertex for \( p_i \) is \( v_{i+1} \).

20.1.8. Line Lists With Adjacency

When the primitive topology is \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY}, each consecutive set of four vertices defines a single line primitive with adjacency, according to the equation:

\[ p_i = \{v_{4i}, v_{4i+1}, v_{4i+2}, v_{4i+3}\} \]

A line primitive is described by the second and third vertices of the total primitive, with the remaining two vertices only accessible in a \texttt{geometry shader}.

The number of primitives generated is equal to \( \lfloor \text{vertexCount}/4 \rfloor \).

The provoking vertex for \( p_i \) is \( v_{4i+1} \).

20.1.9. Line Strips With Adjacency

When the primitive topology is \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY}, one line primitive with adjacency is defined by each vertex and the following vertex, according to the equation:

\[ p_i = \{v_i, v_{i+1}, v_{i+2}, v_{i+3}\} \]

A line primitive is described by the second and third vertices of the total primitive, with the
remaining two vertices only accessible in a geometry shader.

The number of primitives generated is equal to \(\max(0, \text{vertexCount} - 3)\).

The provoking vertex for \(p_i\) is \(v_{i+1}\).

**20.1.10. Triangle Lists With Adjacency**

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY`, each consecutive set of six vertices defines a single triangle primitive with adjacency, according to the equations:

\[
p_i = \{v_{6i}, v_{6i+1}, v_{6i+2}, v_{6i+3}, v_{6i+4}, v_{6i+5}\}
\]

A triangle primitive is described by the first, third, and fifth vertices of the total primitive, with the remaining three vertices only accessible in a geometry shader.

The number of primitives generated is equal to \(\lfloor \text{vertexCount}/6 \rfloor\).

The provoking vertex for \(p_i\) is \(v_{6i}\).

**20.1.11. Triangle Strips With Adjacency**

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY`, one triangle primitive with adjacency is defined by each vertex and the following 5 vertices.

The number of primitives generated, \(n\), is equal to \(\lfloor \max(0, \text{vertexCount} - 4)/2 \rfloor\).

If \(n=1\), the primitive is defined as:

\[
p = \{v_0, v_1, v_2, v_5, v_4, v_3\}
\]

If \(n>1\), the total primitive consists of different vertices according to where it is in the strip:
A triangle primitive is described by the first, third, and fifth vertices of the total primitive in all cases, with the remaining three vertices only accessible in a geometry shader.

The provoking vertex for \( p_i \) is always \( v_{2i} \).

**Note**

The ordering of the vertices in each successive triangle is altered so that the winding order is consistent throughout the strip.
20.1.12. Patch Lists

When the primitive topology is `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`, each consecutive set of $m$ vertices defines a single patch primitive, according to the equation:

$$p_i = \{v_{mi}, v_{mi+1}, \ldots, v_{mi+(m-2)}, v_{mi+(m-1)}\}$$

where $m$ is equal to `VkPipelineTessellationStateCreateInfo::patchControlPoints`.

Patch lists are never passed to vertex post-processing, and as such no provoking vertex is defined for patch primitives. The number of primitives generated is equal to $\lceil \text{vertexCount} / m \rceil$.

The vertices comprising a patch have no implied geometry, and are used as inputs to tessellation shaders and the fixed-function tessellator to generate new point, line, or triangle primitives.

20.2. Primitive Order

Primitives generated by drawing commands progress through the stages of the graphics pipeline in primitive order. Primitive order is initially determined in the following way:

1. Submission order determines the initial ordering
2. For indirect drawing commands, the order in which accessed instances of the `VkDrawIndirectCommand` are stored in buffer, from lower indirect buffer addresses to higher addresses.
3. If a drawing command includes multiple instances, the order in which instances are executed, from lower numbered instances to higher.
4. The order in which primitives are specified by a drawing command:
   - For non-indexed draws, from vertices with a lower numbered `vertexIndex` to a higher numbered `vertexIndex`.
   - For indexed draws, vertices sourced from a lower index buffer addresses to higher addresses.

Within this order implementations further sort primitives:

5. If tessellation shading is active, by an implementation-dependent order of new primitives generated by tessellation.
6. If geometry shading is active, by the order new primitives are generated by geometry shading.
7. If the polygon mode is not `VK_POLYGON_MODE_FILL`, by an implementation-dependent ordering of the new primitives generated within the original primitive.

Primitive order is later used to define rasterization order, which determines the order in which fragments output results to a framebuffer.
20.3. Programmable Primitive Shading

Once primitives are assembled, they proceed to the vertex shading stage of the pipeline. If the draw
includes multiple instances, then the set of primitives is sent to the vertex shading stage multiple
times, once for each instance.

It is implementation-dependent whether vertex shading occurs on vertices that are discarded as
part of incomplete primitives, but if it does occur then it operates as if they were vertices in
complete primitives and such invocations can have side effects.

Vertex shading receives two per-vertex inputs from the primitive assembly stage - the \texttt{vertexIndex}
and the \texttt{instanceIndex}. How these values are generated is defined below, with each command.

Drawing commands fall roughly into two categories:

- Non-indexed drawing commands present a sequential \texttt{vertexIndex} to the vertex shader. The
  sequential index is generated automatically by the device (see Fixed-Function Vertex Processing
  for details on both specifying the vertex attributes indexed by \texttt{vertexIndex}, as well as binding
  vertex buffers containing those attributes to a command buffer). These commands are:

  - \texttt{vkCmdDraw}
  - \texttt{vkCmdDrawIndirect}
  - \texttt{vkCmdDrawIndirectCount}

- Indexed drawing commands read index values from an \texttt{index buffer} and use this to compute the
  \texttt{vertexIndex} value for the vertex shader. These commands are:

  - \texttt{vkCmdDrawIndexed}
  - \texttt{vkCmdDrawIndexedIndirect}
  - \texttt{vkCmdDrawIndexedIndirectCount}

To bind an index buffer to a command buffer, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdBindIndexBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    VkIndexType indexType);
```

- \texttt{commandBuffer} is the command buffer into which the command is recorded.
- \texttt{buffer} is the buffer being bound.
- \texttt{offset} is the starting offset in bytes within \texttt{buffer} used in index buffer address calculations.
- \texttt{indexType} is a \texttt{VkIndexType} value specifying the size of the indices.
Valid Usage

• VUID-vkCmdBindIndexBuffer-offset-00431
  offset must be less than the size of buffer

• VUID-vkCmdBindIndexBuffer-offset-00432
  The sum of offset and the address of the range of VkDeviceMemory object that is backing buffer, must be a multiple of the type indicated by indexType

• VUID-vkCmdBindIndexBuffer-buffer-00433
  buffer must have been created with the VK_BUFFER_USAGE_INDEX_BUFFER_BIT flag

• VUID-vkCmdBindIndexBuffer-buffer-00434
  If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

Valid Usage (Implicit)

• VUID-vkCmdBindIndexBuffer-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

• VUID-vkCmdBindIndexBuffer-buffer-parameter
  buffer must be a valid VkBuffer handle

• VUID-vkCmdBindIndexBuffer-indexType-parameter
  indexType must be a valid VkIndexType value

• VUID-vkCmdBindIndexBuffer-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdBindIndexBuffer-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

• VUID-vkCmdBindIndexBuffer-commonparent
  Both of buffer, and commandBuffer must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
Possible values of `vkCmdBindIndexBuffer::indexType`, specifying the size of indices, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkIndexType {
    VK_INDEX_TYPE_UINT16 = 0,
    VK_INDEX_TYPE_UINT32 = 1,
} VkIndexType;
```

- **VK_INDEX_TYPE_UINT16** specifies that indices are 16-bit unsigned integer values.
- **VK_INDEX_TYPE_UINT32** specifies that indices are 32-bit unsigned integer values.

The parameters for each drawing command are specified directly in the command or read from buffer memory, depending on the command. Drawing commands that source their parameters from buffer memory are known as *indirect* drawing commands.

All drawing commands interact with the `robustBufferAccess` feature.

To record a non-indexed draw, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdDraw(
    VkCommandBuffer commandBuffer,
    uint32_t vertexCount,
    uint32_t instanceCount,
    uint32_t firstVertex,
    uint32_t firstInstance);
```

- **commandBuffer** is the command buffer into which the command is recorded.
- **vertexCount** is the number of vertices to draw.
- **instanceCount** is the number of instances to draw.
- **firstVertex** is the index of the first vertex to draw.
- **firstInstance** is the instance ID of the first instance to draw.

When the command is executed, primitives are assembled using the current primitive topology and **vertexCount** consecutive vertex indices with the first **vertexIndex** value equal to **firstVertex**. The primitives are drawn **instanceCount** times with **instanceIndex** starting with **firstInstance** and increasing sequentially for each instance. The assembled primitives execute the bound graphics
Valid Usage

• VUID-vkCmdDraw-magFilter-04553
  If a VkSampler created with magFilter or minFilter equal to VK_FILTER_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

• VUID-vkCmdDraw-mipmapMode-04770
  If a VkSampler created with mipmapMode equal to VK_SAMPLER_MIPMAP_MODE_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

• VUID-vkCmdDraw-None-06479
  If a VkImageView is sampled with depth comparison, the image view's format features must contain VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT

• VUID-vkCmdDraw-None-02691
  If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT

• VUID-vkCmdDraw-None-07888
  If a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT

• VUID-vkCmdDraw-OpTypeImage-07027
  For any VkImageView being written as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

• VUID-vkCmdDraw-OpTypeImage-07028
  For any VkImageView being read as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

• VUID-vkCmdDraw-OpTypeImage-07029
  For any VkBufferView being written as a storage texel buffer where the image format field of the OpTypeImage is Unknown, the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

• VUID-vkCmdDraw-OpTypeImage-07030
  Any VkBufferView being read as a storage texel buffer where the image format field of the OpTypeImage is Unknown then the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

• VUID-vkCmdDraw-None-02697
  For each set n that is statically used by a bound shader, a descriptor set must have been bound to n at the same pipeline bind point, with a VkPipelineLayout that is compatible for
set n, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- **VUID-vkCmdDraw-None-02698**
  For each push constant that is statically used by a bound shader, a push constant value **must** have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- **VUID-vkCmdDraw-maintenance4-06425**
  If the maintenance4 feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value **must** have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- **VUID-vkCmdDraw-None-02699**
  Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, **must** be valid as described by descriptor validity if they are statically used by a bound shader

- **VUID-vkCmdDraw-None-02700**
  A valid pipeline **must** be bound to the pipeline bind point used by this command

- **VUID-vkCmdDraw-None-02859**
  There **must** not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound

- **VUID-vkCmdDraw-None-02702**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler **must** not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage

- **VUID-vkCmdDraw-None-02703**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage

- **VUID-vkCmdDraw-None-02704**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage

- **VUID-vkCmdDraw-None-02705**
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

- **VUID-vkCmdDraw-None-02706**
If the `robustBufferAccess` feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a storage buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

- VUID-vkCmdDraw-commandBuffer-02707
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, any resource accessed by `bound shaders` **must** not be a protected resource

- VUID-vkCmdDraw-None-06550
  If a `bound shader` accesses a `VkSampler` or `VkImageView` object that enables `sampler Y'CbCr conversion`, that object **must** only be used with `OpImageSample*` or `OpImageSparseSample*` instructions

- VUID-vkCmdDraw-ConstOffset-06551
  If a `bound shader` accesses a `VkSampler` or `VkImageView` object that enables `sampler Y'CbCr conversion`, that object **must** not use the `ConstOffset` and `Offset` operands

- VUID-vkCmdDraw-viewType-07752
  If a `VkImageView` is accessed as a result of this command, then the image view's `viewType` **must** match the `Dim` operand of the `OpTypeImage` as described in `Instruction/Sampler/Image View Validation`

- VUID-vkCmdDraw-format-07753
  If a `VkImageView` is accessed as a result of this command, then the numeric type of the image view's `format` and the `Sampled Type` operand of the `OpTypeImage` **must** match

- VUID-vkCmdDraw-None-04115
  If a `VkImageView` is accessed using `OpImageWrite` as a result of this command, then the `Type` of the `Texel` operand of that instruction **must** have at least as many components as the image view's `format`

- VUID-vkCmdDraw-OpImageWrite-04469
  If a `VkBufferView` is accessed using `OpImageWrite` as a result of this command, then the `Type` of the `Texel` operand of that instruction **must** have at least as many components as the buffer view's `format`

- VUID-vkCmdDraw-None-07288
  Any shader invocation executed by this command **must** terminate

- VUID-vkCmdDraw-renderPass-02684
  The current render pass **must** be compatible with the `renderPass` member of the `VkGraphicsPipelineCreateInfo` structure specified when creating the `VkPipeline` bound to `VK_PIPELINE_BIND_POINT_GRAPHICS`

- VUID-vkCmdDraw-subpass-02685
  The subpass index of the current render pass **must** be equal to the `subpass` member of the `VkGraphicsPipelineCreateInfo` structure specified when creating the `VkPipeline` bound to `VK_PIPELINE_BIND_POINT_GRAPHICS`

- VUID-vkCmdDraw-None-07748
  If any shader statically accesses an input attachment, a valid descriptor **must** be bound to the pipeline via a descriptor set

- VUID-vkCmdDraw-OpTypeImage-07468
If any shader executed by this pipeline accesses an `OpTypeImage` variable with a `Dim` operand of `SubpassData`, it **must** be decorated with an `InputAttachmentIndex` that corresponds to a valid input attachment in the current subpass.

- **VUID-vkCmdDraw-None-07469**
  Input attachment views accessed in a subpass **must** be created with the same `VkFormat` as the corresponding subpass definition, and be created with a `VkImageView` that is compatible with the attachment referenced by the subpass’ `pInputAttachments[InputAttachmentIndex]` in the currently bound `VkFramebuffer` as specified by **Fragment Input Attachment Compatibility**.

- **VUID-vkCmdDraw-None-06537**
  Memory backing image subresources used as attachments in the current render pass **must** not be written in any way other than as an attachment by this command.

- **VUID-vkCmdDraw-None-09000**
  If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDraw-None-09001**
  If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDraw-None-09002**
  If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDraw-None-06539**
  If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command **must** not write to that image subresource as an attachment.

- **VUID-vkCmdDraw-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, **depth writes must** be disabled.

- **VUID-vkCmdDraw-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back `writeMask` are not zero, and stencil test is enabled, **all stencil ops must** be `VK_STENCIL_OP_KEEP`.

- **VUID-vkCmdDraw-None-07831**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_VIEWPORT` dynamic state enabled then `vkCmdSetViewport` **must** have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDraw-None-07832**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_SCISSOR` dynamic state enabled then `vkCmdSetScissor` **must** have been called in the current command buffer prior to this drawing command.
If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_LINE_WIDTH` dynamic state enabled then `vkCmdSetLineWidth` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS` dynamic state enabled then `vkCmdSetDepthBias` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled then `vkCmdSetBlendConstants` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS` dynamic state enabled then `vkCmdSetDepthBounds` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled then `vkCmdSetStencilCompareMask` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled then `vkCmdSetStencilWriteMask` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference` must have been called in the current command buffer prior to this drawing command.

If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to `VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex`.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_CULL_MODE` dynamic state enabled then `vkCmdSetCullMode` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_FRONT_FACE` dynamic state enabled then `vkCmdSetFrontFace` must have been called in the current command buffer prior to this drawing command.
If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` dynamic state enabled then `vkCmdSetDepthTestEnable` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-None-07844
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE` dynamic state enabled then `vkCmdSetDepthWriteEnable` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-None-07845
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_COMPARE_OP` dynamic state enabled then `vkCmdSetDepthCompareOp` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-None-07846
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE` dynamic state enabled then `vkCmdSetDepthBoundsTestEnable` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-None-07847
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE` dynamic state enabled then `vkCmdSetStencilTestEnable` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-None-07848
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_OP` dynamic state enabled then `vkCmdSetStencilOp` must have been called in the current command buffer prior to this drawing command.

- VUID-vkCmdDraw-viewportCount-03417
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, but not the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, then `vkCmdSetViewportWithCount` must have been called in the current command buffer prior to this drawing command, and the `viewportCount` parameter of `vkCmdSetViewportWithCount` must match the `VkPipelineViewportStateCreateInfo::scissorCount` of the pipeline.

- VUID-vkCmdDraw-scissorCount-03418
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, but not the `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, then `vkCmdSetScissorWithCount` must have been called in the current command buffer prior to this drawing command, and the `scissorCount` parameter of `vkCmdSetScissorWithCount` must match the `VkPipelineViewportStateCreateInfo::viewportCount` of the pipeline.

- VUID-vkCmdDraw-viewportCount-03419
  If the bound graphics pipeline state was created with both the
VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT and VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic states enabled then both vkCmdSetViewportWithCount and vkCmdSetScissorWithCount must have been called in the current command buffer prior to this drawing command, and the viewportCount parameter of vkCmdSetViewportWithCount must match the scissorCount parameter of vkCmdSetScissorWithCount

- VUID-vkCmdDraw-None-04876
If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE dynamic state enabled then vkCmdSetRasterizerDiscardEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDraw-None-04877
If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE dynamic state enabled then vkCmdSetDepthBiasEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDraw-blendEnable-04727
If rasterization is not disabled in the bound graphics pipeline, then for each color attachment in the subpass, if the corresponding image view's format features do not contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT, then the blendEnable member of the corresponding element of the pAttachments member of pColorBlendState must be VK_FALSE

- VUID-vkCmdDraw-rasterizationSamples-04740
If rasterization is not disabled in the bound graphics pipeline, and neither the VK_AMD_mixed_attachment_samples nor the VK_NV_framebuffer_mixed_samples extensions are enabled, then rasterizationSamples for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments

- VUID-vkCmdDraw-imageView-06172
If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

- VUID-vkCmdDraw-imageView-06173
If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

- VUID-vkCmdDraw-imageView-06174
If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

- VUID-vkCmdDraw-imageView-06175
If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, this
command must not write any values to the stencil attachment

- VUID-vkCmdDraw-imageView-06176
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment

- VUID-vkCmdDraw-imageView-06177
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the stencil attachment

- VUID-vkCmdDraw-viewMask-06178
  If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::viewMask` equal to `VkRenderingInfo::viewMask`

- VUID-vkCmdDraw-colorAttachmentCount-06179
  If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::colorAttachmentCount` equal to `VkRenderingInfo::colorAttachmentCount`

- VUID-vkCmdDraw-colorAttachmentCount-06180
  If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` not equal to `VK_NULL_HANDLE` must have been created with a `VkFormat` equal to the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound graphics pipeline

- VUID-vkCmdDraw-colorAttachmentCount-07616
  If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` equal to `VK_NULL_HANDLE` must have the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound pipeline equal to `VK_FORMAT_UNDEFINED`

- VUID-vkCmdDraw-pDepthAttachment-06181
  If the current render pass instance was begun with `vkCmdBeginRendering` and `VkPipelineRenderingCreateInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`

- VUID-vkCmdDraw-pDepthAttachment-07617
  If the current render pass instance was begun with `vkCmdBeginRendering` and `VkPipelineRenderingCreateInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pStencilAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the `VkRenderingInfo::pColorAttachments->imageView` was not `VK_NULL_HANDLE`, then the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, stencil test is enabled and the `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, any resource written to by the `VkPipeline` object bound to the pipeline bind point used by this command must not be an unprotected resource.

If `commandBuffer` is a protected command buffer and `protectedNoFault` is not supported, pipeline stages other than the framebuffer-space and compute stages in the `VkPipeline` object bound to the pipeline bind point used by this command must not write to any resource.

All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have either valid or `VK_NULL_HANDLE` buffers bound.

VUID-vkCmdDraw-None-04007
VUID-vkCmdDraw-None-04008
If the `nullDescriptor` feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must not be `VK_NULL_HANDLE`.

- **VUID-vkCmdDraw-None-02721**
  For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in [Vertex Input Description](#).

- **VUID-vkCmdDraw-None-07842**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then `vkCmdSetPrimitiveTopology` must have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDraw-primitiveTopology-03420**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then the `primitiveTopology` parameter of `vkCmdSetPrimitiveTopology` must be of the same topology class as the pipeline `VkPipelineInputAssemblyStateCreateInfo::topology` state.

- **VUID-vkCmdDraw-pStrides-04884**
  If the bound graphics pipeline was created with the `VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT` dynamic state enabled, then `vkCmdBindVertexBuffers2EXT` must have been called in the current command buffer prior to this drawing command, and the `pStrides` parameter of `vkCmdBindVertexBuffers2EXT` must not be `NULL`.

- **VUID-vkCmdDraw-None-04879**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE` dynamic state enabled then `vkCmdSetPrimitiveRestartEnable` must have been called in the current command buffer prior to this drawing command.

---

**Valid Usage (Implicit)**

- **VUID-vkCmdDraw-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle.

- **VUID-vkCmdDraw-commandBuffer-recording**
  `commandBuffer` must be in the recording state.

- **VUID-vkCmdDraw-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.

- **VUID-vkCmdDraw-renderpass**
  This command must only be called inside of a render pass instance.
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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To record an indexed draw, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdDrawIndexed(
    VkCommandBuffer commandBuffer,
    uint32_t indexCount,
    uint32_t instanceCount,
    uint32_t firstIndex,
    int32_t vertexOffset,
    uint32_t firstInstance);
```

- commandBuffer is the command buffer into which the command is recorded.
- indexCount is the number of vertices to draw.
- instanceCount is the number of instances to draw.
- firstIndex is the base index within the index buffer.
- vertexOffset is the value added to the vertex index before indexing into the vertex buffer.
- firstInstance is the instance ID of the first instance to draw.

When the command is executed, primitives are assembled using the current primitive topology and indexCount vertices whose indices are retrieved from the index buffer. The index buffer is treated as an array of tightly packed unsigned integers of size defined by the vkCmdBindIndexBuffer ::indexType parameter with which the buffer was bound.

The first vertex index is at an offset of firstIndex × indexSize + offset within the bound index buffer, where offset is the offset specified by vkCmdBindIndexBuffer and indexSize is the byte size of the type specified by indexType. Subsequent index values are retrieved from consecutive locations in the index buffer. Indices are first compared to the primitive restart value, then zero extended to 32 bits (if the indexType is VK_INDEX_TYPE_UINT16) and have vertexOffset added to them, before being supplied as the vertexIndex value.
The primitives are drawn instanceCount times with instanceIndex starting with firstInstance and increasing sequentially for each instance. The assembled primitives execute the bound graphics pipeline.

**Valid Usage**

- **VUID-vkCmdDrawIndexed-magFilter-04553**
  If a VkSampler created with magFilter or minFilter equal to VK_FILTER_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

- **VUID-vkCmdDrawIndexed-mipmapMode-04770**
  If a VkSampler created with mipmapMode equal to VK_SAMPLER_MIPMAP_MODE_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

- **VUID-vkCmdDrawIndexed-None-06479**
  If a VkImageView is sampled with depth comparison, the image view's format features must contain VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT

- **VUID-vkCmdDrawIndexed-None-02691**
  If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT

- **VUID-vkCmdDrawIndexed-None-07888**
  If a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

- **VUID-vkCmdDrawIndexed-OpTypeImage-07027**
  For any VkImageView being written as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

- **VUID-vkCmdDrawIndexed-OpTypeImage-07028**
  For any VkImageView being read as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

- **VUID-vkCmdDrawIndexed-OpTypeImage-07029**
  For any VkBufferView being written as a storage texel buffer where the image format field of the OpTypeImage is Unknown, the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

- **VUID-vkCmdDrawIndexed-OpTypeImage-07030**
  Any VkBufferView being read as a storage texel buffer where the image format field of the OpTypeImage is Unknown then the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

- **VUID-vkCmdDrawIndexed-None-02697**
For each set $n$ that is statically used by a bound shader, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a VkPipelineLayout that is compatible for set $n$, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- VUID-vkCmdDrawIndexed-None-02698
  For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- VUID-vkCmdDrawIndexed-maintenance4-06425
  If the maintenance4 feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

- VUID-vkCmdDrawIndexed-None-02699
  Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid as described by descriptor validity if they are statically used by a bound shader

- VUID-vkCmdDrawIndexed-None-02700
  A valid pipeline must be bound to the pipeline bind point used by this command

- VUID-vkCmdDrawIndexed-None-02859
  There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound

- VUID-vkCmdDrawIndexed-None-02702
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage

- VUID-vkCmdDrawIndexed-None-02703
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage

- VUID-vkCmdDrawIndexed-None-02704
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage

- VUID-vkCmdDrawIndexed-None-02705
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the
same pipeline bind point

- VUID-vkCmdDrawIndexed-None-02706
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- VUID-vkCmdDrawIndexed-commandBuffer-02707
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, any resource accessed by bound shaders must not be a protected resource.

- VUID-vkCmdDrawIndexed-None-06550
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y’C_b conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions.

- VUID-vkCmdDrawIndexed-ConstOffset-06551
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y’C_b conversion, that object must not use the ConstOffset and Offset operands.

- VUID-vkCmdDrawIndexed-viewType-07752
  If a VkImageView is accessed as a result of this command, then the image view’s viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image View Validation.

- VUID-vkCmdDrawIndexed-format-07753
  If a VkImageView is accessed as a result of this command, then the numeric type of the image view’s format and the Sampled Type operand of the OpTypeImage must match.

- VUID-vkCmdDrawIndexed-None-04115
  If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view’s format.

- VUID-vkCmdDrawIndexed-OpImageWrite-04469
  If a VkBufferView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view’s format.

- VUID-vkCmdDrawIndexed-None-07288
  Any shader invocation executed by this command must terminate.

- VUID-vkCmdDrawIndexed-renderPass-02684
  The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

- VUID-vkCmdDrawIndexed-subpass-02685
  The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

- VUID-vkCmdDrawIndexed-None-07748
  If any shader statically accesses an input attachment, a valid descriptor must be bound to...
the pipeline via a descriptor set

- **VUID-vkCmdDrawIndexed-OpTypeImage-07468**
  If any shader executed by this pipeline accesses an `OpTypeImage` variable with a `Dim` operand of `SubpassData`, it **must** be decorated with an `InputAttachmentIndex` that corresponds to a valid input attachment in the current subpass.

- **VUID-vkCmdDrawIndexed-None-07469**
  Input attachment views accessed in a subpass **must** be created with the same `VkFormat` as the corresponding subpass definition, and be created with a `VkImageView` that is compatible with the attachment referenced by the subpass' `pInputAttachments[InputAttachmentIndex]` in the currently bound `VkFramebuffer` as specified by Fragment Input Attachment Compatibility.

- **VUID-vkCmdDrawIndexed-None-06537**
  Memory backing image subresources used as attachments in the current render pass **must** not be written in any way other than as an attachment by this command.

- **VUID-vkCmdDrawIndexed-None-09000**
  If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDrawIndexed-None-09001**
  If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDrawIndexed-None-09002**
  If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it **must** not be accessed in any way other than as an attachment by this command.

- **VUID-vkCmdDrawIndexed-None-06539**
  If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command **must** not write to that image subresource as an attachment.

- **VUID-vkCmdDrawIndexed-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, **depth writes must** be disabled.

- **VUID-vkCmdDrawIndexed-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back `writeMask` are not zero, and stencil test is enabled, **all stencil ops must** be `VK_STENCIL_OP_KEEP`.

- **VUID-vkCmdDrawIndexed-None-07831**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_VIEWPORT` dynamic state enabled then `vkCmdSetViewport` **must** have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDrawIndexed-None-07832**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_SCISSOR`
...dynamic state enabled then `vkCmdSetScissor must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07833`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_LINE_WIDTH` dynamic state enabled then `vkCmdSetLineWidth must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07834`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS` dynamic state enabled then `vkCmdSetDepthBias must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07835`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled then `vkCmdSetBlendConstants must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07836`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH.Bounds` dynamic state enabled then `vkCmdSetDepthBounds must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07837`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled then `vkCmdSetStencilCompareMask must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07838`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled then `vkCmdSetStencilWriteMask must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07839`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-maxMultiviewInstanceIndex-02688`
  If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index `must` be less than or equal to `VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex`

- `VUID-vkCmdDrawIndexed-None-07840`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_CULL_MODE` dynamic state enabled then `vkCmdSetCullMode must` have been called in the current command buffer prior to this drawing command

- `VUID-vkCmdDrawIndexed-None-07841`
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_FRONT_FACE` dynamic state enabled then `vkCmdSetFrontFace must` have been called in the current
command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexed-None-07843**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` dynamic state enabled then
  `vkCmdSetDepthTestEnable` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-None-07844**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE` dynamic state enabled then
  `vkCmdSetDepthWriteEnable` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-None-07845**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_DEPTH_COMPARE_OP` dynamic state enabled then
  `vkCmdSetDepthCompareOp` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-None-07846**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE` dynamic state enabled then
  `vkCmdSetDepthBoundsTestEnable` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-None-07847**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE` dynamic state enabled then
  `vkCmdSetStencilTestEnable` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-None-07848**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_STENCIL_OP` dynamic state enabled then
  `vkCmdSetStencilOp` must have been called in the current command buffer prior to
  this drawing command

- **VUID-vkCmdDrawIndexed-viewportCount-03417**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, but not the
  `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, then
  `vkCmdSetViewportWithCount` must have been called in the current command buffer prior to
  this drawing command, and the `viewportCount` parameter of
  `vkCmdSetViewportWithCount` must match the `VkPipelineViewportStateCreateInfo::scissorCount` of the pipeline

- **VUID-vkCmdDrawIndexed-scissorCount-03418**
  If the bound graphics pipeline state was created with the
  `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, but not the
  `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, then
  `vkCmdSetScissorWithCount` must have been called in the current command buffer prior to
  this drawing command, and the `scissorCount` parameter of `vkCmdSetScissorWithCount` must match the `VkPipelineViewportStateCreateInfo::viewportCount` of the pipeline
If the bound graphics pipeline state was created with both the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` and `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic states enabled then both `vkCmdSetViewportWithCount` and `vkCmdSetScissorWithCount` must have been called in the current command buffer prior to this drawing command, and the `viewportCount` parameter of `vkCmdSetViewportWithCount` must match the `scissorCount` parameter of `vkCmdSetScissorWithCount`.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE` dynamic state enabled then `vkCmdSetRasterizerDiscardEnable` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE` dynamic state enabled then `vkCmdSetDepthBiasEnable` must have been called in the current command buffer prior to this drawing command.

If rasterization is not disabled in the bound graphics pipeline, then for each color attachment in the subpass, if the corresponding image view’s format features do not contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`, then the `blendEnable` member of the corresponding element of the `pAttachments` member of `pColorBlendState` must be `VK_FALSE`.

If rasterization is not disabled in the bound graphics pipeline, and neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, then `rasterizationSamples` for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments.

If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the layout member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment.

If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the layout member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the stencil attachment.

If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the layout member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, this command must not write any values to the depth attachment.

If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the layout member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, this command must not write any values to the stencil attachment.
member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

• VUID-vkCmdDrawIndexed-imageView-06176  
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

• VUID-vkCmdDrawIndexed-imageView-06177  
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

• VUID-vkCmdDrawIndexed-viewMask-06178  
  If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::viewMask equal to VkRenderingInfo::viewMask

• VUID-vkCmdDrawIndexed-colorAttachmentCount-06179  
  If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::colorAttachmentCount equal to VkRenderingInfo::colorAttachmentCount

• VUID-vkCmdDrawIndexed-colorAttachmentCount-06180  
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::colorAttachmentCount greater than 0, then each element of the VkRenderingInfo::pColorAttachments array with a imageView not equal to VK_NULL_HANDLE must have been created with a VkFormat equal to the corresponding element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats used to create the currently bound graphics pipeline

• VUID-vkCmdDrawIndexed-colorAttachmentCount-07616  
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::colorAttachmentCount greater than 0, then each element of the VkRenderingInfo::pColorAttachments array with a imageView equal to VK_NULL_HANDLE must have the corresponding element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats used to create the currently bound pipeline equal to VK_FORMAT_UNDEFINED

• VUID-vkCmdDrawIndexed-pDepthAttachment-06181  
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::pDepthAttachment->imageView was not VK_NULL_HANDLE, the value of VkPipelineRenderingCreateInfo::depthAttachmentFormat used to create the currently bound graphics pipeline must be equal to the VkFormat used to create VkRenderingInfo::pDepthAttachment->imageView

• VUID-vkCmdDrawIndexed-pDepthAttachment-07617  
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::pDepthAttachment->imageView was VK_NULL_HANDLE, the value of VkPipelineRenderingCreateInfo::depthAttachmentFormat used to create the currently bound
graphics pipeline must be equal to VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexed-pStencilAttachment-06182
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::pStencilAttachment->imageView was not VK_NULL_HANDLE, the value of VkPipelineRenderingCreateInfo::stencilAttachmentFormat used to create the currently bound graphics pipeline must be equal to the VkFormat used to create VkRenderingInfo::pStencilAttachment->imageView

- VUID-vkCmdDrawIndexed-pStencilAttachment-07618
  If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::pStencilAttachment->imageView was VK_NULL_HANDLE, the value of VkPipelineRenderingCreateInfo::stencilAttachmentFormat used to create the currently bound graphics pipeline must be equal to VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexed-pColorAttachments-08963
  If the current render pass instance was begun with vkCmdBeginRendering, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the VkRenderingInfo::pColorAttachments->imageView was not VK_NULL_HANDLE, then the corresponding element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats used to create the pipeline must not be VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexed-pDepthAttachment-08964
  If the current render pass instance was begun with vkCmdBeginRendering, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the VkRenderingInfo::pDepthAttachment->imageView was not VK_NULL_HANDLE, then the VkPipelineRenderingCreateInfo::depthAttachmentFormat used to create the pipeline must not be VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexed-pStencilAttachment-08965
  If the current render pass instance was begun with vkCmdBeginRendering, there is a graphics pipeline bound, stencil test is enabled and the VkRenderingInfo::pStencilAttachment->imageView was not VK_NULL_HANDLE, then the VkPipelineRenderingCreateInfo::stencilAttachmentFormat used to create the pipeline must not be VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexed-commandBuffer-02712
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource

- VUID-vkCmdDrawIndexed-commandBuffer-02713
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, pipeline stages other than the framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point used by this command must not write to any resource

- VUID-vkCmdDrawIndexed-None-04007
  All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have either valid or VK_NULL_HANDLE buffers bound
If the **nullDescriptor** feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** not be `VK_NULL_HANDLE`.

For a given vertex buffer binding, any attribute data fetched **must** be entirely contained within the corresponding vertex buffer binding, as described in **Vertex Input Description**.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then `vkCmdSetPrimitiveTopology` **must** have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline was created with the `VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT` dynamic state enabled, then `vkCmdBindVertexBuffer2EXT` **must** have been called in the current command buffer prior to this drawing command, and the `pStrides` parameter of `vkCmdBindVertexBuffer2EXT` **must** not be NULL.

An index buffer **must** be bound.

If **robustBufferAccess2** is not enabled, `(indexSize × (firstIndex + indexCount) + offset) **must** be less than or equal to the size of the bound index buffer, with `indexSize` being based on the type specified by `indexType`, where the index buffer, `indexType`, and `offset` are specified via `vkCmdBindIndexBuffer`.

**Valid Usage (Implicit)**

- **commandBuffer** **must** be a valid `VkCommandBuffer` handle.
- **commandBuffer** **must** be in the `recording` state.
- **commandBuffer** **must** be a valid `VkCommandBuffer` handle.
To record a non-indexed indirect drawing command, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdDrawIndirect(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    uint32_t drawCount,
    uint32_t stride);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `buffer` is the buffer containing draw parameters.
- `offset` is the byte offset into `buffer` where parameters begin.
- `drawCount` is the number of draws to execute, and can be zero.
- `stride` is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndirect` behaves similarly to `vkCmdDraw` except that the parameters are read by the device from a buffer during execution. `drawCount` draws are executed by the command, with parameters taken from `buffer` starting at `offset` and increasing by `stride` bytes for each successive draw. The parameters of each draw are encoded in an array of `VkDrawIndirectCommand` structures. If `drawCount` is less than or equal to one, `stride` is ignored.
Valid Usage

- VUID-vkCmdDrawIndirect-magFilter-04553
  If a VkSampler created with magFilter or minFilter equal to VK_FILTER_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view’s format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

- VUID-vkCmdDrawIndirect-mipmapMode-04770
  If a VkSampler created with.mipmapMode equal to VK_SAMPLER_MIPMAP_MODE_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view’s format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

- VUID-vkCmdDrawIndirect-None-06479
  If a VkImageView is sampled with depth comparison, the image view’s format features must contain VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT

- VUID-vkCmdDrawIndirect-None-02691
  If a VkImageView is accessed using atomic operations as a result of this command, then the image view’s format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT

- VUID-vkCmdDrawIndirect-None-07888
  If a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer’s format features must contain VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT

- VUID-vkCmdDrawIndirect-OpTypeImage-07027
  For any VkImageView being written as a storage image where the image format field of the OpTypeImage is Unknown, the view’s format features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

- VUID-vkCmdDrawIndirect-OpTypeImage-07028
  For any VkImageView being read as a storage image where the image format field of the OpTypeImage is Unknown, the view’s format features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

- VUID-vkCmdDrawIndirect-OpTypeImage-07029
  For any VkBufferView being written as a storage texel buffer where the image format field of the OpTypeImage is Unknown, the view’s buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

- VUID-vkCmdDrawIndirect-OpTypeImage-07030
  Any VkBufferView being read as a storage texel buffer where the image format field of the OpTypeImage is Unknown then the view’s buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

- VUID-vkCmdDrawIndirect-None-02697
  For each set n that is statically used by a bound shader, a descriptor set must have been bound to n at the same pipeline bind point, with a VkPipelineLayout that is compatible for set n, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility
For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

If the maintenance4 feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid as described by descriptor validity if they are statically used by a bound shader.

A valid pipeline must be bound to the pipeline bind point used by this command.

There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access...
values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

- **VUID-vkCmdDrawIndirect-commandBuffer-02707**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, any resource accessed by bound shaders **must** not be a protected resource

- **VUID-vkCmdDrawIndirect-None-06550**
  If a bound shader accesses a `VkSampler` or `VkImageView` object that enables `sampler YC bC rC` conversion, that object **must** only be used with `OpImageSample*` or `OpImageSparseSample*` instructions

- **VUID-vkCmdDrawIndirect-ConstOffset-06551**
  If a bound shader accesses a `VkSampler` or `VkImageView` object that enables `sampler YC bC rC` conversion, that object **must** not use the `ConstOffset` and `Offset` operands

- **VUID-vkCmdDrawIndirect-viewType-07752**
  If a `VkImageView` is accessed as a result of this command, then the image view’s `viewType` **must** match the `Dim` operand of the `OpTypeImage` as described in Instruction/Sampler/Image View Validation

- **VUID-vkCmdDrawIndirect-format-07753**
  If a `VkImageView` is accessed as a result of this command, then the numeric type of the image view’s `format` and the `Sampled Type` operand of the `OpTypeImage` **must** match

- **VUID-vkCmdDrawIndirect-None-04115**
  If a `VkImageView` is accessed using `OpImageWrite` as a result of this command, then the `Type` of the `Texel` operand of that instruction **must** have at least as many components as the image view’s format

- **VUID-vkCmdDrawIndirect-OpImageWrite-04469**
  If a `VkBufferView` is accessed using `OpImageWrite` as a result of this command, then the `Type` of the `Texel` operand of that instruction **must** have at least as many components as the buffer view’s format

- **VUID-vkCmdDrawIndirect-None-07288**
  Any shader invocation executed by this command **must** terminate

- **VUID-vkCmdDrawIndirect-renderPass-02684**
  The current render pass **must** be compatible with the `renderPass` member of the `VkGraphicsPipelineCreateInfo` structure specified when creating the `VkPipeline` bound to `VK_PIPELINE_BIND_POINT_GRAPHICS`

- **VUID-vkCmdDrawIndirect-subpass-02685**
  The subpass index of the current render pass **must** be equal to the `subpass` member of the `VkGraphicsPipelineCreateInfo` structure specified when creating the `VkPipeline` bound to `VK_PIPELINE_BIND_POINT_GRAPHICS`

- **VUID-vkCmdDrawIndirect-None-07748**
  If any shader statically accesses an input attachment, a valid descriptor **must** be bound to the pipeline via a descriptor set

- **VUID-vkCmdDrawIndirect-OpTypeImage-07468**
  If any shader executed by this pipeline accesses an `OpTypeImage` variable with a `Dim` operand of `SubpassData`, it **must** be decorated with an `InputAttachmentIndex` that
corresponds to a valid input attachment in the current subpass

- **VUID-vkCmdDrawIndirect-None-07469**
  Input attachment views accessed in a subpass must be created with the same VkFormat as the corresponding subpass definition, and be created with a VkImageView that is compatible with the attachment referenced by the subpass' pInputAttachments [InputAttachmentIndex] in the currently bound VkFramebuffer as specified by Fragment Input Attachment Compatibility

- **VUID-vkCmdDrawIndirect-None-06537**
  Memory backing image subresources used as attachments in the current render pass must not be written in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirect-None-09000**
  If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirect-None-09001**
  If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirect-None-09002**
  If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirect-None-06539**
  If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command must not write to that image subresource as an attachment

- **VUID-vkCmdDrawIndirect-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, depth writes must be disabled

- **VUID-vkCmdDrawIndirect-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back writeMask are not zero, and stencil test is enabled, all stencil ops must be VK_STENCIL_OP_KEEP

- **VUID-vkCmdDrawIndirect-None-07831**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_VIEWPORT dynamic state enabled then vkCmdSetViewport must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirect-None-07832**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_SCISSOR dynamic state enabled then vkCmdSetScissor must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirect-None-07833**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_LINE_WIDTH
If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS` dynamic state enabled then `vkCmdSetDepthBias` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled then `vkCmdSetBlendConstants` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS` dynamic state enabled then `vkCmdSetDepthBounds` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled then `vkCmdSetStencilCompareMask` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled then `vkCmdSetStencilWriteMask` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference` must have been called in the current command buffer prior to this drawing command.

If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to `VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex`.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_CULL_MODE` dynamic state enabled then `vkCmdSetCullMode` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_FRONT_FACE` dynamic state enabled then `vkCmdSetFrontFace` must have been called in the current command buffer prior to this drawing command.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` dynamic state enabled then
vkCmdSetDepthTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirect-None-07844
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE dynamic state enabled then vkCmdSetDepthWriteEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirect-None-07845
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_COMPARE_OP dynamic state enabled then vkCmdSetDepthCompareOp must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirect-None-07846
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE dynamic state enabled then vkCmdSetDepthBoundsTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirect-None-07847
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE dynamic state enabled then vkCmdSetStencilTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirect-viewportCount-03417
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, but not the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, then vkCmdSetViewportWithCount must have been called in the current command buffer prior to this drawing command, and the viewportCount parameter of VkPipelineViewportStateCreateInfo::scissorCount of the pipeline

- VUID-vkCmdDrawIndirect-scissorCount-03418
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, but not the VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, then vkCmdSetScissorWithCount must have been called in the current command buffer prior to this drawing command, and the scissorCount parameter of vkCmdSetScissorWithCount must match the VkPipelineViewportStateCreateInfo::viewportCount of the pipeline

- VUID-vkCmdDrawIndirect-viewportCount-03419
  If the bound graphics pipeline state was created with both the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT and VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic states enabled then both vkCmdSetViewportWithCount and vkCmdSetScissorWithCount
must have been called in the current command buffer prior to this drawing command, and the viewportCount parameter of vkCmdSetViewportWithCount must match the scissorCount parameter of vkCmdSetScissorWithCount

- **VUID-vkCmdDrawIndirect-None-04876**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE dynamic state enabled then vkCmdSetRasterizerDiscardEnable must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirect-None-04877**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE dynamic state enabled then vkCmdSetDepthBiasEnable must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirect-blendEnable-04727**
  If rasterization is not disabled in the bound graphics pipeline, then for each color attachment in the subpass, if the corresponding image view’s format features do not contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT, then the blendEnable member of the corresponding element of the pAttachments member of pColorBlendState must be VK_FALSE

- **VUID-vkCmdDrawIndirect-rasterizationSamples-04740**
  If rasterization is not disabled in the bound graphics pipeline, and neither the VK_AMD_mixed_attachment_samples nor the VK_NV_framebuffer_mixed_samples extensions are enabled, then rasterizationSamples for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments

- **VUID-vkCmdDrawIndirect-imageView-06172**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndirect-imageView-06173**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

- **VUID-vkCmdDrawIndirect-imageView-06174**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndirect-imageView-06175**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment
If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment.

If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the stencil attachment.

If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::viewMask` equal to `VkRenderingInfo::viewMask`.

If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::colorAttachmentCount` equal to `VkRenderingInfo::colorAttachmentCount`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with an `imageView` not equal to `VK_NULL_HANDLE` must have been created with a `VkFormat` equal to the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound graphics pipeline.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with an `imageView` equal to `VK_NULL_HANDLE` must have the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound pipeline equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::pStencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pStencilAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::pStencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::pStencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.
**VkRenderingInfo::pStencilAttachment->imageView** was not **VK_NULL_HANDLE**, the value of **VkPipelineRenderingCreateInfo::stencilAttachmentFormat** used to create the currently bound graphics pipeline must be equal to the **VkFormat** used to create **VkRenderingInfo::pStencilAttachment->imageView**

- **VUID-vkCmdDrawIndirect-pStencilAttachment-07618**
  If the current render pass instance was begun with **vkCmdBeginRendering** and **VkRenderingInfo::pStencilAttachment->imageView** was **VK_NULL_HANDLE**, the value of **VkPipelineRenderingCreateInfo::stencilAttachmentFormat** used to create the currently bound graphics pipeline must be equal to **VK_FORMAT_UNDEFINED**

- **VUID-vkCmdDrawIndirect-pColorAttachments-08963**
  If the current render pass instance was begun with **vkCmdBeginRendering**, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the **VkRenderingInfo::pColorAttachments->imageView** was not **VK_NULL_HANDLE**, then the corresponding element of **VkPipelineRenderingCreateInfo::pColorAttachmentFormats** used to create the pipeline must not be **VK_FORMAT_UNDEFINED**

- **VUID-vkCmdDrawIndirect-pDepthAttachment-08964**
  If the current render pass instance was begun with **vkCmdBeginRendering**, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the **VkRenderingInfo::pDepthAttachment->imageView** was not **VK_NULL_HANDLE**, then the **VkPipelineRenderingCreateInfo::depthAttachmentFormat** used to create the pipeline must not be **VK_FORMAT_UNDEFINED**

- **VUID-vkCmdDrawIndirect-pStencilAttachment-08965**
  If the current render pass instance was begun with **vkCmdBeginRendering**, there is a graphics pipeline bound, stencil test is enabled and the **VkRenderingInfo::pStencilAttachment->imageView** was not **VK_NULL_HANDLE**, then the **VkPipelineRenderingCreateInfo::stencilAttachmentFormat** used to create the pipeline must not be **VK_FORMAT_UNDEFINED**

- **VUID-vkCmdDrawIndirect-None-04007**
  All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must have either valid or **VK_NULL_HANDLE** buffers bound

- **VUID-vkCmdDrawIndirect-None-04008**
  If the **nullDescriptor** feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must not be **VK_NULL_HANDLE**

- **VUID-vkCmdDrawIndirect-None-02721**
  For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in **Vertex Input Description**

- **VUID-vkCmdDrawIndirect-None-07842**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY** dynamic state enabled then **vkCmdSetPrimitiveTopology** must have been called in the current command buffer prior to this drawing command
If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then the `primitiveTopology` parameter of `vkCmdSetPrimitiveTopology` must be of the same topology class as the pipeline `VkPipelineInputAssemblyStateCreateInfo::topology` state.

If the bound graphics pipeline was created with the `VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT` dynamic state enabled, then `vkCmdBindVertexBuffers2EXT` must have been called in the current command buffer prior to this drawing command, and the `pStrides` parameter of `vkCmdBindVertexBuffers2EXT` must not be `NULL`.

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE` dynamic state enabled then `vkCmdSetPrimitiveRestartEnable` must have been called in the current command buffer prior to this drawing command.

If `buffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

`buffer` must have been created with the `VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT` bit set.

`offset` must be a multiple of 4.

`commandBuffer` must not be a protected command buffer.

If the `multiDrawIndirect` feature is not enabled, `drawCount` must be 0 or 1.

`drawCount` must be less than or equal to `VkPhysicalDeviceLimits::maxDrawIndirectCount`.

If `drawCount` is greater than 1, `stride` must be a multiple of 4 and must be greater than or equal to `sizeof(VkDrawIndirectCommand)`.

If `drawCount` is equal to 1, `(offset + sizeof(VkDrawIndirectCommand))` must be less than or equal to the size of `buffer`.

If `drawCount` is greater than 1, `(stride × (drawCount - 1) + offset + sizeof(VkDrawIndirectCommand))` must be less than or equal to the size of `buffer`.

Valid Usage (Implicit)

- VUID-vkCmdDrawIndirect-commandBuffer-parameter
commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdDrawIndirect-buffer-parameter
  buffer must be a valid VkBuffer handle

- VUID-vkCmdDrawIndirect-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdDrawIndirect-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

- VUID-vkCmdDrawIndirect-renderpass
  This command must only be called inside of a render pass instance

- VUID-vkCmdDrawIndirect-commonparent
  Both of buffer, and commandBuffer must have been created, allocated, or retrieved from the same VkDevice

### Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

### Command Properties

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The VkDrawIndirectCommand structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDrawIndirectCommand {
    uint32_t vertexCount;
    uint32_t instanceCount;
    uint32_t firstVertex;
    uint32_t firstInstance;
} VkDrawIndirectCommand;
```

- vertexCount is the number of vertices to draw.
- instanceCount is the number of instances to draw.
- firstVertex is the index of the first vertex to draw.
• **firstInstance** is the instance ID of the first instance to draw.

The members of **VkDrawIndirectCommand** have the same meaning as the similarly named parameters of **vkCmdDraw**.

---

### Valid Usage

- **VUID-VkDrawIndirectCommand-None-00500**
  For a given vertex buffer binding, any attribute data fetched **must** be entirely contained within the corresponding vertex buffer binding, as described in **Vertex Input Description**

- **VUID-VkDrawIndirectCommand-firstInstance-00501**
  If the **drawIndirectFirstInstance** feature is not enabled, **firstInstance** **must** be 0

---

To record a non-indexed draw call with a draw call count sourced from a buffer, call:

```c
// Provided by VK_VERSION_1_2
void vkCmdDrawIndirectCount(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    VkBuffer countBuffer,
    VkDeviceSize countBufferOffset,
    uint32_t maxDrawCount,
    uint32_t stride);
```

- **commandBuffer** is the command buffer into which the command is recorded.
- **buffer** is the buffer containing draw parameters.
- **offset** is the byte offset into **buffer** where parameters begin.
- **countBuffer** is the buffer containing the draw count.
- **countBufferOffset** is the byte offset into **countBuffer** where the draw count begins.
- **maxDrawCount** specifies the maximum number of draws that will be executed. The actual number of executed draw calls is the minimum of the count specified in **countBuffer** and **maxDrawCount**.
- **stride** is the byte stride between successive sets of draw parameters.

**vkCmdDrawIndirectCount** behaves similarly to **vkCmdDrawIndirect** except that the draw count is read by the device from a buffer during execution. The command will read an unsigned 32-bit integer from **countBuffer** located at **countBufferOffset** and use this as the draw count.

---

### Valid Usage

- **VUID-vkCmdDrawIndirectCount-magFilter-04553**
  If a **VkSampler** created with **magFilter** or **minFilter** equal to **VK_FILTER_LINEAR** and **compareEnable** equal to **VK_FALSE** is used to sample a **VkImageView** as a result of this command, then the image view’s **format features** **must** contain...
• VUID-vkCmdDrawIndirectCount-mipmapMode-04770
  If a VkSampler created with mipmapMode equal to VK_SAMPLER_MIPMAP_MODE_LINEAR and compareEnable equal to VK_FALSE is used to sample a VkImageView as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT

• VUID-vkCmdDrawIndirectCount-None-06479
  If a VkImageView is sampled with depth comparison, the image view's format features must contain VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT

• VUID-vkCmdDrawIndirectCount-None-02691
  If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT

• VUID-vkCmdDrawIndirectCount-None-07888
  If a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT

• VUID-vkCmdDrawIndirectCount-OpTypeImage-07027
  For any VkImageView being written as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

• VUID-vkCmdDrawIndirectCount-OpTypeImage-07028
  For any VkImageView being read as a storage image where the image format field of the OpTypeImage is Unknown, the view's format features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

• VUID-vkCmdDrawIndirectCount-OpTypeImage-07029
  For any VkBufferView being written as a storage texel buffer where the image format field of the OpTypeImage is Unknown, the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT

• VUID-vkCmdDrawIndirectCount-OpTypeImage-07030
  Any VkBufferView being read as a storage texel buffer where the image format field of the OpTypeImage is Unknown then the view's buffer features must contain VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT

• VUID-vkCmdDrawIndirectCount-None-02697
  For each set n that is statically used by a bound shader, a descriptor set must have been bound to n at the same pipeline bind point, with a VkPipelineLayout that is compatible for set n, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility

• VUID-vkCmdDrawIndirectCount-None-02698
  For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility
If the **maintenance4** feature is not enabled, then for each push constant that is statically used by a **bound shader**, a push constant value **must** have been set for the same pipeline bind point, with a **VkPipelineLayout** that is compatible for push constants, with the **VkPipelineLayout** used to create the current **VkPipeline**, as described in **Pipeline Layout Compatibility**.

Descriptors in each bound descriptor set, specified via **vkCmdBindDescriptorSets**, **must** be valid as described by **descriptor validity** if they are statically used by a **bound shader**.

A valid pipeline **must** be bound to the pipeline bind point used by this command.

There **must** not have been any calls to dynamic state setting commands for any state not specified as dynamic in the **VkPipeline** object bound to the pipeline bind point used by this command, since that pipeline was bound.

If the **VkPipeline** object bound to the pipeline bind point used by this command accesses a **VkSampler** object that uses unnormalized coordinates, that sampler **must** not be used to sample from any **VkImage** with a ** VkImageView** of the type **VK_IMAGE_VIEW_TYPE_3D**, **VK_IMAGE_VIEW_TYPE_CUBE**, **VK_IMAGE_VIEW_TYPE_1D_ARRAY**, **VK_IMAGE_VIEW_TYPE_2D_ARRAY** or **VK_IMAGE_VIEW_TYPE_CUBE_ARRAY**, in any shader stage.

If the **VkPipeline** object bound to the pipeline bind point used by this command accesses a **VkSampler** object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V **OpImageSample** or **OpImageSparseSample** instructions with **ImplicitLod**, **Dref** or **Proj** in their name, in any shader stage.

If the **VkPipeline** object bound to the pipeline bind point used by this command accesses a **VkSampler** object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V **OpImageSample** or **OpImageSparseSample** instructions that includes a LOD bias or any offset values, in any shader stage.

If the **robustBufferAccess** feature is not enabled, and if the **VkPipeline** object bound to the pipeline bind point used by this command accesses a uniform buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

If the **robustBufferAccess** feature is not enabled, and if the **VkPipeline** object bound to the pipeline bind point used by this command accesses a storage buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

If **commandBuffer** is an unprotected command buffer and **protectedNoFault** is not supported, any resource accessed by **bound shaders** **must** not be a protected resource.
If a bound shader accesses a VkSampler or VkImageView object that enables sampler YC’aC’a conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions.

If a bound shader accesses a VkSampler or VkImageView object that enables sampler YC’aC’a conversion, that object must not use the ConstOffset and Offset operands.

If a VkImageView is accessed as a result of this command, then the image view’s viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image View Validation.

If a VkImageView is accessed as a result of this command, then the numeric type of the image view’s format and the Sampled Type operand of the OpTypeImage must match.

If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view’s format.

If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view’s format.

Any shader invocation executed by this command must terminate.

The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

If any shader statically accesses an input attachment, a valid descriptor must be bound to the pipeline via a descriptor set.

If any shader executed by this pipeline accesses an OpTypeImage variable with a Dim operand of SubpassData, it must be decorated with an InputAttachmentIndex that corresponds to a valid input attachment in the current subpass.

Input attachment views accessed in a subpass must be created with the same VkFormat as the corresponding subpass definition, and be created with a VkImageView that is compatible with the attachment referenced by the subpass’ pInputAttachments.
[InputAttachmentIndex] in the currently bound VkFramebuffer as specified by Fragment Input Attachment Compatibility

- **VUID-vkCmdDrawIndirectCount-None-06537**
  Memory backing image subresources used as attachments in the current render pass must not be written in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirectCount-None-09000**
  If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirectCount-None-09001**
  If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirectCount-None-09002**
  If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndirectCount-None-06539**
  If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command must not write to that image subresource as an attachment

- **VUID-vkCmdDrawIndirectCount-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, depth writes must be disabled

- **VUID-vkCmdDrawIndirectCount-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back writeMask are not zero, and stencil test is enabled, all stencil ops must be VK_STENCIL_OP_KEEP

- **VUID-vkCmdDrawIndirectCount-None-07831**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_VIEWPORT dynamic state enabled then vkCmdSetViewport must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-None-07832**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_SCISSOR dynamic state enabled then vkCmdSetScissor must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-None-07833**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_LINE_WIDTH dynamic state enabled then vkCmdSetLineWidth must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-None-07834**
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BIAS dynamic state enabled then vkCmdSetDepthBias must have been called in the current
command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07835
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled then `vkCmdSetBlendConstants` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07836
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS` dynamic state enabled then `vkCmdSetDepthBounds` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07837
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled then `vkCmdSetStencilCompareMask` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07838
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled then `vkCmdSetStencilWriteMask` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07839
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07840
  If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to `VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex`

- VUID-vkCmdDrawIndirectCount-None-07841
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_CULL_MODE` dynamic state enabled then `vkCmdSetCullMode` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07842
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_FRONT_FACE` dynamic state enabled then `vkCmdSetFrontFace` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07843
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` dynamic state enabled then `vkCmdSetDepthTestEnable` must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07844
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE` dynamic state enabled then
vkCmdSetDepthWriteEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07845
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_COMPARE_OP dynamic state enabled then vkCmdSetDepthCompareOp must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07846
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE dynamic state enabled then vkCmdSetDepthBoundsTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07847
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE dynamic state enabled then vkCmdSetStencilTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-None-07848
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_OP dynamic state enabled then vkCmdSetStencilOp must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndirectCount-viewportCount-03417
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, but not the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, then vkCmdSetViewportWithCount must have been called in the current command buffer prior to this drawing command, and the viewportCount parameter of vkCmdSetViewportWithCount must match the VkPipelineViewportStateCreateInfo::scissorCount of the pipeline

- VUID-vkCmdDrawIndirectCount-scissorCount-03418
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, but not the VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, then vkCmdSetScissorWithCount must have been called in the current command buffer prior to this drawing command, and the scissorCount parameter of vkCmdSetScissorWithCount must match the VkPipelineViewportStateCreateInfo::viewportCount of the pipeline

- VUID-vkCmdDrawIndirectCount-viewportCount-03419
  If the bound graphics pipeline state was created with both the VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT and VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic states enabled then both vkCmdSetViewportWithCount and vkCmdSetScissorWithCount must have been called in the current command buffer prior to this drawing command, and the viewportCount parameter of vkCmdSetViewportWithCount must match the scissorCount parameter of vkCmdSetScissorWithCount

- VUID-vkCmdDrawIndirectCount-None-04876
  If the bound graphics pipeline state was created with the
VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE dynamic state enabled then `vkCmdSetRasterizerDiscardEnable` must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-None-04877**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE` dynamic state enabled then `vkCmdSetDepthBiasEnable` must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-blendEnable-04727**
  If rasterization is not disabled in the bound graphics pipeline, then for each color attachment in the subpass, if the corresponding image view's `format features` do not contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`, then the `blendEnable` member of the corresponding element of the `pAttachments` member of `pColorBlendState` must be `VK_FALSE`

- **VUID-vkCmdDrawIndirectCount-rasterizationSamples-04740**
  If rasterization is not disabled in the bound graphics pipeline, and neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, then `rasterizationSamples` for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments

- **VUID-vkCmdDrawIndirectCount-imageView-06172**
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndirectCount-imageView-06173**
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the stencil attachment

- **VUID-vkCmdDrawIndirectCount-imageView-06174**
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndirectCount-imageView-06175**
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, this command must not write any values to the stencil attachment

- **VUID-vkCmdDrawIndirectCount-imageView-06176**
  If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pDepthAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pDepthAttachment` is `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, this command must not write any values to the depth attachment
• VUID-vkCmdDrawIndirectCount-imageView-06177
If the current render pass instance was begun with `vkCmdBeginRendering`, the `imageView` member of `pStencilAttachment` is not `VK_NULL_HANDLE`, and the `layout` member of `pStencilAttachment` is `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`, this command must not write any values to the stencil attachment.

• VUID-vkCmdDrawIndirectCount-viewMask-06178
If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::viewMask` equal to `VkRenderingInfo::viewMask`.

• VUID-vkCmdDrawIndirectCount-colorAttachmentCount-06179
If the current render pass instance was begun with `vkCmdBeginRendering`, the currently bound graphics pipeline must have been created with a `VkPipelineRenderingCreateInfo::colorAttachmentCount` equal to `VkRenderingInfo::colorAttachmentCount`.

• VUID-vkCmdDrawIndirectCount-colorAttachmentCount-06180
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` not equal to `VK_NULL_HANDLE` must have been created with a `VkFormat` equal to the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound graphics pipeline.

• VUID-vkCmdDrawIndirectCount-colorAttachmentCount-07616
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` equal to `VK_NULL_HANDLE` must have the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound pipeline equal to `VK_FORMAT_UNDEFINED`.

• VUID-vkCmdDrawIndirectCount-pDepthAttachment-06181
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`.

• VUID-vkCmdDrawIndirectCount-pDepthAttachment-07617
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

• VUID-vkCmdDrawIndirectCount-pStencilAttachment-06182
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pStencilAttachment->imageView`.

• VUID-vkCmdDrawIndirectCount-pStencilAttachment-07618
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline **must** be equal to `VK_FORMAT_UNDEFINED`

- **VUID-vkCmdDrawIndirectCount-pColorAttachments-08963**
  If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the `VkRenderingInfo::pColorAttachments->imageView` was not `VK_NULL_HANDLE`, then the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the pipeline **must** not be `VK_FORMAT_UNDEFINED`

- **VUID-vkCmdDrawIndirectCount-pDepthAttachment-08964**
  If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the pipeline **must** not be `VK_FORMAT_UNDEFINED`

- **VUID-vkCmdDrawIndirectCount-pStencilAttachment-08965**
  If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, stencil test is enabled and the `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the pipeline **must** not be `VK_FORMAT_UNDEFINED`

- **VUID-vkCmdDrawIndirectCount-None-04007**
  All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have either valid or `VK_NULL_HANDLE` buffers bound

- **VUID-vkCmdDrawIndirectCount-None-04008**
  If the `nullDescriptor` feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** not be `VK_NULL_HANDLE`

- **VUID-vkCmdDrawIndirectCount-None-02721**
  For a given vertex buffer binding, any attribute data fetched **must** be entirely contained within the corresponding vertex buffer binding, as described in [Vertex Input Description](#)

- **VUID-vkCmdDrawIndirectCount-None-07842**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then `vkCmdSetPrimitiveTopology` **must** have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndirectCount-primitiveTopology-03420**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then the `primitiveTopology` parameter of `vkCmdSetPrimitiveTopology` **must** be of the same topology class as the pipeline `VkPipelineInputAssemblyStateCreateInfo::topology` state
If the bound graphics pipeline was created with the
`VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT` dynamic state enabled, then
`vkCmdBindVertexBuffers2EXT` must have been called in the current command buffer prior
to this drawing command, and the `pStrides` parameter of `vkCmdBindVertexBuffers2EXT` must not be `NULL`.

If the bound graphics pipeline state was created with the
`VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE` dynamic state enabled then
`vkCmdSetPrimitiveRestartEnable` must have been called in the current command buffer
prior to this drawing command.

If `buffer` is non-sparse then it must be bound completely and contiguously to a single
`VkDeviceMemory` object.

`buffer` must have been created with the `VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT` bit set.

offset must be a multiple of 4.

`commandBuffer` must not be a protected command buffer.

If `countBuffer` is non-sparse then it must be bound completely and contiguously to a single
`VkDeviceMemory` object.

`countBuffer` must have been created with the `VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT` bit set.

offset must be a multiple of 4.

The count stored in `countBuffer` must be less than or equal to `VkPhysicalDeviceLimits::maxDrawIndirectCount`.

`(countBufferOffset + sizeof(uint32_t))` must be less than or equal to the size of `countBuffer`.

If `drawIndirectCount` is not enabled this function must not be used.

Stride must be a multiple of 4 and must be greater than or equal to
`sizeof(VkDrawIndirectCommand)`.

If `maxDrawCount` is greater than or equal to 1, `(stride × (maxDrawCount - 1) + offset +
`sizeof(VkDrawIndirectCommand))` must be less than or equal to the size of `buffer`.

The count stored in `countBuffer` must be less than or equal to `VkPhysicalDeviceLimits::maxDrawIndirectCount`.

`(countBufferOffset + sizeof(uint32_t))` must be less than or equal to the size of `countBuffer`.

If `drawIndirectCount` is not enabled this function must not be used.

Stride must be a multiple of 4 and must be greater than or equal to
`sizeof(VkDrawIndirectCommand)`.

If `maxDrawCount` is greater than or equal to 1, `(stride × (maxDrawCount - 1) + offset +
`sizeof(VkDrawIndirectCommand))` must be less than or equal to the size of `buffer`.
If the count stored in \texttt{countBuffer} is equal to \texttt{1}, \((\texttt{offset} + \texttt{sizeof(VkDrawIndirectCommand)})\) \textbf{must} be less than or equal to the size of \texttt{buffer}

- VUID-vkCmdDrawIndirectCount-countBuffer-03122
  If the count stored in \texttt{countBuffer} is greater than \texttt{1}, \((\texttt{stride} \times (\texttt{drawCount} - 1) + \texttt{offset} + \texttt{sizeof(VkDrawIndirectCommand)})\) \textbf{must} be less than or equal to the size of \texttt{buffer}

### Valid Usage (Implicit)

- VUID-vkCmdDrawIndirectCount-commandBuffer-parameter
  \texttt{commandBuffer} \textbf{must} be a valid \texttt{VkCommandBuffer} handle

- VUID-vkCmdDrawIndirectCount-buffer-parameter
  \texttt{buffer} \textbf{must} be a valid \texttt{VkBuffer} handle

- VUID-vkCmdDrawIndirectCount-countBuffer-parameter
  \texttt{countBuffer} \textbf{must} be a valid \texttt{VkBuffer} handle

- VUID-vkCmdDrawIndirectCount-commandBuffer-recording
  \texttt{commandBuffer} \textbf{must} be in the \texttt{recording state}

- VUID-vkCmdDrawIndirectCount-commandBuffer-cmdpool
  The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} support graphics operations

- VUID-vkCmdDrawIndirectCount-renderpass
  This command \textbf{must} only be called inside of a render pass instance

- VUID-vkCmdDrawIndirectCount-commonparent
  Each of \texttt{buffer}, \texttt{commandBuffer}, and \texttt{countBuffer} \textbf{must} have been created, allocated, or retrieved from the same \texttt{VkDevice}

### Host Synchronization

- Host access to \texttt{commandBuffer} \textbf{must} be externally synchronized

- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} be externally synchronized

### Command Properties

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To record an indexed indirect drawing command, call:
// Provided by VK_VERSION_1_0

void vkCmdDrawIndexedIndirect(
  VkCommandBuffer commandBuffer,
  VkBuffer buffer,
  VkDeviceSize offset,
  uint32_t drawCount,
  uint32_t stride);

- **commandBuffer** is the command buffer into which the command is recorded.
- **buffer** is the buffer containing draw parameters.
- **offset** is the byte offset into **buffer** where parameters begin.
- **drawCount** is the number of draws to execute, and can be zero.
- **stride** is the byte stride between successive sets of draw parameters.

The *vkCmdDrawIndexedIndirect* function behaves similarly to *vkCmdDrawIndexed* except that the parameters are read by the device from a buffer during execution. *drawCount* draws are executed by the command, with parameters taken from **buffer** starting at **offset** and increasing by **stride** bytes for each successive draw. The parameters of each draw are encoded in an array of **VkDrawIndexedIndirectCommand** structures. If **drawCount** is less than or equal to one, **stride** is ignored.

### Valid Usage

- **VUID-vkCmdDrawIndexedIndirect-magFilter-04553**
  If a **VkSampler** created with **magFilter** or **minFilter** equal to **VK_FILTER_LINEAR** and **compareEnable** equal to **VK_FALSE** is used to sample a **VkImageView** as a result of this command, then the image view's format features must contain **VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT**

- **VUID-vkCmdDrawIndexedIndirect-mipmapMode-04770**
  If a **VkSampler** created with **mipmapMode** equal to **VK_SAMPLER_MIPMAP_MODE_LINEAR** and **compareEnable** equal to **VK_FALSE** is used to sample a **VkImageView** as a result of this command, then the image view's format features must contain **VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT**

- **VUID-vkCmdDrawIndexedIndirect-None-06479**
  If a **VkImageView** is sampled with depth comparison, the image view's format features must contain **VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT**

- **VUID-vkCmdDrawIndexedIndirect-None-02691**
  If a **VkImageView** is accessed using atomic operations as a result of this command, then the image view's format features must contain **VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT**

- **VUID-vkCmdDrawIndexedIndirect-None-07888**
  If a **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT**
For any `VkImageView` being written as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view’s format features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

For any `VkImageView` being read as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view’s format features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For any `VkBufferView` being written as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, the view’s buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

For any `VkBufferView` being read as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, then the view’s buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For each set `n` that is statically used by a bound shader, a descriptor set must have been bound to `n` at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set `n`, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

If the `maintenance4` feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid as described by descriptor validity if they are statically used by a bound shader.

A valid pipeline must be bound to the pipeline bind point used by this command.

There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound.

If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to...
sample from any VkImage with a VkImageView of the type 

VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or

VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage

• VUID-vkCmdDrawIndexedIndirect-None-02703
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a
  VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage

• VUID-vkCmdDrawIndexedIndirect-None-02704
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a
  VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage

• VUID-vkCmdDrawIndexedIndirect-None-02705
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

• VUID-vkCmdDrawIndexedIndirect-None-02706
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

• VUID-vkCmdDrawIndexedIndirect-commandBuffer-02707
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, any resource accessed by bound shaders must not be a protected resource

• VUID-vkCmdDrawIndexedIndirect-None-06550
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y′C B C R conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions

• VUID-vkCmdDrawIndexedIndirect-ConstOffset-06551
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y′C B C R conversion, that object must not use the ConstOffset and Offset operands

• VUID-vkCmdDrawIndexedIndirect-viewType-07752
  If a VkImageView is accessed as a result of this command, then the image view’s viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image View Validation

• VUID-vkCmdDrawIndexedIndirect-format-07753
  If a VkImageView is accessed as a result of this command, then the numeric type of the image view’s format and the Sampled Type operand of the OpTypeImage must match

• VUID-vkCmdDrawIndexedIndirect-None-04115
  If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view’s format
• VUID-vkCmdDrawIndexedIndirect-OpImageWrite-04469
If a VkBufferView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view's format.

• VUID-vkCmdDrawIndexedIndirect-None-07288
Any shader invocation executed by this command must terminate.

• VUID-vkCmdDrawIndexedIndirect-renderPass-02684
The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• VUID-vkCmdDrawIndexedIndirect-subpass-02685
The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• VUID-vkCmdDrawIndexedIndirect-None-07748
If any shader statically accesses an input attachment, a valid descriptor must be bound to the pipeline via a descriptor set.

• VUID-vkCmdDrawIndexedIndirect-OpTypeImage-07468
If any shader executed by this pipeline accesses an OpTypeImage variable with a Dim operand of SubpassData, it must be decorated with an InputAttachmentIndex that corresponds to a valid input attachment in the current subpass.

• VUID-vkCmdDrawIndexedIndirect-None-07469
Input attachment views accessed in a subpass must be created with the same VkFormat as the corresponding subpass definition, and be created with a VkImageView that is compatible with the attachment referenced by the subpass' pInputAttachments[InputAttachmentIndex] in the currently bound VkFramebuffer as specified by Fragment Input Attachment Compatibility.

• VUID-vkCmdDrawIndexedIndirect-None-06537
Memory backing image subresources used as attachments in the current render pass must not be written in any way other than as an attachment by this command.

• VUID-vkCmdDrawIndexedIndirect-None-09000
If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command.

• VUID-vkCmdDrawIndexedIndirect-None-09001
If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command.

• VUID-vkCmdDrawIndexedIndirect-None-09002
If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command.

• VUID-vkCmdDrawIndexedIndirect-None-06539
If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command **must** not write to that image subresource as an attachment

- **VUID-vkCmdDrawIndexedIndirect-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, **depth writes must be disabled**

- **VUID-vkCmdDrawIndexedIndirect-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back writeMask are not zero, and stencil test is enabled, **all stencil ops must be VK_STENCIL_OP_KEEP**

- **VUID-vkCmdDrawIndexedIndirect-None-07831**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_VIEWPORT** dynamic state enabled then **vkCmdSetViewport must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07832**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_SCISSOR** dynamic state enabled then **vkCmdSetScissor must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07833**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_LINE_WIDTH** dynamic state enabled then **vkCmdSetLineWidth must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07834**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_DEPTH_BIAS** dynamic state enabled then **vkCmdSetDepthBias must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07835**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_BLEND_CONSTANTS** dynamic state enabled then **vkCmdSetBlendConstants must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07836**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_DEPTH_BOUNDS** dynamic state enabled then **vkCmdSetDepthBounds must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07837**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK** dynamic state enabled then **vkCmdSetStencilCompareMask must have been called in the current command buffer prior to this drawing command**

- **VUID-vkCmdDrawIndexedIndirect-None-07838**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_STENCIL_WRITE_MASK** dynamic state enabled then **vkCmdSetStencilWriteMask must have been called in the current command buffer prior to this drawing command**
If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference` must have been called in the current command buffer prior to this drawing command

If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to `VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex`

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_CULL_MODE` dynamic state enabled then `vkCmdSetCullMode` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_FRONT_FACE` dynamic state enabled then `vkCmdSetFrontFace` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` dynamic state enabled then `vkCmdSetDepthTestEnable` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE` dynamic state enabled then `vkCmdSetDepthWriteEnable` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_COMPARE_OP` dynamic state enabled then `vkCmdSetDepthCompareOp` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE` dynamic state enabled then `vkCmdSetDepthBoundsTestEnable` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE` dynamic state enabled then `vkCmdSetStencilTestEnable` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_OP` dynamic state enabled then `vkCmdSetStencilOp` must have been called in the current command buffer prior to this drawing command

If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled then `vkCmdSetStencilReference` must have been called in the current command buffer prior to this drawing command
If dynamic state enabled then `vkCmdSetStencilOp` must have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDrawIndexedIndirect-viewportCount-03417**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, but not the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, then `vkCmdSetViewportWithCount` must have been called in the current command buffer prior to this drawing command, and the `viewportCount` parameter of `vkCmdSetViewportWithCount` must match the `VkPipelineViewportStateCreateInfo`::`scissorCount` of the pipeline.

- **VUID-vkCmdDrawIndexedIndirect-scissorCount-03418**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` dynamic state enabled, but not the `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic state enabled, then `vkCmdSetScissorWithCount` must have been called in the current command buffer prior to this drawing command, and the `scissorCount` parameter of `vkCmdSetScissorWithCount` must match the `VkPipelineViewportStateCreateInfo`::`viewportCount` of the pipeline.

- **VUID-vkCmdDrawIndexedIndirect-viewportCount-03419**
  If the bound graphics pipeline state was created with both the `VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT` and `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` dynamic states enabled then both `vkCmdSetViewportWithCount` and `vkCmdSetScissorWithCount` must have been called in the current command buffer prior to this drawing command, and the `viewportCount` parameter of `vkCmdSetViewportWithCount` must match the `scissorCount` parameter of `vkCmdSetScissorWithCount`.

- **VUID-vkCmdDrawIndexedIndirect-None-04876**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE` dynamic state enabled then `vkCmdSetRasterizerDiscardEnable` must have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDrawIndexedIndirect-None-04877**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE` dynamic state enabled then `vkCmdSetDepthBiasEnable` must have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDrawIndexedIndirect-blendEnable-04727**
  If rasterization is not disabled in the bound graphics pipeline, then for each color attachment in the subpass, if the corresponding image view's `format features` do not contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`, then the `blendEnable` member of the corresponding element of the `pAttachments` member of `pColorBlendState` must be `VK_FALSE`.

- **VUID-vkCmdDrawIndexedIndirect-rasterizationSamples-04740**
  If rasterization is not disabled in the bound graphics pipeline, and neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, then `rasterizationSamples` for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments.
If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, this command must not write any values to the depth attachment

If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::viewMask equal to VkRenderingInfo::viewMask

If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::colorAttachmentCount equal to VkRenderingInfo::colorAttachmentCount

If the current render pass instance was begun with vkCmdBeginRendering and VkRenderingInfo::colorAttachmentCount greater than 0, then each element of the VkRenderingInfo::pColorAttachments array with an imageView not equal to VK_NULL_HANDLE must have been created with a VkFormat equal to the corresponding element of VkPipelineRenderingCreateInfo::pColorAttachmentFormats used to create the currently bound graphics pipeline
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` equal to `VK_NULL_HANDLE` must have the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound pipeline equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pStencilAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the `VkRenderingInfo::pColorAttachments->imageView` was not `VK_NULL_HANDLE`, then the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, stencil test is enabled and the `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`. 
::pStencilAttachment->imageView was not VK_NULL_HANDLE, then the VkPipelineRenderingCreateInfo::stencilAttachmentFormat used to create the pipeline must not be VK_FORMAT_UNDEFINED

- VUID-vkCmdDrawIndexedIndirect-None-04007
  All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have either valid or VK_NULL_HANDLE buffers bound

- VUID-vkCmdDrawIndexedIndirect-None-04008
  If the nullDescriptor feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must not be VK_NULL_HANDLE

- VUID-vkCmdDrawIndexedIndirect-None-02721
  For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description

- VUID-vkCmdDrawIndexedIndirect-None-07842
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY dynamic state enabled then vkCmdSetPrimitiveTopology must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirect-primitiveTopology-03420
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY dynamic state enabled then the primitiveTopology parameter of vkCmdSetPrimitiveTopology must be of the same topology class as the pipeline VkPipelineInputAssemblyStateCreateInfo::topology state

- VUID-vkCmdDrawIndexedIndirect-pStrides-04884
  If the bound graphics pipeline was created with the VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT dynamic state enabled, then vkCmdBindVertexBuffers2EXT must have been called in the current command buffer prior to this drawing command, and the pStrides parameter of vkCmdBindVertexBuffers2EXT must not be NULL

- VUID-vkCmdDrawIndexedIndirect-None-04879
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE dynamic state enabled then vkCmdSetPrimitiveRestartEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirect-buffer-02708
  If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- VUID-vkCmdDrawIndexedIndirect-buffer-02709
  buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set

- VUID-vkCmdDrawIndexedIndirect-offset-02710
  offset must be a multiple of 4

- VUID-vkCmdDrawIndexedIndirect-commandBuffer-02711
commandBuffer must not be a protected command buffer

- VUID-vkCmdDrawIndexedIndirect-drawCount-02718
  If the multiDrawIndirect feature is not enabled, drawCount must be 0 or 1

- VUID-vkCmdDrawIndexedIndirect-drawCount-02719
  drawCount must be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount

- VUID-vkCmdDrawIndexedIndirect-None-07312
  An index buffer must be bound

- VUID-vkCmdDrawIndexedIndirect-robustBufferAccess2-07825
  If robustBufferAccess2 is not enabled, (indexSize * (firstIndex + indexCount) + offset) must be less than or equal to the size of the bound index buffer, with indexSize being based on the type specified by indexType, where the index buffer, indexType, and offset are specified via vkCmdBindIndexBuffer

- VUID-vkCmdDrawIndexedIndirect-drawCount-00528
  If drawCount is greater than 1, stride must be a multiple of 4 and must be greater than or equal to sizeof(VkDrawIndexedIndirectCommand)

- VUID-vkCmdDrawIndexedIndirect-drawCount-00539
  If drawCount is equal to 1, (offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer

- VUID-vkCmdDrawIndexedIndirect-drawCount-00540
  If drawCount is greater than 1, (stride * (drawCount - 1) + offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer

Valid Usage (Implicit)

- VUID-vkCmdDrawIndexedIndirect-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdDrawIndexedIndirect-buffer-parameter
  buffer must be a valid VkBuffer handle

- VUID-vkCmdDrawIndexedIndirect-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdDrawIndexedIndirect-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

- VUID-vkCmdDrawIndexedIndirect-renderpass
  This command must only be called inside of a render pass instance

- VUID-vkCmdDrawIndexedIndirect-commonparent
  Both of buffer, and commandBuffer must have been created, allocated, or retrieved from the same VkDevice
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

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The `VkDrawIndexedIndirectCommand` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDrawIndexedIndirectCommand {
    uint32_t indexCount;
    uint32_t instanceCount;
    uint32_t firstIndex;
    int32_t vertexOffset;
    uint32_t firstInstance;
} VkDrawIndexedIndirectCommand;
```

- `indexCount` is the number of vertices to draw.
- `instanceCount` is the number of instances to draw.
- `firstIndex` is the base index within the index buffer.
- `vertexOffset` is the value added to the vertex index before indexing into the vertex buffer.
- `firstInstance` is the instance ID of the first instance to draw.

The members of `VkDrawIndexedIndirectCommand` have the same meaning as the similarly named parameters of `vkCmdDrawIndexed`.

Valid Usage

- VUID-VkDrawIndexedIndirectCommand-None-00552
  For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

- VUID-VkDrawIndexedIndirectCommand-firstInstance-00554
  If the `drawIndirectFirstInstance` feature is not enabled, `firstInstance` must be 0.
To record an indexed draw call with a draw call count sourced from a buffer, call:

```c
// Provided by VK_VERSION_1_2
void vkCmdDrawIndexedIndirectCount(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    VkBuffer countBuffer,
    VkDeviceSize countBufferOffset,
    uint32_t maxDrawCount,
    uint32_t stride);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `buffer` is the buffer containing draw parameters.
- `offset` is the byte offset into `buffer` where parameters begin.
- `countBuffer` is the buffer containing the draw count.
- `countBufferOffset` is the byte offset into `countBuffer` where the draw count begins.
- `maxDrawCount` specifies the maximum number of draws that will be executed. The actual number of executed draw calls is the minimum of the count specified in `countBuffer` and `maxDrawCount`.
- `stride` is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndexedIndirectCount` behaves similarly to `vkCmdDrawIndexedIndirect` except that the draw count is read by the device from a buffer during execution. The command will read an unsigned 32-bit integer from `countBuffer` located at `countBufferOffset` and use this as the draw count.

### Valid Usage

- **VUID-vkCmdDrawIndexedIndirectCount-magFilter-04553**
  If a `VkSampler` created with `magFilter` or `minFilter` equal to `VK_FILTER_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's format features **must** contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- **VUID-vkCmdDrawIndexedIndirectCount-mipmapMode-04770**
  If a `VkSampler` created with `mipmapMode` equal to `VK_SAMPLER_MIPMAP_MODE_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's format features **must** contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- **VUID-vkCmdDrawIndexedIndirectCount-None-06479**
  If a `VkImageView` is sampled with depth comparison, the image view's format features **must** contain `VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT`

- **VUID-vkCmdDrawIndexedIndirectCount-None-02691**
  If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features **must** contain
If a `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`.

For any `VkImageView` being written as a storage image where the image format field of the `OpTypeImage` is Unknown, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

For any `VkImageView` being read as a storage image where the image format field of the `OpTypeImage` is Unknown, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For any `VkBufferView` being written as a storage texel buffer where the image format field of the `OpTypeImage` is Unknown, the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

For any `VkBufferView` being read as a storage texel buffer where the image format field of the `OpTypeImage` is Unknown, then the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For each set `n` that is statically used by a bound shader, a descriptor set must have been bound to `n` at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set `n`, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

If the `maintenance4` feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid as described by descriptor validity if they are statically used by a bound shader.

A valid pipeline must be bound to the pipeline bind point used by this command.

 must be bound to the pipeline bind point used by this command.
There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- VUID-vkCmdDrawIndexedIndirectCount-None-02702
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- VUID-vkCmdDrawIndexedIndirectCount-None-02703
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- VUID-vkCmdDrawIndexedIndirectCount-None-02704
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- VUID-vkCmdDrawIndexedIndirectCount-None-02705
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- VUID-vkCmdDrawIndexedIndirectCount-None-02706
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- VUID-vkCmdDrawIndexedIndirectCount-None-02707
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- VUID-vkCmdDrawIndexedIndirectCount-commandBuffer-02708
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, any resource accessed by bound shaders must not be a protected resource.

- VUID-vkCmdDrawIndexedIndirectCount-None-06550
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler YCₜᵣ conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions.

- VUID-vkCmdDrawIndexedIndirectCount-ConstOffset-06551
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler YCₜᵣ conversion, that object must not use the ConstOffset and Offset operands.

- VUID-vkCmdDrawIndexedIndirectCount-viewType-07752
  If a VkImageView is accessed as a result of this command, then the image view's viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image View Validation.

- VUID-vkCmdDrawIndexedIndirectCount-format-07753
If a VkImageView is accessed as a result of this command, then the numeric type of the image view's format and the Sampled Type operand of the OpTypeImage must match.

- VUID-vkCmdDrawIndexedIndirectCount-None-04115
  If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view's format.

- VUID-vkCmdDrawIndexedIndirectCount-OpImageWrite-04469
  If a VkBufferView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view's format.

- VUID-vkCmdDrawIndexedIndirectCount-None-07288
  Any shader invocation executed by this command must terminate.

- VUID-vkCmdDrawIndexedIndirectCount-renderPass-02684
  The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

- VUID-vkCmdDrawIndexedIndirectCount-subpass-02685
  The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

- VUID-vkCmdDrawIndexedIndirectCount-None-07748
  If any shader statically accesses an input attachment, a valid descriptor must be bound to the pipeline via a descriptor set.

- VUID-vkCmdDrawIndexedIndirectCount-OpTypeImage-07468
  If any shader executed by this pipeline accesses an OpTypeImage variable with a Dim operand of SubpassData, it must be decorated with an InputAttachmentIndex that corresponds to a valid input attachment in the current subpass.

- VUID-vkCmdDrawIndexedIndirectCount-None-07469
  Input attachment views accessed in a subpass must be created with the same VkFormat as the corresponding subpass definition, and be created with a VkImageView that is compatible with the attachment referenced by the subpass' pInputAttachments [InputAttachmentIndex] in the currently bound VkFramebuffer as specified by Fragment Input Attachment Compatibility.

- VUID-vkCmdDrawIndexedIndirectCount-None-06537
  Memory backing image subresources used as attachments in the current render pass must not be written in any way other than as an attachment by this command.

- VUID-vkCmdDrawIndexedIndirectCount-None-09000
  If a color attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command.

- VUID-vkCmdDrawIndexedIndirectCount-None-09001
  If a depth attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other
than as an attachment by this command

- **VUID-vkCmdDrawIndexedIndirectCount-None-09002**
  If a stencil attachment is written by any prior command in this subpass or by the load, store, or resolve operations for this subpass, it must not be accessed in any way other than as an attachment by this command

- **VUID-vkCmdDrawIndexedIndirectCount-None-06539**
  If any previously recorded command in the current subpass accessed an image subresource used as an attachment in this subpass in any way other than as an attachment, this command must not write to that image subresource as an attachment

- **VUID-vkCmdDrawIndexedIndirectCount-None-06886**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the depth aspect, depth writes must be disabled

- **VUID-vkCmdDrawIndexedIndirectCount-None-06887**
  If the current render pass instance uses a depth/stencil attachment with a read-only layout for the stencil aspect, both front and back writeMask are not zero, and stencil test is enabled, all stencil ops must be **VK_STENCIL_OP_KEEP**

- **VUID-vkCmdDrawIndexedIndirectCount-None-07831**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_VIEWPORT** dynamic state enabled then **vkCmdSetViewport** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07832**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_SCISSOR** dynamic state enabled then **vkCmdSetScissor** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07833**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_LINE_WIDTH** dynamic state enabled then **vkCmdSetLineWidth** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07834**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_DEPTH_BIAS** dynamic state enabled then **vkCmdSetDepthBias** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07835**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_BLEND_CONSTANTS** dynamic state enabled then **vkCmdSetBlendConstants** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07836**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_DEPTH_BOUNDS** dynamic state enabled then **vkCmdSetDepthBounds** must have been called in the current command buffer prior to this drawing command

- **VUID-vkCmdDrawIndexedIndirectCount-None-07837**
  If the bound graphics pipeline state was created with the **VK_DYNAMIC_STATE_STENCILCOMPAREMASK** dynamic state enabled then
vkCmdSetStencilCompareMask must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07838
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_WRITE_MASK dynamic state enabled then vkCmdSetStencilWriteMask must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07839
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_REFERENCE dynamic state enabled then vkCmdSetStencilReference must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-maxMultiviewInstanceIndex-02688
  If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex

- VUID-vkCmdDrawIndexedIndirectCount-None-07840
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_CULL_MODE dynamic state enabled then vkCmdSetCullMode must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07841
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_FRONT_FACE dynamic state enabled then vkCmdSetFrontFace must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07843
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE dynamic state enabled then vkCmdSetDepthTestEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07844
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE dynamic state enabled then vkCmdSetDepthWriteEnable must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07845
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_COMPARE_OP dynamic state enabled then vkCmdSetDepthCompareOp must have been called in the current command buffer prior to this drawing command

- VUID-vkCmdDrawIndexedIndirectCount-None-07846
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE dynamic state enabled then vkCmdSetDepthBoundsTestEnable must have been called in the current command buffer prior to this drawing command
• VUID-vkCmdDrawIndexedIndirectCount-None-07847
  If the bound graphics pipeline state was created with the
  VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE dynamic state enabled then
  vkCmdSetStencilTestEnable must have been called in the current command buffer prior
  to this drawing command

• VUID-vkCmdDrawIndexedIndirectCount-None-07848
  If the bound graphics pipeline state was created with the VK_DYNAMIC_STATE_STENCIL_OP
dynamic state enabled then vkCmdSetStencilOp must have been called in the current
  command buffer prior to this drawing command

• VUID-vkCmdDrawIndexedIndirectCount-viewportCount-03417
  If the bound graphics pipeline state was created with the
  VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, but not the
  VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, then
  vkCmdSetViewportWithCount must have been called in the current command buffer prior
  to this drawing command, and the viewportCount parameter of
  vkCmdSetViewportWithCount must match the VkPipelineViewportStateCreateInfo
  ::viewportCount of the pipeline

• VUID-vkCmdDrawIndexedIndirectCount-scissorCount-03418
  If the bound graphics pipeline state was created with the
  VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT dynamic state enabled, but not the
  VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic state enabled, then
  vkCmdSetScissorWithCount must have been called in the current command buffer prior
  to this drawing command, and the scissorCount parameter of
  vkCmdSetScissorWithCount must match the VkPipelineViewportStateCreateInfo
  ::viewportCount of the pipeline

• VUID-vkCmdDrawIndexedIndirectCount-viewportCount-03419
  If the bound graphics pipeline state was created with both the
  VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT and VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT dynamic
  states enabled then both
  vkCmdSetViewportWithCount and vkCmdSetScissorWithCount
  must have been called in the current command buffer prior to this drawing command,
  and the viewportCount parameter of
  vkCmdSetViewportWithCount must match the scissorCount parameter of
  vkCmdSetScissorWithCount

• VUID-vkCmdDrawIndexedIndirectCount-None-04876
  If the bound graphics pipeline state was created with the
  VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE dynamic state enabled then
  vkCmdSetRasterizerDiscardEnable must have been called in the current command buffer
  prior to this drawing command

• VUID-vkCmdDrawIndexedIndirectCount-None-04877
  If the bound graphics pipeline state was created with the
  VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE dynamic state enabled then
  vkCmdSetDepthBiasEnable must have been called in the current command buffer prior
  to this drawing command

• VUID-vkCmdDrawIndexedIndirectCount-blendEnable-04727
  If rasterization is not disabled in the bound graphics pipeline, then for each color
  attachment in the subpass, if the corresponding image view’s format features do not
  contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT, then the blendEnable member of
the corresponding element of the pAttachments member of pColorBlendState must be VK_FALSE

- **VUID-vkCmdDrawIndexedIndirectCount-rasterizationSamples-04740**
  If rasterization is not disabled in the bound graphics pipeline, and neither the VK_AMD_mixed_attachment_samples nor the VK_NV_framebuffer_mixed_samples extensions are enabled, then rasterizationSamples for the currently bound graphics pipeline must be the same as the current subpass color and/or depth/stencil attachments

- **VUID-vkCmdDrawIndexedIndirectCount-imageView-06172**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndexedIndirectCount-imageView-06173**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

- **VUID-vkCmdDrawIndexedIndirectCount-imageView-06174**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pDepthAttachment is not VK_NULL_HANDLE, and the layout member of pDepthAttachment is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, this command must not write any values to the depth attachment

- **VUID-vkCmdDrawIndexedIndirectCount-imageView-06175**
  If the current render pass instance was begun with vkCmdBeginRendering, the imageView member of pStencilAttachment is not VK_NULL_HANDLE, and the layout member of pStencilAttachment is VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL, this command must not write any values to the stencil attachment

- **VUID-vkCmdDrawIndexedIndirectCount-viewMask-06178**
  If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::viewMask equal to VkRenderingInfo::viewMask

- **VUID-vkCmdDrawIndexedIndirectCount-colorAttachmentCount-06179**
  If the current render pass instance was begun with vkCmdBeginRendering, the currently bound graphics pipeline must have been created with a VkPipelineRenderingCreateInfo::viewMask
If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` not equal to `VK_NULL_HANDLE` must have been created with a `VkFormat` equal to the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound graphics pipeline.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::colorAttachmentCount` greater than 0, then each element of the `VkRenderingInfo::pColorAttachments` array with a `imageView` equal to `VK_NULL_HANDLE` must have the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the currently bound pipeline equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pStencilAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pStencilAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the currently bound pipeline must be equal to `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound with a fragment shader that statically writes to a color attachment, the color write mask is not zero, color writes are enabled, and the corresponding element of the `VkRenderingInfo::pColorAttachments->imageView` was not `VK_NULL_HANDLE`, then the corresponding element of `VkPipelineRenderingCreateInfo::pColorAttachmentFormats` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound graphics pipeline must be equal to the `VkFormat` used to create `VkRenderingInfo::pDepthAttachment->imageView`.

If the current render pass instance was begun with `vkCmdBeginRendering` and `VkRenderingInfo::pDepthAttachment->imageView` was `VK_NULL_HANDLE`, the value of `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the currently bound pipeline must be equal to `VK_FORMAT_UNDEFINED`.
If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, depth test is enabled, depth write is enabled, and the `VkRenderingInfo::pDepthAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::depthAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

- **VUID-vkCmdDrawIndexedIndirectCount-pStencilAttachment-08965**
  If the current render pass instance was begun with `vkCmdBeginRendering`, there is a graphics pipeline bound, stencil test is enabled and the `VkRenderingInfo::pStencilAttachment->imageView` was not `VK_NULL_HANDLE`, then the `VkPipelineRenderingCreateInfo::stencilAttachmentFormat` used to create the pipeline must not be `VK_FORMAT_UNDEFINED`.

- **VUID-vkCmdDrawIndexedIndirectCount-None-04007**
  All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have either valid or `VK_NULL_HANDLE` buffers bound.

- **VUID-vkCmdDrawIndexedIndirectCount-None-04008**
  If the `nullDescriptor` feature is not enabled, all vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must not be `VK_NULL_HANDLE`.

- **VUID-vkCmdDrawIndexedIndirectCount-None-02721**
  For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

- **VUID-vkCmdDrawIndexedIndirectCount-None-07842**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then `vkCmdSetPrimitiveTopology` must have been called in the current command buffer prior to this drawing command.

- **VUID-vkCmdDrawIndexedIndirectCount-primitiveTopology-03420**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY` dynamic state enabled then the `primitiveTopology` parameter of `vkCmdSetPrimitiveTopology` must be of the same topology class as the pipeline `VkPipelineInputAssemblyStateCreateInfo::topology` state.

- **VUID-vkCmdDrawIndexedIndirectCount-pStrides-04884**
  If the bound graphics pipeline was created with the `VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE_EXT` dynamic state enabled, then `vkCmdBindVertexBuffers2EXT` must have been called in the current command buffer prior to this drawing command, and the `pStrides` parameter of `vkCmdBindVertexBuffers2EXT` must not be `NULL`.

- **VUID-vkCmdDrawIndexedIndirectCount-None-04879**
  If the bound graphics pipeline state was created with the `VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE` dynamic state enabled then `vkCmdSetPrimitiveRestartEnable` must have been called in the current command buffer prior to this drawing command.
If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

offset must be a multiple of 4.

commandBuffer must not be a protected command buffer.

If countBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

countBuffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

countBufferOffset must be a multiple of 4.

The count stored in countBuffer must be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount.

(countBufferOffset + sizeof(uint32_t)) must be less than or equal to the size of countBuffer.

If drawIndirectCount is not enabled this function must not be used.

An index buffer must be bound.

If robustBufferAccess2 is not enabled, (indexSize × (firstIndex + indexCount) + offset) must be less than or equal to the size of the bound index buffer, with indexSize being based on the type specified by indexType, where the index buffer, indexType, and offset are specified via vkCmdBindIndexBuffer.

stride must be a multiple of 4 and must be greater than or equal to sizeof(VkDrawIndexedIndirectCommand).

If maxDrawCount is greater than or equal to 1, (stride × (maxDrawCount - 1) + offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer.

If count stored in countBuffer is equal to 1, (offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer.

If count stored in countBuffer is greater than 1, (stride × (drawCount - 1) + offset +
sizeof(
VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer

valid usage (implicit)

- VUID-vkCmdDrawIndexedIndirectCount-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle
- VUID-vkCmdDrawIndexedIndirectCount-buffer-parameter
  buffer must be a valid VkBuffer handle
- VUID-vkCmdDrawIndexedIndirectCount-countBuffer-parameter
  countBuffer must be a valid VkBuffer handle
- VUID-vkCmdDrawIndexedIndirectCount-commandBuffer-recording
  commandBuffer must be in the recording state
- VUID-vkCmdDrawIndexedIndirectCount-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations
- VUID-vkCmdDrawIndexedIndirectCount-renderpass
  This command must only be called inside of a render pass instance
- VUID-vkCmdDrawIndexedIndirectCount-commonparent
  Each of buffer, commandBuffer, and countBuffer must have been created, allocated, or retrieved from the same VkDevice

host synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

command properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary, Secondary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Action</td>
</tr>
</tbody>
</table>
Chapter 21. Fixed-Function Vertex Processing

Vertex fetching is controlled via configurable state, as a logically distinct graphics pipeline stage.

21.1. Vertex Attributes

Vertex shaders can define input variables, which receive vertex attribute data transferred from one or more VkBuffer(s) by drawing commands. Vertex shader input variables are bound to buffers via an indirect binding where the vertex shader associates a vertex input attribute number with each variable, vertex input attributes are associated to vertex input bindings on a per-pipeline basis, and vertex input bindings are associated with specific buffers on a per-draw basis via the vkCmdBindVertexBuffers command. Vertex input attribute and vertex input binding descriptions also contain format information controlling how data is extracted from buffer memory and converted to the format expected by the vertex shader.

There are VkPhysicalDeviceLimits::maxVertexInputAttributes number of vertex input attributes and VkPhysicalDeviceLimits::maxVertexInputBindings number of vertex input bindings (each referred to by zero-based indices), where there are at least as many vertex input attributes as there are vertex input bindings. Applications can store multiple vertex input attributes interleaved in a single buffer, and use a single vertex input binding to access those attributes.

In GLSL, vertex shaders associate input variables with a vertex input attribute number using the location layout qualifier. The Component layout qualifier associates components of a vertex shader input variable with components of a vertex input attribute.

GLSL example

```glsl
// Assign location M to variableName
layout (location=M, component=2) in vec2 variableName;

// Assign locations [N,N+L) to the array elements of variableNameArray
layout (location=N) in vec4 variableNameArray[L];
```

In SPIR-V, vertex shaders associate input variables with a vertex input attribute number using the Location decoration. The Component decoration associates components of a vertex shader input variable with components of a vertex input attribute. The Location and Component decorations are specified via the OpDecorate instruction.

SPIR-V example

```spir-v
...%1 = OpExtInstImport "GLSL.std.450"
...OpName %9 "variableName"
OpName %15 "variableNameArray"
OpDecorate %18 BuiltIn VertexIndex
```
21.1.1. Attribute Location and Component Assignment

The `Location` decoration specifies which vertex input attribute is used to read and interpret the data that a variable will consume.

When a vertex shader input variable declared using a 16- or 32-bit scalar or vector data type is assigned a `Location`, its value(s) are taken from the components of the input attribute specified with the corresponding `VkVertexInputAttributeDescription::location`. The components used depend on the type of variable and the `Component` decoration specified in the variable declaration, as identified in `Input attribute components accessed by 16-bit and 32-bit input variables`. Any 16-bit or 32-bit scalar or vector input will consume a single `Location`. For 16-bit and 32-bit data types, missing components are filled in with default values as described below.

Table 21. Input attribute components accessed by 16-bit and 32-bit input variables

<table>
<thead>
<tr>
<th>16-bit or 32-bit data type</th>
<th>Component decoration</th>
<th>Components consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>0 or unspecified</td>
<td>(x, o, o, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>1</td>
<td>(o, y, o, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>2</td>
<td>(o, o, z, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>3</td>
<td>(o, o, o, w)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>0 or unspecified</td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>1</td>
<td>(o, y, z, o)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>2</td>
<td>(o, o, z, w)</td>
</tr>
<tr>
<td>three-component vector</td>
<td>0 or unspecified</td>
<td>(x, y, z, o)</td>
</tr>
<tr>
<td>three-component vector</td>
<td>1</td>
<td>(o, y, z, w)</td>
</tr>
</tbody>
</table>
Components indicated by “o” are available for use by other input variables which are sourced from the same attribute, and if used, are either filled with the corresponding component from the input format (if present), or the default value.

When a vertex shader input variable declared using a 32-bit floating point matrix type is assigned a Location $i$, its values are taken from consecutive input attributes starting with the corresponding VkVertexInputAttributeDescription::location. Such matrices are treated as an array of column vectors with values taken from the input attributes identified in Input attributes accessed by 32-bit input matrix variables. The VkVertexInputAttributeDescription::format must be specified with a VkFormat that corresponds to the appropriate type of column vector. The Component decoration must not be used with matrix types.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Column vector type</th>
<th>Locations consumed</th>
<th>Components consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>mat2</td>
<td>two-component vector</td>
<td>$i, i+1$</td>
<td>$(x, y, o, o), (x, y, o, o)$</td>
</tr>
<tr>
<td>mat2x3</td>
<td>three-component vector</td>
<td>$i, i+1$</td>
<td>$(x, y, z, o), (x, y, z, o)$</td>
</tr>
<tr>
<td>mat2x4</td>
<td>four-component vector</td>
<td>$i, i+1$</td>
<td>$(x, y, z, w), (x, y, z, w)$</td>
</tr>
<tr>
<td>mat3x2</td>
<td>two-component vector</td>
<td>$i, i+1, i+2$</td>
<td>$(x, y, o, o), (x, y, o, o), (x, y, o, o)$</td>
</tr>
<tr>
<td>mat3</td>
<td>three-component vector</td>
<td>$i, i+1, i+2$</td>
<td>$(x, y, z, o), (x, y, z, o), (x, y, z, o)$</td>
</tr>
<tr>
<td>mat3x4</td>
<td>four-component vector</td>
<td>$i, i+1, i+2$</td>
<td>$(x, y, z, w), (x, y, z, w), (x, y, z, w)$</td>
</tr>
<tr>
<td>mat4x2</td>
<td>two-component vector</td>
<td>$i, i+1, i+2, i+3$</td>
<td>$(x, y, o, o), (x, y, o, o), (x, y, o, o), (x, y, o, o)$</td>
</tr>
<tr>
<td>mat4x3</td>
<td>three-component vector</td>
<td>$i, i+1, i+2, i+3$</td>
<td>$(x, y, z, o), (x, y, z, o), (x, y, z, o), (x, y, z, o)$</td>
</tr>
<tr>
<td>mat4</td>
<td>four-component vector</td>
<td>$i, i+1, i+2, i+3$</td>
<td>$(x, y, z, w), (x, y, z, w), (x, y, z, w), (x, y, z, w)$</td>
</tr>
</tbody>
</table>

Components indicated by “o” are available for use by other input variables which are sourced from the same attribute, and if used, are either filled with the corresponding component from the input format (if present), or the default value.

When a vertex shader input variable declared using a scalar or vector 64-bit data type is assigned a Location $i$, its values are taken from consecutive input attributes starting with the corresponding VkVertexInputAttributeDescription::location. The Location slots and Component words used depend on the type of variable and the Component decoration specified in the variable declaration, as identified in Input attribute locations and components accessed by 64-bit input variables. For 64-bit...
data types, no default attribute values are provided. Input variables **must** not use more components than provided by the attribute.

*Table 23. Input attribute locations and components accessed by 64-bit input variables*

<table>
<thead>
<tr>
<th>Input format</th>
<th>Locations consumed</th>
<th>64-bit data type</th>
<th>Location decoration</th>
<th>Component decoration</th>
<th>32-bit component consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>R64</td>
<td>i</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, -, -)</td>
</tr>
<tr>
<td>R64G64</td>
<td>i</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w)</td>
</tr>
<tr>
<td>R64G64B64</td>
<td>i, i+1</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o), (o, o, o, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w), (o, o, o, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o), (x, y, -, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w), (o, o, o, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>three-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w), (x, y, -, -)</td>
</tr>
<tr>
<td>R64G64B64A64</td>
<td>i, i+1</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o), (o, o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w), (o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o), (x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>2</td>
<td>(o, o, o, o), (o, o, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w), (o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o), (x, y, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>three-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w), (x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>four-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w), (x, y, z, w)</td>
</tr>
</tbody>
</table>

Components indicated by “o” are available for use by other input variables which are sourced from the same attribute. Components indicated by “-” are not available for input variables as there are...
no default values provided for 64-bit data types, and there is no data provided by the input format.

When a vertex shader input variable declared using a 64-bit floating-point matrix type is assigned a \texttt{Location} \( i \), its values are taken from consecutive input attribute locations. Such matrices are treated as an array of column vectors with values taken from the input attributes as shown in Input attribute locations and components accessed by 64-bit input variables. Each column vector starts at the \texttt{Location} immediately following the last \texttt{Location} of the previous column vector. The number of attributes and components assigned to each matrix is determined by the matrix dimensions and ranges from two to eight locations.

When a vertex shader input variable declared using an array type is assigned a location, its values are taken from consecutive input attributes starting with the corresponding \texttt{VkVertexInputAttributeDescription::location}. The number of attributes and components assigned to each element are determined according to the data type of the array elements and Component decoration (if any) specified in the declaration of the array, as described above. Each element of the array, in order, is assigned to consecutive locations, but all at the same specified component within each location.

Only input variables declared with the data types and component decorations as specified above are supported. Two variables are allowed to share the same \texttt{Location} slot only if their Component words do not overlap. If multiple variables share the same \texttt{Location} slot, they must all have the same SPIR-V floating-point component type or all have the same width scalar type components.

### 21.2. Vertex Input Description

Applications specify vertex input attribute and vertex input binding descriptions as part of graphics pipeline creation by setting the \texttt{VkGraphicsPipelineCreateInfo::pVertexInputState} pointer to a \texttt{VkPipelineVertexInputStateCreateInfo} structure.

The \texttt{VkPipelineVertexInputStateCreateInfo} structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineVertexInputStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineVertexInputStateCreateFlags flags;
    uint32_t vertexBindingDescriptionCount;
    const VkVertexInputBindingDescription* pVertexBindingDescriptions;
    uint32_t vertexAttributeDescriptionCount;
    const VkVertexInputAttributeDescription* pVertexAttributeDescriptions;
} VkPipelineVertexInputStateCreateInfo;
```

- \texttt{sType} is a \texttt{VkStructureType} value identifying this structure.
- \texttt{pNext} is \texttt{NULL} or a pointer to a structure extending this structure.
- \texttt{flags} is reserved for future use.
- \texttt{vertexBindingDescriptionCount} is the number of vertex binding descriptions provided in p\texttt{VertexBindingDescriptions}.
• `pVertexBindingDescriptions` is a pointer to an array of `VkVertexInputBindingDescription` structures.

• `vertexAttributeDescriptionCount` is the number of vertex attribute descriptions provided in `pVertexAttributeDescriptions`.

• `pVertexAttributeDescriptions` is a pointer to an array of `VkVertexInputAttributeDescription` structures.

**Valid Usage**

• VUID-VkPipelineVertexInputStateCreateInfo-vertexBindingDescriptionCount-00613
  `vertexBindingDescriptionCount` must be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputBindings`

• VUID-VkPipelineVertexInputStateCreateInfo-vertexAttributeDescriptionCount-00614
  `vertexAttributeDescriptionCount` must be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputAttributes`

• VUID-VkPipelineVertexInputStateCreateInfo-binding-00615
  For every binding specified by each element of `pVertexAttributeDescriptions`, a `VkVertexInputBindingDescription` must exist in `pVertexBindingDescriptions` with the same value of binding

• VUID-VkPipelineVertexInputStateCreateInfo-pVertexBindingDescriptions-00616
  All elements of `pVertexBindingDescriptions` must describe distinct binding numbers

• VUID-VkPipelineVertexInputStateCreateInfo-pVertexAttributeDescriptions-00617
  All elements of `pVertexAttributeDescriptions` must describe distinct attribute locations

**Valid Usage (Implicit)**

• VUID-VkPipelineVertexInputStateCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO`

• VUID-VkPipelineVertexInputStateCreateInfo-pNext-pNext
  `pNext` must be `NULL`

• VUID-VkPipelineVertexInputStateCreateInfo-flags-zerobitmask
  `flags` must be `0`

• VUID-VkPipelineVertexInputStateCreateInfo-pVertexBindingDescriptions-parameter
  If `vertexBindingDescriptionCount` is not `0`, `pVertexBindingDescriptions` must be a valid pointer to an array of `vertexBindingDescriptionCount` valid `VkVertexInputBindingDescription` structures

• VUID-VkPipelineVertexInputStateCreateInfo-pVertexAttributeDescriptions-parameter
  If `vertexAttributeDescriptionCount` is not `0`, `pVertexAttributeDescriptions` must be a valid pointer to an array of `vertexAttributeDescriptionCount` valid `VkVertexInputAttributeDescription` structures
typedef VkFlags VkPipelineVertexInputStateCreateFlags;

VkPipelineVertexInputStateCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

Each vertex input binding is specified by the VkVertexInputBindingDescription structure, defined as:

typedef struct VkVertexInputBindingDescription {
    uint32_t binding;
    uint32_t stride;
    VkVertexInputRate inputRate;
} VkVertexInputBindingDescription;

- binding is the binding number that this structure describes.
- stride is the byte stride between consecutive elements within the buffer.
- inputRate is a VkVertexInputRate value specifying whether vertex attribute addressing is a function of the vertex index or of the instance index.

Valid Usage

- VUID-VkVertexInputBindingDescription-binding-00618
  binding must be less than VkPhysicalDeviceLimits::maxVertexInputBindings

- VUID-VkVertexInputBindingDescription-stride-00619
  stride must be less than or equal to VkPhysicalDeviceLimits::maxVertexInputBindingStride

Valid Usage (Implicit)

- VUID-VkVertexInputBindingDescription-inputRate-parameter
  inputRate must be a valid VkVertexInputRate value

Possible values of VkVertexInputBindingDescription::inputRate, specifying the rate at which vertex attributes are pulled from buffers, are:

// Provided by VK_VERSION_1_0
typedef enum VkVertexInputRate {
    VK_VERTEX_INPUT_RATE_VERTEX = 0,
    VK_VERTEX_INPUT_RATE_INSTANCE = 1,
} VkVertexInputRate;

- VK_VERTEX_INPUT_RATE_VERTEX specifies that vertex attribute addressing is a function of the vertex index.
• **VK_VERTEX_INPUT_RATE_INSTANCE** specifies that vertex attribute addressing is a function of the instance index.

Each vertex input attribute is specified by the `VkVertexInputAttributeDescription` structure, defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkVertexInputAttributeDescription {
    uint32_t location;
    uint32_t binding;
    VkFormat format;
    uint32_t offset;
} VkVertexInputAttributeDescription;
```

- **location** is the shader input location number for this attribute.
- **binding** is the binding number which this attribute takes its data from.
- **format** is the size and type of the vertex attribute data.
- **offset** is a byte offset of this attribute relative to the start of an element in the vertex input binding.

### Valid Usage

- **VUID-VkVertexInputAttributeDescription-location-00620**
  
  `location` **must** be less than `VkPhysicalDeviceLimits::maxVertexInputAttributes`

- **VUID-VkVertexInputAttributeDescription-binding-00621**
  
  `binding` **must** be less than `VkPhysicalDeviceLimits::maxVertexInputBindings`

- **VUID-VkVertexInputAttributeDescription-offset-00622**
  
  `offset` **must** be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputAttributeOffset`

- **VUID-VkVertexInputAttributeDescription-format-00623**
  
  The **format features** of `format` **must** contain `VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT`

### Valid Usage (Implicit)

- **VUID-VkVertexInputAttributeDescription-format-parameter**
  
  `format` **must** be a valid `VkFormat` value

To bind vertex buffers to a command buffer for use in subsequent drawing commands, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdBindVertexBuffers(
    VkCommandBuffer commandBuffer,
    uint32_t firstBinding,
    uint32_t bindingCount, ...
);
```


```c
uint32_t bindingCount,
const VkBuffer* pBuffers,
const VkDeviceSize* pOffsets);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `firstBinding` is the index of the first vertex input binding whose state is updated by the command.
- `bindingCount` is the number of vertex input bindings whose state is updated by the command.
- `pBuffers` is a pointer to an array of buffer handles.
- `pOffsets` is a pointer to an array of buffer offsets.

The values taken from elements \( i \) of `pBuffers` and `pOffsets` replace the current state for the vertex input binding \( \text{firstBinding} + i \), for \( i \) in \([0, \text{bindingCount})\). The vertex input binding is updated to start at the offset indicated by \( \text{pOffsets}[i] \) from the start of the buffer \( \text{pBuffers}[i] \). All vertex input attributes that use each of these bindings will use these updated addresses in their address calculations for subsequent drawing commands.

### Valid Usage

- VUID-vkCmdBindVertexBuffers-firstBinding-00624
  \( \text{firstBinding} \) must be less than `VkPhysicalDeviceLimits::maxVertexInputBindings`

- VUID-vkCmdBindVertexBuffers-firstBinding-00625
  The sum of `firstBinding` and `bindingCount` must be less than or equal to
  `VkPhysicalDeviceLimits::maxVertexInputBindings`

- VUID-vkCmdBindVertexBuffers-pOffsets-00626
  All elements of `pOffsets` must be less than the size of the corresponding element in `pBuffers`

- VUID-vkCmdBindVertexBuffers-pBuffers-00627
  All elements of `pBuffers` must have been created with the `VK_BUFFER_USAGE_VERTEX_BUFFER_BIT` flag

- VUID-vkCmdBindVertexBuffers-pBuffers-00628
  Each element of `pBuffers` that is non-sparse must be bound completely and contiguously to a single `VkDeviceMemory` object

- VUID-vkCmdBindVertexBuffers-pBuffers-04001
  If the nullDescriptor feature is not enabled, all elements of `pBuffers` must not be `VK_NULL_HANDLE`

### Valid Usage (Implicit)

- VUID-vkCmdBindVertexBuffers-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- VUID-vkCmdBindVertexBuffers-pBuffers-parameter
**pBuffers** **must** be a valid pointer to an array of `bindingCount` valid or **VK_NULL_HANDLE** `VkBuffer` handles

- **VUID-vkCmdBindVertexBuffers-pOffsets-parameter**
  * `pOffsets` **must** be a valid pointer to an array of `bindingCount` `VkDeviceSize` values

- **VUID-vkCmdBindVertexBuffers-commandBuffer-recording**
  * `commandBuffer` **must** be in the *recording state*

- **VUID-vkCmdBindVertexBuffers-commandBuffer-cmdpool**
  * The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

- **VUID-vkCmdBindVertexBuffers-bindingCount-arraylength**
  * `bindingCount` **must** be greater than 0

- **VUID-vkCmdBindVertexBuffers-commonparent**
  * Both of `commandBuffer`, and the elements of `pBuffers` that are valid handles of non-ignored parameters **must** have been created, allocated, or retrieved from the same `VkDevice`

---

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

---

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Alternatively, to bind vertex buffers, along with their sizes and strides, to a command buffer for use in subsequent drawing commands, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdBindVertexBuffers2(
    VkCommandBuffer commandBuffer,
    uint32_t firstBinding,
    uint32_t bindingCount,
    const VkBuffer* pBuffers,
    const VkDeviceSize* pOffsets,
    const VkDeviceSize* pSizes,
    const VkDeviceSize* pStrides);
```

- `commandBuffer` is the command buffer into which the command is recorded.
• **firstBinding** is the index of the first vertex input binding whose state is updated by the command.

• **bindingCount** is the number of vertex input bindings whose state is updated by the command.

• **pBuffers** is a pointer to an array of buffer handles.

• **pOffsets** is a pointer to an array of buffer offsets.

• **pSizes** is **NULL** or a pointer to an array of the size in bytes of vertex data bound from **pBuffers**.

• **pStrides** is **NULL** or a pointer to an array of buffer strides.

The values taken from elements i of **pBuffers** and **pOffsets** replace the current state for the vertex input binding **firstBinding** + i, for i in [0, **bindingCount**). The vertex input binding is updated to start at the offset indicated by **pOffsets**[i] from the start of the buffer **pBuffers**[i]. If **pSizes** is not **NULL** then **pSizes**[i] specifies the bound size of the vertex buffer starting from the corresponding elements of **pBuffers**[i] plus **pOffsets**[i]. All vertex input attributes that use each of these bindings will use these updated addresses in their address calculations for subsequent drawing commands.

This command also **dynamically sets** the byte strides between consecutive elements within buffer **pBuffers**[i] to the corresponding **pStrides**[i] value when the graphics pipeline is created with **VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE** set in **VkPipelineDynamicStateCreateInfo**::**pDynamicStates**. Otherwise, strides are specified by the **VkVertexInputBindingDescription**::**stride** values used to create the currently active pipeline.

**Note**

Unlike the static state to set the same, **pStrides** must be between 0 and the maximum extent of the attributes in the binding.

### Valid Usage

- VUID-vkCmdBindVertexBuffers2-firstBinding-03355
  * **firstBinding** must be less than **VkPhysicalDeviceLimits**:maxVertexInputBindings

- VUID-vkCmdBindVertexBuffers2-firstBinding-03356
  * The sum of **firstBinding** and **bindingCount** must be less than or equal to **VkPhysicalDeviceLimits**:maxVertexInputBindings

- VUID-vkCmdBindVertexBuffers2-pOffsets-03357
  * All elements of **pOffsets** must be less than the size of the corresponding element in **pBuffers**

- VUID-vkCmdBindVertexBuffers2-pSizes-03358
  * If **pSizes** is not **NULL**, all elements of **pOffsets** plus **pSizes** must be less than or equal to the size of the corresponding element in **pBuffers**

- VUID-vkCmdBindVertexBuffers2-pBuffers-03359
  * All elements of **pBuffers** must have been created with the **VK_BUFFER_USAGE_VERTEX_BUFFER_BIT** flag

- VUID-vkCmdBindVertexBuffers2-pBuffers-03360
  * Each element of **pBuffers** that is non-sparse must be bound completely and contiguously
to a single \texttt{VkDeviceMemory} object

- VUID-vkCmdBindVertexBuffers2-pBuffers-04111
  If the \texttt{nullDescriptor} feature is not enabled, all elements of \texttt{pBuffers} \textbf{must} not be \texttt{VK_NULL_HANDLE}

- VUID-vkCmdBindVertexBuffers2-pStrides-03362
  If \texttt{pStrides} is not \texttt{NULL} each element of \texttt{pStrides} \textbf{must} be less than or equal to \texttt{VkPhysicalDeviceLimits::maxVertexInputBindingStride}

- VUID-vkCmdBindVertexBuffers2-pStrides-06209
  If \texttt{pStrides} is not \texttt{NULL} each element of \texttt{pStrides} \textbf{must} be either 0 or greater than or equal to the maximum extent of all vertex input attributes fetched from the corresponding binding, where the extent is calculated as the \texttt{VkVertexInputAttributeDescription::offset} plus \texttt{VkVertexInputAttributeDescription::format} size

\section*{Valid Usage (Implicit)}

- VUID-vkCmdBindVertexBuffers2-commandBuffer-parameter
  \texttt{commandBuffer} \textbf{must} be a valid \texttt{VkCommandBuffer} handle

- VUID-vkCmdBindVertexBuffers2-pBuffers-parameter
  \texttt{pBuffers} \textbf{must} be a valid pointer to an array of \texttt{bindingCount} valid or \texttt{VK_NULL_HANDLE} \texttt{VkBuffer} handles

- VUID-vkCmdBindVertexBuffers2-pOffsets-parameter
  \texttt{pOffsets} \textbf{must} be a valid pointer to an array of \texttt{bindingCount} \texttt{VkDeviceSize} values

- VUID-vkCmdBindVertexBuffers2-pSizes-parameter
  If \texttt{pSizes} is not \texttt{NULL}, \texttt{pSizes} \textbf{must} be a valid pointer to an array of \texttt{bindingCount} \texttt{VkDeviceSize} values

- VUID-vkCmdBindVertexBuffers2-pStrides-parameter
  If \texttt{pStrides} is not \texttt{NULL}, \texttt{pStrides} \textbf{must} be a valid pointer to an array of \texttt{bindingCount} \texttt{VkDeviceSize} values

- VUID-vkCmdBindVertexBuffers2-commandBuffer-recording
  \texttt{commandBuffer} \textbf{must} be in the \texttt{recording state}

- VUID-vkCmdBindVertexBuffers2-commandBuffer-cmdpool
  The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} support graphics operations

- VUID-vkCmdBindVertexBuffers2-bindingCount-arraylength
  If any of \texttt{pSizes}, or \texttt{pStrides} are not \texttt{NULL}, \texttt{bindingCount} \textbf{must} be greater than 0

- VUID-vkCmdBindVertexBuffers2-commonparent
  Both of \texttt{commandBuffer}, and the elements of \texttt{pBuffers} that are valid handles of non-ignored parameters \textbf{must} have been created, allocated, or retrieved from the same \texttt{VkDevice}
Host Synchronization

• Host access to `commandBuffer` must be externally synchronized

• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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21.3. Vertex Input Address Calculation

The address of each attribute for each `vertexIndex` and `instanceIndex` is calculated as follows:

- Let `attribDesc` be the member of `VkPipelineVertexInputStateCreateInfo`'s `pVertexAttributeDescriptions` with `VkVertexInputAttributeDescription::location` equal to the vertex input attribute number.

- Let `bindingDesc` be the member of `VkPipelineVertexInputStateCreateInfo`'s `pVertexBindingDescriptions` with `VkVertexInputAttributeDescription::binding` equal to `attribDesc.binding`.

- Let `vertexIndex` be the index of the vertex within the draw (a value between `firstVertex` and `firstVertex+vertexCount` for `vkCmdDraw`, or a value taken from the index buffer plus `vertexOffset` for `vkCmdDrawIndexed`), and let `instanceIndex` be the instance number of the draw (a value between `firstInstance` and `firstInstance+instanceCount`).

- Let `offset` be an array of offsets into the currently bound vertex buffers specified during `vkCmdBindVertexBuffers` or `vkCmdBindVertexBuffers2` with `pOffsets`.

```
bufferBindingAddress = buffer[binding].baseAddress + offset[binding];

if (bindingDesc.inputRate == VK_VERTEX_INPUT_RATE_VERTEX)
    effectiveVertexOffset = vertexIndex * bindingDesc.stride;
else
    effectiveVertexOffset = instanceIndex * bindingDesc.stride;

attribAddress = bufferBindingAddress + effectiveVertexOffset + attribDesc.offset;
```

21.3.1. Vertex Input Extraction

For each attribute, raw data is extracted starting at `attribAddress` and is converted from the
VkVertexInputAttributeDescription's format to either floating-point, unsigned integer, or signed integer based on the numeric type of format. The numeric type of format must match the numeric type of the input variable in the shader. The input variable in the shader must be declared as a 64-bit data type if and only if format is a 64-bit data type. If format is a packed format, attribAddress must be a multiple of the size in bytes of the whole attribute data type as described in Packed Formats. Otherwise, attribAddress must be a multiple of the size in bytes of the component type indicated by format (see Formats). For attributes that are not 64-bit data types, each component is converted to the format of the input variable based on its type and size (as defined in the Format Definition section for each VkFormat), using the appropriate equations in 16-Bit Floating-Point Numbers, Unsigned 11-Bit Floating-Point Numbers, Unsigned 10-Bit Floating-Point Numbers, Fixed-Point Data Conversion, and Shared Exponent to RGB. Signed integer components smaller than 32 bits are sign-extended. Attributes that are not 64-bit data types are expanded to four components in the same way as described in conversion to RGBA. The number of components in the vertex shader input variable need not exactly match the number of components in the format. If the vertex shader has fewer components, the extra components are discarded.
Chapter 22. Tessellation

Tessellation involves three pipeline stages. First, a tessellation control shader transforms control points of a patch and can produce per-patch data. Second, a fixed-function tessellator generates multiple primitives corresponding to a tessellation of the patch in \((u,v)\) or \((u,v,w)\) parameter space. Third, a tessellation evaluation shader transforms the vertices of the tessellated patch, for example to compute their positions and attributes as part of the tessellated surface. The tessellator is enabled when the pipeline contains both a tessellation control shader and a tessellation evaluation shader.

22.1. Tessellator

If a pipeline includes both tessellation shaders (control and evaluation), the tessellator consumes each input patch (after vertex shading) and produces a new set of independent primitives (points, lines, or triangles). These primitives are logically produced by subdividing a geometric primitive (rectangle or triangle) according to the per-patch outer and inner tessellation levels written by the tessellation control shader. These levels are specified using the built-in variables \texttt{TessLevelOuter} and \texttt{TessLevelInner}, respectively. This subdivision is performed in an implementation-dependent manner. If no tessellation shaders are present in the pipeline, the tessellator is disabled and incoming primitives are passed through without modification.

The type of subdivision performed by the tessellator is specified by an \texttt{OpExecutionMode} instruction using one of the \texttt{Triangles}, \texttt{Quads}, or \texttt{IsoLines} execution modes. This instruction may be specified in either the tessellation evaluation or tessellation control shader. Other tessellation-related execution modes can also be specified in either the tessellation control or tessellation evaluation shaders.

Any tessellation-related modes specified in both the tessellation control and tessellation evaluation shaders must be the same.

Tessellation execution modes include:

- \texttt{Triangles}, \texttt{Quads}, and \texttt{IsoLines}. These control the type of subdivision and topology of the output primitives. One mode must be set in at least one of the tessellation shader stages.
- \texttt{VertexOrderCw} and \texttt{VertexOrderCcw}. These control the orientation of triangles generated by the tessellator. One mode must be set in at least one of the tessellation shader stages.
- \texttt{PointMode}. Controls generation of points rather than triangles or lines. This functionality defaults to disabled, and is enabled if either shader stage includes the execution mode.
- \texttt{SpacingEqual}, \texttt{SpacingFractionalEven}, and \texttt{SpacingFractionalOdd}. Controls the spacing of segments on the edges of tessellated primitives. One mode must be set in at least one of the tessellation shader stages.
- \texttt{OutputVertices}. Controls the size of the output patch of the tessellation control shader. One value must be set in at least one of the tessellation shader stages.

For triangles, the tessellator subdivides a triangle primitive into smaller triangles. For quads, the tessellator subdivides a rectangle primitive into smaller triangles. For isolines, the tessellator subdivides a rectangle primitive into a collection of line segments arranged in strips stretching...
across the rectangle in the u dimension (i.e. the coordinates in TessCoord are of the form (0,x) through (1,x) for all tessellation evaluation shader invocations that share a line).

Each vertex produced by the tessellator has an associated (u,v,w) or (u,v) position in a normalized parameter space, with parameter values in the range [0,1], as illustrated in figures Domain parameterization for tessellation primitive modes (upper-left origin) and Domain parameterization for tessellation primitive modes (lower-left origin). The domain space can have either an upper-left or lower-left origin, selected by the domainOrigin member of VkPipelineTessellationDomainOriginStateCreateInfo.

Figure 11. Domain parameterization for tessellation primitive modes (upper-left origin)
Figure 12. Domain parameterization for tessellation primitive modes (lower-left origin)

Caption

In the domain parameterization diagrams, the coordinates illustrate the value of \texttt{TessCoord} at the corners of the domain. The labels on the edges indicate the inner (IL0 and IL1) and outer (OL0 through OL3) tessellation level values used to control the number of subdivisions along each edge of the domain.

For triangles, the vertex's position is a barycentric coordinate \((u,v,w)\), where \(u + v + w = 1.0\), and indicates the relative influence of the three vertices of the triangle on the position of the vertex. For quads and isolines, the position is a \((u,v)\) coordinate indicating the relative horizontal and vertical position of the vertex relative to the subdivided rectangle. The subdivision process is explained in more detail in subsequent sections.

22.2. Tessellator Patch Discard

A patch is discarded by the tessellator if any relevant outer tessellation level is less than or equal to zero.

Patches will also be discarded if any relevant outer tessellation level corresponds to a floating-point
NaN (not a number) in implementations supporting NaN.

No new primitives are generated and the tessellation evaluation shader is not executed for patches that are discarded. For Quads, all four outer levels are relevant. For Triangles and IsoLines, only the first three or two outer levels, respectively, are relevant. Negative inner levels will not cause a patch to be discarded; they will be clamped as described below.

22.3. Tessellator Spacing

Each of the tessellation levels is used to determine the number and spacing of segments used to subdivide a corresponding edge. The method used to derive the number and spacing of segments is specified by an OpExecutionMode in the tessellation control or tessellation evaluation shader using one of the identifiers SpacingEqual, SpacingFractionalEven, or SpacingFractionalOdd.

If SpacingEqual is used, the floating-point tessellation level is first clamped to $[1, \text{maxLevel}]$, where maxLevel is the implementation-dependent maximum tessellation level (VkPhysicalDeviceLimits::maxTessellationGenerationLevel). The result is rounded up to the nearest integer $n$, and the corresponding edge is divided into $n$ segments of equal length in $(u,v)$ space.

If SpacingFractionalEven is used, the tessellation level is first clamped to $[2, \text{maxLevel}]$ and then rounded up to the nearest even integer $n$. If SpacingFractionalOdd is used, the tessellation level is clamped to $[1, \text{maxLevel} - 1]$ and then rounded up to the nearest odd integer $n$. If $n$ is one, the edge will not be subdivided. Otherwise, the corresponding edge will be divided into $n - 2$ segments of equal length, and two additional segments of equal length that are typically shorter than the other segments. The length of the two additional segments relative to the others will decrease monotonically with $n - f$, where $f$ is the clamped floating-point tessellation level. When $n - f$ is zero, the additional segments will have equal length to the other segments. As $n - f$ approaches 2.0, the relative length of the additional segments approaches zero. The two additional segments must be placed symmetrically on opposite sides of the subdivided edge. The relative location of these two segments is implementation-dependent, but must be identical for any pair of subdivided edges with identical values of $f$.

When tessellating triangles or quads using point mode with fractional odd spacing, the tessellator may produce interior vertices that are positioned on the edge of the patch if an inner tessellation level is less than or equal to one. Such vertices are considered distinct from vertices produced by subdividing the outer edge of the patch, even if there are pairs of vertices with identical coordinates.

22.4. Tessellation Primitive Ordering

Few guarantees are provided for the relative ordering of primitives produced by tessellation, as they pertain to primitive order.

- The output primitives generated from each input primitive are passed to subsequent pipeline stages in an implementation-dependent order.
- All output primitives generated from a given input primitive are passed to subsequent pipeline stages before any output primitives generated from subsequent input primitives.
22.5. Tessellator Vertex Winding Order

When the tessellator produces triangles (in the Triangles or Quads modes), the orientation of all triangles is specified with an OpExecutionMode of VertexOrderCw or VertexOrderCcw in the tessellation control or tessellation evaluation shaders. If the order is VertexOrderCw, the vertices of all generated triangles will have clockwise ordering in (u,v) or (u,v,w) space. If the order is VertexOrderCcw, the vertices will have counter-clockwise ordering in that space.

If the tessellation domain has an upper-left origin, the vertices of a triangle have counter-clockwise ordering if

\[ a = u_0 v_1 - u_1 v_0 + u_1 v_2 - u_2 v_1 + u_2 v_0 - u_0 v_2 \]

is negative, and clockwise ordering if \( a \) is positive. \( u_i \) and \( v_i \) are the \( u \) and \( v \) coordinates in normalized parameter space of the \( i \)th vertex of the triangle. If the tessellation domain has a lower-left origin, the vertices of a triangle have counter-clockwise ordering if \( a \) is positive, and clockwise ordering if \( a \) is negative.

*Note*

The value \( a \) is proportional (with a positive factor) to the signed area of the triangle.

In Triangles mode, even though the vertex coordinates have a \( w \) value, it does not participate directly in the computation of \( a \), being an affine combination of \( u \) and \( v \).

22.6. Triangle Tessellation

If the tessellation primitive mode is Triangles, an equilateral triangle is subdivided into a collection of triangles covering the area of the original triangle. First, the original triangle is subdivided into a collection of concentric equilateral triangles. The edges of each of these triangles are subdivided, and the area between each triangle pair is filled by triangles produced by joining the vertices on the subdivided edges. The number of concentric triangles and the number of subdivisions along each triangle except the outermost is derived from the first inner tessellation level. The edges of the outermost triangle are subdivided independently, using the first, second, and third outer tessellation levels to control the number of subdivisions of the \( u = 0 \) (left), \( v = 0 \) (bottom), and \( w = 0 \) (right) edges, respectively. The second inner tessellation level and the fourth outer tessellation level have no effect in this mode.

If the first inner tessellation level and all three outer tessellation levels are exactly one after clamping and rounding, only a single triangle with \((u,v,w)\) coordinates of \((0,0,1)\), \((1,0,0)\), and \((0,1,0)\) is generated. If the inner tessellation level is one and any of the outer tessellation levels is greater than one, the inner tessellation level is treated as though it were originally specified as \(1 + \varepsilon\) and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce inner vertices positioned on the edge of the triangle.
If any tessellation level is greater than one, tessellation begins by producing a set of concentric inner triangles and subdividing their edges. First, the three outer edges are temporarily subdivided using the clamped and rounded first inner tessellation level and the specified tessellation spacing, generating n segments. For the outermost inner triangle, the inner triangle is degenerate—a single point at the center of the triangle—if n is two. Otherwise, for each corner of the outer triangle, an inner triangle corner is produced at the intersection of two lines extended perpendicular to the corner’s two adjacent edges running through the vertex of the subdivided outer edge nearest that corner. If n is three, the edges of the inner triangle are not subdivided and it is the final triangle in the set of concentric triangles. Otherwise, each edge of the inner triangle is divided into n - 2 segments, with the n - 1 vertices of this subdivision produced by intersecting the inner edge with lines perpendicular to the edge running through the n - 1 innermost vertices of the subdivision of the outer edge. Once the outermost inner triangle is subdivided, the previous subdivision process repeats itself, using the generated triangle as an outer triangle. This subdivision process is illustrated in Inner Triangle Tessellation.

![Inner Triangle Tessellation](image)

**Caption**

In the Inner Triangle Tessellation diagram, inner tessellation levels of (a) four and (b) five are shown (not to scale). Solid black circles depict vertices along the edges of the concentric triangles. The edges of inner triangles are subdivided by intersecting the edge with segments perpendicular to the edge passing through each inner vertex of the subdivided outer edge. Dotted lines depict edges connecting corresponding vertices on the inner and outer triangle edges.

Once all the concentric triangles are produced and their edges are subdivided, the area between each pair of adjacent inner triangles is filled completely with a set of non-overlapping triangles. In this subdivision, two of the three vertices of each triangle are taken from adjacent vertices on a subdivided edge of one triangle; the third is one of the vertices on the corresponding edge of the other triangle. If the innermost triangle is degenerate (i.e., a point), the triangle containing it is subdivided into six triangles by connecting each of the six vertices on that triangle with the center point. If the innermost triangle is not degenerate, that triangle is added to the set of generated triangles as-is.
After the area corresponding to any inner triangles is filled, the tessellator generates triangles to cover the area between the outermost triangle and the outermost inner triangle. To do this, the temporary subdivision of the outer triangle edge above is discarded. Instead, the \( u = 0, v = 0, \) and \( w = 0 \) edges are subdivided according to the first, second, and third outer tessellation levels, respectively, and the tessellation spacing. The original subdivision of the first inner triangle is retained. The area between the outer and first inner triangles is completely filled by non-overlapping triangles as described above. If the first (and only) inner triangle is degenerate, a set of triangles is produced by connecting each vertex on the outer triangle edges with the center point.

After all triangles are generated, each vertex in the subdivided triangle is assigned a barycentric \((u,v,w)\) coordinate based on its location relative to the three vertices of the outer triangle.

The algorithm used to subdivide the triangular domain in \((u,v,w)\) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles.

Output triangles are generated with a topology similar to triangle lists, except that the order in which each triangle is generated, and the order in which the vertices are generated for each triangle, are implementation-dependent. However, the order of vertices in each triangle is consistent across the domain as described in Tessellator Vertex Winding Order.

### 22.7. Quad Tessellation

If the tessellation primitive mode is Quads, a rectangle is subdivided into a collection of triangles covering the area of the original rectangle. First, the original rectangle is subdivided into a regular mesh of rectangles, where the number of rectangles along the \( u = 0 \) and \( u = 1 \) (vertical) and \( v = 0 \) and \( v = 1 \) (horizontal) edges are derived from the first and second inner tessellation levels, respectively. All rectangles, except those adjacent to one of the outer rectangle edges, are decomposed into triangle pairs. The outermost rectangle edges are subdivided independently, using the first, second, third, and fourth outer tessellation levels to control the number of subdivisions of the \( u = 0 \) (left), \( v = 0 \) (bottom), \( u = 1 \) (right), and \( v = 1 \) (top) edges, respectively. The area between the inner rectangles of the mesh and the outer rectangle edges are filled by triangles produced by joining the vertices on the subdivided outer edges to the vertices on the edge of the inner rectangle mesh.

If both clamped inner tessellation levels and all four clamped outer tessellation levels are exactly one, only a single triangle pair covering the outer rectangle is generated. Otherwise, if either clamped inner tessellation level is one, that tessellation level is treated as though it was originally specified as \( 1 + \varepsilon \) and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce inner vertices positioned on the edge of the rectangle.

If any tessellation level is greater than one, tessellation begins by subdividing the \( u = 0 \) and \( u = 1 \) edges of the outer rectangle into \( m \) segments using the clamped and rounded first inner tessellation level and the tessellation spacing. The \( v = 0 \) and \( v = 1 \) edges are subdivided into \( n \) segments using the second inner tessellation level. Each vertex on the \( u = 0 \) and \( v = 0 \) edges are joined with the corresponding vertex on the \( u = 1 \) and \( v = 1 \) edges to produce a set of vertical and horizontal lines that divide the rectangle into a grid of smaller rectangles. The primitive generator emits a pair of
non-overlapping triangles covering each such rectangle not adjacent to an edge of the outer rectangle. The boundary of the region covered by these triangles forms an inner rectangle, the edges of which are subdivided by the grid vertices that lie on the edge. If either \( m \) or \( n \) is two, the inner rectangle is degenerate, and one or both of the rectangle’s edges consist of a single point. This subdivision is illustrated in Figure Inner Quad Tessellation.

![Inner Quad Tessellation Diagram](image)

**Figure 14. Inner Quad Tessellation**

**Caption**

In the **Inner Quad Tessellation** diagram, inner quad tessellation levels of (a) \((4,2)\) and (b) \((7,4)\) are shown. The regions highlighted in red in figure (b) depict the 10 inner rectangles, each of which will be subdivided into two triangles. Solid black circles depict vertices on the boundary of the outer and inner rectangles, where the inner rectangle of figure (a) is degenerate (a single line segment). Dotted lines depict the horizontal and vertical edges connecting corresponding vertices on the inner and outer rectangle edges.

After the area corresponding to the inner rectangle is filled, the tessellator **must** produce triangles to cover the area between the inner and outer rectangles. To do this, the subdivision of the outer rectangle edge above is discarded. Instead, the \( u = 0, v = 0, u = 1, \) and \( v = 1 \) edges are subdivided according to the first, second, third, and fourth outer tessellation levels, respectively, and the tessellation spacing. The original subdivision of the inner rectangle is retained. The area between the outer and inner rectangles is completely filled by non-overlapping triangles. Two of the three vertices of each triangle are adjacent vertices on a subdivided edge of one rectangle; the third is one of the vertices on the corresponding edge of the other rectangle. If either edge of the innermost rectangle is degenerate, the area near the corresponding outer edges is filled by connecting each vertex on the outer edge with the single vertex making up the inner edge.

The algorithm used to subdivide the rectangular domain in \((u,v)\) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles.

Output triangles are generated with a topology similar to **triangle lists**, except that the order in which each triangle is generated, and the order in which the vertices are generated for each triangle, are implementation-dependent. However, the order of vertices in each triangle is
consistent across the domain as described in Tessellator Vertex Winding Order.

### 22.8. Isoline Tessellation

If the tessellation primitive mode is **IsoLines**, a set of independent horizontal line segments is drawn. The segments are arranged into connected strips called **isolines**, where the vertices of each isoline have a constant v coordinate and u coordinates covering the full range \([0,1]\). The number of isolines generated is derived from the first outer tessellation level; the number of segments in each isoline is derived from the second outer tessellation level. Both inner tessellation levels and the third and fourth outer tessellation levels have no effect in this mode.

As with quad tessellation above, isoline tessellation begins with a rectangle. The \(u = 0\) and \(u = 1\) edges of the rectangle are subdivided according to the first outer tessellation level. For the purposes of this subdivision, the tessellation spacing mode is ignored and treated as equal_spacing. An isoline is drawn connecting each vertex on the \(u = 0\) rectangle edge to the corresponding vertex on the \(u = 1\) rectangle edge, except that no line is drawn between \((0,1)\) and \((1,1)\). If the number of isolines on the subdivided \(u = 0\) and \(u = 1\) edges is \(n\), this process will result in \(n\) equally spaced lines with constant v coordinates of \(0, \frac{1}{n}, \frac{2}{n}, ..., \frac{n-1}{n}\).

Each of the \(n\) isolines is then subdivided according to the second outer tessellation level and the tessellation spacing, resulting in \(m\) line segments. Each segment of each line is emitted by the tessellator. These line segments are generated with a topology similar to **line lists**, except that the order in which each line is generated, and the order in which the vertices are generated for each line segment, are implementation-dependent.

### 22.9. Tessellation Point Mode

For all primitive modes, the tessellator is capable of generating points instead of lines or triangles. If the tessellation control or tessellation evaluation shader specifies the **OpExecutionMode PointMode**, the primitive generator will generate one point for each distinct vertex produced by tessellation, rather than emitting triangles or lines. Otherwise, the tessellator will produce a collection of line segments or triangles according to the primitive mode. These points are generated with a topology similar to **point lists**, except the order in which the points are generated for each input primitive is undefined.

### 22.10. Tessellation Pipeline State

The **pTessellationState** member of **VkGraphicsPipelineCreateInfo** is a pointer to a **VkPipelineTessellationStateCreateInfo** structure.

The **VkPipelineTessellationStateCreateInfo** structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineTessellationStateCreateInfo {
    VkStructureType sType;
    const void*pNext;
    VkPipelineTessellationStateCreateFlags flags;
} VkPipelineTessellationStateCreateInfo;
```
uint32_t patchControlPoints;
} VkPipelineTessellationStateCreateInfo;

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `patchControlPoints` is the number of control points per patch.

### Valid Usage

- VUID-VkPipelineTessellationStateCreateInfo-patchControlPoints-01214
  `patchControlPoints` must be greater than zero and less than or equal to `VkPhysicalDeviceLimits::maxTessellationPatchSize`

### Valid Usage (Implicit)

- VUID-VkPipelineTessellationStateCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO`
- VUID-VkPipelineTessellationStateCreateInfo-pNext-pNext
  `pNext` must be `NULL` or a pointer to a valid instance of `VkPipelineTessellationDomainOriginStateCreateInfo`
- VUID-VkPipelineTessellationStateCreateInfo-sType-unique
  The `sType` value of each struct in the `pNext` chain must be unique
- VUID-VkPipelineTessellationStateCreateInfo-flags-zerobitmask
  `flags` must be `0`

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineTessellationStateCreateFlags;
```

`VkPipelineTessellationStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The `VkPipelineTessellationDomainOriginStateCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPipelineTessellationDomainOriginStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkTessellationDomainOrigin domainOrigin;
} VkPipelineTessellationDomainOriginStateCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
• \textit{pNext} is NULL or a pointer to a structure extending this structure.

• \textit{domainOrigin} is a \texttt{VkTessellationDomainOrigin} value controlling the origin of the tessellation domain space.

If the \texttt{VkPipelineTessellationDomainOriginStateCreateInfo} structure is included in the \textit{pNext} chain of \texttt{VkPipelineTessellationStateCreateInfo}, it controls the origin of the tessellation domain. If this structure is not present, it is as if \textit{domainOrigin} was \texttt{VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT}.

**Valid Usage (Implicit)**

- VUID-VkPipelineTessellationDomainOriginStateCreateInfo-sType-sType \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO}

- VUID-VkPipelineTessellationDomainOriginStateCreateInfo-domainOrigin-parameter \textit{domainOrigin} must be a valid \texttt{VkTessellationDomainOrigin} value

The possible tessellation domain origins are specified by the \texttt{VkTessellationDomainOrigin} enumeration:

```c
// Provided by VK_VERSION_1_1
typedef enum VkTessellationDomainOrigin {
    VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT = 0,
    VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT = 1,
} VkTessellationDomainOrigin;
```

- \texttt{VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT} specifies that the origin of the domain space is in the upper left corner, as shown in figure \textit{Domain parameterization for tessellation primitive modes (upper-left origin)}.

- \texttt{VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT} specifies that the origin of the domain space is in the lower left corner, as shown in figure \textit{Domain parameterization for tessellation primitive modes (lower-left origin)}.

This enum affects how the \texttt{VertexOrderCw} and \texttt{VertexOrderCcw} tessellation execution modes are interpreted, since the winding is defined relative to the orientation of the domain.
Chapter 23. Geometry Shading

The geometry shader operates on a group of vertices and their associated data assembled from a single input primitive, and emits zero or more output primitives and the group of vertices and their associated data required for each output primitive. Geometry shading is enabled when a geometry shader is included in the pipeline.

23.1. Geometry Shader Input Primitives

Each geometry shader invocation has access to all vertices in the primitive (and their associated data), which are presented to the shader as an array of inputs.

The input primitive type expected by the geometry shader is specified with an `OpExecutionMode` instruction in the geometry shader, and **must** match the incoming primitive type specified by either the pipeline's **primitive topology** if tessellation is inactive, or the **tessellation mode** if tessellation is active, as follows:

- **An input primitive type of InputPoints** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_POINT_LIST`, or with a tessellation shader specifying `PointMode`. The input arrays always contain one element, as described by the **point list topology** or **tessellation in point mode**.

- **An input primitive type of InputLines** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_LINE_LIST` or `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP`, or with a tessellation shader specifying `IsoLines` that does not specify `PointMode`. The input arrays always contain two elements, as described by the **line list topology** or **line strip topology**, or by **isoline tessellation**.

- **An input primitive type of InputLinesAdjacency** **must** only be used when tessellation is inactive, with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY`. The input arrays always contain four elements, as described by the **line list with adjacency topology** or **line strip with adjacency topology**.

- **An input primitive type of Triangles** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`, or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`; or with a tessellation shader specifying `Quads` or `Triangles` that does not specify `PointMode`. The input arrays always contain three elements, as described by the **triangle list topology**, **triangle strip topology**, or **triangle fan topology**, or by **triangle or quad tessellation**. Vertices **may** be in a different absolute order than specified by the topology, but **must** adhere to the specified winding order.

- **An input primitive type of InputTrianglesAdjacency** **must** only be used when tessellation is inactive, with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY`. The input arrays always contain six elements, as described by the **triangle list with adjacency topology** or **triangle strip with adjacency topology**. Vertices **may** be in a different absolute order than specified by the topology, but **must** adhere to the specified winding order, and the vertices making up the main primitive **must** still occur at the first, third, and fifth index.
23.2. Geometry Shader Output Primitives

A geometry shader generates primitives in one of three output modes: points, line strips, or triangle strips. The primitive mode is specified in the shader using an `OpExecutionMode` instruction with the `OutputPoints`, `OutputLineStrip` or `OutputTriangleStrip` modes, respectively. Each geometry shader must include exactly one output primitive mode.

The vertices output by the geometry shader are assembled into points, lines, or triangles based on the output primitive type and the resulting primitives are then further processed as described in Rasterization. If the number of vertices emitted by the geometry shader is not sufficient to produce a single primitive, vertices corresponding to incomplete primitives are not processed by subsequent pipeline stages. The number of vertices output by the geometry shader is limited to a maximum count specified in the shader.

The maximum output vertex count is specified in the shader using an `OpExecutionMode` instruction with the mode set to `OutputVertices` and the maximum number of vertices that will be produced by the geometry shader specified as a literal. Each geometry shader must specify a maximum output vertex count.

23.3. Multiple Invocations of Geometry Shaders

Geometry shaders can be invoked more than one time for each input primitive. This is known as geometry shader instancing and is requested by including an `OpExecutionMode` instruction with `mode` specified as `Invocations` and the number of invocations specified as an integer literal.

In this mode, the geometry shader will execute at least \( n \) times for each input primitive, where \( n \) is the number of invocations specified in the `OpExecutionMode` instruction. The instance number is available to each invocation as a built-in input using `InvocationId`.

23.4. Geometry Shader Primitive Ordering

Limited guarantees are provided for the relative ordering of primitives produced by a geometry shader, as they pertain to primitive order.

- For instanced geometry shaders, the output primitives generated from each input primitive are passed to subsequent pipeline stages using the invocation number to order the primitives, from least to greatest.
- All output primitives generated from a given input primitive are passed to subsequent pipeline stages before any output primitives generated from subsequent input primitives.
Chapter 24. Fixed-Function Vertex Post-Processing

After pre-rasterization shader stages, the following fixed-function operations are applied to vertices of the resulting primitives:

- Flat shading (see Flat Shading).
- Primitive clipping, including client-defined half-spaces (see Primitive Clipping).
- Shader output attribute clipping (see Clipping Shader Outputs).
- Perspective division on clip coordinates (see Coordinate Transformations).
- Viewport mapping, including depth range scaling (see Controlling the Viewport).
- Front face determination for polygon primitives (see Basic Polygon Rasterization).

Next, rasterization is performed on primitives as described in chapter Rasterization.

24.1. Flat Shading

Flat shading a vertex output attribute means to assign all vertices of the primitive the same value for that output. The output values assigned are those of the provoking vertex of the primitive. Flat shading is applied to those vertex attributes that match fragment input attributes which are decorated as Flat.

If neither geometry nor tessellation shading is active, the provoking vertex is determined by the primitive topology defined by VkPipelineInputAssemblyStateCreateInfo:topology used to execute the drawing command.

If geometry shading is active, the provoking vertex is determined by the primitive topology defined by the OutputPoints, OutputLineStrips, or OutputTriangleStrips execution mode.

If tessellation shading is active but geometry shading is not, the provoking vertex may be any of the vertices in each primitive.

24.2. Primitive Clipping

Primitives are culled against the cull volume and then clipped to the clip volume. In clip coordinates, the view volume is defined by:

\[-W_c \leq x_c \leq W_c\]
\[-W_c \leq y_c \leq W_c\]
\[-z_m \leq z_c \leq W_c\]

where \(z_m\) is equal to zero.

This view volume can be further restricted by as many as VkPhysicalDeviceLimits:maxClipDistances client-defined half-spaces.
The cull volume is the intersection of up to `VkPhysicalDeviceLimits::maxCullDistances` client-defined half-spaces (if no client-defined cull half-spaces are enabled, culling against the cull volume is skipped).

A shader **must** write a single cull distance for each enabled cull half-space to elements of the `CullDistance` array. If the cull distance for any enabled cull half-space is negative for all of the vertices of the primitive under consideration, the primitive is discarded. Otherwise the primitive is clipped against the clip volume as defined below.

The clip volume is the intersection of up to `VkPhysicalDeviceLimits::maxClipDistances` client-defined half-spaces with the view volume (if no client-defined clip half-spaces are enabled, the clip volume is the view volume).

A shader **must** write a single clip distance for each enabled clip half-space to elements of the `ClipDistance` array. Clip half-space $i$ is then given by the set of points satisfying the inequality

$$c_i(P) \geq 0$$

where $c_i(P)$ is the clip distance $i$ at point $P$. For point primitives, $c_i(P)$ is simply the clip distance for the vertex in question. For line and triangle primitives, per-vertex clip distances are interpolated using a weighted mean, with weights derived according to the algorithms described in sections Basic Line Segment Rasterization and Basic Polygon Rasterization, using the perspective interpolation equations.

The number of client-defined clip and cull half-spaces that are enabled is determined by the explicit size of the built-in arrays `ClipDistance` and `CullDistance`, respectively, declared as an output in the interface of the entry point of the final shader stage before clipping.

Depth clamping is enabled or disabled via the `depthClampEnable` enable of the `VkPipelineRasterizationStateCreateInfo` structure. Depth clipping is disabled when `depthClampEnable` is `VK_TRUE`.

When depth clipping is disabled, the plane equation

$$z_m \leq z_c \leq w_c$$

(see the clip volume definition above) is ignored by view volume clipping (effectively, there is no near or far plane clipping).

If the primitive under consideration is a point or line segment, then clipping passes it unchanged if its vertices lie entirely within the clip volume.

Possible values of `VkPhysicalDevicePointClippingProperties::pointClippingBehavior`, specifying clipping behavior of a point primitive whose vertex lies outside the clip volume, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkPointClippingBehavior {
    VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIP_PLANES = 0,
    // ...
} VkPointClippingBehavior;
```
VK_POINT_CLIPPING_BEHAVIOR_USER_CLIP_PLANES_ONLY = 1,
} VkPointClippingBehavior;

- **VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIP_PLANES** specifies that the primitive is discarded if the vertex lies outside any clip plane, including the planes bounding the view volume.

- **VK_POINT_CLIPPING_BEHAVIOR_USER_CLIP_PLANES_ONLY** specifies that the primitive is discarded only if the vertex lies outside any user clip plane.

If either of a line segment’s vertices lie outside of the clip volume, the line segment may be clipped, with new vertex coordinates computed for each vertex that lies outside the clip volume. A clipped line segment endpoint lies on both the original line segment and the boundary of the clip volume.

This clipping produces a value, $0 \leq t \leq 1$, for each clipped vertex. If the coordinates of a clipped vertex are $P$ and the unclipped line segment’s vertex coordinates are $P_1$ and $P_2$, then $t$ satisfies the following equation

$$P = tP_1 + (1-t)P_2.$$ $t$ is used to clip vertex output attributes as described in Clipping Shader Outputs.

If the primitive is a polygon, it passes unchanged if every one of its edges lies entirely inside the clip volume, and is either clipped or discarded otherwise. If the edges of the polygon intersect the boundary of the clip volume, the intersecting edges are reconnected by new edges that lie along the boundary of the clip volume - in some cases requiring the introduction of new vertices into a polygon.

If a polygon intersects an edge of the clip volume’s boundary, the clipped polygon must include a point on this boundary edge.

Primitives rendered with user-defined half-spaces must satisfy a complementarity criterion. Suppose a series of primitives is drawn where each vertex $i$ has a single specified clip distance $d_i$ (or a number of similarly specified clip distances, if multiple half-spaces are enabled). Next, suppose that the same series of primitives are drawn again with each such clip distance replaced by $-d_i$ (and the graphics pipeline is otherwise the same). In this case, primitives must not be missing any pixels, and pixels must not be drawn twice in regions where those primitives are cut by the clip planes.

### 24.3. Clipping Shader Outputs

Next, vertex output attributes are clipped. The output values associated with a vertex that lies within the clip volume are unaffected by clipping. If a primitive is clipped, however, the output values assigned to vertices produced by clipping are clipped.

Let the output values assigned to the two vertices $P_1$ and $P_2$ of an unclipped edge be $c_1$ and $c_2$. The value of $t$ (see Primitive Clipping) for a clipped point $P$ is used to obtain the output value associated with $P$ as
\[ c = t \, c_1 + (1-t) \, c_2. \]

(Multiplying an output value by a scalar means multiplying each of \( x, y, z, \) and \( w \) by the scalar.)

Since this computation is performed in clip space before division by \( w \), clipped output values are perspective-correct.

Polygon clipping creates a clipped vertex along an edge of the clip volume’s boundary. This situation is handled by noting that polygon clipping proceeds by clipping against one half-space at a time. Output value clipping is done in the same way, so that clipped points always occur at the intersection of polygon edges (possibly already clipped) with the clip volume’s boundary.

For vertex output attributes whose matching fragment input attributes are decorated with \texttt{NoPerspective}, the value of \( t \) used to obtain the output value associated with \( P \) will be adjusted to produce results that vary linearly in framebuffer space.

Output attributes of integer or unsigned integer type \textbf{must} always be flat shaded. Flat shaded attributes are constant over the primitive being rasterized (see Basic Line Segment Rasterization and Basic Polygon Rasterization), and no interpolation is performed. The output value \( c \) is taken from either \( c_1 \) or \( c_2 \), since flat shading has already occurred and the two values are identical.

### 24.4. Coordinate Transformations

\textit{Clip coordinates} for a vertex result from shader execution, which yields a vertex coordinate \texttt{Position}.

Perspective division on clip coordinates yields \textit{normalized device coordinates}, followed by a \texttt{viewport} transformation (see Controlling the Viewport) to convert these coordinates into \textit{framebuffer coordinates}.

If a vertex in clip coordinates has a position given by

\[
\begin{pmatrix}
  x_c \\
  y_c \\
  z_c \\
  w_c
\end{pmatrix}
\]

then the vertex’s normalized device coordinates are

\[
\begin{pmatrix}
  x_d \\
  y_d \\
  z_d
\end{pmatrix} = \begin{pmatrix}
  x_c \\
  y_c \\
  z_c \\
  w_c
\end{pmatrix}
\]
24.5. Controlling the Viewport

The viewport transformation is determined by the selected viewport’s width and height in pixels, \( p_x \) and \( p_y \), respectively, and its center \((o_x, o_y)\) (also in pixels), as well as its depth range min and max determining a depth range scale value \( p_z \) and a depth range bias value \( o_z \) (defined below). The vertex’s framebuffer coordinates \((x_f, y_f, z_f)\) are given by

\[
\begin{align*}
    x_f &= \left(\frac{p_x}{2}\right) x_d + o_x \\
    y_f &= \left(\frac{p_y}{2}\right) y_d + o_y \\
    z_f &= p_z \times z_d + o_z
\end{align*}
\]

Multiple viewports are available, numbered zero up to \( \text{VkPhysicalDeviceLimits::maxViewports} \) minus one. The number of viewports used by a pipeline is controlled by the \text{viewportCount} member of the \text{VkPipelineViewportStateCreateInfo} structure used in pipeline creation.

\( x_f \) and \( y_f \) have limited precision, where the number of fractional bits retained is specified by \( \text{VkPhysicalDeviceLimits::subPixelPrecisionBits} \).

The \text{VkPipelineViewportStateCreateInfo} structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineViewportStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineViewportStateCreateFlags flags;
    uint32_t viewportCount;
    const VkViewport* pViewports;
    uint32_t scissorCount;
    const VkRect2D* pScissors;
} VkPipelineViewportStateCreateInfo;
```

- \text{sType} is a \text{VkStructureType} value identifying this structure.
- \text{pNext} is NULL or a pointer to a structure extending this structure.
- \text{flags} is reserved for future use.
- \text{viewportCount} is the number of viewports used by the pipeline.
- \text{pViewports} is a pointer to an array of \text{VkViewport} structures, defining the viewport transforms. If the viewport state is dynamic, this member is ignored.
- \text{scissorCount} is the number of \text{scissors} and \text{must} match the number of viewports.
- \text{pScissors} is a pointer to an array of \text{VkRect2D} structures defining the rectangular bounds of the scissor for the corresponding viewport. If the scissor state is dynamic, this member is ignored.
Valid Usage

- VUID-VkPipelineViewportStateCreateInfo-viewportCount-01216
  If the multiViewport feature is not enabled, viewportCount must not be greater than 1

- VUID-VkPipelineViewportStateCreateInfo-scissorCount-01217
  If the multiViewport feature is not enabled, scissorCount must not be greater than 1

- VUID-VkPipelineViewportStateCreateInfo-viewportCount-01218
  viewportCount must be less than or equal to VkPhysicalDeviceLimits::maxViewports

- VUID-VkPipelineViewportStateCreateInfo-scissorCount-01219
  scissorCount must be less than or equal to VkPhysicalDeviceLimits::maxViewports

- VUID-VkPipelineViewportStateCreateInfo-x-02821
  The x and y members of offset member of any element of pScissors must be greater than or equal to 0

- VUID-VkPipelineViewportStateCreateInfo-offset-02822
  Evaluation of (offset.x + extent.width) must not cause a signed integer addition overflow for any element of pScissors

- VUID-VkPipelineViewportStateCreateInfo-offset-02823
  Evaluation of (offset.y + extent.height) must not cause a signed integer addition overflow for any element of pScissors

- VUID-VkPipelineViewportStateCreateInfo-scissorCount-04134
  If scissorCount and viewportCount are both not dynamic, then scissorCount and viewportCount must be identical

- VUID-VkPipelineViewportStateCreateInfo-viewportCount-04135
  If the graphics pipeline is being created with VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT set then viewportCount must be 0, otherwise it must be greater than 0

- VUID-VkPipelineViewportStateCreateInfo-scissorCount-04136
  If the graphics pipeline is being created with VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT set then scissorCount must be 0, otherwise it must be greater than 0

Valid Usage (Implicit)

- VUID-VkPipelineViewportStateCreateInfo-sType-sType
  sType must be VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO

- VUID-VkPipelineViewportStateCreateInfo-pNext-pNext
  pNext must be NULL

- VUID-VkPipelineViewportStateCreateInfo-flags-zerobitmask
  flags must be 0

To dynamically set the viewport count and viewports, call:

```c
// Provided by VK_VERSION_1_3
```
void vkCmdSetViewportWithCount(
    VkCommandBuffer commandBuffer, 
    uint32_t viewportCount, 
    const VkViewport* pViewports);

- `commandBuffer` is the command buffer into which the command will be recorded.
- `viewportCount` specifies the viewport count.
- `pViewports` specifies the viewports to use for drawing.

This command sets the viewport count and viewports state for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the corresponding `VkPipelineViewportStateCreateInfo::viewportCount` and `pViewports` values used to create the currently active pipeline.

### Valid Usage

- VUID-vkCmdSetViewportWithCount-None-08971
  At least one of the following must be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3
  - VUID-vkCmdSetViewportWithCount-viewportCount-03394
    `viewportCount` must be between 1 and `VkPhysicalDeviceLimits::maxViewports`, inclusive
  - VUID-vkCmdSetViewportWithCount-viewportCount-03395
    If the `multiViewport` feature is not enabled, `viewportCount` must be 1

### Valid Usage (Implicit)

- VUID-vkCmdSetViewportWithCount-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- VUID-vkCmdSetViewportWithCount-pViewports-parameter
  `pViewports` must be a valid pointer to an array of `viewportCount` valid `VkViewport` structures
- VUID-vkCmdSetViewportWithCount-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdSetViewportWithCount-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- VUID-vkCmdSetViewportWithCount-viewportCount-arraylength
  `viewportCount` must be greater than 0
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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</table>

To dynamically set the scissor count and scissor rectangular bounds, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetScissorWithCount(
    VkCommandBuffer commandBuffer,
    uint32_t scissorCount,
    const VkRect2D* pScissors);
```

- commandBuffer is the command buffer into which the command will be recorded.
- scissorCount specifies the scissor count.
- pScissors specifies the scissors to use for drawing.

This command sets the scissor count and scissor rectangular bounds state for subsequent drawing commands when the graphics pipeline is created with VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT set in VkPipelineDynamicStateCreateInfo::pDynamicStates. Otherwise, this state is specified by the corresponding VkPipelineViewportStateCreateInfo::scissorCount and pScissors values used to create the currently active pipeline.

Valid Usage

- VUID-vkCmdSetScissorWithCount-None-08971
  At least one of the following must be true:
  - the value of VkApplicationInfo::apiVersion used to create the VkInstance parent of commandBuffer is greater than or equal to Version 1.3
- VUID-vkCmdSetScissorWithCount-scissorCount-03397
  scissorCount must be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
- VUID-vkCmdSetScissorWithCount-scissorCount-03398
  If the multiViewport feature is not enabled, scissorCount must be 1
• VUID-vkCmdSetScissorWithCount-x-03399
  The x and y members of offset member of any element of pScissors must be greater than or equal to 0

• VUID-vkCmdSetScissorWithCount-offset-03400
  Evaluation of (offset.x + extent.width) must not cause a signed integer addition overflow for any element of pScissors

• VUID-vkCmdSetScissorWithCount-offset-03401
  Evaluation of (offset.y + extent.height) must not cause a signed integer addition overflow for any element of pScissors

Valid Usage (Implicit)

• VUID-vkCmdSetScissorWithCount-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

• VUID-vkCmdSetScissorWithCount-pScissors-parameter
  pScissors must be a valid pointer to an array of scissorCount VkRect2D structures

• VUID-vkCmdSetScissorWithCount-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdSetScissorWithCount-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

• VUID-vkCmdSetScissorWithCount-scissorCount-arraylength
  scissorCount must be greater than 0

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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<tbody>
<tr>
<td>Primary Secondary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
</tbody>
</table>

// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineViewportStateCreateFlags;
VkPipelineViewportStateCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

A pre-rasterization shader stage can direct each primitive to one of several viewports. The destination viewport for a primitive is selected by the last active pre-rasterization shader stage that has an output variable decorated with ViewportIndex. The viewport transform uses the viewport corresponding to the value assigned to ViewportIndex, and taken from an implementation-dependent vertex of each primitive. If ViewportIndex is outside the range zero to viewportCount minus one for a primitive, or if the last active pre-rasterization shader stage did not assign a value to ViewportIndex for all vertices of a primitive due to flow control, the values resulting from the viewport transformation of the vertices of such primitives are undefined. If the last pre-rasterization shader stage does not have an output decorated with ViewportIndex, the viewport numbered zero is used by the viewport transformation.

A single vertex can be used in more than one individual primitive, in primitives such as VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP. In this case, the viewport transformation is applied separately for each primitive.

To dynamically set the viewport transformation parameters, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetViewport(
    VkCommandBuffer commandBuffer,
    uint32_t firstViewport,
    uint32_t viewportCount,
    const VkViewport* pViewports);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `firstViewport` is the index of the first viewport whose parameters are updated by the command.
- `viewportCount` is the number of viewports whose parameters are updated by the command.
- `pViewports` is a pointer to an array of `VkViewport` structures specifying viewport parameters.

This command sets the viewport transformation parameters state for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_VIEWPORT` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineViewportStateCreateInfo::pViewports` values used to create the currently active pipeline.

The viewport parameters taken from element `i` of `pViewports` replace the current state for the viewport index `firstViewport + i`, for `i` in `[0, viewportCount).

### Valid Usage

- VUID-vkCmdSetViewport-firstViewport-01223
  The sum of `firstViewport` and `viewportCount` must be between 1 and `VkPhysicalDeviceLimits::maxViewports`, inclusive
- VUID-vkCmdSetViewport-firstViewport-01224
If the multiViewport feature is not enabled, firstViewport must be 0

- VUID-vkCmdSetViewport-viewportCount-01225
If the multiViewport feature is not enabled, viewportCount must be 1

Valid Usage (Implicit)

- VUID-vkCmdSetViewport-commandBuffer-parameter
commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdSetViewport-pViewports-parameter
pViewports must be a valid pointer to an array of viewportCount valid VkViewport structures

- VUID-vkCmdSetViewport-commandBuffer-recording
commandBuffer must be in the recording state

- VUID-vkCmdSetViewport-commandBuffer-cmdpool
The VkCommandPool that commandBuffer was allocated from must support graphics operations

- VUID-vkCmdSetViewport-viewportCount-arraylength
viewportCount must be greater than 0

Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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</tr>
<tr>
<td>Secondary</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Both VkPipelineViewportStateCreateInfo and vkCmdSetViewport use VkViewport to set the viewport transformation parameters.

The VkViewport structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkViewport {
    float   x;
    float   y;
};
```
float width;
float height;
float minDepth;
float maxDepth;
} VkViewport;

• $x$ and $y$ are the viewport's upper left corner ($x,y$).
• $width$ and $height$ are the viewport's width and height, respectively.
• $minDepth$ and $maxDepth$ are the depth range for the viewport.

**Note**
Despite their names, $minDepth$ **can** be less than, equal to, or greater than $maxDepth$.

The framebuffer depth coordinate $z_f$ may be represented using either a fixed-point or floating-point representation. However, a floating-point representation **must** be used if the depth/stencil attachment has a floating-point depth component. If an $m$-bit fixed-point representation is used, we assume that it represents each value $\frac{k}{2^m-1}$, where $k \in \{0, 1, ..., 2^m-1\}$, as $k$ (e.g. 1.0 is represented in binary as a string of all ones).

The viewport parameters shown in the above equations are found from these values as

$$o_x = x + \frac{width}{2}$$

$$o_y = y + \frac{height}{2}$$

$$o_z = minDepth$$

$$p_x = width$$

$$p_y = height$$

$$p_z = maxDepth - minDepth$$

The application **can** specify a negative term for $height$, which has the effect of negating the $y$ coordinate in clip space before performing the transform. When using a negative $height$, the application **should** also adjust the $y$ value to point to the lower left corner of the viewport instead of the upper left corner. Using the negative $height$ allows the application to avoid having to negate the $y$ component of the $Position$ output from the last pre-rasterization shader stage.

The width and height of the **implementation-dependent maximum viewport dimensions** **must** be greater than or equal to the width and height of the largest image which **can** be created and
attached to a framebuffer.

The floating-point viewport bounds are represented with an implementation-dependent precision.

Valid Usage

- VUID-VkViewport-width-01770
  width must be greater than 0.0

- VUID-VkViewport-width-01771
  width must be less than or equal to VkPhysicalDeviceLimits::maxViewportDimensions[0]

- VUID-VkViewport-apiVersion-07917
  If the VK_KHR_maintenance1 extension is not enabled, the VK_AMD_negative_viewport_height extension is not enabled, and VkPhysicalDeviceProperties::apiVersion is less than Vulkan 1.1, height must be greater than 0.0

- VUID-VkViewport-height-01773
  The absolute value of height must be less than or equal to VkPhysicalDeviceLimits::maxViewportDimensions[1]

- VUID-VkViewport-x-01774
  x must be greater than or equal to viewportBoundsRange[0]

- VUID-VkViewport-x-01232
  (x + width) must be less than or equal to viewportBoundsRange[1]

- VUID-VkViewport-y-01775
  y must be greater than or equal to viewportBoundsRange[0]

- VUID-VkViewport-y-01776
  y must be less than or equal to viewportBoundsRange[1]

- VUID-VkViewport-y-01777
  (y + height) must be greater than or equal to viewportBoundsRange[0]

- VUID-VkViewport-y-01233
  (y + height) must be less than or equal to viewportBoundsRange[1]

- VUID-VkViewport-minDepth-02540
  minDepth must be between 0.0 and 1.0, inclusive

- VUID-VkViewport-maxDepth-02541
  maxDepth must be between 0.0 and 1.0, inclusive
Chapter 25. Rasterization

Rasterization is the process by which a primitive is converted to a two-dimensional image. Each discrete location of this image contains associated data such as depth, color, or other attributes.

Rasterizing a primitive begins by determining which squares of an integer grid in framebuffer coordinates are occupied by the primitive, and assigning one or more depth values to each such square. This process is described below for points, lines, and polygons.

A grid square, including its (x,y) framebuffer coordinates, z (depth), and associated data added by fragment shaders, is called a fragment. A fragment is located by its upper left corner, which lies on integer grid coordinates.

Rasterization operations also refer to a fragment’s sample locations, which are offset by fractional values from its upper left corner. The rasterization rules for points, lines, and triangles involve testing whether each sample location is inside the primitive. Fragments need not actually be square, and rasterization rules are not affected by the aspect ratio of fragments. Display of non-square grids, however, will cause rasterized points and line segments to appear fatter in one direction than the other.

We assume that fragments are square, since it simplifies antialiasing and texturing. After rasterization, fragments are processed by fragment operations.

Several factors affect rasterization, including the members of VkPipelineRasterizationStateCreateInfo and VkPipelineMultisampleStateCreateInfo.

The VkPipelineRasterizationStateCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineRasterizationStateCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkPipelineRasterizationStateCreateFlags flags;
    VkBool32                  depthClampEnable;
    VkBool32                  rasterizerDiscardEnable;
    VkPolygonMode             polygonMode;
    VkCullModeFlags           cullMode;
    VkFrontFace               frontFace;
    VkBool32                  depthBiasEnable;
    float                     depthBiasConstantFactor;
    float                     depthBiasClamp;
    float                     depthBiasSlopeFactor;
    float                     lineWidth;
} VkPipelineRasterizationStateCreateInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **flags** is reserved for future use.
• `depthClampEnable` controls whether to clamp the fragment’s depth values as described in Depth Test. Enabling depth clamp will also disable clipping primitives to the z planes of the frustrum as described in Primitive Clipping.

• `rasterizerDiscardEnable` controls whether primitives are discarded immediately before the rasterization stage.

• `polygonMode` is the triangle rendering mode. See VkPolygonMode.

• `cullMode` is the triangle facing direction used for primitive culling. See VkCullModeFlagBits.

• `frontFace` is a VkFrontFace value specifying the front-facing triangle orientation to be used for culling.

• `depthBiasEnable` controls whether to bias fragment depth values.

• `depthBiasConstantFactor` is a scalar factor controlling the constant depth value added to each fragment.

• `depthBiasClamp` is the maximum (or minimum) depth bias of a fragment.

• `depthBiasSlopeFactor` is a scalar factor applied to a fragment's slope in depth bias calculations.

• `lineWidth` is the width of rasterized line segments.

---

**Valid Usage**

- VUID-VkPipelineRasterizationStateCreateInfo-depthClampEnable-00782
  If the depthClamp feature is not enabled, `depthClampEnable` must be VK_FALSE

- VUID-VkPipelineRasterizationStateCreateInfo-polygonMode-01413
  If the fillModeNonSolid feature is not enabled, `polygonMode` must be VK_POLYGON_MODE_FILL

---

**Valid Usage (Implicit)**

- VUID-VkPipelineRasterizationStateCreateInfo-sType-sType
  `sType` must be VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO

- VUID-VkPipelineRasterizationStateCreateInfo-pNext-pNext
  `pNext` must be NULL

- VUID-VkPipelineRasterizationStateCreateInfo-flags-zerobitmask
  `flags` must be 0

- VUID-VkPipelineRasterizationStateCreateInfo-polygonMode-parameter
  `polygonMode` must be a valid VkPolygonMode value

- VUID-VkPipelineRasterizationStateCreateInfo-cullMode-parameter
  `cullMode` must be a valid combination of VkCullModeFlagBits values

- VUID-VkPipelineRasterizationStateCreateInfo-frontFace-parameter
  `frontFace` must be a valid VkFrontFace value

---

// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineRasterizationStateCreateFlags;

VkPipelineRasterizationStateCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

The VkPipelineMultisampleStateCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineMultisampleStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineMultisampleStateCreateFlags flags;
    VkSampleCountFlagBits rasterizationSamples;
    VkBool32 sampleShadingEnable;
    float minSampleShading;
    const VkSampleMask* pSampleMask;
    VkBool32 alphaToCoverageEnable;
    VkBool32 alphaToOneEnable;
} VkPipelineMultisampleStateCreateInfo;
```

- `sType` is a VkStructureType value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `rasterizationSamples` is a VkSampleCountFlagBits value specifying the number of samples used in rasterization.
- `sampleShadingEnable` can be used to enable Sample Shading.
- `minSampleShading` specifies a minimum fraction of sample shading if `sampleShadingEnable` is set to VK_TRUE.
- `pSampleMask` is a pointer to an array of VkSampleMask values used in the sample mask test.
- `alphaToCoverageEnable` controls whether a temporary coverage value is generated based on the alpha component of the fragment’s first color output as specified in the Multisample Coverage section.
- `alphaToOneEnable` controls whether the alpha component of the fragment’s first color output is replaced with one as described in Multisample Coverage.

Each bit in the sample mask is associated with a unique sample index as defined for the coverage mask. Each bit b for mask word w in the sample mask corresponds to sample index i, where i = 32 × w + b. pSampleMask has a length equal to ⌈rasterizationSamples / 32⌉ words.

If `pSampleMask` is NULL, it is treated as if the mask has all bits set to 1.

Valid Usage

- VUID-VkPipelineMultisampleStateCreateInfo-sampleShadingEnable-00784
If the `sampleRateShading` feature is not enabled, `sampleShadingEnable` must be `VK_FALSE`.

- VUID-VkPipelineMultisampleStateCreateInfo-alphaToOneEnable-00785
  If the `alphaToOne` feature is not enabled, `alphaToOneEnable` must be `VK_FALSE`.

- VUID-VkPipelineMultisampleStateCreateInfo-minSampleShading-00786
  `minSampleShading` must be in the range `[0,1]`.

### Valid Usage (Implicit)

- VUID-VkPipelineMultisampleStateCreateInfo-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO`.

- VUID-VkPipelineMultisampleStateCreateInfo-pNext-pNext
  `pNext` must be `NULL`.

- VUID-VkPipelineMultisampleStateCreateInfo-flags-zeroBitmask
  `flags` must be `0`.

- VUID-VkPipelineMultisampleStateCreateInfo-rasterizationSamples-parameter
  `rasterizationSamples` must be a valid `VkSampleCountFlagBits` value.

- VUID-VkPipelineMultisampleStateCreateInfo-pSampleMask-parameter
  If `pSampleMask` is not `NULL`, `pSampleMask` must be a valid pointer to an array of `VkSampleMask` values.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkPipelineMultisampleStateCreateFlags;
```

`VkPipelineMultisampleStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The elements of the sample mask array are of type `VkSampleMask`, each representing 32 bits of coverage information:

```c
// Provided by VK_VERSION_1_0
typedef uint32_t VkSampleMask;
```

Rasterization only generates fragments which cover one or more pixels inside the framebuffer. Pixels outside the framebuffer are never considered covered in the fragment. Fragments which would be produced by application of any of the primitive rasterization rules described below but which lie outside the framebuffer are not produced, nor are they processed by any later stage of the pipeline, including any of the fragment operations.

Surviving fragments are processed by fragment shaders. Fragment shaders determine associated data for fragments, and can also modify or replace their assigned depth values.
25.1. Discarding Primitives Before Rasterization

Primitives are discarded before rasterization if the `rasterizerDiscardEnable` member of `VkPipelineRasterizationStateCreateInfo` is enabled. When enabled, primitives are discarded after they are processed by the last active shader stage in the pipeline before rasterization.

To **dynamically enable** whether primitives are discarded before the rasterization stage, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetRasterizerDiscardEnable(
    VkCommandBuffer commandBuffer,       // commandBuffer is the command buffer into which the command will be recorded.
    VkBool32 rasterizerDiscardEnable);   // rasterizerDiscardEnable controls whether primitives are discarded immediately before the rasterization stage.
```

This command sets the discard enable for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineRasterizationStateCreateInfo::rasterizerDiscardEnable` value used to create the currently active pipeline.

### Valid Usage

- **VUID-vkCmdSetRasterizerDiscardEnable-None-08970**
  At least one of the following **must** be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- **VUID-vkCmdSetRasterizerDiscardEnable-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- **VUID-vkCmdSetRasterizerDiscardEnable-commandBuffer-recording**
  `commandBuffer` **must** be in the `recording state`
- **VUID-vkCmdSetRasterizerDiscardEnable-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

### Command Properties

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<tbody>
<tr>
<td>Primary Secondary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
</tbody>
</table>

#### 25.2. Rasterization Order

Within a subpass of a render pass instance, for a given (x,y,layer,sample) sample location, the following operations are guaranteed to execute in rasterization order, for each separate primitive that includes that sample location:

1. **Fragment operations**, in the order defined
2. **Blending, logic operations**, and color writes

Execution of these operations for each primitive in a subpass occurs in **primitive order**.

#### 25.3. Multisampling

Multisampling is a mechanism to antialias all Vulkan primitives: points, lines, and polygons. The technique is to sample all primitives multiple times at each pixel. Each sample in each framebuffer attachment has storage for a color, depth, and/or stencil value, such that per-fragment operations apply to each sample independently. The color sample values can be later resolved to a single color (see Resolving Multisample Images and the Render Pass chapter for more details on how to resolve multisample images to non-multisample images).

Vulkan defines rasterization rules for single-sample modes in a way that is equivalent to a multisample mode with a single sample in the center of each fragment.

Each fragment includes a coverage mask with a single bit for each sample in the fragment, and a number of depth values and associated data for each sample.

It is understood that each pixel has `rasterizationSamples` locations associated with it. These locations are exact positions, rather than regions or areas, and each is referred to as a sample point. The sample points associated with a pixel must be located inside or on the boundary of the unit square that is considered to bound the pixel. Furthermore, the relative locations of sample points may be identical for each pixel in the framebuffer, or they may differ.

If the current pipeline includes a fragment shader with one or more variables in its interface decorated with `Sample` and `Input`, the data associated with those variables will be assigned independently for each sample. The values for each sample must be evaluated at the location of the
sample. The data associated with any other variables not decorated with Sample and Input need not be evaluated independently for each sample.

A coverage mask is generated for each fragment, based on which samples within that fragment are determined to be within the area of the primitive that generated the fragment.

Single pixel fragments have one set of samples. Each set of samples has a number of samples determined by VkPipelineMultisampleStateCreateInfo::rasterizationSamples. Each sample in a set is assigned a unique sample index \(i\) in the range \([0, \text{rasterizationSamples})\).

Each sample in a fragment is also assigned a unique coverage index \(j\) in the range \([0, n \times \text{rasterizationSamples})\), where \(n\) is the number of sets in the fragment. If the fragment contains a single set of samples, the coverage index is always equal to the sample index.

The coverage mask includes \(B\) bits packed into \(W\) words, defined as:

\[
B = n \times \text{rasterizationSamples}
\]

\[
W = \lceil B/32 \rceil
\]

Bit \(b\) in coverage mask word \(w\) is 1 if the sample with coverage index \(j = 32 \times w + b\) is covered, and 0 otherwise.

If the standardSampleLocations member of VkPhysicalDeviceLimits is VK_TRUE, then the sample counts VK_SAMPLE_COUNT_1_BIT, VK_SAMPLE_COUNT_2_BIT, VK_SAMPLE_COUNT_4_BIT, VK_SAMPLE_COUNT_8_BIT, and VK_SAMPLE_COUNT_16_BIT have sample locations as listed in the following table, with the \(i\)th entry in the table corresponding to sample index \(i\). VK_SAMPLE_COUNT_32_BIT and VK_SAMPLE_COUNT_64_BIT do not have standard sample locations. Locations are defined relative to an origin in the upper left corner of the fragment.
Table 24. Standard sample locations

<table>
<thead>
<tr>
<th>Sample count</th>
<th>Sample Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_SAMPLE_COUNT_1_BIT</td>
<td>(0.5,0.5)</td>
</tr>
<tr>
<td>VK_SAMPLE_COUNT_2_BIT</td>
<td>(0.75,0.75) (0.25,0.25)</td>
</tr>
<tr>
<td>VK_SAMPLE_COUNT_4_BIT</td>
<td>(0.375, 0.125) (0.875, 0.375) (0.125, 0.625) (0.625, 0.875)</td>
</tr>
<tr>
<td>VK_SAMPLE_COUNT_8_BIT</td>
<td>(0.5625, 0.3125) (0.4375, 0.6875) (0.8125, 0.5625) (0.3125, 0.1875) (0.1875, 0.8125) (0.0625, 0.4375) (0.6875, 0.9375) (0.9375, 0.0625)</td>
</tr>
<tr>
<td>VK_SAMPLE_COUNT_16_BIT</td>
<td>(0.5625, 0.5625) (0.4375, 0.3125) (0.3125, 0.625) (0.75, 0.4375) (0.1875, 0.375) (0.625, 0.8125) (0.8125, 0.6875) (0.6875, 0.1875) (0.375, 0.875) (0.5, 0.0625) (0.25, 0.125) (0.125, 0.75) (0.0, 0.5) (0.9375, 0.25) (0.875, 0.9375) (0.0625, 0.0)</td>
</tr>
</tbody>
</table>
25.4. Sample Shading

Sample shading can be used to specify a minimum number of unique samples to process for each fragment. If sample shading is enabled, an implementation must invoke the fragment shader at least \( \max(\lceil \text{VkPipelineMultisampleStateCreateInfo::minSampleShading} \times \text{VkPipelineMultisampleStateCreateInfo::rasterizationSamples} \rceil, 1) \) times per fragment. If \( \text{VkPipelineMultisampleStateCreateInfo::sampleShadingEnable} \) is set to \( \text{VK_TRUE} \), sample shading is enabled.

If a fragment shader entry point statically uses an input variable decorated with a \text{BuiltIn} of \text{SampleId} or \text{SamplePosition}, sample shading is enabled and a value of 1.0 is used instead of \text{minSampleShading}. If a fragment shader entry point statically uses an input variable decorated with \text{Sample}, sample shading may be enabled and a value of 1.0 will be used instead of \text{minSampleShading} if it is.

Note

If a shader decorates an input variable with \text{Sample} and that value meaningfully impacts the output of a shader, sample shading will be enabled to ensure that the input is in fact interpolated per-sample. This is inherent to the specification and not spelled out here - if an application simply declares such a variable it is implementation-defined whether sample shading is enabled or not. It is possible to see the effects of this by using atomics in the shader or using a pipeline statistics query to query the number of fragment invocations, even if the shader itself does not use any per-sample variables.

If there are fewer fragment invocations than covered samples, implementations may include those samples in fragment shader invocations in any manner as long as covered samples are all shaded at least once, and each invocation that is not a helper invocation covers at least one sample.

25.5. Points

A point is drawn by generating a set of fragments in the shape of a square centered around the vertex of the point. Each vertex has an associated point size controlling the width/height of that square. The point size is taken from the (potentially clipped) shader built-in \text{PointSize} written by:

- the geometry shader, if active;
- the tessellation evaluation shader, if active and no geometry shader is active;
- the vertex shader, otherwise

and clamped to the implementation-dependent point size range \([\text{pointSizeRange}[0], \text{pointSizeRange}[1]]\). The value written to \text{PointSize} must be greater than zero.

Not all point sizes need be supported, but the size 1.0 must be supported. The range of supported sizes and the size of evenly-spaced gradations within that range are implementation-dependent. The range and gradations are obtained from the \text{pointSizeRange} and \text{pointSizeGranularity} members of \text{VkPhysicalDeviceLimits}. If, for instance, the size range is from 0.1 to 2.0 and the gradation size is 0.1, then the sizes 0.1, 0.2, ..., 1.9, 2.0 are supported. Additional point sizes may also be supported.
There is no requirement that these sizes be equally spaced. If an unsupported size is requested, the nearest supported size is used instead.

25.5.1. Basic Point Rasterization

Point rasterization produces a fragment for each fragment area group of framebuffer pixels with one or more sample points that intersect a region centered at the point’s \((x_f, y_f)\). This region is a square with side equal to the current point size. Coverage bits that correspond to sample points that intersect the region are 1, other coverage bits are 0. All fragments produced in rasterizing a point are assigned the same associated data, which are those of the vertex corresponding to the point. However, the fragment shader built-in `PointCoord` contains point sprite texture coordinates. The \(s\) and \(t\) point sprite texture coordinates vary from zero to one across the point horizontally left-to-right and vertically top-to-bottom, respectively. The following formulas are used to evaluate \(s\) and \(t\):

\[
\begin{align*}
    s &= \frac{1}{2} + \frac{(x_p - x_f)}{\text{size}} \\
    t &= \frac{1}{2} + \frac{(y_p - y_f)}{\text{size}}
\end{align*}
\]

where \(\text{size}\) is the point's size; \((x_p,y_p)\) is the location at which the point sprite coordinates are evaluated - this may be the framebuffer coordinates of the fragment center, or the location of a sample; and \((x_f,y_f)\) is the exact, unrounded framebuffer coordinate of the vertex for the point.

25.6. Line Segments

To dynamically set the line width, call:

```cpp
// Provided by VK_VERSION_1_0
void vkCmdSetLineWidth(
    VkCommandBuffer commandBuffer, 
    float lineWidth);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `lineWidth` is the width of rasterized line segments.

This command sets the line width for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_LINE_WIDTH` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineRasterizationStateCreateInfo::lineWidth` value used to create the currently active pipeline.

### Valid Usage

- VUID-vkCmdSetLineWidth-lineWidth-00788
  If the `wideLines` feature is not enabled, `lineWidth` must be 1.0
Valid Usage (Implicit)

- VUID-vkCmdSetLineWidth-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- VUID-vkCmdSetLineWidth-commandBuffer-recording
  `commandBuffer` must be in the recording state

- VUID-vkCmdSetLineWidth-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not all line widths need be supported for line segment rasterization, but width 1.0 antialiased segments must be provided. The range and gradations are obtained from the `lineWidthRange` and `lineWidthGranularity` members of `VkPhysicalDeviceLimits`. If, for instance, the size range is from 0.1 to 2.0 and the gradation size is 0.1, then the sizes 0.1, 0.2, ..., 1.9, 2.0 are supported. Additional line widths may also be supported. There is no requirement that these widths be equally spaced. If an unsupported width is requested, the nearest supported width is used instead.

25.6.1. Basic Line Segment Rasterization

Rasterized line segments produce fragments which intersect a rectangle centered on the line segment. Two of the edges are parallel to the specified line segment; each is at a distance of one-half the current width from that segment in directions perpendicular to the direction of the line. The other two edges pass through the line endpoints and are perpendicular to the direction of the specified line segment. Coverage bits that correspond to sample points that intersect the rectangle are 1, other coverage bits are 0.

Next we specify how the data associated with each rasterized fragment are obtained. Let \( p_r = (x_d, y_d) \) be the framebuffer coordinates at which associated data are evaluated. This may be the center of a fragment or the location of a sample within the fragment. When `rasterizationSamples` is `VK_SAMPLE_COUNT_1_BIT`, the fragment center must be used. Let \( p_a = (x_a, y_a) \) and \( p_b = (x_b, y_b) \) be initial
and final endpoints of the line segment, respectively. Set

\[ t = \frac{(\mathbf{p}_r - \mathbf{p}_a) \cdot (\mathbf{p}_b - \mathbf{p}_a)}{\| \mathbf{p}_b - \mathbf{p}_a \|^2} \]

(Note that \( t = 0 \) at \( \mathbf{p}_a \) and \( t = 1 \) at \( \mathbf{p}_b \). Also note that this calculation projects the vector from \( \mathbf{p}_a \) to \( \mathbf{p}_r \) onto the line, and thus computes the normalized distance of the fragment along the line.)

If \( \text{strictLines} \) is \( \text{VK_TRUE} \), line segments are rasterized using perspective or linear interpolation.

**Perspective interpolation** for a line segment interpolates two values in a manner that is correct when taking the perspective of the viewport into consideration, by way of the line segment’s clip coordinates. An interpolated value \( f \) can be determined by

\[ f = \frac{(1 - t)f_a / w_a + t f_b / w_b}{(1 - t) / w_a + t / w_b} \]

where \( f_a \) and \( f_b \) are the data associated with the starting and ending endpoints of the segment, respectively; \( w_a \) and \( w_b \) are the clip \( w \) coordinates of the starting and ending endpoints of the segment, respectively.

**Linear interpolation** for a line segment directly interpolates two values, and an interpolated value \( f \) can be determined by

\[ f = (1 - t) f_a + t f_b \]

where \( f_a \) and \( f_b \) are the data associated with the starting and ending endpoints of the segment, respectively.

The clip coordinate \( w \) for a sample is determined using perspective interpolation. The depth value \( z \) for a sample is determined using linear interpolation. Interpolation of fragment shader input values are determined by **Interpolation decorations**.

The above description documents the preferred method of line rasterization, and **must** be used when the implementation advertises the **strictLines** limit in **VkPhysicalDeviceLimits** as **VK_TRUE**.

When **strictLines** is **VK_FALSE**, the edges of the lines are generated as a parallelogram surrounding the original line. The major axis is chosen by noting the axis in which there is the greatest distance between the line start and end points. If the difference is equal in both directions then the X axis is chosen as the major axis. Edges 2 and 3 are aligned to the minor axis and are centered on the endpoints of the line as in **Non strict lines**, and each is **lineWidth** long. Edges 0 and 1 are parallel to the line and connect the endpoints of edges 2 and 3. Coverage bits that correspond to sample points that intersect the parallelogram are 1, other coverage bits are 0.

Samples that fall exactly on the edge of the parallelogram follow the polygon rasterization rules.

Interpolation occurs as if the parallelogram was decomposed into two triangles where each pair of vertices at each end of the line has identical attributes.
Only when `strictLines` is `VK_FALSE` implementations may deviate from the non-strict line algorithm described above in the following ways:

- Implementations may instead interpolate each fragment according to the formula in Basic Line Segment Rasterization using the original line segment endpoints.
- Rasterization of non-antialiased non-strict line segments may be performed using the rules defined in Bresenham Line Segment Rasterization.

### 25.6.2. Bresenham Line Segment Rasterization

Non-strict lines may also follow these rasterization rules for non-antialiased lines.

Line segment rasterization begins by characterizing the segment as either x-major or y-major. x-major line segments have slope in the closed interval \([-1,1]\); all other line segments are y-major (slope is determined by the segment's endpoints). We specify rasterization only for x-major segments except in cases where the modifications for y-major segments are not self-evident.

Ideally, Vulkan uses a diamond-exit rule to determine those fragments that are produced by rasterizing a line segment. For each fragment \(f\) with center at framebuffer coordinates \(x_f\) and \(y_f\), define a diamond-shaped region that is the intersection of four half planes:

\[
R_f = \{(x, y) \mid |x - x_f| + |y - y_f| < \frac{1}{2}\}
\]

Essentially, a line segment starting at \(p_a\) and ending at \(p_b\) produces those fragments \(f\) for which the segment intersects \(R_c\) except if \(p_b\) is contained in \(R_c\).
To avoid difficulties when an endpoint lies on a boundary of $R_f$ we (in principle) perturb the supplied endpoints by a tiny amount. Let $p_a$ and $p_b$ have framebuffer coordinates $(x_a, y_a)$ and $(x_b, y_b)$, respectively. Obtain the perturbed endpoints $p'_a$ given by $(x_a, y_a) - (\epsilon, \epsilon^2)$ and $p'_b$ given by $(x_b, y_b) - (\epsilon, \epsilon^2)$. Rasterizing the line segment starting at $p_a$ and ending at $p_b$ produces those fragments $f$ for which the segment starting at $p'_a$ and ending on $p'_b$ intersects $R_f$, except if $p'_b$ is contained in $R_f$. $\epsilon$ is chosen to be so small that rasterizing the line segment produces the same fragments when $\delta$ is substituted for $\epsilon$ for any $0 < \delta \leq \epsilon$.

When $p_a$ and $p_b$ lie on fragment centers, this characterization of fragments reduces to Bresenham’s algorithm with one modification: lines produced in this description are “half-open”, meaning that the final fragment (corresponding to $p_b$) is not drawn. This means that when rasterizing a series of connected line segments, shared endpoints will be produced only once rather than twice (as would occur with Bresenham’s algorithm).

Implementations may use other line segment rasterization algorithms, subject to the following rules:

- The coordinates of a fragment produced by the algorithm must not deviate by more than one unit in either x or y framebuffer coordinates from a corresponding fragment produced by the diamond-exit rule.
- The total number of fragments produced by the algorithm must not differ from that produced by the diamond-exit rule by no more than one.
- For an x-major line, two fragments that lie in the same framebuffer-coordinate column must not be produced (for a y-major line, two fragments that lie in the same framebuffer-coordinate row must not be produced).
- If two line segments share a common endpoint, and both segments are either x-major (both left-to-right or both right-to-left) or y-major (both bottom-to-top or both top-to-bottom), then rasterizing both segments must not produce duplicate fragments. Fragments also must not be omitted so as to interrupt continuity of the connected segments.

The actual width \( w \) of Bresenham lines is determined by rounding the line width to the nearest integer, clamping it to the implementation-dependent `lineWidthRange` (with both values rounded to the nearest integer), then clamping it to be no less than 1.

Bresenham line segments of width other than one are rasterized by offsetting them in the minor direction (for an x-major line, the minor direction is y, and for a y-major line, the minor direction is x) and producing a row or column of fragments in the minor direction. If the line segment has endpoints given by \((x_0, y_0)\) and \((x_1, y_1)\) in framebuffer coordinates, the segment with endpoints \((x_0, y_0 - \frac{w-1}{2})\) and \((x_1, y_1 - \frac{w-1}{2})\) is rasterized, but instead of a single fragment, a column of fragments of height \( w \) (a row of fragments of length \( w \) for a y-major segment) is produced at each x (y for y-major) location. The lowest fragment of this column is the fragment that would be produced by rasterizing the segment of width 1 with the modified coordinates.

The preferred method of attribute interpolation for a wide line is to generate the same attribute values for all fragments in the row or column described above, as if the adjusted line was used for interpolation and those values replicated to the other fragments, except for `FragCoord` which is interpolated as usual. Implementations may instead interpolate each fragment according to the formula in `Basic Line Segment Rasterization`, using the original line segment endpoints.

When Bresenham lines are being rasterized, sample locations may all be treated as being at the pixel center (this may affect attribute and depth interpolation).

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<td>The sample locations described above are not used for determining coverage, they are only used for things like attribute interpolation. The rasterization rules that determine coverage are defined in terms of whether the line intersects pixels, as opposed to the point sampling rules used for other primitive types. So these rules are independent of the sample locations. One consequence of this is that Bresenham lines cover the same pixels regardless of the number of rasterization samples, and cover all samples in those pixels (unless masked out or killed).</td>
</tr>
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</table>

### 25.7. Polygons

A polygon results from the decomposition of a triangle strip, triangle fan or a series of independent triangles. Like points and line segments, polygon rasterization is controlled by several variables in the `VkPipelineRasterizationStateCreateInfo` structure.

#### 25.7.1. Basic Polygon Rasterization

The first step of polygon rasterization is to determine whether the triangle is back-facing or front-facing. This determination is made based on the sign of the (clipped or unclipped) polygon’s area computed in framebuffer coordinates. One way to compute this area is:
\[ a = -\frac{1}{2} \sum_{i=0}^{n-1} x_i y_{i+1} - x_{i+1} y_i \]

where \( x_i \) and \( y_i \) are the x and y framebuffer coordinates of the \( i \)th vertex of the \( n \)-vertex polygon (vertices are numbered starting at zero for the purposes of this computation) and \( i \oplus 1 \) is \((i + 1) \mod n\).

The interpretation of the sign of \( a \) is determined by the `VkPipelineRasterizationStateCreateInfo`::`frontFace` property of the currently active pipeline. Possible values are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkFrontFace {
    VK_FRONT_FACE_COUNTER_CLOCKWISE = 0,
    VK_FRONT_FACE_CLOCKWISE = 1,
} VkFrontFace;
```

- `VK_FRONT_FACE_COUNTER_CLOCKWISE` specifies that a triangle with positive area is considered front-facing.
- `VK_FRONT_FACE_CLOCKWISE` specifies that a triangle with negative area is considered front-facing.

Any triangle which is not front-facing is back-facing, including zero-area triangles.

To **dynamically set** the front face orientation, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetFrontFace(
    VkCommandBuffer commandBuffer,
    VkFrontFace frontFace);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `frontFace` is a `VkFrontFace` value specifying the front-facing triangle orientation to be used for culling.

This command sets the front face orientation for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_FRONT_FACE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineRasterizationStateCreateInfo::frontFace` value used to create the currently active pipeline.

**Valid Usage**

- `VUID-vkCmdSetFrontFace-None-08971` At least one of the following **must** be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3
Valid Usage (Implicit)

- VUID-vkCmdSetFrontFace-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdSetFrontFace-frontFace-parameter
  frontFace must be a valid VkFace value

- VUID-vkCmdSetFrontFace-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdSetFrontFace-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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Once the orientation of triangles is determined, they are culled according to the VkPipelineRasterizationStateCreateInfo::cullMode property of the currently active pipeline. Possible values are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkCullModeFlagBits {
    VK_CULL_MODE_NONE = 0,
    VK_CULL_MODE_FRONT_BIT = 0x00000001,
    VK_CULL_MODE_BACK_BIT = 0x00000002,
    VK_CULL_MODE_FRONT_AND_BACK = 0x00000003,
} VkCullModeFlagBits;
```

- **VK_CULL_MODE_NONE** specifies that no triangles are discarded
- **VK_CULL_MODE_FRONT_BIT** specifies that front-facing triangles are discarded
- **VK_CULL_MODE_BACK_BIT** specifies that back-facing triangles are discarded
VK_CULL_MODE_FRONT_AND_BACK specifies that all triangles are discarded.

Following culling, fragments are produced for any triangles which have not been discarded.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkCullModeFlags;
```

**VkCullModeFlags** is a bitmask type for setting a mask of zero or more **VkCullModeFlagBits**.

To **dynamically set** the cull mode, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetCullMode(
    VkCommandBuffer commandBuffer,  
    VkCullModeFlags cullMode);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **cullMode** specifies the cull mode property to use for drawing.

This command sets the cull mode for subsequent drawing commands when the graphics pipeline is created with **VK_DYNAMIC_STATE_CULL_MODE** set in **VkPipelineDynamicStateCreateInfo::pDynamicStates**. Otherwise, this state is specified by the **VkPipelineRasterizationStateCreateInfo::cullMode** value used to create the currently active pipeline.

### Valid Usage

- **VUID-vkCmdSetCullMode-None-08971**
  At least one of the following **must** be true:
  - the value of **VkApplicationInfo::apiVersion** used to create the **VkInstance** parent of **commandBuffer** is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- **VUID-vkCmdSetCullMode-commandBuffer-parameter**
  **commandBuffer** **must** be a valid **VkCommandBuffer** handle
- **VUID-vkCmdSetCullMode-cullMode-parameter**
  **cullMode** **must** be a valid combination of **VkCullModeFlagBits** values
- **VUID-vkCmdSetCullMode-commandBuffer-recording**
  **commandBuffer** **must** be in the **recording state**
- **VUID-vkCmdSetCullMode-commandBuffer-cmdpool**
  The **VkCommandPool** that **commandBuffer** was allocated from **must** support graphics operations
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

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The rule for determining which fragments are produced by polygon rasterization is called point sampling. The two-dimensional projection obtained by taking the x and y framebuffer coordinates of the polygon’s vertices is formed. Fragments are produced for any fragment area groups of pixels for which any sample points lie inside of this polygon. Coverage bits that correspond to sample points that satisfy the point sampling criteria are 1, other coverage bits are 0. Special treatment is given to a sample whose sample location lies on a polygon edge. In such a case, if two polygons lie on either side of a common edge (with identical endpoints) on which a sample point lies, then exactly one of the polygons must result in a covered sample for that fragment during rasterization.

As for the data associated with each fragment produced by rasterizing a polygon, we begin by specifying how these values are produced for fragments in a triangle.

**Barycentric coordinates** are a set of three numbers, a, b, and c, each in the range [0,1], with a + b + c = 1. These coordinates uniquely specify any point p within the triangle or on the triangle’s boundary as

\[ p = a p_a + b p_b + c p_c \]

where \( p_a, p_b, \) and \( p_c \) are the vertices of the triangle. a, b, and c are determined by:

\[
\begin{align*}
    a &= \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)}, \\
    b &= \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)}, \\
    c &= \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)},
\end{align*}
\]

where \( A(lmn) \) denotes the area in framebuffer coordinates of the triangle with vertices l, m, and n.

Denote an associated datum at \( p_a, p_b, \) or \( p_c \) as \( f_a, f_b, \) or \( f_c, \) respectively.

**Perspective interpolation** for a triangle interpolates three values in a manner that is correct when taking the perspective of the viewport into consideration, by way of the triangle’s clip coordinates. An interpolated value \( f \) can be determined by

\[
f = \frac{a f_a / w_a + b f_b / w_b + c f_c / w_c}{a / w_a + b / w_b + c / w_c}
\]
where \( w_a, w_b, \) and \( w_c \) are the clip \( w \) coordinates of \( p_a, p_b, \) and \( p_c \) respectively. \( a, b, \) and \( c \) are the barycentric coordinates of the location at which the data are produced.

**Linear interpolation** for a triangle directly interpolates three values, and an interpolated value \( f \) can be determined by

\[
f = a f_a + b f_b + c f_c
\]

where \( f_a, f_b, \) and \( f_c \) are the data associated with \( p_a, p_b, \) and \( p_c, \) respectively.

The clip coordinate \( w \) for a sample is determined using perspective interpolation. The depth value \( z \) for a sample is determined using linear interpolation. Interpolation of fragment shader input values are determined by **Interpolation decorations**.

For a polygon with more than three edges, such as are produced by clipping a triangle, a convex combination of the values of the datum at the polygon’s vertices **must** be used to obtain the value assigned to each fragment produced by the rasterization algorithm. That is, it **must** be the case that at every fragment

\[
f = \sum_{i=1}^{n} a_i f_i
\]

where \( n \) is the number of vertices in the polygon and \( f_i \) is the value of \( f \) at vertex \( i \). For each \( i, 0 \leq a_i \leq 1 \) and \( \sum_{i=1}^{n} a_i = 1 \). The values of \( a_i \) **may** differ from fragment to fragment, but at vertex \( i \), \( a_i = 1 \) and \( a_j = 0 \) for \( j \neq i \).

---

**Note**

One algorithm that achieves the required behavior is to triangulate a polygon (without adding any vertices) and then treat each triangle individually as already discussed. A scan-line rasterizer that linearly interpolates data along each edge and then linearly interpolates data across each horizontal span from edge to edge also satisfies the restrictions (in this case the numerator and denominator of **perspective interpolation** are iterated independently, and a division is performed for each fragment).

### 25.7.2. Polygon Mode

Possible values of the `VkPipelineRasterizationStateCreateInfo::polygonMode` property of the currently active pipeline, specifying the method of rasterization for polygons, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkPolygonMode {
    VK_POLYGON_MODE_FILL = 0,
    VK_POLYGON_MODE_LINE = 1,
    VK_POLYGON_MODE_POINT = 2,
} VkPolygonMode;
```
• **VK_POLYGON_MODE_POINT** specifies that polygon vertices are drawn as points.
• **VK_POLYGON_MODE_LINE** specifies that polygon edges are drawn as line segments.
• **VK_POLYGON_MODE_FILL** specifies that polygons are rendered using the polygon rasterization rules in this section.

These modes affect only the final rasterization of polygons: in particular, a polygon’s vertices are shaded and the polygon is clipped and possibly culled before these modes are applied.

### 25.7.3. Depth Bias

The depth values of all fragments generated by the rasterization of a polygon can be biased (offset) by a single depth bias value $\delta$ that is computed for that polygon.

#### Depth Bias Enable

The depth bias computation is enabled by the `depthBiasEnable` set with `vkCmdSetDepthBiasEnable` or the corresponding `VkPipelineRasterizationStateCreateInfo::depthBiasEnable` value used to create the currently active pipeline. If the depth bias enable is `VK_FALSE`, no bias is applied and the fragment’s depth values are unchanged.

To dynamically enable whether to bias fragment depth values, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetDepthBiasEnable(
    VkCommandBuffer commandBuffer,
    VkBool32 depthBiasEnable);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `depthBiasEnable` controls whether to bias fragment depth values.

This command sets the depth bias enable for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineRasterizationStateCreateInfo::depthBiasEnable` value used to create the currently active pipeline.

### Valid Usage

- VUID-vkCmdSetDepthBiasEnable-None-08970
At least one of the following must be true:

  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3
Valid Usage (Implicit)

- VUID-vkCmdSetDepthBiasEnable-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle
- VUID-vkCmdSetDepthBiasEnable-commandBuffer-recording
  commandBuffer must be in the recording state
- VUID-vkCmdSetDepthBiasEnable-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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Depth Bias Computation

The depth bias depends on three parameters:

- $\text{depthBiasSlopeFactor}$ scales the maximum depth slope $m$ of the polygon
- $\text{depthBiasConstantFactor}$ scales the parameter $r$ of the depth attachment
- the scaled terms are summed to produce a value which is then clamped to a minimum or maximum value specified by $\text{depthBiasClamp}$

$\text{depthBiasSlopeFactor}, \text{depthBiasConstantFactor},$ and $\text{depthBiasClamp}$ can each be positive, negative, or zero. These parameters are set as described for $\text{vkCmdSetDepthBias}$ below.

The maximum depth slope $m$ of a triangle is

$$m = \sqrt{\left(\frac{\partial z_f}{\partial x_f}\right)^2 + \left(\frac{\partial z_f}{\partial y_f}\right)^2}$$

where $(x_0, y_0, z_0)$ is a point on the triangle. $m$ may be approximated as
\[ m = \max \left( \frac{\partial Z_f}{\partial x_f}, \frac{\partial Z_f}{\partial y_f} \right), \]

\( r \) is the minimum resolvable difference that depends on the depth attachment representation. It is the smallest difference in framebuffer coordinate \( z \) values that is guaranteed to remain distinct throughout polygon rasterization and in the depth attachment. All pairs of fragments generated by the rasterization of two polygons with otherwise identical vertices, but \( z_f \) values that differ by \( r \), will have distinct depth values.

For fixed-point depth attachment representations, \( r \) is constant throughout the range of the entire depth attachment.

Its value is implementation-dependent but \textbf{must} be at most

\[ r = 2 \times 2^n \]

where \( n \) is the number of bits used for the depth aspect.

For floating-point depth attachment, there is no single minimum resolvable difference. In this case, the minimum resolvable difference for a given polygon is dependent on the maximum exponent, \( e \), in the range of \( z \) values spanned by the primitive. If \( n \) is the number of bits in the floating-point mantissa, the minimum resolvable difference, \( r \), for the given primitive is defined as

\[ r = 2^e \cdot 2^{-n} \]

If no depth attachment is present, \( r \) is undefined.

The bias value \( o \) for a polygon is

\[ o = \text{dbclamp}(m \times \text{depthBiasSlopeFactor} + r \times \text{depthBiasConstantFactor}) \]

where \( \text{dbclamp}(x) = \begin{cases} 
  x & \text{depthBiasClamp} = 0 \text{ or } \text{NaN} \\
  \min(x, \text{depthBiasClamp}) & \text{depthBiasClamp} > 0 \\
  \max(x, \text{depthBiasClamp}) & \text{depthBiasClamp} < 0 
\end{cases} \]

\( m \) is computed as described above. If the depth attachment uses a fixed-point representation, \( m \) is a function of depth values in the range \([0,1]\), and \( o \) is applied to depth values in the same range.

Depth bias is applied to triangle topology primitives received by the rasterizer regardless of polygon mode. Depth bias \textbf{may} also be applied to line and point topology primitives received by the rasterizer.

To \textbf{dynamically set} the depth bias parameters, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetDepthBias(
    VkCommandBuffer commandBuffer,
    float depthBiasConstantFactor,
    float depthBiasClamp,
    float depthBiasSlopeFactor
);
```
float depthBiasSlopeFactor);

- **commandBuffer** is the command buffer into which the command will be recorded.
- **depthBiasConstantFactor** is a scalar factor controlling the constant depth value added to each fragment.
- **depthBiasClamp** is the maximum (or minimum) depth bias of a fragment.
- **depthBiasSlopeFactor** is a scalar factor applied to a fragment’s slope in depth bias calculations.

This command sets the depth bias parameters for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_BIAS` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the corresponding `VkPipelineRasterizationStateCreateInfo::depthBiasConstantFactor`, `depthBiasClamp`, and `depthBiasSlopeFactor` values used to create the currently active pipeline.

### Valid Usage

- VUID-vkCmdSetDepthBias-depthBiasClamp-00790
  If the `depthBiasClamp` feature is not enabled, `depthBiasClamp` must be 0.0

### Valid Usage (Implicit)

- VUID-vkCmdSetDepthBias-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- VUID-vkCmdSetDepthBias-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdSetDepthBias-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

### Command Properties

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Chapter 26. Fragment Operations

Fragments produced by rasterization go through a number of operations to determine whether or how values produced by fragment shading are written to the framebuffer.

The following fragment operations adhere to rasterization order, and are typically performed in this order:

1. Scissor test
2. Sample mask test
3. Certain Fragment shading operations:
   ◦ Sample Mask Accesses
   ◦ Depth Replacement
4. Multisample coverage
5. Depth bounds test
6. Stencil test
7. Depth test
8. Sample counting
9. Coverage reduction

The coverage mask generated by rasterization describes the initial coverage of each sample covered by the fragment. Fragment operations will update the coverage mask to add or subtract coverage where appropriate. If a fragment operation results in all bits of the coverage mask being 0, the fragment is discarded, and no further operations are performed. Fragments can also be programmatically discarded in a fragment shader by executing one of

- OpTerminateInvocation
- OpDemoteToHelperInvocationEXT
- OpKill.

When one of the fragment operations in this chapter is described as “replacing” a fragment shader output, that output is replaced unconditionally, even if no fragment shader previously wrote to that output.

If there is a fragment shader and it declares the EarlyFragmentTests execution mode, fragment shading and multisample coverage operations should instead be performed after sample counting, and sample mask test may instead be performed after sample counting.

For a pipeline with the following properties:

- a fragment shader is specified
- the fragment shader does not write to storage resources;
- the fragment shader specifies the DepthReplacing execution mode; and
• either
  ◦ the fragment shader specifies the `DepthUnchanged` execution mode;
  ◦ the fragment shader specifies the `DepthLess` execution mode and the pipeline uses a `VkPipelineDepthStencilStateCreateInfo::depthCompareOp` of `VK_COMPARE_OP_GREATER` or `VK_COMPARE_OP_GREATER_OR_EQUAL`; or
  ◦ the fragment shader specifies the `DepthGreater` execution mode and the pipeline uses a `VkPipelineDepthStencilStateCreateInfo::depthCompareOp` of `VK_COMPARE_OP_LESS` or `VK_COMPARE_OP_LESS_OR_EQUAL`.

The implementation may perform depth bounds test before fragment shading and perform an additional depth test immediately after that using the interpolated depth value generated by rasterization.

Once all fragment operations have completed, fragment shader outputs for covered color attachment samples pass through framebuffer operations.

### 26.1. Scissor Test

The scissor test compares the framebuffer coordinates `(x_f, y_f)` of each sample covered by a fragment against a scissor rectangle at the index equal to the fragment's `ViewportIndex`.

Each scissor rectangle is defined by a `VkRect2D`. These values are either set by the `VkPipelineViewportStateCreateInfo` structure during pipeline creation, or dynamically by the `vkCmdSetScissor` command.

A given sample is considered inside a scissor rectangle if `x_f` is in the range `[VkRect2D::offset.x, VkRect2D::offset.x + VkRect2D::extent.x)`, and `y_f` is in the range `[VkRect2D::offset.y, VkRect2D::offset.y + VkRect2D::extent.y)`. Samples with coordinates outside the scissor rectangle at the corresponding `ViewportIndex` will have their coverage set to 0.

To dynamically set the scissor rectangles, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetScissor(
    VkCommandBuffer commandBuffer,
    uint32_t firstScissor,
    uint32_t scissorCount,
    const VkRect2D* pScissors);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `firstScissor` is the index of the first scissor whose state is updated by the command.
- `scissorCount` is the number of scissors whose rectangles are updated by the command.
- `pScissors` is a pointer to an array of `VkRect2D` structures defining scissor rectangles.

The scissor rectangles taken from element `i` of `pScissors` replace the current state for the scissor index `firstScissor + i`, for `i` in `[0, scissorCount)`. 
This command sets the scissor rectangles for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_SCISSOR` set in `VkPipelineDynamicStateCreateInfo ::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineViewportStateCreateInfo ::pScissors` values used to create the currently active pipeline.

Valid Usage

- **VUID-vkCmdSetScissor-firstScissor-00592**
  The sum of `firstScissor` and `scissorCount` must be between 1 and `VkPhysicalDeviceLimits::maxViewports`, inclusive

- **VUID-vkCmdSetScissor-firstScissor-00593**
  If the `multiViewport` feature is not enabled, `firstScissor` must be 0

- **VUID-vkCmdSetScissor-scissorCount-00594**
  If the `multiViewport` feature is not enabled, `scissorCount` must be 1

- **VUID-vkCmdSetScissor-x-00595**
  The x and y members of `offset` member of any element of `pScissors` must be greater than or equal to 0

- **VUID-vkCmdSetScissor-offset-00596**
  Evaluation of `(offset.x + extent.width)` must not cause a signed integer addition overflow for any element of `pScissors`

- **VUID-vkCmdSetScissor-offset-00597**
  Evaluation of `(offset.y + extent.height)` must not cause a signed integer addition overflow for any element of `pScissors`

Valid Usage (Implicit)

- **VUID-vkCmdSetScissor-commandBuffer-parameter**
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- **VUID-vkCmdSetScissor-pScissors-parameter**
  `pScissors` must be a valid pointer to an array of `scissorCount` `VkRect2D` structures

- **VUID-vkCmdSetScissor-commandBuffer-recording**
  `commandBuffer` must be in the recording state

- **VUID-vkCmdSetScissor-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

- **VUID-vkCmdSetScissor-scissorCount-arraylength**
  `scissorCount` must be greater than 0

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

# Command Properties

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## 26.2. Sample Mask Test

The sample mask test compares the coverage mask for a fragment with the sample mask defined by `VkPipelineMultisampleStateCreateInfo::pSampleMask`.

Each bit of the coverage mask is associated with a sample index as described in the [rasterization chapter](#). If the bit in `VkPipelineMultisampleStateCreateInfo::pSampleMask` which is associated with that same sample index is set to 0, the coverage mask bit is set to 0.

## 26.3. Fragment Shading

Fragment shaders are invoked for each fragment, or as helper invocations.

Most operations in the fragment shader are not performed in rasterization order, with exceptions called out in the following sections.

For fragment shaders invoked by fragments, the following rules apply:

• A fragment shader must not be executed if a fragment operation that executes before fragment shading discards the fragment.

• A fragment shader may not be executed if:

  ◦ An implementation determines that another fragment shader, invoked by a subsequent primitive in primitive order, overwrites all results computed by the shader (including writes to storage resources).
  
  ◦ Any other fragment operation discards the fragment, and the shader does not write to any storage resources.

• Otherwise, at least one fragment shader must be executed.

  ◦ If sample shading is enabled and multiple invocations per fragment are required, additional invocations must be executed as specified.
  
  ◦ Each covered sample must be included in at least one fragment shader invocation.

If no fragment shader is included in the pipeline, no fragment shader is executed, and undefined values may be written to all color attachment outputs during this fragment operation.
Note

Multiple fragment shader invocations may be executed for the same fragment for any number of implementation-dependent reasons. When there is more than one fragment shader invocation per fragment, the association of samples to invocations is implementation-dependent. Stores and atomics performed by these additional invocations have the normal effect.

For example, if the subpass includes multiple views in its view mask, a fragment shader may be invoked separately for each view.

### 26.3.1. Sample Mask

Reading from the `SampleMask` built-in in the `Input` storage class will return the coverage mask for the current fragment as calculated by fragment operations that executed prior to fragment shading.

If `sample shading` is enabled, fragment shaders will only see values of `1` for samples being shaded - other bits will be `0`.

Each bit of the coverage mask is associated with a sample index as described in the rasterization chapter. If the bit in `SampleMask` which is associated with that same sample index is set to `0`, that coverage mask bit is set to `0`.

Values written to the `SampleMask` built-in in the `Output` storage class will be used by the multisample coverage operation, with the same encoding as the input built-in.

### 26.3.2. Depth Replacement

Writing to the `FragDepth` built-in will replace the fragment’s calculated depth values for each sample in the input `SampleMask`. Depth testing performed after the fragment shader for this fragment will use this new value as $z_f$.

### 26.4. Multisample Coverage

If a fragment shader is active and its entry point’s interface includes a built-in output variable decorated with `SampleMask`, the coverage mask is ANDed with the bits of the `SampleMask` built-in to generate a new coverage mask. If `sample shading` is enabled, bits written to `SampleMask` corresponding to samples that are not being shaded by the fragment shader invocation are ignored. If no fragment shader is active, or if the active fragment shader does not include `SampleMask` in its interface, the coverage mask is not modified.

Next, the fragment alpha value and coverage mask are modified based on the `alphaToCoverageEnable` and `alphaToOneEnable` members of the `VkPipelineMultisampleStateCreateInfo` structure.

All alpha values in this section refer only to the alpha component of the fragment shader output that has a `Location` and `Index` decoration of zero (see the Fragment Output Interface section). If that shader output has an integer or unsigned integer type, then these operations are skipped.
If `alphaToCoverageEnable` is enabled, a temporary coverage mask is generated where each bit is
determined by the fragment’s alpha value, which is ANDed with the fragment coverage mask.

No specific algorithm is specified for converting the alpha value to a temporary coverage mask. It is
intended that the number of 1’s in this value be proportional to the alpha value (clamped to \([0,1]\)),
with all 1’s corresponding to a value of 1.0 and all 0’s corresponding to 0.0. The algorithm may be
different at different framebuffer coordinates.

Note
Using different algorithms at different framebuffer coordinates may help to avoid
artifacts caused by regular coverage sample locations.

Finally, if `alphaToOneEnable` is enabled, each alpha value is replaced by the maximum representable
alpha value for fixed-point color attachments, or by 1.0 for floating-point attachments. Otherwise,
the alpha values are not changed.

26.5. Depth and Stencil Operations

Pipeline state controlling the depth bounds tests, stencil test, and depth test is specified through the
members of the `VkPipelineDepthStencilStateCreateInfo` structure.

The `VkPipelineDepthStencilStateCreateInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineDepthStencilStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineDepthStencilStateCreateFlags flags;
    VkBool32 depthTestEnable;
    VkBool32 depthWriteEnable;
    VkCompareOp depthCompareOp;
    VkBool32 depthBoundsTestEnable;
    VkBool32 stencilTestEnable;
    VkStencilOpState front;
    VkStencilOpState back;
    float minDepthBounds;
    float maxDepthBounds;
} VkPipelineDepthStencilStateCreateInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `flags` is reserved for future use.
- `depthTestEnable` controls whether depth testing is enabled.
- `depthWriteEnable` controls whether depth writes are enabled when `depthTestEnable` is `VK_TRUE`.
  Depth writes are always disabled when `depthTestEnable` is `VK_FALSE`.
- `depthCompareOp` is a `VkCompareOp` value specifying the comparison operator to use in the Depth
Comparison step of the depth test.

- **depthBoundsTestEnable** controls whether depth bounds testing is enabled.
- **stencilTestEnable** controls whether stencil testing is enabled.
- **front** and **back** are **VkStencilOpState** values controlling the corresponding parameters of the stencil test.
- **minDepthBounds** is the minimum depth bound used in the depth bounds test.
- **maxDepthBounds** is the maximum depth bound used in the depth bounds test.

**Valid Usage**

- VUID-VkPipelineDepthStencilStateCreateInfo-depthBoundsTestEnable-00598
  If the depthBounds feature is not enabled, depthBoundsTestEnable must be **VK_FALSE**

**Valid Usage (Implicit)**

- VUID-VkPipelineDepthStencilStateCreateInfo-sType-sType
  sType must be **VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO**
- VUID-VkPipelineDepthStencilStateCreateInfo-pNext-pNext
  pNext must be **NULL**
- VUID-VkPipelineDepthStencilStateCreateInfo-flags-zerobitmask
  flags must be 0
- VUID-VkPipelineDepthStencilStateCreateInfo-depthCompareOp-parameter
  depthCompareOp must be a valid **VkCompareOp** value
- VUID-VkPipelineDepthStencilStateCreateInfo-front-parameter
  front must be a valid **VkStencilOpState** structure
- VUID-VkPipelineDepthStencilStateCreateInfo-back-parameter
  back must be a valid **VkStencilOpState** structure

// Provided by VK VERSION 1.0
typedef VkFlags VkPipelineDepthStencilStateCreateFlags;

**VkPipelineDepthStencilStateCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

**26.6. Depth Bounds Test**

The depth bounds test compares the depth value \( z_i \) in the depth/stencil attachment at each sample’s framebuffer coordinates \( (x_f, y_f) \) and sample index \( i \) against a set of depth bounds.

The depth bounds are determined by two floating point values defining a minimum (minDepthBounds) and maximum (maxDepthBounds) depth value. These values are either set by the
VkPipelineDepthStencilStateCreateInfo structure during pipeline creation, or dynamically by vkCmdSetDepthBoundsTestEnable and vkCmdSetDepthBounds.

A given sample is considered within the depth bounds if \( z_a \) is in the range \([\text{minDepthBounds}, \text{maxDepthBounds}]\). Samples with depth attachment values outside of the depth bounds will have their coverage set to 0.

If the depth bounds test is disabled, or if there is no depth attachment, the coverage mask is unmodified by this operation.

To **dynamically enable or disable** the depth bounds test, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetDepthBoundsTestEnable(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer into which the command will be recorded.
    VkBool32 depthBoundsTestEnable  // depthBoundsTestEnable specifies if the depth bounds test is enabled.
);
```

This command sets the depth bounds enable for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineDepthStencilStateCreateInfo::depthBoundsTestEnable` value used to create the currently active pipeline.

### Valid Usage

- **VUID-vkCmdSetDepthBoundsTestEnable-None-08971**
  At least one of the following **must** be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- **VUID-vkCmdSetDepthBoundsTestEnable-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- **VUID-vkCmdSetDepthBoundsTestEnable-commandBuffer-recording**
  `commandBuffer` **must** be in the recording state
- **VUID-vkCmdSetDepthBoundsTestEnable-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

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To dynamically set the depth bounds range, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetDepthBounds(
    VkCommandBuffer commandBuffer,
    float minDepthBounds,
    float maxDepthBounds);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `minDepthBounds` is the minimum depth bound.
- `maxDepthBounds` is the maximum depth bound.

This command sets the depth bounds range for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_BOUNDS` set in `VkPipelineDynamicStateCreateInfo`::pDynamicStates. Otherwise, this state is specified by the `VkPipelineDepthStencilStateCreateInfo`::minDepthBounds and `VkPipelineDepthStencilStateCreateInfo`::maxDepthBounds values used to create the currently active pipeline.

Valid Usage

- VUID-vkCmdSetDepthBounds-minDepthBounds-02508
  `minDepthBounds` must be between 0.0 and 1.0, inclusive

- VUID-vkCmdSetDepthBounds-maxDepthBounds-02509
  `maxDepthBounds` must be between 0.0 and 1.0, inclusive

Valid Usage (Implicit)

- VUID-vkCmdSetDepthBounds-commandBuffer-parameter
**commandBuffer** must be a valid `VkCommandBuffer` handle

- VUID-vkCmdSetDepthBounds-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdSetDepthBounds-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

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**26.7. Stencil Test**

The stencil test compares the stencil attachment value $s_a$ in the depth/stencil attachment at each sample's framebuffer coordinates $(x_f, y_f)$ and sample index $i$ against a stencil reference value.

If the stencil test is not enabled, as specified by `vkCmdSetStencilTestEnable` or `VkPipelineDepthStencilStateCreateInfo::stencilTestEnable`, or if there is no stencil attachment, the coverage mask is unmodified by this operation.

The stencil test is controlled by one of two sets of stencil-related state, the front stencil state and the back stencil state. Stencil tests and writes use the back stencil state when processing fragments generated by back-facing polygons, and the front stencil state when processing fragments generated by front-facing polygons or any other primitives.

The comparison operation performed is determined by the `VkCompareOp` value set by `vkCmdSetStencilOp::compareOp`, or by `VkStencilOpState::compareOp` during pipeline creation.

The compare mask $s_c$ and stencil reference value $s_r$ of the front or the back stencil state set determine arguments of the comparison operation. $s_c$ is set by the `VkPipelineDepthStencilStateCreateInfo` structure during pipeline creation, or by the `vkCmdSetStencilCompareMask` command. $s_r$ is set by `VkPipelineDepthStencilStateCreateInfo` or by `vkCmdSetStencilReference`.

$s_r$ and $s_a$ are each independently combined with $s_c$ using a bitwise **AND** operation to create masked...
reference and attachment values \( s'_r \) and \( s'_a \). \( s'_r \) and \( s'_a \) are used as the reference and test values, respectively, in the operation specified by the \( \text{VkCompareOp} \).

If the comparison evaluates to false, the coverage for the sample is set to 0.

A new stencil value \( s_g \) is generated according to a stencil operation defined by \( \text{VkStencilOp} \) parameters set by \( \text{vkCmdSetStencilOp} \) or \( \text{VkPipelineDepthStencilStateCreateInfo} \). If the stencil test fails, \( \text{failOp} \) defines the stencil operation used. If the stencil test passes however, the stencil op used is based on the depth test - if it passes, \( \text{VkPipelineDepthStencilStateCreateInfo}::\text{passOp} \) is used, otherwise \( \text{VkPipelineDepthStencilStateCreateInfo}::\text{depthFailOp} \) is used.

The stencil attachment value \( s_a \) is then updated with the generated stencil value \( s_g \) according to the write mask \( s_w \) defined by \( \text{writeMask} \) in \( \text{VkPipelineDepthStencilStateCreateInfo}::\text{front} \) and \( \text{VkPipelineDepthStencilStateCreateInfo}::\text{back} \) as:

\[
    s_a = (s_a & \neg s_w) \lor (s_g & s_w)
\]

To dynamically enable or disable the stencil test, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetStencilTestEnable(
    VkCommandBuffer commandBuffer,
    VkBool32 stencilTestEnable);
```

- \( \text{commandBuffer} \) is the command buffer into which the command will be recorded.
- \( \text{stencilTestEnable} \) specifies if the stencil test is enabled.

This command sets the stencil test enable for subsequent drawing commands when the graphics pipeline is created with \( \text{VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE} \) set in \( \text{VkPipelineDynamicStateCreateInfo}::\text{pDynamicStates} \). Otherwise, this state is specified by the \( \text{VkPipelineDepthStencilStateCreateInfo}::\text{stencilTestEnable} \) value used to create the currently active pipeline.

### Valid Usage

- VUID-vkCmdSetStencilTestEnable-None-08971
  At least one of the following must be true:
  - the value of \( \text{VkApplicationInfo}::\text{apiVersion} \) used to create the \( \text{VkInstance} \) parent of \( \text{commandBuffer} \) is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- VUID-vkCmdSetStencilTestEnable-commandBuffer-parameter
  \( \text{commandBuffer} \) must be a valid \( \text{VkCommandBuffer} \) handle
- VUID-vkCmdSetStencilTestEnable-commandBuffer-recording
commandBuffer must be in the recording state

- VUID-vkCmdSetStencilTestEnable-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

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To dynamically set the stencil operation, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetStencilOp(
  VkCommandBuffer commandBuffer,
  VkStencilFaceFlags faceMask,
  VkStencilOp failOp,
  VkStencilOp passOp,
  VkStencilOp depthFailOp,
  VkCompareOp compareOp);
```

- commandBuffer is the command buffer into which the command will be recorded.
- faceMask is a bitmask of VkStencilFaceFlagBits specifying the set of stencil state for which to update the stencil operation.
- failOp is a VkStencilOp value specifying the action performed on samples that fail the stencil test.
- passOp is a VkStencilOp value specifying the action performed on samples that pass both the depth and stencil tests.
- depthFailOp is a VkStencilOp value specifying the action performed on samples that pass the stencil test and fail the depth test.
- compareOp is a VkCompareOp value specifying the comparison operator used in the stencil test.

This command sets the stencil operation for subsequent drawing commands when when the
graphics pipeline is created with `VK_DYNAMIC_STATE_STENCIL_OP` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the corresponding `VkPipelineDepthStencilStateCreateInfo::failOp`, `passOp`, `depthFailOp`, and `compareOp` values used to create the currently active pipeline, for both front and back faces.

**Valid Usage**

- VUID-vkCmdSetStencilOp-None-08971
  At least one of the following must be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3

**Valid Usage (Implicit)**

- VUID-vkCmdSetStencilOp-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle
- VUID-vkCmdSetStencilOp-faceMask-parameter
  `faceMask` must be a valid combination of `VkStencilFaceFlagBits` values
- VUID-vkCmdSetStencilOp-faceMask-required bitmask
  `faceMask` must not be 0
- VUID-vkCmdSetStencilOp-failOp-parameter
  `failOp` must be a valid `VkStencilOp` value
- VUID-vkCmdSetStencilOp-passOp-parameter
  `passOp` must be a valid `VkStencilOp` value
- VUID-vkCmdSetStencilOp-depthFailOp-parameter
  `depthFailOp` must be a valid `VkStencilOp` value
- VUID-vkCmdSetStencilOp-compareOp-parameter
  `compareOp` must be a valid `VkCompareOp` value
- VUID-vkCmdSetStencilOp-commandBuffer-recording
  `commandBuffer` must be in the recording state
- VUID-vkCmdSetStencilOp-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
The `VkStencilOpState` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkStencilOpState {
    VkStencilOp failOp;
    VkStencilOp passOp;
    VkStencilOp depthFailOp;
    VkCompareOp compareOp;
    uint32_t compareMask;
    uint32_t writeMask;
    uint32_t reference;
} VkStencilOpState;
```

- `failOp` is a `VkStencilOp` value specifying the action performed on samples that fail the stencil test.
- `passOp` is a `VkStencilOp` value specifying the action performed on samples that pass both the depth and stencil tests.
- `depthFailOp` is a `VkStencilOp` value specifying the action performed on samples that pass the stencil test and fail the depth test.
- `compareOp` is a `VkCompareOp` value specifying the comparison operator used in the stencil test.
- `compareMask` selects the bits of the unsigned integer stencil values participating in the stencil test.
- `writeMask` selects the bits of the unsigned integer stencil values updated by the stencil test in the stencil framebuffer attachment.
- `reference` is an integer stencil reference value that is used in the unsigned stencil comparison.

### Valid Usage (Implicit)

- VUID-VkStencilOpState-failOp-parameter
  - `failOp` must be a valid `VkStencilOp` value
- VUID-VkStencilOpState-passOp-parameter
  - `passOp` must be a valid `VkStencilOp` value
- VUID-VkStencilOpState-depthFailOp-parameter
  - `depthFailOp` must be a valid `VkStencilOp` value
- VUID-VkStencilOpState-compareOp-parameter
  - `compareOp` must be a valid `VkCompareOp` value
To **dynamically set** the stencil compare mask, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetStencilCompareMask(
    VkCommandBuffer commandBuffer,
    VkStencilFaceFlags faceMask,
    uint32_t compareMask);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **faceMask** is a bitmask of `VkStencilFaceFlagBits` specifying the set of stencil state for which to update the compare mask.
- **compareMask** is the new value to use as the stencil compare mask.

This command sets the stencil compare mask for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkStencilOpState::compareMask` value used to create the currently active pipeline, for both front and back faces.

### Valid Usage (Implicit)

- VUID-vkCmdSetStencilCompareMask-commandBuffer-parameter
  - `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- VUID-vkCmdSetStencilCompareMask-faceMask-parameter
  - `faceMask` **must** be a valid combination of `VkStencilFaceFlagBits` values
- VUID-vkCmdSetStencilCompareMask-faceMask-required bitmask
  - `faceMask` **must** not be 0
- VUID-vkCmdSetStencilCompareMask-commandBuffer-recording
  - `commandBuffer` **must** be in the recording state
- VUID-vkCmdSetStencilCompareMask-commandBuffer-cmdpool
  - The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized
**Command Properties**

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</tr>
</tbody>
</table>

VkStencilFaceFlagBits values are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkStencilFaceFlagBits {
    VK_STENCIL_FACE_FRONT_BIT = 0x00000001,
    VK_STENCIL_FACE_BACK_BIT = 0x00000002,
    VK_STENCIL_FACE_FRONT_AND_BACK = 0x00000003,
    VK_STENCIL_FRONT_AND_BACK = VK_STENCIL_FACE_FRONT_AND_BACK,
} VkStencilFaceFlagBits;
```

- **VK_STENCIL_FACE_FRONT_BIT** specifies that only the front set of stencil state is updated.
- **VK_STENCIL_FACE_BACK_BIT** specifies that only the back set of stencil state is updated.
- **VK_STENCIL_FACE_FRONT_AND_BACK** is the combination of **VK_STENCIL_FACE_FRONT_BIT** and **VK_STENCIL_FACE_BACK_BIT**, and specifies that both sets of stencil state are updated.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkStencilFaceFlags;
```

VkStencilFaceFlags is a bitmask type for setting a mask of zero or more VkStencilFaceFlagBits.

To dynamically set the stencil write mask, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetStencilWriteMask(
    VkCommandBuffer commandBuffer,  
    VkStencilFaceFlags faceMask,    
    uint32_t writeMask);
```

- commandBuffer is the command buffer into which the command will be recorded.
- faceMask is a bitmask of VkStencilFaceFlagBits specifying the set of stencil state for which to update the write mask, as described above for vkCmdSetStencilCompareMask.
- writeMask is the new value to use as the stencil write mask.

This command sets the stencil write mask for subsequent drawing commands when the graphics pipeline is created with **VK_DYNAMIC_STATE_STENCIL_WRITE_MASK** set in VkPipelineDynamicStateCreateInfo::pDynamicStates. Otherwise, this state is specified by the
writeMask value used to create the currently active pipeline, for both
VkPipelineDepthStencilStateCreateInfo::front and VkPipelineDepthStencilStateCreateInfo::back
faces.

**Valid Usage (Implicit)**

- VUID-vkCmdSetStencilWriteMask-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle
- VUID-vkCmdSetStencilWriteMask-faceMask-parameter
  faceMask must be a valid combination of VkStencilFaceFlagBits values
- VUID-vkCmdSetStencilWriteMask-faceMask-requiredbitmask
  faceMask must not be 0
- VUID-vkCmdSetStencilWriteMask-commandBuffer-recording
  commandBuffer must be in the recording state
- VUID-vkCmdSetStencilWriteMask-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

**Host Synchronization**

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

**Command Properties**

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</tbody>
</table>

To dynamically set the stencil reference value, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetStencilReference(
    VkCommandBuffer commandBuffer,  
    VkStencilFaceFlags faceMask,  
    uint32_t reference);
```

- commandBuffer is the command buffer into which the command will be recorded.
- faceMask is a bitmask of VkStencilFaceFlagBits specifying the set of stencil state for which to
update the reference value, as described above for `vkCmdSetStencilCompareMask`.

- **reference** is the new value to use as the stencil reference value.

This command sets the stencil reference value for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_STENCIL_REFERENCE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineDepthStencilStateCreateInfo::reference` value used to create the currently active pipeline, for both front and back faces.

Valid Usage (Implicit)

- VUID-vkCmdSetStencilReference-commandBuffer-parameter
  `commandBuffer` must be a valid `VkCommandBuffer` handle

- VUID-vkCmdSetStencilReference-faceMask-parameter
  `faceMask` must be a valid combination of `VkStencilFaceFlagBits` values

- VUID-vkCmdSetStencilReference-faceMask-requiredbitmask
  `faceMask` must not be 0

- VUID-vkCmdSetStencilReference-commandBuffer-recording
  `commandBuffer` must be in the recording state

- VUID-vkCmdSetStencilReference-commandBuffer-cmdpool
  The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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Possible values of the `failOp`, `passOp`, and `depthFailOp` members of `VkStencilOpState`, specifying what happens to the stored stencil value if this or certain subsequent tests fail or pass, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkStencilOp {
    VK_STENCIL_OP_KEEP = 0,
```
VK_STENCIL_OP_ZERO = 1,
VK_STENCIL_OP_REPLACE = 2,
VK_STENCIL_OP_INCREMENT_AND_CLAMP = 3,
VK_STENCIL_OP_DECREMENT_AND_CLAMP = 4,
VK_STENCIL_OP_INVERT = 5,
VK_STENCIL_OP_INCREMENT_AND_WRAP = 6,
VK_STENCIL_OP_DECREMENT_AND_WRAP = 7,
} VkStencilOp;

- **VK_STENCIL_OP_KEEP** keeps the current value.
- **VK_STENCIL_OP_ZERO** sets the value to 0.
- **VK_STENCIL_OP_REPLACE** sets the value to reference.
- **VK_STENCIL_OP_INCREMENT_AND_CLAMP** increments the current value and clamps to the maximum representable unsigned value.
- **VK_STENCIL_OP_DECREMENT_AND_CLAMP** decrements the current value and clamps to 0.
- **VK_STENCIL_OP_INVERT** bitwise-inverts the current value.
- **VK_STENCIL_OP_INCREMENT_AND_WRAP** increments the current value and wraps to 0 when the maximum value would have been exceeded.
- **VK_STENCIL_OP_DECREMENT_AND_WRAP** decrements the current value and wraps to the maximum possible value when the value would go below 0.

For purposes of increment and decrement, the stencil bits are considered as an unsigned integer.

### 26.8. Depth Test

The depth test compares the depth value $z_a$ in the depth/stencil attachment at each sample's framebuffer coordinates $(x_f, y_f)$ and sample index $i$ against the sample’s depth value $z_f$. If there is no depth attachment then the depth test is skipped.

The depth test occurs in three stages, as detailed in the following sections.

#### 26.8.1. Depth Clamping and Range Adjustment

If VkPipelineRasterizationStateCreateInfo::depthClampEnable is enabled, $z_f$ is clamped to $[z_{min}, z_{max}]$, where $z_{min} = \min(n, f)$, $z_{max} = \max(n, f)$, and $n$ and $f$ are the minDepth and maxDepth depth range values of the viewport used by this fragment, respectively.

Following depth clamping:

- If $z_f$ is not in the range $[z_{min}, z_{max}]$, then $z_f$ is undefined following this step.

#### 26.8.2. Depth Comparison

If the depth test is not enabled, as specified by vkCmdSetDepthTestEnable or VkPipelineDepthStencilStateCreateInfo::depthTestEnable, then this step is skipped.
The comparison operation performed is determined by the `VkCompareOp` value set by `vkCmdSetDepthCompareOp`, or by `VkPipelineDepthStencilStateCreateInfo::depthCompareOp` during pipeline creation. \( z_f \) and \( z_a \) are used as the reference and test values, respectively, in the operation specified by the `VkCompareOp`.

If the comparison evaluates to false, the coverage for the sample is set to 0.

### 26.8.3. Depth Attachment Writes

If depth writes are enabled, as specified by `vkCmdSetDepthWriteEnable` or `VkPipelineDepthStencilStateCreateInfo::depthWriteEnable`, and the comparison evaluated to true, the depth attachment value \( z_a \) is set to the sample's depth value \( z_f \). If there is no depth attachment, no value is written.

To **dynamically enable or disable** the depth test, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetDepthTestEnable(
    VkCommandBuffer commandBuffer,  // Provided by VK_VERSION_1_3
    VkBool32 depthTestEnable);      // Provided by VK_VERSION_1_3
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `depthTestEnable` specifies if the depth test is enabled.

This command sets the depth test enable for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineDepthStencilStateCreateInfo::depthTestEnable` value used to create the currently active pipeline.

### Valid Usage

- **VUID-vkCmdSetDepthTestEnable-None-08971**
  At least one of the following **must** be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3

### Valid Usage (Implicit)

- **VUID-vkCmdSetDepthTestEnable-commandBuffer-parameter**
  `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- **VUID-vkCmdSetDepthTestEnable-commandBuffer-recording**
  `commandBuffer` **must** be in the recording state
- **VUID-vkCmdSetDepthTestEnable-commandBuffer-cmdpool**
  The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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To dynamically set the depth compare operator, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetDepthCompareOp(  
    VkCommandBuffer commandBuffer,  
    VkCompareOp depthCompareOp);  
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `depthCompareOp` is a `VkCompareOp` value specifying the comparison operator used for the Depth Comparison step of the depth test.

This command sets the depth comparison operator for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_DEPTH_COMPARE_OP` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineDepthStencilStateCreateInfo::depthCompareOp` value used to create the currently active pipeline.

Valid Usage

- VUID-vkCmdSetDepthCompareOp-None-08971
  At least one of the following must be true:
  - the value of `VkApplicationInfo::apiVersion` used to create the `VkInstance` parent of `commandBuffer` is greater than or equal to Version 1.3
Valid Usage (Implicit)

- VUID-vkCmdSetDepthCompareOp-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdSetDepthCompareOp-depthCompareOp-parameter
  depthCompareOp must be a valid VkCompareOp value

- VUID-vkCmdSetDepthCompareOp-commandBuffer-recording
  commandBuffer must be in the recording state

- VUID-vkCmdSetDepthCompareOp-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

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To dynamically set the depth write enable, call:

```c
// Provided by VK_VERSION_1_3
void vkCmdSetDepthWriteEnable(
    VkCommandBuffer commandBuffer,
    VkBool32 depthWriteEnable);
```

- commandBuffer is the command buffer into which the command will be recorded.
- depthWriteEnable specifies if depth writes are enabled.

This command sets the depth write enable for subsequent drawing commands when the graphics pipeline is created with VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE set in VkPipelineDynamicStateCreateInfo::pDynamicStates. Otherwise, this state is specified by the VkPipelineDepthStencilStateCreateInfo::depthWriteEnable value used to create the currently active pipeline.
Valid Usage

- VUID-vkCmdSetDepthWriteEnable-None-08971
  At least one of the following must be true:
  - the value of VkApplicationInfo::apiVersion used to create the VkInstance parent of commandBuffer is greater than or equal to Version 1.3

Valid Usage (Implicit)

- VUID-vkCmdSetDepthWriteEnable-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle
- VUID-vkCmdSetDepthWriteEnable-commandBuffer-recording
  commandBuffer must be in the recording state
- VUID-vkCmdSetDepthWriteEnable-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

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26.9. Sample Counting

Occlusion queries use query pool entries to track the number of samples that pass all the per-fragment tests. The mechanism of collecting an occlusion query value is described in Occlusion Queries.

The occlusion query sample counter increments by one for each sample with a coverage value of 1 in each fragment that survives all the per-fragment tests, including scissor, sample mask, alpha to coverage, stencil, and depth tests.
26.10. Coverage Reduction

Coverage reduction takes the coverage information for a fragment and converts that to a boolean coverage value for each color sample in each pixel covered by the fragment.

26.10.1. Pixel Coverage

Coverage for each pixel is first extracted from the total fragment coverage mask. This consists of \( r \) unique coverage samples for each pixel in the fragment area, each with a unique sample index. If the fragment only contains a single pixel, coverage for the pixel is equivalent to the fragment coverage.

26.10.2. Color Sample Coverage

Once pixel coverage is determined, coverage for each individual color sample corresponding to that pixel is determined.

The number of \( r \) samples is identical to the number of samples in the color attachments. A color sample is covered if the pixel coverage sample with the same sample index is covered.
Chapter 27. The Framebuffer

27.1. Blending

Blending combines the incoming source fragment’s R, G, B, and A values with the destination R, G, B, and A values of each sample stored in the framebuffer at the fragment’s \((x_f, y_f)\) location. Blending is performed for each color sample covered by the fragment, rather than just once for each fragment.

Source and destination values are combined according to the blend operation, quadruplets of source and destination weighting factors determined by the blend factors, and a blend constant, to obtain a new set of R, G, B, and A values, as described below.

Blending is computed and applied separately to each color attachment used by the subpass, with separate controls for each attachment.

Prior to performing the blend operation, signed and unsigned normalized fixed-point color components undergo an implied conversion to floating-point as specified by Conversion from Normalized Fixed-Point to Floating-Point. Blending computations are treated as if carried out in floating-point, and basic blend operations are performed with a precision and dynamic range no lower than that used to represent destination components.

```
Note
Blending is only defined for floating-point, UNORM, SNORM, and sRGB formats. Within those formats, the implementation may only support blending on some subset of them. Which formats support blending is indicated by VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT.
```

The pipeline blend state is included in the `VkPipelineColorBlendStateCreateInfo` structure during graphics pipeline creation:

```
The VkPipelineColorBlendStateCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineColorBlendStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineColorBlendStateCreateFlags flags;
    VkBool32 logicOpEnable;
    VkLogicOp logicOp;
    uint32_t attachmentCount;
    const VkPipelineColorBlendAttachmentState* pAttachments;
    float blendConstants[4];
} VkPipelineColorBlendStateCreateInfo;
```

* `sType` is a `VkStructureType` value identifying this structure.
* `pNext` is `NULL` or a pointer to a structure extending this structure.
• **flags** is reserved for future use.

• **logicOpEnable** controls whether to apply Logical Operations.

• **logicOp** selects which logical operation to apply.

• **attachmentCount** is the number of **VkPipelineColorBlendAttachmentState** elements in **pAttachments**.

• **pAttachments** is a pointer to an array of **VkPipelineColorBlendAttachmentState** structures defining blend state for each color attachment.

• **blendConstants** is a pointer to an array of four values used as the R, G, B, and A components of the blend constant that are used in blending, depending on the **blend factor**.

---

### Valid Usage

- **VUID-VkPipelineColorBlendStateCreateInfo-pAttachments-00605**
  If the **independentBlend** feature is not enabled, all elements of **pAttachments** **must** be identical

- **VUID-VkPipelineColorBlendStateCreateInfo-logicOpEnable-00606**
  If the **logicOp** feature is not enabled, **logicOpEnable** **must** be **VK_FALSE**

- **VUID-VkPipelineColorBlendStateCreateInfo-logicOpEnable-00607**
  If **logicOpEnable** is **VK_TRUE**, **logicOp** **must** be a valid **VkLogicOp** value

- **VUID-VkPipelineColorBlendStateCreateInfo-pAttachments-07354**
  If **attachmentCount** is not **0**, **pAttachments** **must** be a valid pointer to an array of **attachmentCount** valid **VkPipelineColorBlendAttachmentState** structures

---

### Valid Usage (Implicit)

- **VUID-VkPipelineColorBlendStateCreateInfo-sType-sType**
  **sType** **must** be **VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO**

- **VUID-VkPipelineColorBlendStateCreateInfo-pNext-pNext**
  **pNext** **must** be **NULL**

- **VUID-VkPipelineColorBlendStateCreateInfo-flags-zerobitmask**
  **flags** **must** be **0**

- **VUID-VkPipelineColorBlendStateCreateInfo-pAttachments-parameter**
  If **attachmentCount** is not **0**, and **pAttachments** is not **NULL**, **pAttachments** **must** be a valid pointer to an array of **attachmentCount** valid **VkPipelineColorBlendAttachmentState** structures

---

// Provided by VK_VERSION_1_0

typedef VkFlags VkPipelineColorBlendStateCreateFlags;

**VkPipelineColorBlendStateCreateFlags** is a bitmask type for setting a mask, but is currently reserved
The `VkPipelineColorBlendAttachmentState` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPipelineColorBlendAttachmentState {
    VkBool32 blendEnable;
    VkBlendFactor srcColorBlendFactor;
    VkBlendFactor dstColorBlendFactor;
    VkBlendOp colorBlendOp;
    VkBlendFactor srcAlphaBlendFactor;
    VkBlendFactor dstAlphaBlendFactor;
    VkBlendOp alphaBlendOp;
    VkColorComponentFlags colorWriteMask;
} VkPipelineColorBlendAttachmentState;
```

- `blendEnable` controls whether blending is enabled for the corresponding color attachment. If blending is not enabled, the source fragment's color for that attachment is passed through unmodified.
- `srcColorBlendFactor` selects which blend factor is used to determine the source factors \( (S_r,S_g,S_b) \).
- `dstColorBlendFactor` selects which blend factor is used to determine the destination factors \( (D_r,D_g,D_b) \).
- `colorBlendOp` selects which blend operation is used to calculate the RGB values to write to the color attachment.
- `srcAlphaBlendFactor` selects which blend factor is used to determine the source factor \( S_a \).
- `dstAlphaBlendFactor` selects which blend factor is used to determine the destination factor \( D_a \).
- `alphaBlendOp` selects which blend operation is used to calculate the alpha values to write to the color attachment.
- `colorWriteMask` is a bitmask of `VkColorComponentFlagBits` specifying which of the R, G, B, and/or A components are enabled for writing, as described for the Color Write Mask.

### Valid Usage

- **VUID-VkPipelineColorBlendAttachmentState-srcColorBlendFactor-00608**
  If the `dualSrcBlend` feature is not enabled, `srcColorBlendFactor` must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

- **VUID-VkPipelineColorBlendAttachmentState-dstColorBlendFactor-00609**
  If the `dualSrcBlend` feature is not enabled, `dstColorBlendFactor` must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

- **VUID-VkPipelineColorBlendAttachmentState-srcAlphaBlendFactor-00610**
  If the `dualSrcBlend` feature is not enabled, `srcAlphaBlendFactor` must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.
VK_BLEND_FACTOR_SRC1_ALPHA, or VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA

- VUID-VkPipelineColorBlendAttachmentState-dstAlphaBlendFactor-00611
  If the dualSrcBlend feature is not enabled, dstAlphaBlendFactor must not be
  VK_BLEND_FACTOR_SRC1_COLOR, VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR,
  VK_BLEND_FACTOR_SRC1_ALPHA, or VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA

### Valid Usage (Implicit)

- VUID-VkPipelineColorBlendAttachmentState-srcColorBlendFactor-parameter
  srcColorBlendFactor must be a valid VkBlendFactor value
- VUID-VkPipelineColorBlendAttachmentState-dstColorBlendFactor-parameter
  dstColorBlendFactor must be a valid VkBlendFactor value
- VUID-VkPipelineColorBlendAttachmentState-colorBlendOp-parameter
  colorBlendOp must be a valid VkBlendOp value
- VUID-VkPipelineColorBlendAttachmentState-srcAlphaBlendFactor-parameter
  srcAlphaBlendFactor must be a valid VkBlendFactor value
- VUID-VkPipelineColorBlendAttachmentState-dstAlphaBlendFactor-parameter
  dstAlphaBlendFactor must be a valid VkBlendFactor value
- VUID-VkPipelineColorBlendAttachmentState-alphaBlendOp-parameter
  alphaBlendOp must be a valid VkBlendOp value
- VUID-VkPipelineColorBlendAttachmentState-colorWriteMask-parameter
  colorWriteMask must be a valid combination of VkColorComponentFlagBits values

### 27.1.1. Blend Factors

The source and destination color and alpha blending factors are selected from the enum:

```c
// Provided by VK_VERSION_1_0
typedef enum VkBlendFactor {
    VK_BLEND_FACTOR_ZERO = 0,
    VK_BLEND_FACTOR_ONE = 1,
    VK_BLEND_FACTOR_SRC_COLOR = 2,
    VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR = 3,
    VK_BLEND_FACTOR_DST_COLOR = 4,
    VK_BLEND_FACTOR_ONE_MINUS_DST_COLOR = 5,
    VK_BLEND_FACTOR_SRC_ALPHA = 6,
    VK_BLEND_FACTOR_ONE_MINUS_SRC_ALPHA = 7,
    VK_BLEND_FACTOR_DST_ALPHA = 8,
    VK_BLEND_FACTOR_ONE_MINUS_DST_ALPHA = 9,
    VK_BLEND_FACTOR_CONSTANT_COLOR = 10,
    VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_COLOR = 11,
    VK_BLEND_FACTOR_CONSTANT_ALPHA = 12,
    VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_ALPHA = 13,
    VK_BLEND_FACTOR_SRC_ALPHA_SATURATE = 14,
};
```
The semantics of the enum values are described in the table below:

**Table 25. Blend Factors**

<table>
<thead>
<tr>
<th>VkBlendFactor</th>
<th>RGB Blend Factors ((S_r,S_g,S_b)) or ((D_r,D_g,D_b))</th>
<th>Alpha Blend Factor ((S_a) or (D_a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BLEND_FACTOR_ZERO</td>
<td>((0,0,0))</td>
<td>0</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE</td>
<td>((1,1,1))</td>
<td>1</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_COLOR</td>
<td>((R_{s0},G_{s0},B_{s0}))</td>
<td>(A_{s0})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR</td>
<td>((1-R_{s0},1-G_{s0},1-B_{s0}))</td>
<td>1-(A_{s0})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_DST_COLOR</td>
<td>((R_{d},G_{d},B_{d}))</td>
<td>(A_{d})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_DST_COLOR</td>
<td>((1-R_{d},1-G_{d},1-B_{d}))</td>
<td>1-(A_{d})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_ALPHA</td>
<td>((A_{s0},A_{s0},A_{s0}))</td>
<td>(A_{s0})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC_ALPHA</td>
<td>((1-A_{s0},1-A_{s0},1-A_{s0}))</td>
<td>1-(A_{s0})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_DST_ALPHA</td>
<td>((A_{d},A_{d},A_{d}))</td>
<td>(A_{d})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_DST_ALPHA</td>
<td>((1-A_{d},1-A_{d},1-A_{d}))</td>
<td>1-(A_{d})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_CONSTANT_COLOR</td>
<td>((R_{c},G_{c},B_{c}))</td>
<td>(A_{c})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_COLOR</td>
<td>((1-R_{c},1-G_{c},1-B_{c}))</td>
<td>1-(A_{c})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_CONSTANT_ALPHA</td>
<td>((A_{c},A_{c},A_{c}))</td>
<td>(A_{c})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_ALPHA</td>
<td>((1-A_{c},1-A_{c},1-A_{c}))</td>
<td>1-(A_{c})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_ALPHA_SATURATE</td>
<td>((f,f,f); f = \min(A_{s0},1-A_{d}))</td>
<td>1</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC1_COLOR</td>
<td>((R_{s1},G_{s1},B_{s1}))</td>
<td>(A_{s1})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR</td>
<td>((1-R_{s1},1-G_{s1},1-B_{s1}))</td>
<td>1-(A_{s1})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC1_ALPHA</td>
<td>((A_{s1},A_{s1},A_{s1}))</td>
<td>(A_{s1})</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA</td>
<td>((1-A_{s1},1-A_{s1},1-A_{s1}))</td>
<td>1-(A_{s1})</td>
</tr>
</tbody>
</table>

In this table, the following conventions are used:

- \(R_{s0},G_{s0},B_{s0}\) and \(A_{s0}\) represent the first source color R, G, B, and A components, respectively, for the fragment output location corresponding to the color attachment being blended.

- \(R_{s1},G_{s1},B_{s1}\) and \(A_{s1}\) represent the second source color R, G, B, and A components, respectively, used in dual source blending modes, for the fragment output location corresponding to the color attachment being blended.
• $R_d, G_d, B_d$ and $A_d$ represent the R, G, B, and A components of the destination color. That is, the color currently in the corresponding color attachment for this fragment/sample.
• $R_c, G_c, B_c$ and $A_c$ represent the blend constant R, G, B, and A components, respectively.

To **dynamically set and change** the blend constants, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdSetBlendConstants(
    VkCommandBuffer commandBuffer,
    const float blendConstants[4]);
```

• `commandBuffer` is the command buffer into which the command will be recorded.
• `blendConstants` is a pointer to an array of four values specifying the $R_c$, $G_c$, $B_c$, and $A_c$ components of the blend constant color used in blending, depending on the blend factor.

This command sets blend constants for subsequent drawing commands when the graphics pipeline is created with `VK_DYNAMIC_STATE_BLEND_CONSTANTS` set in `VkPipelineDynamicStateCreateInfo::pDynamicStates`. Otherwise, this state is specified by the `VkPipelineColorBlendStateCreateInfo::blendConstants` values used to create the currently active pipeline.

**Valid Usage (Implicit)**

• VUID-vkCmdSetBlendConstants-commandBuffer-parameter `commandBuffer` must be a valid `VkCommandBuffer` handle
• VUID-vkCmdSetBlendConstants-commandBuffer-recording `commandBuffer` must be in the recording state
• VUID-vkCmdSetBlendConstants-commandBuffer-cmdpool The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

**Host Synchronization**

• Host access to `commandBuffer` must be externally synchronized
• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Command Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td>State</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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27.1.2. Dual-Source Blending

Blend factors that use the secondary color input \((R_{s1}, G_{s1}, B_{s1}, A_{s1})\) \(\text{VK_BLEND_FACTOR_SRC1_COLOR, VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR, VK_BLEND_FACTOR_SRC1_ALPHA, and VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA}\) may consume implementation resources that could otherwise be used for rendering to multiple color attachments. Therefore, the number of color attachments that can be used in a framebuffer may be lower when using dual-source blending.

Dual-source blending is only supported if the dualSrcBlend feature is enabled.

The maximum number of color attachments that can be used in a subpass when using dual-source blending functions is implementation-dependent and is reported as the maxFragmentDualSrcAttachments member of VkPhysicalDeviceLimits.

When using a fragment shader with dual-source blending functions, the color outputs are bound to the first and second inputs of the blender using the Index decoration, as described in Fragment Output Interface. If the second color input to the blender is not written in the shader, or if no output is bound to the second input of a blender, the result of the blending operation is not defined.

27.1.3. Blend Operations

Once the source and destination blend factors have been selected, they along with the source and destination components are passed to the blending operations. RGB and alpha components can use different operations. Possible values of VkBlendOp, specifying the operations, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkBlendOp {
    VK_BLEND_OP_ADD = 0,
    VK_BLEND_OP_SUBTRACT = 1,
    VK_BLEND_OP_REVERSE_SUBTRACT = 2,
    VK_BLEND_OP_MIN = 3,
    VK_BLEND_OP_MAX = 4,
} VkBlendOp;
```
The semantics of the basic blend operations are described in the table below:

<table>
<thead>
<tr>
<th>VkBlendOp</th>
<th>RGB Components</th>
<th>Alpha Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BLEND_Op_ADD</td>
<td>( R = R_s \times S_r + R_d \times D_r )</td>
<td>( A = A_s \times S_a + A_d \times D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_s \times S_g + G_d \times D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_s \times S_b + B_d \times D_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_Op_SUBTRACT</td>
<td>( R = R_s \times S_r - R_d \times D_r )</td>
<td>( A = A_s \times S_a - A_d \times D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_s \times S_g - G_d \times D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_s \times S_b - B_d \times D_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_Op.Reverse_SUBTRACT</td>
<td>( R = R_d \times D_r - R_s \times S_r )</td>
<td>( A = A_d \times D_a - A_s \times S_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_d \times D_g - G_s \times S_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_d \times D_b - B_s \times S_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_Op_MIN</td>
<td>( R = \min(R_s, R_d) )</td>
<td>( A = \min(A_s, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \min(G_s, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \min(B_s, B_d) )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_Op_MAX</td>
<td>( R = \max(R_s, R_d) )</td>
<td>( A = \max(A_s, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \max(G_s, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \max(B_s, B_d) )</td>
<td></td>
</tr>
</tbody>
</table>

In this table, the following conventions are used:

- \( R_s, G_s, B_s \) and \( A_s \) represent the first source color R, G, B, and A components, respectively.
- \( R_d, G_d, B_d \) and \( A_d \) represent the R, G, B, and A components of the destination color. That is, the color currently in the corresponding color attachment for this fragment/sample.
- \( S_r, S_g, S_b \) and \( S_a \) represent the source blend factor R, G, B, and A components, respectively.
- \( D_r, D_g, D_b \) and \( D_a \) represent the destination blend factor R, G, B, and A components, respectively.

The blending operation produces a new set of values R, G, B, and A, which are written to the framebuffer attachment. If blending is not enabled for this attachment, then R, G, B and A are assigned \( R_s, G_s, B_s \) and \( A_s \), respectively.

If the color attachment is fixed-point, the components of the source and destination values and blend factors are each clamped to [0,1] or [-1,1] respectively for an unsigned normalized or signed normalized color attachment prior to evaluating the blend operations. If the color attachment is floating-point, no clamping occurs.

If the numeric format of a framebuffer attachment uses sRGB encoding, the R, G, and B destination color values (after conversion from fixed-point to floating-point) are considered to be encoded for the sRGB color space and hence are linearized prior to their use in blending. Each R, G, and B component is converted from nonlinear to linear as described in the “sRGB EOTF” section of the Khronos Data Format Specification. If the format is not sRGB, no linearization is performed.

If the numeric format of a framebuffer attachment uses sRGB encoding, then the final R, G and B values are converted into the nonlinear sRGB representation before being written to the framebuffer attachment as described in the “sRGB EOTF” section of the Khronos Data Format Specification.
Specification.

If the numeric format of a framebuffer color attachment is not sRGB encoded then the resulting \( c \) values for R, G and B are unmodified. The value of A is never sRGB encoded. That is, the alpha component is always stored in memory as linear.

If the framebuffer color attachment is `VK_ATTACHMENT_UNUSED`, no writes are performed through that attachment. Writes are not performed to framebuffer color attachments greater than or equal to the `VkSubpassDescription::colorAttachmentCount` or `VkSubpassDescription2::colorAttachmentCount` value.

### 27.2. Logical Operations

The application can enable a logical operation between the fragment's color values and the existing value in the framebuffer attachment. This logical operation is applied prior to updating the framebuffer attachment. Logical operations are applied only for signed and unsigned integer and normalized integer framebuffers. Logical operations are not applied to floating-point or sRGB format color attachments.

Logical operations are controlled by the `logicOpEnable` and `logicOp` members of `VkPipelineColorBlendStateCreateInfo`. If `logicOpEnable` is `VK_TRUE`, then a logical operation selected by `logicOp` is applied between each color attachment and the fragment's corresponding output value, and blending of all attachments is treated as if it were disabled. Any attachments using color formats for which logical operations are not supported simply pass through the color values unmodified. The logical operation is applied independently for each of the red, green, blue, and alpha components. The `logicOp` is selected from the following operations:

```c
// Provided by VK_VERSION_1_0
typedef enum VkLogicOp {
    VK_LOGIC_OP_CLEAR = 0,
    VK_LOGIC_OP_AND = 1,
    VK_LOGIC_OP_AND_REVERSE = 2,
    VK_LOGIC_OP_COPY = 3,
    VK_LOGIC_OP_AND_INVERTED = 4,
    VK_LOGIC_OP_NO_OP = 5,
    VK_LOGIC_OP_XOR = 6,
    VK_LOGIC_OP_OR = 7,
    VK_LOGIC_OP_NOR = 8,
    VK_LOGIC_OP_EQUIVALENT = 9,
    VK_LOGIC_OP_INVERT = 10,
    VK_LOGIC_OP_OR_REVERSE = 11,
    VK_LOGIC_OP_COPY_INVERTED = 12,
    VK_LOGIC_OP_OR_INVERTED = 13,
    VK_LOGIC_OP_NAND = 14,
    VK_LOGIC_OP_SET = 15,
} VkLogicOp;
```
The logical operations supported by Vulkan are summarized in the following table in which

- \(\neg\) is bitwise invert,
- \(\&\) is bitwise and,
- \(\lor\) is bitwise or,
- \(\oplus\) is bitwise exclusive or,
- \(s\) is the fragment's \(R_{s0}, G_{s0}, B_{s0}\) or \(A_{s0}\) component value for the fragment output corresponding to the color attachment being updated, and
- \(d\) is the color attachment's \(R, G, B\) or \(A\) component value:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_LOGIC_OP_CLEAR</td>
<td>0</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND</td>
<td>(s &amp; d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_REVERSE</td>
<td>(s &amp; \neg d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY</td>
<td>(s)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_INVERTED</td>
<td>(\neg s &amp; d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NO_OP</td>
<td>(d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_XOR</td>
<td>(s \oplus d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR</td>
<td>(s \lor d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NOR</td>
<td>(\neg (s \lor d))</td>
</tr>
<tr>
<td>VK_LOGIC_OP_EQUIVALENT</td>
<td>(\neg (s \oplus d))</td>
</tr>
<tr>
<td>VK_LOGIC_OP_INVERT</td>
<td>(\neg d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_REVERSE</td>
<td>(s \lor \neg d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY_INVERTED</td>
<td>(\neg s)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_INVERTED</td>
<td>(\neg s \lor d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NAND</td>
<td>(\neg (s \land d))</td>
</tr>
<tr>
<td>VK_LOGIC_OP_SET</td>
<td>all 1s</td>
</tr>
</tbody>
</table>

The result of the logical operation is then written to the color attachment as controlled by the component write mask, described in Blend Operations.

### 27.3. Color Write Mask

Bits which **can** be set in VkPipelineColorBlendAttachmentState::colorWriteMask, determining whether the final color values \(R, G, B\) and \(A\) are written to the framebuffer attachment, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkColorComponentFlagBits {
```
VK_COLOR_COMPONENT_R_BIT = 0x00000001,
VK_COLOR_COMPONENT_G_BIT = 0x00000002,
VK_COLOR_COMPONENT_B_BIT = 0x00000004,
VK_COLOR_COMPONENT_A_BIT = 0x00000008,
}

VkColorComponentFlagBits;

- VK_COLOR_COMPONENT_R_BIT specifies that the R value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- VK_COLOR_COMPONENT_G_BIT specifies that the G value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- VK_COLOR_COMPONENT_B_BIT specifies that the B value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- VK_COLOR_COMPONENT_A_BIT specifies that the A value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.

The color write mask operation is applied regardless of whether blending is enabled.

// Provided by VK_VERSION_1_0
typedef VkFlags VkColorComponentFlags;

VkColorComponentFlags is a bitmask type for setting a mask of zero or more VkColorComponentFlagBits.
Chapter 28. Dispatching Commands

*Dispatching commands* (commands with `Dispatch` in the name) provoke work in a compute pipeline. Dispatching commands are recorded into a command buffer and when executed by a queue, will produce work which executes according to the bound compute pipeline. A compute pipeline must be bound to a command buffer before any dispatching commands are recorded in that command buffer.

To record a dispatch, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdDispatch(
    VkCommandBuffer commandBuffer,
    uint32_t groupCountX,
    uint32_t groupCountY,
    uint32_t groupCountZ);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `groupCountX` is the number of local workgroups to dispatch in the X dimension.
- `groupCountY` is the number of local workgroups to dispatch in the Y dimension.
- `groupCountZ` is the number of local workgroups to dispatch in the Z dimension.

When the command is executed, a global workgroup consisting of `groupCountX × groupCountY × groupCountZ` local workgroups is assembled.

**Valid Usage**

- **VUID-vkCmdDispatch-magFilter-04553**
  If a `VkSampler` created with `magFilter` or `minFilter` equal to `VK_FILTER_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- **VUID-vkCmdDispatch-mipmapMode-04770**
  If a `VkSampler` created with `mipmapMode` equal to `VK_SAMPLER_MIPMAP_MODE_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- **VUID-vkCmdDispatch-None-06479**
  If a `VkImageView` is sampled with depth comparison, the image view's format features must contain `VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT`

- **VUID-vkCmdDispatch-None-02691**
  If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`
If a `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`.

For any `VkImageView` being written as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

For any `VkImageView` being read as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For any `VkBufferView` being written as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

Any `VkBufferView` being read as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown` then the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

For each set $n$ that is statically used by a bound shader, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set $n$, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

For each set $n$ that is statically used by a bound shader, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set $n$, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

If the `maintenance4` feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid as described by descriptor validity if they are statically used by a bound shader.

A valid pipeline must be bound to the pipeline bind point used by this command.

There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by
this command, since that pipeline was bound

- **VUID-vkCmdDispatch-None-02702**
  If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler **must** not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage.

- **VUID-vkCmdDispatch-None-02703**
  If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage.

- **VUID-vkCmdDispatch-None-02704**
  If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler **must** not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage.

- **VUID-vkCmdDispatch-None-02705**
  If the `robustBufferAccess` feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- **VUID-vkCmdDispatch-None-02706**
  If the `robustBufferAccess` feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a storage buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- **VUID-vkCmdDispatch-commandBuffer-02707**
  If `commandBuffer` is an unprotected command buffer and `protectedNoFault` is not supported, any resource accessed by `bound shaders` **must** not be a protected resource.

- **VUID-vkCmdDispatch-None-06550**
  If a `bound shader` accesses a `VkSampler` or `VkImageView` object that enables `sampler Y'CbCr conversion`, that object **must** only be used with `OpImageSample*` or `OpImageSparseSample*` instructions.

- **VUID-vkCmdDispatch-ConstOffset-06551**
  If a `bound shader` accesses a `VkSampler` or `VkImageView` object that enables `sampler Y'CbCr conversion`, that object **must** not use the `ConstOffset` and `Offset` operands.

- **VUID-vkCmdDispatch-viewType-07752**
  If a `VkImageView` is accessed as a result of this command, then the image view's `viewType` **must** match the `Dim` operand of the `OpTypeImage` as described in `Instruction/Sampler/Image View Validation`.

- **VUID-vkCmdDispatch-format-07753**
  If a `VkImageView` is accessed as a result of this command, then the numeric `type` of the image view's `format` and the `Sampled Type` operand of the `OpTypeImage` **must** match.
• VUID-vkCmdDispatch-None-04115
  If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view's format

• VUID-vkCmdDispatch-OpImageWrite-04469
  If a VkBufferView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view's format

• VUID-vkCmdDispatch-None-07288
  Any shader invocation executed by this command must terminate

• VUID-vkCmdDispatch-commandBuffer-02712
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource

• VUID-vkCmdDispatch-commandBuffer-02713
  If commandBuffer is a protected command buffer and protectedNoFault is not supported, pipeline stages other than the framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point used by this command must not write to any resource

• VUID-vkCmdDispatch-groupCountX-00386
  groupCountX must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]

• VUID-vkCmdDispatch-groupCountY-00387
  groupCountY must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]

• VUID-vkCmdDispatch-groupCountZ-00388
  groupCountZ must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]

Valid Usage (Implicit)

• VUID-vkCmdDispatch-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

• VUID-vkCmdDispatch-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdDispatch-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support compute operations

• VUID-vkCmdDispatch-renderpass
  This command must only be called outside of a render pass instance
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

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To record an indirect dispatching command, call:

```c
// Provided by VK_VERSION_1_0
void vkCmdDispatchIndirect(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `buffer` is the buffer containing dispatch parameters.
- `offset` is the byte offset into `buffer` where parameters begin.

`vkCmdDispatchIndirect` behaves similarly to `vkCmdDispatch` except that the parameters are read by the device from a buffer during execution. The parameters of the dispatch are encoded in a `VkDispatchIndirectCommand` structure taken from `buffer` starting at `offset`.

Valid Usage

- VUID-vkCmdDispatchIndirect-magFilter-04553
  If a `VkSampler` created with `magFilter` or `minFilter` equal to `VK_FILTER_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view’s format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- VUID-vkCmdDispatchIndirect-mipmapMode-04770
  If a `VkSampler` created with `mipmapMode` equal to `VK_SAMPLER_MIPMAP_MODE_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view’s format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- VUID-vkCmdDispatchIndirect-None-06479
If a `VkImageView` is sampled with depth comparison, the image view’s format features must contain `VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT`.

- VUID-vkCmdDispatchIndirect-None-02691
  If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view’s format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

- VUID-vkCmdDispatchIndirect-None-07888
  If a `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer’s format features must contain `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`.

- VUID-vkCmdDispatchIndirect-OpTypeImage-07027
  For any `VkImageView` being written as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view’s format features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

- VUID-vkCmdDispatchIndirect-OpTypeImage-07028
  For any `VkImageView` being read as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view’s format features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

- VUID-vkCmdDispatchIndirect-OpTypeImage-07029
  For any `VkBufferView` being written as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, the view’s buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT`.

- VUID-vkCmdDispatchIndirect-OpTypeImage-07030
  For any `VkBufferView` being read as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, then the view’s buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT`.

- VUID-vkCmdDispatchIndirect-None-02697
  For each set `n` that is statically used by a bound shader, a descriptor set must have been bound to `n` at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set `n`, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

- VUID-vkCmdDispatchIndirect-None-02698
  For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

- VUID-vkCmdDispatchIndirect-maintenance4-06425
  If the `maintenance4` feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

- VUID-vkCmdDispatchIndirect-None-02699
  Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be
valid as described by descriptor validity if they are statically used by a bound shader

- **VUID-vkCmdDispatchIndirect-None-02700**
  A valid pipeline must be bound to the pipeline bind point used by this command.

- **VUID-vkCmdDispatchIndirect-None-02859**
  There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- **VUID-vkCmdDispatchIndirect-None-02702**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- **VUID-vkCmdDispatchIndirect-None-02703**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- **VUID-vkCmdDispatchIndirect-None-02704**
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- **VUID-vkCmdDispatchIndirect-None-02705**
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- **VUID-vkCmdDispatchIndirect-None-02706**
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

- **VUID-vkCmdDispatchIndirect-commandBuffer-02707**
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, any resource accessed by bound shaders must not be a protected resource.

- **VUID-vkCmdDispatchIndirect-None-06550**
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y'CbCr conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions.

- **VUID-vkCmdDispatchIndirect-ConstOffset-06551**
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler Y'CbCr conversion, that object must not use the ConstOffset and Offset operands.
• VUID-vkCmdDispatchIndirect-viewType-07752
  If a VkImageView is accessed as a result of this command, then the image view’s viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image View Validation

• VUID-vkCmdDispatchIndirect-format-07753
  If a VkImageView is accessed as a result of this command, then the numeric type of the image view’s format and the Sampled Type operand of the OpTypeImage must match

• VUID-vkCmdDispatchIndirect-None-04115
  If a VkImageView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the image view’s format

• VUID-vkCmdDispatchIndirect-OpImageWrite-04469
  If a VkBufferView is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction must have at least as many components as the buffer view’s format

• VUID-vkCmdDispatchIndirect-None-07288
  Any shader invocation executed by this command must terminate

• VUID-vkCmdDispatchIndirect-buffer-02708
  If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

• VUID-vkCmdDispatchIndirect-buffer-02709
  buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set

• VUID-vkCmdDispatchIndirect-offset-02710
  offset must be a multiple of 4

• VUID-vkCmdDispatchIndirect-commandBuffer-02711
  commandBuffer must not be a protected command buffer

• VUID-vkCmdDispatchIndirect-offset-00407
  The sum of offset and the size of VkDispatchIndirectCommand must be less than or equal to the size of buffer

Valid Usage (Implicit)

• VUID-vkCmdDispatchIndirect-commandBuffer-parameter
  commandBuffer must be a valid VkCommandBuffer handle

• VUID-vkCmdDispatchIndirect-buffer-parameter
  buffer must be a valid VkBuffer handle

• VUID-vkCmdDispatchIndirect-commandBuffer-recording
  commandBuffer must be in the recording state

• VUID-vkCmdDispatchIndirect-commandBuffer-cmdpool
  The VkCommandPool that commandBuffer was allocated from must support compute operations
### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized.

### Command Properties

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The `VkDispatchIndirectCommand` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkDispatchIndirectCommand {
    uint32_t x;
    uint32_t y;
    uint32_t z;
} VkDispatchIndirectCommand;
```

- `x` is the number of local workgroups to dispatch in the X dimension.
- `y` is the number of local workgroups to dispatch in the Y dimension.
- `z` is the number of local workgroups to dispatch in the Z dimension.

The members of `VkDispatchIndirectCommand` have the same meaning as the corresponding parameters of `vkCmdDispatch`.

### Valid Usage

- **VUID-VkDispatchIndirectCommand-x-00417**
  - `x` **must** be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]`
- **VUID-VkDispatchIndirectCommand-y-00418**
  - `y` **must** be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]`
To record a dispatch using non-zero base values for the components of WorkgroupId, call:

```c
void vkCmdDispatchBase(
    VkCommandBuffer commandBuffer,
    uint32_t baseGroupX,
    uint32_t baseGroupY,
    uint32_t baseGroupZ,
    uint32_t groupCountX,
    uint32_t groupCountY,
    uint32_t groupCountZ);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `baseGroupX` is the start value for the X component of WorkgroupId.
- `baseGroupY` is the start value for the Y component of WorkgroupId.
- `baseGroupZ` is the start value for the Z component of WorkgroupId.
- `groupCountX` is the number of local workgroups to dispatch in the X dimension.
- `groupCountY` is the number of local workgroups to dispatch in the Y dimension.
- `groupCountZ` is the number of local workgroups to dispatch in the Z dimension.

When the command is executed, a global workgroup consisting of $\text{groupCountX} \times \text{groupCountY} \times \text{groupCountZ}$ local workgroups is assembled, with WorkgroupId values ranging from $(\text{baseGroupX}, \text{baseGroupY} + \text{groupCountY}, \text{baseGroupZ} + \text{groupCountZ})$ in each component. `vkCmdDispatch` is equivalent to `vkCmdDispatchBase(0,0,0,\text{groupCountX},\text{groupCountY},\text{groupCountZ})`.

### Valid Usage

- **VUID-vkCmdDispatchBase-magFilter-04553**
  If a `VkSampler` created with `magFilter` or `minFilter` equal to `VK_FILTER_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`.

- **VUID-vkCmdDispatchBase-mipmapMode-04770**
  If a `VkSampler` created with `mipmapMode` equal to `VK_SAMPLER_MIPMAP_MODE_LINEAR` and `compareEnable` equal to `VK_FALSE` is used to sample a `VkImageView` as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`.

- **VUID-vkCmdDispatchBase-None-06479**
  If a `VkImageView` is sampled with depth comparison, the image view's `format features` must contain `VK_FORMAT_FEATURE_2SAMPLED_IMAGE_DEPTH_COMPARISON_BIT`.
If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

If a `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` descriptor is accessed using atomic operations as a result of this command, then the storage texel buffer's format features must contain `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`.

For any `VkImageView` being written as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITEWITHOUT_FORMAT_BIT`.

For any `VkImageView` being read as a storage image where the image format field of the `OpTypeImage` is `Unknown`, the view's format features must contain `VK_FORMAT_FEATURE_2_STORAGE_READWITHOUT_FORMAT_BIT`.

For any `VkBufferView` being written as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown`, the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_WRITEWITHOUT_FORMAT_BIT`.

For any `VkBufferView` being read as a storage texel buffer where the image format field of the `OpTypeImage` is `Unknown` then the view's buffer features must contain `VK_FORMAT_FEATURE_2_STORAGE_READWITHOUT_FORMAT_BIT`.

For each set `n` that is statically used by a bound shader, a descriptor set must have been bound to `n` at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set `n`, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

For each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

If the maintenance4 feature is not enabled, then for each push constant that is statically used by a bound shader, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid as described by descriptor validity if they are statically used by a bound shader.

Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid as described by descriptor validity if they are statically used by a bound shader.
A valid pipeline must be bound to the pipeline bind point used by this command

- VUID-vkCmdDispatchBase-None-02859
  There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound

- VUID-vkCmdDispatchBase-None-02702
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage

- VUID-vkCmdDispatchBase-None-02703
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage

- VUID-vkCmdDispatchBase-None-02704
  If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage

- VUID-vkCmdDispatchBase-None-02705
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

- VUID-vkCmdDispatchBase-None-02706
  If the robustBufferAccess feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point

- VUID-vkCmdDispatchBase-commandBuffer-02707
  If commandBuffer is an unprotected command buffer and protectedNoFault is not supported, any resource accessed by bound shaders must not be a protected resource

- VUID-vkCmdDispatchBase-ConstOffset-06551
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler YC aCr conversion, that object must only be used with OpImageSample* or OpImageSparseSample* instructions

- VUID-vkCmdDispatchBase-ConstOffset-06551
  If a bound shader accesses a VkSampler or VkImageView object that enables sampler YC aCr conversion, that object must not use the ConstOffset and Offset operands

- VUID-vkCmdDispatchBase-viewType-07752
  If a VkImageView is accessed as a result of this command, then the image view’s viewType must match the Dim operand of the OpTypeImage as described in Instruction/Sampler/Image
View Validation

- **VUID-vkCmdDispatchBase-format-07753**
  If a `VkImageView` is accessed as a result of this command, then the numeric type of the image view’s format and the Sampled Type operand of the OpTypeImage **must** match.

- **VUID-vkCmdDispatchBase-None-04115**
  If a `VkImageView` is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction **must** have at least as many components as the image view’s format.

- **VUID-vkCmdDispatchBase-OpImageWrite-04469**
  If a `VkBufferView` is accessed using OpImageWrite as a result of this command, then the Type of the Texel operand of that instruction **must** have at least as many components as the buffer view’s format.

- **VUID-vkCmdDispatchBase-None-07288**
  Any shader invocation executed by this command **must** terminate.

- **VUID-vkCmdDispatchBase-commandBuffer-02712**
  If `commandBuffer` is a protected command buffer and protectedNoFault is not supported, any resource written to by the `VkPipeline` object bound to the pipeline bind point used by this command **must** not be an unprotected resource.

- **VUID-vkCmdDispatchBase-commandBuffer-02713**
  If `commandBuffer` is a protected command buffer and protectedNoFault is not supported, pipeline stages other than the framebuffer-space and compute stages in the `VkPipeline` object bound to the pipeline bind point used by this command **must** not write to any resource.

- **VUID-vkCmdDispatchBase-baseGroupX-00421**
  `baseGroupX` **must** be less than `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]`.

- **VUID-vkCmdDispatchBase-baseGroupX-00422**
  `baseGroupY` **must** be less than `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]`.

- **VUID-vkCmdDispatchBase-baseGroupZ-00423**
  `baseGroupZ` **must** be less than `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]`.

- **VUID-vkCmdDispatchBase-groupCountX-00424**
  `groupCountX` **must** be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0] minus baseGroupX`.

- **VUID-vkCmdDispatchBase-groupCountY-00425**
  `groupCountY` **must** be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1] minus baseGroupY`.

- **VUID-vkCmdDispatchBase-groupCountZ-00426**
  `groupCountZ` **must** be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2] minus baseGroupZ`.

- **VUID-vkCmdDispatchBase-baseGroupX-00427**
  If any of `baseGroupX`, `baseGroupY`, or `baseGroupZ` are not zero, then the bound compute pipeline **must** have been created with the `VK_PIPELINE_CREATE_DISPATCH_BASE` flag.
Valid Usage (Implicit)

- VUID-vkCmdDispatchBase-commandBuffer-parameter
  
  commandBuffer must be a valid VkCommandBuffer handle

- VUID-vkCmdDispatchBase-commandBuffer-recording
  
  commandBuffer must be in the recording state

- VUID-vkCmdDispatchBase-commandBuffer-cmdpool
  
  The VkCommandPool that commandBuffer was allocated from must support compute operations

- VUID-vkCmdDispatchBase-renderpass
  
  This command must only be called outside of a render pass instance

Host Synchronization

- Host access to commandBuffer must be externally synchronized

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

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<td>Compute</td>
<td>Action</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 29. Sparse Resources

As documented in Resource Memory Association, VkBuffer and VkImage resources in Vulkan must be bound completely and contiguously to a single VkDeviceMemory object. This binding must be done before the resource is used, and the binding is immutable for the lifetime of the resource.

Sparse resources relax these restrictions and provide these additional features:

- Sparse resources can be bound non-contiguously to one or more VkDeviceMemory allocations.
- Sparse resources can be re-bound to different memory allocations over the lifetime of the resource.
- Sparse resources can have descriptors generated and used orthogonally with memory binding commands.

29.1. Sparse Resource Features

Sparse resources have several features that must be enabled explicitly at resource creation time. The features are enabled by including bits in the flags parameter of VkImageCreateInfo or VkBufferCreateInfo. Each feature also has one or more corresponding feature enables specified in VkPhysicalDeviceFeatures.

- The sparseBinding feature is the base, and provides the following capabilities:
  - Resources can be bound at some defined (sparse block) granularity.
  - The entire resource must be bound to memory before use regardless of regions actually accessed.
  - No specific mapping of image region to memory offset is defined, i.e. the location that each texel corresponds to in memory is implementation-dependent.
  - Sparse buffers have a well-defined mapping of buffer range to memory range, where an offset into a range of the buffer that is bound to a single contiguous range of memory corresponds to an identical offset within that range of memory.
  - Requested via the VK_IMAGE_CREATE_SPARSE_BINDING_BIT and VK_BUFFER_CREATE_SPARSE_BINDING_BIT bits.
  - A sparse image created using VK_IMAGE_CREATE_SPARSE_BINDING_BIT (but not VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT) supports all formats that non-sparse usage supports, and supports both VK_IMAGE_TILING_OPTIMAL and VK_IMAGE_TILING_LINEAR tiling.

- Sparse Residency builds on (and requires) the sparseBinding feature. It includes the following capabilities:
  - Resources do not have to be completely bound to memory before use on the device.
  - Images have a prescribed sparse image block layout, allowing specific rectangular regions of the image to be bound to specific offsets in memory allocations.
  - Consistency of access to unbound regions of the resource is defined by the absence or presence of VkPhysicalDeviceSparseProperties::residencyNonResidentStrict. If this property is present, accesses to unbound regions of the resource are well defined and behave as if the
data bound is populated with all zeros; writes are discarded. When this property is absent, accesses are considered safe, but reads will return undefined values.

- Requested via the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` and `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` bits.

- Sparse residency support is advertised on a finer grain via the following features:
  
  - The `sparseResidencyBuffer` feature provides support for creating `VkBuffer` objects with the `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidencyImage2D` feature provides support for creating 2D single-sampled `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidencyImage3D` feature provides support for creating 3D `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidency2Samples` feature provides support for creating 2D `VkImage` objects with 2 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidency4Samples` feature provides support for creating 2D `VkImage` objects with 4 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidency8Samples` feature provides support for creating 2D `VkImage` objects with 8 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  
  - The `sparseResidency16Samples` feature provides support for creating 2D `VkImage` objects with 16 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

Implementations supporting `sparseResidencyImage2D` are only required to support sparse 2D, single-sampled images. Support for sparse 3D and MSAA images is optional and can be enabled via `sparseResidencyImage3D`, `sparseResidency2Samples`, `sparseResidency4Samples`, `sparseResidency8Samples`, and `sparseResidency16Samples`.

- A sparse image created using `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` supports all non-compressed color formats with power-of-two element size that non-sparse usage supports. Additional formats may also be supported and can be queried via `vkGetPhysicalDeviceSparseImageFormatProperties`. `VK_IMAGE_TILING_LINEAR` tiling is not supported.

- The `sparseResidencyAliased` feature provides the following capability that can be enabled per resource:
  
  Allows physical memory ranges to be shared between multiple locations in the same sparse resource or between multiple sparse resources, with each binding of a memory location observing a consistent interpretation of the memory contents.

  See Sparse Memory Aliasing for more information.

### 29.2. Sparse Buffers and Fully-Resident Images

Both `VkBuffer` and `VkImage` objects created with the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` or `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` bits can be thought of as a linear region of address space. In the `VkImage` case if `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` is not used, this linear region is entirely
opaque, meaning that there is no application-visible mapping between texel location and memory offset.

Unless `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` or `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` are also used, the entire resource must be bound to one or more `VkDeviceMemory` objects before use.

### 29.2.1. Sparse Buffer and Fully-Resident Image Block Size

The sparse block size in bytes for sparse buffers and fully-resident images is reported as `VkMemoryRequirements::alignment`. `alignment` represents both the memory alignment requirement and the binding granularity (in bytes) for sparse resources.

### 29.3. Sparse Partially-Resident Buffers

`VkBuffer` objects created with the `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` bit allow the buffer to be made only partially resident. Partially resident `VkBuffer` objects are allocated and bound identically to `VkBuffer` objects using only the `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` feature. The only difference is the ability for some regions of the buffer to be unbound during device use.

### 29.4. Sparse Partially-Resident Images

`VkImage` objects created with the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` bit allow specific rectangular regions of the image called sparse image blocks to be bound to specific ranges of memory. This allows the application to manage residency at either image subresource or sparse image block granularity. Each image subresource (outside of the `mip tail`) starts on a sparse block boundary and has dimensions that are integer multiples of the corresponding dimensions of the sparse image block.

---

**Note**

Applications **can** use these types of images to control LOD based on total memory consumption. If memory pressure becomes an issue the application **can** unbind and disable specific mipmap levels of images without having to recreate resources or modify texel data of unaffected levels.

The application **can** also use this functionality to access subregions of the image in a “megatexture” fashion. The application **can** create a large image and only populate the region of the image that is currently being used in the scene.

### 29.4.1. Accessing Unbound Regions

The following member of `VkPhysicalDeviceSparseProperties` affects how data in unbound regions of sparse resources are handled by the implementation:

- `residencyNonResidentStrict`

If this property is not present, reads of unbound regions of the image will return undefined values. Both reads and writes are still considered **safe** and will not affect other resources or populated regions of the image.
If this property is present, all reads of unbound regions of the image will behave as if the region was bound to memory populated with all zeros; writes will be discarded.

**Image operations** performed on unbound memory **may** still alter some component values in the natural way for those accesses, e.g. substituting a value of one for alpha in formats that do not have an alpha component.

Example: Reading the alpha component of an unbacked `VK_FORMAT_R8_UNORM` image will return a value of 1.0f.

See **Physical Device Enumeration** for instructions for retrieving physical device properties.

**Implementor’s Note**

For implementations that **cannot** natively handle access to unbound regions of a resource, the implementation **may** allocate and bind memory to the unbound regions. Reads and writes to unbound regions will access the implementation-managed memory instead.

Given that the values resulting from reads of unbound regions are undefined in this scenario, implementations **may** use the same physical memory for all unbound regions of multiple resources within the same process.

### 29.4.2. Mip Tail Regions

Sparse images created using `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` (without also using `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`) have no specific mapping of image region or image subresource to memory offset defined, so the entire image can be thought of as a linear opaque address region. However, images created with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` do have a prescribed sparse image block layout, and hence each image subresource **must** start on a sparse block boundary. Within each array layer, the set of mip levels that have a smaller size than the sparse block size in bytes are grouped together into a **mip tail region**.

If the `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` flag is present in the `flags` member of `VkSparseImageFormatProperties`, for the image's `format`, then any mip level which has dimensions that are not integer multiples of the corresponding dimensions of the sparse image block, and all subsequent mip levels, are also included in the mip tail region.

The following member of `VkPhysicalDeviceSparseProperties` **may** affect how the implementation places mip levels in the mip tail region:

- `residencyAlignedMipSize`

Each mip tail region is bound to memory as an opaque region (i.e. **must** be bound using a `VkSparseImageOpaqueMemoryBindInfo` structure) and **may** be of a size greater than or equal to the sparse block size in bytes. This size is guaranteed to be an integer multiple of the sparse block size in bytes.
An implementation may choose to allow each array-layer's mip tail region to be bound to memory independently or require that all array-layer's mip tail regions be treated as one. This is dictated by `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` in `VkSparseImageMemoryRequirements::flags`.

The following diagrams depict how `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` and `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` alter memory usage and requirements.

![Sparse Image Diagram](image)

In the absence of `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` and `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`, each array layer contains a mip tail region containing texel data for all mip levels smaller than the sparse image block in any dimension.

Mip levels that are as large or larger than a sparse image block in all dimensions can be bound individually. Right-edges and bottom-edges of each level are allowed to have partially used sparse blocks. Any bound partially-used-sparse-blocks must still have their full sparse block size in bytes allocated in memory.
When `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` is present all array layers will share a single mip tail region.

---

**Note**
The mip tail regions are presented here in 2D arrays simply for figure size reasons. Each mip tail is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.

When `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` is present the first mip level that would contain partially used sparse blocks begins the mip tail region. This level and all subsequent levels are placed in the mip tail. Only the first N mip levels whose dimensions are an exact multiple of the sparse image block dimensions can be bound and unbound on a sparse block basis.

![Array Layer 0](image1.png)
![Array Layer 1](image2.png)
![Array Layer 2](image3.png)

**Figure 20. Sparse Image with Aligned Mip Size and Single Mip Tail**

**Note**
The mip tail region is presented here in a 2D array simply for figure size reasons. It is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.

When both `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` and `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` are present the constraints from each of these flags are in effect.

### 29.4.3. Standard Sparse Image Block Shapes

Standard sparse image block shapes define a standard set of dimensions for sparse image blocks that depend on the format of the image. Layout of texels or compressed texel blocks within a sparse image block is implementation-dependent. All currently defined standard sparse image block shapes are 64 KB in size.

For block-compressed formats (e.g., `VK_FORMAT_BC5_UNORM_BLOCK`), the texel size is the size of the compressed texel block (e.g., 128-bit for BC5) thus the dimensions of the standard sparse image block
shapes apply in terms of compressed texel blocks.

Note

For block-compressed formats, the dimensions of a sparse image block in terms of texels can be calculated by multiplying the sparse image block dimensions by the compressed texel block dimensions.
Table 28. Standard Sparse Image Block Shapes (Single Sample)

<table>
<thead>
<tr>
<th>TEXEL SIZE (bits)</th>
<th>Block Shape (2D)</th>
<th>Block Shape (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Bit</td>
<td>256 × 256 × 1</td>
<td>64 × 32 × 32</td>
</tr>
<tr>
<td>16-Bit</td>
<td>256 × 128 × 1</td>
<td>32 × 32 × 32</td>
</tr>
<tr>
<td>32-Bit</td>
<td>128 × 128 × 1</td>
<td>32 × 32 × 16</td>
</tr>
<tr>
<td>64-Bit</td>
<td>128 × 64 × 1</td>
<td>32 × 16 × 16</td>
</tr>
<tr>
<td>128-Bit</td>
<td>64 × 64 × 1</td>
<td>16 × 16 × 16</td>
</tr>
</tbody>
</table>

Table 29. Standard Sparse Image Block Shapes (MSAA)

<table>
<thead>
<tr>
<th>TEXEL SIZE (bits)</th>
<th>Block Shape (2X)</th>
<th>Block Shape (4X)</th>
<th>Block Shape (8X)</th>
<th>Block Shape (16X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Bit</td>
<td>128 × 256 × 1</td>
<td>128 × 128 × 1</td>
<td>64 × 128 × 1</td>
<td>64 × 64 × 1</td>
</tr>
<tr>
<td>16-Bit</td>
<td>128 × 128 × 1</td>
<td>128 × 64 × 1</td>
<td>64 × 64 × 1</td>
<td>64 × 32 × 1</td>
</tr>
<tr>
<td>32-Bit</td>
<td>64 × 128 × 1</td>
<td>64 × 64 × 1</td>
<td>32 × 64 × 1</td>
<td>32 × 32 × 1</td>
</tr>
<tr>
<td>64-Bit</td>
<td>64 × 64 × 1</td>
<td>64 × 32 × 1</td>
<td>32 × 32 × 1</td>
<td>32 × 16 × 1</td>
</tr>
<tr>
<td>128-Bit</td>
<td>32 × 64 × 1</td>
<td>32 × 32 × 1</td>
<td>16 × 32 × 1</td>
<td>16 × 16 × 1</td>
</tr>
</tbody>
</table>

Implementations that support the standard sparse image block shape for all formats listed in the Standard Sparse Image Block Shapes (Single Sample) and Standard Sparse Image Block Shapes (MSAA) tables may advertise the following VkPhysicalDeviceSparseProperties:

- residencyStandard2DBlockShape
- residencyStandard2DMultisampleBlockShape
- residencyStandard3DBlockShape

Reporting each of these features does not imply that all possible image types are supported as sparse. Instead, this indicates that no supported sparse image of the corresponding type will use custom sparse image block dimensions for any formats that have a corresponding standard sparse image block shape.

29.4.4. Custom Sparse Image Block Shapes

An implementation that does not support a standard image block shape for a particular sparse partially-resident image may choose to support a custom sparse image block shape for it instead. The dimensions of such a custom sparse image block shape are reported in VkSparseImageFormatProperties::imageGranularity. As with standard sparse image block shapes, the size in bytes of the custom sparse image block shape will be reported in VkMemoryRequirements::alignment.

Custom sparse image block dimensions are reported through vkGetPhysicalDeviceSparseImageFormatProperties and vkGetImageSparseMemoryRequirements.

An implementation must not support both the standard sparse image block shape and a custom
sparse image block shape for the same image. The standard sparse image block shape must be used if it is supported.

29.4.5. Multiple Aspects

Partially resident images are allowed to report separate sparse properties for different aspects of the image. One example is for depth/stencil images where the implementation separates the depth and stencil data into separate planes. Another reason for multiple aspects is to allow the application to manage memory allocation for implementation-private metadata associated with the image. See the figure below:

![Multiple Aspect Sparse Image](image)

*Figure 21. Multiple Aspect Sparse Image*

**Note**

The mip tail regions are presented here in 2D arrays simply for figure size reasons. Each mip tail is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.

In the figure above the depth, stencil, and metadata aspects all have unique sparse properties. The
per-texel stencil data is \( \frac{1}{4} \) the size of the depth data, hence the stencil sparse blocks include \( 4 \times \) the number of texels. The sparse block size in bytes for all of the aspects is identical and defined by \( \text{VkMemoryRequirements::alignment} \).

**Metadata**

The metadata aspect of an image has the following constraints:

- All metadata is reported in the mip tail region of the metadata aspect.
- All metadata **must** be bound prior to device use of the sparse image.

### 29.5. Sparse Memory Aliasing

By default sparse resources have the same aliasing rules as non-sparse resources. See [Memory Aliasing](#) for more information.

\( \text{VkDevice} \) objects that have the \( \text{sparseResidencyAliased} \) feature enabled are able to use the \( \text{VK_BUFFER_CREATE_SPARSE_ALIASED_BIT} \) and \( \text{VK_IMAGE_CREATE_SPARSE_ALIASED_BIT} \) flags for resource creation. These flags allow resources to access physical memory bound into multiple locations within one or more sparse resources in a *data consistent* fashion. This means that reading physical memory from multiple aliased locations will return the same value.

Care **must** be taken when performing a write operation to aliased physical memory. Memory dependencies **must** be used to separate writes to one alias from reads or writes to another alias. Writes to aliased memory that are not properly guarded against accesses to different aliases will have undefined results for all accesses to the aliased memory.

Applications that wish to make use of data consistent sparse memory aliasing **must** abide by the following guidelines:

- All sparse resources that are bound to aliased physical memory **must** be created with the \( \text{VK_BUFFER_CREATE_SPARSE_ALIASED_BIT} / \text{VK_IMAGE_CREATE_SPARSE_ALIASED_BIT} \) flag.
- All resources that access aliased physical memory **must** interpret the memory in the same way. This implies the following:
  - Buffers and images **cannot** alias the same physical memory in a data consistent fashion. The physical memory ranges **must** be used exclusively by buffers or used exclusively by images for data consistency to be guaranteed.
  - Memory in sparse image mip tail regions **cannot** access aliased memory in a data consistent fashion.
  - Sparse images that alias the same physical memory **must** have compatible formats and be using the same sparse image block shape in order to access aliased memory in a data consistent fashion.

Failure to follow any of the above guidelines will require the application to abide by the normal, non-sparse resource [aliasing rules](#). In this case memory **cannot** be accessed in a data consistent fashion.
Note

Enabling sparse resource memory aliasing can be a way to lower physical memory use, but it may reduce performance on some implementations. An application developer can test on their target HW and balance the memory / performance trade-offs measured.

29.6. Sparse Resource Implementation Guidelines (Informative)

This section is Informative. It is included to aid in implementors’ understanding of sparse resources.

Device Virtual Address

The basic sparseBinding feature allows the resource to reserve its own device virtual address range at resource creation time rather than relying on a bind operation to set this. Without any other creation flags, no other constraints are relaxed compared to normal resources. All pages must be bound to physical memory before the device accesses the resource.

The sparseResidency features allow sparse resources to be used even when not all pages are bound to memory. Implementations that support access to unbound pages without causing a fault may support residencyNonResidentStrict.

Not faulting on access to unbound pages is not enough to support residencyNonResidentStrict. An implementation must also guarantee that reads after writes to unbound regions of the resource always return data for the read as if the memory contains zeros. Depending on any caching hierarchy of the implementation this may not always be possible.

Any implementation that does not fault, but does not guarantee correct read values must not support residencyNonResidentStrict.

Any implementation that cannot access unbound pages without causing a fault will require the implementation to bind the entire device virtual address range to physical memory. Any pages that the application does not bind to memory may be bound to one (or more) "placeholder" physical page(s) allocated by the implementation. Given the following properties:

- A process must not access memory from another process
- Reads return undefined values

It is sufficient for each host process to allocate these placeholder pages and use them for all resources in that process. Implementations may allocate more often (per instance, per device, or per resource).

Binding Memory

The byte size reported in VkMemoryRequirements::size must be greater than or equal to the amount of physical memory required to fully populate the resource. Some implementations
require “holes” in the device virtual address range that are never accessed. These holes may be included in the size reported for the resource.

Including or not including the device virtual address holes in the resource size will alter how the implementation provides support for `VkSparseImageOpaqueMemoryBindInfo`. This operation must be supported for all sparse images, even ones created with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the holes are included in the size, this bind function becomes very easy. In most cases the `resourceOffset` is simply a device virtual address offset and the implementation can easily determine what device virtual address to bind. The cost is that the application may allocate more physical memory for the resource than it needs.

- If the holes are not included in the size, the application can allocate less physical memory than otherwise for the resource. However, in this case the implementation must account for the holes when mapping `resourceOffset` to the actual device virtual address intended to be mapped.

**Note**

If the application always uses `VkSparseImageMemoryBindInfo` to bind memory for the non-tail mip levels, any holes that are present in the resource size may never be bound.

Since `VkSparseImageMemoryBindInfo` uses texel locations to determine which device virtual addresses to bind, it is impossible to bind device virtual address holes with this operation.

**Binding Metadata Memory**

All metadata for sparse images have their own sparse properties and are embedded in the mip tail region for said properties. See the `Multiaspect` section for details.

Given that metadata is in a mip tail region, and the mip tail region must be reported as contiguous (either globally or per-array-layer), some implementations will have to resort to complicated offset → device virtual address mapping for handling `VkSparseImageOpaqueMemoryBindInfo`.

To make this easier on the implementation, the `VK_SPARSE_MEMORY_BIND_METADATA_BIT` explicitly specifies when metadata is bound with `VkSparseImageOpaqueMemoryBindInfo`. When this flag is not present, the `resourceOffset` may be treated as a strict device virtual address offset.

When `VK_SPARSE_MEMORY_BIND_METADATA_BIT` is present, the `resourceOffset` must have been derived explicitly from the `imageMipTailOffset` in the sparse resource properties returned for the metadata aspect. By manipulating the value returned for `imageMipTailOffset`, the `resourceOffset` does not have to correlate directly to a device virtual address offset, and may instead be whatever value makes it easiest for the implementation to derive the correct device virtual address.
29.7. Sparse Resource API

The APIs related to sparse resources are grouped into the following categories:

- Physical Device Features
- Physical Device Sparse Properties
- Sparse Image Format Properties
- Sparse Resource Creation
- Sparse Resource Memory Requirements
- Binding Resource Memory

29.7.1. Physical Device Features

Some sparse-resource related features are reported and enabled in \( \text{VkPhysicalDeviceFeatures} \). These features **must** be supported and enabled on the \( \text{VkDevice} \) object before applications **can** use them. See **Physical Device Features** for information on how to get and set enabled device features, and for more detailed explanations of these features.

**Sparse Physical Device Features**

- **sparseBinding**: Support for creating \( \text{VkBuffer} \) and \( \text{VkImage} \) objects with the \( \text{VK_BUFFER_CREATE_SPARSE_BINDING_BIT} \) and \( \text{VK_IMAGE_CREATE_SPARSE_BINDING_BIT} \) flags, respectively.
- **sparseResidencyBuffer**: Support for creating \( \text{VkBuffer} \) objects with the \( \text{VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidencyImage2D**: Support for creating 2D single-sampled \( \text{VkImage} \) objects with the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidencyImage3D**: Support for creating 3D \( \text{VkImage} \) objects with the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidency2Samples**: Support for creating 2D \( \text{VkImage} \) objects with 2 samples and the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidency4Samples**: Support for creating 2D \( \text{VkImage} \) objects with 4 samples and the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidency8Samples**: Support for creating 2D \( \text{VkImage} \) objects with 8 samples and the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidency16Samples**: Support for creating 2D \( \text{VkImage} \) objects with 16 samples and the \( \text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} \) flag.
- **sparseResidencyAliased**: Support for creating \( \text{VkBuffer} \) and \( \text{VkImage} \) objects with the \( \text{VK_BUFFER_CREATE_SPARSE_ALIASED_BIT} \) and \( \text{VK_IMAGE_CREATE_SPARSE_ALIASED_BIT} \) flags, respectively.

29.7.2. Physical Device Sparse Properties

Some features of the implementation are not possible to disable, and are reported to allow applications to alter their sparse resource usage accordingly. These read-only capabilities are
reported in the `VkPhysicalDeviceProperties::sparseProperties` member, which is a `VkPhysicalDeviceSparseProperties` structure.

The `VkPhysicalDeviceSparseProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPhysicalDeviceSparseProperties {
    VkBool32 residencyStandard2DBlockShape;
    VkBool32 residencyStandard2DMultisampleBlockShape;
    VkBool32 residencyStandard3DBlockShape;
    VkBool32 residencyAlignedMipSize;
    VkBool32 residencyNonResidentStrict;
} VkPhysicalDeviceSparseProperties;
```

- `residencyStandard2DBlockShape` is `VK_TRUE` if the physical device will access all single-sample 2D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (Single Sample) table. If this property is not supported, the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for single-sample 2D images is not required to match the standard sparse image block dimensions listed in the table.

- `residencyStandard2DMultisampleBlockShape` is `VK_TRUE` if the physical device will access all multisample 2D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (MSAA) table. If this property is not supported, the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for multisample 2D images is not required to match the standard sparse image block dimensions listed in the table.

- `residencyStandard3DBlockShape` is `VK_TRUE` if the physical device will access all 3D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (Single Sample) table. If this property is not supported, the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for 3D images is not required to match the standard sparse image block dimensions listed in the table.

- `residencyAlignedMipSize` is `VK_TRUE` if images with mip level dimensions that are not integer multiples of the corresponding dimensions of the sparse image block may be placed in the mip tail. If this property is not reported, only mip levels with dimensions smaller than the `imageGranularity` member of the `VkSparseImageFormatProperties` structure will be placed in the mip tail. If this property is reported the implementation is allowed to return `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` in the flags member of `VkSparseImageFormatProperties`, indicating that mip level dimensions that are not integer multiples of the corresponding dimensions of the sparse image block will be placed in the mip tail.

- `residencyNonResidentStrict` specifies whether the physical device can consistently access non-resident regions of a resource. If this property is `VK_TRUE`, access to non-resident regions of resources will be guaranteed to return values as if the resource was populated with 0; writes to non-resident regions will be discarded.
29.7.3. Sparse Image Format Properties

Given that certain aspects of sparse image support, including the sparse image block dimensions, may be implementation-dependent, vkGetPhysicalDeviceSparseImageFormatProperties can be used to query for sparse image format properties prior to resource creation. This command is used to check whether a given set of sparse image parameters is supported and what the sparse image block shape will be.

Sparse Image Format Properties API

The VkSparseImageFormatProperties structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseImageFormatProperties {
    VkImageAspectFlags aspectMask;
    VkExtent3D imageGranularity;
    VkSparseImageFormatFlags flags;
} VkSparseImageFormatProperties;
```

- **aspectMask** is a bitmask `VkImageAspectFlagBits` specifying which aspects of the image the properties apply to.
- **imageGranularity** is the width, height, and depth of the sparse image block in texels or compressed texel blocks.
- **flags** is a bitmask of `VkSparseImageFormatFlagBits` specifying additional information about the sparse resource.

Bits which may be set in `VkSparseImageFormatProperties::flags`, specifying additional information about the sparse resource, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSparseImageFormatFlagBits {
    VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT = 0x00000001,
    VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT = 0x00000002,
    VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT = 0x00000004,
} VkSparseImageFormatFlagBits;
```

- **VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT** specifies that the image uses a single mip tail region for all array layers.
- **VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT** specifies that the first mip level whose dimensions are not integer multiples of the corresponding dimensions of the sparse image block begins the mip tail region.
- **VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT** specifies that the image uses non-standard sparse image block dimensions, and the `imageGranularity` values do not match the standard sparse image block dimensions for the given format.
typedef VkFlags VkSparseImageFormatFlags;

VkSparseImageFormatFlags is a bitmask type for setting a mask of zero or more VkSparseImageFormatFlagBits.

vkGetPhysicalDeviceSparseImageFormatProperties returns an array of VkSparseImageFormatProperties. Each element will describe properties for one set of image aspects that are bound simultaneously in the image. This is usually one element for each aspect in the image, but for interleaved depth/stencil images there is only one element describing the combined aspects.

void vkGetPhysicalDeviceSparseImageFormatProperties(
    VkPhysicalDevice physicalDevice, 
    VkFormat format, 
    VkImageType type, 
    VkSampleCountFlagBits samples, 
    VkImageUsageFlags usage, 
    VkImageTiling tiling, 
    uint32_t* pPropertyCount, 
    VkSparseImageFormatProperties* pProperties);

- **physicalDevice** is the physical device from which to query the sparse image format properties.
- **format** is the image format.
- **type** is the dimensionality of image.
- **samples** is a VkSampleCountFlagBits value specifying the number of samples per texel.
- **usage** is a bitmask describing the intended usage of the image.
- **tiling** is the tiling arrangement of the texel blocks in memory.
- **pPropertyCount** is a pointer to an integer related to the number of sparse format properties available or queried, as described below.
- **pProperties** is either NULL or a pointer to an array of VkSparseImageFormatProperties structures.

If pProperties is NULL, then the number of sparse format properties available is returned in pPropertyCount. Otherwise, pPropertyCount must point to a variable set by the user to the number of elements in the pProperties array, and on return the variable is overwritten with the number of structures actually written to pProperties. If pPropertyCount is less than the number of sparse format properties available, at most pPropertyCount structures will be written.

If VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT is not supported for the given arguments, pPropertyCount will be set to zero upon return, and no data will be written to pProperties.

Multiple aspects are returned for depth/stencil images that are implemented as separate planes by the implementation. The depth and stencil data planes each have unique
**VkSparseImageFormatProperties** data.

Depth/stencil images with depth and stencil data interleaved into a single plane will return a single **VkSparseImageFormatProperties** structure with the **aspectMask** set to **VK_IMAGE_ASPECT_DEPTH_BIT | VK_IMAGE_ASPECT_STENCIL_BIT**.

### Valid Usage

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-samples-01094**
  
  *samples must* be a bit value that is set in **VkImageFormatProperties::sampleCounts** returned by **vkGetPhysicalDeviceImageFormatProperties** with **format**, **type**, **tiling**, and **usage** equal to those in this command and **flags** equal to the value that is set in **VkImageCreateInfo::flags** when the image is created.

### Valid Usage (Implicit)

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-physicalDevice-parameter**
  
  **physicalDevice must** be a valid **VkPhysicalDevice** handle.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-format-parameter**
  
  **format must** be a valid **VkFormat** value.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-type-parameter**
  
  **type must** be a valid **VkImageType** value.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-samples-parameter**
  
  **samples must** be a valid **VkSampleCountFlagBits** value.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-usage-parameter**
  
  **usage must** be a valid combination of **VkImageUsageFlagBits** values.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-usage-requiredbitsetmask**
  
  **usage must** not be 0.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-tiling-parameter**
  
  **tiling must** be a valid **VkImageTiling** value.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-pPropertyCount-parameter**
  
  **pPropertyCount must** be a valid pointer to a **uint32_t** value.

- **VUID-vkGetPhysicalDeviceSparseImageFormatProperties-pProperties-parameter**
  
  If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not **NULL**, **pProperties must** be a valid pointer to an array of **pPropertyCount** **VkSparseImageFormatProperties** structures.

**vkGetPhysicalDeviceSparseImageFormatProperties2** returns an array of **VkSparseImageFormatProperties2**. Each element will describe properties for one set of image aspects that are bound simultaneously in the image. This is usually one element for each aspect in the image, but for interleaved depth/stencil images there is only one element describing the combined aspects.
void vkGetPhysicalDeviceSparseImageFormatProperties2(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceSparseImageFormatInfo2* pFormatInfo,
    uint32_t* pPropertyCount,
    VkSparseImageFormatProperties2* pProperties);

• physicalDevice is the physical device from which to query the sparse image format properties.
• pFormatInfo is a pointer to a VkPhysicalDeviceSparseImageFormatInfo2 structure containing input parameters to the command.
• pPropertyCount is a pointer to an integer related to the number of sparse format properties available or queried, as described below.
• pProperties is either NULL or a pointer to an array of VkSparseImageFormatProperties2 structures.

vkGetPhysicalDeviceSparseImageFormatProperties2 behaves identically to vkGetPhysicalDeviceSparseImageFormatProperties, with the ability to return extended information by adding extending structures to the pNext chain of its pProperties parameter.

Valid Usage (Implicit)

• VUID-vkGetPhysicalDeviceSparseImageFormatProperties2-physicalDevice-parameter physicalDevice must be a valid VkPhysicalDevice handle
• VUID-vkGetPhysicalDeviceSparseImageFormatProperties2-pFormatInfo-parameter pFormatInfo must be a valid pointer to a valid VkPhysicalDeviceSparseImageFormatInfo2 structure
• VUID-vkGetPhysicalDeviceSparseImageFormatProperties2-pPropertyCount-parameter pPropertyCount must be a valid pointer to a uint32_t value
• VUID-vkGetPhysicalDeviceSparseImageFormatProperties2-pProperties-parameter If the value referenced by pPropertyCount is not 0, and pProperties is not NULL, pProperties must be a valid pointer to an array of pPropertyCount VkSparseImageFormatProperties2 structures

The VkPhysicalDeviceSparseImageFormatInfo2 structure is defined as:

typedef struct VkPhysicalDeviceSparseImageFormatInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkFormat format;
    VkImageType type;
    VkSampleCountFlagBits samples;
    VkImageUsageFlags usage;
    VkImageTiling tiling;
}
• **sType** is a `VkStructureType` value identifying this structure.
• **pNext** is `NULL` or a pointer to a structure extending this structure.
• **format** is the image format.
• **type** is the dimensionality of image.
• **samples** is a `VkSampleCountFlagBits` value specifying the number of samples per texel.
• **usage** is a bitmask describing the intended usage of the image.
• **tiling** is the tiling arrangement of the texel blocks in memory.

### Valid Usage

- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-samples-01095**
  - `samples` must be a bit value that is set in `VkImageFormatProperties::sampleCounts` returned by `vkGetPhysicalDeviceImageFormatProperties` with `format`, `type`, `tiling`, and `usage` equal to those in this command and `flags` equal to the value that is set in `VkImageCreateInfo` `::flags` when the image is created.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-sType-sType**
  - `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2`
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-pNext-pNext**
  - `pNext` must be `NULL`
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-format-parameter**
  - `format` must be a valid `VkFormat` value
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-type-parameter**
  - `type` must be a valid `VkImageType` value
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-samples-parameter**
  - `samples` must be a valid `VkSampleCountFlagBits` value
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-usage-parameter**
  - `usage` must be a valid combination of `VkImageUsageFlagBits` values
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-usage-requiredbitmask**
  - `usage` must not be `0`
- **VUID-VkPhysicalDeviceSparseImageFormatInfo2-tiling-parameter**
  - `tiling` must be a valid `VkImageTiling` value

The `VkSparseImageFormatProperties2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
```
typedef struct VkSparseImageFormatProperties2 {
    VkStructureType sType;
    void* pNext;
    VkSparseImageFormatProperties properties;
} VkSparseImageFormatProperties2;

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- properties is a VkSparseImageFormatProperties structure which is populated with the same values as in vkGetPhysicalDeviceSparseImageFormatProperties.

### Valid Usage (Implicit)

- VUID-VkSparseImageFormatProperties2-sType-sType
  sType must be VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2
- VUID-VkSparseImageFormatProperties2-pNext-pNext
  pNext must be NULL

#### 29.7.4. Sparse Resource Creation

Sparse resources require that one or more sparse feature flags be specified (as part of the VkPhysicalDeviceFeatures structure described previously in the Physical Device Features section) when calling vkCreateDevice. When the appropriate device features are enabled, the VK_BUFFER_CREATE_SPARSE_* and VK_IMAGE_CREATE_SPARSE_* flags can be used. See vkCreateBuffer and vkCreateImage for details of the resource creation APIs.

**Note**

Specifying VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT or VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT requires specifying VK_BUFFER_CREATE_SPARSE_BINDING_BIT or VK_IMAGE_CREATE_SPARSE_BINDING_BIT, respectively, as well. This means that resources must be created with the appropriate *_SPARSE_BINDING_BIT to be used with the sparse binding command (vkQueueBindSparse).

#### 29.7.5. Sparse Resource Memory Requirements

Sparse resources have specific memory requirements related to binding sparse memory. These memory requirements are reported differently for VkBuffer objects and VkImage objects.

### Buffer and Fully-Resident Images

Buffers (both fully and partially resident) and fully-resident images can be bound to memory using only the data from VkMemoryRequirements. For all sparse resources the VkMemoryRequirements alignment member specifies both the bindable sparse block size in bytes and required alignment of VkDeviceMemory.
**Partially Resident Images**

Partially resident images have a different method for binding memory. As with buffers and fully resident images, the `VkMemoryRequirements::alignment` field specifies the bindable sparse block size in bytes for the image.

Requesting sparse memory requirements for `VkImage` objects using `vkGetImageSparseMemoryRequirements` will return an array of one or more `VkSparseImageMemoryRequirements` structures. Each structure describes the sparse memory requirements for a group of aspects of the image.

The sparse image **must** have been created using the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` flag to retrieve valid sparse image memory requirements.

**Sparse Image Memory Requirements**

The `VkSparseImageMemoryRequirements` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseImageMemoryRequirements {
    VkSparseImageFormatProperties formatProperties;
    uint32_t imageMipTailFirstLod;
    VkDeviceSize imageMipTailSize;
    VkDeviceSize imageMipTailOffset;
    VkDeviceSize imageMipTailStride;
} VkSparseImageMemoryRequirements;
```

- `formatProperties` is a `VkSparseImageFormatProperties` structure specifying properties of the image format.
- `imageMipTailFirstLod` is the first mip level at which image subresources are included in the mip tail region.
- `imageMipTailSize` is the memory size (in bytes) of the mip tail region. If `formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`, this is the size of the whole mip tail, otherwise this is the size of the mip tail of a single array layer. This value is guaranteed to be a multiple of the sparse block size in bytes.
- `imageMipTailOffset` is the opaque memory offset used with `VkSparseImageOpaqueMemoryBindInfo` to bind the mip tail region(s).
- `imageMipTailStride` is the offset stride between each array-layer's mip tail, if `formatProperties.flags` does not contain `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` (otherwise the value is undefined).

To query sparse memory requirements for an image, call:

```c
// Provided by VK_VERSION_1_0
void vkGetImageSparseMemoryRequirements(
    VkDevice device,
    VkImage image,
    ...);
```
uint32_t* pSparseMemoryRequirementCount,
VkSparseImageMemoryRequirements* pSparseMemoryRequirements);
To query sparse memory requirements for an image, call:

```c
// Provided by VK_VERSION_1_1
void vkGetImageSparseMemoryRequirements2(
    VkDevice device,
    const VkImageSparseMemoryRequirementsInfo2* pInfo,
    uint32_t* pSparseMemoryRequirementCount,
    VkSparseImageMemoryRequirements2* pSparseMemoryRequirements);
```

- `device` is the logical device that owns the image.
- `pInfo` is a pointer to a `VkImageSparseMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.
- `pSparseMemoryRequirementCount` is a pointer to an integer related to the number of sparse memory requirements available or queried, as described below.
- `pSparseMemoryRequirements` is either `NULL` or a pointer to an array of `VkSparseImageMemoryRequirements2` structures.

**Valid Usage (Implicit)**

- VUID-vkGetImageSparseMemoryRequirements2-device-parameter: `device` must be a valid `VkDevice` handle
- VUID-vkGetImageSparseMemoryRequirements2-pInfo-parameter: `pInfo` must be a valid pointer to a valid `VkImageSparseMemoryRequirementsInfo2` structure
- VUID-vkGetImageSparseMemoryRequirements2-pSparseMemoryRequirementCount-parameter: `pSparseMemoryRequirementCount` must be a valid pointer to a `uint32_t` value
- VUID-vkGetImageSparseMemoryRequirements2-pSparseMemoryRequirements-parameter: If the value referenced by `pSparseMemoryRequirementCount` is not 0, and `pSparseMemoryRequirements` is not `NULL`, `pSparseMemoryRequirements` must be a valid pointer to an array of `VkSparseImageMemoryRequirements2` structures

To determine the sparse memory requirements for an image resource without creating an object, call:

```c
// Provided by VK_VERSION_1_3
void vkGetDeviceImageSparseMemoryRequirements(
    VkDevice device,
    const VkDeviceImageMemoryRequirements* pInfo,
    uint32_t* pSparseMemoryRequirementCount,
    VkSparseImageMemoryRequirements2* pSparseMemoryRequirements);
```
• **device** is the logical device intended to own the image.

• **pInfo** is a pointer to a `VkDeviceImageMemoryRequirements` structure containing parameters required for the memory requirements query.

• **pSparseMemoryRequirementCount** is a pointer to an integer related to the number of sparse memory requirements available or queried, as described below.

• **pSparseMemoryRequirements** is either `NULL` or a pointer to an array of `VkSparseImageMemoryRequirements2` structures.

### Valid Usage (Implicit)

- **VUID-vkGetDeviceImageSparseMemoryRequirements-device-parameter**
  
  The **device** must be a valid `VkDevice` handle.

- **VUID-vkGetDeviceImageSparseMemoryRequirements-pInfo-parameter**
  
  The **pInfo** must be a valid pointer to a valid `VkDeviceImageMemoryRequirements` structure.

- **VUID-vkGetDeviceImageSparseMemoryRequirements-pSparseMemoryRequirementCount-parameter**
  
  The **pSparseMemoryRequirementCount** must be a valid pointer to a `uint32_t` value.

- **VUID-vkGetDeviceImageSparseMemoryRequirements-pSparseMemoryRequirements-parameter**
  
  If the value referenced by **pSparseMemoryRequirementCount** is not 0, and **pSparseMemoryRequirements** is not `NULL`, **pSparseMemoryRequirements** must be a valid pointer to an array of `VkSparseImageMemoryRequirements2` structures.

The `VkImageSparseMemoryRequirementsInfo2` structure is defined as:

```
// Provided by VK_VERSION_1_1
typedef struct VkImageSparseMemoryRequirementsInfo2 {
  VkStructureType sType;
  const void* pNext;
  VkImage image;
} VkImageSparseMemoryRequirementsInfo2;
```

- **sType** is a `VkStructureType` value identifying this structure.

- **pNext** is `NULL` or a pointer to a structure extending this structure.

- **image** is the image to query.

### Valid Usage (Implicit)

- **VUID-VkImageSparseMemoryRequirementsInfo2-sType-sType**
  
  The **sType** must be `VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2`.

- **VUID-VkImageSparseMemoryRequirementsInfo2-pNext-pNext**
  
  The **pNext** must be `NULL` or a pointer to a structure extending this structure.
pNext must be NULL

- VUID-VkImageSparseMemoryRequirementsInfo2-image-parameter
  image must be a valid VkImage handle

The VkSparseImageMemoryRequirements2 structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkSparseImageMemoryRequirements2 {
    VkStructureType sType;
    void* pNext;
    VkSparseImageMemoryRequirements memoryRequirements;
} VkSparseImageMemoryRequirements2;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- memoryRequirements is a VkSparseImageMemoryRequirements structure describing the memory requirements of the sparse image.

### Valid Usage (Implicit)

- VUID-VkSparseImageMemoryRequirements2-sType-sType
  sType must be VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2
- VUID-VkSparseImageMemoryRequirements2-pNext-pNext
  pNext must be NULL

#### 29.7.6. Binding Resource Memory

Non-sparse resources are backed by a single physical allocation prior to device use (via vkBindImageMemory or vkBindBufferMemory), and their backing must not be changed. On the other hand, sparse resources can be bound to memory non-contiguously and these bindings can be altered during the lifetime of the resource.

**Note**

It is important to note that freeing a VkDeviceMemory object with vkFreeMemory will not cause resources (or resource regions) bound to the memory object to become unbound. Applications must not access resources bound to memory that has been freed.

Sparse memory bindings execute on a queue that includes the VK_QUEUE_SPARSE_BINDING_BIT bit. Applications must use synchronization primitives to guarantee that other queues do not access ranges of memory concurrently with a binding change. Applications can access other ranges of the same resource while a bind operation is executing.

**Note**
Implementations **must** provide a guarantee that simultaneously binding sparse blocks while another queue accesses those same sparse blocks via a sparse resource **must** not access memory owned by another process or otherwise corrupt the system.

While some implementations **may** include `VK_QUEUE_SPARSE_BINDING_BIT` support in queue families that also include graphics and compute support, other implementations **may** only expose a `VK_QUEUE_SPARSE_BINDING_BIT`-only queue family. In either case, applications **must** use synchronization primitives to explicitly request any ordering dependencies between sparse memory binding operations and other graphics/compute/transfer operations, as sparse binding operations are not automatically ordered against command buffer execution, even within a single queue.

When binding memory explicitly for the `VK_IMAGE_ASPECT_METADATA_BIT` the application **must** use the `VK_SPARSE_MEMORY_BIND_METADATA_BIT` in the `VkSparseMemoryBind::flags` field when binding memory. Binding memory for metadata is done the same way as binding memory for the mip tail, with the addition of the `VK_SPARSE_MEMORY_BIND_METADATA_BIT` flag.

Binding the mip tail for any aspect **must** only be performed using `VkSparseImageOpaqueMemoryBindInfo`. If `formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`, then it **can** be bound with a single `VkSparseMemoryBind` structure, with `resourceOffset = imageMipTailOffset` and `size = imageMipTailSize`.

If `formatProperties.flags` does not contain `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` then the offset for the mip tail in each array layer is given as:

```
arrayMipTailOffset = imageMipTailOffset + arrayLayer * imageMipTailStride;
```

and the mip tail **can** be bound with `layerCount` `VkSparseMemoryBind` structures, each using `size = imageMipTailSize` and `resourceOffset = arrayMipTailOffset` as defined above.

Sparse memory binding is handled by the following APIs and related data structures.

**Sparse Memory Binding Functions**

The `VkSparseMemoryBind` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseMemoryBind {
    VkDeviceSize resourceOffset;
    VkDeviceSize size;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
    VkSparseMemoryBindFlags flags;
} VkSparseMemoryBind;
```

- `resourceOffset` is the offset into the resource.
• **size** is the size of the memory region to be bound.

• **memory** is the `VkDeviceMemory` object that the range of the resource is bound to. If `memory` is `VK_NULL_HANDLE`, the range is unbound.

• **memoryOffset** is the offset into the `VkDeviceMemory` object to bind the resource range to. If `memory` is `VK_NULL_HANDLE`, this value is ignored.

• **flags** is a bitmask of `VkSparseMemoryBindFlagBits` specifying usage of the binding operation.

The binding range \([resourceOffset, resourceOffset + size]\) has different constraints based on `flags`. If `flags` contains `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range **must** be within the mip tail region of the metadata aspect. This metadata region is defined by:

\[
\text{metadataRegion} = [base, base + \text{imageMipTailSize})
\]

\[
base = \text{imageMipTailOffset} + \text{imageMipTailStride} \times n
\]

and `imageMipTailOffset`, `imageMipTailSize`, and `imageMipTailStride` values are from the `VkSparseImageMemoryRequirements` corresponding to the metadata aspect of the image, and `n` is a valid array layer index for the image,

`imageMipTailStride` is considered to be zero for aspects where `VkSparseImageMemoryRequirements::formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`.

If `flags` does not contain `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range **must** be within the range \([0, \text{VkMemoryRequirements::size})\).

---

### Valid Usage

- **VUID-VkSparseMemoryBind-memory-01096**
  If `memory` is not `VK_NULL_HANDLE`, `memory` and `memoryOffset` **must** match the memory requirements of the resource, as described in section Resource Memory Association.

- **VUID-VkSparseMemoryBind-memory-01097**
  If `memory` is not `VK_NULL_HANDLE`, `memory` **must** not have been created with a memory type that reports `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set.

- **VUID-VkSparseMemoryBind-size-01098**
  `size` **must** be greater than 0.

- **VUID-VkSparseMemoryBind-resourceOffset-01099**
  `resourceOffset` **must** be less than the size of the resource.

- **VUID-VkSparseMemoryBind-size-01100**
  `size` **must** be less than or equal to the size of the resource minus `resourceOffset`.

- **VUID-VkSparseMemoryBind-memoryOffset-01101**
  `memoryOffset` **must** be less than the size of `memory`.

- **VUID-VkSparseMemoryBind-size-01102**
  `size` **must** be less than or equal to the size of `memory` minus `memoryOffset`.
If memory was created with `VkExportMemoryAllocateInfo::handleTypes` not equal to 0, at least one handle type it contained must also have been set in `VkExternalMemoryBufferCreateInfo::handleTypes` or `VkExternalMemoryImageCreateInfo::handleTypes` when the resource was created.

If memory was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryBufferCreateInfo::handleTypes` or `VkExternalMemoryImageCreateInfo::handleTypes` when the resource was created.

### Valid Usage (Implicit)

- **VUID-VkSparseMemoryBind-memory-parameter**
  If memory is not `VK_NULL_HANDLE`, memory must be a valid `VkDeviceMemory` handle.

- **VUID-VkSparseMemoryBind-flags-parameter**
  flags must be a valid combination of `VkSparseMemoryBindFlagBits` values.

Bits which can be set in `VkSparseMemoryBind::flags`, specifying usage of a sparse memory binding operation, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSparseMemoryBindFlagBits {
    VK_SPARSE_MEMORY_BIND_METADATA_BIT = 0x00000001,
} VkSparseMemoryBindFlagBits;
```

- **VK_SPARSE_MEMORY_BIND_METADATA_BIT** specifies that the memory being bound is only for the metadata aspect.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkSparseMemoryBindFlags;
```

`VkSparseMemoryBindFlags` is a bitmask type for setting a mask of zero or more `VkSparseMemoryBindFlagBits`.

Memory is bound to `VkBuffer` objects created with the `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` flag using the following structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseBufferMemoryBindInfo {
    VkBuffer buffer;
    uint32_t bindCount;
    const VkSparseMemoryBind* pBinds;
} VkSparseBufferMemoryBindInfo;
```
VkSparseBufferMemoryBindInfo:

- **buffer** is the VkBuffer object to be bound.
- **bindCount** is the number of VkSparseMemoryBind structures in the **pBinds** array.
- **pBinds** is a pointer to an array of VkSparseMemoryBind structures.

### Valid Usage (Implicit)

- VUID-VkSparseBufferMemoryBindInfo-buffer-parameter
  **buffer** must be a valid VkBuffer handle
- VUID-VkSparseBufferMemoryBindInfo-pBinds-parameter
  **pBinds** must be a valid pointer to an array of **bindCount** valid VkSparseMemoryBind structures
- VUID-VkSparseBufferMemoryBindInfo-bindCount-arraylength
  **bindCount** must be greater than 0

Memory is bound to opaque regions of VkImage objects created with the VK_IMAGE_CREATE_SPARSE_BINDING_BIT flag using the following structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseImageOpaqueMemoryBindInfo {
    VkImage         image;
    uint32_t        bindCount;
    const VkSparseMemoryBind* pBinds;
} VkSparseImageOpaqueMemoryBindInfo;
```

- **image** is the VkImage object to be bound.
- **bindCount** is the number of VkSparseMemoryBind structures in the **pBinds** array.
- **pBinds** is a pointer to an array of VkSparseMemoryBind structures.

### Valid Usage

- VUID-VkSparseImageOpaqueMemoryBindInfo-pBinds-01103
  If the flags member of any element of **pBinds** contains VK_SPARSE_MEMORY_BIND_METADATA_BIT, the binding range defined must be within the mip tail region of the metadata aspect of **image**

### Valid Usage (Implicit)

- VUID-VkSparseImageOpaqueMemoryBindInfo-image-parameter
  **image** must be a valid VkImage handle
- VUID-VkSparseImageOpaqueMemoryBindInfo-pBinds-parameter
**pBinds** must be a valid pointer to an array of **bindCount** valid VkSparseMemoryBind structures

- VUID-VkSparseImageOpaqueMemoryBindInfo-bindCount-arraylength
  
  **bindCount** must be greater than 0

**Note**

This operation is normally used to bind memory to fully-resident sparse images or for mip tail regions of partially resident images. However, it can also be used to bind memory for the entire binding range of partially resident images.

In case **flags** does not contain VK_SPARSE_MEMORY_BIND_METADATA_BIT, the resourceOffset is in the range [0, VkMemoryRequirements::size), This range includes data from all aspects of the image, including metadata. For most implementations this will probably mean that the resourceOffset is a simple device address offset within the resource. It is possible for an application to bind a range of memory that includes both resource data and metadata. However, the application would not know what part of the image the memory is used for, or if any range is being used for metadata.

When **flags** contains VK_SPARSE_MEMORY_BIND_METADATA_BIT, the binding range specified must be within the mip tail region of the metadata aspect. In this case the resourceOffset is not required to be a simple device address offset within the resource. However, it is defined to be within [imageMipTailOffset, imageMipTailOffset + imageMipTailSize) for the metadata aspect. See VkSparseMemoryBind for the full constraints on binding region with this flag present.

Memory can be bound to sparse image blocks of VkImage objects created with the VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT flag using the following structure:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseImageMemoryBindInfo {
    VkImage image;
    uint32_t bindCount;
    const VkSparseImageMemoryBind* pBinds;
} VkSparseImageMemoryBindInfo;
```

- **image** is the VkImage object to be bound
- **bindCount** is the number of VkSparseImageMemoryBind structures in **pBinds** array
- **pBinds** is a pointer to an array of VkSparseImageMemoryBind structures

**Valid Usage**

- VUID-VkSparseImageMemoryBindInfo-subresource-01722
  The subresource.mipLevel member of each element of **pBinds** must be less than the
mipLevels specified in VkImageCreateInfo when image was created

- VUID-VkSparseImageMemoryBindInfo-subresource-01723
  The subresource.arrayLayer member of each element of pBinds must be less than the arrayLayers specified in VkImageCreateInfo when image was created

- VUID-VkSparseImageMemoryBindInfo-image-02901
  image must have been created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set

Valid Usage (Implicit)

- VUID-VkSparseImageMemoryBindInfo-image-parameter
  image must be a valid VkImage handle

- VUID-VkSparseImageMemoryBindInfo-pBinds-parameter
  pBinds must be a valid pointer to an array of bindCount valid VkSparseImageMemoryBind structures

- VUID-VkSparseImageMemoryBindInfo-bindCount-arraylength
  bindCount must be greater than 0

The VkSparseImageMemoryBind structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkSparseImageMemoryBind {
    VkImageSubresource subresource;
    VkOffset3D offset;
    VkExtent3D extent;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
    VkSparseMemoryBindFlags flags;
} VkSparseImageMemoryBind;
```

- subresource is the image aspect and region of interest in the image.

- offset are the coordinates of the first texel within the image subresource to bind.

- extent is the size in texels of the region within the image subresource to bind. The extent must be a multiple of the sparse image block dimensions, except when binding sparse image blocks along the edge of an image subresource it can instead be such that any coordinate of offset + extent equals the corresponding dimensions of the image subresource.

- memory is the VkDeviceMemory object that the sparse image blocks of the image are bound to. If memory is VK_NULL_HANDLE, the sparse image blocks are unbound.

- memoryOffset is an offset into VkDeviceMemory object. If memory is VK_NULL_HANDLE, this value is ignored.

- flags are sparse memory binding flags.
Valid Usage

- VUID-VkSparseImageMemoryBind-memory-01104
  If the `sparseResidencyAliased` feature is not enabled, and if any other resources are bound to ranges of `memory`, the range of `memory` being bound must not overlap with those bound ranges.

- VUID-VkSparseImageMemoryBind-memory-01105
  `memory` and `memoryOffset` must match the memory requirements of the calling command's `image`, as described in section Resource Memory Association.

- VUID-VkSparseImageMemoryBind-subresource-01106
  `subresource` must be a valid image subresource for `image` (see Image Views).

- VUID-VkSparseImageMemoryBind-offset-01107
  `offset.x` must be a multiple of the sparse image block width (`VkSparseImageFormatProperties::imageGranularity.width`) of the image.

- VUID-VkSparseImageMemoryBind-extent-01108
  `extent.width` must either be a multiple of the sparse image block width of the image, or else (`extent.width + offset.x`) must equal the width of the image subresource.

- VUID-VkSparseImageMemoryBind-offset-01109
  `offset.y` must be a multiple of the sparse image block height (`VkSparseImageFormatProperties::imageGranularity.height`) of the image.

- VUID-VkSparseImageMemoryBind-extent-01110
  `extent.height` must either be a multiple of the sparse image block height of the image, or else (`extent.height + offset.y`) must equal the height of the image subresource.

- VUID-VkSparseImageMemoryBind-offset-01111
  `offset.z` must be a multiple of the sparse image block depth (`VkSparseImageFormatProperties::imageGranularity.depth`) of the image.

- VUID-VkSparseImageMemoryBind-extent-01112
  `extent.depth` must either be a multiple of the sparse image block depth of the image, or else (`extent.depth + offset.z`) must equal the depth of the image subresource.

- VUID-VkSparseImageMemoryBind-memory-02732
  If `memory` was created with `VkExportMemoryAllocateInfo::handleTypes` not equal to 0, at least one handle type it contained must also have been set in `VkExternalMemoryImageCreateInfo::handleTypes` when the image was created.

- VUID-VkSparseImageMemoryBind-memory-02733
  If `memory` was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryImageCreateInfo::handleTypes` when `image` was created.

Valid Usage (Implicit)

- VUID-VkSparseImageMemoryBind-subresource-parameter
  `subresource` must be a valid `VkImageSubresource` structure.
If `memory` is not `VK_NULL_HANDLE`, `memory` must be a valid `VkDeviceMemory` handle.

Flags `must` be a valid combination of `VkSparseMemoryBindFlagBits` values.

To submit sparse binding operations to a queue, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkQueueBindSparse(
    VkQueue queue,
    uint32_t bindInfoCount,
    const VkBindSparseInfo* pBindInfo,
    VkFence fence);
```

- `queue` is the queue that the sparse binding operations will be submitted to.
- `bindInfoCount` is the number of elements in the `pBindInfo` array.
- `pBindInfo` is a pointer to an array of `VkBindSparseInfo` structures, each specifying a sparse binding submission batch.
- `fence` is an optional handle to a fence to be signaled. If `fence` is not `VK_NULL_HANDLE`, it defines a fence signal operation.

`vkQueueBindSparse` is a queue submission command, with each batch defined by an element of `pBindInfo` as a `VkBindSparseInfo` structure. Batches begin execution in the order they appear in `pBindInfo`, but may complete out of order.

Within a batch, a given range of a resource must not be bound more than once. Across batches, if a range is to be bound to one allocation and offset and then to another allocation and offset, then the application must guarantee (usually using semaphores) that the binding operations are executed in the correct order, as well as to order binding operations against the execution of command buffer submissions.

As no operation to `vkQueueBindSparse` causes any pipeline stage to access memory, synchronization primitives used in this command effectively only define execution dependencies.

Additional information about fence and semaphore operation is described in the synchronization chapter.

## Valid Usage

- VUID-vkQueueBindSparse-fence-01113
  If `fence` is not `VK_NULL_HANDLE`, `fence` must be unsignaled

- VUID-vkQueueBindSparse-fence-01114
  If `fence` is not `VK_NULL_HANDLE`, `fence` must not be associated with any other queue command that has not yet completed execution on that queue

- VUID-vkQueueBindSparse-pSignalSemaphores-01115
Each element of the `pSignalSemaphores` member of each element of `pBindInfo` must be unsignaled when the semaphore signal operation it defines is executed on the device.

- **VUID-vkQueueBindSparse-pWaitSemaphores-01116**
  When a semaphore wait operation referring to a binary semaphore defined by any element of the `pWaitSemaphores` member of any element of `pBindInfo` executes on `queue`, there must be no other queues waiting on the same semaphore.

- **VUID-vkQueueBindSparse-pWaitSemaphores-03245**
  All elements of the `pWaitSemaphores` member of all elements of `pBindInfo` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` must reference a semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) must have also been submitted for execution.

Valid Usage (Implicit)

- **VUID-vkQueueBindSparse-queue-parameter**
  `queue` must be a valid `VkQueue` handle.

- **VUID-vkQueueBindSparse-pBindInfo-parameter**
  If `bindInfoCount` is not 0, `pBindInfo` must be a valid pointer to an array of `bindInfoCount` valid `VkBindSparseInfo` structures.

- **VUID-vkQueueBindSparse-fence-parameter**
  If `fence` is not `VK_NULL_HANDLE`, `fence` must be a valid `VkFence` handle.

- **VUID-vkQueueBindSparse-queuetype**
  The `queue` must support sparse binding operations.

- **VUID-vkQueueBindSparse-commonparent**
  Both of `fence`, and `queue` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`.

Host Synchronization

- Host access to `queue` must be externally synchronized.
- Host access to `fence` must be externally synchronized.

Command Properties

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Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

The VkBindSparseInfo structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkBindSparseInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t waitSemaphoreCount;
    const VkSemaphore* pWaitSemaphores;
    uint32_t bufferBindCount;
    const VkSparseBufferMemoryBindInfo* pBufferBinds;
    uint32_t imageOpaqueBindCount;
    const VkSparseImageOpaqueMemoryBindInfo* pImageOpaqueBinds;
    uint32_t imageBindCount;
    const VkSparseImageMemoryBindInfo* pImageBinds;
    uint32_t signalSemaphoreCount;
    const VkSemaphore* pSignalSemaphores;
} VkBindSparseInfo;
```

- `sType` is a VkStructureType value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `waitSemaphoreCount` is the number of semaphores upon which to wait before executing the sparse binding operations for the batch.
- `pWaitSemaphores` is a pointer to an array of semaphores upon which to wait on before the sparse binding operations for this batch begin execution. If semaphores to wait on are provided, they define a semaphore wait operation.
- `bufferBindCount` is the number of sparse buffer bindings to perform in the batch.
- `pBufferBinds` is a pointer to an array of VkSparseBufferMemoryBindInfo structures.
- `imageOpaqueBindCount` is the number of opaque sparse image bindings to perform.
- `pImageOpaqueBinds` is a pointer to an array of VkSparseImageOpaqueMemoryBindInfo structures, indicating opaque sparse image bindings to perform.
- `imageBindCount` is the number of sparse image bindings to perform.
- `pImageBinds` is a pointer to an array of VkSparseImageMemoryBindInfo structures, indicating sparse image bindings to perform.
• **signalSemaphoreCount** is the number of semaphores to be signaled once the sparse binding operations specified by the structure have completed execution.

• **pSignalSemaphores** is a pointer to an array of semaphores which will be signaled when the sparse binding operations for this batch have completed execution. If semaphores to be signaled are provided, they define a **semaphore signal operation**.

---

**Valid Usage**

• **VUID-VkBindSparseInfo-pWaitSemaphores-03246**
  If any element of **pWaitSemaphores** or **pSignalSemaphores** was created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** then the **pNext** chain must include a **VkTimelineSemaphoreSubmitInfo** structure.

• **VUID-VkBindSparseInfo-pNext-03247**
  If the **pNext** chain of this structure includes a **VkTimelineSemaphoreSubmitInfo** structure and any element of **pWaitSemaphores** was created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** then its **waitSemaphoreValueCount** member must equal **waitSemaphoreCount**.

• **VUID-VkBindSparseInfo-pNext-03248**
  If the **pNext** chain of this structure includes a **VkTimelineSemaphoreSubmitInfo** structure and any element of **pSignalSemaphores** was created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** then its **signalSemaphoreValueCount** member must equal **signalSemaphoreCount**.

• **VUID-VkBindSparseInfo-pSignalSemaphores-03249**
  For each element of **pSignalSemaphores** created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** the corresponding element of **VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues** must have a value greater than the current value of the semaphore when the **semaphore signal operation** is executed.

• **VUID-VkBindSparseInfo-pWaitSemaphores-03250**
  For each element of **pWaitSemaphores** created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** the corresponding element of **VkTimelineSemaphoreSubmitInfo::pWaitSemaphoreValues** must have a value which does not differ from the current value of the semaphore or from the value of any outstanding semaphore wait or signal operation on that semaphore by more than **maxTimelineSemaphoreValueDifference**.

• **VUID-VkBindSparseInfo-pSignalSemaphores-03251**
  For each element of **pSignalSemaphores** created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_TIMELINE** the corresponding element of **VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues** must have a value which does not differ from the current value of the semaphore or from the value of any outstanding semaphore wait or signal operation on that semaphore by more than **maxTimelineSemaphoreValueDifference**.
Valid Usage (Implicit)

- VUID-VkBindSparseInfo-sType-sType
  sType **must** be `VK_STRUCTURE_TYPE_BIND_SPARSE_INFO`

- VUID-VkBindSparseInfo-pNext-pNext
  Each `pNext` member of any structure (including this one) in the `pNext` chain **must** be either `NULL` or a pointer to a valid instance of `VkDeviceGroupBindSparseInfo` or `VkTimelineSemaphoreSubmitInfo`

- VUID-VkBindSparseInfo-sType-unique
  The `sType` value of each struct in the `pNext` chain **must** be unique

- VUID-VkBindSparseInfo-pWaitSemaphores-parameter
  If `waitSemaphoreCount` is not 0, `pWaitSemaphores` **must** be a valid pointer to an array of `waitSemaphoreCount` valid `VkSemaphore` handles

- VUID-VkBindSparseInfo-pBufferBinds-parameter
  If `bufferBindCount` is not 0, `pBufferBinds` **must** be a valid pointer to an array of `bufferBindCount` valid `VkSparseBufferMemoryBindInfo` structures

- VUID-VkBindSparseInfo-pImageOpaqueBinds-parameter
  If `imageOpaqueBindCount` is not 0, `pImageOpaqueBinds` **must** be a valid pointer to an array of `imageOpaqueBindCount` valid `VkSparseImageOpaqueMemoryBindInfo` structures

- VUID-VkBindSparseInfo-pImageBinds-parameter
  If `imageBindCount` is not 0, `pImageBinds` **must** be a valid pointer to an array of `imageBindCount` valid `VkSparseImageMemoryBindInfo` structures

- VUID-VkBindSparseInfo-pSignalSemaphores-parameter
  If `signalSemaphoreCount` is not 0, `pSignalSemaphores` **must** be a valid pointer to an array of `signalSemaphoreCount` valid `VkSemaphore` handles

- VUID-VkBindSparseInfo-commonparent
  Both of the elements of `pSignalSemaphores`, and the elements of `pWaitSemaphores` that are valid handles of non-ignored parameters **must** have been created, allocated, or retrieved from the same `VkDevice`

To specify the values to use when waiting for and signaling semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, add a `VkTimelineSemaphoreSubmitInfo` structure to the `pNext` chain of the `VkBindSparseInfo` structure.

If the `pNext` chain of `VkBindSparseInfo` includes a `VkDeviceGroupBindSparseInfo` structure, then that structure includes device indices specifying which instance of the resources and memory are bound.

The `VkDeviceGroupBindSparseInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkDeviceGroupBindSparseInfo {
    VkStructureType sType;
    const void* pNext;
} VkDeviceGroupBindSparseInfo;
```
uint32_t resourceDeviceIndex;
uint32_t memoryDeviceIndex;
} VkDeviceGroupBindSparseInfo;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **resourceDeviceIndex** is a device index indicating which instance of the resource is bound.
- **memoryDeviceIndex** is a device index indicating which instance of the memory the resource instance is bound to.

These device indices apply to all buffer and image memory binds included in the batch pointing to this structure. The semaphore waits and signals for the batch are executed only by the physical device specified by the resourceDeviceIndex.

If this structure is not present, resourceDeviceIndex and memoryDeviceIndex are assumed to be zero.

### Valid Usage

- **VUID-VkDeviceGroupBindSparseInfo-resourceDeviceIndex-01118**
  - resourceDeviceIndex and memoryDeviceIndex must both be valid device indices

- **VUID-VkDeviceGroupBindSparseInfo-memoryDeviceIndex-01119**
  - Each memory allocation bound in this batch must have allocated an instance for memoryDeviceIndex

### Valid Usage (Implicit)

- **VUID-VkDeviceGroupBindSparseInfo-sType-sType**
  - sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO
Chapter 30. Private Data

The private data extension provides a way for users to associate arbitrary user defined data with Vulkan objects. This association is accomplished by storing 64-bit unsigned integers of user defined data in private data slots. A private data slot represents a storage allocation for one data item for each child object of the device.

An application can reserve private data slots at device creation. To reserve private data slots, insert a VkDevicePrivateDataCreateInfo in the pNext chain in VkDeviceCreateInfo before device creation. Multiple VkDevicePrivateDataCreateInfo structures can be chained together, and the sum of the requested slots will be reserved. This is an exception to the specified valid usage for structure pointer chains. Reserving slots in this manner is not strictly necessary but it may improve performance.

Private data slots are represented by VkPrivateDataSlot handles:

```
// Provided by VK_VERSION_1_3
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPrivateDataSlot)
```

To create a private data slot, call:

```
// Provided by VK_VERSION_1_3
VkResult vkCreatePrivateDataSlot(
    VkDevice device,
    const VkPrivateDataSlotCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkPrivateDataSlot* pPrivateDataSlot);
```

- `device` is the logical device associated with the creation of the object(s) holding the private data slot.
- `pCreateInfo` is a pointer to a VkPrivateDataSlotCreateInfo
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pPrivateDataSlot` is a pointer to a VkPrivateDataSlot handle in which the resulting private data slot is returned

### Valid Usage

- VUID-vkCreatePrivateDataSlot-privateData-04564
  The privateData feature must be enabled

### Valid Usage (Implicit)

- VUID-vkCreatePrivateDataSlot-device-parameter
  device must be a valid VkDevice handle
Return Codes

Success

• VK_SUCCESS

Failure

• VK_ERROR_OUT_OF_HOST_MEMORY

The VkPrivateDataSlotCreateInfo structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPrivateDataSlotCreateInfo {
    VkStructureType   sType;
    const void*       pNext;
    VkPrivateDataSlotCreateFlags flags;
} VkPrivateDataSlotCreateInfo;
```

• `sType` is a VkStructureType value identifying this structure.
• `pNext` is NULL or a pointer to a structure extending this structure.
• `flags` is reserved for future use.

Valid Usage (Implicit)

• VUID-VkPrivateDataSlotCreateInfo-sType-sType 
  `sType` must be VK_STRUCTURE_TYPE_PRIVATE_DATA_SLOT_CREATE_INFO

• VUID-VkPrivateDataSlotCreateInfo-pNext-pNext 
  `pNext` must be NULL

• VUID-VkPrivateDataSlotCreateInfo-flags-zerobitmask 
  `flags` must be 0

```c
// Provided by VK_VERSION_1_3
typedef VkFlags VkPrivateDataSlotCreateFlags;
```

VkPrivateDataSlotCreateFlags is a bitmask type for setting a mask, but is currently reserved for
To destroy a private data slot, call:

```c
// Provided by VK_VERSION_1_3
void vkDestroyPrivateDataSlot(
    VkDevice device,
    VkPrivateDataSlot privateDataSlot,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device associated with the creation of the object(s) holding the private data slot.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `privateDataSlot` is the private data slot to destroy.

### Valid Usage

- VUID-vkDestroyPrivateDataSlot-privateDataSlot-04062
  If `VkAllocationCallbacks` were provided when `privateDataSlot` was created, a compatible set of callbacks must be provided here
- VUID-vkDestroyPrivateDataSlot-privateDataSlot-04063
  If no `VkAllocationCallbacks` were provided when `privateDataSlot` was created, `pAllocator` must be `NULL`

### Valid Usage (Implicit)

- VUID-vkDestroyPrivateDataSlot-device-parameter
  `device` must be a valid `VkDevice` handle
- VUID-vkDestroyPrivateDataSlot-privateDataSlot-parameter
  If `privateDataSlot` is not `VK_NULL_HANDLE`, `privateDataSlot` must be a valid `VkPrivateDataSlot` handle
- VUID-vkDestroyPrivateDataSlot-pAllocator-parameter
  If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- VUID-vkDestroyPrivateDataSlot-privateDataSlot-parent
  If `privateDataSlot` is a valid handle, it must have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to `privateDataSlot` must be externally synchronized
To store user defined data in a slot associated with a Vulkan object, call:

```c
// Provided by VK_VERSION_1_3
VkResult vkSetPrivateData(
    VkDevice device,
    VkObjectType objectType,
    uint64_t objectHandle,
    VkPrivateDataSlot privateDataSlot,
    uint64_t data);
```

- `device` is the device that created the object.
- `objectType` is a `VkObjectType` specifying the type of object to associate data with.
- `objectHandle` is a handle to the object to associate data with.
- `privateDataSlot` is a handle to a `VkPrivateDataSlot` specifying location of private data storage.
- `data` is user defined data to associate the object with. This data will be stored at `privateDataSlot`.

### Valid Usage

- VUID-vkSetPrivateData-objectHandle-04016
  `objectHandle` must be `device` or a child of `device`

- VUID-vkSetPrivateData-objectHandle-04017
  `objectHandle` must be a valid handle to an object of type `objectType`

### Valid Usage (Implicit)

- VUID-vkSetPrivateData-device-parameter
  `device` must be a valid `VkDevice` handle

- VUID-vkSetPrivateData-objectType-parameter
  `objectType` must be a valid `VkObjectType` value

- VUID-vkSetPrivateData-privateDataSlot-parameter
  `privateDataSlot` must be a valid `VkPrivateDataSlot` handle

- VUID-vkSetPrivateData-privateDataSlot-parent
  `privateDataSlot` must have been created, allocated, or retrieved from `device`

### Return Codes

- **Success**
  - `VK_SUCCESS`

- **Failure**
  - `VK_ERROR_OUT_OF_HOST_MEMORY`
To retrieve user defined data from a slot associated with a Vulkan object, call:

```c
// Provided by VK_VERSION_1_3
void vkGetPrivateData(
    VkDevice device,
    VkObjectType objectType,
    uint64_t objectHandle,
    VkPrivateDataSlot privateDataSlot,
    uint64_t* pData);
```

- `device` is the device that created the object
- `objectType` is a `VkObjectType` specifying the type of object data is associated with.
- `objectHandle` is a handle to the object data is associated with.
- `privateDataSlot` is a handle to a `VkPrivateDataSlot` specifying location of private data pointer storage.
- `pData` is a pointer to specify where user data is returned. `0` will be written in the absence of a previous call to `vkSetPrivateData` using the object specified by `objectHandle`.

**Note**
Due to platform details on Android, implementations might not be able to reliably return `0` from calls to `vkGetPrivateData` for `VkSwapchainKHR` objects on which `vkSetPrivateData` has not previously been called. This erratum is exclusive to the Android platform and objects of type `VkSwapchainKHR`.

**Valid Usage**

- **VUID-vkGetPrivateData-objectType-04018**
  - `objectType` must be `VK_OBJECT_TYPE_DEVICE`, or an object type whose parent is `VkDevice`

**Valid Usage (Implicit)**

- **VUID-vkGetPrivateData-device-parameter**
  - `device` must be a valid `VkDevice` handle

- **VUID-vkGetPrivateData-objectType-parameter**
  - `objectType` must be a valid `VkObjectType` value

- **VUID-vkGetPrivateData-privateDataSlot-parameter**
  - `privateDataSlot` must be a valid `VkPrivateDataSlot` handle

- **VUID-vkGetPrivateData-pData-parameter**
  - `pData` must be a valid pointer to a `uint64_t` value

- **VUID-vkGetPrivateData-privateDataSlot-parent**
  - `privateDataSlot` must have been created, allocated, or retrieved from `device`
Chapter 31. Extending Vulkan

New functionality may be added to Vulkan via either new extensions or new versions of the core, or new versions of an extension in some cases.

This chapter describes how Vulkan is versioned, how compatibility is affected between different versions, and compatibility rules that are followed by the Vulkan Working Group.

31.1. Instance and Device Functionality

Commands that enumerate instance properties, or that accept a `VkInstance` object as a parameter, are considered instance-level functionality.

Commands that dispatch from a `VkDevice` object or a child object of a `VkDevice`, or take any of them as a parameter, are considered device-level functionality. Types defined by a `device extension` are also considered device-level functionality.

Commands that dispatch from `VkPhysicalDevice`, or accept a `VkPhysicalDevice` object as a parameter, are considered either instance-level or device-level functionality depending if the functionality is specified by an `instance extension` or `device extension` respectively.

Additionally, commands that enumerate physical device properties are considered device-level functionality.

**Note**
Applications usually interface to Vulkan using a loader that implements only instance-level functionality, passing device-level functionality to implementations of the full Vulkan API on the system. In some circumstances, as these may be implemented independently, it is possible that the loader and device implementations on a given installation will support different versions. To allow for this and call out when it happens, the Vulkan specification enumerates device and instance level functionality separately - they have independent version queries.

**Note**
Vulkan 1.0 initially specified new physical device enumeration functionality as instance-level, requiring it to be included in an instance extension. As the capabilities of device-level functionality require discovery via physical device enumeration, this led to the situation where many device extensions required an instance extension as well. To alleviate this extra work, `VK_KHR_get_physical_device_properties2` (and subsequently Vulkan 1.1) redefined device-level functionality to include physical device enumeration.

31.2. Core Versions

The Vulkan Specification is regularly updated with bug fixes and clarifications. Occasionally new
functionality is added to the core and at some point it is expected that there will be a desire to perform a large, breaking change to the API. In order to indicate to developers how and when these changes are made to the specification, and to provide a way to identify each set of changes, the Vulkan API maintains a version number.

### 31.2.1. Version Numbers

The Vulkan version number comprises four parts indicating the variant, major, minor and patch version of the Vulkan API Specification.

The **variant** indicates the variant of the Vulkan API supported by the implementation. This is always 0 for the Vulkan API.

*Note*

A non-zero variant indicates the API is a variant of the Vulkan API and applications will typically need to be modified to run against it. The variant field was a later addition to the version number, added in version 1.2.175 of the Specification. As Vulkan uses variant 0, this change is fully backwards compatible with the previous version number format for Vulkan implementations. New version number macros have been added for this change and the old macros deprecated. For existing applications using the older format and macros, an implementation with non-zero variant will decode as a very high Vulkan version. The high version number should be detectable by applications performing suitable version checking.

The **major version** indicates a significant change in the API, which will encompass a wholly new version of the specification.

The **minor version** indicates the incorporation of new functionality into the core specification.

The **patch version** indicates bug fixes, clarifications, and language improvements have been incorporated into the specification.

Compatibility guarantees made about versions of the API sharing any of the same version numbers are documented in [Core Versions](#).

The version number is used in several places in the API. In each such use, the version numbers are packed into a 32-bit integer as follows:

- The variant is a 3-bit integer packed into bits 31-29.
- The major version is a 7-bit integer packed into bits 28-22.
- The minor version number is a 10-bit integer packed into bits 21-12.
- The patch version number is a 12-bit integer packed into bits 11-0.

`VK_API_VERSION_VARIANT` extracts the API variant number from a packed version number:

```c
// Provided by VK_VERSION_1_0
```
#define VK_API_VERSION_VARIANT(version) ((uint32_t)(version) >> 29U)

**VK_API_VERSION_MAJOR** extracts the API major version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
#define VK_API_VERSION_MAJOR(version) (((uint32_t)(version) >> 22U) & 0x7FU)
```

**VK_VERSION_MAJOR** extracts the API major version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
// DEPRECATED: This define is deprecated. VK_API_VERSION_MAJOR should be used instead.
#define VK_VERSION_MAJOR(version) ((uint32_t)(version) >> 22U)
```

**VK_API_VERSION_MINOR** extracts the API minor version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
#define VK_API_VERSION_MINOR(version) (((uint32_t)(version) >> 12U) & 0x3FFU)
```

**VK_VERSION_MINOR** extracts the API minor version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
// DEPRECATED: This define is deprecated. VK_API_VERSION_MINOR should be used instead.
#define VK_VERSION_MINOR(version) (((uint32_t)(version) >> 12U) & 0x3FFU)
```

**VK_API_VERSION_PATCH** extracts the API patch version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
#define VK_API_VERSION_PATCH(version) ((uint32_t)(version) & 0xFFFU)
```

**VK_VERSION_PATCH** extracts the API patch version number from a packed version number:

```c
// Provided by VK_VERSION_1_0
// DEPRECATED: This define is deprecated. VK_API_VERSION_PATCH should be used instead.
#define VK_VERSION_PATCH(version) ((uint32_t)(version) & 0xFFFU)
```

**VK_MAKE_API_VERSION** constructs an API version number.

```c
// Provided by VK_VERSION_1_0
#define VK_MAKE_API_VERSION(variant, major, minor, patch) \
    (((uint32_t)(variant)) << 29U) | (((uint32_t)(major)) << 22U) | \
    (((uint32_t)(minor)) << 12U) | ((uint32_t)(patch)))
```
• **variant** is the variant number.
• **major** is the major version number.
• **minor** is the minor version number.
• **patch** is the patch version number.

**VK_MAKE_VERSION** constructs an API version number.

```c
// Provided by VK_VERSION_1_0
// DEPRECATED: This define is deprecated. VK_MAKE_API_VERSION should be used instead.
#define VK_MAKE_VERSION(major, minor, patch) 
  (((uint32_t)(major)) << 22U) | (((uint32_t)(minor)) << 12U) | 
  ((uint32_t)(patch))
```

• **major** is the major version number.
• **minor** is the minor version number.
• **patch** is the patch version number.

**VK_API_VERSION_1_0** returns the API version number for Vulkan 1.0.0.

```c
// Provided by VK_VERSION_1_0
// Vulkan 1.0 version number
#define VK_API_VERSION_1_0 VK_MAKE_API_VERSION(0, 1, 0, 0)// Patch version should always be set to 0
```

**VK_API_VERSION_1_1** returns the API version number for Vulkan 1.1.0.

```c
// Provided by VK_VERSION_1_1
// Vulkan 1.1 version number
#define VK_API_VERSION_1_1 VK_MAKE_API_VERSION(0, 1, 1, 0)// Patch version should always be set to 0
```

**VK_API_VERSION_1_2** returns the API version number for Vulkan 1.2.0.

```c
// Provided by VK_VERSION_1_2
// Vulkan 1.2 version number
#define VK_API_VERSION_1_2 VK_MAKE_API_VERSION(0, 1, 2, 0)// Patch version should always be set to 0
```

**VK_API_VERSION_1_3** returns the API version number for Vulkan 1.3.0.

```c
// Provided by VK_VERSION_1_3
// Vulkan 1.3 version number
#define VK_API_VERSION_1_3 VK_MAKE_API_VERSION(0, 1, 3, 0)// Patch version should
31.2.2. Querying Version Support

The version of instance-level functionality can be queried by calling \texttt{vkEnumerateInstanceVersion}.

The version of device-level functionality can be queried by calling \texttt{vkGetPhysicalDeviceProperties} or \texttt{vkGetPhysicalDeviceProperties2}, and is returned in \texttt{VkPhysicalDeviceProperties::apiVersion}, encoded as described in Version Numbers.

31.3. Layers

When a layer is enabled, it inserts itself into the call chain for Vulkan commands the layer is interested in. Layers can be used for a variety of tasks that extend the base behavior of Vulkan beyond what is required by the specification - such as call logging, tracing, validation, or providing additional extensions.

\textbf{Note}

For example, an implementation is not expected to check that the value of enums used by the application fall within allowed ranges. Instead, a validation layer would do those checks and flag issues. This avoids a performance penalty during production use of the application because those layers would not be enabled in production.

\textbf{Note}

Vulkan layers may wrap object handles (i.e. return a different handle value to the application than that generated by the implementation). This is generally discouraged, as it increases the probability of incompatibilities with new extensions. The validation layers wrap handles in order to track the proper use and destruction of each object. See the "Architecture of the Vulkan Loader Interfaces" document for additional information.

To query the available layers, call:

\begin{verbatim}
// Provided by VK_VERSION_1_0
VkResult vkEnumerateInstanceLayerProperties(
    uint32_t* pPropertyCount,
    VkLayerProperties* pProperties);
\end{verbatim}

- \texttt{pPropertyCount} is a pointer to an integer related to the number of layer properties available or queried, as described below.
- \texttt{pProperties} is either \texttt{NULL} or a pointer to an array of \texttt{VkLayerProperties} structures.

If \texttt{pProperties} is \texttt{NULL}, then the number of layer properties available is returned in \texttt{pPropertyCount}. Otherwise, \texttt{pPropertyCount} must point to a variable set by the user to the number of elements in the \texttt{pProperties} array, and on return the variable is overwritten with the number of structures actually
written to pProperties. If pPropertyCount is less than the number of layer properties available, at most pPropertyCount structures will be written, and VK_INCOMPLETE will be returned instead of VK_SUCCESS, to indicate that not all the available properties were returned.

The list of available layers may change at any time due to actions outside of the Vulkan implementation, so two calls to vkEnumerateInstanceLayerProperties with the same parameters may return different results, or retrieve different pPropertyCount values or pProperties contents. Once an instance has been created, the layers enabled for that instance will continue to be enabled and valid for the lifetime of that instance, even if some of them become unavailable for future instances.

**Valid Usage (Implicit)**

- VUID-vkEnumerateInstanceLayerProperties-pPropertyCount-parameter
  pPropertyCount must be a valid pointer to a uint32_t value

- VUID-vkEnumerateInstanceLayerProperties-pProperties-parameter
  If the value referenced by pPropertyCount is not 0, and pProperties is not NULL, pProperties must be a valid pointer to an array of pPropertyCount VkLayerProperties structures

**Return Codes**

**Success**
- VK_SUCCESS
- VK_INCOMPLETE

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkLayerProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkLayerProperties {
    char     layerName[VK_MAX_EXTENSION_NAME_SIZE];
    uint32_t specVersion;
    uint32_t implementationVersion;
    char     description[VK_MAX_DESCRIPTION_SIZE];
} VkLayerProperties;
```

- `layerName` is an array of VK_MAX_EXTENSION_NAME_SIZE char containing a null-terminated UTF-8 string which is the name of the layer. Use this name in the `ppEnabledLayerNames` array passed in the `VkInstanceCreateInfo` structure to enable this layer for an instance.

- `specVersion` is the Vulkan version the layer was written to, encoded as described in Version Numbers.
• \texttt{implementationVersion} is the version of this layer. It is an integer, increasing with backward compatible changes.

• \texttt{description} is an array of \texttt{VK\_MAX\_DESCRIPTION\_SIZE char} containing a null-terminated UTF-8 string which provides additional details that \texttt{can} be used by the application to identify the layer.

\texttt{VK\_MAX\_EXTENSION\_NAME\_SIZE} is the length in \texttt{char} values of an array containing a layer or extension name string, as returned in \texttt{VkLayerProperties::layerName}, \texttt{VkExtensionProperties::extensionName}, and other queries.

\begin{verbatim}
#define VK_MAX_EXTENSION_NAME_SIZE 256U
\end{verbatim}

\texttt{VK\_MAX\_DESCRIPTION\_SIZE} is the length in \texttt{char} values of an array containing a string with additional descriptive information about a query, as returned in \texttt{VkLayerProperties::description} and other queries.

\begin{verbatim}
#define VK_MAX_DESCRIPTION_SIZE 256U
\end{verbatim}

To enable a layer, the name of the layer \textbf{should} be added to the \texttt{ppEnabledLayerNames} member of \texttt{VkInstanceCreateInfo} when creating a \texttt{VkInstance}.

Loader implementations \textbf{may} provide mechanisms outside the Vulkan API for enabling specific layers. Layers enabled through such a mechanism are \emph{implicitly enabled}, while layers enabled by including the layer name in the \texttt{ppEnabledLayerNames} member of \texttt{VkInstanceCreateInfo} are \emph{explicitly enabled}. Implicitly enabled layers are loaded before explicitly enabled layers, such that implicitly enabled layers are closer to the application, and explicitly enabled layers are closer to the driver. Except where otherwise specified, implicitly enabled and explicitly enabled layers differ only in the way they are enabled, and the order in which they are loaded. Explicitly enabling a layer that is implicitly enabled results in this layer being loaded as an implicitly enabled layer; it has no additional effect.

\subsection{31.3.1. Device Layer Deprecation}

Previous versions of this specification distinguished between instance and device layers. Instance layers were only able to intercept commands that operate on \texttt{VkInstance} and \texttt{VkPhysicalDevice}, except they were not able to intercept \texttt{vkCreateDevice}. Device layers were enabled for individual devices when they were created, and could only intercept commands operating on that device or its child objects.

Device-only layers are now deprecated, and this specification no longer distinguishes between instance and device layers. Layers are enabled during instance creation, and are able to intercept all commands operating on that instance or any of its child objects. At the time of deprecation there were no known device-only layers and no compelling reason to create one.

In order to maintain compatibility with implementations released prior to device-layer deprecation, applications \textbf{should} still enumerate and enable device layers. The behavior of \texttt{vkEnumerateDeviceLayerProperties} and valid usage of the \texttt{ppEnabledLayerNames} member of \texttt{VkDeviceCreateInfo} maximizes compatibility with applications written to work with the previous
requirements.

To enumerate device layers, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkEnumerateDeviceLayerProperties(
    VkPhysicalDevice physicalDevice,
    uint32_t* pPropertyCount,
    VkLayerProperties* pProperties);
```

- `physicalDevice` is the physical device that will be queried.
- `pPropertyCount` is a pointer to an integer related to the number of layer properties available or queried.
- `pProperties` is either `NULL` or a pointer to an array of `VkLayerProperties` structures.

If `pProperties` is `NULL`, then the number of layer properties available is returned in `pPropertyCount`. Otherwise, `pPropertyCount` must point to a variable set by the user to the number of elements in the `pProperties` array, and on return the variable is overwritten with the number of structures actually written to `pProperties`. If `pPropertyCount` is less than the number of layer properties available, at most `pPropertyCount` structures will be written, and `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available properties were returned.

The list of layers enumerated by `vkEnumerateDeviceLayerProperties` must be exactly the sequence of layers enabled for the instance. The members of `VkLayerProperties` for each enumerated layer must be the same as the properties when the layer was enumerated by `vkEnumerateInstanceLayerProperties`.

**Note**

Due to platform details on Android, `vkEnumerateDeviceLayerProperties` may be called with `physicalDevice` equal to `NULL` during layer discovery. This behaviour will only be observed by layer implementations, and not the underlying Vulkan driver.

**Valid Usage (Implicit)**

- VUID-vkEnumerateDeviceLayerProperties-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkEnumerateDeviceLayerProperties-pPropertyCount-parameter `pPropertyCount` must be a valid pointer to a `uint32_t` value
- VUID-vkEnumerateDeviceLayerProperties-pProperties-parameter If the value referenced by `pPropertyCount` is not 0, and `pProperties` is not `NULL`, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkLayerProperties` structures
### Return Codes

**Success**
- VK_SUCCESS
- VK_INCOMPLETE

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `ppEnabledLayerNames` and `enabledLayerCount` members of `VkDeviceCreateInfo` are deprecated and their values must be ignored by implementations. However, for compatibility, only an empty list of layers or a list that exactly matches the sequence enabled at instance creation time are valid, and validation layers should issue diagnostics for other cases.

Regardless of the enabled layer list provided in `VkDeviceCreateInfo`, the sequence of layers active for a device will be exactly the sequence of layers enabled when the parent instance was created.

### 31.4. Extensions

Extensions may define new Vulkan commands, structures, and enumerants. For compilation purposes, the interfaces defined by registered extensions, including new structures and enumerants as well as function pointer types for new commands, are defined in the Khronos-supplied `vulkan_core.h` together with the core API. However, commands defined by extensions may not be available for static linking - in which case function pointers to these commands should be queried at runtime as described in Command Function Pointers. Extensions may be provided by layers as well as by a Vulkan implementation.

Because extensions may extend or change the behavior of the Vulkan API, extension authors should add support for their extensions to the Khronos validation layers. This is especially important for new commands whose parameters have been wrapped by the validation layers. See the “Architecture of the Vulkan Loader Interfaces” document for additional information.

---

**Note**

To enable an instance extension, the name of the extension can be added to the `ppEnabledExtensionNames` member of `VkInstanceCreateInfo` when creating a `VkInstance`.

To enable a device extension, the name of the extension can be added to the `ppEnabledExtensionNames` member of `VkDeviceCreateInfo` when creating a `VkDevice`.

Physical-Device-Level functionality does not have any enabling mechanism and can be used as long as the `VkPhysicalDevice` supports the device extension as determined by `vkEnumerateDeviceExtensionProperties`.

Enabling an extension (with no further use of that extension) does not change the behavior of functionality exposed by the core Vulkan API or any other extension,
other than making valid the use of the commands, enums and structures defined by that extension.

Valid Usage sections for individual commands and structures do not currently contain which extensions have to be enabled in order to make their use valid, although they might do so in the future. It is defined only in the Valid Usage for Extensions section.

31.4.1. Instance Extensions

Instance extensions add new instance-level functionality to the API, outside of the core specification.

To query the available instance extensions, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkEnumerateInstanceExtensionProperties(
    const char* pLayerName,             // pLayerName is either NULL or a pointer to a null-terminated UTF-8 string naming the layer to retrieve extensions from.
    uint32_t* pPropertyCount,            // pPropertyCount is a pointer to an integer related to the number of extension properties available or queried, as described below.
    VkExtensionProperties* pProperties   // pProperties is either NULL or a pointer to an array of VkExtensionProperties structures.
);
```

When pLayerName parameter is NULL, only extensions provided by the Vulkan implementation or by implicitly enabled layers are returned. When pLayerName is the name of a layer, the instance extensions provided by that layer are returned.

If pProperties is NULL, then the number of extensions properties available is returned in pPropertyCount. Otherwise, pPropertyCount must point to a variable set by the user to the number of elements in the pProperties array, and on return the variable is overwritten with the number of structures actually written to pProperties. If pPropertyCount is less than the number of extension properties available, at most pPropertyCount structures will be written, and VK_INCOMPLETE will be returned instead of VK_SUCCESS, to indicate that not all the available properties were returned.

Because the list of available layers may change externally between calls to vkEnumerateInstanceExtensionProperties, two calls may retrieve different results if a pLayerName is available in one call but not in another. The extensions supported by a layer may also change between two calls, e.g. if the layer implementation is replaced by a different version between those calls.

Implementations must not advertise any pair of extensions that cannot be enabled together due to behavioral differences, or any extension that cannot be enabled against the advertised version.
Valid Usage (Implicit)

- **VUID-vkEnumerateInstanceExtensionProperties-pLayerName-parameter**
  If `pLayerName` is not `NULL`, `pLayerName` must be a null-terminated UTF-8 string.

- **VUID-vkEnumerateInstanceExtensionProperties-pPropertyCount-parameter**
  `pPropertyCount` must be a valid pointer to a `uint32_t` value.

- **VUID-vkEnumerateInstanceExtensionProperties-pProperties-parameter**
  If the value referenced by `pPropertyCount` is not `0`, and `pProperties` is not `NULL`, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkExtensionProperties` structures.

Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_LAYER_NOT_PRESENT`

31.4.2. Device Extensions

Device extensions add new device-level functionality to the API, outside of the core specification.

To query the extensions available to a given physical device, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkEnumerateDeviceExtensionProperties(
    VkPhysicalDevice physicalDevice,
    const char* pLayerName,
    uint32_t* pPropertyCount,
    VkExtensionProperties* pProperties);
```

- `physicalDevice` is the physical device that will be queried.
- `pLayerName` is either `NULL` or a pointer to a null-terminated UTF-8 string naming the layer to retrieve extensions from.
- `pPropertyCount` is a pointer to an integer related to the number of extension properties available or queried, and is treated in the same fashion as the `vkEnumerateInstanceExtensionProperties` ::`pPropertyCount` parameter.
- `pProperties` is either `NULL` or a pointer to an array of `VkExtensionProperties` structures.
When `pLayerName` parameter is `NULL`, only extensions provided by the Vulkan implementation or by implicitly enabled layers are returned. When `pLayerName` is the name of a layer, the device extensions provided by that layer are returned.

Implementations **must** not advertise any pair of extensions that cannot be enabled together due to behavioral differences, or any extension that cannot be enabled against the advertised version.

Implementations claiming support for the Roadmap 2022 profile **must** advertise the `VK_KHR_global_priority` extension in `pProperties`.

---

**Note**
Due to platform details on Android, `vkEnumerateDeviceExtensionProperties` may be called with `physicalDevice` equal to `NULL` during layer discovery. This behaviour will only be observed by layer implementations, and not the underlying Vulkan driver.

---

### Valid Usage (Implicit)

- `VUID-vkEnumerateDeviceExtensionProperties-physicalDevice-parameter`
  - `physicalDevice` **must** be a valid `VkPhysicalDevice` handle
- `VUID-vkEnumerateDeviceExtensionProperties-pLayerName-parameter`
  - If `pLayerName` is not `NULL`, `pLayerName` **must** be a null-terminated UTF-8 string
- `VUID-vkEnumerateDeviceExtensionProperties-pPropertyCount-parameter`
  - `pPropertyCount` **must** be a valid pointer to a `uint32_t` value
- `VUID-vkEnumerateDeviceExtensionProperties-pProperties-parameter`
  - If the value referenced by `pPropertyCount` is not `0`, and `pProperties` is not `NULL`, `pProperties` **must** be a valid pointer to an array of `pPropertyCount` `VkExtensionProperties` structures

### Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_LAYER_NOT_PRESENT`

The `VkExtensionProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkExtensionProperties {
```
### Accessing device-level functionality from a VkPhysicalDevice

Some device extensions also add support for physical-device-level functionality. Physical-device-level functionality **can** be used, if the required extension is supported as advertised by `vkEnumerateDeviceExtensionProperties` for a given `VkPhysicalDevice`.

### Accessing device-level functionality from a VkDevice

For commands that are dispatched from a `VkDevice`, or from a child object of a `VkDevice`, device extensions **must** be enabled in `vkCreateDevice`.

### 31.5. Extension Dependencies

Some extensions are dependent on other extensions, or on specific core API versions, to function. To enable extensions with dependencies, any **required extensions** **must** also be enabled through the same API mechanisms when creating an instance with `vkCreateInstance` or a device with `vkCreateDevice`. Each extension which has such dependencies documents them in the **appendix summarizing that extension**.

If an extension is supported (as queried by `vkEnumerateInstanceExtensionProperties` or `vkEnumerateDeviceExtensionProperties`), then **required extensions** of that extension **must** also be supported for the same instance or physical device.

Any device extension that has an instance extension dependency that is not enabled by `vkCreateInstance` is considered to be unsupported, hence it **must** not be returned by `vkEnumerateDeviceExtensionProperties` for any `VkPhysicalDevice` child of the instance. Instance extensions do not have dependencies on device extensions.

If a required extension has been **promoted** to another extension or to a core API version, then as a **general** rule, the dependency is also satisfied by the promoted extension or core version. This will be true so long as any features required by the original extension are also required or enabled by the promoted extension or core version. However, in some cases an extension is promoted while making some of its features optional in the promoted extension or core version. In this case, the dependency **may** not be satisfied. The only way to be certain is to look at the descriptions of the original dependency and the promoted version in the **Layers & Extensions** and **Core Revisions** appendices.

---

**Note**

There is metadata in `vk.xml` describing some aspects of promotion, especially...
requires, promotedTo and deprecatedBy attributes of <extension> tags. However, the metadata does not yet fully describe this scenario. In the future, we may extend the XML schema to describe the full set of extensions and versions satisfying a dependency.

### 31.6. Compatibility Guarantees (Informative)

This section is marked as informal as there is no binding responsibility on implementations of the Vulkan API - these guarantees are however a contract between the Vulkan Working Group and developers using this Specification.

#### 31.6.1. Core Versions

Each of the **major, minor, and patch versions** of the Vulkan specification provide different compatibility guarantees.

**Patch Versions**

A difference in the patch version indicates that a set of bug fixes or clarifications have been made to the Specification. Informative enums returned by Vulkan commands that will not affect the runtime behavior of a valid application may be added in a patch version (e.g. `VkVendorId`).

The specification's patch version is strictly increasing for a given major version of the specification; any change to a specification as described above will result in the patch version being increased by 1. Patch versions are applied to all minor versions, even if a given minor version is not affected by the provoking change.

Specifications with different patch versions but the same major and minor version are **fully compatible** with each other - such that a valid application written against one will work with an implementation of another.

*Note*

If a patch version includes a bug fix or clarification that could have a significant impact on developer expectations, these will be highlighted in the change log. Generally the Vulkan Working Group tries to avoid these kinds of changes, instead fixing them in either an extension or core version.

**Minor Versions**

Changes in the minor version of the specification indicate that new functionality has been added to the core specification. This will usually include new interfaces in the header, and **may** also include behavior changes and bug fixes. Core functionality **may** be deprecated in a minor version, but will not be obsoleted or removed.

The specification's minor version is strictly increasing for a given major version of the specification; any change to a specification as described above will result in the minor version being increased by 1. Changes that can be accommodated in a patch version will not increase the minor version.
Specifications with a lower minor version are *backwards compatible* with an implementation of a specification with a higher minor version for core functionality and extensions issued with the KHR vendor tag. Vendor and multi-vendor extensions are not guaranteed to remain functional across minor versions, though in general they are with few exceptions - see Obsoletion for more information.

**Major Versions**

A difference in the major version of specifications indicates a large set of changes which will likely include interface changes, behavioral changes, removal of deprecated functionality, and the modification, addition, or replacement of other functionality.

The specification's major version is monotonically increasing; any change to the specification as described above will result in the major version being increased. Changes that can be accommodated in a patch or minor version will not increase the major version.

The Vulkan Working Group intends to only issue a new major version of the Specification in order to realise significant improvements to the Vulkan API that will necessarily require breaking compatibility.

A new major version will likely include a wholly new version of the specification to be issued - which could include an overhaul of the versioning semantics for the minor and patch versions. The patch and minor versions of a specification are therefore not meaningful across major versions. If a major version of the specification includes similar versioning semantics, it is expected that the patch and the minor version will be reset to 0 for that major version.

**31.6.2. Extensions**

A KHR extension **must** be able to be enabled alongside any other KHR extension, and for any minor or patch version of the core Specification beyond the minimum version it requires. A multi-vendor extension **should** be able to be enabled alongside any KHR extension or other multi-vendor extension, and for any minor or patch version of the core Specification beyond the minimum version it requires. A vendor extension **should** be able to be enabled alongside any KHR extension, multi-vendor extension, or other vendor extension from the same vendor, and for any minor or patch version of the core Specification beyond the minimum version it requires. A vendor extension **may** be able to be enabled alongside vendor extensions from another vendor.

The one other exception to this is if a vendor or multi-vendor extension is made obsolete by either a core version or another extension, which will be highlighted in the extension appendix.

**Promotion**

Extensions, or features of an extension, **may** be promoted to a new core version of the API, or a newer extension which an equal or greater number of implementors are in favour of.

When extension functionality is promoted, minor changes **may** be introduced, limited to the following:

- Naming
• Non-intrusive parameters changes
• Feature advertisement/enablement
• Combining structure parameters into larger structures
• Author ID suffixes changed or removed

**Note**
If extension functionality is promoted, there is no guarantee of direct compatibility, however it should require little effort to port code from the original feature to the promoted one.

The Vulkan Working Group endeavours to ensure that larger changes are marked as either deprecate or obsoleted as appropriate, and can do so retroactively if necessary.

Extensions that are promoted are listed as being promoted in their extension appendices, with reference to where they were promoted to.

When an extension is promoted, any backwards compatibility aliases which exist in the extension will **not** be promoted.

**Note**
As a hypothetical example, if the VKKHR_surface extension were promoted to part of a future core version, the VK_COLORSPACE_SRGB_NONLINEAR_KHR token defined by that extension would be promoted to VK_COLORSPACE_SRGB_NONLINEAR. However, the VKCOLORSPACE_SRGB_NONLINEAR_KHR token aliases VK_COLORSPACE_SRGB_NONLINEAR_KHR. The VKCOLORSPACE_SRGB_NONLINEAR_KHR would not be promoted, because it is a backwards compatibility alias that exists only due to a naming mistake when the extension was initially published.

**Deprecation**
Extensions **may** be marked as deprecated when the intended use cases either become irrelevant or can be solved in other ways. Generally, a new feature will become available to solve the use case in another extension or core version of the API, but it is not guaranteed.

**Note**
Features that are intended to replace deprecated functionality have no guarantees of compatibility, and applications may require drastic modification in order to make use of the new features.

Extensions that are deprecated are listed as being deprecated in their extension appendices, with an explanation of the deprecation and any features that are relevant.

**Obsoletion**
Occasionally, an extension will be marked as obsolete if a new version of the core API or a new extension is fundamentally incompatible with it. An obsoleted extension **must** not be used with the
extension or core version that obsoleted it.

Extensions that are obsoleted are listed as being obsoleted in their extension appendices, with reference to what they were obsoleted by.

**Aliases**

When an extension is promoted or deprecated by a newer feature, some or all of its functionality may be replicated into the newer feature. Rather than duplication of all the documentation and definitions, the specification instead identifies the identical commands and types as *aliases* of one another. Each alias is mentioned together with the definition it aliases, with the older aliases marked as “equivalents”. Each alias of the same command has identical behavior, and each alias of the same type has identical meaning - they can be used interchangeably in an application with no compatibility issues.

*Note*

For promoted types, the aliased extension type is semantically identical to the new core type. The C99 headers simply `typedef` the older aliases to the promoted types.

For promoted command aliases, however, there are two separate entry point definitions, due to the fact that the C99 ABI has no way to alias command definitions without resorting to macros. Calling via either entry point definition will produce identical behavior within the bounds of the specification, and should still invoke the same entry point in the implementation. Debug tools may use separate entry points with different debug behavior; to write the appropriate command name to an output log, for instance.

**Special Use Extensions**

Some extensions exist only to support a specific purpose or specific class of application. These are referred to as “special use extensions”. Use of these extensions in applications not meeting the special use criteria is not recommended.

Special use cases are restricted, and only those defined below are used to describe extensions:

*Table 30. Extension Special Use Cases*

<table>
<thead>
<tr>
<th>Special Use</th>
<th>XML Tag</th>
<th>Full Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD support</td>
<td>cadsupport</td>
<td>Extension is intended to support specialized functionality used by CAD/CAM apps.</td>
</tr>
<tr>
<td>D3D support</td>
<td>d3demulation</td>
<td>Extension is intended to support D3D emulation layers, and apps ported from D3D.</td>
</tr>
<tr>
<td>Developer tools</td>
<td>devtools</td>
<td>Extension is intended to support developer tools such as capture-replay libraries.</td>
</tr>
<tr>
<td>Debugging tools</td>
<td>debugging</td>
<td>Extension is intended for use by apps when debugging.</td>
</tr>
<tr>
<td>Special Use</td>
<td>XML Tag</td>
<td>Full Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>OpenGL / ES support</td>
<td>glemulation</td>
<td>Extension is intended to support OpenGL and/or OpenGL ES emulation layers, and applications ported from those APIs, by adding functionality specific to those APIs.</td>
</tr>
</tbody>
</table>

Special use extensions are identified in the metadata for each such extension in the Layers & Extensions appendix, using the name in the “Special Use” column above.

Special use extensions are also identified in vk.xml with the short name in “XML Tag” column above, as described in the “API Extensions (extension tag)” section of the registry schema documentation.
Chapter 32. Features

Features describe functionality which is not supported on all implementations. Features are properties of the physical device. Features are optional, and must be explicitly enabled before use. Support for features is reported and enabled on a per-feature basis.

Note
Features are reported via the basic VkPhysicalDeviceFeatures structure, as well as the extensible structure VkPhysicalDeviceFeatures2, which was added in the VK_KHR_get_physical_device_properties2 extension and included in Vulkan 1.1. When new features are added in future Vulkan versions or extensions, each extension should introduce one new feature structure, if needed. This structure can be added to the pNext chain of the VkPhysicalDeviceFeatures2 structure.

For convenience, new core versions of Vulkan may introduce new unified feature structures for features promoted from extensions. At the same time, the extension's original feature structure (if any) is also promoted to the core API, and is an alias of the extension's structure. This results in multiple names for the same feature: in the original extension's feature structure and the promoted structure alias, in the unified feature structure. When a feature was implicitly supported and enabled in the extension, but an explicit name was added during promotion, then the extension itself acts as an alias for the feature as listed in the table below.

All aliases of the same feature in the core API must be reported consistently: either all must be reported as supported, or none of them. When a promoted extension is available, any corresponding feature aliases must be supported.

Table 31. Extension Feature Aliases

<table>
<thead>
<tr>
<th>Extension</th>
<th>Feature(s)</th>
</tr>
</thead>
</table>

To query supported features, call:

```c
// Provided by VK_VERSION_1_0
do void vkGetPhysicalDeviceFeatures(
    VkPhysicalDevice physicalDevice,  
    VkPhysicalDeviceFeatures* pFeatures);
```

- physicalDevice is the physical device from which to query the supported features.
- pFeatures is a pointer to a VkPhysicalDeviceFeatures structure in which the physical device features are returned. For each feature, a value of VK_TRUE specifies that the feature is supported on this physical device, and VK_FALSE specifies that the feature is not supported.

Valid Usage (Implicit)

- VUID-vkGetPhysicalDeviceFeatures-physicalDevice-parameter physicalDevice must be a valid VkPhysicalDevice handle
Fine-grained features used by a logical device must be enabled at VkDevice creation time. If a feature is enabled that the physical device does not support, VkDevice creation will fail and return VK_ERROR_FEATURE_NOT_PRESENT.

The fine-grained features are enabled by passing a pointer to the VkPhysicalDeviceFeatures structure via the pEnabledFeatures member of the VkDeviceCreateInfo structure that is passed into the vkCreateDevice call. If a member of pEnabledFeatures is set to VK_TRUE or VK_FALSE, then the device will be created with the indicated feature enabled or disabled, respectively. Features can also be enabled by using the VkPhysicalDeviceFeatures2 structure.

If an application wishes to enable all features supported by a device, it can simply pass in the VkPhysicalDeviceFeatures structure that was previously returned by vkGetPhysicalDeviceFeatures. To disable an individual feature, the application can set the desired member to VK_FALSE in the same structure. Setting pEnabledFeatures to NULL and not including a VkPhysicalDeviceFeatures2 in the pNext chain of VkDeviceCreateInfo is equivalent to setting all members of the structure to VK_FALSE.

**Note**

Some features, such as robustBufferAccess, may incur a runtime performance cost. Application writers should carefully consider the implications of enabling all supported features.

To query supported features defined by the core or extensions, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceFeatures2(
    VkPhysicalDevice  physicalDevice,
    VkPhysicalDeviceFeatures2*  pFeatures);
```

- **physicalDevice** is the physical device from which to query the supported features.
- **pFeatures** is a pointer to a VkPhysicalDeviceFeatures2 structure in which the physical device features are returned.

Each structure in pFeatures and its pNext chain contains members corresponding to fine-grained features. vkGetPhysicalDeviceFeatures2 writes each member to a boolean value indicating whether that feature is supported.

**Valid Usage (Implicit)**

- VUID-vkGetPhysicalDeviceFeatures2-physicalDevice-parameter
  `physicalDevice` must be a valid VkPhysicalDevice handle
- VUID-vkGetPhysicalDeviceFeatures2-pFeatures-parameter
  `pFeatures` must be a valid pointer to a VkPhysicalDeviceFeatures2 structure
The `VkPhysicalDeviceFeatures2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceFeatures2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceFeatures features;
} VkPhysicalDeviceFeatures2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `features` is a `VkPhysicalDeviceFeatures` structure describing the fine-grained features of the Vulkan 1.0 API.

The `pNext` chain of this structure is used to extend the structure with features defined by extensions. This structure can be used in `vkGetPhysicalDeviceFeatures2` or can be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which features are enabled on the device in lieu of `pEnabledFeatures`.

### Valid Usage (Implicit)

- `VUID-VkPhysicalDeviceFeatures2-sType-sType`
  - `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2`

The `VkPhysicalDeviceFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPhysicalDeviceFeatures {
    VkBool32 robustBufferAccess;
    VkBool32 fullDrawIndexUint32;
    VkBool32 imageCubeArray;
    VkBool32 independentBlend;
    VkBool32 geometryShader;
    VkBool32 tessellationShader;
    VkBool32 sampleRateShading;
    VkBool32 dualSrcBlend;
    VkBool32 logicOp;
    VkBool32 multiDrawIndirect;
    VkBool32 drawIndirectFirstInstance;
    VkBool32 depthClamp;
    VkBool32 depthBiasClamp;
    VkBool32 fillModeNonSolid;
    VkBool32 depthBounds;
    VkBool32 wideLines;
    VkBool32 largePoints;
    VkBool32 alphaToOne;
    VkBool32 multiViewport;
} VkPhysicalDeviceFeatures;
```
This structure describes the following features:

- **robustBufferAccess** specifies that accesses to buffers are bounds-checked against the range of the buffer descriptor (as determined by `VkDescriptorBufferInfo::range`, `VkBufferViewCreateInfo::range`, or the size of the buffer). Out of bounds accesses must not cause application termination, and the effects of shader loads, stores, and atomics must conform to an implementation-dependent behavior as described below.

  A buffer access is considered to be out of bounds if any of the following are true:
  
  - The pointer was formed by `OpImageTexelPointer` and the coordinate is less than zero or greater than or equal to the number of whole elements in the bound range.
  
  - The pointer was not formed by `OpImageTexelPointer` and the object pointed to is not
wholly contained within the bound range. This includes accesses performed via \textit{variable pointers} where the buffer descriptor being accessed cannot be statically determined. Uninitialized pointers and pointers equal to \texttt{OpConstantNull} are treated as pointing to a zero-sized object, so all accesses through such pointers are considered to be out of bounds. Buffer accesses through buffer device addresses are not bounds-checked.

\begin{note}
If a SPIR-V \texttt{OpLoad} instruction loads a structure and the tail end of the structure is out of bounds, then all members of the structure are considered out of bounds even if the members at the end are not statically used.
\end{note}

- If any buffer access is determined to be out of bounds, then any other access of the same type (load, store, or atomic) to the same buffer that accesses an address less than 16 bytes away from the out of bounds address \texttt{may} also be considered out of bounds.
- If the access is a load that reads from the same memory locations as a prior store in the same shader invocation, with no other intervening accesses to the same memory locations in that shader invocation, then the result of the load \texttt{may} be the value stored by the store instruction, even if the access is out of bounds. If the load is \texttt{Volatile}, then an out of bounds load \texttt{must} return the appropriate out of bounds value.

\begin{itemize}
  \item Out-of-bounds buffer loads will return any of the following values:
    \begin{itemize}
      \item Values from anywhere within the memory range(s) bound to the buffer (possibly including bytes of memory past the end of the buffer, up to the end of the bound range).
      \item Zero values, or \texttt{(0,0,0,x)} vectors for vector reads where \texttt{x} is a valid value represented in the type of the vector components and \texttt{may} be any of:
        \begin{itemize}
          \item 0, 1, or the maximum representable positive integer value, for signed or unsigned integer components
          \item 0.0 or 1.0, for floating-point components
        \end{itemize}
    \end{itemize}
  \item Out-of-bounds writes \texttt{may} modify values within the memory range(s) bound to the buffer, but \texttt{must} not modify any other memory.
  \item Out-of-bounds atomics \texttt{may} modify values within the memory range(s) bound to the buffer, but \texttt{must} not modify any other memory, and return an undefined value.
  \item Vertex input attributes are considered out of bounds if the offset of the attribute in the bound vertex buffer range plus the size of the attribute is greater than either:
    \begin{itemize}
      \item \texttt{vertexBufferRangeSize}, if \texttt{bindingStride} == 0; or
      \item \texttt{(vertexBufferRangeSize - (vertexBufferRangeSize \% bindingStride))}
    \end{itemize}
\end{itemize}

where \texttt{vertexBufferRangeSize} is the byte size of the memory range bound to the vertex buffer binding and \texttt{bindingStride} is the byte stride of the corresponding vertex input binding. Further, if any vertex input attribute using a specific vertex input binding is out of bounds, then all vertex input attributes using that vertex input binding for that vertex shader invocation are considered out of bounds.

- If a vertex input attribute is out of bounds, it will be assigned one of the following
values:
  • Values from anywhere within the memory range(s) bound to the buffer, converted according to the format of the attribute.
  • Zero values, format converted according to the format of the attribute.
  • Zero values, or (0,0,0,x) vectors, as described above.
  ◦ If robustBufferAccess is not enabled, applications must not perform out of bounds accesses.

• fullDrawIndexUint32 specifies the full 32-bit range of indices is supported for indexed draw calls when using a VkIndexType of VK_INDEX_TYPE_UINT32. maxDrawIndexedIndexValue is the maximum index value that may be used (aside from the primitive restart index, which is always \(2^{32}-1\) when the VkIndexType is VK_INDEX_TYPE_UINT32). If this feature is supported, maxDrawIndexedIndexValue must be \(2^{32}-1\); otherwise it must be no smaller than \(2^{24}-1\). See maxDrawIndexedIndexValue.

• imageCubeArray specifies whether image views with a VkImageViewType of VK_IMAGE_VIEW_TYPE_CUBE_ARRAY can be created, and that the corresponding SampledCubeArray and ImageCubeArray SPIR-V capabilities can be used in shader code.

• independentBlend specifies whether the VkPipelineColorBlendAttachmentState settings are controlled independently per-attachment. If this feature is not enabled, the VkPipelineColorBlendAttachmentState settings for all color attachments must be identical. Otherwise, a different VkPipelineColorBlendAttachmentState can be provided for each bound color attachment.

• geometryShader specifies whether geometry shaders are supported. If this feature is not enabled, the VK_SHADER_STAGE_GEOMETRY_BIT and VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT enum values must not be used. This also specifies whether shader modules can declare the Geometry capability.

• tessellationShader specifies whether tessellation control and evaluation shaders are supported. If this feature is not enabled, the VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT, VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, and VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO enum values must not be used. This also specifies whether shader modules can declare the Tessellation capability.

• sampleRateShading specifies whether Sample Shading and multisample interpolation are supported. If this feature is not enabled, the sampleShadingEnable member of the VkPipelineMultisampleStateCreateInfo structure must be set to VK_FALSE and the minSampleShading member is ignored. This also specifies whether shader modules can declare the SampleRateShading capability.

• dualSrcBlend specifies whether blend operations which take two sources are supported. If this feature is not enabled, the VK_BLEND_FACTOR_SRC1_COLOR, VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR, VK_BLEND_FACTOR_SRC1_ALPHA, and VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA enum values must not be used as source or destination blending factors. See Dual-Source Blending.

• logicOp specifies whether logic operations are supported. If this feature is not enabled, the logicOpEnable member of the VkPipelineColorBlendStateCreateInfo structure must be set to VK_FALSE, and the logicOp member is ignored.

• multiDrawIndirect specifies whether multiple draw indirect is supported. If this feature is not
enabled, the drawCount parameter to the vkCmdDrawIndirect and vkCmdDrawIndexedIndirect commands must be 0 or 1. The maxDrawIndirectCount member of the VkPhysicalDeviceLimits structure must also be 1 if this feature is not supported. See maxDrawIndirectCount.

- drawIndirectFirstInstance specifies whether indirect drawing calls support the firstInstance parameter. If this feature is not enabled, the firstInstance member of all VkDrawIndirectCommand and VkDrawIndexedIndirectCommand structures that are provided to the vkCmdDrawIndirect and vkCmdDrawIndexedIndirect commands must be 0.

- depthClamp specifies whether depth clamping is supported. If this feature is not enabled, the depthClampEnable member of the VkPipelineRasterizationStateCreateInfo structure must be set to VK_FALSE. Otherwise, setting depthClampEnable to VK_TRUE will enable depth clamping.

- depthBiasClamp specifies whether depth bias clamping is supported. If this feature is not enabled, the depthBiasClamp member of the VkPipelineRasterizationStateCreateInfo structure must be set to 0.0 unless the VK_DYNAMIC_STATE_DEPTH_BIAS dynamic state is enabled, and the depthBiasClamp parameter to vkCmdSetDepthBias must be set to 0.0.

- fillModeNonSolid specifies whether point and wireframe fill modes are supported. If this feature is not enabled, the VK_POLYGON_MODE_POINT and VK_POLYGON_MODE_LINE enum values must not be used.

- depthBounds specifies whether depth bounds tests are supported. If this feature is not enabled, the depthBoundsTestEnable member of the VkPipelineDepthStencilStateCreateInfo structure must be set to VK_FALSE. When depthBoundsTestEnable is set to VK_FALSE, the minDepthBounds and maxDepthBounds members of the VkPipelineDepthStencilStateCreateInfo structure are ignored.

- wideLines specifies whether lines with width other than 1.0 are supported. If this feature is not enabled, the lineWidth member of the VkPipelineRasterizationStateCreateInfo structure must be set to 1.0 unless the VK_DYNAMIC_STATE_LINE_WIDTH dynamic state is enabled, and the lineWidth parameter to vkCmdSetLineWidth must be set to 1.0. When this feature is supported, the range and granularity of supported line widths are indicated by the lineWidthRange and lineWidthGranularity members of the VkPhysicalDeviceLimits structure, respectively.

- largePoints specifies whether points with size greater than 1.0 are supported. If this feature is not enabled, only a point size of 1.0 written by a shader is supported. The range and granularity of supported point sizes are indicated by the pointSizeRange and pointSizeGranularity members of the VkPhysicalDeviceLimits structure, respectively.

- alphaToOne specifies whether the implementation is able to replace the alpha value of the fragment shader color output in the Multisample Coverage fragment operation. If this feature is not enabled, then the alphaToOneEnable member of the VkPipelineMultisampleStateCreateInfo structure must be set to VK_FALSE. Otherwise setting alphaToOneEnable to VK_TRUE will enable alpha-to-one behavior.

- multiViewport specifies whether more than one viewport is supported. If this feature is not enabled:
  - The viewportCount and scissorCount members of the VkPipelineViewportStateCreateInfo structure must be set to 1.
  - The firstViewport and viewportCount parameters to the vkCmdSetViewport command must be set to 0 and 1, respectively.
  - The firstScissor and scissorCount parameters to the vkCmdSetScissor command must be set
to 0 and 1, respectively.

- **samplerAnisotropy** specifies whether anisotropic filtering is supported. If this feature is not enabled, the `anisotropyEnable` member of the `VkSamplerCreateInfo` structure must be `VK_FALSE`.

- **textureCompressionETC2** specifies whether all of the ETC2 and EAC compressed texture formats are supported. If this feature is enabled, then the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for the following formats:

  - `VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK`
  - `VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK`
  - `VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK`
  - `VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK`
  - `VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK`
  - `VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK`
  - `VK_FORMAT_EAC_R11_UNORM_BLOCK`
  - `VK_FORMAT_EAC_R11_SNORM_BLOCK`
  - `VK_FORMAT_EAC_R11G11_UNORM_BLOCK`
  - `VK_FORMAT_EAC_R11G11_SNORM_BLOCK`

To query for additional properties, or if the feature is not enabled, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats as normal.

- **textureCompressionASTC_LDR** specifies whether all of the ASTC LDR compressed texture formats are supported. If this feature is enabled, then the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for the following formats:

  - `VK_FORMAT_ASTC_4x4_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_4x4_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_5x4_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_5x4_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_5x5_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_5x5_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_6x5_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_6x5_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_6x6_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_6x6_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_8x5_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_8x5_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_8x6_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_8x6_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_8x8_UNORM_BLOCK`
  - `VK_FORMAT_ASTC_8x8_SRGB_BLOCK`
  - `VK_FORMAT_ASTC_8x9_SRGB_BLOCK`
To query for additional properties, or if the feature is not enabled, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats as normal.

- `textureCompressionBC` specifies whether all of the BC compressed texture formats are supported. If this feature is enabled, then the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for the following formats:

  - `VK_FORMAT_BC1_RGB_UNORM_BLOCK`
  - `VK_FORMAT_BC1_RGB_SRGB_BLOCK`
  - `VK_FORMAT_BC1_RGBA_UNORM_BLOCK`
  - `VK_FORMAT_BC1_RGBA_SRGB_BLOCK`
  - `VK_FORMAT_BC2_UNORM_BLOCK`
  - `VK_FORMAT_BC2_SRGB_BLOCK`
  - `VK_FORMAT_BC3_UNORM_BLOCK`
  - `VK_FORMAT_BC3_SRGB_BLOCK`
  - `VK_FORMAT_BC4_UNORM_BLOCK`
  - `VK_FORMAT_BC4_SNORM_BLOCK`
  - `VK_FORMAT_BC5_UNORM_BLOCK`
  - `VK_FORMAT_BC5_SNORM_BLOCK`
• **occlusionQueryPrecise** specifies whether occlusion queries returning actual sample counts are supported. Occlusion queries are created in a `VkQueryPool` by specifying the `queryType` of `VK_QUERY_TYPE_OCCLUSION` in the `VkQueryPoolCreateInfo` structure which is passed to `vkCreateQueryPool`. If this feature is enabled, queries of this type can enable `VK_QUERY_CONTROL_PRECISE_BIT` in the `flags` parameter to `vkCmdBeginQuery`. If this feature is not supported, the implementation supports only boolean occlusion queries. When any samples are passed, boolean queries will return a non-zero result value, otherwise a result value of zero is returned. When this feature is enabled and `VK_QUERY_CONTROL_PRECISE_BIT` is set, occlusion queries will report the actual number of samples passed.

• **pipelineStatisticsQuery** specifies whether the pipeline statistics queries are supported. If this feature is not enabled, queries of type `VK_QUERY_TYPE_PIPELINE_STATISTICS` cannot be created, and none of the `VkQueryPipelineStatisticFlagBits` bits can be set in the `pipelineStatistics` member of the `VkQueryPoolCreateInfo` structure.

• **vertexPipelineStoresAndAtomics** specifies whether storage buffers and images support stores and atomic operations in the vertex, tessellation, and geometry shader stages. If this feature is not enabled, all storage image, storage texel buffer, and storage buffer variables used by these stages in shader modules must be decorated with the `NonWritable` decoration (or the `readonly` memory qualifier in GLSL).

• **fragmentStoresAndAtomics** specifies whether storage buffers and images support stores and atomic operations in the fragment shader stage. If this feature is not enabled, all storage image, storage texel buffer, and storage buffer variables used by the fragment stage in shader modules must be decorated with the `NonWritable` decoration (or the `readonly` memory qualifier in GLSL).

• **shaderTessellationAndGeometryPointSize** specifies whether the `PointSize` built-in decoration is available in the tessellation control, tessellation evaluation, and geometry shader stages. If this feature is not enabled, members decorated with the `PointSize` built-in decoration must not be read from or written to and all points written from a tessellation or geometry shader will have a size of 1.0. This also specifies whether shader modules can declare the `TessellationPointSize` capability for tessellation control and evaluation shaders, or if the shader modules can declare the `GeometryPointSize` capability for geometry shaders. An implementation supporting this feature must also support one or both of the `tessellationShader` or `geometryShader` features.

• **shaderImageGatherExtended** specifies whether the extended set of image gather instructions are available in shader code. If this feature is not enabled, the `OpImage*Gather` instructions do not support the `Offset` and `ConstOffsets` operands. This also specifies whether shader modules can declare the `ImageGatherExtended` capability.

• **shaderStorageImageExtendedFormats** specifies whether all the “storage image extended formats” below are supported; if this feature is supported, then the `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`
must be supported in `optimalTilingFeatures` for the following formats:

- `VK_FORMAT_R16G16_SFLOAT`
- `VK_FORMAT_B10G11R11_UFLOAT_PACK32`
- `VK_FORMAT_R16_SFLOAT`
- `VK_FORMAT_R16G16B16A16_UNORM`
- `VK_FORMAT_A2B10G10R10_UNORM_PACK32`
- `VK_FORMAT_R16G16_UNORM`
- `VK_FORMAT_R8G8_UNORM`
- `VK_FORMAT_R16_UNORM`
- `VK_FORMAT_R8_UNORM`
- `VK_FORMAT_R16G16B16A16_SNORM`
- `VK_FORMAT_R16G16_SNORM`
- `VK_FORMAT_R8G8_SNORM`
- `VK_FORMAT_R16_SNORM`
- `VK_FORMAT_R8_SNORM`
- `VK_FORMAT_R16G16_SINT`
- `VK_FORMAT_R8G8_SINT`
- `VK_FORMAT_R16_SINT`
- `VK_FORMAT_R8_SINT`
- `VK_FORMAT_A2B10G10R10_UINT_PACK32`
- `VK_FORMAT_R16G16_UINT`
- `VK_FORMAT_R8G8_UINT`
- `VK_FORMAT_R16_UINT`
- `VK_FORMAT_R8_UINT`

**Note**

`shaderStorageImageExtendedFormats` feature only adds a guarantee of format support, which is specified for the whole physical device. Therefore enabling or disabling the feature via `vkCreateDevice` has no practical effect.

To query for additional properties, or if the feature is not supported, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats, as usual rules allow.

`VK_FORMAT_R32G32_UINT`, `VK_FORMAT_R32G32_SINT`, and `VK_FORMAT_R32G32_SFLOAT` from `StorageImageExtendedFormats` SPIR-V capability, are already covered by core Vulkan `mandatory format support`. 
• shaderStorageImageMultisample specifies whether multisampled storage images are supported. If this feature is not enabled, images that are created with a usage that includes VK_IMAGE_USAGE_STORAGE_BIT must be created with samples equal to VK_SAMPLE_COUNT_1_BIT. This also specifies whether shader modules can declare the StorageImageMultisample and ImageMSArray capabilities.

• shaderStorageImageReadWithoutFormat specifies whether storage images and storage texel buffers require a format qualifier to be specified when reading. shaderStorageImageReadWithoutFormat applies only to formats listed in the storage without format list.

• shaderStorageImageWriteWithoutFormat specifies whether storage images and storage texel buffers require a format qualifier to be specified when writing. shaderStorageImageWriteWithoutFormat applies only to formats listed in the storage without format list.

• shaderUniformBufferArrayDynamicIndexing specifies whether arrays of uniform buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the UniformBufferArrayDynamicIndexing capability.

• shaderSampledImageArrayDynamicIndexing specifies whether arrays of samplers or sampled images can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_SAMPLER, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, or VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the SampledImageArrayDynamicIndexing capability.

• shaderStorageBufferArrayDynamicIndexing specifies whether arrays of storage buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the StorageBufferArrayDynamicIndexing capability.

• shaderStorageImageArrayDynamicIndexing specifies whether arrays of storage images can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_IMAGE must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the StorageImageArrayDynamicIndexing capability.

• shaderClipDistance specifies whether clip distances are supported in shader code. If this feature is not enabled, any members decorated with the ClipDistance built-in decoration must not be read from or written to in shader modules. This also specifies whether shader modules can declare the ClipDistance capability.

• shaderCullDistance specifies whether cull distances are supported in shader code. If this feature is not enabled, any members decorated with the CullDistance built-in decoration must not be read from or written to in shader modules. This also specifies whether shader modules can declare the CullDistance capability.
• **shaderFloat64** specifies whether 64-bit floats (doubles) are supported in shader code. If this feature is not enabled, 64-bit floating-point types **must** not be used in shader code. This also specifies whether shader modules **can** declare the **Float64** capability. Declaring and using 64-bit floats is enabled for all storage classes that SPIR-V allows with the **Float64** capability.

• **shaderInt64** specifies whether 64-bit integers (signed and unsigned) are supported in shader code. If this feature is not enabled, 64-bit integer types **must** not be used in shader code. This also specifies whether shader modules **can** declare the **Int64** capability. Declaring and using 64-bit integers is enabled for all storage classes that SPIR-V allows with the **Int64** capability.

• **shaderInt16** specifies whether 16-bit integers (signed and unsigned) are supported in shader code. If this feature is not enabled, 16-bit integer types **must** not be used in shader code. This also specifies whether shader modules **can** declare the **Int16** capability. However, this only enables a subset of the storage classes that SPIR-V allows for the **Int16** SPIR-V capability: Declaring and using 16-bit integers in the **Private**, **Workgroup**, and **Function** storage classes is enabled, while declaring them in the interface storage classes (e.g., **UniformConstant**, **Uniform**, **StorageBuffer**, **Input**, **Output**, and **PushConstant**) is not enabled.

• **shaderResourceResidency** specifies whether image operations that return resource residency information are supported in shader code. If this feature is not enabled, the **OpImageSparse** instructions **must** not be used in shader code. This also specifies whether shader modules **can** declare the **SparseResidency** capability. The feature requires at least one of the **sparseResidency** features to be supported.

• **shaderResourceMinLod** specifies whether image operations specifying the minimum resource LOD are supported in shader code. If this feature is not enabled, the **MinLod** image operand **must** not be used in shader code. This also specifies whether shader modules **can** declare the **MinLod** capability.

• **sparseBinding** specifies whether resource memory **can** be managed at opaque sparse block level instead of at the object level. If this feature is not enabled, resource memory **must** be bound only on a per-object basis using the **vkBindBufferMemory** and **vkBindImageMemory** commands. In this case, buffers and images **must** not be created with **VK_BUFFER_CREATE_SPARSE_BINDING_BIT** and **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** set in the **flags** member of the **VkBufferCreateInfo** and **VkImageCreateInfo** structures, respectively. Otherwise resource memory **can** be managed as described in **Sparse Resource Features**.

• **sparseResidencyBuffer** specifies whether the device **can** access partially resident buffers. If this feature is not enabled, buffers **must** not be created with **VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT** set in the **flags** member of the **VkBufferCreateInfo** structure.

• **sparseResidencyImage2D** specifies whether the device **can** access partially resident 2D images with 1 sample per pixel. If this feature is not enabled, images with an **imageType** of **VK_IMAGE_TYPE_2D** and **samples** set to **VK_SAMPLE_COUNT_1_BIT** **must** not be created with **VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT** set in the **flags** member of the **VkImageCreateInfo** structure.

• **sparseResidencyImage3D** specifies whether the device **can** access partially resident 3D images. If this feature is not enabled, images with an **imageType** of **VK_IMAGE_TYPE_3D** **must** not be created with **VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT** set in the **flags** member of the **VkImageCreateInfo** structure.

• **sparseResidency2Samples** specifies whether the physical device **can** access partially resident 2D
images with 2 samples per pixel. If this feature is not enabled, images with an `imageType` of
`VK_IMAGE_TYPE_2D` and `samples` set to `VK_SAMPLE_COUNT_2_BIT` must not be created with
`VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set in the `flags` member of the `VkImageCreateInfo` structure.

- `sparseResidency4Samples` specifies whether the physical device can access partially resident 2D
images with 4 samples per pixel. If this feature is not enabled, images with an `imageType` of
`VK_IMAGE_TYPE_2D` and `samples` set to `VK_SAMPLE_COUNT_4_BIT` must not be created with
`VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set in the `flags` member of the `VkImageCreateInfo` structure.

- `sparseResidency8Samples` specifies whether the physical device can access partially resident 2D
images with 8 samples per pixel. If this feature is not enabled, images with an `imageType` of
`VK_IMAGE_TYPE_2D` and `samples` set to `VK_SAMPLE_COUNT_8_BIT` must not be created with
`VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set in the `flags` member of the `VkImageCreateInfo` structure.

- `sparseResidency16Samples` specifies whether the physical device can access partially resident 2D
images with 16 samples per pixel. If this feature is not enabled, images with an `imageType` of
`VK_IMAGE_TYPE_2D` and `samples` set to `VK_SAMPLE_COUNT_16_BIT` must not be created with
`VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set in the `flags` member of the `VkImageCreateInfo` structure.

- `sparseResidencyAliased` specifies whether the physical device can correctly access data aliased
into multiple locations. If this feature is not enabled, the `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT`
and `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` enum values must not be used in `flags` members of the
`VkBufferCreateInfo` and `VkImageCreateInfo` structures, respectively.

- `variableMultisampleRate` specifies whether all pipelines that will be bound to a command buffer
during a subpass which uses no attachments must have the same value for
`VkPipelineMultisampleStateCreateInfo::rasterizationSamples`. If set to `VK_TRUE`, the
implementation supports variable multisample rates in a subpass which uses no attachments. If
set to `VK_FALSE`, then all pipelines bound in such a subpass must have the same multisample
rate. This has no effect in situations where a subpass uses any attachments.

- `inheritedQueries` specifies whether a secondary command buffer may be executed while a
query is active.

The `VkPhysicalDeviceVulkan11Features` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceVulkan11Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 storageBuffer16BitAccess;
    VkBool32 uniformAndStorageBuffer16BitAccess;
    VkBool32 storagePushConstant16;
    VkBool32 storageInputOutput16;
    VkBool32 multiview;
    VkBool32 multiviewGeometryShader;
    VkBool32 multiviewTessellationShader;
    VkBool32 variablePointersStorageBuffer;
};
```
This structure describes the following features:

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **storageBuffer16BitAccess** specifies whether objects in the **StorageBuffer**, or **PhysicalStorageBuffer** storage class with the **Block** decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the **StorageBuffer16BitAccess** capability.
- **uniformAndStorageBuffer16BitAccess** specifies whether objects in the **Uniform** storage class with the **Block** decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the **UniformAndStorageBuffer16BitAccess** capability.
- **storagePushConstant16** specifies whether objects in the **PushConstant** storage class can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or floating-point members must not be used in such objects. This also specifies whether shader modules can declare the **StoragePushConstant16** capability.
- **storageInputOutput16** specifies whether objects in the **Input** and **Output** storage classes can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the **StorageInputOutput16** capability.
- **multiview** specifies whether the implementation supports multiview rendering within a render pass. If this feature is not enabled, the view mask of each subpass must always be zero.
- **multiviewGeometryShader** specifies whether the implementation supports multiview rendering within a render pass, with geometry shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include a geometry shader.
- **multiviewTessellationShader** specifies whether the implementation supports multiview rendering within a render pass, with tessellation shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include any tessellation shaders.
- **variablePointersStorageBuffer** specifies whether the implementation supports the SPIR-V **VariablePointersStorageBuffer** capability. When this feature is not enabled, shader modules must not declare the **SPV_KHR_variable_pointers** extension or the **VariablePointersStorageBuffer** capability.
- **variablePointers** specifies whether the implementation supports the SPIR-V **VariablePointers** capability. When this feature is not enabled, shader modules must not declare the
VariablePointers capability.

- **protectedMemory** specifies whether protected memory is supported.

- **samplerYcbcrConversion** specifies whether the implementation supports sampler \( Y' \) conversion. If `samplerYcbcrConversion` is `VK_FALSE`, sampler \( Y' \) conversion is not supported, and samplers using sampler \( Y' \) conversion must not be used.

- **shaderDrawParameters** specifies whether the implementation supports the SPIR-V `DrawParameters` capability. When this feature is not enabled, shader modules must not declare the `SPV_KHR_shader_draw_parameters` extension or the `DrawParameters` capability.

If the `VkPhysicalDeviceVulkan11Features` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceVulkan11Features` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceVulkan11Features-sType-sType**

  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_FEATURES`

The `VkPhysicalDeviceVulkan12Features` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceVulkan12Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 samplerMirrorClampToEdge;
    VkBool32 drawIndirectCount;
    VkBool32 storageBuffer8BitAccess;
    VkBool32 uniformAndStorageBuffer8BitAccess;
    VkBool32 storagePushConstant8;
    VkBool32 shaderBufferInt64Atomics;
    VkBool32 shaderSharedInt64Atomics;
    VkBool32 shaderFloat16;
    VkBool32 shaderInt8;
    VkBool32 descriptorIndexing;
    VkBool32 shaderInputAttachmentArrayDynamicIndexing;
    VkBool32 shaderUniformTexelBufferArrayDynamicIndexing;
    VkBool32 shaderStorageTexelBufferArrayDynamicIndexing;
    VkBool32 shaderUniformBufferArrayNonUniformIndexing;
    VkBool32 shaderSampledImageArrayNonUniformIndexing;
    VkBool32 shaderStorageBufferArrayNonUniformIndexing;
    VkBool32 shaderStorageImageArrayNonUniformIndexing;
    VkBool32 shaderInputAttachmentArrayNonUniformIndexing;
    VkBool32 shaderUniformTexelBufferArrayNonUniformIndexing;
    VkBool32 shaderStorageTexelBufferArrayNonUniformIndexing;
    VkBool32 descriptorBindingUniformBufferUpdateAfterBind;
    VkBool32 descriptorBindingSampledImageUpdateAfterBind;
} VkPhysicalDeviceVulkan12Features;
```
This structure describes the following features:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **samplerMirrorClampToEdge** indicates whether the implementation supports the VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE sampler address mode. If this feature is not enabled, the VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE sampler address mode must not be used.
- **drawIndirectCount** indicates whether the implementation supports the vkCmdDrawIndirectCount and vkCmdDrawIndexedIndirectCount functions. If this feature is not enabled, these functions must not be used.
- **storageBuffer8BitAccess** indicates whether objects in the StorageBuffer, or PhysicalStorageBuffer storage class with the Block decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the StorageBuffer8BitAccess capability.
- **uniformAndStorageBuffer8BitAccess** indicates whether objects in the Uniform storage class with the Block decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the UniformAndStorageBuffer8BitAccess capability.
• `storagePushConstant8` indicates whether objects in the `PushConstant` storage class can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `StoragePushConstant8` capability.

• `shaderBufferInt64Atomics` indicates whether shaders can perform 64-bit unsigned and signed integer atomic operations on buffers.

• `shaderSharedInt64Atomics` indicates whether shaders can perform 64-bit unsigned and signed integer atomic operations on shared memory.

• `shaderFloat16` indicates whether 16-bit floats (halves) are supported in shader code. This also indicates whether shader modules can declare the `Float16` capability. However, this only enables a subset of the storage classes that SPIR-V allows for the `Float16` SPIR-V capability: Declaring and using 16-bit floats in the `Private`, `Workgroup`, and `Function` storage classes is enabled, while declaring them in the interface storage classes (e.g., `UniformConstant`, `Uniform`, `StorageBuffer`, `Input`, `Output`, and `PushConstant`) is not enabled.

• `shaderInt8` indicates whether 8-bit integers (signed and unsigned) are supported in shader code. This also indicates whether shader modules can declare the `Int8` capability. However, this only enables a subset of the storage classes that SPIR-V allows for the `Int8` SPIR-V capability: Declaring and using 8-bit integers in the `Private`, `Workgroup`, and `Function` storage classes is enabled, while declaring them in the interface storage classes (e.g., `UniformConstant`, `Uniform`, `StorageBuffer`, `Input`, `Output`, and `PushConstant`) is not enabled.

• `descriptorIndexing` indicates whether the implementation supports the minimum set of descriptor indexing features as described in the Feature Requirements section. Enabling the `descriptorIndexing` member when `vkCreateDevice` is called does not imply the other minimum descriptor indexing features are also enabled. Those other descriptor indexing features must be enabled individually as needed by the application.

• `shaderInputAttachmentArrayDynamicIndexing` indicates whether arrays of input attachments can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayDynamicIndexing` capability.

• `shaderUniformTexelBufferArrayDynamicIndexing` indicates whether arrays of uniform texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayDynamicIndexing` capability.

• `shaderStorageTexelBufferArrayDynamicIndexing` indicates whether arrays of storage texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shadermodules can declare the `StorageTexelBufferArrayDynamicIndexing` capability.

• `shaderUniformBufferArrayNonUniformIndexing` indicates whether arrays of uniform buffers can be
indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformBufferArrayNonUniformIndexing` capability.

- `shaderSampledImageArrayNonUniformIndexing` indicates whether arrays of samplers or sampled images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_SAMPLER`, `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, or `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `SampledImageArrayNonUniformIndexing` capability.

- `shaderStorageBufferArrayNonUniformIndexing` indicates whether arrays of storage buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageBufferArrayNonUniformIndexing` capability.

- `shaderStorageImageArrayNonUniformIndexing` indicates whether arrays of storage images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageImageArrayNonUniformIndexing` capability.

- `shaderInputAttachmentArrayNonUniformIndexing` indicates whether arrays of input attachments can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayNonUniformIndexing` capability.

- `shaderUniformTexelBufferArrayNonUniformIndexing` indicates whether arrays of uniform texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayNonUniformIndexing` capability.

- `shaderStorageTexelBufferArrayNonUniformIndexing` indicates whether arrays of storage texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageTexelBufferArrayNonUniformIndexing` capability.

- `descriptorBindingUniformBufferUpdateAfterBind` indicates whether the implementation supports updating uniform buffer descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with
• **descriptorBindingSampledImageUpdateAfterBind** indicates whether the implementation supports updating sampled image descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_SAMPLER**, **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER**, or **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**.

• **descriptorBindingStorageImageUpdateAfterBind** indicates whether the implementation supports updating storage image descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE**.

• **descriptorBindingStorageBufferUpdateAfterBind** indicates whether the implementation supports updating storage buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER**.

• **descriptorBindingUniformTexelBufferUpdateAfterBind** indicates whether the implementation supports updating uniform texel buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER**.

• **descriptorBindingStorageTexelBufferUpdateAfterBind** indicates whether the implementation supports updating storage texel buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER**.

• **descriptorBindingUpdateUnusedWhilePending** indicates whether the implementation supports updating descriptors while the set is in use. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT** must not be used.

• **descriptorBindingPartiallyBound** indicates whether the implementation supports statically using a descriptor set binding in which some descriptors are not valid. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** must not be used.

• **descriptorBindingVariableDescriptorCount** indicates whether the implementation supports descriptor sets with a variable-sized last binding. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT** must not be used.

• **runtimeDescriptorArray** indicates whether the implementation supports the SPIR-V RuntimeDescriptorArray capability. If this feature is not enabled, descriptors must not be declared in runtime arrays.

• **samplerFilterMinmax** indicates whether the implementation supports a minimum set of required formats supporting min/max filtering as defined by the **filterMinmaxSingleComponentFormats** property minimum requirements. If this feature is not enabled, then **VkSamplerReductionModeCreateInfo** must only use **VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE**.

• **scalarBlockLayout** indicates that the implementation supports the layout of resource blocks in shaders using scalar alignment.

• **imagelessFramebuffer** indicates that the implementation supports specifying the image view for attachments at render pass begin time via **VkRenderPassAttachmentBeginInfo**.
• **uniformBufferStandardLayout** indicates that the implementation supports the same layouts for uniform buffers as for storage and other kinds of buffers. See Standard Buffer Layout.

• **shaderSubgroupExtendedTypes** is a boolean specifying whether subgroup operations can use 8-bit integer, 16-bit integer, 64-bit integer, 16-bit floating-point, and vectors of these types in group operations with subgroup scope, if the implementation supports the types.

• **separateDepthStencilLayouts** indicates whether the implementation supports a VkImageMemoryBarrier for a depth/stencil image with only one of VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT set, and whether VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL can be used.

• **hostQueryReset** indicates that the implementation supports resetting queries from the host with vkResetQueryPool.

• **timelineSemaphore** indicates whether semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE are supported.

• **bufferDeviceAddress** indicates that the implementation supports accessing buffer memory in shaders as storage buffers via an address queried from vkGetBufferDeviceAddress.

• **bufferDeviceAddressCaptureReplay** indicates that the implementation supports saving and reusing buffer and device addresses, e.g. for trace capture and replay.

• **bufferDeviceAddressMultiDevice** indicates that the implementation supports the bufferDeviceAddress feature for logical devices created with multiple physical devices. If this feature is not supported, buffer addresses must not be queried on a logical device created with more than one physical device.

• **vulkanMemoryModel** indicates whether shader modules can declare the VulkanMemoryModel capability.

• **vulkanMemoryModelDeviceScope** indicates whether the Vulkan Memory Model can use Device scope synchronization. This also indicates whether shader modules can declare the VulkanMemoryModelDeviceScope capability.

• **vulkanMemoryModelAvailabilityVisibilityChains** indicates whether the Vulkan Memory Model can use availability and visibility chains with more than one element.

• **shaderOutputViewportIndex** indicates whether the implementation supports the ShaderViewportIndex SPIR-V capability enabling variables decorated with the ViewportIndex built-in to be exported from vertex or tessellation evaluation shaders. If this feature is not enabled, the ViewportIndex built-in decoration must not be used on outputs in vertex or tessellation evaluation shaders.

• **shaderOutputLayer** indicates whether the implementation supports the ShaderLayer SPIR-V capability enabling variables decorated with the Layer built-in to be exported from vertex or tessellation evaluation shaders. If this feature is not enabled, the Layer built-in decoration must not be used on outputs in vertex or tessellation evaluation shaders.

• If subgroupBroadcastDynamicId is VK_TRUE, the “Id” operand of OpGroupNonUniformBroadcast can be dynamically uniform within a subgroup, and the “Index” operand of OpGroupNonUniformQuadBroadcast can be dynamically uniform within the derivative group. If it is VK_FALSE, these operands must be constants.
If the VkPhysicalDeviceVulkan12Features structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceVulkan12Features can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceVulkan12Features-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_FEATURES

The VkPhysicalDeviceVulkan13Features structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceVulkan13Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 robustImageAccess;
    VkBool32 inlineUniformBlock;
    VkBool32 descriptorBindingInlineUniformBlockUpdateAfterBind;
    VkBool32 pipelineCreationCacheControl;
    VkBool32 privateData;
    VkBool32 shaderDemoteToHelperInvocation;
    VkBool32 shaderTerminateInvocation;
    VkBool32 subgroupSizeControl;
    VkBool32 computeFullSubgroups;
    VkBool32 synchronization2;
    VkBool32 textureCompressionASTC_HDR;
    VkBool32 shaderZeroInitializeWorkgroupMemory;
    VkBool32 dynamicRendering;
    VkBool32 shaderIntegerDotProduct;
    VkBool32 maintenance4;
} VkPhysicalDeviceVulkan13Features;
```

This structure describes the following features:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **robustImageAccess** indicates whether image accesses are tightly bounds-checked against the dimensions of the image view. Invalid texels resulting from out of bounds image loads will be replaced as described in Texel Replacement, with either (0,0,1) or (0,0,0) values inserted for missing G, B, or A components based on the format.
- **inlineUniformBlock** indicates whether the implementation supports inline uniform block descriptors. If this feature is not enabled, VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK must not be used.
- **descriptorBindingInlineUniformBlockUpdateAfterBind** indicates whether the implementation
supports updating inline uniform block descriptors after a set is bound. If this feature is not
enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with
**VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK**.

- **pipelineCreationCacheControl** indicates that the implementation supports:
  - The following can be used in Vk*PipelineCreateInfo::flags:
    - **VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT**
    - **VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT**
  - The following can be used in VkPipelineCacheCreateInfo::flags:
    - **VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT**
- **privateData** indicates whether the implementation supports private data. See [Private Data](#).
- **shaderDemoteToHelperInvocation** indicates whether the implementation supports the SPIR-V
  DemoteToHelperInvocationEXT capability.
- **shaderTerminateInvocation** specifies whether the implementation supports SPIR-V modules that
  use the **SPV_KHR_terminate_invocation** extension.
- **subgroupSizeControl** indicates whether the implementation supports controlling shader
  subgroup sizes via the **VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT** flag
  and the **VkPipelineShaderStageRequiredSubgroupSizeCreateInfo** structure.
- **computeFullSubgroups** indicates whether the implementation supports requiring full subgroups
  in compute shaders via the **VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT** flag.
- **synchronization2** indicates whether the implementation supports the new set of
  synchronization commands introduced in **VK_KHR_synchronization2**.
- **textureCompressionASTC_HDR** indicates whether all of the ASTC HDR compressed texture formats
  are supported. If this feature is enabled, then the **VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT**, **VK_FORMAT_FEATURE_BLIT_SRC_BIT**
  and **VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT** features must be supported in **optimalTilingFeatures** for the following formats:
  - **VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK**
  - **VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK**
- **VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK**
- **VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK**

To query for additional properties, or if the feature is not enabled, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats as normal.

- `shaderZeroInitializeWorkgroupMemory` specifies whether the implementation supports initializing a variable in Workgroup storage class.

- `dynamicRendering` specifies that the implementation supports dynamic render pass instances using the `vkCmdBeginRendering` command.

- `shaderIntegerDotProduct` specifies whether shader modules can declare the `DotProductInputAllKHR`, `DotProductInput4x8BitKHR`, `DotProductInput4x8BitPackedKHR` and `DotProductKHR` capabilities.

- `maintenance4` indicates that the implementation supports the following:
  - The application may destroy a `VkPipelineLayout` object immediately after using it to create another object.
  - `LocalSizeId` can be used as an alternative to `LocalSize` to specify the local workgroup size with specialization constants.
  - Images created with identical creation parameters will always have the same alignment requirements.
  - The size memory requirement of a buffer or image is never greater than that of another buffer or image created with a greater or equal size.
  - Push constants do not have to be initialized before they are dynamically accessed.
  - The interface matching rules allow a larger output vector to match with a smaller input vector, with additional values being discarded.

If the `VkPhysicalDeviceVulkan13Features` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceVulkan13Features` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- `VUID-VkPhysicalDeviceVulkan13Features-sType-sType`  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_3_FEATURES`

The `VkPhysicalDeviceVariablePointersFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceVariablePointersFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 variablePointersStorageBuffer;
} VkPhysicalDeviceVariablePointersFeatures;
```
VkBool32 variablePointers;
} VkPhysicalDeviceVariablePointersFeatures;

// Provided by VK_VERSION_1_1
typedef VkPhysicalDeviceVariablePointersFeatures
VkPhysicalDeviceVariablePointerFeatures;

This structure describes the following features:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **variablePointersStorageBuffer** specifies whether the implementation supports the SPIR-V `VariablePointersStorageBuffer` capability. When this feature is not enabled, shader modules must not declare the `SPV_KHR_variable_pointers` extension or the `VariablePointersStorageBuffer` capability.
- **variablePointers** specifies whether the implementation supports the SPIR-V `VariablePointers` capability. When this feature is not enabled, shader modules must not declare the `VariablePointers` capability.

If the `VkPhysicalDeviceVariablePointersFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceVariablePointersFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage

- VUID-VkPhysicalDeviceVariablePointersFeatures-variablePointers-01431
  If `variablePointers` is enabled then `variablePointersStorageBuffer` must also be enabled

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceVariablePointersFeatures-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES`

The `VkPhysicalDeviceMultiviewFeatures` structure is defined as:

// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceMultiviewFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 multiview;
    VkBool32 multiviewGeometryShader;
} VkPhysicalDeviceMultiviewFeatures;
This structure describes the following features:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `multiview` specifies whether the implementation supports multiview rendering within a render pass. If this feature is not enabled, the view mask of each subpass must always be zero.
- `multiviewGeometryShader` specifies whether the implementation supports multiview rendering within a render pass, with geometry shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include a geometry shader.
- `multiviewTessellationShader` specifies whether the implementation supports multiview rendering within a render pass, with tessellation shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include any tessellation shaders.

If the `VkPhysicalDeviceMultiviewFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceMultiviewFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage

- VUID-VkPhysicalDeviceMultiviewFeatures-multiviewGeometryShader-00580
  If `multiviewGeometryShader` is enabled then `multiview` must also be enabled

- VUID-VkPhysicalDeviceMultiviewFeatures-multiviewTessellationShader-00581
  If `multiviewTessellationShader` is enabled then `multiview` must also be enabled

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceMultiviewFeatures-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES`

The `VkPhysicalDeviceShaderAtomicInt64Features` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceShaderAtomicInt64Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderBufferInt64Atomics;
    VkBool32 shaderSharedInt64Atomics;
} VkPhysicalDeviceShaderAtomicInt64Features;
```
This structure describes the following features:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **shaderBufferInt64Atomics** indicates whether shaders can perform 64-bit unsigned and signed integer atomic operations on buffers.
- **shaderSharedInt64Atomics** indicates whether shaders can perform 64-bit unsigned and signed integer atomic operations on shared memory.

If the `VkPhysicalDeviceShaderAtomicInt64Features` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceShaderAtomicInt64Features` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceShaderAtomicInt64Features-sType-sType**
  
  **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES`

The `VkPhysicalDevice8BitStorageFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDevice8BitStorageFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 storageBuffer8BitAccess;
    VkBool32 uniformAndStorageBuffer8BitAccess;
    VkBool32 storagePushConstant8;
} VkPhysicalDevice8BitStorageFeatures;
```

This structure describes the following features:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **storageBuffer8BitAccess** indicates whether objects in the `StorageBuffer`, or `PhysicalStorageBuffer` storage class with the `Block` decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `StorageBuffer8BitAccess` capability.
- **uniformAndStorageBuffer8BitAccess** indicates whether objects in the `Uniform` storage class with the `Block` decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `UniformAndStorageBuffer8BitAccess` capability.
- **storagePushConstant8** indicates whether objects in the `PushConstant` storage class can have 8-bit
integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the StoragePushConstant8 capability.

If the VkPhysicalDevice8BitStorageFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDevice8BitStorageFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDevice8BitStorageFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES

The VkPhysicalDevice16BitStorageFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDevice16BitStorageFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 storageBuffer16BitAccess;
    VkBool32 uniformAndStorageBuffer16BitAccess;
    VkBool32 storagePushConstant16;
    VkBool32 storageInputOutput16;
} VkPhysicalDevice16BitStorageFeatures;
```

This structure describes the following features:

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.

- storageBuffer16BitAccess specifies whether objects in the StorageBuffer, or PhysicalStorageBuffer storage class with the Block decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StorageBuffer16BitAccess capability.

- uniformAndStorageBuffer16BitAccess specifies whether objects in the Uniform storage class with the Block decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the UniformAndStorageBuffer16BitAccess capability.

- storagePushConstant16 specifies whether objects in the PushConstant storage class can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StoragePushConstant16 capability.

- storageInputOutput16 specifies whether objects in the Input and Output storage classes can have
16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StorageInputOutput16 capability.

If the VkPhysicalDevice16BitStorageFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDevice16BitStorageFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDevice16BitStorageFeatures-sType-sType
  
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES

The VkPhysicalDeviceShaderFloat16Int8Features structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceShaderFloat16Int8Features {
    VkStructureType   sType;
    void*             pNext;
    VkBool32          shaderFloat16;
    VkBool32          shaderInt8;
} VkPhysicalDeviceShaderFloat16Int8Features;
```

This structure describes the following features:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **shaderFloat16** indicates whether 16-bit floats (halves) are supported in shader code. This also indicates whether shader modules can declare the Float16 capability. However, this only enables a subset of the storage classes that SPIR-V allows for the Float16 SPIR-V capability: Declaring and using 16-bit floats in the Private, Workgroup, and Function storage classes is enabled, while declaring them in the interface storage classes (e.g., UniformConstant, Uniform, StorageBuffer, Input, Output, and PushConstant) is not enabled.
- **shaderInt8** indicates whether 8-bit integers (signed and unsigned) are supported in shader code. This also indicates whether shader modules can declare the Int8 capability. However, this only enables a subset of the storage classes that SPIR-V allows for the Int8 SPIR-V capability: Declaring and using 8-bit integers in the Private, Workgroup, and Function storage classes is enabled, while declaring them in the interface storage classes (e.g., UniformConstant, Uniform, StorageBuffer, Input, Output, and PushConstant) is not enabled.

If the VkPhysicalDeviceShaderFloat16Int8Features structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceShaderFloat16Int8Features can also be used in the pNext chain of
VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

• VUID-VkPhysicalDeviceShaderFloat16Int8Features-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES

The VkPhysicalDeviceSamplerYcbcrConversionFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceSamplerYcbcrConversionFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 samplerYcbcrConversion;
} VkPhysicalDeviceSamplerYcbcrConversionFeatures;
```

This structure describes the following feature:

• **sType** is a VkStructureType value identifying this structure.
• **pNext** is NULL or a pointer to a structure extending this structure.
• **samplerYcbcrConversion** specifies whether the implementation supports sampler Y′C_bC_R conversion. If samplerYcbcrConversion is VK_FALSE, sampler Y′C_bC_R conversion is not supported, and samplers using sampler Y′C_bC_R conversion must not be used.

If the VkPhysicalDeviceSamplerYcbcrConversionFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceSamplerYcbcrConversionFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

• VUID-VkPhysicalDeviceSamplerYcbcrConversionFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_YCBCR_CONVERSION_FEATURES

The VkPhysicalDeviceProtectedMemoryFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceProtectedMemoryFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 protectedMemory;
} VkPhysicalDeviceProtectedMemoryFeatures;
```
This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **protectedMemory** specifies whether protected memory is supported.

If the `VkPhysicalDeviceProtectedMemoryFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceProtectedMemoryFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceProtectedMemoryFeatures-sType-sType
  
  * **sType must** be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_FEATURES`

The `VkPhysicalDeviceShaderDrawParametersFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VKPhysicalDeviceShaderDrawParametersFeatures {
  VkStructureType sType;
  void* pNext;
  VkBool32 shaderDrawParameters;
} VkPhysicalDeviceShaderDrawParametersFeatures;
```

This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **shaderDrawParameters** specifies whether the implementation supports the SPIR-V `DrawParameters` capability. When this feature is not enabled, shader modules must not declare the `SPV_KHR_shader_draw_parameters` extension or the `DrawParameters` capability.

If the `VkPhysicalDeviceShaderDrawParametersFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceShaderDrawParametersFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.
Valid Usage (Implicit)

- VUID-VkPhysicalDeviceShaderDrawParametersFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES

The VkPhysicalDeviceDescriptorIndexingFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceDescriptorIndexingFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderInputAttachmentArrayDynamicIndexing;
    VkBool32 shaderUniformTexelBufferArrayDynamicIndexing;
    VkBool32 shaderStorageTexelBufferArrayDynamicIndexing;
    VkBool32 shaderUniformBufferArrayNonUniformIndexing;
    VkBool32 shaderSampledImageArrayNonUniformIndexing;
    VkBool32 shaderStorageBufferArrayNonUniformIndexing;
    VkBool32 shaderInputAttachmentArrayNonUniformIndexing;
    VkBool32 shaderUniformTexelBufferArrayNonUniformIndexing;
    VkBool32 shaderStorageTexelBufferArrayNonUniformIndexing;
    VkBool32 descriptorBindingUniformBufferUpdateAfterBind;
    VkBool32 descriptorBindingSampledImageUpdateAfterBind;
    VkBool32 descriptorBindingStorageImageUpdateAfterBind;
    VkBool32 descriptorBindingStorageBufferUpdateAfterBind;
    VkBool32 descriptorBindingUniformTexelBufferUpdateAfterBind;
    VkBool32 descriptorBindingStorageTexelBufferUpdateAfterBind;
    VkBool32 descriptorBindingUpdateUnusedWhilePending;
    VkBool32 descriptorBindingPartiallyBound;
    VkBool32 descriptorBindingVariableDescriptorCount;
    VkBool32 runtimeDescriptorArray;
} VkPhysicalDeviceDescriptorIndexingFeatures;
```

This structure describes the following features:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.

- **shaderInputAttachmentArrayDynamicIndexing** indicates whether arrays of input attachments can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the InputAttachmentArrayDynamicIndexing capability.

- **shaderUniformTexelBufferArrayDynamicIndexing** indicates whether arrays of uniform texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of
VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the UniformTexelBufferArrayDynamicIndexing capability.

- shaderStorageTexelBufferArrayDynamicIndexing indicates whether arrays of storage texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the StorageTexelBufferArrayDynamicIndexing capability.

- shaderUniformBufferArrayNonUniformIndexing indicates whether arrays of uniform buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the UniformBufferArrayNonUniformIndexing capability.

- shaderSampledImageArrayNonUniformIndexing indicates whether arrays of samplers or sampled images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_SAMPLER, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, or VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the SampledImageArrayNonUniformIndexing capability.

- shaderStorageBufferArrayNonUniformIndexing indicates whether arrays of storage buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the StorageBufferArrayNonUniformIndexing capability.

- shaderStorageImageArrayNonUniformIndexing indicates whether arrays of storage images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_IMAGE must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the StorageImageArrayNonUniformIndexing capability.

- shaderInputAttachmentArrayNonUniformIndexing indicates whether arrays of input attachments can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the InputAttachmentArrayNonUniformIndexing capability.

- shaderUniformTexelBufferArrayNonUniformIndexing indicates whether arrays of uniform texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the
UniformTexelBufferArrayNonUniformIndexing capability.

- shaderStorageTexelBufferArrayNonUniformIndexing indicates whether arrays of storage texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the StorageTexelBufferArrayNonUniformIndexing capability.

- descriptorBindingUniformBufferUpdateAfterBind indicates whether the implementation supports updating uniform buffer descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER.

- descriptorBindingSampledImageUpdateAfterBind indicates whether the implementation supports updating sampled image descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_SAMPLER, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, or VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE.

- descriptorBindingStorageImageUpdateAfterBind indicates whether the implementation supports updating storage image descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_STORAGE_IMAGE.

- descriptorBindingStorageBufferUpdateAfterBind indicates whether the implementation supports updating storage buffer descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_STORAGE_BUFFER.

- descriptorBindingUniformTexelBufferUpdateAfterBind indicates whether the implementation supports updating uniform texel buffer descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER.

- descriptorBindingStorageTexelBufferUpdateAfterBind indicates whether the implementation supports updating storage texel buffer descriptors after a set is bound. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT must not be used with VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER.

- descriptorBindingUpdateUnusedWhilePending indicates whether the implementation supports updating descriptors while the set is in use. If this feature is not enabled, VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT must not be used.

- descriptorBindingPartiallyBound indicates whether the implementation supports statically using a descriptor set binding in which some descriptors are not valid. If this feature is not enabled, VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT must not be used.

- descriptorBindingVariableDescriptorCount indicates whether the implementation supports descriptor sets with a variable-sized last binding. If this feature is not enabled, VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT must not be used.

- runtimeDescriptorArray indicates whether the implementation supports the SPIR-V RuntimeDescriptorArray capability. If this feature is not enabled, descriptors must not be
declared in runtime arrays.

If the `VkPhysicalDeviceDescriptorIndexingFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceDescriptorIndexingFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceDescriptorIndexingFeatures-sType-sType**
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_FEATURES`

The `VkPhysicalDeviceVulkanMemoryModelFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceVulkanMemoryModelFeatures {
    VkStructureType           sType;
    void*                     pNext;
    VkBool32                  vulkanMemoryModel;
    VkBool32                  vulkanMemoryModelDeviceScope;
    VkBool32                  vulkanMemoryModelAvailabilityVisibilityChains;
} VkPhysicalDeviceVulkanMemoryModelFeatures;
```

This structure describes the following features:

- **sType** is a `VkStructureType` value identifying this structure.

- **pNext** is `NULL` or a pointer to a structure extending this structure.

- **vulkanMemoryModel** indicates whether shader modules can declare the `VulkanMemoryModel` capability.

- **vulkanMemoryModelDeviceScope** indicates whether the Vulkan Memory Model can use `Device` scope synchronization. This also indicates whether shader modules can declare the `VulkanMemoryModelDeviceScope` capability.

- **vulkanMemoryModelAvailabilityVisibilityChains** indicates whether the Vulkan Memory Model can use availability and visibility chains with more than one element.

If the `VkPhysicalDeviceVulkanMemoryModelFeaturesKHR` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceVulkanMemoryModelFeaturesKHR` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceVulkanMemoryModelFeatures-sType-sType**

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The `VkPhysicalDeviceInlineUniformBlockFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceInlineUniformBlockFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 inlineUniformBlock;
    VkBool32 descriptorBindingInlineUniformBlockUpdateAfterBind;
} VkPhysicalDeviceInlineUniformBlockFeatures;
```

This structure describes the following features:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `inlineUniformBlock` indicates whether the implementation supports inline uniform block descriptors. If this feature is not enabled, `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` must not be used.
- `descriptorBindingInlineUniformBlockUpdateAfterBind` indicates whether the implementation supports updating inline uniform block descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK`.

If the `VkPhysicalDeviceInlineUniformBlockFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceInlineUniformBlockFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

**Valid Usage (Implicit)**

- `VUID-VkPhysicalDeviceInlineUniformBlockFeatures-sType-sType`  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_FEATURES`

The `VkPhysicalDeviceScalarBlockLayoutFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceScalarBlockLayoutFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 scalarBlockLayout;
} VkPhysicalDeviceScalarBlockLayoutFeatures;
```
This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **scalarBlockLayout** indicates that the implementation supports the layout of resource blocks in shaders using **scalar alignment**.

If the `VkPhysicalDeviceScalarBlockLayoutFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceScalarBlockLayoutFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- `VUID-VkPhysicalDeviceScalarBlockLayoutFeatures-sType-sType`
  - **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SCALAR_BLOCK_LAYOUT_FEATURES`

The `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceUniformBufferStandardLayoutFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 uniformBufferStandardLayout;
} VkPhysicalDeviceUniformBufferStandardLayoutFeatures;
```

This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **uniformBufferStandardLayout** indicates that the implementation supports the same layouts for uniform buffers as for storage and other kinds of buffers. See **Standard Buffer Layout**.

If the `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- `VUID-VkPhysicalDeviceUniformBufferStandardLayoutFeatures-sType-sType`
  - **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_UNIFORM_BUFFER_STANDARD_LAYOUT_FEATURES`
The `VkPhysicalDeviceBufferDeviceAddressFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceBufferDeviceAddressFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 bufferDeviceAddress;
    VkBool32 bufferDeviceAddressCaptureReplay;
    VkBool32 bufferDeviceAddressMultiDevice;
} VkPhysicalDeviceBufferDeviceAddressFeatures;
```

This structure describes the following features:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **bufferDeviceAddress** indicates that the implementation supports accessing buffer memory in shaders as storage buffers via an address queried from `vkGetBufferDeviceAddress`.
- **bufferDeviceAddressCaptureReplay** indicates that the implementation supports saving and reusing buffer and device addresses, e.g. for trace capture and replay.
- **bufferDeviceAddressMultiDevice** indicates that the implementation supports the `bufferDeviceAddress` feature for logical devices created with multiple physical devices. If this feature is not supported, buffer addresses must not be queried on a logical device created with more than one physical device.

**Note**

`bufferDeviceAddressMultiDevice` exists to allow certain legacy platforms to be able to support `bufferDeviceAddress` without needing to support shared GPU virtual addresses for multi-device configurations.

See `vkGetBufferDeviceAddress` for more information.

If the `VkPhysicalDeviceBufferDeviceAddressFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceBufferDeviceAddressFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceBufferDeviceAddressFeatures-sType-sType
  sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS_FEATURES`

The `VkPhysicalDeviceImagelessFramebufferFeatures` structure is defined as:
typedef struct VkPhysicalDeviceImagelessFramebufferFeatures {
    VkStructureType   sType;
    void*              pNext;
    VkBool32           imagelessFramebuffer;
} VkPhysicalDeviceImagelessFramebufferFeatures;

This structure describes the following feature:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **imagelessFramebuffer** indicates that the implementation supports specifying the image view for attachments at render pass begin time via VkRenderPassAttachmentBeginInfo.

If the VkPhysicalDeviceImagelessFramebufferFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported.

VkPhysicalDeviceImagelessFramebufferFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceImagelessFramebufferFeatures-sType-sType**
  - sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER_FEATURES

The VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures structure is defined as:

typedef struct VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures {
    VkStructureType   sType;
    void*              pNext;
    VkBool32           shaderSubgroupExtendedTypes;
} VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures;

This structure describes the following feature:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **shaderSubgroupExtendedTypes** is a boolean specifying whether subgroup operations can use 8-bit integer, 16-bit integer, 64-bit integer, 16-bit floating-point, and vectors of these types in group operations with subgroup scope, if the implementation supports the types.

If the VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to
indicate whether each corresponding feature is supported. 

VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

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### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures-sType-sType**
  
  - **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES**

The **VkPhysicalDeviceHostQueryResetFeatures** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceHostQueryResetFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 hostQueryReset;
} VkPhysicalDeviceHostQueryResetFeatures;
```

This structure describes the following feature:

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **hostQueryReset** indicates that the implementation supports resetting queries from the host with vkResetQueryPool.

If the **VkPhysicalDeviceHostQueryResetFeatures** structure is included in the pNext chain of the **VkPhysicalDeviceFeatures2** structure passed to **vkGetPhysicalDeviceFeatures2**, it is filled in to indicate whether each corresponding feature is supported. **VkPhysicalDeviceHostQueryResetFeatures** can also be used in the pNext chain of **VkDeviceCreateInfo** to selectively enable these features.

---

### Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceHostQueryResetFeatures-sType-sType**
  
  - **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_HOST_QUERY_RESET_FEATURES**

The **VkPhysicalDeviceTimelineSemaphoreFeatures** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceTimelineSemaphoreFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 timelineSemaphore;
} VkPhysicalDeviceTimelineSemaphoreFeatures;
```
This structure describes the following feature:

- **sType** is a *VkStructureType* value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **timelineSemaphore** indicates whether semaphores created with a *VkSemaphoreType* of *VK_SEMAPHORE_TYPE_TIMELINE* are supported.

If the *VkPhysicalDeviceTimelineSemaphoreFeatures* structure is included in the **pNext** chain of the *VkPhysicalDeviceFeatures2* structure passed to *vkGetPhysicalDeviceFeatures2*, it is filled in to indicate whether each corresponding feature is supported. *VkPhysicalDeviceTimelineSemaphoreFeatures* can also be used in the **pNext** chain of *VkDeviceCreateInfo* to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceTimelineSemaphoreFeatures-sType-sType
  
  **sType** **must** be *VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_FEATURES*

The *VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures* structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures {
    VkStructureType     sType;
    void*               pNext;
    VkBool32            separateDepthStencilLayouts;
} VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures;
```

This structure describes the following feature:

- **sType** is a *VkStructureType* value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **separateDepthStencilLayouts** indicates whether the implementation supports a *VkImageMemoryBarrier* for a depth/stencil image with only one of *VK_IMAGE_ASPECT_DEPTH_BIT* or *VK_IMAGE_ASPECT_STENCIL_BIT* set, and whether *VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL*, *VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL*, *VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL*, or *VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL* can be used.

If the *VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures* structure is included in the **pNext** chain of the *VkPhysicalDeviceFeatures2* structure passed to *vkGetPhysicalDeviceFeatures2*, it is filled in to indicate whether each corresponding feature is supported. *VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures* can also be used in the **pNext** chain of *VkDeviceCreateInfo* to selectively enable these features.
Valid Usage (Implicit)

- VUID-VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures-sType-sType must be
  VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES

The `VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderDemoteToHelperInvocation;
} VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures;
```

This structure describes the following feature:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `shaderDemoteToHelperInvocation` indicates whether the implementation supports the SPIR-V DemoteToHelperInvocationEXT capability.

If the `VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures-sType-sType must be
  VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DEMOTE_TO_HELPER_INVOCATION_FEATURES

The `VkPhysicalDeviceTextureCompressionASTCHDRFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceTextureCompressionASTCHDRFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 textureCompressionASTC_HDR;
} VkPhysicalDeviceTextureCompressionASTCHDRFeatures;
```

This structure describes the following feature:
• sType is a VkStructureType value identifying this structure.

• pNext is NULL or a pointer to a structure extending this structure.

• textureCompressionASTC_HDR indicates whether all of the ASTC HDR compressed texture formats are supported. If this feature is enabled, then the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_FORMAT_FEATURE_BLIT_SRC_BIT and VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT features must be supported in optimalTilingFeatures for the following formats:
  ◦ VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK
  ◦ VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK

To query for additional properties, or if the feature is not enabled, vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties can be used to check for supported properties of individual formats as normal.

If the VkPhysicalDeviceTextureCompressionASTCHDRFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceTextureCompressionASTCHDRFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

• VUID-VkPhysicalDeviceTextureCompressionASTCHDRFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXTURE_COMPRESSION_ASTC_HDR_FEATURES

The VkPhysicalDeviceSubgroupSizeControlFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceSubgroupSizeControlFeatures {
    VkStructureType sType;
} VkPhysicalDeviceSubgroupSizeControlFeatures;
```
This structure describes the following features:

• **sType** is a VkStructureType value identifying this structure.

• **pNext** is NULL or a pointer to a structure extending this structure.

• **subgroupSizeControl** indicates whether the implementation supports controlling shader subgroup sizes via the VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT flag and the VkPipelineShaderStageRequiredSubgroupSizeCreateInfo structure.

• **computeFullSubgroups** indicates whether the implementation supports requiring full subgroups in compute shaders via the VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT flag.

If the VkPhysicalDeviceSubgroupSizeControlFeatures structure is included in the **pNext** chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceSubgroupSizeControlFeatures can also be used in the **pNext** chain of VkDeviceCreateInfo to selectively enable these features.

**Note**

The VkPhysicalDeviceSubgroupSizeControlFeaturesEXT structure was added in version 2 of the VK_EXT_subgroup_size_control extension. Version 1 implementations of this extension will not fill out the features structure but applications may assume that both subgroupSizeControl and computeFullSubgroups are supported if the extension is supported. (See also the Feature Requirements section.) Applications are advised to add a VkPhysicalDeviceSubgroupSizeControlFeaturesEXT structure to the **pNext** chain of VkDeviceCreateInfo to enable the features regardless of the version of the extension supported by the implementation. If the implementation only supports version 1, it will safely ignore the VkPhysicalDeviceSubgroupSizeControlFeaturesEXT structure.

Vulkan 1.3 implementations always support the features structure.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceSubgroupSizeControlFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_SIZE_CONTROL_FEATURES

The VkPhysicalDevicePipelineCreationCacheControlFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDevicePipelineCreationCacheControlFeatures {
```
VkStructureType sType;
void* pNext;
VkBool32 pipelineCreationCacheControl;
} VkPhysicalDevicePipelineCreationCacheControlFeatures;

This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **pipelineCreationCacheControl** indicates that the implementation supports:
  - The following can be used in `Vk*PipelineCreateInfo::flags`:
    - `VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT`
    - `VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT`
  - The following can be used in `VkPipelineCacheCreateInfo::flags`:
    - `VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT`

If the `VkPhysicalDevicePipelineCreationCacheControlFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDevicePipelineCreationCacheControlFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDevicePipelineCreationCacheControlFeatures-sType-sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PIPELINE_CREATION_CACHE_CONTROL_FEATURES`

The `VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderZeroInitializeWorkgroupMemory;
} VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures;
```

This structure describes the following feature:

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is `NULL` or a pointer to a structure extending this structure.
- **shaderZeroInitializeWorkgroupMemory** specifies whether the implementation supports initializing a variable in Workgroup storage class.
If the `VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures-sType-sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ZERO_INITIALIZE_WORKGROUP_MEMORY_FEATURES`

The `VkPhysicalDevicePrivateDataFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDevicePrivateDataFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 privateData;
} VkPhysicalDevicePrivateDataFeatures;
```

This structure describes the following feature:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `privateData` indicates whether the implementation supports private data. See Private Data.

If the `VkPhysicalDevicePrivateDataFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDevicePrivateDataFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDevicePrivateDataFeatures-sType-sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PRIVATE_DATA_FEATURES`

nullDescriptor support requires the `VK_EXT_robustness2` extension.

The `VkPhysicalDeviceImageRobustnessFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceImageRobustnessFeatures {
    VkStructureType sType;
    void* pNext;
} VkPhysicalDeviceImageRobustnessFeatures;
```
This structure describes the following feature:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `robustImageAccess` indicates whether image accesses are tightly bounds-checked against the dimensions of the image view. Invalid texels resulting from out of bounds image loads will be replaced as described in Texel Replacement, with either (0,0,1) or (0,0,0) values inserted for missing G, B, or A components based on the format.

If the `VkPhysicalDeviceImageRobustnessFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceImageRobustnessFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceImageRobustnessFeatures-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_ROBUSTNESS_FEATURES`

The `VkPhysicalDeviceShaderTerminateInvocationFeatures` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceShaderTerminateInvocationFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderTerminateInvocation;
} VkPhysicalDeviceShaderTerminateInvocationFeatures;
```

This structure describes the following feature:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `shaderTerminateInvocation` specifies whether the implementation supports SPIR-V modules that use the `SPV_KHR_terminate_invocation` extension.

If the `VkPhysicalDeviceShaderTerminateInvocationFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceShaderTerminateInvocationFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.
Valid Usage (Implicit)

- VUID-VkPhysicalDeviceShaderTerminateInvocationFeatures-sType-sType
  
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_TERMINATE_INVOCATION_FEATURES

The VkPhysicalDeviceSynchronization2Features structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceSynchronization2Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 synchronization2;
} VkPhysicalDeviceSynchronization2Features;
```

This structure describes the following feature:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **synchronization2** indicates whether the implementation supports the new set of synchronization commands introduced in VK_KHR_synchronization2.

If the VkPhysicalDeviceSynchronization2Features structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceSynchronization2Features can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceSynchronization2Features-sType-sType
  
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SYNCHRONIZATION_2_FEATURES

The VkPhysicalDeviceShaderIntegerDotProductFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceShaderIntegerDotProductFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 shaderIntegerDotProduct;
} VkPhysicalDeviceShaderIntegerDotProductFeatures;
```

This structure describes the following feature:

- **sType** is a VkStructureType value identifying this structure.
• `pNext` is NULL or a pointer to a structure extending this structure.

• `shaderIntegerDotProduct` specifies whether shader modules can declare the `DotProductInputAllKHR`, `DotProductInput4x8BitKHR`, `DotProductInput4x8BitPackedKHR` and `DotProductKHR` capabilities.

If the `VkPhysicalDeviceShaderIntegerDotProductFeatures` structure is included in the `pNext` chain of the `VkPhysicalDeviceFeatures2` structure passed to `vkGetPhysicalDeviceFeatures2`, it is filled in to indicate whether each corresponding feature is supported. `VkPhysicalDeviceShaderIntegerDotProductFeatures` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to selectively enable these features.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceShaderIntegerDotProductFeatures-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_FEATURES`

The `VkPhysicalDeviceMaintenance4Features` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceMaintenance4Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 maintenance4;
} VkPhysicalDeviceMaintenance4Features;
```

This structure describes the following feature:

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `maintenance4` indicates that the implementation supports the following:
  - The application may destroy a `VkPipelineLayout` object immediately after using it to create another object.
  - `LocalSizeId` can be used as an alternative to `LocalSize` to specify the local workgroup size with specialization constants.
  - Images created with identical creation parameters will always have the same alignment requirements.
  - The size memory requirement of a buffer or image is never greater than that of another buffer or image created with a greater or equal size.
  - Push constants do not have to be initialized before they are dynamically accessed.
  - The interface matching rules allow a larger output vector to match with a smaller input vector, with additional values being discarded.

If the `VkPhysicalDeviceMaintenance4Features` structure is included in the `pNext` chain of the
VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceMaintenance4Features can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceMaintenance4Features-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_4_FEATURES

The VkPhysicalDeviceDynamicRenderingFeatures structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceDynamicRenderingFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 dynamicRendering;
} VkPhysicalDeviceDynamicRenderingFeatures;
```

This structure describes the following feature:

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **dynamicRendering** specifies that the implementation supports dynamic render pass instances using the vkCmdBeginRendering command.

If the VkPhysicalDeviceDynamicRenderingFeatures structure is included in the pNext chain of the VkPhysicalDeviceFeatures2 structure passed to vkGetPhysicalDeviceFeatures2, it is filled in to indicate whether each corresponding feature is supported. VkPhysicalDeviceDynamicRenderingFeatures can also be used in the pNext chain of VkDeviceCreateInfo to selectively enable these features.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceDynamicRenderingFeatures-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DYNAMIC_RENDERING_FEATURES

32.1. Feature Requirements

All Vulkan graphics implementations must support the following features:

- **robustBufferAccess**
- **multiview**, if Vulkan 1.1 is supported.
- **uniformBufferStandardLayout**, if Vulkan 1.2 or the VK_KHR_uniform_buffer_standard_layout extension is supported.
• storageBuffer8BitAccess, if uniformAndStorageBuffer8BitAccess is enabled.

• If the descriptorIndexing feature is supported, or if the VK_EXT_descriptor_indexing extension is supported:
  ◦ shaderSampledImageArrayDynamicIndexing
  ◦ shaderStorageBufferArrayDynamicIndexing
  ◦ shaderUniformTexelBufferArrayDynamicIndexing
  ◦ shaderStorageTexelBufferArrayDynamicIndexing
  ◦ shaderSampledImageArrayNonUniformIndexing
  ◦ shaderStorageBufferArrayNonUniformIndexing
  ◦ shaderUniformTexelBufferArrayNonUniformIndexing
  ◦ descriptorBindingSampledImageUpdateAfterBind
  ◦ descriptorBindingStorageImageUpdateAfterBind
  ◦ descriptorBindingStorageBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
  ◦ descriptorBindingUniformTexelBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
  ◦ descriptorBindingStorageTexelBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
  ◦ descriptorBindingUpdateUnusedWhilePending
  ◦ descriptorBindingPartiallyBound
  ◦ runtimeDescriptorArray

• If Vulkan 1.3 is supported:
  ◦ vulkanMemoryModel
  ◦ vulkanMemoryModelDeviceScope

• inlineUniformBlock, if Vulkan 1.3 or the VK_EXT_inline_uniform_block extension is supported.

• descriptorBindingInlineUniformBlockUpdateAfterBind, if Vulkan 1.3 or the VK_EXT_inline_uniform_block extension is supported; and if the descriptorIndexing feature is supported, or the VK_EXT_descriptor_indexing extension is supported.

• subgroupBroadcastDynamicId, if Vulkan 1.2 is supported.

• subgroupSizeControl, if Vulkan 1.3 or the VK_EXT_subgroup_size_control extension is supported.

• computeFullSubgroups, if Vulkan 1.3 or the VK_EXT_subgroup_size_control extension is supported.

• imagelessFramebuffer, if Vulkan 1.2 or the VK_KHR_imageless_framebuffer extension is supported.

• separateDepthStencilLayouts, if Vulkan 1.2 or the VK_KHR_separate_depthStencil_layouts extension is supported.

• hostQueryReset, if Vulkan 1.2 or the VK_EXT_host_query_reset extension is supported.

• timelineSemaphore, if Vulkan 1.2 or the VK_KHR_timeline_semaphore extension is supported.

• pipelineCreationCacheControl, if Vulkan 1.3 or the VK_EXT_pipeline_creation_cache_control extension is supported.
• shaderSubgroupExtendedTypes, if Vulkan 1.2 or the VK_KHR_shader_subgroup_extended_types extension is supported.

• textureCompressionASTC_HDR, if the VK_EXT_texture_compression_astc_hdr extension is supported.

• shaderDemoteToHelperInvocation, if Vulkan 1.3 or the VK_EXT_shader_demote_to_helper_invocation extension is supported.

• texelBufferAlignment, if Vulkan 1.3 or the VK_EXT_texel_buffer_alignment extension is supported.

• bufferDeviceAddress, if Vulkan 1.3 or the VK_KHR_buffer_device_address extension is supported.

• shaderInt64, if the shaderSharedInt64Atomics or shaderBufferInt64Atomics features are supported.

• storageBuffer16BitAccess, if uniformAndStorageBuffer16BitAccess is enabled.

• robustImageAccess, if Vulkan 1.3 or the VK_EXT_image_robustness extension is supported.

• shaderTerminateInvocation if Vulkan 1.3 or the VK_KHR_shader_terminate_invocation extension is supported.

• shaderZeroInitializeWorkgroupMemory, if Vulkan 1.3 or the VK_KHR_zero_initialize_workgroup_memory extension is supported.

• synchronization2 if Vulkan 1.3 or the VK_KHR_synchronization2 extension is supported.

• shaderIntegerDotProduct if Vulkan 1.3 or the VK_KHR_shader_integer_dot_product extension is supported.

• maintenance4, if Vulkan 1.3 or the VK_KHR_maintenance4 extension is supported.

• privateData, if Vulkan 1.3 or the VK_EXT_private_data extension is supported.

• dynamicRendering, if Vulkan 1.3 or the VK_KHR_dynamic_rendering extension is supported.

All other features defined in the Specification are **optional**.

**32.2. Profile Features**

**32.2.1. Roadmap 2022**

Implementations that claim support for the Roadmap 2022 profile **must** support the following features:

• fullDrawIndexUint32

• imageCubeArray

• independentBlend

• sampleRateShading

• drawIndirectFirstInstance

• depthClamp

• depthBiasClamp

• samplerAnisotropy

• occlusionQueryPrecise
• fragmentStoresAndAtomics
• shaderStorageImageExtendedFormats
• shaderUniformBufferArrayDynamicIndexing
• shaderSampledImageArrayDynamicIndexing
• shaderStorageBufferArrayDynamicIndexing
• shaderStorageImageArrayDynamicIndexing
• samplerYcbcrConversion
• samplerMirrorClampToEdge
• descriptorIndexing
• shaderUniformTexelBufferArrayDynamicIndexing
• shaderStorageTexelBufferArrayDynamicIndexing
• shaderUniformBufferArrayNonUniformIndexing
• shaderSampledImageArrayNonUniformIndexing
• shaderStorageBufferArrayNonUniformIndexing
• shaderStorageImageArrayNonUniformIndexing
• shaderUniformTexelBufferArrayNonUniformIndexing
• shaderStorageTexelBufferArrayNonUniformIndexing
• descriptorBindingSampledImageUpdateAfterBind
• descriptorBindingStorageImageUpdateAfterBind
• descriptorBindingStorageBufferUpdateAfterBind
• descriptorBindingUniformTexelBufferUpdateAfterBind
• descriptorBindingStorageTexelBufferUpdateAfterBind
• descriptorBindingUpdateUnusedWhilePending
• descriptorBindingPartiallyBound
• descriptorBindingVariableDescriptorCount
• runtimeDescriptorArray
• scalarBlockLayout
Chapter 33. Limits

Limits are implementation-dependent minimums, maximums, and other device characteristics that an application may need to be aware of.

Note

Limits are reported via the basic VkPhysicalDeviceLimits structure as well as the extensible structure VkPhysicalDeviceProperties2, which was added in VK_KHR_get_physical_device_properties2 and included in Vulkan 1.1. When limits are added in future Vulkan versions or extensions, each extension should introduce one new limit structure, if needed. This structure can be added to the pNext chain of the VkPhysicalDeviceProperties2 structure.

The VkPhysicalDeviceLimits structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkPhysicalDeviceLimits {
    uint32_t maxImageDimension1D;
    uint32_t maxImageDimension2D;
    uint32_t maxImageDimension3D;
    uint32_t maxImageDimensionCube;
    uint32_t maxImageArrayLayers;
    uint32_t maxTexelBufferElements;
    uint32_t maxUniformBufferRange;
    uint32_t maxStorageBufferRange;
    uint32_t maxPushConstantsSize;
    uint32_t maxMemoryAllocationCount;
    uint32_t maxSamplerAllocationCount;
    VkDeviceSize bufferImageGranularity;
    VkDeviceSize sparseAddressSpaceSize;
    uint32_t maxBoundDescriptorSets;
    uint32_t maxPerStageDescriptorSamplers;
    uint32_t maxPerStageDescriptorUniformBuffers;
    uint32_t maxPerStageDescriptorStorageBuffers;
    uint32_t maxPerStageDescriptorSamplerdImages;
    uint32_t maxPerStageDescriptorStorageImages;
    uint32_t maxPerStageDescriptorInputAttachments;
    uint32_t maxPerStageResources;
    uint32_t maxDescriptorSetSamplers;
    uint32_t maxDescriptorSetUniformBuffers;
    uint32_t maxDescriptorSetUniformBuffersDynamic;
    uint32_t maxDescriptorSetStorageBuffers;
    uint32_t maxDescriptorSetStorageBuffersDynamic;
    uint32_t maxDescriptorSetSamplerdImages;
    uint32_t maxDescriptorSetStorageImages;
    uint32_t maxDescriptorSetInputAttachments;
    uint32_t maxVertexInputAttributes;
    uint32_t maxVertexInputBindings;
    uint32_t maxVertexInputAttributeOffset;
};
```

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uint32_t maxVertexInputBindingStride;
uint32_t maxVertexOutputComponents;
uint32_t maxTessellationGenerationLevel;
uint32_t maxTessellationPatchSize;
uint32_t maxTessellationControlPerVertexInputComponents;
uint32_t maxTessellationControlPerVertexOutputComponents;
uint32_t maxTessellationControlPerPatchOutputComponents;
uint32_t maxTessellationControlTotalOutputComponents;
uint32_t maxTessellationEvaluationInputComponents;
uint32_t maxTessellationEvaluationOutputComponents;
uint32_t maxGeometryShaderInvocations;
uint32_t maxGeometryInputComponents;
uint32_t maxGeometryOutputComponents;
uint32_t maxGeometryOutputVertices;
uint32_t maxGeometryTotalOutputComponents;
uint32_t maxFragmentInputComponents;
uint32_t maxFragmentOutputAttachments;
uint32_t maxFragmentDualSrcAttachments;
uint32_t maxFragmentCombinedOutputResources;
uint32_t maxComputeSharedMemorySize;
uint32_t maxComputeWorkGroupCount[3];
uint32_t maxComputeWorkGroupInvocations;
uint32_t maxComputeWorkGroupSize[3];
uint32_t subPixelPrecisionBits;
uint32_t subTexelPrecisionBits;
uint32_t mipmapPrecisionBits;
uint32_t maxDrawIndexedIndexValue;
uint32_t maxDrawIndirectCount;
float maxSamplerLodBias;
float maxSamplerAnisotropy;
uint32_t maxViewports;
uint32_t maxViewportDimensions[2];
float viewportBoundsRange[2];
uint32_t viewportSubPixelBits;
size_t minMemoryMapAlignment;
VkDeviceSize minTexelBufferOffsetAlignment;
VkDeviceSize minUniformBufferOffsetAlignment;
VkDeviceSize minStorageBufferOffsetAlignment;
int32_t minTexelOffset;
uint32_t maxTexelOffset;
int32_t minTexelGatherOffset;
uint32_t maxTexelGatherOffset;
float minInterpolationOffset;
float maxInterpolationOffset;
uint32_t subPixelInterpolationOffsetBits;
uint32_t maxFramebufferWidth;
uint32_t maxFramebufferHeight;
uint32_t maxFramebufferLayers;
VkSampleCountFlags framebufferColorSampleCounts;
VkSampleCountFlags framebufferDepthSampleCounts;
VkSampleCountFlags framebufferStencilSampleCounts;
The `VkPhysicalDeviceLimits` are properties of the physical device. These are available in the `limits` member of the `VkPhysicalDeviceProperties` structure which is returned from `vkGetPhysicalDeviceProperties`.

- `maxImageDimension1D` is the largest dimension (width) that is guaranteed to be supported for all images created with an `imageType` of `VK_IMAGE_TYPE_1D`. Some combinations of image parameters (format, usage, etc.) may allow support for larger dimensions, which can be queried using `vkGetPhysicalDeviceImageFormatProperties`.

- `maxImageDimension2D` is the largest dimension (width or height) that is guaranteed to be supported for all images created with an `imageType` of `VK_IMAGE_TYPE_2D` and without `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT` set in `flags`. Some combinations of image parameters (format, usage, etc.) may allow support for larger dimensions, which can be queried using `vkGetPhysicalDeviceImageFormatProperties`.

- `maxImageDimension3D` is the largest dimension (width, height, or depth) that is guaranteed to be supported for all images created with an `imageType` of `VK_IMAGE_TYPE_3D`. Some combinations of image parameters (format, usage, etc.) may allow support for larger dimensions, which can be queried using `vkGetPhysicalDeviceImageFormatProperties`.

- `maxImageDimensionCube` is the largest dimension (width or height) that is guaranteed to be supported for all images created with an `imageType` of `VK_IMAGE_TYPE_2D` and with `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT` set in `flags`. Some combinations of image parameters (format, usage, etc.) may allow support for larger dimensions, which can be queried using `vkGetPhysicalDeviceImageFormatProperties`.
- **maxImageArrayLayers** is the maximum number of layers (`arrayLayers`) for an image.

- **maxTexelBufferElements** is the maximum number of addressable texels for a buffer view created on a buffer which was created with the `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT` or `VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT` set in the `usage` member of the `VkBufferCreateInfo` structure.

- **maxUniformBufferRange** is the maximum value that **can** be specified in the `range` member of a `VkDescriptorBufferInfo` structure passed to `vkUpdateDescriptorSets` for descriptors of type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`.

- **maxStorageBufferRange** is the maximum value that **can** be specified in the `range` member of a `VkDescriptorBufferInfo` structure passed to `vkUpdateDescriptorSets` for descriptors of type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`.

- **maxPushConstantsSize** is the maximum size, in bytes, of the pool of push constant memory. For each of the push constant ranges indicated by the `pPushConstantRanges` member of the `VkPipelineLayoutCreateInfo` structure, `(offset + size)` **must** be less than or equal to this limit.

- **maxMemoryAllocationCount** is the maximum number of device memory allocations, as created by `vkAllocateMemory`, which **can** simultaneously exist.

- **maxSamplerAllocationCount** is the maximum number of sampler objects, as created by `vkCreateSampler`, which **can** simultaneously exist on a device.

- **bufferImageGranularity** is the granularity, in bytes, at which buffer or linear image resources, and optimal image resources **can** be bound to adjacent offsets in the same `VkDeviceMemory` object without aliasing. See Buffer-Image Granularity for more details.

- **sparseAddressSpaceSize** is the total amount of address space available, in bytes, for sparse memory resources. This is an upper bound on the sum of the sizes of all sparse resources, regardless of whether any memory is bound to them.

- **maxBoundDescriptorSets** is the maximum number of descriptor sets that **can** be simultaneously used by a pipeline. All `DescriptorSet` decorations in shader modules **must** have a value less than `maxBoundDescriptorSets`. See Descriptor Sets.

- **maxPerStageDescriptorSamplers** is the maximum number of samplers that **can** be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Sampler and Combined Image Sampler.

- **maxPerStageDescriptorUniformBuffers** is the maximum number of uniform buffers that **can** be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Uniform Buffer and Dynamic Uniform Buffer.
• **maxPerStageDescriptorStorageBuffers** is the maximum number of storage buffers that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See **Storage Buffer** and **Dynamic Storage Buffer**.

• **maxPerStageDescriptorSampledImages** is the maximum number of sampled images that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, or `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See **Combined Image Sampler**, **Sampled Image**, and **Uniform Texel Buffer**.

• **maxPerStageDescriptorStorageImages** is the maximum number of storage images that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, or `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See **Storage Image**, and **Storage Texel Buffer**.

• **maxPerStageDescriptorInputAttachments** is the maximum number of input attachments that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. These are only supported for the fragment stage. See **Input Attachment**.

• **maxPerStageResources** is the maximum number of resources that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER`, `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`, `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, or `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. For the fragment shader stage the framebuffer color attachments also count against this limit.

• **maxDescriptorSetSamplers** is the maximum number of samplers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See
Sampler and Combined Image Sampler.

- **maxDescriptorSetUniformBuffers** is the maximum number of uniform buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Uniform Buffer and Dynamic Uniform Buffer.

- **maxDescriptorSetUniformBuffersDynamic** is the maximum number of dynamic uniform buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Dynamic Uniform Buffer.

- **maxDescriptorSetStorageBuffers** is the maximum number of storage buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Storage Buffer and Dynamic Storage Buffer.

- **maxDescriptorSetStorageBuffersDynamic** is the maximum number of dynamic storage buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Dynamic Storage Buffer.

- **maxDescriptorSetSampledImages** is the maximum number of sampled images that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, or `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Combined Image Sampler, Sampled Image, and Uniform Texel Buffer.

- **maxDescriptorSetStorageImages** is the maximum number of storage images that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, or `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Storage Image, and Storage Texel Buffer.

- **maxDescriptorSetInputAttachments** is the maximum number of input attachments that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` count against this limit. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit. See Input Attachment.

- **maxVertexInputAttributes** is the maximum number of vertex input attributes that can be specified for a graphics pipeline. These are described in the array of `VkVertexInputAttributeDescription` structures that are provided at graphics pipeline creation time via the `pVertexAttributeDescriptions` member of the `VkPipelineVertexInputStateCreateInfo` structure.
structure. See Vertex Attributes and Vertex Input Description.

- **maxVertexInputBindings** is the maximum number of vertex buffers that can be specified for providing vertex attributes to a graphics pipeline. These are described in the array of VkVertexInputBindingDescription structures that are provided at graphics pipeline creation time via the pVertexBindingDescriptions member of the VkPipelineVertexInputStateCreateInfo structure. The binding member of VkVertexInputBindingDescription must be less than this limit. See Vertex Input Description.

- **maxVertexInputAttributeOffset** is the maximum vertex input attribute offset that can be added to the vertex input binding stride. The offset member of the VkVertexInputAttributeDescription structure must be less than or equal to this limit. See Vertex Input Description.

- **maxVertexInputBindingStride** is the maximum vertex input binding stride that can be specified in a vertex input binding. The stride member of the VkVertexInputBindingDescription structure must be less than or equal to this limit. See Vertex Input Description.

- **maxVertexOutputComponents** is the maximum number of components of output variables which can be output by a vertex shader. See Vertex Shaders.

- **maxTessellationGenerationLevel** is the maximum tessellation generation level supported by the fixed-function tessellation primitive generator. See Tessellation.

- **maxTessellationPatchSize** is the maximum patch size, in vertices, of patches that can be processed by the tessellation control shader and tessellation primitive generator. The patchControlPoints member of the VkPipelineTessellationStateCreateInfo structure specified at pipeline creation time and the value provided in the OutputVertices execution mode of shader modules must be less than or equal to this limit. See Tessellation.

- **maxTessellationControlPerVertexInputComponents** is the maximum number of components of input variables which can be provided as per-vertex inputs to the tessellation control shader stage.

- **maxTessellationControlPerVertexOutputComponents** is the maximum number of components of per-vertex output variables which can be output from the tessellation control shader stage.

- **maxTessellationControlPerPatchOutputComponents** is the maximum number of components of per-patch output variables which can be output from the tessellation control shader stage.

- **maxTessellationControlTotalOutputComponents** is the maximum total number of components of per-vertex and per-patch output variables which can be output from the tessellation control shader stage.

- **maxTessellationEvaluationInputComponents** is the maximum number of components of input variables which can be provided as per-vertex inputs to the tessellation evaluation shader stage.

- **maxTessellationEvaluationOutputComponents** is the maximum number of components of per-vertex output variables which can be output from the tessellation evaluation shader stage.

- **maxGeometryShaderInvocations** is the maximum invocation count supported for instanced geometry shaders. The value provided in the Invocations execution mode of shader modules must be less than or equal to this limit. See Geometry Shading.

- **maxGeometryInputComponents** is the maximum number of components of input variables which can be provided as inputs to the geometry shader stage.
maxGeometryOutputComponents is the maximum number of components of output variables which can be output from the geometry shader stage.

maxGeometryOutputVertices is the maximum number of vertices which can be emitted by any geometry shader.

maxGeometryTotalOutputComponents is the maximum total number of components of output variables, across all emitted vertices, which can be output from the geometry shader stage.

maxFragmentInputComponents is the maximum number of components of input variables which can be provided as inputs to the fragment shader stage.

maxFragmentOutputAttachments is the maximum number of output attachments which can be written to by the fragment shader stage.

maxFragmentDualSrcAttachments is the maximum number of output attachments which can be written to by the fragment shader stage when blending is enabled and one of the dual source blend modes is in use. See Dual-Source Blending and dualSrcBlend.

maxFragmentCombinedOutputResources is the total number of storage buffers, storage images, and output Location decorated color attachments (described in Fragment Output Interface) which can be used in the fragment shader stage.

maxComputeSharedMemorySize is the maximum total storage size, in bytes, available for variables declared with the Workgroup storage class in shader modules (or with the shared storage qualifier in GLSL) in the compute shader stage.

maxComputeWorkGroupCount[3] is the maximum number of local workgroups that can be dispatched by a single dispatching command. These three values represent the maximum number of local workgroups for the X, Y, and Z dimensions, respectively. The workgroup count parameters to the dispatching commands must be less than or equal to the corresponding limit. See Dispatching Commands.

maxComputeWorkGroupInvocations is the maximum total number of compute shader invocations in a single local workgroup. The product of the X, Y, and Z sizes, as specified by the LocalSize or LocalSizeId execution mode in shader modules or by the object decorated by the WorkgroupSize decoration, must be less than or equal to this limit.

maxComputeWorkGroupSize[3] is the maximum size of a local compute workgroup, per dimension. These three values represent the maximum local workgroup size in the X, Y, and Z dimensions, respectively. The x, y, and z sizes, as specified by the LocalSize or LocalSizeId execution mode or by the object decorated by the WorkgroupSize decoration in shader modules, must be less than or equal to the corresponding limit.

subPixelPrecisionBits is the number of bits of subpixel precision in framebuffer coordinates \( x_f \) and \( y_f \). See Rasterization.

subTexelPrecisionBits is the number of bits of precision in the division along an axis of an image used for minification and magnification filters. \( 2^{\text{subTexelPrecisionBits}} \) is the actual number of divisions along each axis of the image represented. Sub-texel values calculated during image sampling will snap to these locations when generating the filtered results.

mipmapPrecisionBits is the number of bits of division that the LOD calculation for mipmap fetching get snapped to when determining the contribution from each mip level to the mip filtered results. \( 2^{\text{mipmapPrecisionBits}} \) is the actual number of divisions.
- **maxDrawIndexedIndexValue** is the maximum index value that can be used for indexed draw calls when using 32-bit indices. This excludes the primitive restart index value of 0xFFFFFFFF. See fullDrawIndexedUint32.

- **maxDrawIndirectCount** is the maximum draw count that is supported for indirect drawing calls. See multiDrawIndirect.

- **maxSamplerLodBias** is the maximum absolute sampler LOD bias. The sum of the mipLodBias member of the VkSamplerCreateInfo structure and the Bias operand of image sampling operations in shader modules (or 0 if no Bias operand is provided to an image sampling operation) are clamped to the range \([-\text{maxSamplerLodBias}, +\text{maxSamplerLodBias}]\). See [samplers-mipLodBias].

- **maxSamplerAnisotropy** is the maximum degree of sampler anisotropy. The maximum degree of anisotropic filtering used for an image sampling operation is the minimum of the maxAnisotropy member of the VkSamplerCreateInfo structure and this limit. See [samplers-maxAnisotropy].

- **maxViewports** is the maximum number of active viewports. The viewportCount member of the VkPipelineViewportStateCreateInfo structure that is provided at pipeline creation must be less than or equal to this limit.

- **maxViewportDimensions[2]** are the maximum viewport dimensions in the X (width) and Y (height) dimensions, respectively. The maximum viewport dimensions must be greater than or equal to the largest image which can be created and used as a framebuffer attachment. See Controlling the Viewport.

- **viewportBoundsRange[2]** is the range that the corners of a viewport must be contained in. This range must be at least \([-2 \times \text{size}, 2 \times \text{size} - 1]\), where \(\text{size} = \max(\text{maxViewportDimensions}[0], \text{maxViewportDimensions}[1])\). See Controlling the Viewport.

  **Note**
  The intent of the viewportBoundsRange limit is to allow a maximum sized viewport to be arbitrarily shifted relative to the output target as long as at least some portion intersects. This would give a bounds limit of \([-\text{size} + 1, 2 \times \text{size} - 1]\) which would allow all possible non-empty-set intersections of the output target and the viewport. Since these numbers are typically powers of two, picking the signed number range using the smallest possible number of bits ends up with the specified range.

- **viewportSubPixelBits** is the number of bits of subpixel precision for viewport bounds. The subpixel precision that floating-point viewport bounds are interpreted at is given by this limit.

- **minMemoryMapAlignment** is the minimum required alignment, in bytes, of host visible memory allocations within the host address space. When mapping a memory allocation with vkMapMemory, subtracting offset bytes from the returned pointer will always produce an integer multiple of this limit. See Host Access to Device Memory Objects. The value must be a power of two.

- **minTexelBufferOffsetAlignment** is the minimum required alignment, in bytes, for the offset member of the VkBufferViewCreateInfo structure for texel buffers. The value must be a power of two. If texelBufferAlignment is enabled, this limit is equivalent to the maximum of the uniformTexelBufferOffsetAlignmentBytes and storageTexelBufferOffsetAlignmentBytes members.
of `VkPhysicalDeviceTexelBufferAlignmentProperties`, but smaller alignment is optionally allowed by `storageTexelBufferOffsetSingleTexelAlignment` and `uniformTexelBufferOffsetSingleTexelAlignment`. If `texelBufferAlignment` is not enabled, `VkBufferViewCreateInfo::offset` must be a multiple of this value.

- **minUniformBufferOffsetAlignment** is the minimum required alignment, in bytes, for the `offset` member of the `VkDescriptorBufferInfo` structure for uniform buffers. When a descriptor of type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` is updated, the `offset` must be an integer multiple of this limit. Similarly, dynamic offsets for uniform buffers must be multiples of this limit. The value must be a power of two.

- **minStorageBufferOffsetAlignment** is the minimum required alignment, in bytes, for the `offset` member of the `VkDescriptorBufferInfo` structure for storage buffers. When a descriptor of type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` is updated, the `offset` must be an integer multiple of this limit. Similarly, dynamic offsets for storage buffers must be multiples of this limit. The value must be a power of two.

- **minTexelOffset** is the minimum offset value for the `ConstOffset` image operand of any of the `OpImageSample*` or `OpImageFetch*` image instructions.

- **maxTexelOffset** is the maximum offset value for the `ConstOffset` image operand of any of the `OpImageSample*` or `OpImageFetch*` image instructions.

- **minTexelGatherOffset** is the minimum offset value for the `Offset`, `ConstOffset`, or `ConstOffsets` image operands of any of the `OpImage*Gather` image instructions.

- **maxTexelGatherOffset** is the maximum offset value for the `Offset`, `ConstOffset`, or `ConstOffsets` image operands of any of the `OpImage*Gather` image instructions.

- **minInterpolationOffset** is the base minimum (inclusive) negative offset value for the `Offset` operand of the `InterpolateAtOffset` extended instruction.

- **maxInterpolationOffset** is the base maximum (inclusive) positive offset value for the `Offset` operand of the `InterpolateAtOffset` extended instruction.

- **subPixelInterpolationOffsetBits** is the number of fractional bits that the `x` and `y` offsets to the `InterpolateAtOffset` extended instruction may be rounded to as fixed-point values.

- **maxFramebufferWidth** is the maximum width for a framebuffer. The `width` member of the `VkFramebufferCreateInfo` structure must be less than or equal to this limit.

- **maxFramebufferHeight** is the maximum height for a framebuffer. The `height` member of the `VkFramebufferCreateInfo` structure must be less than or equal to this limit.

- **maxFramebufferLayers** is the maximum layer count for a layered framebuffer. The `layers` member of the `VkFramebufferCreateInfo` structure must be less than or equal to this limit.

- **framebufferColorSampleCounts** is a bitmask of `VkSampleCountFlagBits` indicating the color sample counts that are supported for all framebuffer color attachments with floating- or fixed-point formats. For color attachments with integer formats, see `framebufferIntegerColorSampleCounts`.

- **framebufferDepthSampleCounts** is a bitmask of `VkSampleCountFlagBits` indicating the supported depth sample counts for all framebuffer depth/stencil attachments, when the format includes a depth component.

- **framebufferStencilSampleCounts** is a bitmask of `VkSampleCountFlagBits` indicating the
supported stencil sample counts for all framebuffer depth/stencil attachments, when the format includes a stencil component.

- **framebufferNoAttachmentsSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the supported sample counts for a subpass which uses no attachments.

- **maxColorAttachments** is the maximum number of color attachments that can be used by a subpass in a render pass. The **colorAttachmentCount** member of the **VkSubpassDescription** or **VkSubpassDescription2** structure must be less than or equal to this limit.

- **sampledImageColorSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the sample counts supported for all 2D images created with **VK_IMAGE_TILING_OPTIMAL**, usage containing **VK_IMAGE_USAGE_SAMPLED_BIT**, and a non-integer color format.

- **sampledImageIntegerSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the sample counts supported for all 2D images created with **VK_IMAGE_TILING_OPTIMAL**, usage containing **VK_IMAGE_USAGE_SAMPLED_BIT**, and an integer color format.

- **sampledImageDepthSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the sample counts supported for all 2D images created with **VK_IMAGE_TILING_OPTIMAL**, usage containing **VK_IMAGE_USAGE_SAMPLED_BIT**, and a depth format.

- **sampledImageStencilSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the sample counts supported for all 2D images created with **VK_IMAGE_TILING_OPTIMAL**, usage containing **VK_IMAGE_USAGE_SAMPLED_BIT**, and a stencil format.

- **storageImageSampleCounts** is a bitmask\(^1\) of **VkSampleCountFlagBits** indicating the sample counts supported for all 2D images created with **VK_IMAGE_TILING_OPTIMAL**, and usage containing **VK_IMAGE_USAGE_STORAGE_BIT**.

- **maxSampleMaskWords** is the maximum number of array elements of a variable decorated with the **SampleMask** built-in decoration.

- **timestampComputeAndGraphics** specifies support for timestamps on all graphics and compute queues. If this limit is set to **VK_TRUE**, all queues that advertise the **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT** in the **VkQueueFamilyProperties::queueFlags** support **VkQueueFamilyProperties::timestampValidBits** of at least 36. See **Timestamp Queries**.

- **timestampPeriod** is the number of nanoseconds required for a timestamp query to be incremented by 1. See **Timestamp Queries**.

- **maxClipDistances** is the maximum number of clip distances that can be used in a single shader stage. The size of any array declared with the **ClipDistance** built-in decoration in a shader module must be less than or equal to this limit.

- **maxCullDistances** is the maximum number of cull distances that can be used in a single shader stage. The size of any array declared with the **CullDistance** built-in decoration in a shader module must be less than or equal to this limit.

- **maxCombinedClipAndCullDistances** is the maximum combined number of clip and cull distances that can be used in a single shader stage. The sum of the sizes of any pair of arrays declared with the **ClipDistance** and **CullDistance** built-in decoration used by a single shader stage in a shader module must be less than or equal to this limit.

- **discreteQueuePriorities** is the number of discrete priorities that can be assigned to a queue based on the value of each member of **VkDeviceQueueCreateInfo::pQueuePriorities**. This must
be at least 2, and levels **must** be spread evenly over the range, with at least one level at 1.0, and another at 0.0. See Queue Priority.

- **pointSizeRange[2]** is the range \([\text{minimum, maximum}]\) of supported sizes for points. Values written to variables decorated with the `PointSize` built-in decoration are clamped to this range.

- **lineWidthRange[2]** is the range \([\text{minimum, maximum}]\) of supported widths for lines. Values specified by the `lineWidth` member of the `VkPipelineRasterizationStateCreateInfo` or the `lineWidth` parameter to `vkCmdSetLineWidth` are clamped to this range.

- **pointSizeGranularity** is the granularity of supported point sizes. Not all point sizes in the range defined by `pointSizeRange` are supported. This limit specifies the granularity (or increment) between successive supported point sizes.

- **lineWidthGranularity** is the granularity of supported line widths. Not all line widths in the range defined by `lineWidthRange` are supported. This limit specifies the granularity (or increment) between successive supported line widths.

- **strictLines** specifies whether lines are rasterized according to the preferred method of rasterization. If set to `VK_FALSE`, lines **may** be rasterized under a relaxed set of rules. If set to `VK_TRUE`, lines are rasterized as per the strict definition. See Basic Line Segment Rasterization.

- **standardSampleLocations** specifies whether rasterization uses the standard sample locations as documented in Multisampling. If set to `VK_TRUE`, the implementation uses the documented sample locations. If set to `VK_FALSE`, the implementation **may** use different sample locations.

- **optimalBufferCopyOffsetAlignment** is the optimal buffer offset alignment in bytes for `vkCmdCopyBufferToImage2`, `vkCmdCopyBufferToImage`, `vkCmdCopyImageToBuffer2`, and `vkCmdCopyImageToBuffer`. The per texel alignment requirements are enforced, but applications **should** use the optimal alignment for optimal performance and power use. The value **must** be a power of two.

- **optimalBufferCopyRowPitchAlignment** is the optimal buffer row pitch alignment in bytes for `vkCmdCopyBufferToImage2`, `vkCmdCopyBufferToImage`, `vkCmdCopyImageToBuffer2`, and `vkCmdCopyImageToBuffer`. Row pitch is the number of bytes between texels with the same X coordinate in adjacent rows (Y coordinates differ by one). The per texel alignment requirements are enforced, but applications **should** use the optimal alignment for optimal performance and power use. The value **must** be a power of two.

- **nonCoherentAtomSize** is the size and alignment in bytes that bounds concurrent access to host-mapped device memory. The value **must** be a power of two.

1

For all bitmasks of `VkSampleCountFlagBits`, the sample count limits defined above represent the minimum supported sample counts for each image type. Individual images **may** support additional sample counts, which are queried using `vkGetPhysicalDeviceImageFormatProperties` as described in Supported Sample Counts.

Bits which **may** be set in the sample count limits returned by `VkPhysicalDeviceLimits`, as well as in other queries and structures representing image sample counts, are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkSampleCountFlagBits {
```
VK_SAMPLE_COUNT_1_BIT = 0x00000001,
VK_SAMPLE_COUNT_2_BIT = 0x00000002,
VK_SAMPLE_COUNT_4_BIT = 0x00000004,
VK_SAMPLE_COUNT_8_BIT = 0x00000008,
VK_SAMPLE_COUNT_16_BIT = 0x00000010,
VK_SAMPLE_COUNT_32_BIT = 0x00000020,
VK_SAMPLE_COUNT_64_BIT = 0x00000040,

VkSampleCountFlagBits;

• VK_SAMPLE_COUNT_1_BIT specifies an image with one sample per pixel.
• VK_SAMPLE_COUNT_2_BIT specifies an image with 2 samples per pixel.
• VK_SAMPLE_COUNT_4_BIT specifies an image with 4 samples per pixel.
• VK_SAMPLE_COUNT_8_BIT specifies an image with 8 samples per pixel.
• VK_SAMPLE_COUNT_16_BIT specifies an image with 16 samples per pixel.
• VK_SAMPLE_COUNT_32_BIT specifies an image with 32 samples per pixel.
• VK_SAMPLE_COUNT_64_BIT specifies an image with 64 samples per pixel.

// Provided by VK_VERSION_1_0
typedef VkFlags VkSampleCountFlags;

VkSampleCountFlags is a bitmask type for setting a mask of zero or more VkSampleCountFlagBits.

The VkPhysicalDeviceMultiviewProperties structure is defined as:

// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceMultiviewProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t maxMultiviewViewCount;
    uint32_t maxMultiviewInstanceIndex;
} VkPhysicalDeviceMultiviewProperties;

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• maxMultiviewViewCount is one greater than the maximum view index that can be used in a subpass.
• maxMultiviewInstanceIndex is the maximum valid value of instance index allowed to be generated by a drawing command recorded within a subpass of a multiview render pass instance.

If the VkPhysicalDeviceMultiviewProperties structure is included in the pNext chain of the VkPhysicalDeviceProperties2 structure passed to vkGetPhysicalDeviceProperties2, it is filled in with each corresponding implementation-dependent property.
Valid Usage (Implicit)

- **VUID-VkPhysicalDeviceMultiviewProperties-sType-sType**
  
  *sType* must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES**

The **VkPhysicalDeviceFloatControlsProperties** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceFloatControlsProperties {
  VkStructureType sType;
  void* pNext;
  VkShaderFloatControlsIndependence denormBehaviorIndependence;
  VkShaderFloatControlsIndependence roundingModeIndependence;
  VkBool32 shaderSignedZeroInfNanPreserveFloat16;
  VkBool32 shaderSignedZeroInfNanPreserveFloat32;
  VkBool32 shaderSignedZeroInfNanPreserveFloat64;
  VkBool32 shaderDenormPreserveFloat16;
  VkBool32 shaderDenormPreserveFloat32;
  VkBool32 shaderDenormPreserveFloat64;
  VkBool32 shaderDenormFlushToZeroFloat16;
  VkBool32 shaderDenormFlushToZeroFloat32;
  VkBool32 shaderDenormFlushToZeroFloat64;
  VkBool32 shaderRoundingModeRTEFloat16;
  VkBool32 shaderRoundingModeRTEFloat32;
  VkBool32 shaderRoundingModeRTEFloat64;
  VkBool32 shaderRoundingModeRTZFloat16;
  VkBool32 shaderRoundingModeRTZFloat32;
  VkBool32 shaderRoundingModeRTZFloat64;
} VkPhysicalDeviceFloatControlsProperties;
```

- **sType** is a **VkStructureType** value identifying this structure.
- **pNext** is **NULL** or a pointer to a structure extending this structure.
- **denormBehaviorIndependence** is a **VkShaderFloatControlsIndependence** value indicating whether, and how, denorm behavior can be set independently for different bit widths.
- **roundingModeIndependence** is a **VkShaderFloatControlsIndependence** value indicating whether, and how, rounding modes can be set independently for different bit widths.
- **shaderSignedZeroInfNanPreserveFloat16** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 16-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 16-bit floating-point types.
- **shaderSignedZeroInfNanPreserveFloat32** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 32-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 32-bit floating-point types.
- **shaderSignedZeroInfNanPreserveFloat64** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 64-bit floating-point computations. It also indicates whether...
the SignedZeroInfNanPreserve execution mode can be used for 64-bit floating-point types.

- shaderDenormPreserveFloat16 is a boolean value indicating whether denormals can be preserved in 16-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 16-bit floating-point types.

- shaderDenormPreserveFloat32 is a boolean value indicating whether denormals can be preserved in 32-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 32-bit floating-point types.

- shaderDenormPreserveFloat64 is a boolean value indicating whether denormals can be preserved in 64-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 64-bit floating-point types.

- shaderDenormFlushToZeroFloat16 is a boolean value indicating whether denormals can be flushed to zero in 16-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 16-bit floating-point types.

- shaderDenormFlushToZeroFloat32 is a boolean value indicating whether denormals can be flushed to zero in 32-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 32-bit floating-point types.

- shaderDenormFlushToZeroFloat64 is a boolean value indicating whether denormals can be flushed to zero in 64-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 64-bit floating-point types.

- shaderRoundingModeRTEFloat16 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 16-bit floating-point types.

- shaderRoundingModeRTEFloat32 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 32-bit floating-point types.

- shaderRoundingModeRTEFloat64 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 64-bit floating-point types.

- shaderRoundingModeRTZFloat16 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 16-bit floating-point types.

- shaderRoundingModeRTZFloat32 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 32-bit floating-point types.

- shaderRoundingModeRTZFloat64 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 64-bit floating-point types.
If the `VkPhysicalDeviceFloatControlsProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceFloatControlsProperties-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES`

Values which **may** be returned in the `denormBehaviorIndependence` and `roundingModeIndependence` fields of `VkPhysicalDeviceFloatControlsProperties` are:

```c
// Provided by VK_VERSION_1_2
typedef enum VkShaderFloatControlsIndependence {
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY = 0,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL = 1,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE = 2,
} VkShaderFloatControlsIndependence;
```

- `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY` specifies that shader float controls for 32-bit floating point can be set independently; other bit widths must be set identically to each other.
- `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL` specifies that shader float controls for all bit widths can be set independently.
- `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE` specifies that shader float controls for all bit widths must be set identically.

The `VkPhysicalDevicePointClippingProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDevicePointClippingProperties {
    VkStructureType sType;
    void* pNext;
    VkPointClippingBehavior pointClippingBehavior;
} VkPhysicalDevicePointClippingProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `pointClippingBehavior` is a `VkPointClippingBehavior` value specifying the point clipping behavior supported by the implementation.

If the `VkPhysicalDevicePointClippingProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.
The `VkPhysicalDeviceSubgroupProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceSubgroupProperties {
    VkStructureType     sType;
    void*                pNext;
    uint32_t             subgroupSize;
    VkShaderStageFlags   supportedStages;
    VkSubgroupFeatureFlags supportedOperations;
    VkBool32             quadOperationsInAllStages;
} VkPhysicalDeviceSubgroupProperties;
```

- `sType` is a ` VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `subgroupSize` is the default number of invocations in each subgroup. `subgroupSize` is at least 1 if any of the physical device’s queues support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`. `subgroupSize` is a power-of-two.
- `supportedStages` is a bitfield of `VkShaderStageFlagBits` describing the shader stages that group operations with subgroup scope are supported in. `supportedStages` will have the `VK_SHADER_STAGE_COMPUTE_BIT` bit set if any of the physical device’s queues support `VK_QUEUE_COMPUTE_BIT`.
- `supportedOperations` is a bitmask of `VkSubgroupFeatureFlagBits` specifying the sets of group operations with subgroup scope supported on this device. `supportedOperations` will have the `VK_SUBGROUP_FEATURE_BASIC_BIT` bit set if any of the physical device’s queues support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`.
- `quadOperationsInAllStages` is a boolean specifying whether quad group operations are available in all stages, or are restricted to fragment and compute stages.

If the `VkPhysicalDeviceSubgroupProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

If `supportedOperations` includes `VK_SUBGROUP_FEATURE_QUAD_BIT`, `subgroupSize` must be greater than or equal to 4.
Bits which can be set in `VkPhysicalDeviceSubgroupProperties::supportedOperations` and `VkPhysicalDeviceVulkan11Properties::subgroupSupportedOperations` to specify supported group operations with subgroup scope are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkSubgroupFeatureFlagBits {
    VK_SUBGROUP_FEATURE_BASIC_BIT = 0x00000001,
    VK_SUBGROUP_FEATURE_VOTE_BIT = 0x00000002,
    VK_SUBGROUP_FEATURE_ARITHMETIC_BIT = 0x00000004,
    VK_SUBGROUP_FEATURE_BALLOT_BIT = 0x00000008,
    VK_SUBGROUP_FEATURE_SHUFFLE_BIT = 0x00000010,
    VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT = 0x00000020,
    VK_SUBGROUP_FEATURE_CLUSTERED_BIT = 0x00000040,
    VK_SUBGROUP_FEATURE_QUAD_BIT = 0x00000080,
} VkSubgroupFeatureFlagBits;
```

- **VK_SUBGROUP_FEATURE_BASIC_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniform` capability.
- **VK_SUBGROUP_FEATURE_VOTE_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformVote` capability.
- **VK_SUBGROUP_FEATURE_ARITHMETIC_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformArithmetic` capability.
- **VK_SUBGROUP_FEATURE_BALLOT_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformBallot` capability.
- **VK_SUBGROUP_FEATURE_SHUFFLE_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformShuffle` capability.
- **VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformShuffleRelative` capability.
- **VK_SUBGROUP_FEATURE_CLUSTERED_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformClustered` capability.
- **VK_SUBGROUP_FEATURE_QUAD_BIT** specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformQuad` capability.

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkSubgroupFeatureFlags;
```

`VkSubgroupFeatureFlags` is a bitmask type for setting a mask of zero or more `VkSubgroupFeatureFlagBits`.

The `VkPhysicalDeviceSubgroupSizeControlProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceSubgroupSizeControlProperties {
    VkStructureType sType;
} VkPhysicalDeviceSubgroupSizeControlProperties;
```
void*          pNext;
uint32_t       minSubgroupSize;
uint32_t       maxSubgroupSize;
uint32_t       maxComputeWorkgroupSubgroups;
VkShaderStageFlags  requiredSubgroupSizeStages;
} VkPhysicalDeviceSubgroupSizeControlProperties;

• **sType** is a **VkStructureType** value identifying this structure.
• **pNext** is **NULL** or a pointer to a structure extending this structure.

• **minSubgroupSize** is the minimum subgroup size supported by this device. **minSubgroupSize** is at least one if any of the physical device’s queues support **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT**. **minSubgroupSize** is a power-of-two. **minSubgroupSize** is less than or equal to **maxSubgroupSize**. **minSubgroupSize** is less than or equal to **subgroupSize**.

• **maxSubgroupSize** is the maximum subgroup size supported by this device. **maxSubgroupSize** is at least one if any of the physical device’s queues support **VK_QUEUE_GRAPHICS_BIT** or **VK_QUEUE_COMPUTE_BIT**. **maxSubgroupSize** is a power-of-two. **maxSubgroupSize** is greater than or equal to **minSubgroupSize**. **maxSubgroupSize** is greater than or equal to **subgroupSize**.

• **maxComputeWorkgroupSubgroups** is the maximum number of subgroups supported by the implementation within a workgroup.

• **requiredSubgroupSizeStages** is a bitfield of what shader stages support having a required subgroup size specified.

If the **VkPhysicalDeviceSubgroupSizeControlProperties** structure is included in the **pNext** chain of the **VkPhysicalDeviceProperties2** structure passed to **vkGetPhysicalDeviceProperties2**, it is filled in with each corresponding implementation-dependent property.

If **VkPhysicalDeviceSubgroupProperties::supportedOperations** includes **VK_SUBGROUP_FEATURE_QUAD_BIT**, **minSubgroupSize** **must** be greater than or equal to 4.

### Valid Usage (Implicit)

• VUID-VkPhysicalDeviceSubgroupSizeControlProperties-sType-sType
  
  **sType** **must** be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_SIZE_CONTROL_PROPERTIES**

The **VkPhysicalDeviceSamplerFilterMinmaxProperties** structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceSamplerFilterMinmaxProperties {
    VkStructureType sType;
    void*           pNext;
    VkBool32        filterMinmaxSingleComponentFormats;
    VkBool32        filterMinmaxImageComponentMapping;
} VkPhysicalDeviceSamplerFilterMinmaxProperties;
```
• **sType** is a `VkStructureType` value identifying this structure.

• **pNext** is **NULL** or a pointer to a structure extending this structure.

• **filterMinmaxSingleComponentFormats** is a boolean value indicating whether a minimum set of required formats support min/max filtering.

• **filterMinmaxImageComponentMapping** is a boolean value indicating whether the implementation supports non-identity component mapping of the image when doing min/max filtering.

If the `VkPhysicalDeviceSamplerFilterMinmaxProperties` structure is included in the **pNext** chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

If `filterMinmaxSingleComponentFormats` is **VK_TRUE**, the following formats **must** support the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT` feature with `VK_IMAGE_TILING_OPTIMAL`, if they support `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`:

- `VK_FORMAT_R8_UNORM`
- `VK_FORMAT_R8_SNORM`
- `VK_FORMAT_R16_UNORM`
- `VK_FORMAT_R16_SNORM`
- `VK_FORMAT_R16_SFLOAT`
- `VK_FORMAT_R32_SFLOAT`
- `VK_FORMAT_D16_UNORM`
- `VK_FORMAT_X8_D24_UNORM_PACK32`
- `VK_FORMAT_D32_SFLOAT`
- `VK_FORMAT_D16_UNORM_S8_UINT`
- `VK_FORMAT_D24_UNORM_S8_UINT`
- `VK_FORMAT_D32_SFLOAT_S8_UINT`

If the format is a depth/stencil format, this bit only specifies that the depth aspect (not the stencil aspect) of an image of this format supports min/max filtering, and that min/max filtering of the depth aspect is supported when depth compare is disabled in the sampler.

If `filterMinmaxImageComponentMapping` is **VK_FALSE** the component mapping of the image view used with min/max filtering **must** have been created with the `r` component set to the identity swizzle. Only the `r` component of the sampled image value is defined and the other component values are undefined. If `filterMinmaxImageComponentMapping` is **VK_TRUE** this restriction does not apply and image component mapping works as normal.

---

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceSamplerFilterMinmaxProperties-sType-sType
  `sType` **must** be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_FILTER_MINMAX_PROPERTIES`
The `VkPhysicalDeviceProtectedMemoryProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceProtectedMemoryProperties {
    VkStructureType sType;
    void* pNext;
    VkBool32 protectedNoFault;
} VkPhysicalDeviceProtectedMemoryProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `protectedNoFault` specifies how an implementation behaves when an application attempts to write to unprotected memory in a protected queue operation, read from protected memory in an unprotected queue operation, or perform a query in a protected queue operation. If this limit is `VK_TRUE`, such writes will be discarded or have undefined values written, reads and queries will return undefined values. If this limit is `VK_FALSE`, applications must not perform these operations. See Protected Memory Access Rules for more information.

If the `VkPhysicalDeviceProtectedMemoryProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceProtectedMemoryProperties-sType-sType
  - `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_PROPERTIES`

The `VkPhysicalDeviceMaintenance3Properties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceMaintenance3Properties {
    VkStructureType sType;
    void* pNext;
    uint32_t maxPerSetDescriptors;
    VkDeviceSize maxMemoryAllocationSize;
} VkPhysicalDeviceMaintenance3Properties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `maxPerSetDescriptors` is a maximum number of descriptors (summed over all descriptor types) in a single descriptor set that is guaranteed to satisfy any implementation-dependent constraints on the size of a descriptor set itself. Applications can query whether a descriptor set that goes beyond this limit is supported using `vkGetDescriptorSetLayoutSupport`. 
• `maxMemoryAllocationSize` is the maximum size of a memory allocation that can be created, even if there is more space available in the heap.

If the `VkPhysicalDeviceMaintenance3Properties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceMaintenance3Properties-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES`

The `VkPhysicalDeviceMaintenance4Properties` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceMaintenance4Properties {
    VkStructureType             sType;
    void*                        pNext;
    VkDeviceSize                 maxBufferSize;
} VkPhysicalDeviceMaintenance4Properties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure.
- `maxBufferSize` is the maximum size `VkBuffer` that can be created.

If the `VkPhysicalDeviceMaintenance4Properties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceMaintenance4Properties-sType-sType
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL DEVICE_MAINTENANCE_4_PROPERTIES`

The `VkPhysicalDeviceDescriptorIndexingProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceDescriptorIndexingProperties {
    VkStructureType             sType;
    void*                        pNext;
    uint32_t                     maxUpdateAfterBindDescriptorsInAllPools;
    VkBool32                     shaderUniformBufferArrayNonUniformIndexingNative;
    VkBool32                     shaderSampledImageArrayNonUniformIndexingNative;
    VkBool32                     shaderStorageBufferArrayNonUniformIndexingNative;
    VkBool32                     shaderStorageImageArrayNonUniformIndexingNative;
} VkPhysicalDeviceDescriptorIndexingProperties;
```
VkBool32 shaderInputAttachmentArrayNonUniformIndexingNative;
VkBool32 robustBufferAccessUpdateAfterBind;
VkBool32 quadDivergentImplicitLod;
uint32_t maxPerStageDescriptorUpdateAfterBindSamplers;
uint32_t maxPerStageDescriptorUpdateAfterBindUniformBuffers;
uint32_t maxPerStageDescriptorUpdateAfterBindStorageBuffers;
uint32_t maxPerStageDescriptorUpdateAfterBindSampledImages;
uint32_t maxPerStageDescriptorUpdateAfterBindStorageImages;
uint32_t maxPerStageDescriptorUpdateAfterBindInputAttachments;
uint32_t maxPerStageUpdateAfterBindResources;
uint32_t maxDescriptorSetUpdateAfterBindSamplers;
uint32_t maxDescriptorSetUpdateAfterBindUniformBuffers;
uint32_t maxDescriptorSetUpdateAfterBindUniformBuffersDynamic;
uint32_t maxDescriptorSetUpdateAfterBindStorageBuffers;
uint32_t maxDescriptorSetUpdateAfterBindStorageBuffersDynamic;
uint32_t maxDescriptorSetUpdateAfterBindSampledImages;
uint32_t maxDescriptorSetUpdateAfterBindStorageImages;
uint32_t maxDescriptorSetUpdateAfterBindInputAttachments;

VkPhysicalDeviceDescriptorIndexingProperties;

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.

• maxUpdateAfterBindDescriptorsInAllPools is the maximum number of descriptors (summed over all descriptor types) that can be created across all pools that are created with the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT bit set. Pool creation may fail when this limit is exceeded, or when the space this limit represents is unable to satisfy a pool creation due to fragmentation.

• shaderUniformBufferArrayNonUniformIndexingNative is a boolean value indicating whether uniform buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of uniform buffers may execute multiple times in order to access all the descriptors.

• shaderSampledImageArrayNonUniformIndexingNative is a boolean value indicating whether sampler and image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of samplers or images may execute multiple times in order to access all the descriptors.

• shaderStorageBufferArrayNonUniformIndexingNative is a boolean value indicating whether storage buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage buffers may execute multiple times in order to access all the descriptors.

• shaderStorageImageArrayNonUniformIndexingNative is a boolean value indicating whether storage image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage images may execute multiple times in order to access all the descriptors.

• shaderInputAttachmentArrayNonUniformIndexingNative is a boolean value indicating whether input attachment descriptors natively support nonuniform indexing. If this is VK_FALSE, then a
single dynamic instance of an instruction that nonuniformly indexes an array of input attachments may execute multiple times in order to access all the descriptors.

- **robustBufferAccessUpdateAfterBind** is a boolean value indicating whether robustBufferAccess can be enabled on a device simultaneously with descriptorBindingUniformBufferUpdateAfterBind, descriptorBindingStorageBufferUpdateAfterBind, descriptorBindingUniformTexelBufferUpdateAfterBind, and/or descriptorBindingStorageTexelBufferUpdateAfterBind. If this is VK_FALSE, then either robustBufferAccess must be disabled or all of these update-after-bind features must be disabled.

- **quadDivergentImplicitLod** is a boolean value indicating whether implicit LOD calculations for image operations have well-defined results when the image and/or sampler objects used for the instruction are not uniform within a quad. See Derivative Image Operations.

- **maxPerStageDescriptorUpdateAfterBindSamplers** is similar to maxPerStageDescriptorSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindUniformBuffers** is similar to maxPerStageDescriptorUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindStorageBuffers** is similar to maxPerStageDescriptorStorageBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindSampledImages** is similar to maxPerStageDescriptorSampledImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindStorageImages** is similar to maxPerStageDescriptorStorageImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindInputAttachments** is similar to maxPerStageDescriptorInputAttachments but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageUpdateAfterBindResources** is similar to maxPerStageResources but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxDescriptorSetUpdateAfterBindSamplers** is similar to maxDescriptorSetSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxDescriptorSetUpdateAfterBindUniformBuffers** is similar to maxDescriptorSetUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxDescriptorSetUpdateAfterBindUniformBuffersDynamic** is similar to maxDescriptorSetUniformBuffersDynamic but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set. While an application can allocate dynamic uniform buffer descriptors from a pool created with the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT, bindings for these descriptors...
must not be present in any descriptor set layout that includes bindings created with `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.

- `maxDescriptorSetUpdateAfterBindStorageBuffers` is similar to `maxDescriptorSetStorageBuffers` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageBuffersDynamic` is similar to `maxDescriptorSetStorageBuffersDynamic` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set. While an application can allocate dynamic storage buffer descriptors from a pool created with the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT`, bindings for these descriptors must not be present in any descriptor set layout that includes bindings created with `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.

- `maxDescriptorSetUpdateAfterBindSampledImages` is similar to `maxDescriptorSetSampledImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageImages` is similar to `maxDescriptorSetStorageImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindInputAttachments` is similar to `maxDescriptorSetInputAttachments` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

If the `VkPhysicalDeviceDescriptorIndexingProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

**Valid Usage (Implicit)**

- **VUID-VkPhysicalDeviceDescriptorIndexingProperties-sType-sType**
  
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_PROPERTIES`

The `VkPhysicalDeviceInlineUniformBlockProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceInlineUniformBlockProperties {
    VkStructureType     sType;
    void*               pNext;
    uint32_t            maxInlineUniformBlockSize;
    uint32_t            maxPerStageDescriptorInlineUniformBlocks;
    uint32_t            maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks;
    uint32_t            maxDescriptorSetInlineUniformBlocks;
    uint32_t            maxDescriptorSetUpdateAfterBindInlineUniformBlocks;
} VkPhysicalDeviceInlineUniformBlockProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
• `pNext` is NULL or a pointer to a structure extending this structure.

• `maxInlineUniformBlockSize` is the maximum size in bytes of an inline uniform block binding.

• `maxPerStageDescriptorInlineUniformBlock` is the maximum number of inline uniform block bindings that can be accessible to a single shader stage in a pipeline layout. Descriptor bindings with a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` count against this limit. Only descriptor bindings in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit.

• `maxPerStageDescriptorUpdateAfterBindInlineUniformBlocks` is similar to `maxPerStageDescriptorInlineUniformBlocks` but counts descriptor bindings from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetInlineUniformBlocks` is the maximum number of inline uniform block bindings that can be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptor bindings with a descriptor type of `VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK` count against this limit. Only descriptor bindings in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set count against this limit.

• `maxDescriptorSetUpdateAfterBindInlineUniformBlocks` is similar to `maxDescriptorSetInlineUniformBlocks` but counts descriptor bindings from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

If the `VkPhysicalDeviceInlineUniformBlockProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

Valid Usage (Implicit)

• `VUID-VkPhysicalDeviceInlineUniformBlockProperties-sType-sType`
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_PROPERTIES`

The `VkPhysicalDeviceDepthStencilResolveProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceDepthStencilResolveProperties {
    VkStructureType sType;
    void* pNext;
    VkResolveModeFlags supportedDepthResolveModes;
    VkResolveModeFlags supportedStencilResolveModes;
    VkBool32 independentResolveNone;
    VkBool32 independentResolve;
} VkPhysicalDeviceDepthStencilResolveProperties;
```

• `sType` is a `VkStructureType` value identifying this structure.

• `pNext` is NULL or a pointer to a structure extending this structure.
• `supportedDepthResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported depth resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations may support additional modes.

• `supportedStencilResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported stencil resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations may support additional modes. `VK_RESOLVE_MODE_AVERAGE_BIT` must not be included in the set.

• `independentResolveNone` is `VK_TRUE` if the implementation supports setting the depth and stencil resolve modes to different values when one of those modes is `VK_RESOLVE_MODE_NONE`. Otherwise the implementation only supports setting both modes to the same value.

• `independentResolve` is `VK_TRUE` if the implementation supports all combinations of the supported depth and stencil resolve modes, including setting either depth or stencil resolve mode to `VK_RESOLVE_MODE_NONE`. An implementation that supports `independentResolve` must also support `independentResolveNone`.

If the `VkPhysicalDeviceDepthStencilResolveProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

• VUID-VkPhysicalDeviceDepthStencilResolveProperties-sType-sType
  sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES`

The `VkPhysicalDeviceTexelBufferAlignmentProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkPhysicalDeviceTexelBufferAlignmentProperties {
    VkStructureType sType;
    void* pNext;
    VkDeviceSize storageTexelBufferOffsetAlignmentBytes;
    VkBool32 storageTexelBufferOffsetSingleTexelAlignment;
    VkDeviceSize uniformTexelBufferOffsetAlignmentBytes;
    VkBool32 uniformTexelBufferOffsetSingleTexelAlignment;
} VkPhysicalDeviceTexelBufferAlignmentProperties;
```

• `sType` is a `VkStructureType` value identifying this structure.

• `pNext` is NULL or a pointer to a structure extending this structure.

• `storageTexelBufferOffsetAlignmentBytes` is a byte alignment that is sufficient for a storage texel buffer of any format. The value must be a power of two.

• `storageTexelBufferOffsetSingleTexelAlignment` indicates whether single texel alignment is sufficient for a storage texel buffer of any format.

• `uniformTexelBufferOffsetAlignmentBytes` is a byte alignment that is sufficient for a uniform texel buffer of any format. The value must be a power of two.
• **uniformTexelBufferOffsetSingleTexelAlignment** indicates whether single texel alignment is sufficient for a uniform texel buffer of any format.

If the `VkPhysicalDeviceTexelBufferAlignmentProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

If the single texel alignment property is `VK_FALSE`, then the buffer view’s offset must be aligned to the corresponding byte alignment value. If the single texel alignment property is `VK_TRUE`, then the buffer view’s offset must be aligned to the lesser of the corresponding byte alignment value or the size of a single texel, based on `VkBufferViewCreateInfo::format`. If the size of a single texel is a multiple of three bytes, then the size of a single component of the format is used instead.

These limits must not advertise a larger alignment than the required maximum minimum value of `VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment`, for any format that supports use as a texel buffer.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceTexelBufferAlignmentProperties-sType-sType <br>  *sType* must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXEL_BUFFER_ALIGNMENT_PROPERTIES`

The `VkPhysicalDeviceTimelineSemaphoreProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_2
typedef struct VkPhysicalDeviceTimelineSemaphoreProperties {
    VkStructureType sType;
    void* pNext;
    uint64_t maxTimelineSemaphoreValueDifference;
} VkPhysicalDeviceTimelineSemaphoreProperties;
```

- **sType** is a `VkStructureType` value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **maxTimelineSemaphoreValueDifference** indicates the maximum difference allowed by the implementation between the current value of a timeline semaphore and any pending signal or wait operations.

If the `VkPhysicalDeviceTimelineSemaphoreProperties` structure is included in the `pNext` chain of the `VkPhysicalDeviceProperties2` structure passed to `vkGetPhysicalDeviceProperties2`, it is filled in with each corresponding implementation-dependent property.

### Valid Usage (Implicit)

- VUID-VkPhysicalDeviceTimelineSemaphoreProperties-sType-sType <br>  *sType* must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_PROPERTIES`
33.1. Limit Requirements

The following table specifies the required minimum/maximum for all Vulkan graphics implementations. Where a limit corresponds to a fine-grained device feature which is optional, the feature name is listed with two required limits, one when the feature is supported and one when it is not supported. If an implementation supports a feature, the limits reported are the same whether or not the feature is enabled.

Table 32. Required Limit Types

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Table 33. Required Limits

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1. The **Limit Type** column specifies the limit is either the minimum limit all implementations **must** support, the maximum limit all implementations **must** support, or the exact value all implementations **must** support. For bitmasks a minimum limit is the least bits all implementations **must** set, but they **may** have additional bits set beyond this minimum.

2. The **maxPerStageResources** **must** be at least the smallest of the following:
   - the sum of the `maxPerStageDescriptorUniformBuffers`, `maxPerStageDescriptorStorageBuffers`, `maxPerStageDescriptorSampledImages`, `maxPerStageDescriptorStorageImages`, `maxPerStageDescriptorInputAttachments`, `maxColorAttachments` limits, or
   - 128.
   It **may** not be possible to reach this limit in every stage.

3. See `maxViewportDimensions` for the **required** relationship to other limits.

4. See `viewportBoundsRange` for the **required** relationship to other limits.

5. The values `minInterpolationOffset` and `maxInterpolationOffset` describe the closed interval of supported interpolation offsets: \([\text{minInterpolationOffset}, \text{maxInterpolationOffset}]\). The ULP is determined by `subPixelInterpolationOffsetBits`. If `subPixelInterpolationOffsetBits` is 4, this provides increments of \(1/(2^4) = 0.0625\), and thus the range of supported interpolation offsets would be \([-0.5, 0.4375]\).

6. The point size ULP is determined by `pointSizeGranularity`. If the `pointSizeGranularity` is 0.125, the range of supported point sizes **must** be at least \([1.0, 63.875]\).
The line width ULP is determined by `lineWidthGranularity`. If the `lineWidthGranularity` is 0.0625, the range of supported line widths **must** be at least [1.0, 7.9375].

The minimum `maxDescriptorSet` limit is \( n \) times the corresponding specification minimum `maxPerStageDescriptor` limit, where \( n \) is the number of shader stages supported by the `VkPhysicalDevice`. If all shader stages are supported, \( n = 6 \) (vertex, tessellation control, tessellation evaluation, geometry, fragment, compute).

The `UpdateAfterBind` descriptor limits **must** each be greater than or equal to the corresponding non-`UpdateAfterBind` limit.

### 33.2. Profile Limits

#### 33.2.1. Roadmap 2022

Implementations that claim support for the **Roadmap 2022** profile **must** satisfy the following additional limit requirements:

<table>
<thead>
<tr>
<th>Limit</th>
<th>Supported Limit</th>
<th>Limit Type</th>
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</thead>
<tbody>
<tr>
<td><code>maxImageDimension1D</code></td>
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<td><code>maxImageDimension2D</code></td>
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</tr>
<tr>
<td><code>maxImageDimensionCube</code></td>
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</tr>
<tr>
<td><code>maxImageArrayLayers</code></td>
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<td>min</td>
</tr>
<tr>
<td><code>maxUniformBufferRange</code></td>
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</tr>
<tr>
<td><code>bufferImageGranularity</code></td>
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</tr>
<tr>
<td><code>maxPerStageDescriptorSamplers</code></td>
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<tr>
<td><code>maxPerStageDescriptorUniformBuffers</code></td>
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</tr>
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</tr>
<tr>
<td><code>maxPerStageDescriptorStorageImages</code></td>
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</tr>
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<tr>
<td><code>maxFragmentCombinedOutputResources</code></td>
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<td>Limit</td>
<td>Supported Limit</td>
<td>Limit Type</td>
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<td>mipmapPrecisionBits</td>
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<td>VK_SUBGROUP_FEATURE VOTE_BIT</td>
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<td>VK_SUBGROUP_FEATURE_ARITHMETIC_BIT</td>
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<tr>
<td>maxPerStageDescriptorUpdateAfterBindInputAttachments</td>
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</tr>
</tbody>
</table>
Chapter 34. Formats

Supported buffer and image formats may vary across implementations. A minimum set of format features are guaranteed, but others must be explicitly queried before use to ensure they are supported by the implementation.

The features for the set of formats (VkFormat) supported by the implementation are queried individually using the vkGetPhysicalDeviceFormatProperties command.

34.1. Format Definition

The following image formats can be passed to, and may be returned from Vulkan commands. The memory required to store each format is discussed with that format, and also summarized in the Representation and Texel Block Size section and the Compatible formats table.

```c
// Provided by VK_VERSION_1_0
typedef enum VkFormat {
    VK_FORMAT_UNDEFINED = 0,
    VK_FORMAT_R4G4_UNORM_PACK8 = 1,
    VK_FORMAT_R4G4B4A4_UNORM_PACK16 = 2,
    VK_FORMAT_B4G4R4A4_UNORM_PACK16 = 3,
    VK_FORMAT_R5G6B5_UNORM_PACK16 = 4,
    VK_FORMAT_B5G6R5_UNORM_PACK16 = 5,
    VK_FORMAT_R5G5B5A1_UNORM_PACK16 = 6,
    VK_FORMAT_B5G5R5A1_UNORM_PACK16 = 7,
    VK_FORMAT_A1R5G5B5_UNORM_PACK16 = 8,
    VK_FORMAT_R8_UNORM = 9,
    VK_FORMAT_R8_SNORM = 10,
    VK_FORMAT_R8_USCALED = 11,
    VK_FORMAT_R8_SSCALED = 12,
    VK_FORMAT_R8_UINT = 13,
    VK_FORMAT_R8_SINT = 14,
    VK_FORMAT_R8_SRGB = 15,
    VK_FORMAT_R8G8_UNORM = 16,
    VK_FORMAT_R8G8_SNORM = 17,
    VK_FORMAT_R8G8_USCALED = 18,
    VK_FORMAT_R8G8_SSCALED = 19,
    VK_FORMAT_R8G8_UINT = 20,
    VK_FORMAT_R8G8_SINT = 21,
    VK_FORMAT_R8G8_SRGB = 22,
    VK_FORMAT_R8G8B8_UNORM = 23,
    VK_FORMAT_R8G8B8_SNORM = 24,
    VK_FORMAT_R8G8B8_USCALED = 25,
    VK_FORMAT_R8G8B8_SSCALED = 26,
    VK_FORMAT_R8G8B8_UINT = 27,
    VK_FORMAT_R8G8B8_SINT = 28,
    VK_FORMAT_R8G8B8_SRGB = 29,
    VK_FORMAT_B8G8R8_UNORM = 30,
    VK_FORMAT_B8G8R8_SNORM = 31,
};
```
VK_FORMAT_B8G8R8_USCALED = 32,
VK_FORMAT_B8G8R8_SSCALED = 33,
VK_FORMAT_B8G8R8_UINT = 34,
VK_FORMAT_B8G8R8_SINT = 35,
VK_FORMAT_B8G8R8_SRGB = 36,
VK_FORMAT_R8G8B8A8_UNORM = 37,
VK_FORMAT_R8G8B8A8_SNORM = 38,
VK_FORMAT_R8G8B8A8_USCALED = 39,
VK_FORMAT_R8G8B8A8_SSCALED = 40,
VK_FORMAT_R8G8B8A8_UINT = 41,
VK_FORMAT_R8G8B8A8_SINT = 42,
VK_FORMAT_R8G8B8A8_SRGB = 43,
VK_FORMAT_A8B8G8R8_UNORM_PACK32 = 51,
VK_FORMAT_A8B8G8R8_SNORM_PACK32 = 52,
VK_FORMAT_A8B8G8R8_USCALED_PACK32 = 53,
VK_FORMAT_A8B8G8R8_SSCALED_PACK32 = 54,
VK_FORMAT_A8B8G8R8_UINT_PACK32 = 55,
VK_FORMAT_A8B8G8R8_SINT_PACK32 = 56,
VK_FORMAT_A8B8G8R8_SRGB_PACK32 = 57,
VK_FORMAT_A2R10G10B10_UNORM_PACK32 = 58,
VK_FORMAT_A2R10G10B10_SNORM_PACK32 = 59,
VK_FORMAT_A2R10G10B10_USCALED_PACK32 = 60,
VK_FORMAT_A2R10G10B10_SSCALEDPACK32 = 61,
VK_FORMAT_A2R10G10B10_UINT_PACK32 = 62,
VK_FORMAT_A2R10G10B10_SINTPACK32 = 63,
VK_FORMAT_A2B10G10R10_UNORM_PACK32 = 64,
VK_FORMAT_A2B10G10R10_SNORM_PACK32 = 65,
VK_FORMAT_A2B10G10R10_USCALED_PACK32 = 66,
VK_FORMAT_A2B10G10R10_SSCALED_PACK32 = 67,
VK_FORMAT_A2B10G10R10_UINT_PACK32 = 68,
VK_FORMAT_A2B10G10R10_SINT_PACK32 = 69,
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VK_FORMAT_R16_SNORM = 71,
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VK_FORMAT_R16_SSCALED = 73,
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VK_FORMAT_R16_SINT = 75,
VK_FORMAT_R16_SFLOAT = 76,
VK_FORMAT_R16G16_UNORM = 77,
VK_FORMAT_R16G16_SNORM = 78,
VK_FORMAT_R16G16_USCALED = 79,
VK_FORMAT_R16G16_SSCALED = 80,
VK_FORMAT_R16G16_UINT = 81,
VK_FORMAT_R16G16_SINT = 82,
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VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16 = 1000156011,
VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16 = 1000156012,
VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16 = 1000156013,
VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16 = 1000156014,
VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16 = 1000156015,
VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16 = 1000156016,
VK_FORMAT_R12X4_UNORM_PACK16 = 1000156017,
VK_FORMAT_R12X4G12X4_UNORM_2PACK16 = 1000156018,
VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16 = 1000156019,
VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16 = 1000156020,
VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16 = 1000156021,
VK_FORMAT_G12X4_B12X4_R12X4_2PLANE_422_UNORM_3PACK16 = 1000156025,
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VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16 = 1000156026,
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VK_FORMAT_G16B16G16R16_422_UNORM = 1000156027,
// Provided by VK_VERSION_1_1
VK_FORMAT_B16G16R16_2PLANE_420_UNORM = 1000156028,
// Provided by VK_VERSION_1_1
VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM = 1000156029,
// Provided by VK_VERSION_1_1
VK_FORMAT_G16_B16R16_2PLANE_420_UNORM = 1000156030,
// Provided by VK_VERSION_1_1
VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM = 1000156031,
// Provided by VK_VERSION_1_1
VK_FORMAT_G16_B16R16_2PLANE_422_UNORM = 1000156032,
// Provided by VK_VERSION_1_1
VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM = 1000156033,
// Provided by VK_VERSION_1_1
VK_FORMAT_G8_B8R8_2PLANE_444_UNORM = 1000330000,
// Provided by VK_VERSION_1_3
VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16 = 1000330001,
// Provided by VK_VERSION_1_3
VK_FORMAT_G12X4_B12X4R12X4_2PLANE_444_UNORM_3PACK16 = 1000330002,
// Provided by VK_VERSION_1_3
VK_FORMAT_G16_B16R16_2PLANE_444_UNORM = 1000330003,
// Provided by VK_VERSION_1_3
VK_FORMAT_A4R4G4B4_UNORM_PACK16 = 1000340000,
// Provided by VK_VERSION_1_3
VK_FORMAT_A4B4G4R4_UNORM_PACK16 = 1000340001,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK = 1000066000,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK = 1000066001,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK = 1000066002,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK = 1000066003,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK = 1000066004,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK = 1000066005,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK = 1000066006,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK = 1000066007,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK = 1000066008,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK = 1000066009,
// Provided by VK_VERSION_1_3
VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK = 1000066010,
VK_FORMAT_UNDEFINED specifies that the format is not specified.

VK_FORMAT_R4G4_UNORM_PACK8 specifies a two-component, 8-bit packed unsigned normalized format that has a 4-bit R component in bits 4..7, and a 4-bit G component in bits 0..3.

VK_FORMAT_R4G4B4A4_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit R component in bits 12..15, a 4-bit G component in bits 8..11, a 4-bit B component in bits 4..7, and a 4-bit A component in bits 0..3.

VK_FORMAT_B4G4R4A4_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit B component in bits 12..15, a 4-bit G component in bits 8..11, a 4-bit R component in bits 4..7, and a 4-bit A component in bits 0..3.

VK_FORMAT_A4R4G4B4_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit A component in bits 12..15, a 4-bit R component in bits 8..11, a 4-bit G component in bits 4..7, and a 4-bit B component in bits 0..3.

VK_FORMAT_A4B4G4R4_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit A component in bits 12..15, a 4-bit B component in bits 8..11, a 4-bit G component in bits 4..7, and a 4-bit R component in bits 0..3.

VK_FORMAT_R5G5B5A1_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 5-bit R component in bits 11..15, a 5-bit G component in bits 6..10, a 5-bit B component in bits 1..5, and a 1-bit A component in bit 0.

VK_FORMAT_B5G5R5A1_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 5-bit B component in bits 11..15, a 5-bit G component in bits 6..10, a 5-bit R component in bits 1..5, and a 1-bit A component in bit 0.

VK_FORMAT_A1R5G5B5_UNORM_PACK16 specifies a four-component, 16-bit packed unsigned normalized format that has a 1-bit A component in bit 15, a 5-bit R component in bits 10..14, a 5-bit G component in bits 5..9, and a 5-bit B component in bits 0..4.

VK_FORMAT_R8_UNORM specifies a one-component, 8-bit unsigned normalized format that has a single 8-bit R component.

VK_FORMAT_R8_SNORM specifies a one-component, 8-bit signed normalized format that has a single 8-bit R component.

VK_FORMAT_R8_USCALED specifies a one-component, 8-bit unsigned scaled integer format that has a
single 8-bit R component.

- **VK_FORMAT_R8_SSCALED** specifies a one-component, 8-bit signed scaled integer format that has a single 8-bit R component.
- **VK_FORMAT_R8_UINT** specifies a one-component, 8-bit unsigned integer format that has a single 8-bit R component.
- **VK_FORMAT_R8_SINT** specifies a one-component, 8-bit signed integer format that has a single 8-bit R component.
- **VK_FORMAT_R8_SR8** specifies a one-component, 8-bit unsigned normalized format that has a single 8-bit R component stored with sRGB nonlinear encoding.
- **VK_FORMAT_R8G8_UNORM** specifies a two-component, 16-bit unsigned normalized format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_SNORM** specifies a two-component, 16-bit signed normalized format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_USCALED** specifies a two-component, 16-bit unsigned scaled integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_SSCALED** specifies a two-component, 16-bit signed scaled integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_UINT** specifies a two-component, 16-bit unsigned integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_SINT** specifies a two-component, 16-bit signed integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
- **VK_FORMAT_R8G8_SRGB** specifies a two-component, 16-bit unsigned normalized format that has an 8-bit R component stored with sRGB nonlinear encoding in byte 0, and an 8-bit G component stored with sRGB nonlinear encoding in byte 1.
- **VK_FORMAT_R8G8B8_UNORM** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_SNORM** specifies a three-component, 24-bit signed normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_USCALED** specifies a three-component, 24-bit unsigned scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_SSCALED** specifies a three-component, 24-bit signed scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_UINT** specifies a three-component, 24-bit unsigned integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_SINT** specifies a three-component, 24-bit signed integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.
- **VK_FORMAT_R8G8B8_SRGB** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit R component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, and an 8-bit B component stored with sRGB nonlinear encoding in byte 2.
nonlinear encoding in byte 2.

- **VK_FORMAT_B8G8R8_UNORM** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SNORM** specifies a three-component, 24-bit signed normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_USCALED** specifies a three-component, 24-bit unsigned scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SSCALED** specifies a three-component, 24-bit signed scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_UINT** specifies a three-component, 24-bit unsigned integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SINT** specifies a three-component, 24-bit signed integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SRGB** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit B component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, and an 8-bit R component stored with sRGB nonlinear encoding in byte 2.

- **VK_FORMAT_R8G8B8A8_UNORM** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_SNORM** specifies a four-component, 32-bit signed normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_USCALED** specifies a four-component, 32-bit unsigned scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_SSCALED** specifies a four-component, 32-bit signed scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_UINT** specifies a four-component, 32-bit unsigned integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_SINT** specifies a four-component, 32-bit signed integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_SRGB** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit R component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, an 8-bit B component stored with sRGB nonlinear encoding in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_UNORM** specifies a four-component, 32-bit unsigned normalized format that
has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_SNORM** specifies a four-component, 32-bit signed normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_USCALED** specifies a four-component, 32-bit unsigned scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_SSCALED** specifies a four-component, 32-bit signed scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_UINT** specifies a four-component, 32-bit unsigned integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_SINT** specifies a four-component, 32-bit signed integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_B8G8R8A8_SRGB** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit B component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, an 8-bit R component stored with sRGB nonlinear encoding in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_A8B8G8R8_UNORM_PACK32** specifies a four-component, 32-bit packed unsigned normalized format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_SNORM_PACK32** specifies a four-component, 32-bit packed signed normalized format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_USCALED_PACK32** specifies a four-component, 32-bit packed unsigned scaled integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_SSCALED_PACK32** specifies a four-component, 32-bit packed signed scaled integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_UINT_PACK32** specifies a four-component, 32-bit packed unsigned integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_SINT_PACK32** specifies a four-component, 32-bit packed signed integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

- **VK_FORMAT_A8B8G8R8_SRGB_PACK32** specifies a four-component, 32-bit packed unsigned normalized format that has an 8-bit A component in bits 24..31, an 8-bit B component stored with sRGB nonlinear encoding in bits 16..23, an 8-bit G component stored with sRGB nonlinear encoding in bits 8..15, and an 8-bit R component stored with sRGB nonlinear encoding in bits 0..7.
VK_FORMAT_A2R10G10B10_UNORM_PACK32 specifies a four-component, 32-bit packed unsigned normalized format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_A2R10G10B10_SNORM_PACK32 specifies a four-component, 32-bit packed signed normalized format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_A2R10G10B10_USCALED_PACK32 specifies a four-component, 32-bit packed unsigned scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_A2R10G10B10_SSCALED_PACK32 specifies a four-component, 32-bit packed signed scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_A2R10G10B10_UINT_PACK32 specifies a four-component, 32-bit packed unsigned integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_A2R10G10B10_SINT_PACK32 specifies a four-component, 32-bit packed signed integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

VK_FORMAT_R16_UNORM specifies a one-component, 16-bit unsigned normalized format that has a single 16-bit R component.

VK_FORMAT_R16_SNORM specifies a one-component, 16-bit signed normalized format that has a single 16-bit R component.

VK_FORMAT_R16_USCALED specifies a one-component, 16-bit unsigned scaled integer format that has a single 16-bit R component.
• **VK_FORMAT_R16_SSCALED** specifies a one-component, 16-bit signed scaled integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_UINT** specifies a one-component, 16-bit unsigned integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_SINT** specifies a one-component, 16-bit signed integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_SFLOAT** specifies a one-component, 16-bit signed floating-point format that has a single 16-bit R component.

• **VK_FORMAT_R16G16_UNORM** specifies a two-component, 32-bit unsigned normalized format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SNORM** specifies a two-component, 32-bit signed normalized format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_USCALED** specifies a two-component, 32-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SSCALED** specifies a two-component, 32-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_UINT** specifies a two-component, 32-bit unsigned integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SINT** specifies a two-component, 32-bit signed integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SFLOAT** specifies a two-component, 32-bit signed floating-point format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16B16_UNORM** specifies a three-component, 48-bit unsigned normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_SNORM** specifies a three-component, 48-bit signed normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_USCALED** specifies a three-component, 48-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_SSCALED** specifies a three-component, 48-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_UINT** specifies a three-component, 48-bit unsigned integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_SINT** specifies a three-component, 48-bit signed integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

• **VK_FORMAT_R16G16B16_SFLOAT** specifies a three-component, 48-bit signed floating-point format that
• **VK_FORMAT_R16G16B16A16_UNORM** specifies a four-component, 64-bit unsigned normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_SNORM** specifies a four-component, 64-bit signed normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_USCALED** specifies a four-component, 64-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_SSCALED** specifies a four-component, 64-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_UINT** specifies a four-component, 64-bit unsigned integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_SINT** specifies a four-component, 64-bit signed integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R16G16B16A16_SFLOAT** specifies a four-component, 64-bit signed floating-point format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

• **VK_FORMAT_R32_UINT** specifies a one-component, 32-bit unsigned integer format that has a single 32-bit R component.

• **VK_FORMAT_R32_SINT** specifies a one-component, 32-bit signed integer format that has a single 32-bit R component.

• **VK_FORMAT_R32_SFLOAT** specifies a one-component, 32-bit signed floating-point format that has a single 32-bit R component.

• **VK_FORMAT_R32G32_UINT** specifies a two-component, 64-bit unsigned integer format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.

• **VK_FORMAT_R32G32_SINT** specifies a two-component, 64-bit signed integer format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.

• **VK_FORMAT_R32G32_SFLOAT** specifies a two-component, 64-bit signed floating-point format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.

• **VK_FORMAT_R32G32B32_UINT** specifies a three-component, 96-bit unsigned integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.

• **VK_FORMAT_R32G32B32_SINT** specifies a three-component, 96-bit signed integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.
• **VK_FORMAT_R32G32B32_SFLOAT** specifies a three-component, 96-bit signed floating-point format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.

• **VK_FORMAT_R32G32B32A32_UINT** specifies a four-component, 128-bit unsigned integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.

• **VK_FORMAT_R32G32B32A32_SINT** specifies a four-component, 128-bit signed integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.

• **VK_FORMAT_R32G32B32A32_SFLOAT** specifies a four-component, 128-bit signed floating-point format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.

• **VK_FORMAT_R64_UINT** specifies a one-component, 64-bit unsigned integer format that has a single 64-bit R component.

• **VK_FORMAT_R64_SINT** specifies a one-component, 64-bit signed integer format that has a single 64-bit R component.

• **VK_FORMAT_R64_SFLOAT** specifies a one-component, 64-bit signed floating-point format that has a single 64-bit R component.

• **VK_FORMAT_R64G64_UINT** specifies a two-component, 128-bit unsigned integer format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.

• **VK_FORMAT_R64G64_SINT** specifies a two-component, 128-bit signed integer format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.

• **VK_FORMAT_R64G64_SFLOAT** specifies a two-component, 128-bit signed floating-point format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.

• **VK_FORMAT_R64G64B64_UINT** specifies a three-component, 192-bit unsigned integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64_SINT** specifies a three-component, 192-bit signed integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64_SFLOAT** specifies a three-component, 192-bit signed floating-point format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64A64_UINT** specifies a four-component, 256-bit unsigned integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.

• **VK_FORMAT_R64G64B64A64_SINT** specifies a four-component, 256-bit signed integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.

• **VK_FORMAT_R64G64B64A64_SFLOAT** specifies a four-component, 256-bit signed floating-point format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.
VK_FORMAT_B10G11R11_UFLOAT_PACK32 specifies a three-component, 32-bit packed unsigned floating-point format that has a 10-bit B component in bits 22..31, an 11-bit G component in bits 11..21, and an 11-bit R component in bits 0..10. See Unsigned 10-Bit Floating-Point Numbers and Unsigned 11-Bit Floating-Point Numbers.

VK_FORMAT_E5B9G9R9_UFLOAT_PACK32 specifies a three-component, 32-bit packed unsigned floating-point format that has a 5-bit shared exponent in bits 27..31, a 9-bit B component mantissa in bits 18..26, a 9-bit G component mantissa in bits 9..17, and a 9-bit R component mantissa in bits 0..8.

VK_FORMAT_D16_UNORM specifies a one-component, 16-bit unsigned normalized format that has a single 16-bit depth component.

VK_FORMAT_X8_D24_UNORM_PACK32 specifies a two-component, 32-bit format that has 24 unsigned normalized bits in the depth component and, optionally, 8 bits that are unused.

VK_FORMAT_D32_SFLOAT specifies a one-component, 32-bit signed floating-point format that has 32 bits in the depth component.

VK_FORMAT_S8_UINT specifies a one-component, 8-bit unsigned integer format that has 8 bits in the stencil component.

VK_FORMAT_D16_UNORM_S8_UINT specifies a two-component, 24-bit format that has 16 unsigned normalized bits in the depth component and 8 unsigned integer bits in the stencil component.

VK_FORMAT_D24_UNORM_S8_UINT specifies a two-component, 32-bit packed format that has 8 unsigned integer bits in the stencil component, and 24 unsigned normalized bits in the depth component.

VK_FORMAT_D32_SFLOAT_S8_UINT specifies a two-component format that has 32 signed float bits in the depth component and 8 unsigned integer bits in the stencil component. There are optionally 24 bits that are unused.

VK_FORMAT_BC1_RGB_UNORM_BLOCK specifies a three-component, block-compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

VK_FORMAT_BC1_RGB_SRGB_BLOCK specifies a three-component, block-compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding. This format has no alpha and is considered opaque.

VK_FORMAT_BC1_RGBA_UNORM_BLOCK specifies a four-component, block-compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

VK_FORMAT_BC1_RGBA_SRGB_BLOCK specifies a four-component, block-compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.

VK_FORMAT_BC2_UNORM_BLOCK specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

VK_FORMAT_BC2_SRGB_BLOCK specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values with sRGB nonlinear encoding.
• **VK_FORMAT_BC3_UNORM_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

• **VK_FORMAT_BC3_SRGB_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding.

• **VK_FORMAT_BC4_UNORM_BLOCK** specifies a one-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized red texel data.

• **VK_FORMAT_BC4_SNORM_BLOCK** specifies a one-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of signed normalized red texel data.

• **VK_FORMAT_BC5_UNORM_BLOCK** specifies a two-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

• **VK_FORMAT_BC5_SNORM_BLOCK** specifies a two-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of signed normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

• **VK_FORMAT_BC6H_UFLOAT_BLOCK** specifies a three-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned floating-point RGB texel data.

• **VK_FORMAT_BC6H_SFLOAT_BLOCK** specifies a three-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of signed floating-point RGB texel data.

• **VK_FORMAT_BC7_UNORM_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_BC7_SRGB_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK** specifies a three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

• **VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK** specifies a three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding. This format has no alpha and is considered opaque.

• **VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK** specifies a four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

• **VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK** specifies a four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.

• **VK_FORMAT_ETC2_R8G8B8B8_UNORM_BLOCK** specifies a four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.
RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

- **VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK** specifies a four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values with sRGB nonlinear encoding applied.

- **VK_FORMAT_EAC_R11_UNORM_BLOCK** specifies a one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized red texel data.

- **VK_FORMAT_EAC_R11_SNORM_BLOCK** specifies a one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of signed normalized red texel data.

- **VK_FORMAT_EAC_R11G11_UNORM_BLOCK** specifies a two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

- **VK_FORMAT_EAC_R11G11_SNORM_BLOCK** specifies a two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of signed normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

- **VK_FORMAT_ASTC_4x4_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data.

- **VK_FORMAT_ASTC_4x4_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

- **VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of signed floating-point RGBA texel data.

- **VK_FORMAT_ASTC_5x4_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×4 rectangle of unsigned normalized RGBA texel data.

- **VK_FORMAT_ASTC_5x4_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

- **VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×4 rectangle of signed floating-point RGBA texel data.

- **VK_FORMAT_ASTC_5x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×5 rectangle of unsigned normalized RGBA texel data.

- **VK_FORMAT_ASTC_5x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

- **VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×5 rectangle of signed floating-point RGBA texel data.
• **VK_FORMAT_ASTC_6x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_6x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×5 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_6x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_6x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×6 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_8x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×5 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_8x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×6 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_8x8_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×8 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x8_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×8 rectangle of unsigned normalized RGBA texel data.
• **VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×8 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_10x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×5 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_10x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×6 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_10x8_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×8 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x8_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×8 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×8 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_10x10_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×10 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x10_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×10 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_12x10_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.
• **VK_FORMAT_ASTC_12x10_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×10 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_ASTC_12x12_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×12 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_12x12_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×12 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×12 rectangle of signed floating-point RGBA texel data.

• **VK_FORMAT_G8B8G8R8_422_UNORM** specifies a four-component, 32-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has an 8-bit G component for the even i coordinate in byte 0, an 8-bit B component in byte 1, an 8-bit G component for the odd i coordinate in byte 2, and an 8-bit R component in byte 3. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

• **VK_FORMAT_B8G8R8G8_422_UNORM** specifies a four-component, 32-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has an 8-bit B component in byte 0, an 8-bit G component for the even i coordinate in byte 1, an 8-bit R component in byte 2, and an 8-bit G component for the odd i coordinate in byte 3. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

• **VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, an 8-bit B component in plane 1, and an 8-bit R component in plane 2. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \[i_G \times 0.5] = i_B = i_R \text{ and } \lfloor j_G \times 0.5 \rfloor = j_B = j_R.\] The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. This format only supports images with a width and height that is a multiple of two.

• **VK_FORMAT_G8_B8R8_2PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that
has an 8-bit G component in plane 0, and a two-component, 16-bit BR plane 1 consisting of an 8-bit B component in byte 0 and an 8-bit R component in byte 1. The horizontal and vertical dimensions of the BR plane are halved relative to the image dimensions, and each R and B value is shared with the G components for which \(|i_G \times 0.5| = i_B = i_R\) and \(|j_G \times 0.5| = j_B = j_R\). The location of each plane when this image is in linear layout can be determined via \(vkGetImageSubresourceLayout\), using \(VK_IMAGE_ASPECT_PLANE_0_BIT\) for the G plane, and \(VK_IMAGE_ASPECT_PLANE_1_BIT\) for the BR plane. This format only supports images with a width and height that is a multiple of two.

- **VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, an 8-bit B component in plane 1, and an 8-bit R component in plane 2. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \(|i_G \times 0.5| = i_B = i_R\). The location of each plane when this image is in linear layout can be determined via \(vkGetImageSubresourceLayout\), using \(VK_IMAGE_ASPECT_PLANE_0_BIT\) for the G plane, \(VK_IMAGE_ASPECT_PLANE_1_BIT\) for the B plane, and \(VK_IMAGE_ASPECT_PLANE_2_BIT\) for the R plane. This format only supports images with a width that is a multiple of two.

- **VK_FORMAT_G8_B8R8_2PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, and a two-component, 16-bit BR plane 1 consisting of an 8-bit B component in byte 0 and an 8-bit R component in byte 1. The horizontal dimension of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \(|i_G \times 0.5| = i_B = i_R\). The location of each plane when this image is in linear layout can be determined via \(vkGetImageSubresourceLayout\), using \(VK_IMAGE_ASPECT_PLANE_0_BIT\) for the G plane, and \(VK_IMAGE_ASPECT_PLANE_1_BIT\) for the BR plane. This format only supports images with a width that is a multiple of two.

- **VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM** specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, an 8-bit B component in plane 1, and an 8-bit R component in plane 2. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via \(vkGetImageSubresourceLayout\), using \(VK_IMAGE_ASPECT_PLANE_0_BIT\) for the G plane, \(VK_IMAGE_ASPECT_PLANE_1_BIT\) for the B plane, and \(VK_IMAGE_ASPECT_PLANE_2_BIT\) for the R plane.

- **VK_FORMAT_R10X6_UNORM_PACK16** specifies a one-component, 16-bit unsigned normalized format that has a single 10-bit R component in the top 10 bits of a 16-bit word, with the bottom 6 bits unused.

- **VK_FORMAT_R10X6G10X6_UNORM_2PACK16** specifies a two-component, 32-bit unsigned normalized format that has a 10-bit R component in the top 10 bits of the word in bytes 0..1, and a 10-bit G component in the top 10 bits of the word in bytes 2..3, with the bottom 6 bits of each word unused.

- **VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16** specifies a four-component, 64-bit unsigned normalized format that has a 10-bit R component in the top 10 bits of the word in bytes 0..1, a 10-bit G component in the top 10 bits of the word in bytes 2..3, a 10-bit B component in the top 10 bits of the word in bytes 4..5, and a 10-bit A component in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused.

- **VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i
coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 10-bit G component for the even \( i \) coordinate in the top 10 bits of the word in bytes 0..1, a 10-bit B component in the top 10 bits of the word in bytes 2..3, a 10-bit G component for the odd \( i \) coordinate in the top 10 bits of the word in bytes 4..5, and a 10-bit R component in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 10-bit B component in the top 10 bits of the word in bytes 0..1, a 10-bit G component for the even \( i \) coordinate in the top 10 bits of the word in bytes 2..3, a 10-bit R component in the top 10 bits of the word in bytes 4..5, and a 10-bit G component for the odd \( i \) coordinate in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, a 10-bit B component in the top 10 bits of each 16-bit word of plane 1, and a 10-bit R component in the top 10 bits of each 16-bit word of plane 2, with the bottom 6 bits of each word unused. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \) and \( |j_G \times 0.5| = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the B plane, and \( \text{VK_IMAGE_ASPECT_PLANE_2_BIT} \) for the R plane. This format only supports images with a width and height that is a multiple of two.

- **VK_FORMAT_G10X6_B10X6_R10X6_2PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, with the bottom 6 bits of each word unused. The horizontal and vertical dimensions of the BR plane are halved relative to the image dimensions, and each R and B value is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \) and \( |j_G \times 0.5| = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, and \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the BR plane. This format only supports images with a width and height that is a multiple of two.

- **VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, a 10-bit B component in the top 10 bits of each 16-bit word of plane 1, and a 10-bit R component in the top 10 bits of each 16-bit word of plane 2, with the bottom 6 bits of each word unused. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \). The location of each
plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. This format only supports images with a width that is a multiple of two.

- `VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16` specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, with the bottom 6 bits of each word unused. The horizontal dimension of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $i_G \times 0.5 = i_B = i_R$. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. This format only supports images with a width that is a multiple of two.

- `VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16` specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, a 10-bit B component in the top 10 bits of each 16-bit word of plane 1, and a 10-bit R component in the top 10 bits of each 16-bit word of plane 2, with the bottom 6 bits of each word unused. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane.

- `VK_FORMAT_R12X4_UNORM_PACK16` specifies a one-component, 16-bit unsigned normalized format that has a single 12-bit R component in the top 12 bits of a 16-bit word, with the bottom 4 bits unused.

- `VK_FORMAT_R12X4G12X4_UNORM_2PACK16` specifies a two-component, 32-bit unsigned normalized format that has a 12-bit R component in the top 12 bits of the word in bytes 0..1, and a 12-bit G component in the top 12 bits of the word in bytes 2..3, with the bottom 4 bits of each word unused.

- `VK_FORMAT_R12X4G12X4B12X4_422_UNORM_4PACK16` specifies a four-component, 64-bit unsigned normalized format that has a 12-bit R component in the top 12 bits of the word in bytes 0..1, a 12-bit G component in the top 12 bits of the word in bytes 2..3, a 12-bit B component in the top 12 bits of the word in bytes 4..5, and a 12-bit A component in the top 12 bits of the word in bytes 6..7, with the bottom 4 bits of each word unused. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.
• **VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 12-bit B component in the top 12 bits of the word in bytes 0..1, a 12-bit G component for the even \( i \) coordinate in the top 12 bits of the word in bytes 2..3, a 12-bit R component in the top 12 bits of the word in bytes 4..5, and a 12-bit G component for the odd \( i \) coordinate in the top 12 bits of the word in bytes 6..7, with the bottom 4 bits of each word unused. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

• **VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \) and \( |j_G \times 0.5| = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. This format only supports images with a width and height that is a multiple of two.

• **VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 12-bit B component in the top 12 bits of the word in bytes 0..1, and a 12-bit R component in the top 12 bits of the word in bytes 2..3, with the bottom 4 bits of each word unused. The horizontal and vertical dimensions of the BR plane are halved relative to the image dimensions, and each R and B value is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \) and \( |j_G \times 0.5| = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. This format only supports images with a width and height that is a multiple of two.

• **VK_FORMAT_G12X4_B12X4R12X4_3PLANE_422_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. This format only supports images with a width that is a multiple of two.

• **VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 12-bit B component in the top 12 bits of the word in bytes 0..1, and a 12-bit R component in the top 12 bits of the word in bytes 2..3, with
the bottom 4 bits of each word unused. The horizontal dimension of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, and \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the BR plane. This format only supports images with a width that is a multiple of two.

- **VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the B plane, and \( \text{VK_IMAGE_ASPECT_PLANE_2_BIT} \) for the R plane.

- **VK_FORMAT_G16B16G16R16_422_UNORM** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 16-bit G component for the even \( i \) coordinate in the word in bytes 0..1, a 16-bit B component in the word in bytes 2..3, a 16-bit G component for the odd \( i \) coordinate in the word in bytes 4..5, and a 16-bit R component in the word in bytes 6..7. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_B16G16R16G16_422_UNORM** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 16-bit B component in the word in bytes 0..1, a 16-bit G component for the even \( i \) coordinate in the word in bytes 2..3, a 16-bit R component in the word in bytes 4..5, and a 16-bit G component for the odd \( i \) coordinate in the word in bytes 6..7. This format only supports images with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \( |i_G \times 0.5| = i_B = i_R \) and \( |j_G \times 0.5| = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the B plane, and \( \text{VK_IMAGE_ASPECT_PLANE_2_BIT} \) for the R plane. This format only supports images with a width and height that is a multiple of two.

- **VK_FORMAT_G16_B16R16_2PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 16-bit B component in the word in bytes 0..1, and a 16-bit R component in the word in bytes 2..3. The horizontal and vertical dimensions of the BR plane are halved relative to the image dimensions, and each R and B value is shared with the G components for
which $i_G \times 0.5 = i_R$ and $j_G \times 0.5 = j_R$. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. This format only supports images with a width and height that is a multiple of two.

- **VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $i_G \times 0.5 = i_R$. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. This format only supports images with a width that is a multiple of two.

- **VK_FORMAT_G16_B16R16_2PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 16-bit B component in the word in bytes 0..1, and a 16-bit R component in the word in bytes 2..3. The horizontal dimension of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $i_G \times 0.5 = i_R$. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. This format only supports images with a width that is a multiple of two.

- **VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane.

- **VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, the bottom 6 bits of each word unused. Both planes have the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane.

- **VK_FORMAT_G12X4_B12X4R12X4_2PLANE_444_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, the bottom 6 bits of each word unused. Both planes have the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane.
planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 12-bit B component in the top 12 bits of the word in bytes 0..1, and a 12-bit R component in the top 12 bits of the word in bytes 2..3, the bottom 4 bits of each word unused. Both planes have the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane.

- `VK_FORMAT_G16_B16R16_2PLANE_444_UNORM` specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 16-bit B component in the word in bytes 0..1, and a 16-bit R component in the word in bytes 2..3. Both planes have the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane.

### 34.1.1. Compatible formats of planes of multi-planar formats

Individual planes of multi-planar formats are size-compatible with single-plane color formats if they occupy the same number of bits per texel block, and are compatible with those formats if they have the same block extent.

In the following table, individual planes of a multi-planar format are compatible with the format listed against the relevant plane index for that multi-planar format, and any format compatible with the listed single-plane format according to Format Compatibility Classes. These planes are also size-compatible with any format that is size-compatible with the listed single-plane format.

<table>
<thead>
<tr>
<th>Plane</th>
<th>Compatible format for plane</th>
<th>Width relative to the width w of the plane with the largest dimensions</th>
<th>Height relative to the height h of the plane with the largest dimensions</th>
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<td>Plane</td>
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<td>$h/2$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>$w$</td>
<td>$h$</td>
</tr>
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<td>VK_FORMAT_R12X4_G12X4_R12X4_3PLANE_422_UNORM_3PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td>Plane</td>
<td>Compatible format for plane</td>
<td>Width relative to the width $w$ of the plane with the largest dimensions</td>
<td>Height relative to the height $h$ of the plane with the largest dimensions</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>0</td>
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<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</td>
<td></td>
<td></td>
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<td>$w$</td>
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</tr>
<tr>
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<td>$w/2$</td>
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<tr>
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<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16</td>
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</tr>
<tr>
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<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
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<td>$h$</td>
</tr>
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<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
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<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
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<td>$w/2$</td>
<td>$h/2$</td>
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<tr>
<td>2</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
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<td></td>
<td>VK_FORMAT_G16_B16R16_2PLANE_420_UNORM</td>
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<td>$h$</td>
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<tr>
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<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
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<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
<td></td>
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<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R16G16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
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<tr>
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<td>VK_FORMAT_G8_B8R8_2PLANE_444_UNORM</td>
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<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane</td>
<td>Compatible format for plane</td>
<td>Width relative to the width $w$ of the plane with the largest dimensions</td>
<td>Height relative to the height $h$ of the plane with the largest dimensions</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
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<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
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<tr>
<td>1</td>
<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_444_UNORM_3PACK16</td>
<td>$w$</td>
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<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
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<td>$h$</td>
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<tr>
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<td>VK_FORMAT_R12X4G12X4_UNORM_2PACK16</td>
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<td>$h$</td>
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<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16G16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
</tbody>
</table>

34.1.2. Multi-planar format image aspect

When using `VkImageAspectFlagBits` to select a plane of a multi-planar format, the following are the valid options:

- Two planes
  - VK_IMAGE_ASPECT_PLANE_0_BIT
  - VK_IMAGE_ASPECT_PLANE_1_BIT
- Three planes
  - VK_IMAGE_ASPECT_PLANE_0_BIT
  - VK_IMAGE_ASPECT_PLANE_1_BIT
  - VK_IMAGE_ASPECT_PLANE_2_BIT

34.1.3. Packed Formats

For the purposes of address alignment when accessing buffer memory containing vertex attribute or texel data, the following formats are considered *packed* - components of the texels or attributes are stored in bitfields packed into one or more 8-, 16-, or 32-bit fundamental data type.

- Packed into 8-bit data types:
  - VK_FORMAT_R4G4_UNORM_PACK8
- Packed into 16-bit data types:
  - VK_FORMAT_R4G4B4A4_UNORM_PACK16
  - VK_FORMAT_B4G4R4A4_UNORM_PACK16
  - VK_FORMAT_R5G6B5_UNORM_PACK16
  - VK_FORMAT_B5G6R5_UNORMPACK16
  - VK_FORMAT_R5G5B5A1_UNORM_PACK16
  - VK_FORMAT_R5G5B5A1_UNORM_PACK16
- VK_FORMAT_B5G5R5A1_UNORM_PACK16
- VK_FORMAT_A1R5G5B5_UNORM_PACK16
- VK_FORMAT_R10X6_UNORM_PACK16
- VK_FORMAT_R10X6G10X6_UNORM_2PACK16
- VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16
- VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16
- VK_FORMAT_G10X6B10X6G10X6R10X6_3PLANE_420_UNORM_3PACK16
- VK_FORMAT_G10X6B10X6G10X6R10X6_2PLANE_420_UNORM_3PACK16
- VK_FORMAT_G10X6B10X6G10X6R10X6_3PLANE_422_UNORM_3PACK16
- VK_FORMAT_G10X6B10X6G10X6R10X6_2PLANE_422_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_3PLANE_420_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16
- VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16
- VK_FORMAT_A4R4G4B4_UNORM_PACK16
- VK_FORMAT_A4B4G4R4_UNORM_PACK16

- Packed into 32-bit data types:
  - VK_FORMAT_A8B8G8R8_UNORM_PACK32
  - VK_FORMAT_A8B8G8R8_SNORM_PACK32
  - VK_FORMAT_A8B8G8R8_USCALED_PACK32
  - VK_FORMAT_A8B8G8R8_SSCALED_PACK32
  - VK_FORMAT_A8B8G8R8_UINT_PACK32
  - VK_FORMAT_A8B8G8R8_SINT_PACK32
  - VK_FORMAT_A8B8G8R8_SRGB_PACK32
  - VK_FORMAT_A2R10G10B10_UNORM_PACK32

- VK_FORMAT_A8B8G8R8_SNORM_PACK32
- VK_FORMAT_A8B8G8R8_USCALED_PACK32
- VK_FORMAT_A8B8G8R8_SSCALED_PACK32
- VK_FORMAT_A8B8G8R8_UINT PACK32
- VK_FORMAT_A8B8G8R8_SINT_PACK32
- VK_FORMAT_A8B8G8R8_SRGB_PACK32
- VK_FORMAT_A2R10G10B10_UNORM PACK32
34.1.4. Identification of Formats

A “format" is represented by a single enum value. The name of a format is usually built up by using the following pattern:

```
VK_FORMAT_{component-format|compression-scheme}_{numeric-format}
```

The component-format indicates either the size of the R, G, B, and A components (if they are present) in the case of a color format, or the size of the depth (D) and stencil (S) components (if they are present) in the case of a depth/stencil format (see below). An X indicates a component that is unused, but **may** be present for padding.
### Table 35. Interpretation of Numeric Format

<table>
<thead>
<tr>
<th>Numeric format</th>
<th>Type-Declaration instructions</th>
<th>Numeric type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNORM</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are unsigned normalized values in the range [0,1]</td>
</tr>
<tr>
<td>SNORM</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are signed normalized values in the range [-1,1]</td>
</tr>
<tr>
<td>USCALED</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are unsigned integer values that get converted to floating-point in the range [0,2^n-1]</td>
</tr>
<tr>
<td>SSCALED</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are signed integer values that get converted to floating-point in the range [-2^n-1,2^n-1-1]</td>
</tr>
<tr>
<td>UINT</td>
<td>OpTypeInt</td>
<td>unsigned integer</td>
<td>The components are unsigned integer values in the range [0,2^n-1]</td>
</tr>
<tr>
<td>SINT</td>
<td>OpTypeInt</td>
<td>signed integer</td>
<td>The components are signed integer values in the range [-2^n-1,2^n-1-1]</td>
</tr>
<tr>
<td>UFLOAT</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are unsigned floating-point numbers (used by packed, shared exponent, and some compressed formats)</td>
</tr>
<tr>
<td>SFLOAT</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The components are signed floating-point numbers</td>
</tr>
<tr>
<td>SRGB</td>
<td>OpTypeFloat</td>
<td>floating-point</td>
<td>The R, G, and B components are unsigned normalized values that represent values using sRGB nonlinear encoding, while the A component (if one exists) is a regular unsigned normalized value</td>
</tr>
</tbody>
</table>

n is the number of bits in the component.

The suffix _PACKnn indicates that the format is packed into an underlying type with nn bits. The suffix _mPACKnn is a short-hand that indicates that the format has m groups of components (which may or may not be stored in separate planes) that are each packed into an underlying type with nn bits.

The suffix _BLOCK indicates that the format is a block-compressed format, with the representation of multiple pixels encoded interdependently within a region.

### Table 36. Interpretation of Compression Scheme

<table>
<thead>
<tr>
<th>Compression scheme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Block Compression. See <a href="#">Block-Compressed Image Formats</a>.</td>
</tr>
<tr>
<td>ETC2</td>
<td>Ericsson Texture Compression. See <a href="#">ETC Compressed Image Formats</a>.</td>
</tr>
<tr>
<td>EAC</td>
<td>ETC2 Alpha Compression. See <a href="#">ETC Compressed Image Formats</a>.</td>
</tr>
</tbody>
</table>
### Compression scheme Description

<table>
<thead>
<tr>
<th>Compression scheme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTC</td>
<td>Adaptive Scalable Texture Compression (LDR Profile). See ASTC Compressed Image Formats.</td>
</tr>
</tbody>
</table>

For multi-planar images, the components in separate planes are separated by underscores, and the number of planes is indicated by the addition of a _2PLANE or _3PLANE suffix. Similarly, the separate aspects of depth-stencil formats are separated by underscores, although these are not considered separate planes. Formats are suffixed by _422 to indicate that planes other than the first are reduced in size by a factor of two horizontally or that the R and B values appear at half the horizontal frequency of the G values, _420 to indicate that planes other than the first are reduced in size by a factor of two both horizontally and vertically, and _444 for consistency to indicate that all three planes of a three-planar image are the same size.

**Note**
No common format has a single plane containing both R and B components but does not store these components at reduced horizontal resolution.

### 34.1.5. Representation and Texel Block Size

Color formats **must** be represented in memory in exactly the form indicated by the format’s name. This means that promoting one format to another with more bits per component and/or additional components **must** not occur for color formats. Depth/stencil formats have more relaxed requirements as discussed below.

Each format has a texel block size, the number of bytes used to store one texel block (a single addressable element of an uncompressed image, or a single compressed block of a compressed image). The texel block size for each format is shown in the Compatible formats table.

The representation of non-packed formats is that the first component specified in the name of the format is in the lowest memory addresses and the last component specified is in the highest memory addresses. See Byte mappings for non-packed/compressed color formats. The in-memory ordering of bytes within a component is determined by the host endianness.

#### Table 37. Byte mappings for non-packed/compressed color formats

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>← Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
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<td>VK_FORMAT_R8_*</td>
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<td>G</td>
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<td>G</td>
<td>B</td>
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<td></td>
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<td>VK_FORMAT_R8G8B8_*</td>
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</tr>
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<td>G</td>
<td>B</td>
<td>A</td>
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<tr>
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<td>A</td>
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<td></td>
<td>VK_FORMAT_B8G8R8A8_*</td>
</tr>
<tr>
<td>G₀ B</td>
<td>G₁</td>
<td>R</td>
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<td>G₁</td>
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<td></td>
<td></td>
<td></td>
<td>VK_FORMAT_B8G8R8G8_422_UNORM</td>
</tr>
</tbody>
</table>
Packed formats store multiple components within one underlying type. The bit representation is that the first component specified in the name of the format is in the most-significant bits and the last component specified is in the least-significant bits of the underlying type. The in-memory ordering of bytes comprising the underlying type is determined by the host endianness.

**Table 38. Bit mappings for packed 8-bit formats**

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<thead>
<tr>
<th>Bit</th>
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<th>5</th>
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<tr>
<td>R</td>
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<td>G</td>
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</tr>
</tbody>
</table>

**Table 39. Bit mappings for packed 16-bit formats**

<table>
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<th>5</th>
<th>4</th>
<th>3</th>
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</tr>
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<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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Table 40. Bit mappings for packed 32-bit formats

<table>
<thead>
<tr>
<th>Bit</th>
<th>VK_FORMAT_A4R4G4B4_UNORM_PACK16</th>
<th>VK_FORMAT_A4B4G4R4_UNORM_PACK16</th>
<th>VK_FORMAT_R5G6B5_UNORM_PACK16</th>
<th>VK_FORMAT_B5G6R5_UNORM_PACK16</th>
<th>VK_FORMAT_R5G5B5A1_UNORM_PACK16</th>
<th>VK_FORMAT_B5G5R5A1_UNORM_PACK16</th>
<th>VK_FORMAT_A1R5G5B5_UNORM_PACK16</th>
<th>VK_FORMAT_R10X6_UNORM_PACK16</th>
<th>VK_FORMAT_R12X4_UNORM_PACK16</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
<td>0 4 3 2 1 0</td>
</tr>
</tbody>
</table>

Table 40. Bit mappings for packed 32-bit formats

<table>
<thead>
<tr>
<th>Bit</th>
<th>VK_FORMAT_A8B8G8R8_*_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_*_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_*_PACK32</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0</td>
<td>A</td>
<td>R</td>
<td>B</td>
</tr>
<tr>
<td>7 6 5 4 3 2 1 0</td>
<td>1 0 9 8 7 6 5 4 3 2 1 0</td>
<td>1 0 9 8 7 6 5 4 3 2 1 0</td>
<td>1 0 9 8 7 6 5 4 3 2 1 0</td>
</tr>
</tbody>
</table>
34.1.6. Depth/Stencil Formats

Depth/stencil formats are considered opaque and need not be stored in the exact number of bits per texel or component ordering indicated by the format enum. However, implementations **must** not substitute a different depth or stencil precision than is described in the format (e.g. D16 **must** not be implemented as D24 or D32).

34.1.7. Format Compatibility Classes

Uncompressed color formats are *compatible* with each other if they occupy the same number of bits per texel block. Compressed color formats are compatible with each other if the only difference between them is the numeric format of the uncompressed pixels. Each depth/stencil format is only compatible with itself. In the following table, all the formats in the same row are compatible. Each format has a defined *texel block extent* specifying how many texels each texel block represents in each dimension.

*Table 41. Compatible Formats*

<table>
<thead>
<tr>
<th>Class, Texel Block Size, Texel Block Extent, # Texels/Block</th>
<th>Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-bit Block size 1 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R4G4_UNORM_PACK8, VK_FORMAT_R8_UNORM, VK_FORMAT_R8_SNORM, VK_FORMAT_R8_USCALED, VK_FORMAT_R8_SSCALED, VK_FORMAT_R8_UINT, VK_FORMAT_R8_SINT, VK_FORMAT_R8_SRGB</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>--------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td><strong>16-bit</strong>&lt;br&gt;Block size 2 byte&lt;br&gt;1x1x1 block extent&lt;br&gt;1 texel/block</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16, VK_FORMAT_R12X4_UNORM_PACK16, VK_FORMAT_A4R4G4B4_UNORM_PACK16, VK_FORMAT_A4B4G4R4_UNORM_PACK16, VK_FORMAT_R4G4B4A4_UNORM_PACK16, VK_FORMAT_B4G4R4A4_UNORM_PACK16, VK_FORMAT_R5G6B5_UNORM_PACK16, VK_FORMAT_B5G6R5_UNORM_PACK16, VK_FORMAT_R5G5B5A1_UNORM_PACK16, VK_FORMAT_B5G5R5A1_UNORM_PACK16, VK_FORMAT_A1R5G5B5_UNORM_PACK16, VK_FORMAT_R8G8_UNORM, VK_FORMAT_R8G8_SNORM, VK_FORMAT_R8G8_USCALED, VK_FORMAT_R8G8_SSCALED, VK_FORMAT_R8G8_UINT, VK_FORMAT_R8G8_SINT, VK_FORMAT_R8G8_SRGB, VK_FORMAT_R16_UNORM, VK_FORMAT_R16_SNORM, VK_FORMAT_R16_USCALED, VK_FORMAT_R16_SSCALED, VK_FORMAT_R16_UINT, VK_FORMAT_R16_SINT, VK_FORMAT_R16_SFLOAT</td>
</tr>
<tr>
<td><strong>24-bit</strong>&lt;br&gt;Block size 3 byte&lt;br&gt;1x1x1 block extent&lt;br&gt;1 texel/block</td>
<td>VK_FORMAT_R8G8B8_UNORM, VK_FORMAT_R8G8B8_SNORM, VK_FORMAT_R8G8B8_USCALED, VK_FORMAT_R8G8B8_SSCALED, VK_FORMAT_R8G8B8_UINT, VK_FORMAT_R8G8B8_SINT, VK_FORMAT_R8G8B8_SRGB, VK_FORMAT_B8G8R8_UNORM, VK_FORMAT_B8G8R8_SNORM, VK_FORMAT_B8G8R8_USCALED, VK_FORMAT_B8G8R8_SSCALED, VK_FORMAT_B8G8R8_UINT, VK_FORMAT_B8G8R8_SINT, VK_FORMAT_B8G8R8_SRGB</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>-------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>32-bit Block size 4 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16, VK_FORMAT_R12X4G12X4_UNORM_2PACK16, VK_FORMAT_R8G8B8A8_UNORM, VK_FORMAT_R8G8B8A8_SNORM, VK_FORMAT_R8G8B8A8_USCALED, VK_FORMAT_R8G8B8A8_SSCALED, VK_FORMAT_R8G8B8A8_UINT, VK_FORMAT_R8G8B8A8_SINT, VK_FORMAT_R8G8B8A8_SRGB, VK_FORMAT_B8G8R8A8_UNORM, VK_FORMAT_B8G8R8A8_SNORM, VK_FORMAT_B8G8R8A8_USCALED, VK_FORMAT_B8G8R8A8_SSCALED, VK_FORMAT_B8G8R8A8_UINT, VK_FORMAT_B8G8R8A8_SINT, VK_FORMAT_B8G8R8A8_SRGB, VK_FORMAT_A8B8G8R8_UNORM_PACK32, VK_FORMAT_A8B8G8R8_SNORM_PACK32, VK_FORMAT_A8B8G8R8_USCALED_PACK32, VK_FORMAT_A8B8G8R8_SSCALED_PACK32, VK_FORMAT_A8B8G8R8_UINT_PACK32, VK_FORMAT_A8B8G8R8_SINT_PACK32, VK_FORMAT_A2R10G10B10_UNORM_PACK32, VK_FORMAT_A2R10G10B10_SNORM_PACK32, VK_FORMAT_A2R10G10B10_USCALED_PACK32, VK_FORMAT_A2R10G10B10_SSCALED_PACK32, VK_FORMAT_A2R10G10B10_UINT_PACK32, VK_FORMAT_A2R10G10B10_SINT_PACK32, VK_FORMAT_R16G16_UNORM, VK_FORMAT_R16G16_SNORM, VK_FORMAT_R16G16_USCALED, VK_FORMAT_R16G16_SSCALED, VK_FORMAT_R16G16_UINT, VK_FORMAT_R16G16_SINT, VK_FORMAT_R16G16_SFLOAT, VK_FORMAT_R32_UINT, VK_FORMAT_R32_SINT, VK_FORMAT_R32_SFLOAT, VK_FORMAT_B10G11R11_UFLOAT_PACK32, VK_FORMAT_E5B9G9R9_UFLOAT_PACK32</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>48-bit Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R16G16B16_UNORM, VK_FORMAT_R16G16B16_SNORM, VK_FORMAT_R16G16B16_USCALED, VK_FORMAT_R16G16B16_SSCALED, VK_FORMAT_R16G16B16_UINT, VK_FORMAT_R16G16B16_SINT, VK_FORMAT_R16G16B16_SFLOAT</td>
</tr>
<tr>
<td>96-bit Block size 12 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R32G32B32_UINT, VK_FORMAT_R32G32B32_SINT, VK_FORMAT_R32G32B32_SFLOAT</td>
</tr>
<tr>
<td>128-bit Block size 16 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R32G32B32A32_UINT, VK_FORMAT_R32G32B32A32_SINT, VK_FORMAT_R32G32B32A32_SFLOAT, VK_FORMAT_R64G64_UINT, VK_FORMAT_R64G64_SINT, VK_FORMAT_R64G64_SFLOAT</td>
</tr>
<tr>
<td>192-bit Block size 24 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R64G64B64A64_UINT, VK_FORMAT_R64G64B64A64_SINT, VK_FORMAT_R64G64B64A64_SFLOAT</td>
</tr>
<tr>
<td>256-bit Block size 32 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R64G64B64A64_UINT, VK_FORMAT_R64G64B64A64_SINT, VK_FORMAT_R64G64B64A64_SFLOAT</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>D16 Block size 2 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_D16_UNORM</td>
</tr>
<tr>
<td>D24 Block size 4 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
</tr>
<tr>
<td>D32 Block size 4 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_D32_SFLOAT</td>
</tr>
<tr>
<td>S8 Block size 1 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_S8_UINT</td>
</tr>
<tr>
<td>D16S8 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_D16_UNORM_S8_UINT</td>
</tr>
<tr>
<td>D24S8 Block size 4 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_D24_UNORM_S8_UINT</td>
</tr>
<tr>
<td>D32S8 Block size 5 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_D32_SFLOAT_S8_UINT</td>
</tr>
<tr>
<td>BC1.RGB Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK, VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC1.RGBA Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK, VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC2 Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC2_UNORM_BLOCK, VK_FORMAT_BC2_SRGB_BLOCK</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
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<td>---------</td>
</tr>
<tr>
<td>BC3 Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC3_UNORM_BLOCK, VK_FORMAT_BC3_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC4 Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC4_UNORM_BLOCK, VK_FORMAT_BC4_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC5 Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC5_UNORM_BLOCK, VK_FORMAT_BC5_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC6H Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK, VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
</tr>
<tr>
<td>BC7 Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_BC7_UNORM_BLOCK, VK_FORMAT_BC7_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_RGB Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_RGBA Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_EAC_RGBA Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
</tr>
<tr>
<td>EAC_R Block size 8 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK, VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
</tr>
<tr>
<td>EAC_RG Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK, VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>ASTC_4x4 Block size 16 byte 4x4x1 block extent 16 texel/block</td>
<td>VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK, VK_FORMAT_ASTC_4x4_UNORM_BLOCK, VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_5x4 Block size 16 byte 5x4x1 block extent 20 texel/block</td>
<td>VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK, VK_FORMAT_ASTC_5x4_UNORM_BLOCK, VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_5x5 Block size 16 byte 5x5x1 block extent 25 texel/block</td>
<td>VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK, VK_FORMAT_ASTC_5x5_UNORM_BLOCK, VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_6x5 Block size 16 byte 6x5x1 block extent 30 texel/block</td>
<td>VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK, VK_FORMAT_ASTC_6x5_UNORM_BLOCK, VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_6x6 Block size 16 byte 6x6x1 block extent 36 texel/block</td>
<td>VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK, VK_FORMAT_ASTC_6x6_UNORM_BLOCK, VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x5 Block size 16 byte 8x5x1 block extent 40 texel/block</td>
<td>VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK, VK_FORMAT_ASTC_8x5_UNORM_BLOCK, VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x6 Block size 16 byte 8x6x1 block extent 48 texel/block</td>
<td>VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK, VK_FORMAT_ASTC_8x6_UNORM_BLOCK, VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x8 Block size 16 byte 8x8x1 block extent 64 texel/block</td>
<td>VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK, VK_FORMAT_ASTC_8x8_UNORM_BLOCK, VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x5 Block size 16 byte 10x5x1 block extent 50 texel/block</td>
<td>VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK, VK_FORMAT_ASTC_10x5_UNORM_BLOCK, VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x6 Block size 16 byte 10x6x1 block extent 60 texel/block</td>
<td>VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK, VK_FORMAT_ASTC_10x6_UNORM_BLOCK, VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>ASTC_10x8 Block size 16 byte 10x8x1 block extent 80 texel/block</td>
<td>VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK, VK_FORMAT_ASTC_10x8_UNORM_BLOCK, VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x10 Block size 16 byte 10x10x1 block extent 100 texel/block</td>
<td>VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK, VK_FORMAT_ASTC_10x10_UNORM_BLOCK, VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_12x10 Block size 16 byte 12x10x1 block extent 120 texel/block</td>
<td>VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK, VK_FORMAT_ASTC_12x10_UNORM_BLOCK, VK_FORMAT_ASTC_12x10_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_12x12 Block size 16 byte 12x12x1 block extent 144 texel/block</td>
<td>VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK, VK_FORMAT_ASTC_12x12_UNORM_BLOCK, VK_FORMAT_ASTC_12x12_SRGB_BLOCK</td>
</tr>
<tr>
<td>32-bit G8B8G8R8 Block size 4 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8B8G8R8_422_UNORM</td>
</tr>
<tr>
<td>32-bit B8G8R8G8 Block size 4 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_B8G8R8G8_422_UNORM</td>
</tr>
<tr>
<td>8-bit 3-plane 420 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
</tr>
<tr>
<td>8-bit 2-plane 420 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8_B8R8_2PLANE_420_UNORM</td>
</tr>
<tr>
<td>8-bit 3-plane 422 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM</td>
</tr>
<tr>
<td>8-bit 2-plane 422 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8_B8R8_2PLANE_422_UNORM</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>8-bit 3-plane 444 Block size 3 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM</td>
</tr>
<tr>
<td>64-bit R10G10B10A10 Block size 8 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit G10B10G10R10 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit B10G10R10G10 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>10-bit 3-plane 420 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 2-plane 420 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 3-plane 422 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 2-plane 422 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 3-plane 444 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16</td>
</tr>
<tr>
<td>64-bit R12G12B12A12 Block size 8 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16</td>
</tr>
<tr>
<td>Class, Texel Block Size, Texel Block Extent, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>64-bit G12B12G12R12 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit B12G12R12G12 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 420 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 2-plane 420 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 422 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 2-plane 422 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 444 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16</td>
</tr>
<tr>
<td>64-bit G16B16G16R16 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
</tr>
<tr>
<td>64-bit B16G16R16G16 Block size 8 byte 2x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
</tr>
<tr>
<td>16-bit 3-plane 420 Block size 6 byte 1x1x1 block extent 1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</td>
</tr>
</tbody>
</table>
## Class, Texel Block Size, Texel Block Extent, # Texels/Block, Formats

<table>
<thead>
<tr>
<th>Class</th>
<th>Texel Block Size</th>
<th>Texel Block Extent</th>
<th># Texels/Block</th>
<th>Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-bit 2-plane 420</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G16_B16R16_2PLANE_420_UNORM</td>
</tr>
<tr>
<td>16-bit 3-plane 422</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM</td>
</tr>
<tr>
<td>16-bit 2-plane 422</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G16_B16R16_2PLANE_422_UNORM</td>
</tr>
<tr>
<td>16-bit 3-plane 444</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
</tr>
<tr>
<td>8-bit 2-plane 444</td>
<td>Block size 3 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G8_B8R8_2PLANE_444_UNORM</td>
</tr>
<tr>
<td>10-bit 2-plane 444</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 2-plane 444</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_444 UNORM_3PACK16</td>
</tr>
<tr>
<td>16-bit 2-plane 444</td>
<td>Block size 6 byte</td>
<td>1x1x1 block extent</td>
<td>1 texel/block</td>
<td>VK_FORMAT_G16_B16R16_2PLANE_444_UNORM</td>
</tr>
</tbody>
</table>

### Size Compatibility

Color formats with the same texel block size are considered *size-compatible*. If two size-compatible formats have different block extents (i.e. for compressed formats), then an image with size $A \times B \times C$ in one format with a block extent of $a \times b \times c$ can be represented as an image with size $X \times Y \times Z$ in the other format with block extent $x \times y \times z$ at the ratio between the block extents for each format, where...
Note

For example, a 7x3 image in the `VK_FORMAT_ASTC_8x5_UNORM_BLOCK` format can be represented as a 1x1 `VK_FORMAT_R64G64_UINT` image.

Images created with the `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT` flag can have size-compatible views created from them to enable access via different size-compatible formats. Image views created in this way will be sized to match the expectations of the block extents noted above.

Copy operations are able to copy between size-compatible formats in different resources to enable manipulation of data in different formats. The extent used in these copy operations always matches the source image, and is resized to the expectations of the block extents noted above for the destination image.

### 34.2. Format Properties

To query supported format features which are properties of the physical device, call:

```c
// Provided by VK_VERSION_1_0
void vkGetPhysicalDeviceFormatProperties(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
    VkFormatProperties* pFormatProperties);
```

- `physicalDevice` is the physical device from which to query the format properties.
- `format` is the format whose properties are queried.
- `pFormatProperties` is a pointer to a `VkFormatProperties` structure in which physical device properties for `format` are returned.

**Valid Usage (Implicit)**

- VUID-vkGetPhysicalDeviceFormatProperties-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkGetPhysicalDeviceFormatProperties-format-parameter `format` must be a valid `VkFormat` value
- VUID-vkGetPhysicalDeviceFormatProperties-pFormatProperties-parameter `pFormatProperties` must be a valid pointer to a `VkFormatProperties` structure
The `VkFormatProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_0
typedef struct VkFormatProperties{
    VkFormatFeatureFlags linearTilingFeatures;
    VkFormatFeatureFlags optimalTilingFeatures;
    VkFormatFeatureFlags bufferFeatures;
} VkFormatProperties;
```

- `linearTilingFeatures` is a bitmask of `VkFormatFeatureFlagBits` specifying features supported by images created with a `tiling` parameter of `VK_IMAGE_TILING_LINEAR`.
- `optimalTilingFeatures` is a bitmask of `VkFormatFeatureFlagBits` specifying features supported by images created with a `tiling` parameter of `VK_IMAGE_TILING_OPTIMAL`.
- `bufferFeatures` is a bitmask of `VkFormatFeatureFlagBits` specifying features supported by buffers.

**Note**
If no format feature flags are supported, the format itself is not supported, and images of that format cannot be created.

If `format` is a block-compressed format, then `bufferFeatures` must not support any features for the format.

If `format` is not a multi-plane format then `linearTilingFeatures` and `optimalTilingFeatures` must not contain `VK_FORMAT_FEATURE_DISJOINT_BIT`.

Bits which can be set in the `VkFormatProperties` features `linearTilingFeatures`, `optimalTilingFeatures`, and `bufferFeatures` are:

```c
// Provided by VK_VERSION_1_0
typedef enum VkFormatFeatureFlagBits {
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT = 0x00000001,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT = 0x00000002,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT = 0x00000004,
    VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT = 0x00000008,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT = 0x00000010,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT = 0x00000020,
    VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT = 0x00000040,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT = 0x00000080,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT = 0x00000100,
    VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000200,
    VK_FORMAT_FEATURE_BLIT_SRC_BIT = 0x00000400,
    VK_FORMAT_FEATURE_BLIT_DST_BIT = 0x00000800,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT = 0x00001000,
    // Provided by VK_VERSION_1_1
    VK_FORMAT_FEATURE_TRANSFER_SRC_BIT = 0x00004000,
    // Provided by VK_VERSION_1_1
    VK_FORMAT_FEATURE_TRANSFER_SRC_BIT = 0x00004000,
    // Provided by VK_VERSION_1_1
};
```
These values all have the same meaning as the equivalently named values for `VkFormatFeatureFlags2` and may be set in `linearTilingFeatures` and `optimalTilingFeatures`, specifying that the features are supported by images or image views or sampler Y’C₈C₉ conversion objects created with the queried `vkGetPhysicalDeviceFormatProperties::format`:

- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT` specifies that an image view can be sampled from.
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT` specifies that an image view can be used as a storage image.
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT` specifies that an image view can be used as storage image that supports atomic operations.
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT` specifies that an image view can be used as a framebuffer color attachment and as an input attachment.
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT` specifies that an image view can be used as a framebuffer color attachment that supports blending.
- `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT` specifies that an image view can be used as a framebuffer depth/stencil attachment and as an input attachment.
- `VK_FORMAT_FEATURE_BLIT_SRC_BIT` specifies that an image can be used as srcImage for the `vkCmdBlitImage2` and `vkCmdBlitImage` commands.
- `VK_FORMAT_FEATURE_BLIT_DST_BIT` specifies that an image can be used as dstImage for the `vkCmdBlitImage2` and `vkCmdBlitImage` commands.
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` specifies that if
VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT is also set, an image view can be used with a sampler that has either of magFilter or minFilter set to VK_FILTER_LINEAR, or mipmapMode set to VK_SAMPLER_MIPMAP_MODE_LINEAR. If VK_FORMAT_FEATURE_BLIT_SRC_BIT is also set, an image can be used as the srcImage to vkCmdBlitImage2 and vkCmdBlitImage with a filter of VK_FILTER_LINEAR. This bit must only be exposed for formats that also support the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT or VK_FORMAT_FEATURE_BLIT_SRC_BIT.

If the format being queried is a depth/stencil format, this bit only specifies that the depth aspect (not the stencil aspect) of an image of this format supports linear filtering, and that linear filtering of the depth aspect is supported whether depth compare is enabled in the sampler or not. Where depth comparison is supported it may be linear filtered whether this bit is present or not, but where this bit is not present the filtered value may be computed in an implementation-dependent manner which differs from the normal rules of linear filtering. The resulting value must be in the range [0,1] and should be proportional to, or a weighted average of, the number of comparison passes or failures.

- VK_FORMAT_FEATURE_TRANSFER_SRC_BIT specifies that an image can be used as a source image for copy commands. If the application apiVersion is Vulkan 1.0 and VK_KHR_maintenance1 is not supported, VK_FORMAT_FEATURE_TRANSFER_SRC_BIT is implied to be set when the format feature flag is not 0.

- VK_FORMAT_FEATURE_TRANSFER_DST_BIT specifies that an image can be used as a destination image for copy commands and clear commands. If the application apiVersion is Vulkan 1.0 and VK_KHR_maintenance1 is not supported, VK_FORMAT_FEATURE_TRANSFER_DST_BIT is implied to be set when the format feature flag is not 0.

- VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT specifies VkImage can be used as a sampled image with a min or max VkSamplerReductionMode. This bit must only be exposed for formats that also support the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT.

- VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT specifies that an application can define a sampler Y′C_bC_r conversion using this format as a source, and that an image of this format can be used with a VkSamplerYcbcrConversionCreateInfo xChromaOffset and/or yChromaOffset of VK_CHROMA_LOCATION_COSITED_EVEN. Otherwise both xChromaOffset and yChromaOffset must be VK_CHROMA_LOCATION_COSITED_EVEN. If a format does not incorporate chroma downsampling (it is not a “422” or “420” format) but the implementation supports sampler Y′C_bC_r conversion for this format, the implementation must set VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT.

- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT specifies that an application can define a sampler Y′C_bC_r conversion using this format as a source, and that an image of this format can be used with a VkSamplerYcbcrConversionCreateInfo xChromaOffset and/or yChromaOffset of VK_CHROMA_LOCATION_COSITED_EVEN. Otherwise both xChromaOffset and yChromaOffset must be VK_CHROMA_LOCATION_COSITED_EVEN. If neither VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT nor VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT is set, the application must not define a sampler Y′C_bC_r conversion using this format as a source.

- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT specifies that an application can define a sampler Y′C_bC_r conversion using this format as a source with chromaFilter set to VK_FILTER_LINEAR.

- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT specifies that the format can have different chroma, min, and mag filters.
• **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT** specifies that reconstruction is explicit, as described in Chroma Reconstruction. If this bit is not present, reconstruction is implicit by default.

• **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT** specifies that reconstruction can be forcibly made explicit by setting VkSamplerYcbcrConversionCreateInfo::forceExplicitReconstruction to VK_TRUE. If the format being queried supports VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT it must also support VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT.

• **VK_FORMAT_FEATURE_DISJOINT_BIT** specifies that a multi-planar image can have the VK_IMAGE_CREATE_DISJOINT_BIT set during image creation. An implementation must not set VK_FORMAT_FEATURE_DISJOINT_BIT for single-plane formats.

The following bits may be set in bufferFeatures, specifying that the features are supported by buffers or buffer views created with the queried vkGetPhysicalDeviceFormatProperties::format:

• **VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER descriptor.

• **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor.

• **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT** specifies that atomic operations are supported on VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER with this format.

• **VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT** specifies that the format can be used as a vertex attribute format (VkVertexInputAttributeDescription::format).

Note

**VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT** and **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT** are only intended to be advertised for single-component formats, since SPIR-V atomic operations require a scalar type.

```c
// Provided by VK_VERSION_1_0
typedef VkFlags VkFormatFeatureFlags;
```

**VkFormatFeatureFlags** is a bitmask type for setting a mask of zero or more **VkFormatFeatureFlagBits**.

To query supported format features which are properties of the physical device, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceFormatProperties2(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
```


**VkFormatProperties2**

- physicalDevice is the physical device from which to query the format properties.
- format is the format whose properties are queried.
- pFormatProperties is a pointer to a VkFormatProperties2 structure in which physical device properties for format are returned.

vkGetPhysicalDeviceFormatProperties2 behaves similarly to vkGetPhysicalDeviceFormatProperties, with the ability to return extended information in a pNext chain of output structures.

**Valid Usage (Implicit)**

- VUID-vkGetPhysicalDeviceFormatProperties2-physicalDevice-parameter physicalDevice must be a valid VkPhysicalDevice handle
- VUID-vkGetPhysicalDeviceFormatProperties2-format-parameter format must be a valid VkFormat value
- VUID-vkGetPhysicalDeviceFormatProperties2-pFormatProperties-parameter pFormatProperties must be a valid pointer to a VkFormatProperties2 structure

The VkFormatProperties2 structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkFormatProperties2 {
    VkStructureType sType;
    void* pNext;
    VkFormatProperties formatProperties;
} VkFormatProperties2;
```

- sType is a VkStructureType value identifying this structure.
- pNext is NULL or a pointer to a structure extending this structure.
- formatProperties is a VkFormatProperties structure describing features supported by the requested format.

**Valid Usage (Implicit)**

- VUID-VkFormatProperties2-sType-sType sType must be VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2
- VUID-VkFormatProperties2-pNext-pNext pNext must be NULL or a pointer to a valid instance of VkFormatProperties3
- VUID-VkFormatProperties2-sType-unique The sType value of each struct in the pNext chain must be unique
To query supported format extended features which are properties of the physical device, add \texttt{VkFormatProperties3} structure to the \texttt{pNext} chain of \texttt{VkFormatProperties2}.

The \texttt{VkFormatProperties3} structure is defined as:

```c
// Provided by VK_VERSION_1_3
typedef struct VkFormatProperties3 {
    VkStructureType sType;
    void* pNext;
    VkFormatFeatureFlags2 linearTilingFeatures;
    VkFormatFeatureFlags2 optimalTilingFeatures;
    VkFormatFeatureFlags2 bufferFeatures;
} VkFormatProperties3;
```

- \texttt{linearTilingFeatures} is a bitmask of \texttt{VkFormatFeatureFlagBits2} specifying features supported by images created with a \texttt{tiling} parameter of \texttt{VK_IMAGE_TILING_LINEAR}.
- \texttt{optimalTilingFeatures} is a bitmask of \texttt{VkFormatFeatureFlagBits2} specifying features supported by images created with a \texttt{tiling} parameter of \texttt{VK_IMAGE_TILING_OPTIMAL}.
- \texttt{bufferFeatures} is a bitmask of \texttt{VkFormatFeatureFlagBits2} specifying features supported by buffers.

The bits reported in \texttt{linearTilingFeatures}, \texttt{optimalTilingFeatures} and \texttt{bufferFeatures} must include the bits reported in the corresponding fields of \texttt{VkFormatProperties2::formatProperties}.

### Valid Usage (Implicit)

- VUID-VkFormatProperties3-sType-sType
  \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_3}

Bits which can be set in the \texttt{VkFormatProperties3} features \texttt{linearTilingFeatures}, \texttt{optimalTilingFeatures}, and \texttt{bufferFeatures} are:

```c
// Provided by VK_VERSION_1_3
// Flag bits for VkFormatFeatureFlagBits2
typedef VkFlags64 VkFormatFeatureFlagBits2;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT = 0x00000001ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT_KHR = 0x00000001ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_IMAGE_BIT = 0x00000002ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_IMAGE_BIT_KHR = 0x00000002ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_IMAGE_ATOMIC_BIT = 0x00000004ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_IMAGE_ATOMIC_BIT_KHR = 0x00000004ULL;
```
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_UNIFORM_TEXEL_BUFFER_BIT = 0x00000008ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_UNIFORM_TEXEL_BUFFER_BIT_KHR = 0x00000008ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_BIT = 0x00000010ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_BIT_KHR = 0x00000010ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_ATOMIC_BIT = 0x00000020ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_ATOMIC_BIT_KHR = 0x00000020ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_VERTEX_BUFFER_BIT = 0x00000040ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_VERTEX_BUFFER_BIT_KHR = 0x00000040ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BIT = 0x00000080ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BIT_KHR = 0x00000080ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BLEND_BIT = 0x00000100ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BLEND_BIT_KHR = 0x00000100ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000200ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_DEPTH_STENCIL_ATTACHMENT_BIT_KHR = 0x00000200ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_BLIT_SRC_BIT = 0x00000400ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_BLIT_SRC_BIT_KHR = 0x00000400ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_BLIT_DST_BIT = 0x00000800ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_BLIT_DST_BIT_KHR = 0x00000800ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_LINEAR_BIT = 0x00001000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_LINEAR_BIT_KHR = 0x00001000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_CUBIC_BIT = 0x00002000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_CUBIC_BIT_EXT = 0x00002000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_TRANSFER_SRC_BIT = 0x00004000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_TRANSFER_SRC_BIT_KHR = 0x00004000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_TRANSFER_DST_BIT = 0x00008000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_TRANSFER_DST_BIT_KHR = 0x00008000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_MINMAX_BIT = 0x00010000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_MINMAX_BIT_KHR = 0x00010000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_MIDPOINT_CHROMA_SAMPLES_BIT = 0x00020000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_MIDPOINT_CHROMA_SAMPLES_BIT_KHR = 0x00020000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT = 0x00040000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT_KHR = 0x00040000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT = 0x00080000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT_KHR = 0x00080000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT = 0x00100000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT_KHR = 0x00100000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT = 0x00200000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT_KHR = 0x00200000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_DISJOINT_BIT = 0x00400000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_DISJOINT_BIT_KHR = 0x00400000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COSITED_CHROMA_SAMPLES_BIT = 0x00800000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_COSITED_CHROMA_SAMPLES_BIT_KHR = 0x00800000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT = 0x80000000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT_KHR = 0x80000000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT = 0x100000000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT_KHR = 0x100000000ULL;
static const VkFormatFeatureFlagBits2 VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT = 0x200000000ULL;
The following bits may be set in linearTilingFeatures and optimalTilingFeatures, specifying that the features are supported by images or image views or sampler Y′C_bC_r conversion objects created with the queried vkGetPhysicalDeviceFormatProperties2::format:

- **VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT** specifies that an image view can be sampled from.
- **VK_FORMAT_FEATURE_2_STORAGE_IMAGE_BIT** specifies that an image view can be used as a storage image.
- **VK_FORMAT_FEATURE_2_STORAGE_IMAGE_ATOMIC_BIT** specifies that an image view can be used as storage image that supports atomic operations.
- **VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BIT** specifies that an image view can be used as a framebuffer color attachment and as an input attachment.
- **VK_FORMAT_FEATURE_2_COLOR_ATTACHMENT_BLEND_BIT** specifies that an image view can be used as a framebuffer color attachment that supports blending.
- **VK_FORMAT_FEATURE_2_DEPTH_STENCIL_ATTACHMENT_BIT** specifies that an image view can be used as a framebuffer depth/stencil attachment and as an input attachment.
- **VK_FORMAT_FEATURE_2_BLIT_SRC_BIT** specifies that an image can be used as the srcImage for vkCmdBlitImage2 and vkCmdBlitImage.
- **VK_FORMAT_FEATURE_2_BLIT_DST_BIT** specifies that an image can be used as the dstImage for vkCmdBlitImage2 and vkCmdBlitImage.
- **VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_LINEAR_BIT** specifies that if VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT is also set, an image view can be used with a sampler that has either of magFilter or minFilter set to VK_FILTER_LINEAR, or mipmapMode set to VK_SAMPLER_MIPMAP_MODE_LINEAR. If VK_FORMAT_FEATURE_2_BLIT_SRC_BIT is also set, an image can be used as the srcImage for vkCmdBlitImage2 and vkCmdBlitImage with a filter of VK_FILTER_LINEAR. This bit must only be exposed for formats that also support the VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT or VK_FORMAT_FEATURE_2_BLIT_SRC_BIT.

If the format being queried is a depth/stencil format, this bit only specifies that the depth aspect (not the stencil aspect) of an image of this format supports linear filtering. Where depth comparison is supported it may be linear filtered whether this bit is present or not, but where this bit is not present the filtered value may be computed in an implementation-dependent manner which differs from the normal rules of linear filtering. The resulting value must be in the range [0,1] and should be proportional to, or a weighted average of, the number of comparison passes or failures.

- **VK_FORMAT_FEATURE_2_TRANSFER_SRC_BIT** specifies that an image can be used as a source image for copy commands.
- **VK_FORMAT_FEATURE_2_TRANSFER_DST_BIT** specifies that an image can be used as a destination image for copy commands and clear commands.
- **VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_FILTER_MINMAX_BIT** specifies VkImage can be used as a sampled image with a min or max VkSamplerReductionMode. This bit must only be exposed for formats that also support the VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_BIT.
VK_FORMAT_FEATURE_2_MIDPOINT_CHROMA_SAMPLES_BIT specifies that an application can define a sampler Y'C'k conversion using this format as a source, and that an image of this format can be used with a VkSamplerYcbcrConversionCreateInfo xChromaOffset and/or yChromaOffset of VK_CHROMA_LOCATION_MIDPOINT. Otherwise both xChromaOffset and yChromaOffset must be VK_CHROMA_LOCATION_COSITED_EVEN. If a format does not incorporate chroma downsampling (it is not a “422” or “420” format) but the implementation supports sampler Y'C'k conversion for this format, the implementation must set VK_FORMAT_FEATURE_2_MIDPOINT_CHROMA_SAMPLES_BIT.

VK_FORMAT_FEATURE_2_COSITED_CHROMA_SAMPLES_BIT specifies that an application can define a sampler Y'C'k conversion using this format as a source, and that an image of this format can be used with a VkSamplerYcbcrConversionCreateInfo xChromaOffset and/or yChromaOffset of VK_CHROMA_LOCATION_COSITED_EVEN. Otherwise both xChromaOffset and yChromaOffset must be VK_CHROMA_LOCATION_MIDPOINT. If neither VK_FORMAT_FEATURE_2_COSITED_CHROMA_SAMPLES_BIT nor VK_FORMAT_FEATURE_2_MIDPOINT_CHROMA_SAMPLES_BIT is set, the application must not define a sampler Y'C'k conversion using this format as a source.

VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT specifies that an application can define a sampler Y'C'k conversion using this format as a source with chromaFilter set to VK_FILTER_LINEAR.

VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT specifies that the format can have different chroma, min, and mag filters.

VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT specifies that reconstruction is explicit, as described in Chroma Reconstruction. If this bit is not present, reconstruction is implicit by default.

VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT specifies that reconstruction can be forcibly made explicit by setting VkSamplerYcbcrConversionCreateInfo::forceExplicitReconstruction to VK_TRUE. If the format being queried supports VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT it must also support VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT.

VK_FORMAT_FEATURE_2_DISJOINT_BIT specifies that a multi-planar image can have the VK_IMAGE_CREATE_DISJOINT_BIT set during image creation. An implementation must not set VK_FORMAT_FEATURE_2_DISJOINT_BIT for single-plane formats.

VK_FORMAT_FEATURE_2_STORAGE_READWITHOUT_FORMAT_BIT specifies that image views or buffer views created with this format can be used as storage images or storage texel buffers respectively for read operations without specifying a format.

VK_FORMAT_FEATURE_2_STORAGE_WRITEWITHOUT_FORMAT_BIT specifies that image views or buffer views created with this format can be used as storage images or storage texel buffers respectively for write operations without specifying a format.

VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT specifies that image views created with this format can be used for depth comparison performed by OpImage*Dref* instructions.

The following bits may be set in bufferFeatures, specifying that the features are supported by buffers or buffer views created with the queried VkGetPhysicalDeviceFormatProperties2::format:
• **VK_FORMAT_FEATURE_2_UNIFORM_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a **VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER** descriptor.

• **VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** descriptor.

• **VK_FORMAT_FEATURE_2_STORAGE_TEXEL_BUFFER_ATOMIC_BIT** specifies that atomic operations are supported on **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** with this format.

• **VK_FORMAT_FEATURE_2_VERTEX_BUFFER_BIT** specifies that the format can be used as a vertex attribute format (**VkVertexInputAttributeDescription::format**).

• **VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT** specifies that buffer views created with this format can be used as **storage texel buffers** for read operations without specifying a format.

• **VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT** specifies that buffer views created with this format can be used as **storage texel buffers** for write operations without specifying a format.

```c
// Provided by VK_VERSION_1_3
typedef VkFlags64 VkFormatFeatureFlags2;
```

**VkFormatFeatureFlags2** is a bitmask type for setting a mask of zero or more **VkFormatFeatureFlagBits2**.

### 34.2.1. Potential Format Features

Some valid usage conditions depend on the format features supported by a **VkImage** whose **VkImageTiling** is unknown. In such cases the exact **VkFormatFeatureFlagBits** supported by the **VkImage** cannot be determined, so the valid usage conditions are expressed in terms of the potential format features of the **VkImage** format.

The potential format features of a **VkFormat** are defined as follows:

- The union of **VkFormatFeatureFlagBits** and **VkFormatFeatureFlagBits2**, supported when the **VkImageTiling** is **VK_IMAGE_TILING_OPTIMAL** or **VK_IMAGE_TILING_LINEAR**

### 34.3. Required Format Support

Implementations must support at least the following set of features on the listed formats. For images, these features must be supported for every **VkImageType** (including arrayed and cube variants) unless otherwise noted. These features are supported on existing formats without needing to advertise an extension or needing to explicitly enable them. Support for additional functionality beyond the requirements listed here is queried using the **vkGetPhysicalDeviceFormatProperties** command.

**Note**

Unless otherwise excluded below, the required formats are supported for all **VkImageCreateFlags** values as long as those flag values are otherwise allowed.
The following tables show which feature bits **must** be supported for each format. Formats that are required to support `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT` **must** also support `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT` and `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`.

**Table 42. Key for format feature tables**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>✗</td>
<td>This feature <strong>must</strong> be supported on the named format</td>
</tr>
<tr>
<td>†</td>
<td>This feature <strong>must</strong> be supported on at least some of the named formats, with more information in the table where the symbol appears</td>
</tr>
<tr>
<td>‡</td>
<td>This feature <strong>must</strong> be supported with some caveats or preconditions, with more information in the table where the symbol appears</td>
</tr>
</tbody>
</table>

**Table 43. Feature bits in `optimalTilingFeatures`**

- `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`
- `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`
- `VK_FORMAT_FEATURE_BLIT_SRC_BIT`
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`
- `VK_FORMAT_FEATURE_BLIT_DST_BIT`
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`
- `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT`

**Table 44. Feature bits in `bufferFeatures`**

- `VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT`
- `VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT`
- `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT`
- `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`
Table 45. Mandatory format support: sub-byte components

<table>
<thead>
<tr>
<th>Format</th>
<th></th>
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<tbody>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</td>
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</tr>
<tr>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT</td>
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<td>VK_FORMAT_FEATURE_BLIT_DST_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_TEXTURE_ATOMIC_BIT</td>
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<td>VK_FORMAT_FEATURE_TEXTURE_BIT</td>
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</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR Bit</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
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<tr>
<td>Format features marked † <strong>must</strong> be supported for optimalTilingFeatures if the VkPhysicalDevice supports the VkPhysicalDevice4444FormatsFeaturesEXT::formatA4R4G4B4 feature.</td>
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</tr>
</tbody>
</table>

Format features marked ‡ **must** be supported for optimalTilingFeatures if the VkPhysicalDevice supports the VkPhysicalDevice4444FormatsFeaturesEXT::formatA4B4G4R4 feature.
Table 46. Mandatory format support: 1-3 byte-sized components

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_R8_UNORM</th>
<th>VK_FORMAT_R8_SNORM</th>
<th>VK_FORMAT_R8_USCALED</th>
<th>VK_FORMAT_R8_SSCALED</th>
<th>VK_FORMAT_R8_UINT</th>
<th>VK_FORMAT_R8_SINT</th>
<th>VK_FORMAT_R8_SRGB</th>
<th>VK_FORMAT_R8G8_UNORM</th>
<th>VK_FORMAT_R8G8_SNORM</th>
<th>VK_FORMAT_R8G8_USCALED</th>
<th>VK_FORMAT_R8G8_SSCALED</th>
<th>VK_FORMAT_R8G8_UINT</th>
<th>VK_FORMAT_R8G8_SINT</th>
<th>VK_FORMAT_R8G8_SRGB</th>
<th>VK_FORMAT_R8G8B8_UNORM</th>
<th>VK_FORMAT_R8G8B8_SNORM</th>
<th>VK_FORMAT_R8G8B8_USCALED</th>
<th>VK_FORMAT_R8G8B8_SSCALED</th>
<th>VK_FORMAT_R8G8B8_UINT</th>
<th>VK_FORMAT_R8G8B8_SINT</th>
<th>VK_FORMAT_R8G8B8_SRGB</th>
<th>VK_FORMAT_R8G8B8B8_UNORM</th>
<th>VK_FORMAT_R8G8B8B8_SNORM</th>
<th>VK_FORMAT_B8G8R8_UNORM</th>
</tr>
</thead>
</table>

1263
<table>
<thead>
<tr>
<th>Format Name</th>
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<tbody>
<tr>
<td>VK_FORMAT_B8G8R8_USCALED</td>
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<tr>
<td>VK_FORMAT_B8G8R8_SSCALED</td>
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<tr>
<td>VK_FORMAT_B8G8R8_UINT</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8_SINT</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8_SRGB</td>
</tr>
</tbody>
</table>

Format features marked with ‡ must be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
### Table 47. Mandatory format support: 4 byte-sized components

<p>| VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_BLIT_SRC_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_UNORM | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_SNORM | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_USCALED | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_SSCALED | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_UINT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_SINT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_R8G8B8A8_SRGB | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_UNORM | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_SNORM | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_USCALED | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_SSCALED | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_UINT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_SINT | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_B8G8R8A8_SRGB | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_UNORM_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_SNORM_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_USCALED_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_SSCALED_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_UINT_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_SINT_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| VK_FORMAT_A8B8G8R8_SRGB_PACK32 | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |</p>
<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_A2R10G10B10_UNORM_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SNORM_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_USCALED_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SSCALED_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_UINT_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SINT_PACK32</th>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>‡</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Format features marked with ‡ **must** be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
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Table 50. Mandatory format support: 32-bit components

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Table 51. Mandatory format support: 64-bit/uneven components

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<th>VK_FORMAT_R64_SFLOAT</th>
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<th>VK_FORMAT_R64G64B64A64_SINT</th>
<th>VK_FORMAT_R64G64B64A64_SFLOAT</th>
<th>VK_FORMAT_B10G11R11_UFLOAT_PACK32</th>
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Format features marked with ‡ must be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
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<th>Storage Texel Buffer</th>
<th>Uniform Texel Buffer</th>
<th>Vertex Buffer</th>
<th>Depth Stencil Attachment</th>
<th>Color Attachment Blend</th>
<th>Blit Dst</th>
<th>Color Attachment</th>
<th>Storage Image Atomic</th>
<th>Storage Image</th>
<th>Sampled Image Filter Linear</th>
<th>Blit Src</th>
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**Mandatory format support: depth/stencil with VkImageType VK_IMAGE_TYPE_2D**

- **Format**
- **bufferFeatures** **must** not support any features for these formats.

**Feature** **must** be supported for at least one of **VK_FORMAT_X8_D24_UNORM_PACK32** and **VK_FORMAT_D32_SFLOAT**, and **must** be supported for at least one of **VK_FORMAT_D24_UNORM_S8_UINT** and **VK_FORMAT_D32_SFLOAT_S8_UINT**.
Table 53. Mandatory format support: BC compressed formats with \( \text{VkImageType} \) \( \text{VK\_IMAGE\_TYPE\_2D} \) and \( \text{VK\_IMAGE\_TYPE\_3D} \)

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The \( \text{VK\_FORMAT\_FEATURE\_SAMPLED\_IMAGE\_BIT} \), \( \text{VK\_FORMAT\_FEATURE\_BLIT\_SRC\_BIT} \), and \( \text{VK\_FORMAT\_FEATURE\_SAMPLED\_IMAGE\_FILTER\_LINEAR\_BIT} \) features must be supported in optimalTilingFeatures for all the formats in at least one of: this table, Mandatory format support: ETC2 and EAC compressed formats with \( \text{VkImageType} \) \( \text{VK\_IMAGE\_TYPE\_2D} \), or Mandatory format support: ASTC LDR compressed formats with \( \text{VkImageType} \) \( \text{VK\_IMAGE\_TYPE\_2D} \).
Table 54. Mandatory format support: ETC2 and EAC compressed formats with \texttt{VkImageType VK\_IMAGE\_TYPE\_2D}

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<td>\texttt{VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK}</td>
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<td>\texttt{VK_FORMAT_EAC_R11_UNORM_BLOCK}</td>
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The \texttt{VK\_FORMAT\_FEATURE\_SAMPLED\_IMAGE\_BIT}, \texttt{VK\_FORMAT\_FEATURE\_BLIT\_SRC\_BIT} and \texttt{VK\_FORMAT\_FEATURE\_SAMPLED\_IMAGE\_FILTER\_LINEAR\_BIT} features must be supported in \texttt{optimalTilingFeatures} for all the formats in at least one of: this table, Mandatory format support: BC compressed formats with \texttt{VkImageType VK\_IMAGE\_TYPE\_2D} and \texttt{VK\_IMAGE\_TYPE\_3D}, or Mandatory format support: ASTC LDR compressed formats with \texttt{VkImageType VK\_IMAGE\_TYPE\_2D}. 

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Table 55. Mandatory format support: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D

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<tr>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
</tbody>
</table>
The `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for all the formats in at least one of: this table, Mandatory format support: BC compressed formats with `VkImageType VK_IMAGE_TYPE_2D` and `VK_IMAGE_TYPE_3D`, or Mandatory format support: ETC2 and EAC compressed formats with `VkImageType VK_IMAGE_TYPE_2D`.

To be used with `VkImageView` with `subresourceRange.aspectMask` equal to `VK_IMAGE_ASPECT_COLOR_BIT`, sampler Y’C_bC_a conversion must be enabled for the following formats:

Table 56. Formats requiring sampler Y’C_bC_a conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views

<table>
<thead>
<tr>
<th>Format</th>
<th>Planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_G8B8G8R8_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8G8_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_420_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_422_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
</tbody>
</table>
### 34.3.1. Formats without shader storage format

The device-level features for using a storage image or a storage texel buffer with an image format of **Unknown**, `shaderStorageImageReadWithoutFormat` and `shaderStorageImageWriteWithoutFormat`, only apply to the following formats:

<table>
<thead>
<tr>
<th>Format</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_3PLANE_420_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_3PLANE_422_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_3PLANE_444_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_2PLANE_420_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_2PLANE_422_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_444_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_444_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_444_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16R16_2PLANE_444_UNORM</td>
<td>2</td>
</tr>
</tbody>
</table>

Format features marked † must be supported for `optimalTilingFeatures` with `VkImageType VK_IMAGE_TYPE_2D` if the `VkPhysicalDevice supports the VkPhysicalDeviceSamplerYcbcrConversionFeatures` feature.

Implementations are not required to support the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`, or `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` `VkImageCreateFlags` for the above formats that require `sampler Y’C_a,C_b` conversion. To determine whether the implementation supports sparse image creation flags with these formats use `vkGetPhysicalDeviceImageFormatProperties` or `vkGetPhysicalDeviceImageFormatProperties2`.

---

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- VK_FORMAT_R8G8B8A8_UNORM
- VK_FORMAT_R8G8B8A8_SNORM
- VK_FORMAT_R8G8B8A8_UINT
- VK_FORMAT_R8G8B8A8_SINT
- VK_FORMAT_R32_UINT
- VK_FORMAT_R32_SINT
- VK_FORMAT_R32_SFLOAT
- VK_FORMAT_R32G32_UINT
- VK_FORMAT_R32G32_SINT
- VK_FORMAT_R32G32_SFLOAT
- VK_FORMAT_R32G32B32A32_UINT
- VK_FORMAT_R32G32B32A32_SINT
- VK_FORMAT_R32G32B32A32_SFLOAT
- VK_FORMAT_R16G16B16A16_UINT
- VK_FORMAT_R16G16B16A16_SINT
- VK_FORMAT_R16G16B16A16_SFLOAT
- VK_FORMAT_R16G16_SFLOAT
- VK_FORMAT_B10G11R11_UFLOAT_PACK32
- VK_FORMAT_R16_SFLOAT
- VK_FORMAT_R16G16B16A16_UNORM
- VK_FORMAT_A2B10G10R10_UNORM_PACK32
- VK_FORMAT_R16G16_SNORM
- VK_FORMAT_R16_SINT
- VK_FORMAT_R16G16_SINT
- VK_FORMAT_R8_SINT
- VK_FORMAT_A2B10G10R10_UINT_PACK32
• VK_FORMAT_R16G16_UINT
• VK_FORMAT_R8G8_UINT
• VK_FORMAT_R16_UINT
• VK_FORMAT_R8_UINT

Note
This list of formats is the union of required storage formats from Required Format Support section and formats listed in shaderStorageImageExtendedFormats.

An implementation that supports VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT for any format from the given list of formats and supports shaderStorageImageReadWithoutFormat must support VK_FORMAT_FEATURE_2_STORAGE_READ_WITHOUT_FORMAT_BIT for that same format if Vulkan 1.3 or the VK_KHR_format_feature_flags2 extension is supported.

An implementation that supports VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT for any format from the given list of formats and supports shaderStorageImageWriteWithoutFormat must support VK_FORMAT_FEATURE_2_STORAGE_WRITE_WITHOUT_FORMAT_BIT for that same format if Vulkan 1.3 or the VK_KHR_format_feature_flags2 extension is supported.

34.3.2. Depth comparison format support

If Vulkan 1.3 or the VK_KHR_format_feature_flags2 extension is supported, a depth/stencil format with a depth component supporting VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT must support VK_FORMAT_FEATURE_2_SAMPLED_IMAGE_DEPTH_COMPARISON_BIT.

34.3.3. Format feature dependent usage flags

Certain resource usage flags depend on support for the corresponding format feature flag for the format in question. The following tables list the VkBufferUsageFlagBits and VkImageUsageFlagBits that have such dependencies, and the format feature flags they depend on. Additional restrictions, including, but not limited to, further required format feature flags specific to the particular use of the resource may apply, as described in the respective sections of this specification.

Table 57. Format feature dependent buffer usage flags

<table>
<thead>
<tr>
<th>Buffer usage flag</th>
<th>Required format feature flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT</td>
<td>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</td>
</tr>
<tr>
<td>VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT</td>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</td>
</tr>
<tr>
<td>VK_BUFFER_USAGE_VERTEX_BUFFER_BIT</td>
<td>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</td>
</tr>
</tbody>
</table>

Table 58. Format feature dependent image usage flags

<table>
<thead>
<tr>
<th>Image usage flag</th>
<th>Required format feature flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_IMAGE_USAGE_SAMPLED_BIT</td>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</td>
</tr>
<tr>
<td>VK_IMAGE_USAGE_STORAGE_BIT</td>
<td>VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT</td>
</tr>
<tr>
<td>VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT</td>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</td>
</tr>
<tr>
<td>VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
</tr>
<tr>
<td>Image usage flag</td>
<td>Required format feature flag</td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td>VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT</td>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT or</td>
</tr>
<tr>
<td></td>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
</tr>
</tbody>
</table>
Chapter 35. Additional Capabilities

This chapter describes additional capabilities beyond the minimum capabilities described in the Limits and Formats chapters, including:

- Additional Image Capabilities
- Additional Buffer Capabilities
- Optional Semaphore Capabilities
- Optional Fence Capabilities

35.1. Additional Image Capabilities

Additional image capabilities, such as larger dimensions or additional sample counts for certain image types, or additional capabilities for *linear* tiling format images, are described in this section.

To query additional capabilities specific to image types, call:

```c
// Provided by VK_VERSION_1_0
VkResult vkGetPhysicalDeviceImageFormatProperties(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
    VkImageType type,
    VkImageTiling tiling,
    VkImageUsageFlags usage,
    VkImageCreateFlags flags,
    VkImageFormatProperties* pImageFormatProperties);
```

- **physicalDevice** is the physical device from which to query the image capabilities.
- **format** is a *VkFormat* value specifying the image format, corresponding to *VkImageCreateInfo::format*.
- **type** is a *VkImageType* value specifying the image type, corresponding to *VkImageCreateInfo::imageType*.
- **tiling** is a *VkImageTiling* value specifying the image tiling, corresponding to *VkImageCreateInfo::tiling*.
- **usage** is a bitmask of *VkImageUsageFlagBits* specifying the intended usage of the image, corresponding to *VkImageCreateInfo::usage*.
- **flags** is a bitmask of *VkImageCreateFlagBits* specifying additional parameters of the image, corresponding to *VkImageCreateInfo::flags*.
- **pImageFormatProperties** is a pointer to a *VkImageFormatProperties* structure in which capabilities are returned.

The **format**, **type**, **tiling**, **usage**, and **flags** parameters correspond to parameters that would be consumed by *vkCreateImage* (as members of *VkImageCreateInfo*).
If `format` is not a supported image format, or if the combination of `format`, `type`, `tiling`, `usage`, and `flags` is not supported for images, then `vkGetPhysicalDeviceImageFormatProperties` returns `VK_ERROR_FORMAT_NOT_SUPPORTED`.

The limitations on an image format that are reported by `vkGetPhysicalDeviceImageFormatProperties` have the following property: if `usage1` and `usage2` of type `VkImageUsageFlags` are such that the bits set in `usage1` are a subset of the bits set in `usage2`, and `flags1` and `flags2` of type `VkImageCreateFlags` are such that the bits set in `flags1` are a subset of the bits set in `flags2`, then the limitations for `usage1` and `flags1` must be no more strict than the limitations for `usage2` and `flags2`, for all values of `format`, `type`, and `tiling`.

### Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `format` must be a valid `VkFormat` value
- `type` must be a valid `VkImageType` value
- `tiling` must be a valid `VkImageTiling` value
- `usage` must be a valid combination of `VkImageUsageFlagBits` values
- `usage` must not be 0
- `flags` must be a valid combination of `VkImageCreateFlagBits` values
- `pImageFormatProperties` must be a valid pointer to a `VkImageFormatProperties` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_FORMAT_NOT_SUPPORTED`

The `VkImageFormatProperties` structure is defined as:
```c
typedef struct VkImageFormatProperties {
    VkExtent3D      maxExtent;
    uint32_t        maxMipLevels;
    uint32_t        maxArrayLayers;
    VkSampleCountFlags sampleCounts;
    VkDeviceSize    maxResourceSize;
} VkImageFormatProperties;
```

- **maxExtent** are the maximum image dimensions. See the Allowed Extent Values section below for how these values are constrained by `type`.

- **maxMipLevels** is the maximum number of mipmap levels. `maxMipLevels` must be equal to the number of levels in the complete mipmap chain based on the `maxExtent.width`, `maxExtent.height`, and `maxExtent.depth`, except when one of the following conditions is true, in which case it may instead be 1:
  - `vkGetPhysicalDeviceImageFormatProperties::tiling` was `VK_IMAGE_TILING_LINEAR`
  - the `VkPhysicalDeviceImageFormatInfo2::pNext` chain included a `VkPhysicalDeviceExternalImageFormatInfo` structure with a handle type included in the `handleTypes` member for which mipmap image support is not required
  - image format is one of the formats that require a sampler Y’CbCr conversion

- **maxArrayLayers** is the maximum number of array layers. `maxArrayLayers` must be no less than `VkPhysicalDeviceLimits::maxImageArrayLayers`, except when one of the following conditions is true, in which case it may instead be 1:
  - `tiling` is `VK_IMAGE_TILING_LINEAR`
  - `tiling` is `VK_IMAGE_TILING_OPTIMAL` and `type` is `VK_IMAGE_TYPE_3D`
  - `format` is one of the formats that require a sampler Y’CbCr conversion

- **sampleCounts** is a bitmask of `VkSampleCountFlagBits` specifying all the supported sample counts for this image as described below.

- **maxResourceSize** is an upper bound on the total image size in bytes, inclusive of all image subresources. Implementations may have an address space limit on total size of a resource, which is advertised by this property. `maxResourceSize` must be at least $2^{31}$.

  **Note**
  There is no mechanism to query the size of an image before creating it, to compare that size against `maxResourceSize`. If an application attempts to create an image that exceeds this limit, the creation will fail and `vkCreateImage` will return `VK_ERROR_OUT_OF_DEVICE_MEMORY`. While the advertised limit must be at least $2^{31}$, it may not be possible to create an image that approaches that size, particularly for `VK_IMAGE_TYPE_1D`.

If the combination of parameters to `vkGetPhysicalDeviceImageFormatProperties` is not supported by the implementation for use in `vkCreateImage`, then all members of `VkImageFormatProperties` will be filled with zero.
To query additional capabilities specific to image types, call:

```cpp
// Provided by VK_VERSION_1_1
VkResult vkGetPhysicalDeviceImageFormatProperties2(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceImageFormatInfo2* pImageFormatInfo,
    VkImageFormatProperties2* pImageFormatProperties);
```

- `physicalDevice` is the physical device from which to query the image capabilities.
- `pImageFormatInfo` is a pointer to a `VkPhysicalDeviceImageFormatInfo2` structure describing the parameters that would be consumed by `vkCreateImage`.
- `pImageFormatProperties` is a pointer to a `VkImageFormatProperties2` structure in which capabilities are returned.

`vkGetPhysicalDeviceImageFormatProperties2` behaves similarly to `vkGetPhysicalDeviceImageFormatProperties`, with the ability to return extended information in a `pNext` chain of output structures.

### Valid Usage (Implicit)

- VUID-vkGetPhysicalDeviceImageFormatProperties2-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkGetPhysicalDeviceImageFormatProperties2-pImageFormatInfo-parameter `pImageFormatInfo` must be a valid pointer to a valid `VkPhysicalDeviceImageFormatInfo2` structure
- VUID-vkGetPhysicalDeviceImageFormatProperties2-pImageFormatProperties-parameter `pImageFormatProperties` must be a valid pointer to a `VkImageFormatProperties2` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_FORMAT_NOT_SUPPORTED`
The `VkPhysicalDeviceImageFormatInfo2` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceImageFormatInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkFormat format;
    VkImageType type;
    VkImageTiling tiling;
    VkImageUsageFlags usage;
    VkImageCreateFlags flags;
} VkPhysicalDeviceImageFormatInfo2;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is `NULL` or a pointer to a structure extending this structure. The `pNext` chain of `VkPhysicalDeviceImageFormatInfo2` is used to provide additional image parameters to `vkGetPhysicalDeviceImageFormatProperties2`.
- `format` is a `VkFormat` value indicating the image format, corresponding to `VkImageCreateInfo::format`.
- `type` is a `VkImageType` value indicating the image type, corresponding to `VkImageCreateInfo::imageType`.
- `tiling` is a `VkImageTiling` value indicating the image tiling, corresponding to `VkImageCreateInfo::tiling`.
- `usage` is a bitmask of `VkImageUsageFlagBits` indicating the intended usage of the image, corresponding to `VkImageCreateInfo::usage`.
- `flags` is a bitmask of `VkImageCreateFlagBits` indicating additional parameters of the image, corresponding to `VkImageCreateInfo::flags`.

The members of `VkPhysicalDeviceImageFormatInfo2` correspond to the arguments to `vkGetPhysicalDeviceImageFormatProperties`, with `sType` and `pNext` added for extensibility.

**Valid Usage (Implicit)**

- VUID-VkPhysicalDeviceImageFormatInfo2-sType-sType
  `sType` must be `VK_STRUCTURE_TYPE_PHYSICALDEVICE_IMAGEFORMATINFO_2`

- VUID-VkPhysicalDeviceImageFormatInfo2-pNext-pNext
  Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkImageFormatListCreateInfo`, `VkImageStencilUsageCreateInfo`, or `VkPhysicalDeviceExternalImageFormatInfo`

- VUID-VkPhysicalDeviceImageFormatInfo2-sType-unique
  The `sType` value of each struct in the `pNext` chain must be unique

- VUID-VkPhysicalDeviceImageFormatInfo2-format-parameter
  `format` must be a valid `VkFormat` value
• **VUID-VkPhysicalDeviceImageFormatInfo2-type-parameter**
  *type* **must** be a valid *VkImageType* value

• **VUID-VkPhysicalDeviceImageFormatInfo2-tiling-parameter**
  *tiling* **must** be a valid *VkImageTiling* value

• **VUID-VkPhysicalDeviceImageFormatInfo2-usage-parameter**
  *usage* **must** be a valid combination of *VkImageUsageFlagBits* values

• **VUID-VkPhysicalDeviceImageFormatInfo2-usage-requiredbitmask**
  *usage* **must** not be 0

• **VUID-VkPhysicalDeviceImageFormatInfo2-flags-parameter**
  *flags* **must** be a valid combination of *VkImageCreateFlagBits* values

The *VkImageFormatProperties2* structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkImageFormatProperties2 {
    VkStructureType sType;
    void* pNext;
    VkImageFormatProperties imageFormatProperties;
} VkImageFormatProperties2;
```

• *sType* is a *VkStructureType* value identifying this structure.

• *pNext* is NULL or a pointer to a structure extending this structure. The *pNext* chain of *VkImageFormatProperties2* is used to allow the specification of additional capabilities to be returned from *vkGetPhysicalDeviceImageFormatProperties2*.

• *imageFormatProperties* is a *VkImageFormatProperties* structure in which capabilities are returned.

If the combination of parameters to *vkGetPhysicalDeviceImageFormatProperties2* is not supported by the implementation for use in *vkCreateImage*, then all members of *imageFormatProperties* will be filled with zero.

*Note*

Filling *imageFormatProperties* with zero for unsupported formats is an exception to the usual rule that output structures have undefined contents on error. This exception was unintentional, but is preserved for backwards compatibility. This exception only applies to *imageFormatProperties*, not *sType*, *pNext*, or any structures chained from *pNext*.

**Valid Usage**
Valid Usage (Implicit)

- VUID-VkImageFormatProperties2-sType-sType
  
  **sType must be** VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2

- VUID-VkImageFormatProperties2-pNext-pNext
  
  Each **pNext** member of any structure (including this one) in the **pNext** chain **must** be either NULL or a pointer to a valid instance of VkExternalImageFormatProperties or VkSamplerYcbcrConversionImageFormatProperties

- VUID-VkImageFormatProperties2-sType-unique
  
  The **sType** value of each struct in the **pNext** chain **must** be unique

To determine the image capabilities compatible with an external memory handle type, add a VkPhysicalDeviceExternalImageFormatInfo structure to the **pNext** chain of the VkPhysicalDeviceImageFormatInfo2 structure and a VkExternalImageFormatProperties structure to the **pNext** chain of the VkImageFormatProperties2 structure.

The VkPhysicalDeviceExternalImageFormatInfo structure is defined as:

```c
typedef struct VkPhysicalDeviceExternalImageFormatInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalImageFormatInfo;
```

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **handleType** is a VkExternalMemoryHandleTypeFlagBits value specifying the memory handle type that will be used with the memory associated with the image.

If **handleType** is 0, vkGetPhysicalDeviceImageFormatProperties2 will behave as if VkPhysicalDeviceExternalImageFormatInfo was not present, and VkExternalImageFormatProperties will be ignored.

If **handleType** is not compatible with the **format**, **type**, **tiling**, **usage**, and **flags** specified in VkPhysicalDeviceImageFormatInfo2, then vkGetPhysicalDeviceImageFormatProperties2 returns VK_ERROR_FORMAT_NOT_SUPPORTED.

Valid Usage (Implicit)

- VUID-VkPhysicalDeviceExternalImageFormatInfo-sType-sType
  
  **sType must be** VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_IMAGE_FORMAT_INFO

- VUID-VkPhysicalDeviceExternalImageFormatInfo-handleType-parameter
  
  If **handleType** is not 0, **handleType** **must** be a valid VkExternalMemoryHandleTypeFlagBits
Possible values of `VkPhysicalDeviceExternalImageFormatInfo::handleType`, specifying an external memory handle type, are:

```cpp
// Provided by VK_VERSION_1_1
typedef enum VkExternalMemoryHandleTypeFlagBits {
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT = 0x00000008,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT = 0x00000010,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT = 0x00000020,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT = 0x00000040,
} VkExternalMemoryHandleTypeFlagBits;
```

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT** specifies a POSIX file descriptor handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the POSIX system calls `dup`, `dup2`, `close`, and the non-standard system call `dup3`. Additionally, it must be transportable over a socket using an `SCM_RIGHTS` control message. It owns a reference to the underlying memory resource represented by its Vulkan memory object.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT** specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the functions `DuplicateHandle`, `CloseHandle`, `CompareObjectHandles`, `GetHandleInformation`, and `SetHandleInformation`. It owns a reference to the underlying memory resource represented by its Vulkan memory object.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT** specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying memory resource represented by its Vulkan memory object, and will therefore become invalid when all Vulkan memory objects associated with it are destroyed.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT** specifies an NT handle returned by `IDXGIResource1::CreateSharedHandle` referring to a Direct3D 10 or 11 texture resource. It owns a reference to the memory used by the Direct3D resource.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT** specifies a global share handle returned by `IDXGIResource::GetSharedHandle` referring to a Direct3D 10 or 11 texture resource. It does not own a reference to the underlying Direct3D resource, and will therefore become invalid when all Vulkan memory objects and Direct3D resources associated with it are destroyed.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT** specifies an NT handle returned by `ID3D12Device::CreateSharedHandle` referring to a Direct3D 12 heap resource. It owns a reference to the resources used by the Direct3D heap.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT** specifies an NT handle returned by `ID3D12Device::CreateSharedHandle` referring to a Direct3D 12 committed resource. It owns a reference to the memory used by the Direct3D resource.
Some external memory handle types can only be shared within the same underlying physical device and/or the same driver version, as defined in the following table:

**Table 59. External memory handle types compatibility**

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
</tbody>
</table>

// Provided by VK_VERSION_1_1
typedef VkFlags VkExternalMemoryHandleTypeFlags;

VkExternalMemoryHandleTypeFlags is a bitmask type for setting a mask of zero or more VkExternalMemoryHandleTypeFlagBits.

The VkExternalImageFormatProperties structure is defined as:

// Provided by VK_VERSION_1_1
typedef struct VkExternalImageFormatProperties {
    VkStructureType sType;
    void* pNext;
    VkExternalMemoryProperties externalMemoryProperties;
} VkExternalImageFormatProperties;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **externalMemoryProperties** is a VkExternalMemoryProperties structure specifying various capabilities of the external handle type when used with the specified image creation parameters.

**Valid Usage (Implicit)**

- VUID-VkExternalImageFormatProperties-sType-sType
The `VkExternalMemoryProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkExternalMemoryProperties {
    VkExternalMemoryFeatureFlags externalMemoryFeatures;
    VkExternalMemoryHandleTypeFlags exportFromImportedHandleTypes;
    VkExternalMemoryHandleTypeFlags compatibleHandleTypes;
} VkExternalMemoryProperties;
```

- `externalMemoryFeatures` is a bitmask of `VkExternalMemoryFeatureFlagBits` specifying the features of `handleType`.
- `exportFromImportedHandleTypes` is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying which types of imported handle `handleType` can be exported from.
- `compatibleHandleTypes` is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying handle types which can be specified at the same time as `handleType` when creating an image compatible with external memory.

`compatibleHandleTypes` must include at least `handleType`. Inclusion of a handle type in `compatibleHandleTypes` does not imply the values returned in `VkImageFormatProperties2` will be the same when `VkPhysicalDeviceExternalImageFormatInfo::handleType` is set to that type. The application is responsible for querying the capabilities of all handle types intended for concurrent use in a single image and intersecting them to obtain the compatible set of capabilities.

Bits which may be set in `VkExternalMemoryProperties::externalMemoryFeatures`, specifying features of an external memory handle type, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkExternalMemoryFeatureFlagBits {
    VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT = 0x00000001,
    VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT = 0x00000002,
    VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT = 0x00000004,
} VkExternalMemoryFeatureFlagBits;
```

- `VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT` specifies that images or buffers created with the specified parameters and handle type must use the mechanisms defined by `VkMemoryDedicatedRequirements` and `VkMemoryDedicatedAllocateInfo` to create (or import) a dedicated allocation for the image or buffer.
- `VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT` specifies that handles of this type can be exported from Vulkan memory objects.
- `VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT` specifies that handles of this type can be imported as Vulkan memory objects.

Because their semantics in external APIs roughly align with that of an image or buffer with a
dedicated allocation in Vulkan, implementations are **required** to report
`VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT` for the following external handle types:

- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT`
- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT`
- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT`

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkExternalMemoryFeatureFlags;
```

`VkExternalMemoryFeatureFlags` is a bitmask type for setting a mask of zero or more
`VkExternalMemoryFeatureFlagBits`.

To determine the number of combined image samplers required to support a multi-planar format,
add `VkSamplerYcbcrConversionImageFormatProperties` to the `pNext` chain of the

The `VkSamplerYcbcrConversionImageFormatProperties` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkSamplerYcbcrConversionImageFormatProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t combinedImageSamplerDescriptorCount;
} VkSamplerYcbcrConversionImageFormatProperties;
```

- `sType` is a `VkStructureType` value identifying this structure.
- `pNext` is NULL or a pointer to a structure extending this structure.
- `combinedImageSamplerDescriptorCount` is the number of combined image sampler descriptors that
  the implementation uses to access the format.

### Valid Usage (Implicit)

- VUID-VkSamplerYcbcrConversionImageFormatProperties-sType-sType
  
  `sType` **must** be `VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_IMAGE_FORMAT_PROPERTIES`

`combinedImageSamplerDescriptorCount` is a number between 1 and the number of planes in the
format. A descriptor set layout binding with immutable YCbCr conversion samplers will have a maximum
`combinedImageSamplerDescriptorCount` which is the maximum across all formats supported by its samplers of the
`combinedImageSamplerDescriptorCount` for each format. Descriptor sets with
that layout will internally use that maximum `combinedImageSamplerDescriptorCount`
descriptors for each descriptor in the binding. This expanded number of descriptors will be
consumed from the descriptor pool when a descriptor set is allocated, and counts towards the
`maxDescriptorSetSamplers`, `maxDescriptorSetSampledImages`, `maxPerStageDescriptorSamplers`, and
`maxPerStageDescriptorSampledImages` limits.
Note

All descriptors in a binding use the same maximum combinedImageSamplerDescriptorCount descriptors to allow implementations to use a uniform stride for dynamic indexing of the descriptors in the binding.

For example, consider a descriptor set layout binding with two descriptors and immutable samplers for multi-planar formats that have VkSamplerYcbcrConversionImageFormatProperties::combinedImageSamplerDescriptorCount values of 2 and 3 respectively. There are two descriptors in the binding and the maximum combinedImageSamplerDescriptorCount is 3, so descriptor sets with this layout consume 6 descriptors from the descriptor pool. To create a descriptor pool that allows allocating four descriptor sets with this layout, descriptorCount must be at least 24.

35.1.1. Supported Sample Counts

vkGetPhysicalDeviceImageFormatProperties returns a bitmask of VkSampleCountFlagBits in sampleCounts specifying the supported sample counts for the image parameters.

sampleCounts will be set to VK_SAMPLE_COUNT_1_BIT if at least one of the following conditions is true:

- tiling is VK_IMAGE_TILING_LINEAR
- type is not VK_IMAGE_TYPE_2D
- flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT

- Neither the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag nor the VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties is set
- VkPhysicalDeviceExternalImageFormatInfo::handleType is an external handle type for which multisampled image support is not required.
- format is one of the formats that require a sampler Y’CbCr conversion

Otherwise, the bits set in sampleCounts will be the sample counts supported for the specified values of usage and format. For each bit set in usage, the supported sample counts relate to the limits in VkPhysicalDeviceLimits as follows:

- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT and format is a floating- or fixed-point color format, a superset of VkPhysicalDeviceLimits::framebufferColorSampleCounts
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT and format is an integer format, a superset of VkPhysicalDeviceVulkan12Properties::framebufferIntegerColorSampleCounts
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a depth component, a superset of VkPhysicalDeviceLimits::framebufferDepthSampleCounts
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a stencil component, a superset of VkPhysicalDeviceLimits::framebufferStencilSampleCounts
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a color component, a superset of VkPhysicalDeviceLimits::sampledImageColorSampleCounts
If `usage` includes `VK_IMAGE_USAGE_SAMPLED_BIT`, and `format` includes a depth component, a superset of `VkPhysicalDeviceLimits::sampledImageDepthSampleCounts`

If `usage` includes `VK_IMAGE_USAGE_SAMPLED_BIT`, and `format` is an integer format, a superset of `VkPhysicalDeviceLimits::sampledImageIntegerSampleCounts`

If `usage` includes `VK_IMAGE_USAGE_STORAGE_BIT`, a superset of `VkPhysicalDeviceLimits::storageImageSampleCounts`

If multiple bits are set in `usage`, `sampleCounts` will be the intersection of the per-usage values described above.

If none of the bits described above are set in `usage`, then there is no corresponding limit in `VkPhysicalDeviceLimits`. In this case, `sampleCounts` must include at least `VK_SAMPLE_COUNT_1_BIT`.

35.1.2. Allowed Extent Values Based On Image Type

Implementations may support extent values larger than the required minimum/maximum values for certain types of images. `VkImageFormatProperties::maxExtent` for each type is subject to the constraints below.

```
Note
Implementations must support images with dimensions up to the required minimum/maximum values for all types of images. It follows that the query for additional capabilities must return extent values that are at least as large as the required values.
```

For `VK_IMAGE_TYPE_1D`:

- `maxExtent.width` ≥ `VkPhysicalDeviceLimits::maxImageDimension1D`
- `maxExtent.height` = 1
- `maxExtent.depth` = 1

For `VK_IMAGE_TYPE_2D` when `flags` does not contain `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`:

- `maxExtent.width` ≥ `VkPhysicalDeviceLimits::maxImageDimension2D`
- `maxExtent.height` ≥ `VkPhysicalDeviceLimits::maxImageDimension2D`
- `maxExtent.depth` = 1

For `VK_IMAGE_TYPE_2D` when `flags` contains `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`:

- `maxExtent.width` ≥ `VkPhysicalDeviceLimits::maxImageDimensionCube`
- `maxExtent.height` ≥ `VkPhysicalDeviceLimits::maxImageDimensionCube`
- `maxExtent.depth` = 1

For `VK_IMAGE_TYPE_3D`:

- `maxExtent.width` ≥ `VkPhysicalDeviceLimits::maxImageDimension3D`
maxExtent.height ≥ VkPhysicalDeviceLimits::maxImageDimension3D
maxExtent.depth ≥ VkPhysicalDeviceLimits::maxImageDimension3D

35.2. Additional Buffer Capabilities

To query the external handle types supported by buffers, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceExternalBufferProperties(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceExternalBufferInfo* pExternalBufferInfo,
    VkExternalBufferProperties* pExternalBufferProperties);
```

- `physicalDevice` is the physical device from which to query the buffer capabilities.
- `pExternalBufferInfo` is a pointer to a `VkPhysicalDeviceExternalBufferInfo` structure describing the parameters that would be consumed by `vkCreateBuffer`.
- `pExternalBufferProperties` is a pointer to a `VkExternalBufferProperties` structure in which capabilities are returned.

Valid Usage (Implicit)

- VUID-vkGetPhysicalDeviceExternalBufferProperties-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle.
- VUID-vkGetPhysicalDeviceExternalBufferProperties-pExternalBufferInfo-parameter `pExternalBufferInfo` must be a valid pointer to a valid `VkPhysicalDeviceExternalBufferInfo` structure.

The `VkPhysicalDeviceExternalBufferInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceExternalBufferInfo {
    VkStructureType sType;
    const void*pNext;
    VkBufferCreateFlags flags;
    VkBufferUsageFlags usage;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalBufferInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
• \texttt{pNext} is \texttt{NULL} or a pointer to a structure extending this structure.
• \texttt{flags} is a bitmask of \texttt{VkBufferCreateFlagBits} describing additional parameters of the buffer, corresponding to \texttt{VkBufferCreateInfo::flags}.
• \texttt{usage} is a bitmask of \texttt{VkBufferUsageFlagBits} describing the intended usage of the buffer, corresponding to \texttt{VkBufferCreateInfo::usage}.
• \texttt{handleType} is a \texttt{VkExternalMemoryHandleTypeFlagBits} value specifying the memory handle type that will be used with the memory associated with the buffer.

### Valid Usage (Implicit)

- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-sType-sType} \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_INFO}
- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-pNext-pNext} \texttt{pNext} must be \texttt{NULL}
- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-flags-parameter} \texttt{flags} must be a valid combination of \texttt{VkBufferCreateFlagBits} values
- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-usage-parameter} \texttt{usage} must be a valid combination of \texttt{VkBufferUsageFlagBits} values
- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-usage-required bitmask} \texttt{usage} must not be \texttt{0}
- \texttt{VUID-VkPhysicalDeviceExternalBufferInfo-handleType-parameter} \texttt{handleType} must be a valid \texttt{VkExternalMemoryHandleTypeFlagBits} value

The \texttt{VkExternalBufferProperties} structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkExternalBufferProperties {
    VkStructureType sType;
    void* pNext;
    VkExternalMemoryProperties externalMemoryProperties;
} VkExternalBufferProperties;
```

- \texttt{sType} is a \texttt{VkStructureType} value identifying this structure.
- \texttt{pNext} is \texttt{NULL} or a pointer to a structure extending this structure.
- \texttt{externalMemoryProperties} is a \texttt{VkExternalMemoryProperties} structure specifying various capabilities of the external handle type when used with the specified buffer creation parameters.

### Valid Usage (Implicit)

- \texttt{VUID-VkExternalBufferProperties-sType-sType} \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES}
35.3. Optional Semaphore Capabilities

Semaphores may support import and export of their payload to external handles. To query the external handle types supported by semaphores, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceExternalSemaphoreProperties(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceExternalSemaphoreInfo* pExternalSemaphoreInfo,
    VkExternalSemaphoreProperties* pExternalSemaphoreProperties);
```

- `physicalDevice` is the physical device from which to query the semaphore capabilities.
- `pExternalSemaphoreInfo` is a pointer to a `VkPhysicalDeviceExternalSemaphoreInfo` structure describing the parameters that would be consumed by `vkCreateSemaphore`.
- `pExternalSemaphoreProperties` is a pointer to a `VkExternalSemaphoreProperties` structure in which capabilities are returned.

**Valid Usage (Implicit)**

- VUID-vkGetPhysicalDeviceExternalSemaphoreProperties-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkGetPhysicalDeviceExternalSemaphoreProperties-pExternalSemaphoreInfo-parameter `pExternalSemaphoreInfo` must be a valid pointer to a valid `VkPhysicalDeviceExternalSemaphoreInfo` structure
- VUID-vkGetPhysicalDeviceExternalSemaphoreProperties-pExternalSemaphoreProperties-parameter `pExternalSemaphoreProperties` must be a valid pointer to a `VkExternalSemaphoreProperties` structure

The `VkPhysicalDeviceExternalSemaphoreInfo` structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceExternalSemaphoreInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalSemaphoreHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalSemaphoreInfo;
```

- `sType` is a `VkStructureType` value identifying this structure.
• **pNext** is NULL or a pointer to a structure extending this structure.

• **handleType** is a [VkExternalSemaphoreHandleTypeFlagBits](https://www.khronos.org/registry/vulkan/specs/1.1-extensions/vulkan-1.1-extensions.html#VkExternalSemaphoreHandleTypeFlagBits) value specifying the external semaphore handle type for which capabilities will be returned.

---

**Valid Usage (Implicit)**

- **VUID-VkPhysicalDeviceExternalSemaphoreInfo-sType-sType**
  sType must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO`

- **VUID-VkPhysicalDeviceExternalSemaphoreInfo-pNext-pNext**
  pNext must be NULL or a pointer to a valid instance of `VkSemaphoreTypeCreateInfo`

- **VUID-VkPhysicalDeviceExternalSemaphoreInfo-sType-unique**
  The sType value of each struct in the pNext chain must be unique

- **VUID-VkPhysicalDeviceExternalSemaphoreInfo-handleType-parameter**
  handleType must be a valid [VkExternalSemaphoreHandleTypeFlagBits](https://www.khronos.org/registry/vulkan/specs/1.1-extensions/vulkan-1.1-extensions.html#VkExternalSemaphoreHandleTypeFlagBits) value

---

Bits which **may** be set in `VkPhysicalDeviceExternalSemaphoreInfo::handleType`, specifying an external semaphore handle type, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkExternalSemaphoreHandleTypeFlagBits {
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT = 0x00000008,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT = 0x00000010,
} VkExternalSemaphoreHandleTypeFlagBits;
```

• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT** specifies a POSIX file descriptor handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the POSIX system calls `dup`, `dup2`, `close`, and the non-standard system call `dup3`. Additionally, it must be transportable over a socket using an `SCM_RIGHTS` control message. It owns a reference to the underlying synchronization primitive represented by its Vulkan semaphore object.

• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT** specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the functions `DuplicateHandle`, `CloseHandle`, `CompareObjectHandles`, `GetHandleInformation`, and `SetHandleInformation`. It owns a reference to the underlying synchronization primitive represented by its Vulkan semaphore object.

• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT** specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying synchronization primitive represented by its Vulkan semaphore object, and will therefore become invalid when all Vulkan semaphore objects associated with it are destroyed.
• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT** specifies an NT handle returned by `ID3D12Device::CreateSharedHandle` referring to a Direct3D 12 fence, or `ID3D11Device5::CreateFence` referring to a Direct3D 11 fence. It owns a reference to the underlying synchronization primitive associated with the Direct3D fence.

• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D11_FENCE_BIT** is an alias of **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT** with the same meaning. It is provided for convenience and code clarity when interacting with D3D11 fences.

• **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT** specifies a POSIX file descriptor handle to a Linux Sync File or Android Fence object. It can be used with any native API accepting a valid sync file or fence as input. It owns a reference to the underlying synchronization primitive associated with the file descriptor. Implementations which support importing this handle type must accept any type of sync or fence FD supported by the native system they are running on.

**Note**

Handles of type **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT** generated by the implementation may represent either Linux Sync Files or Android Fences at the implementation’s discretion. Applications should only use operations defined for both types of file descriptors, unless they know via means external to Vulkan the type of the file descriptor, or are prepared to deal with the system-defined operation failures resulting from using the wrong type.
Some external semaphore handle types can only be shared within the same underlying physical
device and/or the same driver version, as defined in the following table:

**Table 60. External semaphore handle types compatibility**

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_ZIRCON_EVENT_BIT_FUCHSIA</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
</tbody>
</table>

// Provided by VK_VERSION_1_1

typedef VkFlags VkExternalSemaphoreHandleTypeFlags;

VkExternalSemaphoreHandleTypeFlags is a bitmask type for setting a mask of zero or more
VkExternalSemaphoreHandleTypeFlagBits.

The VkExternalSemaphoreProperties structure is defined as:

// Provided by VK_VERSION_1_1
typedef struct VkExternalSemaphoreProperties {
    VkStructureType sType;
    void* pNext;
    VkExternalSemaphoreHandleTypeFlags exportFromImportedHandleTypes;
    VkExternalSemaphoreHandleTypeFlags compatibleHandleTypes;
    VkExternalSemaphoreFeatureFlags externalSemaphoreFeatures;
} VkExternalSemaphoreProperties;

- **sType** is a VkStructureType value identifying this structure.
- **pNext** is NULL or a pointer to a structure extending this structure.
- **exportFromImportedHandleTypes** is a bitmask of VkExternalSemaphoreHandleTypeFlagBits
  specifying which types of imported handle handleType can be exported from.
- **compatibleHandleTypes** is a bitmask of VkExternalSemaphoreHandleTypeFlagBits specifying
  handle types which can be specified at the same time as handleType when creating a semaphore.
- **externalSemaphoreFeatures** is a bitmask of VkExternalSemaphoreFeatureFlagBits describing the
  features of handleType.
If \texttt{handleType} is not supported by the implementation, then \texttt{VkExternalSemaphoreProperties::externalSemaphoreFeatures} will be set to zero.

### Valid Usage (Implicit)

- \texttt{VUID-VkExternalSemaphoreProperties-sType-sType} \texttt{sType must be VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES}
- \texttt{VUID-VkExternalSemaphoreProperties-pNext-pNext} \texttt{pNext must be NULL}

Bits which \textit{may} be set in \texttt{VkExternalSemaphoreProperties::externalSemaphoreFeatures}, specifying the features of an external semaphore handle type, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkExternalSemaphoreFeatureFlagBits {
    VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT = 0x00000001,
    VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT = 0x00000002,
} VkExternalSemaphoreFeatureFlagBits;
```

- \texttt{VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT} specifies that handles of this type \textit{can} be exported from Vulkan semaphore objects.
- \texttt{VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT} specifies that handles of this type \textit{can} be imported as Vulkan semaphore objects.

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkExternalSemaphoreFeatureFlags;
```

\texttt{VkExternalSemaphoreFeatureFlags} is a bitmask type for setting a mask of zero or more \texttt{VkExternalSemaphoreFeatureFlagBits}.

## 35.4. Optional Fence Capabilities

Fences \textit{may} support import and export of their \texttt{payload} to external handles. To query the external handle types supported by fences, call:

```c
// Provided by VK_VERSION_1_1
void vkGetPhysicalDeviceExternalFenceProperties(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceExternalFenceInfo* pExternalFenceInfo,
    VkExternalFenceProperties* pExternalFenceProperties);
```

- \texttt{physicalDevice} is the physical device from which to query the fence capabilities.
- \texttt{pExternalFenceInfo} is a pointer to a \texttt{VkPhysicalDeviceExternalFenceInfo} structure describing the
parameters that would be consumed by \texttt{vkCreateFence}.

- \texttt{pExternalFenceProperties} is a pointer to a \texttt{VkExternalFenceProperties} structure in which capabilities are returned.

### Valid Usage (Implicit)

- VUID\texttt{-vkCreateFence-}physicalDevice-parameter \texttt{physicalDevice} must be a valid \texttt{VkPhysicalDevice} handle
- VUID\texttt{-vkCreateFence-}pExternalFenceProperties-parameter \texttt{pExternalFenceProperties} must be a valid pointer to a \texttt{VkExternalFenceProperties} structure
- VUID\texttt{-vkCreateFence-}pExternalFenceProperties-parameter \texttt{pExternalFenceProperties} must be a valid pointer to a \texttt{VkExternalFenceProperties} structure

The \texttt{VkPhysicalDeviceExternalFenceInfo} structure is defined as:

```c
// Provided by VK_VERSION_1_1
typedef struct VkPhysicalDeviceExternalFenceInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalFenceHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalFenceInfo;
```

- \texttt{sType} is a \texttt{VkStructureType} value identifying this structure.
- \texttt{pNext} is \texttt{NULL} or a pointer to a structure extending this structure.
- \texttt{handleType} is a \texttt{VkExternalFenceHandleTypeFlagBits} value specifying an external fence handle type for which capabilities will be returned.

\begin{itemize}
  \item \textbf{Note} Handles of type \texttt{VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT} generated by the implementation may represent either Linux Sync Files or Android Fences at the implementation’s discretion. Applications \textbf{should} only use operations defined for both types of file descriptors, unless they know via means external to Vulkan the type of the file descriptor, or are prepared to deal with the system-defined operation failures resulting from using the wrong type.
\end{itemize}

### Valid Usage (Implicit)

- VUID\texttt{-vkCreateFence-}sType-sType \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_FENCE_INFO}
- VUID\texttt{-vkCreateFence-}pNext-pNext \texttt{pNext} must be \texttt{NULL}


- VUID-VkPhysicalDeviceExternalFenceInfo-handleType-parameter

  handleType **must** be a valid `VkExternalFenceHandleTypeFlagBits` value

Bits which **may** be set in

- `VkPhysicalDeviceExternalFenceInfo::handleType`
- `VkExternalFenceProperties::exportFromImportedHandleTypes`
- `VkExternalFenceProperties::compatibleHandleTypes`

indicate external fence handle types, and are:

```cpp
// Provided by VK_VERSION_1_1
typedef enum VkExternalFenceHandleTypeFlagBits {
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT = 0x00000008,
} VkExternalFenceHandleTypeFlagBits;
```

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT** specifies a POSIX file descriptor handle that has only limited valid usage outside of Vulkan and other compatible APIs. It **must** be compatible with the POSIX system calls `dup`, `dup2`, `close`, and the non-standard system call `dup3`. Additionally, it **must** be transportable over a socket using an `SCM_RIGHTS` control message. It owns a reference to the underlying synchronization primitive represented by its Vulkan fence object.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT** specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It **must** be compatible with the functions `DuplicateHandle`, `CloseHandle`, `CompareObjectHandles`, `GetHandleInformation`, and `SetHandleInformation`. It owns a reference to the underlying synchronization primitive represented by its Vulkan fence object.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT** specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying synchronization primitive represented by its Vulkan fence object, and will therefore become invalid when all Vulkan fence objects associated with it are destroyed.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT** specifies a POSIX file descriptor handle to a Linux Sync File or Android Fence. It can be used with any native API accepting a valid sync file or fence as input. It owns a reference to the underlying synchronization primitive associated with the file descriptor. Implementations which support importing this handle type **must** accept any type of sync or fence FD supported by the native system they are running on.
Some external fence handle types can only be shared within the same underlying physical device and/or the same driver version, as defined in the following table:

### Table 61. External fence handle types compatibility

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
</tbody>
</table>

// Provided by VK_VERSION_1_1
typedef VkFlags VkExternalFenceHandleTypeFlags;

VkExternalFenceHandleTypeFlags is a bitmask type for setting a mask of zero or more VkExternalFenceHandleTypeFlagBits.

The VkExternalFenceProperties structure is defined as:

// Provided by VK_VERSION_1_1
typedef struct VkExternalFenceProperties {
  VkStructureType sType;
  void* pNext;
  VkExternalFenceHandleTypeFlags exportFromImportedHandleTypes;
  VkExternalFenceHandleTypeFlags compatibleHandleTypes;
  VkExternalFenceFeatureFlags externalFenceFeatures;
} VkExternalFenceProperties;

- exportFromImportedHandleTypes is a bitmask of VkExternalFenceHandleTypeFlagBits indicating which types of imported handle handleType can be exported from.
- compatibleHandleTypes is a bitmask of VkExternalFenceHandleTypeFlagBits specifying handle types which can be specified at the same time as handleType when creating a fence.
- externalFenceFeatures is a bitmask of VkExternalFenceFeatureFlagBits indicating the features of handleType.

If handleType is not supported by the implementation, then VkExternalFenceProperties::externalFenceFeatures will be set to zero.

**Valid Usage (Implicit)**

- VUID-VkExternalFenceProperties-sType-sType
  sType must be VK_STRUCTURE_TYPE_EXTERNAL_FENCE_PROPERTIES
Bits which **may** be set in `VkExternalFenceProperties::externalFenceFeatures`, indicating features of a fence external handle type, are:

```c
// Provided by VK_VERSION_1_1
typedef enum VkExternalFenceFeatureFlagBits {
    VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT = 0x00000001,
    VK_EXTERNAL_FENCE_FEATURE_IMPORTABLE_BIT = 0x00000002,
} VkExternalFenceFeatureFlagBits;
```

- **VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT** specifies handles of this type **can** be exported from Vulkan fence objects.
- **VK_EXTERNAL_FENCE_FEATURE_IMPORTABLE_BIT** specifies handles of this type **can** be imported to Vulkan fence objects.

```c
// Provided by VK_VERSION_1_1
typedef VkFlags VkExternalFenceFeatureFlags;
```

`VkExternalFenceFeatureFlags` is a bitmask type for setting a mask of zero or more `VkExternalFenceFeatureFlagBits`. 

**VUID-VkExternalFenceProperties-pNext-pNext**  
`pNext` **must** be **NULL**
Chapter 36. Debugging

To aid developers in tracking down errors in the application's use of Vulkan, particularly in combination with an external debugger or profiler, debugging extensions may be available.

The `VkObjectType` enumeration defines values, each of which corresponds to a specific Vulkan handle type. These values can be used to associate debug information with a particular type of object through one or more extensions.

```c
// Provided by VK_VERSION_1_0
typedef enum VkObjectType {
    VK_OBJECT_TYPE_UNKNOWN = 0,
    VK_OBJECT_TYPE_INSTANCE = 1,
    VK_OBJECT_TYPE_PHYSICAL_DEVICE = 2,
    VK_OBJECT_TYPE_DEVICE = 3,
    VK_OBJECT_TYPE_QUEUE = 4,
    VK_OBJECT_TYPE_SEMAPHORE = 5,
    VK_OBJECT_TYPE_COMMAND_BUFFER = 6,
    VK_OBJECT_TYPE_FENCE = 7,
    VK_OBJECT_TYPE_DEVICE_MEMORY = 8,
    VK_OBJECT_TYPE_BUFFER = 9,
    VK_OBJECT_TYPE_IMAGE = 10,
    VK_OBJECT_TYPE_EVENT = 11,
    VK_OBJECT_TYPE_QUERY_POOL = 12,
    VK_OBJECT_TYPE_BUFFER_VIEW = 13,
    VK_OBJECT_TYPE_IMAGE_VIEW = 14,
    VK_OBJECT_TYPE_SHADER_MODULE = 15,
    VK_OBJECT_TYPE_PIPELINE_CACHE = 16,
    VK_OBJECT_TYPE_PIPELINE_LAYOUT = 17,
    VK_OBJECT_TYPE_RENDER_PASS = 18,
    VK_OBJECT_TYPE_PIPELINE = 19,
    VK_OBJECT_TYPE_DESCRIPTOR_SET_LAYOUT = 20,
    VK_OBJECT_TYPE_SAMPLER = 21,
    VK_OBJECT_TYPE_DESCRIPTOR_POOL = 22,
    VK_OBJECT_TYPE_DESCRIPTOR_SET = 23,
    VK_OBJECT_TYPE_FRAMEBUFFER = 24,
    VK_OBJECT_TYPE_COMMAND_POOL = 25,
    // Provided by VK_VERSION_1_1
    VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION = 1000156000,
    // Provided by VK_VERSION_1_1
    VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE = 1000085000,
    // Provided by VK_VERSION_1_3
    VK_OBJECT_TYPE_PRIVATE_DATA_SLOT = 1000295000,
} VkObjectType;
```

Table 62. `VkObjectType` and Vulkan Handle Relationship

<table>
<thead>
<tr>
<th><code>VkObjectType</code></th>
<th>Vulkan Handle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_OBJECT_TYPE_UNKNOWN</td>
<td>Unknown/Undefined Handle</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>VkObjectType</th>
<th>Vulkan Handle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_OBJECT_TYPE_INSTANCE</td>
<td>VkInstance</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PHYSICAL_DEVICE</td>
<td>VkPhysicalDevice</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DEVICE</td>
<td>VkDevice</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_QUEUE</td>
<td>VkQueue</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SEMAPHORE</td>
<td>VkSemaphore</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_COMMAND_BUFFER</td>
<td>VkCommandBuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_FENCE</td>
<td>VkFence</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DEVICE_MEMORY</td>
<td>VkDeviceMemory</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_BUFFER</td>
<td>VkBuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_IMAGE</td>
<td>VkImage</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_EVENT</td>
<td>VkEvent</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_QUERY_POOL</td>
<td>VkQueryPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_BUFFER_VIEW</td>
<td>VkBufferView</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_IMAGE_VIEW</td>
<td>VkImageView</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SHADER_MODULE</td>
<td>VkShaderModule</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE_CACHE</td>
<td>VkPipelineCache</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE_LAYOUT</td>
<td>VkPipelineLayout</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_RENDER_PASS</td>
<td>VkRenderPass</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE</td>
<td>VkPipeline</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_SET_LAYOUT</td>
<td>VkDescriptorSetLayout</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SAMPLER</td>
<td>VkSampler</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_POOL</td>
<td>VkDescriptorPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_SET</td>
<td>VkDescriptorSet</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_FRAMEBUFFER</td>
<td>VkFramebuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_COMMAND_POOL</td>
<td>VkCommandPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION</td>
<td>VkSamplerYcbcrConversion</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE</td>
<td>VkDescriptorUpdateTemplate</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PRIVATE_DATA_SLOT</td>
<td>VkPrivateDataSlot</td>
</tr>
</tbody>
</table>

If this Specification was generated with any such extensions included, they will be described in the remainder of this chapter.

### 36.1. Active Tooling Information

Information about tools providing debugging, profiling, or similar services, active for a given
physical device, can be obtained by calling:

```c
// Provided by VK_VERSION_1_3
VkResult vkGetPhysicalDeviceToolProperties(
    VkPhysicalDevice physicalDevice,
    uint32_t* pToolCount,
    VkPhysicalDeviceToolProperties* pToolProperties);
```

- `physicalDevice` is the handle to the physical device to query for active tools.
- `pToolCount` is a pointer to an integer describing the number of tools active on `physicalDevice`.
- `pToolProperties` is either `NULL` or a pointer to an array of `VkPhysicalDeviceToolProperties` structures.

If `pToolProperties` is `NULL`, then the number of tools currently active on `physicalDevice` is returned in `pToolCount`. Otherwise, `pToolCount` must point to a variable set by the user to the number of elements in the `pToolProperties` array, and on return the variable is overwritten with the number of structures actually written to `pToolProperties`. If `pToolCount` is less than the number of currently active tools, at most `pToolCount` structures will be written.

The count and properties of active tools may change in response to events outside the scope of the specification. An application should assume these properties might change at any given time.

### Valid Usage (Implicit)

- VUID-vkGetPhysicalDeviceToolProperties-physicalDevice-parameter `physicalDevice` must be a valid `VkPhysicalDevice` handle
- VUID-vkGetPhysicalDeviceToolProperties-pToolCount-parameter `pToolCount` must be a valid pointer to a `uint32_t` value
- VUID-vkGetPhysicalDeviceToolProperties-pToolProperties-parameter
  - If the value referenced by `pToolCount` is not 0, and `pToolProperties` is not `NULL`, `pToolProperties` must be a valid pointer to an array of `pToolCount` `VkPhysicalDeviceToolProperties` structures

### Return Codes

**Success**

- VK_SUCCESS
- VK_INCOMPLETE

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY

The `VkPhysicalDeviceToolProperties` structure is defined as:
typedef struct VkPhysicalDeviceToolProperties {
    VkStructureType sType;
    void* pNext;
    char name[VK_MAX_EXTENSION_NAME_SIZE];
    char version[VK_MAX_EXTENSION_NAME_SIZE];
    VkToolPurposeFlags purposes;
    char description[VK_MAX_DESCRIPTION_SIZE];
    char layer[VK_MAX_EXTENSION_NAME_SIZE];
} VkPhysicalDeviceToolProperties;

• sType is a VkStructureType value identifying this structure.
• pNext is NULL or a pointer to a structure extending this structure.
• name is a null-terminated UTF-8 string containing the name of the tool.
• version is a null-terminated UTF-8 string containing the version of the tool.
• purposes is a bitmask of VkToolPurposeFlagBits which is populated with purposes supported by the tool.
• description is a null-terminated UTF-8 string containing a description of the tool.
• layer is a null-terminated UTF-8 string containing the name of the layer implementing the tool, if the tool is implemented in a layer - otherwise it may be an empty string.

Valid Usage (Implicit)

• VUID-VkPhysicalDeviceToolProperties-sType-sType
  sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TOOL_PROPERTIES
• VUID-VkPhysicalDeviceToolProperties-pNext-pNext
  pNext must be NULL

Bits which can be set in VkPhysicalDeviceToolProperties::purposes, specifying the purposes of an active tool, are:

typedef enum VkToolPurposeFlagBits {
    VK_TOOL_PURPOSE_VALIDATION_BIT = 0x00000001,
    VK_TOOL_PURPOSE_PROFILING_BIT = 0x00000002,
    VK_TOOL_PURPOSE_TRACING_BIT = 0x00000004,
    VK_TOOL_PURPOSE_ADDITIONAL_FEATURES_BIT = 0x00000008,
    VK_TOOL_PURPOSE_MODIFYING_FEATURES_BIT = 0x00000010,
    VK_TOOL_PURPOSE_VALIDATION_BIT_EXT = VK_TOOL_PURPOSE_VALIDATION_BIT,
    VK_TOOL_PURPOSE_PROFILING_BIT_EXT = VK_TOOL_PURPOSE_PROFILING_BIT,
    VK_TOOL_PURPOSE_TRACING_BIT_EXT = VK_TOOL_PURPOSE_TRACING_BIT,
    VK_TOOL_PURPOSE_ADDITIONAL_FEATURES_BIT_EXT =
    VK_TOOL_PURPOSE_MODIFYING_FEATURES_BIT_EXT =
• **VK_TOOL_PURPOSE_VALIDATION_BIT** specifies that the tool provides validation of API usage.

• **VK_TOOL_PURPOSE_PROFILING_BIT** specifies that the tool provides profiling of API usage.

• **VK_TOOL_PURPOSE_TRACING_BIT** specifies that the tool is capturing data about the application’s API usage, including anything from simple logging to capturing data for later replay.

• **VK_TOOL_PURPOSE_ADDITIONAL_FEATURES_BIT** specifies that the tool provides additional API features/extensions on top of the underlying implementation.

• **VK_TOOL_PURPOSE_MODIFYING_FEATURES_BIT** specifies that the tool modifies the API features/limits/extensions presented to the application.

```c
// Provided by VK_VERSION_1_3
typedef VkFlags VkToolPurposeFlags;

VkToolPurposeFlags is a bitmask type for setting a mask of zero or more VkToolPurposeFlagBits.
Appendix A: Vulkan Environment for SPIR-V

Shaders for Vulkan are defined by the Khronos SPIR-V Specification as well as the Khronos SPIR-V Extended Instructions for GLSL Specification. This appendix defines additional SPIR-V requirements applying to Vulkan shaders.

Versions and Formats

A Vulkan 1.3 implementation must support the 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, and 1.6 versions of SPIR-V and the 1.0 version of the SPIR-V Extended Instructions for GLSL.

A SPIR-V module passed into vkCreateShaderModule is interpreted as a series of 32-bit words in host endianness, with literal strings packed as described in section 2.2 of the SPIR-V Specification. The first few words of the SPIR-V module must be a magic number and a SPIR-V version number, as described in section 2.3 of the SPIR-V Specification.

Capabilities

The table below lists the set of SPIR-V capabilities that may be supported in Vulkan implementations. The application must not use any of these capabilities in SPIR-V passed to vkCreateShaderModule unless one of the following conditions is met for the VkDevice specified in the device parameter of vkCreateShaderModule:

- The corresponding field in the table is blank.
- Any corresponding Vulkan feature is enabled.
- Any corresponding Vulkan extension is enabled.
- Any corresponding Vulkan property is supported.
- The corresponding core version is supported (as returned by VkPhysicalDeviceProperties::apiVersion).

Table 63. List of SPIR-V Capabilities and corresponding Vulkan features, extensions, or core version

<table>
<thead>
<tr>
<th>SPIR-V OpCapability</th>
<th>Vulkan feature, extension, or core version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>Shader</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>InputAttachment</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>Sampled1D</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>Image1D</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>SPIR-V OpCapability</td>
<td>Vulkan feature, extension, or core version</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>SampledBuffer</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>ImageBuffer</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>ImageQuery</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>DerivativeControl</td>
<td>VK_VERSION_1_0</td>
</tr>
<tr>
<td>Geometry</td>
<td>VkPhysicalDeviceFeatures::geometryShader</td>
</tr>
<tr>
<td>Tessellation</td>
<td>VkPhysicalDeviceFeatures::tessellationShader</td>
</tr>
<tr>
<td>Float64</td>
<td>VkPhysicalDeviceFeatures::shaderFloat64</td>
</tr>
<tr>
<td>Int64</td>
<td>VkPhysicalDeviceFeatures::shaderInt64</td>
</tr>
<tr>
<td>Int64Atomics</td>
<td>VkPhysicalDeviceVulkan12Features::shaderBufferInt64Atomics</td>
</tr>
<tr>
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### SPIR-V OpCapability

**Vulkan feature, extension, or core version**

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<tr>
<td>Vulkan feature, extension, or core version</td>
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**VariablePointers**
- `VkPhysicalDeviceVulkan11Features::variablePointers`

**ShaderViewportIndex**
- `VkPhysicalDeviceVulkan12Features::shaderOutputViewportIndex`

**ShaderLayer**
- `VkPhysicalDeviceVulkan12Features::shaderOutputLayer`

**StorageBuffer16BitAccess**
- `VkPhysicalDeviceVulkan11Features::storageBuffer16BitAccess`

**UniformAndStorageBuffer16BitAccess**
- `VkPhysicalDeviceVulkan11Features::uniformAndStorageBuffer16BitAccess`

**StoragePushConstant16**
- `VkPhysicalDeviceVulkan11Features::storagePushConstant16`

**StorageInputOutput16**
- `VkPhysicalDeviceVulkan11Features::storageInputOutput16`

**GroupNonUniform**
- `VK_SUBGROUP_FEATURE_BASIC_BIT`

**GroupNonUniformVote**
- `VK_SUBGROUP_FEATURE_VOTE_BIT`

**GroupNonUniformArithmetic**
- `VK_SUBGROUP_FEATURE_ARITHMETIC_BIT`

**GroupNonUniformBallot**
- `VK_SUBGROUP_FEATURE_BALLOT_BIT`

**GroupNonUniformShuffle**
- `VK_SUBGROUP_FEATURE_SHUFFLE_BIT`

**GroupNonUniformShuffleRelative**
- `VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT`

**GroupNonUniformClustered**
- `VK_SUBGROUP_FEATURE_CLUSTERED_BIT`

**GroupNonUniformQuad**
- `VK_SUBGROUP_FEATURE_QUAD_BIT`

**ShaderNonUniform**
- `VK_VERSION_1_2`

**RuntimeDescriptorArray**
- `VkPhysicalDeviceVulkan12Features::runtimeDescriptorArray`

**InputAttachmentArrayDynamicIndexing**
- `VkPhysicalDeviceVulkan12Features::shaderInputAttachmentArrayDynamicIndexing`

**UniformTexelBufferArrayDynamicIndexing**
- `VkPhysicalDeviceVulkan12Features::shaderUniformTexelBufferArrayDynamicIndexing`
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<td></td>
<td>VkPhysicalDeviceVulkan12Properties::shaderDenormFlushToZeroFloat64</td>
</tr>
</tbody>
</table>
The application **must** not pass a SPIR-V module containing any of the following to `vkCreateShaderModule`:

- any `OpCapability` not listed above,
- an unsupported capability, or
- a capability which corresponds to a Vulkan feature or extension which has not been enabled.

### SPIR-V Extensions

The following table lists SPIR-V extensions that implementations **may** support. The application **must** not pass a SPIR-V module to `vkCreateShaderModule` that uses the following SPIR-V extensions unless one of the following conditions is met for the `VkDevice` specified in the `device` parameter of `vkCreateShaderModule`:

- Any corresponding Vulkan extension is enabled.
- The corresponding core version is supported (as returned by `VkPhysicalDeviceProperties`)

<table>
<thead>
<tr>
<th>SPIR-V OpCapability</th>
<th>Vulkan feature, extension, or core version</th>
</tr>
</thead>
</table>
| SignedZeroInfNanPreserve | VkPhysicalDeviceVulkan12Properties::shaderSignedZeroInfNanPreserveFloat16  
VkPhysicalDeviceVulkan12Properties::shaderSignedZeroInfNanPreserveFloat32  
VkPhysicalDeviceVulkan12Properties::shaderSignedZeroInfNanPreserveFloat64 |
| RoundingModeRTE | VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTEFloat16  
VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTEFloat32  
VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTEFloat64 |
| RoundingModeRTZ | VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTZFloat16  
VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTZFloat32  
VkPhysicalDeviceVulkan12Properties::shaderRoundingModeRTZFloat64 |
| PhysicalStorageBufferAddresses | VkPhysicalDeviceVulkan12Features::bufferDeviceAddress |
| DemoteToHelperInvocationEXT | VkPhysicalDeviceVulkan13Features::shaderDemoteToHelperInvocation |
| DotProductInputAllKHR | VkPhysicalDeviceVulkan13Features::shaderIntegerDotProduct |
| DotProductInput4x8BitKHR | VkPhysicalDeviceVulkan13Features::shaderIntegerDotProduct |
| DotProductInput4x8BitPackedKHR | VkPhysicalDeviceVulkan13Features::shaderIntegerDotProduct |
| DotProductKHR | VkPhysicalDeviceVulkan13Features::shaderIntegerDotProduct |
Table 64. List of SPIR-V Extensions and corresponding Vulkan extensions or core version

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<tr>
<th>SPIR-V OpExtension</th>
<th>Vulkan extension or core version</th>
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</thead>
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<td>SPV_KHR_variable_pointers</td>
<td>VK_VERSION_1_1</td>
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<tr>
<td>SPV_KHR_shader_draw_parameters</td>
<td>VK_VERSION_1_1</td>
</tr>
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<td>SPV_KHR_8bit_storage</td>
<td>VK_VERSION_1_2</td>
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<tr>
<td>SPV_KHR_16bit_storage</td>
<td>VK_VERSION_1_1</td>
</tr>
<tr>
<td>SPV_KHR_float_controls</td>
<td>VK_VERSION_1_2</td>
</tr>
<tr>
<td>SPV_KHR_storage_buffer_storage_class</td>
<td>VK_VERSION_1_1</td>
</tr>
<tr>
<td>SPV_EXT_shader_viewport_index_layer</td>
<td>VK_VERSION_1_2</td>
</tr>
<tr>
<td>SPV_EXT_descriptor_indexing</td>
<td>VK_VERSION_1_2</td>
</tr>
<tr>
<td>SPV_KHR_vulkan_memory_model</td>
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</tr>
<tr>
<td>SPV_KHR_physical_storage_buffer</td>
<td>VK_VERSION_1_2</td>
</tr>
<tr>
<td>SPV_EXT_demote_to_helper_invocation</td>
<td>VK_VERSION_1_3</td>
</tr>
<tr>
<td>SPV_KHR_non_semantic_info</td>
<td>VK_VERSION_1_3</td>
</tr>
<tr>
<td>SPV_KHR terminate_invocation</td>
<td>VK_VERSION_1_3</td>
</tr>
<tr>
<td>SPV_KHR_multiview</td>
<td>VK_VERSION_1_1</td>
</tr>
<tr>
<td>SPV_KHR_subgroup_uniform_control_flow</td>
<td>VK_VERSION_1_3</td>
</tr>
<tr>
<td>SPV_KHR_integer_dot_product</td>
<td>VK_VERSION_1_3</td>
</tr>
<tr>
<td>SPV_KHR_device_group</td>
<td>VK_VERSION_1_1</td>
</tr>
</tbody>
</table>
Validation Rules within a Module

A SPIR-V module passed to `vkCreateShaderModule` must conform to the following rules:

**Standalone SPIR-V Validation**

The following rules can be validated with only the SPIR-V module itself. They do not depend on knowledge of the implementation and its capabilities or knowledge of runtime information, such as enabled features.

<table>
<thead>
<tr>
<th>Valid Usage</th>
</tr>
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<tbody>
<tr>
<td>• VUID-StandaloneSpirv-None-04633 Every entry point must have no return value and accept no arguments</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04634 The static function-call graph for an entry point must not contain cycles; that is, static recursion is not allowed</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04635 The Logical or PhysicalStorageBuffer64 addressing model must be selected</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04636 Scope for execution must be limited to Workgroup or Subgroup</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04637 If the Scope for execution is Workgroup, then it must only be used in the task, mesh, tessellation control, or compute Execution Model</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04638 Scope for memory must be limited to Device, QueueFamily, Workgroup, ShaderCallKHR, Subgroup, or Invocation</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-ExecutionModel-07320 If the ExecutionModel is TessellationControl, and the MemoryModel is GLSL450, the Scope for memory must not be Workgroup</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-07321 If the Scope for memory is Workgroup, then it must only be used in the task, mesh, tessellation control, or compute Execution Model</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04640 If the Scope for memory is ShaderCallKHR, then it must only be used in ray generation, intersection, closest hit, any-hit, miss, and callable Execution Model</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04641 If the Scope for memory is Invocation, then memory semantics must be None</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-None-04642 Scope for group operations must be limited to Subgroup</td>
</tr>
<tr>
<td>• VUID-StandaloneSpirv-SubgroupVoteKHR-07951 If none of the SubgroupVoteKHR, GroupNonUniform, or SubgroupBallotKHR capabilities are declared, Scope for memory must not be Subgroup</td>
</tr>
</tbody>
</table>
Storage Class must be limited to UniformConstant, Input, Uniform, Output, Workgroup, Private, Function, PushConstant, Image, StorageBuffer, RayPayloadKHR, IncomingRayPayloadKHR, HitAttributeKHR, CallableDataKHR, IncomingCallableDataKHR, ShaderRecordBufferKHR, PhysicalStorageBuffer, or TileImageEXT.

If the Storage Class is Output, then it must not be used in the GlCompute, RayGenerationKHR, IntersectionKHR, AnyHitKHR, ClosestHitKHR, MissKHR, or CallableKHR Execution Model.

If the Storage Class is Workgroup, then it must only be used in the task, mesh, or compute Execution Model.

If the Storage Class is TileImageEXT, then it must only be used in the fragment execution model.

OpAtomicStore must not use Acquire, AcquireRelease, or SequentiallyConsistent memory semantics.

OpAtomicLoad must not use Release, AcquireRelease, or SequentiallyConsistent memory semantics.

OpMemoryBarrier must use one of Acquire, Release, AcquireRelease, or SequentiallyConsistent memory semantics.

OpMemoryBarrier must include at least one Storage Class.

If the semantics for OpControlBarrier includes one of Acquire, Release, AcquireRelease, or SequentiallyConsistent memory semantics, then it must include at least one Storage Class.

Any OpVariable with an Initializer operand must have Output, Private, Function, or Workgroup as its Storage Class operand.

Any OpVariable with an Initializer operand and Workgroup as its Storage Class operand must use OpConstantNull as the initializer.

Scope for OpReadClockKHR must be limited to Subgroup or Device.

The OriginLowerLeft Execution Mode must not be used; fragment entry points must declare OriginUpperLeft.

The PixelCenterInteger Execution Mode must not be used (pixels are always centered at half-integer coordinates).
• **VUID-StandaloneSpirv-UniformConstant-04655**
  Any variable in the *UniformConstant Storage Class* must be typed as either `OpTypeImage`, `OpTypeSampler`, `OpTypeSampledImage`, `OpTypeAccelerationStructureKHR`, or an array of one of these types.

• **VUID-StandaloneSpirv-Uniform-06807**
  Any variable in the *Uniform or StorageBuffer Storage Class* must be typed as `OpTypeStruct` or an array of this type.

• **VUID-StandaloneSpirv-PushConstant-06808**
  Any variable in the *PushConstant Storage Class* must be typed as `OpTypeStruct`.

• **VUID-StandaloneSpirv-OpTypeImage-04656**
  `OpTypeImage` must declare a scalar 32-bit float, 64-bit integer, or 32-bit integer type for the “Sampled Type” (*RelaxedPrecision* can be applied to a sampling instruction and to the variable holding the result of a sampling instruction).

• **VUID-StandaloneSpirv-OpTypeImage-04657**
  `OpTypeImage` must have a “Sampled” operand of 1 (sampled image) or 2 (storage image).

• **VUID-StandaloneSpirv-OpTypeSampledImage-06671**
  `OpTypeSampledImage` must have an `OpTypeImage` with a “Sampled” operand of 1 (sampled image).

• **VUID-StandaloneSpirv-Image-04965**
  The *SPIR-V Type* of the *Image Format* operand of an `OpTypeImage` must match the *Sampled Type*, as defined in *Image Format and Type Matching*.

• **VUID-StandaloneSpirv-OpImageTexelPointer-04658**
  If an `OpImageTexelPointer` is used in an atomic operation, the image type of the image parameter to `OpImageTexelPointer` must have an image format of R64i, R64ui, R32f, R32i, or R32ui.

• **VUID-StandaloneSpirv-OpImageQuerySizeLod-04659**
  `OpImageQuerySizeLod`, `OpImageQueryLod`, and `OpImageQueryLevels` must only consume an “Image” operand whose type has its “Sampled” operand set to 1.

• **VUID-StandaloneSpirv-OpTypeImage-06214**
  An `OpTypeImage` with a “Dim” operand of *SubpassData* must have an “Arrayed” operand of 0 (non-arrayed) and a “Sampled” operand of 2 (storage image).

• **VUID-StandaloneSpirv-SubpassData-04660**
  The (u,v) coordinates used for a *SubpassData* must be the <id> of a constant vector (0,0), or if a layer coordinate is used, must be a vector that was formed with constant 0 for the u and v components.

• **VUID-StandaloneSpirv-OpTypeImage-06924**
  Objects of types `OpTypeImage`, `OpTypeSampler`, `OpTypeSampledImage`, `OpTypeAccelerationStructureKHR`, and arrays of these types must not be stored to or modified.

• **VUID-StandaloneSpirv-Uniform-06925**
  Any variable in the *Uniform Storage Class* decorated as *Block* must not be stored to or modified.

• **VUID-StandaloneSpirv-Offset-04663**
Image operand **Offset must** only be used with **OpImage*Gather** instructions

- **VUID-StandaloneSpirv-Offset-04865**
  Any image instruction which uses an **Offset, ConstOffset, or ConstOffsets** image operand, must only consume a “Sampled Image” operand whose type has its “Sampled” operand set to 1

- **VUID-StandaloneSpirv-OpImageGather-04664**
  The “Component” operand of **OpImageGather**, and **OpImageSparseGather** must be the <id> of a constant instruction

- **VUID-StandaloneSpirv-OpImage*Gref*-04777**
  **OpImage*Dref** instructions must not consume an image whose **Dim** is 3D

- **VUID-StandaloneSpirv-None-04667**
  Structure types must not contain opaque types

- **VUID-StandaloneSpirv-BuiltIn-04668**
  Any **BuiltIn** decoration not listed in **Built-In Variables** must not be used

- **VUID-StandaloneSpirv-Location-06672**
  The **Location** or **Component** decorations must only be used with the **Input, Output, RayPayloadKHR, IncomingRayPayloadKHR, HitAttributeKHR, HitObjectAttributeNV, CallableDataKHR, IncomingCallableDataKHR, or ShaderRecordBufferKHR** storage classes

- **VUID-StandaloneSpirv-Location-04915**
  The **Location** or **Component** decorations must not be used with **BuiltIn**

- **VUID-StandaloneSpirv-Location-04916**
  The **Location** decorations must be used on user-defined variables

- **VUID-StandaloneSpirv-Location-04917**
  If a user-defined variable is a pointer to a **Block** decorated **OpTypeStruct**, then the **OpVariable** must have a **Location** decoration

- **VUID-StandaloneSpirv-Location-04918**
  If a user-defined variable has a **Location** decoration, and the variable is a pointer to a **OpTypeStruct**, then the members of that structure must not have **Location** decorations

- **VUID-StandaloneSpirv-Location-04919**
  If a user-defined variable does not have a **Location** decoration, and the variable is a pointer to a **Block** decorated **OpTypeStruct**, then each member of the struct must have a **Location** decoration

- **VUID-StandaloneSpirv-Component-04920**
  The **Component** decoration value must not be greater than 3

- **VUID-StandaloneSpirv-Component-04921**
  If the **Component** decoration is used on an **OpVariable** that has a **OpTypeVector** type with a **Component Type** with a **Width** that is less than or equal to 32, the sum of its **Component Count** and the **Component** decoration value must be less than or equal to 4

- **VUID-StandaloneSpirv-Component-04922**
  If the **Component** decoration is used on an **OpVariable** that has a **OpTypeVector** type with a **Component Type** with a **Width** that is equal to 64, the sum of two times its **Component Count** and the **Component** decoration value must be less than or equal to 4
The *Component* decorations value **must** not be 1 or 3 for scalar or two-component 64-bit data types.

The *Component* decorations **must** not be used with any type that is not a scalar or vector, or an array of such a type.

The *Component* decorations **must** not be used for a 64-bit vector type with more than two components.

The *GLSLShared* and *GLSLPacked* decorations **must** not be used.

The *Flat*, *NoPerspective*, *Sample*, and *Centroid* decorations **must** only be used on variables with the *Output* or *Input Storage Class*.

The *Flat*, *NoPerspective*, *Sample*, and *Centroid* decorations **must** not be used on variables with the *Output* storage class in a fragment shader.

The *Flat*, *NoPerspective*, *Sample*, and *Centroid* decorations **must** not be used on variables with the *Input* storage class in a vertex shader.

The *PerVertexKHR* decoration **must** only be used on variables with the *Input Storage Class* in a fragment shader.

Any variable with integer or double-precision floating-point type and with *Input Storage Class* in a fragment shader, **must** be decorated *Flat*.

The *ViewportRelativeNV* decoration **must** only be used on a variable decorated with *Layer* in the vertex, tessellation evaluation, or geometry shader stages.

The *ViewportRelativeNV* decoration **must** not be used unless a variable decorated with one of *ViewportIndex* or *ViewportMaskNV* is also statically used by the same *OpEntryPoint*.

The *ViewportMaskNV* and *ViewportIndex* decorations **must** not both be statically used by one or more *OpEntryPoint*’s that form the pre-rasterization shader stages of a graphics pipeline.

Rounding modes other than round-to-nearest-even and round-towards-zero **must** not be used for the *FPRoundingMode* decoration.

Variables decorated with *Invariant* and variables with structure types that have any members decorated with *Invariant** must** be in the *Output* or *Input Storage Class*, *Invariant* used on an *Input Storage Class* variable or structure member has no effect.
If the *VulkanMemoryModel* capability is not declared, the *Volatile* decoration must be used on any variable declaration that includes one of the *SMIDNV*, *WarpIDNV*, *SubgroupSize*, *SubgroupLocalInvocationId*, *SubgroupEqMask*, *SubgroupGtMask*, *SubgroupLeMask*, or *SubgroupLtMask* BuiltIn decorations when used in the ray generation, closest hit, miss, intersection, or callable shaders, or with the *RayTmaxKHR BuiltIn* decoration when used in an intersection shader.

If the *VulkanMemoryModel* capability is declared, the *OpLoad* instruction must use the *Volatile* memory semantics when it accesses into any variable that includes one of the *SMIDNV*, *WarpIDNV*, *SubgroupSize*, *SubgroupLocalInvocationId*, *SubgroupEqMask*, *SubgroupGtMask*, *SubgroupLeMask*, or *SubgroupLtMask* BuiltIn decorations when used in the ray generation, closest hit, miss, intersection, or callable shaders, or with the *RayTmaxKHR BuiltIn* decoration when used in an intersection shader.

*OpTypeRuntimeArray* must only be used for the last member of a Block-decorated *OpTypeStruct* in StorageBuffer or PhysicalStorageBuffer Storage Class; BufferBlock-decorated *OpTypeStruct* in Uniform Storage Class; the outermost dimension of an arrayed variable in the StorageBuffer, Uniform, or UniformConstant Storage Class.

A type *T* that is an array sized with a specialization constant must neither be, nor be contained in, the type *T2* of a variable *V*, unless either: a) *T* is equal to *T2*, b) *V* is declared in the Function, or Private Storage Class, c) *V* is a non-Block variable in the Workgroup Storage Class, or d) *V* is an interface variable with an additional level of arrayness, as described in interface matching, and *T* is the member type of the array type *T2*.

If *OpControlBarrier* is used in ray generation, intersection, any-hit, closest hit, miss, fragment, vertex, tessellation evaluation, or geometry shaders, the execution Scope must be Subgroup.

For each compute shader entry point, either a LocalSize or LocalSizeId Execution Mode, or an object decorated with the WorkgroupSize decoration must be specified.

For compute shaders using the *DerivativeGroupQuadsNV* execution mode, the first two dimensions of the local workgroup size must be a multiple of two.

For compute shaders using the *DerivativeGroupLinearNV* execution mode, the product of the dimensions of the local workgroup size must be a multiple of four.

If *OpGroupNonUniformBallotBitCount* is used, the group operation must be limited to Reduce, InclusiveScan, or ExclusiveScan.

The Pointer operand of all atomic instructions must have a Storage Class limited to Uniform, Workgroup, Image, StorageBuffer, PhysicalStorageBuffer, or TaskPayloadWorkgroupEXT.
• VUID-StandaloneSpirv-Offset-04687
Output variables or block members decorated with Offset that have a 64-bit type, or a composite type containing a 64-bit type, must specify an Offset value aligned to a 8 byte boundary

• VUID-StandaloneSpirv-Offset-04689
The size of any output block containing any member decorated with Offset that is a 64-bit type must be a multiple of 8

• VUID-StandaloneSpirv-Offset-04690
The first member of an output block specifying a Offset decoration must specify a Offset value that is aligned to an 8 byte boundary if that block contains any member decorated with Offset and is a 64-bit type

• VUID-StandaloneSpirv-Offset-04691
Output variables or block members decorated with Offset that have a 32-bit type, or a composite type contains a 32-bit type, must specify an Offset value aligned to a 4 byte boundary

• VUID-StandaloneSpirv-Offset-04692
Output variables, blocks or block members decorated with Offset must only contain base types that have components that are either 32-bit or 64-bit in size

• VUID-StandaloneSpirv-Offset-04716
Only variables or block members in the output interface decorated with Offset can be captured for transform feedback, and those variables or block members must also be decorated with XfbBuffer and XfbStride, or inherit XfbBuffer and XfbStride decorations from a block containing them

• VUID-StandaloneSpirv-XfbBuffer-04693
All variables or block members in the output interface of the entry point being compiled decorated with a specific XfbBuffer value must all be decorated with identical XfbStride values

• VUID-StandaloneSpirv-Stream-04694
If any variables or block members in the output interface of the entry point being compiled are decorated with Stream, then all variables belonging to the same XfbBuffer must specify the same Stream value

• VUID-StandaloneSpirv-XfbBuffer-04696
For any two variables or block members in the output interface of the entry point being compiled with the same XfbBuffer value, the ranges determined by the Offset decoration and the size of the type must not overlap

• VUID-StandaloneSpirv-XfbBuffer-04697
All block members in the output interface of the entry point being compiled that are in the same block and have a declared or inherited XfbBuffer decoration must specify the same XfbBuffer value

• VUID-StandaloneSpirv-RayPayloadKHR-04698
RayPayloadKHR Storage Class must only be used in ray generation, closest hit or miss shaders

• VUID-StandaloneSpirv-IncomingRayPayloadKHR-04699
IncomingRayPayloadKHR Storage Class must only be used in closest hit, any-hit, or miss shaders

- VUID-StandaloneSpirv-IncomingRayPayloadKHR-04700
  There must be at most one variable with the IncomingRayPayloadKHR Storage Class in the input interface of an entry point

- VUID-StandaloneSpirv-HitAttributeKHR-04701
  HitAttributeKHR Storage Class must only be used in intersection, any-hit, or closest hit shaders

- VUID-StandaloneSpirv-HitAttributeKHR-04702
  There must be at most one variable with the HitAttributeKHR Storage Class in the input interface of an entry point

- VUID-StandaloneSpirv-HitAttributeKHR-04703
  A variable with HitAttributeKHR Storage Class must only be written to in an intersection shader

- VUID-StandaloneSpirv-CallableDataKHR-04704
  CallableDataKHR Storage Class must only be used in ray generation, closest hit, miss, and callable shaders

- VUID-StandaloneSpirv-IncomingCallableDataKHR-04705
  IncomingCallableDataKHR Storage Class must only be used in callable shaders

- VUID-StandaloneSpirv-IncomingCallableDataKHR-04706
  There must be at most one variable with the IncomingCallableDataKHR Storage Class in the input interface of an entry point

- VUID-StandaloneSpirv-ShaderRecordBufferKHR-07119
  ShaderRecordBufferKHR Storage Class must only be used in ray generation, intersection, any-hit, closest hit, callable, or miss shaders

- VUID-StandaloneSpirv-Base-07650
  The Base operand of OpPtrAccessChain must have a storage class of Workgroup, StorageBuffer, or PhysicalStorageBuffer

- VUID-StandaloneSpirv-Base-07651
  If the Base operand of OpPtrAccessChain has a Workgroup Storage Class, then the VariablePointers capability must be declared

- VUID-StandaloneSpirv-PhysicalStorageBuffer64-04708
  If the PhysicalStorageBuffer64 addressing model is enabled, all instructions that support memory access operands and that use a physical pointer must include the Aligned operand

- VUID-StandaloneSpirv-PhysicalStorageBuffer64-04709
  If the PhysicalStorageBuffer64 addressing model is enabled, any access chain instruction that accesses into a RowMajor matrix must only be used as the Pointer operand to OpLoad or OpStore
If the PhysicalStorageBuffer64 addressing model is enabled, OpConvertUToPtr and OpConvertPtrToU must use an integer type whose Width is 64.

OpTypeForwardPointer must have a Storage Class of PhysicalStorageBuffer.

All block members in a variable with a Storage Class of PushConstant declared as an array must only be accessed by dynamically uniform indices.

There must not be more than one OpVariable in the PushConstant Storage Class listed in the Interface for each OpEntryPoint.

Each OpEntryPoint must not statically use more than one OpVariable in the PushConstant Storage Class.

Each OpEntryPoint must not have more than one Input variable assigned the same Component word inside a Location slot, either explicitly or implicitly.

Each OpEntryPoint must not have more than one Output variable assigned the same Component word inside a Location slot, either explicitly or implicitly.

The Result Type operand of any OpImageRead or OpImageSparseRead instruction must be a vector of four components.

The Base operand of any OpBitCount, OpBitReverse, OpBitFieldInsert, OpBitFieldSExtract, or OpBitFieldUExtract instruction must be a 32-bit integer scalar or a vector of 32-bit integers.

Any variable in the PushConstant or StorageBuffer storage class must be decorated as Block.

Any variable in the Uniform Storage Class must be decorated as Block or BufferBlock.

Any variable in the UniformConstant, StorageBuffer, or Uniform Storage Class must be decorated with DescriptorSet and Binding.

Variables decorated with InputAttachmentIndex must be in the UniformConstant Storage Class.

If a variable is decorated by DescriptorSet or Binding, the Storage Class must correspond to an entry in Shader Resource and Storage Class Correspondence.

Variables with a Storage Class of Input in a fragment shader stage that are decorated with
PerVertexKHR must be declared as arrays

- VUID-StandaloneSpirv-MeshEXT-07102
  The module must not contain both an entry point that uses the TaskEXT or MeshEXT Execution Model and an entry point that uses the TaskNV or MeshNV Execution Model

- VUID-StandaloneSpirv-MeshEXT-07106
  In mesh shaders using the MeshEXT Execution Model OpSetMeshOutputsEXT must be called before any outputs are written

- VUID-StandaloneSpirv-MeshEXT-07107
  In mesh shaders using the MeshEXT Execution Model all variables declared as output must not be read from

- VUID-StandaloneSpirv-MeshEXT-07108
  In mesh shaders using the MeshEXT Execution Model for OpSetMeshOutputsEXT instructions, the “Vertex Count” and “Primitive Count” operands must not depend on ViewIndex

- VUID-StandaloneSpirv-MeshEXT-07109
  In mesh shaders using the MeshEXT Execution Model variables decorated with PrimitivePointIndicesEXT, PrimitiveLineIndicesEXT, or PrimitiveTriangleIndicesEXT declared as an array must not be accessed by indices that depend on ViewIndex

- VUID-StandaloneSpirv-MeshEXT-07110
  In mesh shaders using the MeshEXT Execution Model any values stored in variables decorated with PrimitivePointIndicesEXT, PrimitiveLineIndicesEXT, or PrimitiveTriangleIndicesEXT must not depend on ViewIndex

- VUID-StandaloneSpirv-MeshEXT-07111
  In mesh shaders using the MeshEXT Execution Model variables in workgroup or private Storage Class declared as or containing a composite type must not be accessed by indices that depend on ViewIndex

- VUID-StandaloneSpirv-MeshEXT-07330
  In mesh shaders using the MeshEXT Execution Model the OutputVertices Execution Mode must be greater than 0

- VUID-StandaloneSpirv-MeshEXT-07331
  In mesh shaders using the MeshEXT Execution Model the OutputPrimitivesEXT Execution Mode must be greater than 0

- VUID-StandaloneSpirv-MeshEXT-07728
  In mesh shaders using the MeshEXT or MeshNV Execution Model and the OutputPoints Execution Mode, if the number of output points is greater than 0, a PointSize decorated variable must be written to for each output point

- VUID-StandaloneSpirv-Input-07290
  Variables with a Storage Class of Input or Output and a type of OpTypeBool must be decorated with the BuiltIn decoration

- VUID-StandaloneSpirv-TileImageEXT-08723
  The tile image variable declarations must obey the constraints on the TileImageEXT Storage Class and the Location decoration described in Fragment Tile Image Interface

- VUID-StandaloneSpirv-None-08724
  The TileImageEXT Storage Class must only be used for declaring tile image variables.
The Storage Class of the Pointer operand to OpCooperativeMatrixLoadKHR or OpCooperativeMatrixStoreKHR must be limited to Workgroup, StorageBuffer, or PhysicalStorageBuffer.

Runtime SPIR-V Validation

The following rules must be validated at runtime. These rules depend on knowledge of the implementation and its capabilities and knowledge of runtime information, such as enabled features.

Valid Usage

- **VUID-RuntimeSpirv-vulkanMemoryModel-06265**
  If vulkanMemoryModel is enabled and vulkanMemoryModelDeviceScope is not enabled, Device memory scope must not be used.

- **VUID-RuntimeSpirv-vulkanMemoryModel-06266**
  If vulkanMemoryModel is not enabled, QueueFamily memory scope must not be used.

- **VUID-RuntimeSpirv-apiVersion-07952**
  If VkPhysicalDeviceProperties::apiVersion is less than Vulkan 1.3, and shaderStorageImageWriteWithoutFormat is not enabled, any variable created with a “Type” of OpTypeImage that has a “Sampled” operand of 2 and an “Image Format” operand of Unknown must be decorated with NonWritable.

- **VUID-RuntimeSpirv-apiVersion-07953**
  If VkPhysicalDeviceProperties::apiVersion is less than Vulkan 1.3, and shaderStorageImageReadWithoutFormat is not enabled, any variable created with a “Type” of OpTypeImage that has a “Sampled” operand of 2 and an “Image Format” operand of Unknown must be decorated with NonReadable.

- **VUID-RuntimeSpirv-OpImageWrite-07112**
  OpImageWrite to any Image whose Image Format is not Unknown must have the Texel operand contain at least as many components as the corresponding VkFormat as given in the SPIR-V Image Format compatibility table.

- **VUID-RuntimeSpirv-Location-06272**
  The sum of Location and the number of locations the variable it decorates consumes must be less than or equal to the value for the matching Execution Model defined in Shader Input and Output Locations.

- **VUID-RuntimeSpirv-Fragment-06427**
  When blending is enabled and one of the dual source blend modes is in use, the maximum number of output attachments written to in the Fragment Execution Model must be less than or equal to maxFragmentDualSrcAttachments.

- **VUID-RuntimeSpirv-Location-06428**
  The maximum number of storage buffers, storage images, and output Location decorated color attachments written to in the Fragment Execution Model must be less than or equal to maxFragmentCombinedOutputResources.
If an instruction loads from or stores to a resource (including atomics and image instructions) and the resource descriptor being accessed is not dynamically uniform, then the operand corresponding to that resource (e.g. the pointer or sampled image operand) **must** be decorated with `NonUniform`.

`shaderSubgroupExtendedTypes` must be enabled for group operations to use 8-bit integer, 16-bit integer, 64-bit integer, 16-bit floating-point, and vectors of these types.

If `subgroupBroadcastDynamicId` is `VK_TRUE`, and the shader module version is 1.5 or higher, the “Index” for `OpGroupNonUniformQuadBroadcast` must be dynamically uniform within the derivative group. Otherwise, “Index” **must** be a constant.

If `subgroupBroadcastDynamicId` is `VK_TRUE`, and the shader module version is 1.5 or higher, the “Id” for `OpGroupNonUniformBroadcast` must be dynamically uniform within the subgroup. Otherwise, “Id” **must** be a constant.

If `denormBehaviorIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY`, then the entry point **must** use the same denormals Execution Mode for both 16-bit and 64-bit floating-point types.

If `denormBehaviorIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE`, then the entry point **must** use the same denormals Execution Mode for all floating-point types.

If `roundingModeIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY`, then the entry point **must** use the same rounding Execution Mode for both 16-bit and 64-bit floating-point types.

If `roundingModeIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE`, then the entry point **must** use the same rounding Execution Mode for all floating-point types.

If `shaderSignedZeroInfNanPreserveFloat16` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 16-bit floating-point type **must** not be used.

If `shaderSignedZeroInfNanPreserveFloat32` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 32-bit floating-point type **must** not be used.

If `shaderSignedZeroInfNanPreserveFloat64` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 64-bit floating-point type **must** not be used.

If `shaderDenormPreserveFloat16` is `VK_FALSE`, then `DenormPreserve` for 16-bit floating-point type **must** not be used.

If `shaderDenormPreserveFloat32` is `VK_FALSE`, then `DenormPreserve` for 32-bit floating-point type **must** not be used.

If `shaderDenormPreserveFloat64` is `VK_FALSE`, then `DenormPreserve` for 64-bit floating-point type **must** not be used.
If \texttt{shaderDenormPreserveFloat32} is \texttt{VK_FALSE}, then \texttt{DenormPreserve} for 32-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderDenormPreserveFloat64-06298}
  If \texttt{shaderDenormPreserveFloat64} is \texttt{VK_FALSE}, then \texttt{DenormPreserve} for 64-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderDenormFlushToZeroFloat16-06299}
  If \texttt{shaderDenormFlushToZeroFloat16} is \texttt{VK_FALSE}, then \texttt{DenormFlushToZero} for 16-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderDenormFlushToZeroFloat32-06300}
  If \texttt{shaderDenormFlushToZeroFloat32} is \texttt{VK_FALSE}, then \texttt{DenormFlushToZero} for 32-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderDenormFlushToZeroFloat64-06301}
  If \texttt{shaderDenormFlushToZeroFloat64} is \texttt{VK_FALSE}, then \texttt{DenormFlushToZero} for 64-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTEFloat16-06302}
  If \texttt{shaderRoundingModeRTEFloat16} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTE} for 16-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTEFloat32-06303}
  If \texttt{shaderRoundingModeRTEFloat32} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTE} for 32-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTEFloat64-06304}
  If \texttt{shaderRoundingModeRTEFloat64} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTE} for 64-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTZFloat16-06305}
  If \texttt{shaderRoundingModeRTZFloat16} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTZ} for 16-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTZFloat32-06306}
  If \texttt{shaderRoundingModeRTZFloat32} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTZ} for 32-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-shaderRoundingModeRTZFloat64-06307}
  If \texttt{shaderRoundingModeRTZFloat64} is \texttt{VK_FALSE}, then \texttt{RoundingModeRTZ} for 64-bit floating-point type \textbf{must} not be used

- \textbf{VUID-RuntimeSpirv-PhysicalStorageBuffer64-06314}
  If the \texttt{PhysicalStorageBuffer64} addressing model is enabled any load or store through a physical pointer type \textbf{must} be aligned to a multiple of the size of the largest scalar type in the pointed-to type

- \textbf{VUID-RuntimeSpirv-PhysicalStorageBuffer64-06315}
  If the \texttt{PhysicalStorageBuffer64} addressing model is enabled the pointer value of a memory access instruction \textbf{must} be at least as aligned as specified by the \texttt{Aligned} memory access operand

- \textbf{VUID-RuntimeSpirv-DescriptorSet-06323}
  \texttt{DescriptorSet} and \texttt{Binding} decorations \textbf{must} obey the constraints on \texttt{Storage Class}, type, and descriptor type described in \texttt{DescriptorSet and Binding Assignment}
If `fragmentStoresAndAtomics` is not enabled, then all storage image, storage texel buffer, and storage buffer variables in the fragment stage must be decorated with the `NonWritable` decoration.

If `vertexPipelineStoresAndAtomics` is not enabled, then all storage image, storage texel buffer, and storage buffer variables in the vertex, tessellation, and geometry stages must be decorated with the `NonWritable` decoration.

If `subgroupQuadOperationsInAllStages` is `VK_FALSE`, then quad subgroup operations must not be used except for in fragment and compute stages.

Group operations with subgroup scope must not be used if the shader stage is not in `subgroupSupportedStages`.

The first element of the `Offset` operand of `InterpolateAtOffset` must be greater than or equal to:
\[ \text{frag}_{\text{width}} \times \text{minInterpolationOffset} \]
where \( \text{frag}_{\text{width}} \) is the width of the current fragment in pixels.

The first element of the `Offset` operand of `InterpolateAtOffset` must be less than or equal to:
\[ \text{frag}_{\text{width}} \times (\text{maxInterpolationOffset + ULP}) - \text{ULP} \]
where \( \text{frag}_{\text{width}} \) is the width of the current fragment in pixels and \( \text{ULP} = \frac{1}{2^{\text{subPixelInterpolationOffsetBits}}} \).

The second element of the `Offset` operand of `InterpolateAtOffset` must be greater than or equal to:
\[ \text{frag}_{\text{height}} \times \text{minInterpolationOffset} \]
where \( \text{frag}_{\text{height}} \) is the height of the current fragment in pixels.

The second element of the `Offset` operand of `InterpolateAtOffset` must be less than or equal to:
\[ \text{frag}_{\text{height}} \times (\text{maxInterpolationOffset + ULP}) - \text{ULP} \]
where \( \text{frag}_{\text{height}} \) is the height of the current fragment in pixels and \( \text{ULP} = \frac{1}{2^{\text{subPixelInterpolationOffsetBits}}} \).

The \( x \) size in `LocalSize` or `LocalSizeId` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupSize[0]`.

The \( y \) size in `LocalSize` or `LocalSizeId` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupSize[1]`.

The \( z \) size in `LocalSize` or `LocalSizeId` must be less than or equal to

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VkPhysicalDeviceLimits::maxComputeWorkGroupSize[2]

- VUID-RuntimeSpirv-x-06432
  The product of $x$ size, $y$ size, and $z$ size in LocalSize or LocalSizeId must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupInvocations

- VUID-RuntimeSpirv-LocalSizeId-06434
  If Execution Mode LocalSizeId is used, maintenance4 must be enabled

- VUID-RuntimeSpirv-maintenance4-06817
  If maintenance4 is not enabled, any OpTypeVector output interface variables must not have a higher Component Count than a matching OpTypeVector input interface variable

- VUID-RuntimeSpirv-OpEntryPoint-08743
  Any user-defined variables shared between the OpEntryPoint of two shader stages, and declared with Input as its Storage Class for the subsequent shader stage, must have all Location slots and Component words declared in the preceding shader stage's OpEntryPoint with Output as the Storage Class

- VUID-RuntimeSpirv-OpEntryPoint-07754
  Any user-defined variables between the OpEntryPoint of two shader stages must have the same type and width for each Component

- VUID-RuntimeSpirv-OpVariable-08746
  Any OpVariable, Block-decorated OpTypeStruct, or Block-decorated OpTypeStruct members shared between the OpEntryPoint of two shader stages must have matching decorations as defined in interface matching

- VUID-RuntimeSpirv-Workgroup-06530
  The sum of size in bytes for variables and padding in the Workgroup Storage Class in the GLCompute Execution Model must be less than or equal to maxComputeSharedMemorySize

- VUID-RuntimeSpirv-shaderZeroInitializeWorkgroupMemory-06372
  If shaderZeroInitializeWorkgroupMemory is not enabled, any OpVariable with Workgroup as its Storage Class must not have an Initializer operand

- VUID-RuntimeSpirv-OpImage-06376
  If an OpImage*Gather operation has an image operand of Offset, ConstOffset, or ConstOffsets the offset value must be greater than or equal to minTexelGatherOffset

- VUID-RuntimeSpirv-OpImage-06377
  If an OpImage*Gather operation has an image operand of Offset, ConstOffset, or ConstOffsets the offset value must be less than or equal to maxTexelGatherOffset

- VUID-RuntimeSpirv-OpImageSample-06435
  If an OpImageSample* or OpImageFetch* operation has an image operand of ConstOffset then the offset value must be greater than or equal to minTexelOffset

- VUID-RuntimeSpirv-OpImageSample-06436
  If an OpImageSample* or OpImageFetch* operation has an image operand of ConstOffset then the offset value must be less than or equal to maxTexelOffset

- VUID-RuntimeSpirv-samples-08725
  If an OpTypeImage has an MS operand 0, its bound image must have been created with VkImageCreateInfo::samples as VK_SAMPLE_COUNT_1_BIT
Precision and Operation of SPIR-V Instructions

The following rules apply to half, single, and double-precision floating point instructions:

• Positive and negative infinities and positive and negative zeros are generated as dictated by IEEE 754, but subject to the precisions allowed in the following table.

• Dividing a non-zero by a zero results in the appropriately signed IEEE 754 infinity.

• Signaling NaNs are not required to be generated and exceptions are never raised. Signaling NaN may be converted to quiet NaNs values by any floating point instruction.

• By default, the implementation may perform optimizations on half, single, or double-precision floating-point instructions that ignore sign of a zero, or assume that arguments and results are not NaNs or infinities. If the entry point is declared with the SignedZeroInfNanPreserve Execution Mode, then NaNs, infinities, and the sign of zero must not be ignored.


• Denormalized values are supported.

  ◦ By default, any half, single, or double-precision denormalized value input into a shader or potentially generated by any instruction (except those listed above) or any extended instructions for GLSL in a shader may be flushed to zero.

  ◦ If the entry point is declared with the DenormFlushToZero Execution Mode then for the affected instructions the denormalized result must be flushed to zero and the denormalized operands may be flushed to zero. Denormalized values obtained via unpacking an integer into a vector of values with smaller bit width and interpreting those values as floating-point numbers must be flushed to zero.

  ◦ The following core SPIR-V instructions must respect the DenormFlushToZero Execution Mode:


The precision of double-precision instructions is at least that of single precision.

The precision of individual operations is defined in Precision of Individual Operations. Subject to the constraints below, however, implementations may reorder or combine operations, resulting in expressions exhibiting different precisions than might be expected from the constituent operations.

**Evaluation of Expressions**

Implementations may rearrange floating-point operations using any of the mathematical properties governing the expressions in precise arithmetic, even where the floating-point operations do not share these properties. This includes, but is not limited to, associativity and distributivity, and may involve a different number of rounding steps than would occur if the operations were not rearranged. In shaders that use the SignedZeroInfNanPreserve Execution Mode the values must be preserved if they are generated after any rearrangement but the Execution Mode does not change which rearrangements are valid. This rearrangement can be prevented for particular operations by using the NoContractation decoration.

**Note**

For example, in the absence of the NoContractation decoration implementations are allowed to implement \( a + b - a \) and \( \frac{a \times b}{a} \) as \( b \). The SignedZeroInfNanPreserve does not prevent these transformations, even though they may overflow to infinity or NaN when evaluated in floating-point.

If the NoContractation decoration is applied then operations may not be rearranged, so, for example, \( a + a - a \) must account for possible overflow to infinity. If infinities are not preserved then the expression may be replaced with \( a \), since the replacement is exact when overflow does not occur and infinities may be replaced with undefined values. If both NoContractation and SignedZeroInfNanPreserve are
used then the result must be infinity for sufficiently large $a$.

**Precision of Individual Operations**

The precision of individual operations is defined either in terms of rounding (correctly rounded), as an error bound in ULP, or as inherited from a formula as follows:

*Correctly Rounded*

Operations described as “correctly rounded” will return the infinitely precise result, $x$, rounded so as to be representable in floating-point. The rounding mode is not specified, unless the entry point is declared with the `RoundingModeRTE` or the `RoundingModeRTZ` Execution Mode. These execution modes affect only correctly rounded SPIR-V instructions. These execution modes do not affect `OpQuantizeToF16`. If the rounding mode is not specified then this rounding is implementation specific, subject to the following rules. If $x$ is exactly representable then $x$ will be returned. Otherwise, either the floating-point value closest to and no less than $x$ or the value closest to and no greater than $x$ will be returned.

*ULP*

Where an error bound of $n$ ULP (units in the last place) is given, for an operation with infinitely precise result $x$, the value returned must be in the range $[x - n \times \text{ulp}(x), x + n \times \text{ulp}(x)]$. The function $\text{ulp}(x)$ is defined as follows:

If there exist non-equal, finite floating-point numbers $a$ and $b$ such that $a \leq x \leq b$ then $\text{ulp}(x)$ is the minimum possible distance between such numbers, $\text{ulp}(x) = \min_{a \neq b} |b - a|$. If such numbers do not exist then $\text{ulp}(x)$ is defined to be the difference between the two non-equal, finite floating-point numbers nearest to $x$.

Where the range of allowed return values includes any value of magnitude larger than that of the largest representable finite floating-point number, operations may, additionally, return either an infinity of the appropriate sign or the finite number with the largest magnitude of the appropriate sign. If the infinitely precise result of the operation is not mathematically defined then the value returned is undefined.

*Inherited From ...*

Where an operation’s precision is described as being inherited from a formula, the result returned must be at least as accurate as the result of computing an approximation to $x$ using a formula equivalent to the given formula applied to the supplied inputs. Specifically, the formula given may be transformed using the mathematical associativity, commutativity and distributivity of the operators involved to yield an equivalent formula. The SPIR-V precision rules, when applied to each such formula and the given input values, define a range of permitted values. If NaN is one of the permitted values then the operation may return any result, otherwise let the largest permitted value in any of the ranges be $F_{\text{max}}$ and the smallest be $F_{\text{min}}$. The operation must return a value in the range $[x - E, x + E]$ where $E = \max(|x - F_{\text{min}}|, |x - F_{\text{max}}|)$. If the entry point is declared with the `DenormFlushToZero` execution mode, then any intermediate denormal value(s) while evaluating the formula may be flushed to zero. Denormal final results must be flushed to zero. If the entry point is declared with the `DenormPreserve Execution Mode`, then denormals must be preserved throughout the formula.
For half- (16 bit) and single- (32 bit) precision instructions, precisions are **required** to be at least as follows:

### Table 65. Precision of core SPIR-V Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Single precision, unless decorated with RelaxedPrecision</th>
<th>Half precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>OpFAdd</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>OpFSub</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>OpDot(x, y)</td>
<td>Inherited from $\sum_{i=0}^{n-1} x_i \times y_i$.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdEqual, OpFUnordEqual</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdLessThan, OpFUnordLessThan</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreaterThan, OpFUnordGreaterThan</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreaterThanEqual, OpFUnordGreaterThanEqual</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFDiv(x, y)</td>
<td>2.5 ULP for $</td>
<td>y</td>
</tr>
<tr>
<td>OpFRem(x, y)</td>
<td>Inherited from $x - y \times \text{trunc}(x/y)$.</td>
<td></td>
</tr>
<tr>
<td>OpFMod(x, y)</td>
<td>Inherited from $x - y \times \text{floor}(x/y)$.</td>
<td></td>
</tr>
<tr>
<td>conversions between types</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
</tbody>
</table>

**Note**

The OpFRem and OpFMod instructions use cheap approximations of remainder, and the error can be large due to the discontinuity in \( \text{trunc}() \) and \( \text{floor}() \). This can produce mathematically unexpected results in some cases, such as \( \text{FMod}(x, x) \) computing \( x \) rather than \( 0 \), and can also cause the result to have a different sign than the infinitely precise result.

### Table 66. Precision of GLSL.std.450 Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Single precision, unless decorated with RelaxedPrecision</th>
<th>Half precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>fma()</td>
<td>Inherited from OpFMul followed by OpFAdd.</td>
<td></td>
</tr>
<tr>
<td>exp(x), exp2(x)</td>
<td>3 + 2 ×</td>
<td>x</td>
</tr>
<tr>
<td>Instruction</td>
<td>Single precision, unless decorated with RelaxedPrecision</td>
<td>Half precision</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>log(), log2()</td>
<td>3 ULP outside the range [0.5, 2.0]. Absolute error &lt; $2^{-21}$ inside the range [0.5, 2.0].</td>
<td>3 ULP outside the range [0.5, 2.0]. Absolute error &lt; $2^{-7}$ inside the range [0.5, 2.0].</td>
</tr>
<tr>
<td>pow(x, y)</td>
<td>Inherited from $\exp_2(y \times \log_2(x))$.</td>
<td></td>
</tr>
<tr>
<td>sqrt()</td>
<td>Inherited from $1.0 / \text{inversesqrt}()$.</td>
<td></td>
</tr>
<tr>
<td>inversesqrt()</td>
<td>2 ULP.</td>
<td></td>
</tr>
<tr>
<td>radians(x)</td>
<td>Inherited from $x \times C_{u,180}$, where $C_{u,180}$ is a correctly rounded approximation to $\frac{\pi}{180}$.</td>
<td></td>
</tr>
<tr>
<td>degrees(x)</td>
<td>Inherited from $x \times C_{180,n}$, where $C_{180,n}$ is a correctly rounded approximation to $\frac{180}{\pi}$.</td>
<td></td>
</tr>
<tr>
<td>sin()</td>
<td>Absolute error $\leq 2^{-13}$ inside the range $[-n, n]$.</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-n, n]$.</td>
</tr>
<tr>
<td>cos()</td>
<td>Absolute error $\leq 2^{-13}$ inside the range $[-n, n]$.</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-n, n]$.</td>
</tr>
<tr>
<td>tan()</td>
<td>Inherited from $\frac{\sin(x)}{\cos(x)}$.</td>
<td></td>
</tr>
<tr>
<td>asin(x)</td>
<td>Inherited from $\text{atan}2(x, \sqrt{1.0 - x \times x})$.</td>
<td></td>
</tr>
<tr>
<td>acos(x)</td>
<td>Inherited from $\text{atan}2(\sqrt{1.0 - x \times x}, x)$.</td>
<td></td>
</tr>
<tr>
<td>atan(), atan2()</td>
<td>4096 ULP</td>
<td>5 ULP.</td>
</tr>
<tr>
<td>sinh(x)</td>
<td>Inherited from $(\exp(x) - \exp(-x)) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>cosh(x)</td>
<td>Inherited from $(\exp(x) + \exp(-x)) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>tanh()</td>
<td>Inherited from $\frac{\sinh(x)}{\cosh(x)}$.</td>
<td></td>
</tr>
<tr>
<td>asinh(x)</td>
<td>Inherited from $\log(x + \sqrt{x \times x + 1.0})$.</td>
<td></td>
</tr>
<tr>
<td>acosh(x)</td>
<td>Inherited from $\log(x + \sqrt{x \times x - 1.0})$.</td>
<td></td>
</tr>
<tr>
<td>atanh(x)</td>
<td>Inherited from $\log\left(\frac{1.0 + x}{1.0 - x}\right) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>frexp()</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>ldexp()</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>length(x)</td>
<td>Inherited from $\sqrt{\text{dot}(x, x)}$.</td>
<td></td>
</tr>
<tr>
<td>distance(x, y)</td>
<td>Inherited from $\text{length}(x - y)$.</td>
<td></td>
</tr>
<tr>
<td>normalize(x)</td>
<td>Inherited from $x \times \text{inversesqrt}(\text{dot}(x, x))$.</td>
<td></td>
</tr>
<tr>
<td>faceforward(N, I, NRef)</td>
<td>Inherited from $\text{dot}(\text{NRef}, I) &lt; 0.0 ? N : -N$.</td>
<td></td>
</tr>
<tr>
<td>reflect(x, y)</td>
<td>Inherited from $x - 2.0 \times \text{dot}(y, x) \times y$.</td>
<td></td>
</tr>
<tr>
<td>refract(I, N, eta)</td>
<td>Inherited from $k &lt; 0.0 ? 0.0 : \text{eta} \times 1 - (\text{eta} \times \text{dot}(N, I) + \sqrt{t}) \times N$, where $k = 1 - \text{eta} \times \text{eta} \times (1.0 - \text{dot}(N, I) \times \text{dot}(N, I))$.</td>
<td></td>
</tr>
<tr>
<td>Instruction</td>
<td>Single precision, unless decorated with RelaxedPrecision</td>
<td>Half precision</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>round</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>roundEven</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>trunc</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fabs</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fsign</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>floor</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>ceil</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fract</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>modf</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmin</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmax</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fclamp</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmix(x, y, a)</td>
<td>Inherited from $x \times (1.0 - a) + y \times a$.</td>
<td></td>
</tr>
<tr>
<td>step</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>smoothStep(edge0, edge1, x)</td>
<td>Inherited from $t \times t \times (3.0 - 2.0 \times t)$, where $t = \text{clamp}(\frac{x - edge0}{edge1 - edge0}, 0.0, 1.0)$.</td>
<td></td>
</tr>
<tr>
<td>nmin</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>nmax</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>nclamp</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
</tbody>
</table>

GLSL.std.450 extended instructions specifically defined in terms of the above instructions inherit the above errors. GLSL.std.450 extended instructions not listed above and not defined in terms of the above have undefined precision.

For the OpSRem and OpSMod instructions, if either operand is negative the result is undefined.

**Note**

While the OpSRem and OpSMod instructions are supported by the Vulkan environment, they require non-negative values and thus do not enable additional functionality beyond what OpUMod provides.

**Signedness of SPIR-V Image Accesses**

SPIR-V associates a signedness with all integer image accesses. This is required in certain parts of the SPIR-V and the Vulkan image access pipeline to ensure defined results. The signedness is determined from a combination of the access instruction’s Image Operands and the underlying image’s Sampled Type as follows:
1. If the instruction’s Image Operands contains the SignExtend operand then the access is signed.
2. If the instruction’s Image Operands contains the ZeroExtend operand then the access is unsigned.
3. Otherwise, the image accesses signedness matches that of the Sampled Type of the OpTypeImage being accessed.

**Image Format and Type Matching**

When specifying the Image Format of an OpTypeImage, the converted bit width and type, as shown in the table below, **must** match the Sampled Type. The signedness **must** match the signedness of any access to the image.

![Note](image)

*Note*

Formatted accesses are always converted from a shader readable type to the resource's format or vice versa via Format Conversion for reads and Texel Output Format Conversion for writes. As such, the bit width and format below do not necessarily match 1:1 with what might be expected for some formats.

For a given Image Format, the Sampled Type **must** be the type described in the Type column of the below table, with its Literal Width set to that in the Bit Width column. Every access that is made to the image **must** have a signedness equal to that in the Signedness column (where applicable).

<table>
<thead>
<tr>
<th>Image Format</th>
<th>Type-Declaration instructions</th>
<th>Bit Width</th>
<th>Signedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>Image Format</td>
<td>Type-Declaration instructions</td>
<td>Bit Width</td>
<td>Signedness</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>Rgba32f</td>
<td>OpTypeFloat</td>
<td>32</td>
<td>N/A</td>
</tr>
<tr>
<td>Rg32f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R32f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgba16f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rg16f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgba16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rg16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgba16Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rg16Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgb10A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R11fG11fB10f</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgba8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rg8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rgba8Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rg8Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8Snorm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The SPIR-V Type is defined by an instruction in SPIR-V, declared with the Type-Declaration Instruction, Bit Width, and Signedness from above.

**Compatibility Between SPIR-V Image Formats And Vulkan Formats**

SPIR-V Image Format values are compatible with VkFormat values as defined below:

**Table 67. SPIR-V and Vulkan Image Format Compatibility**

<table>
<thead>
<tr>
<th>SPIR-V Image Format</th>
<th>Compatible Vulkan Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>Any</td>
</tr>
<tr>
<td>R8</td>
<td>VK_FORMAT_R8_UNORM</td>
</tr>
<tr>
<td>R8Snorm</td>
<td>VK_FORMAT_R8_SNORM</td>
</tr>
<tr>
<td>R8ui</td>
<td>VK_FORMAT_R8_UINT</td>
</tr>
<tr>
<td>R8i</td>
<td>VK_FORMAT_R8_SINT</td>
</tr>
<tr>
<td>Rg8</td>
<td>VK_FORMAT_R8G8_UNORM</td>
</tr>
<tr>
<td>Rg8Snorm</td>
<td>VK_FORMAT_R8G8_SNORM</td>
</tr>
<tr>
<td>SPIR-V Image Format</td>
<td>Compatible Vulkan Format</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Rg8ui</td>
<td>VK_FORMAT_R8G8_UINT</td>
</tr>
<tr>
<td>Rg8i</td>
<td>VK_FORMAT_R8G8_SINT</td>
</tr>
<tr>
<td>Rgba8</td>
<td>VK_FORMAT_R8G8B8B8A8_UNORM</td>
</tr>
<tr>
<td>Rgba8Snorm</td>
<td>VK_FORMAT_R8G8B8B8A8_SNORM</td>
</tr>
<tr>
<td>Rgba8ui</td>
<td>VK_FORMAT_R8G8B8B8A8_UINT</td>
</tr>
<tr>
<td>Rgba8i</td>
<td>VK_FORMAT_R8G8B8B8A8_SINT</td>
</tr>
<tr>
<td>Rgb10A2</td>
<td>VK_FORMAT_A2B10G10R10_UNORM_PACK32</td>
</tr>
<tr>
<td>Rgb10a2ui</td>
<td>VK_FORMAT_A2B10G10R10_UINT_PACK32</td>
</tr>
<tr>
<td>R16</td>
<td>VK_FORMAT_R16_UNORM</td>
</tr>
<tr>
<td>R16Snorm</td>
<td>VK_FORMAT_R16_SNORM</td>
</tr>
<tr>
<td>R16ui</td>
<td>VK_FORMAT_R16_UINT</td>
</tr>
<tr>
<td>R16i</td>
<td>VK_FORMAT_R16_SINT</td>
</tr>
<tr>
<td>R16f</td>
<td>VK_FORMAT_R16_SFLOAT</td>
</tr>
<tr>
<td>Rg16</td>
<td>VK_FORMAT_R16G16_UNORM</td>
</tr>
<tr>
<td>Rg16Snorm</td>
<td>VK_FORMAT_R16G16_SNORM</td>
</tr>
<tr>
<td>Rg16ui</td>
<td>VK_FORMAT_R16G16_UINT</td>
</tr>
<tr>
<td>Rg16i</td>
<td>VK_FORMAT_R16G16_SINT</td>
</tr>
<tr>
<td>Rg16f</td>
<td>VK_FORMAT_R16G16_SFLOAT</td>
</tr>
<tr>
<td>Rgba16</td>
<td>VK_FORMAT_R16G16B16A16_UNORM</td>
</tr>
<tr>
<td>Rgba16Snorm</td>
<td>VK_FORMAT_R16G16B16A16_SNORM</td>
</tr>
<tr>
<td>Rgba16ui</td>
<td>VK_FORMAT_R16G16B16A16_UINT</td>
</tr>
<tr>
<td>Rgba16i</td>
<td>VK_FORMAT_R16G16B16A16_SINT</td>
</tr>
<tr>
<td>Rgba16f</td>
<td>VK_FORMAT_R16G16B16A16_SFLOAT</td>
</tr>
<tr>
<td>R32ui</td>
<td>VK_FORMAT_R32_UINT</td>
</tr>
<tr>
<td>R32f</td>
<td>VK_FORMAT_R32_SINT</td>
</tr>
<tr>
<td>R32i</td>
<td>VK_FORMAT_R32_SFLOAT</td>
</tr>
<tr>
<td>R32gui</td>
<td>VK_FORMAT_R32G32_UINT</td>
</tr>
<tr>
<td>R32g1</td>
<td>VK_FORMAT_R32G32_SINT</td>
</tr>
<tr>
<td>R32f</td>
<td>VK_FORMAT_R32G32_SFLOAT</td>
</tr>
<tr>
<td>Rgba32ui</td>
<td>VK_FORMAT_R32G32B32A32_UINT</td>
</tr>
<tr>
<td>Rgba32i</td>
<td>VK_FORMAT_R32G32B32A32_SINT</td>
</tr>
<tr>
<td>Rgba32f</td>
<td>VK_FORMAT_R32G32B32A32_SFLOAT</td>
</tr>
<tr>
<td>R64ui</td>
<td>VK_FORMAT_R64_UINT</td>
</tr>
<tr>
<td>R64i</td>
<td>VK_FORMAT_R64_SINT</td>
</tr>
<tr>
<td>R11fG11fB10f</td>
<td>VK_FORMAT_B10G11R11_UFLOAT_PACK32</td>
</tr>
</tbody>
</table>
Appendix B: Memory Model

Note
This memory model describes synchronizations provided by all implementations; however, some of the synchronizations defined require extra features to be supported by the implementation. See VkPhysicalDeviceVulkanMemoryModelFeatures.

Agent

Operation is a general term for any task that is executed on the system.

Note
An operation is by definition something that is executed. Thus if an instruction is skipped due to control flow, it does not constitute an operation.

Each operation is executed by a particular agent. Possible agents include each shader invocation, each host thread, and each fixed-function stage of the pipeline.

Memory Location

A memory location identifies unique storage for 8 bits of data. Memory operations access a set of memory locations consisting of one or more memory locations at a time, e.g. an operation accessing a 32-bit integer in memory would read/write a set of four memory locations. Memory operations that access whole aggregates may access any padding bytes between elements or members, but no padding bytes at the end of the aggregate. Two sets of memory locations overlap if the intersection of their sets of memory locations is non-empty. A memory operation must not affect memory at a memory location not within its set of memory locations.

Memory locations for buffers and images are explicitly allocated in VkDeviceMemory objects, and are implicitly allocated for SPIR-V variables in each shader invocation.

Allocation

The values stored in newly allocated memory locations are determined by a SPIR-V variable’s initializer, if present, or else are undefined. At the time an allocation is created there have been no memory operations to any of its memory locations. The initialization is not considered to be a memory operation.

Note
For tessellation control shader output variables, a consequence of initialization not being considered a memory operation is that some implementations may need to insert a barrier between the initialization of the output variables and any reads of those variables.
Memory Operation

For an operation A and memory location M:

- **A reads** M if and only if the data stored in M is an input to A.
- **A writes** M if and only if the data output from A is stored to M.
- **A accesses** M if and only if it either reads or writes (or both) M.

**Note**
A write whose value is the same as what was already in those memory locations is still considered to be a write and has all the same effects.

Reference

A *reference* is an object that a particular agent can use to access a set of memory locations. On the host, a reference is a host virtual address. On the device, a reference is:

- The descriptor that a variable is bound to, for variables in Image, Uniform, or StorageBuffer storage classes. If the variable is an array (or array of arrays, etc.) then each element of the array may be a unique reference.
- The address range for a buffer in PhysicalStorageBuffer storage class, where the base of the address range is queried with vkGetBufferDeviceAddress and the length of the range is the size of the buffer.
- The variable itself for variables in other storage classes.

Two memory accesses through distinct references may require availability and visibility operations as defined below.

Program-Order

A *dynamic instance* of an instruction is defined in SPIR-V (https://registry.khronos.org/spir-v/specs/unified1/SPIRV.html#DynamicInstance) as a way of referring to a particular execution of a static instruction. Program-order is an ordering on dynamic instances of instructions executed by a single shader invocation:

- (Basic block): If instructions A and B are in the same basic block, and A is listed in the module before B, then the n'th dynamic instance of A is program-ordered before the n'th dynamic instance of B.
- (Branch): The dynamic instance of a branch or switch instruction is program-ordered before the dynamic instance of the OpLabel instruction to which it transfers control.
- (Call entry): The dynamic instance of an OpFunctionCall instruction is program-ordered before the dynamic instances of the OpFunctionParameter instructions and the body of the called function.
- (Call exit): The dynamic instance of the instruction following an OpFunctionCall instruction is program-ordered after the dynamic instance of the return instruction executed by the called
function.

- (Transitive Closure): If dynamic instance A of any instruction is program-ordered before dynamic instance B of any instruction and B is program-ordered before dynamic instance C of any instruction then A is program-ordered before C.
- (Complete definition): No other dynamic instances are program-ordered.

For instructions executed on the host, the source language defines the program-order relation (e.g. as “sequenced-before”).

Scope

Atomic and barrier instructions include scopes which identify sets of shader invocations that must obey the requested ordering and atomicity rules of the operation, as defined below.

The various scopes are described in detail in the Shaders chapter.

Atomic Operation

An atomic operation on the device is any SPIR-V operation whose name begins with OpAtomic. An atomic operation on the host is any operation performed with an std::atomic typed object.

Each atomic operation has a memory scope and a semantics. Informally, the scope determines which other agents it is atomic with respect to, and the semantics constrains its ordering against other memory accesses. Device atomic operations have explicit scopes and semantics. Each host atomic operation implicitly uses the CrossDevice scope, and uses a memory semantics equivalent to a C++ std::memory_order value of relaxed, acquire, release, acq_rel, or seq_cst.

Two atomic operations A and B are potentially-mutually-ordered if and only if all of the following are true:

- They access the same set of memory locations.
- They use the same reference.
- A is in the instance of B's memory scope.
- B is in the instance of A's memory scope.
- A and B are not the same operation (irreflexive).

Two atomic operations A and B are mutually-ordered if and only if they are potentially-mutually-ordered and any of the following are true:

- A and B are both device operations.
- A and B are both host operations.
- A is a device operation, B is a host operation, and the implementation supports concurrent host- and device-atomics.

Note
If two atomic operations are not mutually-ordered, and if their sets of memory locations overlap, then each must be synchronized against the other as if they were non-atomic operations.

Scoped Modification Order

For a given atomic write $A$, all atomic writes that are mutually-ordered with $A$ occur in an order known as $A$'s scoped modification order. $A$'s scoped modification order relates no other operations.

Note

Invocations outside the instance of $A$'s memory scope may observe the values at $A$'s set of memory locations becoming visible to it in an order that disagrees with the scoped modification order.

Note

It is valid to have non-atomic operations or atomics in a different scope instance to the same set of memory locations, as long as they are synchronized against each other as if they were non-atomic (if they are not, it is treated as a data race). That means this definition of $A$'s scoped modification order could include atomic operations that occur much later, after intervening non-atomics. That is a bit non-intuitive, but it helps to keep this definition simple and non-circular.

Memory Semantics

Non-atomic memory operations, by default, may be observed by one agent in a different order than they were written by another agent.

Atomics and some synchronization operations include memory semantics, which are flags that constrain the order in which other memory accesses (including non-atomic memory accesses and availability and visibility operations) performed by the same agent can be observed by other agents, or can observe accesses by other agents.

Device instructions that include semantics are $\text{OpAtomic}^*$, $\text{OpControlBarrier}$, $\text{OpMemoryBarrier}$, and $\text{OpMemoryNamedBarrier}$. Host instructions that include semantics are some $\text{std::atomic}$ methods and memory fences.

SPIR-V supports the following memory semantics:

- Relaxed: No constraints on order of other memory accesses.

- Acquire: A memory read with this semantic performs an acquire operation. A memory barrier with this semantic is an acquire barrier.

- Release: A memory write with this semantic performs a release operation. A memory barrier with this semantic is a release barrier.

- AcquireRelease: A memory read-modify-write operation with this semantic performs both an acquire operation and a release operation, and inherits the limitations on ordering from both of those operations. A memory barrier with this semantic is both a release and acquire barrier.
Note
SPIR-V does not support “consume” semantics on the device.

The memory semantics operand also includes storage class semantics which indicate which storage classes are constrained by the synchronization. SPIR-V storage class semantics include:

- UniformMemory
- WorkgroupMemory
- ImageMemory
- OutputMemory

Each SPIR-V memory operation accesses a single storage class. Semantics in synchronization operations can include a combination of storage classes.

The UniformMemory storage class semantic applies to accesses to memory in the PhysicalStorageBuffer, Uniform and StorageBuffer storage classes. The WorkgroupMemory storage class semantic applies to accesses to memory in the Workgroup storage class. The ImageMemory storage class semantic applies to accesses to memory in the Image storage class. The OutputMemory storage class semantic applies to accesses to memory in the Output storage class.

Note
Informally, these constraints limit how memory operations can be reordered, and these limits apply not only to the order of accesses as performed in the agent that executes the instruction, but also to the order the effects of writes become visible to all other agents within the same instance of the instruction’s memory scope.

Note
Release and acquire operations in different threads can act as synchronization operations, to guarantee that writes that happened before the release are visible after the acquire. (This is not a formal definition, just an Informative forward reference.)

Note
The OutputMemory storage class semantic is only useful in tessellation control shaders, which is the only execution model where output variables are shared between invocations.

The memory semantics operand can also include availability and visibility flags, which apply availability and visibility operations as described in availability and visibility. The availability/visibility flags are:

- MakeAvailable: Semantics must be Release or AcquireRelease. Performs an availability operation before the release operation or barrier.
- MakeVisible: Semantics must be Acquire or AcquireRelease. Performs a visibility operation after the acquire operation or barrier.
The specifics of these operations are defined in Availability and Visibility Semantics.

Host atomic operations may support a different list of memory semantics and synchronization operations, depending on the host architecture and source language.

**Release Sequence**

After an atomic operation A performs a release operation on a set of memory locations M, the *release sequence headed by A* is the longest continuous subsequence of A’s scoped modification order that consists of:

- the atomic operation A as its first element
- atomic read-modify-write operations on M by any agent

**Note**
The atomics in the last bullet must be mutually-ordered with A by virtue of being in A's scoped modification order.

**Note**
This intentionally omits “atomic writes to M performed by the same agent that performed A”, which is present in the corresponding C++ definition.

**Synchronizes-With**

*Synchronizes-with* is a relation between operations, where each operation is either an atomic operation or a memory barrier (aka fence on the host).

If A and B are atomic operations, then A synchronizes-with B if and only if all of the following are true:

- A performs a release operation
- B performs an acquire operation
- A and B are mutually-ordered
- B reads a value written by A or by an operation in the release sequence headed by A

OpControlBarrier, OpMemoryBarrier, and OpMemoryNamedBarrier are memory barrier instructions in SPIR-V.

If A is a release barrier and B is an atomic operation that performs an acquire operation, then A synchronizes-with B if and only if all of the following are true:

- there exists an atomic write X (with any memory semantics)
- A is program-ordered before X
- X and B are mutually-ordered
- B reads a value written by X or by an operation in the release sequence headed by X
If X is relaxed, it is still considered to head a hypothetical release sequence for this rule

- A and B are in the instance of each other's memory scopes
- X's storage class is in A's semantics.

If A is an atomic operation that performs a release operation and B is an acquire barrier, then A synchronizes-with B if and only if all of the following are true:

- there exists an atomic read X (with any memory semantics)
- X is program-ordered before B
- X and A are mutually-ordered
- X reads a value written by A or by an operation in the release sequence headed by A
- A and B are in the instance of each other's memory scopes
- X's storage class is in B's semantics.

If A is an acquire barrier and B is an acquire barrier, then A synchronizes-with B if all of the following are true:

- there exists an atomic write X (with any memory semantics)
- A is program-ordered before X
- there exists an atomic read Y (with any memory semantics)
- Y is program-ordered before B
- X and Y are mutually-ordered
- Y reads the value written by X or by an operation in the release sequence headed by X

  - If X is relaxed, it is still considered to head a hypothetical release sequence for this rule
  - A and B are in the instance of each other's memory scopes
  - X's and Y's storage class is in A's and B's semantics.

  - NOTE: X and Y must have the same storage class, because they are mutually ordered.

If A is a release barrier, B is an acquire barrier, and C is a control barrier (where A can equal C, and B can equal C), then A synchronizes-with B if all of the following are true:

- A is program-ordered before (or equals) C
- C is program-ordered before (or equals) B
- A and B are in the instance of each other's memory scopes
- A and B are in the instance of C's execution scope

**Note**

This is similar to the barrier-barrier synchronization above, but with a control barrier filling the role of the relaxed atoms.

No other release and acquire barriers synchronize-with each other.
System-Synchronizes-With

_System-synchronizes-with_ is a relation between arbitrary operations on the device or host. Certain operations system-synchronize-with each other, which informally means the first operation occurs before the second and that the synchronization is performed without using application-visible memory accesses.

If there is an execution dependency between two operations A and B, then the operation in the first synchronization scope system-synchronizes-with the operation in the second synchronization scope.

**Note**

This covers all Vulkan synchronization primitives, including device operations executing before a synchronization primitive is signaled, wait operations happening before subsequent device operations, signal operations happening before host operations that wait on them, and host operations happening before _vkQueueSubmit_. The list is spread throughout the synchronization chapter, and is not repeated here.

System-synchronizes-with implicitly includes all storage class semantics and has _CrossDevice_ scope.

If A system-synchronizes-with B, we also say A is _system-synchronized-before_ B and B is _system-synchronized-after_ A.

**Private vs. Non-Private**

By default, non-atomic memory operations are treated as _private_, meaning such a memory operation is not intended to be used for communication with other agents. Memory operations with the NonPrivatePointer/NonPrivateTexel bit set are treated as _non-private_, and are intended to be used for communication with other agents.

More precisely, for private memory operations to be _Location-Ordered_ between distinct agents requires using system-synchronizes-with rather than shader-based synchronization. Non-private memory operations still obey program-order.

Atomic operations are always considered non-private.

**Inter-Thread-Happens-Before**

Let SC be a non-empty set of storage class semantics. Then (using template syntax) operation A _inter-thread-happens-before<SC>_ operation B if and only if any of the following is true:

- A system-synchronizes-with B
- A synchronizes-with B, and both A and B have all of SC in their semantics
- A is an operation on memory in a storage class in SC or that has all of SC in its semantics, B is a release barrier or release atomic with all of SC in its semantics, and A is program-ordered before B
• A is an acquire barrier or acquire atomic with all of SC in its semantics, B is an operation on memory in a storage class in SC or that has all of SC in its semantics, and A is program-ordered before B

• A and B are both host operations and A inter-thread-happens-before B as defined in the host language specification

• A inter-thread-happens-before<SC> some X and X inter-thread-happens-before<SC> B

**Happens-Before**

Operation A *happens-before* operation B if and only if any of the following is true:

• A is program-ordered before B

• A inter-thread-happens-before<SC> B for some set of storage classes SC

*Happens-after* is defined similarly.

**Note**

Unlike C++, happens-before is not always sufficient for a write to be visible to a read. Additional availability and visibility operations *may* be required for writes to be visible-to other memory accesses.

**Note**

Happens-before is not transitive, but each of program-order and inter-thread-happens-before<SC> are transitive. These can be thought of as covering the “single-threaded” case and the “multi-threaded” case, and it is not necessary (and not valid) to form chains between the two.

**Availability and Visibility**

Availability and visibility are states of a write operation, which (informally) track how far the write has permeated the system, i.e. which agents and references are able to observe the write. Availability state is per *memory domain*. Visibility state is per (agent,reference) pair. Availability and visibility states are per-memory location for each write.

Memory domains are named according to the agents whose memory accesses use the domain. Domains used by shader invocations are organized hierarchically into multiple smaller memory domains which correspond to the different scopes. Each memory domain is considered the dual of a scope, and vice versa. The memory domains defined in Vulkan include:

• *host* - accessible by host agents

• *device* - accessible by all device agents for a particular device

• *shader* - accessible by shader agents for a particular device, corresponding to the *Device* scope

• *queue family instance* - accessible by shader agents in a single queue family, corresponding to the *QueueFamily* scope.
• **workgroup instance** - accessible by shader agents in the same workgroup, corresponding to the **Workgroup** scope.

• **subgroup instance** - accessible by shader agents in the same subgroup, corresponding to the **Subgroup** scope.

The memory domains are nested in the order listed above, with memory domains later in the list nested in the domains earlier in the list.

**Note**

Memory domains do not correspond to storage classes or device-local and host-local **VkDeviceMemory** allocations, rather they indicate whether a write can be made visible only to agents in the same subgroup, same workgroup, in any shader invocation, or anywhere on the device, or host. The shader, queue family instance, workgroup instance, and subgroup instance domains are only used for shader-based availability/visibility operations, in other cases writes can be made available from/visible to the shader via the device domain.

**Availability operations, visibility operations, and memory domain operations** alter the state of the write operations that happen-before them, and which are included in their **source scope** to be available or visible to their **destination scope**.

• For an availability operation, the source scope is a set of (agent,reference,memory location) tuples, and the destination scope is a set of memory domains.

• For a memory domain operation, the source scope is a memory domain and the destination scope is a memory domain.

• For a visibility operation, the source scope is a set of memory domains and the destination scope is a set of (agent,reference,memory location) tuples.

How the scopes are determined depends on the specific operation. Availability and memory domain operations expand the set of memory domains to which the write is available. Visibility operations expand the set of (agent,reference,memory location) tuples to which the write is visible.

Recall that availability and visibility states are per-memory location, and let W be a write operation to one or more locations performed by agent A via reference R. Let L be one of the locations written. (W,L) (the write W to L), is initially not available to any memory domain and only visible to (A,R,L). An availability operation AV that happens-after W and that includes (A,R,L) in its source scope makes (W,L) **available** to the memory domains in its destination scope.

A memory domain operation DOM that happens-after AV and for which (W,L) is available in the source scope makes (W,L) available in the destination memory domain.

A visibility operation VIS that happens-after AV (or DOM) and for which (W,L) is available in any domain in the source scope makes (W,L) **visible** to all (agent,reference,L) tuples included in its destination scope.

If write W₂ happens-after W, and their sets of memory locations overlap, then W will not be available/visible to all agents/references for those memory locations that overlap (and future AV/DOM/VIS ops cannot revive W’s write to those locations).
Availability, memory domain, and visibility operations are treated like other non-atomic memory accesses for the purpose of memory semantics, meaning they can be ordered by release-acquire sequences or memory barriers.

An availability chain is a sequence of availability operations to increasingly broad memory domains, where element N+1 of the chain is performed in the dual scope instance of the destination memory domain of element N and element N happens-before element N+1. An example is an availability operation with destination scope of the workgroup instance domain that happens-before an availability operation to the shader domain performed by an invocation in the same workgroup. An availability chain AVC that happens-after W and that includes (A,R,L) in the source scope makes (W,L) available to the memory domains in its final destination scope. An availability chain with a single element is just the availability operation.

Similarly, a visibility chain is a sequence of visibility operations from increasingly narrow memory domains, where element N of the chain is performed in the dual scope instance of the source memory domain of element N+1 and element N happens-before element N+1. An example is a visibility operation with source scope of the shader domain that happens-before a visibility operation with source scope of the workgroup instance domain performed by an invocation in the same workgroup. A visibility chain VISC that happens-after AVC (or DOM) and for which (W,L) is available in any domain in the source scope makes (W,L) visible to all (agent,reference,L) tuples included in its final destination scope. A visibility chain with a single element is just the visibility operation.

Availability, Visibility, and Domain Operations

The following operations generate availability, visibility, and domain operations. When multiple availability/visibility/domain operations are described, they are system-synchronized-with each other in the order listed.

An operation that performs a memory dependency generates:

- If the source access mask includes VK_ACCESS_HOST_WRITE_BIT, then the dependency includes a memory domain operation from host domain to device domain.
- An availability operation with source scope of all writes in the first access scope of the dependenecy and a destination scope of the device domain.
- A visibility operation with source scope of the device domain and destination scope of the second access scope of the dependency.
- If the destination access mask includes VK_ACCESS_HOST_READ_BIT or VK_ACCESS_HOST_WRITE_BIT, then the dependency includes a memory domain operation from device domain to host domain.

vkFlushMappedMemoryRanges performs an availability operation, with a source scope of (agents,references) = (all host threads, all mapped memory ranges passed to the command), and destination scope of the host domain.

vkInvalidateMappedMemoryRanges performs a visibility operation, with a source scope of the host domain and a destination scope of (agents,references) = (all host threads, all mapped memory ranges passed to the command).
vkQueueSubmit performs a memory domain operation from host to device, and a visibility operation with source scope of the device domain and destination scope of all agents and references on the device.

**Availability and Visibility Semantics**

A memory barrier or atomic operation via agent A that includes MakeAvailable in its semantics performs an availability operation whose source scope includes agent A and all references in the storage classes in that instruction's storage class semantics, and all memory locations, and whose destination scope is a set of memory domains selected as specified below. The implicit availability operation is program-ordered between the barrier or atomic and all other operations program-ordered before the barrier or atomic.

A memory barrier or atomic operation via agent A that includes MakeVisible in its semantics performs a visibility operation whose source scope is a set of memory domains selected as specified below, and whose destination scope includes agent A and all references in the storage classes in that instruction's storage class semantics, and all memory locations. The implicit visibility operation is program-ordered between the barrier or atomic and all other operations program-ordered after the barrier or atomic.

The memory domains are selected based on the memory scope of the instruction as follows:

- **Device** scope uses the shader domain
- **QueueFamily** scope uses the queue family instance domain
- **Workgroup** scope uses the workgroup instance domain
- **Subgroup** uses the subgroup instance domain
- **Invocation** perform no availability/visibility operations.

When an availability operation performed by an agent A includes a memory domain D in its destination scope, where D corresponds to scope instance S, it also includes the memory domains that correspond to each smaller scope instance S’ that is a subset of S and that includes A. Similarly for visibility operations.

**Per-Instruction Availability and Visibility Semantics**

A memory write instruction that includes MakePointerAvailable, or an image write instruction that includes MakeTexelAvailable, performs an availability operation whose source scope includes the agent and reference used to perform the write and the memory locations written by the instruction, and whose destination scope is a set of memory domains selected by the Scope operand specified in Availability and Visibility Semantics. The implicit availability operation is program-ordered between the write and all other operations program-ordered after the write.

A memory read instruction that includes MakePointerVisible, or an image read instruction that includes MakeTexelVisible, performs a visibility operation whose source scope is a set of memory domains selected by the Scope operand as specified in Availability and Visibility Semantics, and whose destination scope includes the agent and reference used to perform the read and the memory locations read by the instruction. The implicit visibility operation is program-ordered
between read and all other operations program-ordered before the read.

Note
Although reads with per-instruction visibility only perform visibility ops from the shader or workgroup instance or subgroup instance domain, they will also see writes that were made visible via the device domain, i.e. those writes previously performed by non-shader agents and made visible via API commands.

Note
It is expected that all invocations in a subgroup execute on the same processor with the same path to memory, and thus availability and visibility operations with subgroup scope can be expected to be “free”.

Location-Ordered

Let X and Y be memory accesses to overlapping sets of memory locations M, where \( X \neq Y \). Let \( (A_X, R_X) \) be the agent and reference used for X, and \( (A_Y, R_Y) \) be the agent and reference used for Y. For now, let “\( ightarrow \)” denote happens-before and “\( \rightarrow_{rcpo} \)” denote the reflexive closure of program-ordered before.

If \( D_1 \) and \( D_2 \) are different memory domains, then let \( \text{DOM}(D_1, D_2) \) be a memory domain operation from \( D_1 \) to \( D_2 \). Otherwise, let \( \text{DOM}(D, D) \) be a placeholder such that \( X \rightarrow \text{DOM}(D, D) \rightarrow Y \) if and only if \( X \rightarrow Y \).

X is location-ordered before Y for a location L in M if and only if any of the following is true:

- \( A_X = A_Y \) and \( R_X = R_Y \) and \( X \rightarrow Y \)
  - NOTE: this case means no availability/visibility ops are required when it is the same (agent,reference).
- X is a read, both X and Y are non-private, and \( X \rightarrow Y \)
- X is a read, and X (transitively) system-synchronizes with Y
- If \( R_X = R_Y \) and \( A_X \) and \( A_Y \) access a common memory domain D (e.g. are in the same workgroup instance if D is the workgroup instance domain), and both X and Y are non-private:
  - X is a write, Y is a write, \( \text{AVC}(A_X, R_X, D, L) \) is an availability chain making \((X, L)\) available to domain D, and \( X \rightarrow_{rcpo} \text{AVC}(A_X, R_X, D, L) \rightarrow Y \)
  - X is a write, Y is a read, \( \text{AVC}(A_X, R_X, D, L) \) is an availability chain making \((X, L)\) available to domain D visible to Y, and \( X \rightarrow_{rcpo} \text{AVC}(A_X, R_X, D, L) \rightarrow \text{VISC}(A_Y, R_Y, D, L) \rightarrow_{rcpo} Y \)
  - If \( \text{VkPhysicalDeviceVulkanMemoryModelFeatures::vulkanMemoryModelAvailabilityVisibilityChains} = \text{VK_FALSE} \), then AVC and VISC must each only have a single element in the chain, in each sub-bullet above.
- Let \( D_X \) and \( D_Y \) each be either the device domain or the host domain, depending on whether \( A_X \) and \( A_Y \) execute on the device or host:
  - X is a write and Y is a write, and \( X \rightarrow \text{AV}(A_X, R_X, D_X, L) \rightarrow \text{DOM}(D_X, D_Y) \rightarrow Y \)
X is a write and Y is a read, and X → AV(A_X, R_X, D_X, L) → DOM(D_X, D_Y) → VIS(A_Y, R_Y, D_Y, L) → Y

Note

The final bullet (synchronization through device/host domain) requires API-level synchronization operations, since the device/host domains are not accessible via shader instructions. And “device domain” is not to be confused with “device scope”, which synchronizes through the “shader domain”.

Data Race

Let X and Y be operations that access overlapping sets of memory locations M, where X != Y, and at least one of X and Y is a write, and X and Y are not mutually-ordered atomic operations. If there does not exist a location-ordered relation between X and Y for each location in M, then there is a data race.

Applications must ensure that no data races occur during the execution of their application.

Note

Data races can only occur due to instructions that are actually executed. For example, an instruction skipped due to control flow must not contribute to a data race.

Visible-To

Let X be a write and Y be a read whose sets of memory locations overlap, and let M be the set of memory locations that overlap. Let M_2 be a non-empty subset of M. Then X is visible-to Y for memory locations M_2 if and only if all of the following are true:

• X is location-ordered before Y for each location L in M_2.
• There does not exist another write Z to any location L in M_2 such that X is location-ordered before Z for location L and Z is location-ordered before Y for location L.

If X is visible-to Y, then Y reads the value written by X for locations M_2.

Note

It is possible for there to be a write between X and Y that overwrites a subset of the memory locations, but the remaining memory locations (M_2) will still be visible-to Y.

Acyclicity

Reads-from is a relation between operations, where the first operation is a write, the second operation is a read, and the second operation reads the value written by the first operation. From-reads is a relation between operations, where the first operation is a read, the second operation is a write, and the first operation reads a value written earlier than the second operation in the second operation’s scoped modification order (or the first operation reads from the initial value, and the
second operation is any write to the same locations).

Then the implementation must guarantee that no cycles exist in the union of the following relations:

- location-ordered
- scoped modification order (over all atomic writes)
- reads-from
- from-reads

Note
This is a "consistency" axiom, which informally guarantees that sequences of operations cannot violate causality.

Scoped Modification Order Coherence

Let A and B be mutually-ordered atomic operations, where A is location-ordered before B. Then the following rules are a consequence of acyclicity:

- If A and B are both reads and A does not read the initial value, then the write that A takes its value from must be earlier in its own scoped modification order than (or the same as) the write that B takes its value from (no cycles between location-order, reads-from, and from-reads).
- If A is a read and B is a write and A does not read the initial value, then A must take its value from a write earlier than B in B's scoped modification order (no cycles between location-order, scope modification order, and reads-from).
- If A is a write and B is a read, then B must take its value from A or a write later than A in A's scoped modification order (no cycles between location-order, scoped modification order, and from-reads).
- If A and B are both writes, then A must be earlier than B in A's scoped modification order (no cycles between location-order and scoped modification order).
- If A is a write and B is a read-modify-write and B reads the value written by A, then B comes immediately after A in A's scoped modification order (no cycles between scoped modification order and from-reads).

Shader I/O

If a shader invocation A in a shader stage other than Vertex performs a memory read operation X from an object in storage class Input, then X is system-synchronized-after all writes to the corresponding Output storage variable(s) in the shader invocation(s) that contribute to generating invocation A, and those writes are all visible-to X.

Note
It is not necessary for the upstream shader invocations to have completed execution, they only need to have generated the output that is being read.
**Deallocation**

A call to `vkFreeMemory` must happen-after all memory operations on all memory locations in that `VkDeviceMemory` object.

**Note**

Normally, device memory operations in a given queue are synchronized with `vkFreeMemory` by having a host thread wait on a fence signaled by that queue, and the wait happens-before the call to `vkFreeMemory` on the host.

The deallocation of SPIR-V variables is managed by the system and happens-after all operations on those variables.

**Descriptions (Informative)**

This subsection offers more easily understandable consequences of the memory model for app/compiler developers.

Let SC be the storage class(es) specified by a release or acquire operation or barrier.

- An atomic write with release semantics must not be reordered against any read or write to SC that is program-ordered before it (regardless of the storage class the atomic is in).
- An atomic read with acquire semantics must not be reordered against any read or write to SC that is program-ordered after it (regardless of the storage class the atomic is in).
- Any write to SC program-ordered after a release barrier must not be reordered against any read or write to SC program-ordered before that barrier.
- Any read from SC program-ordered before an acquire barrier must not be reordered against any read or write to SC program-ordered after the barrier.

A control barrier (even if it has no memory semantics) must not be reordered against any memory barriers.

This memory model allows memory accesses with and without availability and visibility operations, as well as atomic operations, all to be performed on the same memory location. This is critical to allow it to reason about memory that is reused in multiple ways, e.g. across the lifetime of different shader invocations or draw calls. While GLSL (and legacy SPIR-V) applies the “coherent” decoration to variables (for historical reasons), this model treats each memory access instruction as having optional implicit availability/visibility operations. GLSL to SPIR-V compilers should map all (non-atomic) operations on a coherent variable to `Make{Pointer,Texel}{Available}{Visible}` flags in this model.

Atomic operations implicitly have availability/visibility operations, and the scope of those operations is taken from the atomic operation’s scope.
**Tessellation Output Ordering**

For SPIR-V that uses the Vulkan Memory Model, the `OutputMemory` storage class is used to synchronize accesses to tessellation control output variables. For legacy SPIR-V that does not enable the Vulkan Memory Model via `OpMemoryModel`, tessellation outputs can be ordered using a control barrier with no particular memory scope or semantics, as defined below.

Let \( X \) and \( Y \) be memory operations performed by shader invocations \( A_X \) and \( A_Y \). Operation \( X \) is **tessellation-output-ordered** before operation \( Y \) if and only if all of the following are true:

- There is a dynamic instance of an `OpControlBarrier` instruction \( C \) such that \( X \) is program-ordered before \( C \) in \( A_X \) and \( C \) is program-ordered before \( Y \) in \( A_Y \).
- \( A_X \) and \( A_Y \) are in the same instance of \( C \)'s execution scope.

If shader invocations \( A_X \) and \( A_Y \) in the **TessellationControl** execution model execute memory operations \( X \) and \( Y \), respectively, on the `Output` storage class, and \( X \) is tessellation-output-ordered before \( Y \) with a scope of **Workgroup**, then \( X \) is location-ordered before \( Y \), and if \( X \) is a write and \( Y \) is a read then \( X \) is visible-to \( Y \).
Appendix C: Compressed Image Formats

The compressed texture formats used by Vulkan are described in the specifically identified sections of the Khronos Data Format Specification, version 1.3.

Unless otherwise described, the quantities encoded in these compressed formats are treated as normalized, unsigned values.

Those formats listed as sRGB-encoded have in-memory representations of R, G and B components which are nonlinearly-encoded as R', G', and B'; any alpha component is unchanged. As part of filtering, the nonlinear R', G', and B' values are converted to linear R, G, and B components; any alpha component is unchanged. The conversion between linear and nonlinear encoding is performed as described in the “KHR_DF_TRANSFER_SRGB” section of the Khronos Data Format Specification.
Block-Compressed Image Formats

BC1, BC2 and BC3 formats are described in “S3TC Compressed Texture Image Formats” chapter of the Khronos Data Format Specification. BC4 and BC5 are described in the “RGTC Compressed Texture Image Formats” chapter. BC6H and BC7 are described in the “BPTC Compressed Texture Image Formats” chapter.

Table 68. Mapping of Vulkan BC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Khronos Data Format Specification description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formats described in the “S3TC Compressed Texture Image Formats” chapter</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK</td>
<td>BC1 with no alpha</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
<td>BC1 with no alpha, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK</td>
<td>BC1 with alpha</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
<td>BC1 with alpha, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC2_UNORM_BLOCK</td>
<td>BC2</td>
</tr>
<tr>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
<td>BC2, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
<td>BC3</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_SRGB_BLOCK</td>
<td>BC3, sRGB-encoded</td>
</tr>
<tr>
<td>Formats described in the “RGTC Compressed Texture Image Formats” chapter</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC4_UNORM_BLOCK</td>
<td>BC4 unsigned</td>
</tr>
<tr>
<td>VK_FORMAT_BC4_SNORM_BLOCK</td>
<td>BC4 signed</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_UNORM_BLOCK</td>
<td>BC5 unsigned</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_SNORM_BLOCK</td>
<td>BC5 signed</td>
</tr>
<tr>
<td>Formats described in the “BPTC Compressed Texture Image Formats” chapter</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK</td>
<td>BC6H (unsigned version)</td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
<td>BC6H (signed version)</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_UNORM_BLOCK</td>
<td>BC7</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_SRGB_BLOCK</td>
<td>BC7, sRGB-encoded</td>
</tr>
</tbody>
</table>
ETC Compressed Image Formats

The following formats are described in the “ETC2 Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

Table 69. Mapping of Vulkan ETC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Khronos Data Format Specification description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK</td>
<td>RGB ETC2</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
<td>RGB ETC2 with sRGB encoding</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK</td>
<td>RGB ETC2 with punch-through alpha</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
<td>RGB ETC2 with punch-through alpha and sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK</td>
<td>RGBA ETC2</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
<td>RGBA ETC2 with sRGB encoding</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK</td>
<td>Unsigned R11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
<td>Signed R11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</td>
<td>Unsigned RG11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
<td>Signed RG11 EAC</td>
</tr>
</tbody>
</table>
## ASTC Compressed Image Formats

ASTC formats are described in the “ASTC Compressed Texture Image Formats” chapter of the *Khronos Data Format Specification*.

### Table 70. Mapping of Vulkan ASTC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Compressed texel block dimensions</th>
<th>Requested mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_ASTC_4x4_UNORM_BLOCK</td>
<td>4 × 4</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
<td>4 × 4</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_UNORM_BLOCK</td>
<td>5 × 4</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
<td>5 × 4</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK</td>
<td>5 × 5</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
<td>5 × 5</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK</td>
<td>6 × 5</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
<td>6 × 5</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK</td>
<td>6 × 6</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
<td>6 × 6</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK</td>
<td>8 × 5</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
<td>8 × 5</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK</td>
<td>8 × 6</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
<td>8 × 6</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK</td>
<td>8 × 8</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
<td>8 × 8</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK</td>
<td>10 × 5</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
<td>10 × 5</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK</td>
<td>10 × 6</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
<td>10 × 6</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_UNORM_BLOCK</td>
<td>10 × 8</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
<td>10 × 8</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_UNORM_BLOCK</td>
<td>10 × 10</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
<td>10 × 10</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_UNORM_BLOCK</td>
<td>12 × 10</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_SRGB_BLOCK</td>
<td>12 × 10</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_UNORM_BLOCK</td>
<td>12 × 12</td>
<td>Linear LDR</td>
</tr>
<tr>
<td>VkFormat</td>
<td>Compressed texel block dimensions</td>
<td>Requested mode</td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>-----------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_SRGB_BLOCK</td>
<td>12 × 12</td>
<td>sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_SFLOAT_BLOCK</td>
<td>4 × 4</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_SFLOAT_BLOCK</td>
<td>5 × 4</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SFLOAT_BLOCK</td>
<td>5 × 5</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SFLOAT_BLOCK</td>
<td>6 × 5</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SFLOAT_BLOCK</td>
<td>6 × 6</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SFLOAT_BLOCK</td>
<td>8 × 5</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SFLOAT_BLOCK</td>
<td>8 × 6</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SFLOAT_BLOCK</td>
<td>8 × 8</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK</td>
<td>10 × 5</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK</td>
<td>10 × 6</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK</td>
<td>10 × 8</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK</td>
<td>10 × 10</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK</td>
<td>12 × 10</td>
<td>HDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK</td>
<td>12 × 12</td>
<td>HDR</td>
</tr>
</tbody>
</table>

ASTC textures containing HDR block encodings **should** be passed to the API using an ASTC SFLOAT texture format.

**Note**

An HDR block in a texture passed using a LDR UNORM format will return the appropriate ASTC error color if the implementation supports only the ASTC LDR profile, but may result in either the error color or a decompressed HDR color if the implementation supports HDR decoding.

The ASTC decode mode is **decode_float16**.

Note that an implementation **may** use HDR mode when linear LDR mode is requested.
Appendix D: Core Revisions (Informative)

New minor versions of the Vulkan API are defined periodically by the Khronos Vulkan Working Group. These consist of some amount of additional functionality added to the core API, potentially including both new functionality and functionality promoted from extensions.

It is possible to build the specification for earlier versions, but to aid readability of the latest versions, this appendix gives an overview of the changes as compared to earlier versions.

Version 1.3

Vulkan Version 1.3 promoted a number of key extensions into the core API:

- VK_KHR_copy_commands2
- VK_KHR_dynamic_rendering
- VK_KHR_format_feature_flags2
- VK_KHR_maintenance4
- VK_KHR_shader_integer_dot_product
- VK_KHR_shader_non_semantic_info
- VK_KHR_shader_terminate_invocation
- VK_KHR_synchronization2
- VK_KHR_zero_initialize_workgroup_memory
- VK_EXT_4444_formats
- VK_EXT_extended_dynamic_state
- VK_EXT_extended_dynamic_state2
- VK_EXT_image_robustness
- VK_EXT_inline_uniform_block
- VK_EXT_pipeline_creation_cache_control
- VK_EXT_pipeline_creation_feedback
- VK_EXT_private_data
- VK_EXT_shader_demote_to_helper_invocation
- VK_EXT_subgroup_size_control
- VK_EXT_texel_buffer_alignment
- VK_EXT_texture_compression_astc_hdr
- VK_EXT_tooling_info
- VK_EXT_ycbcr_2plane_444_formats
All differences in behavior between these extensions and the corresponding Vulkan 1.3 functionality are summarized below.

**Differences relative to VK_EXT_4444_formats**

If the VK_EXT_4444_formats extension is not supported, support for all formats defined by it are optional in Vulkan 1.3. There are no members in the VkPhysicalDeviceVulkan13Features structure corresponding to the VkPhysicalDevice4444FormatsFeaturesEXT structure.

**Differences relative to VK_EXT_extended_dynamic_state**

All dynamic state enumerants and entry points defined by VK_EXT_extended_dynamic_state are required in Vulkan 1.3. There are no members in the VkPhysicalDeviceVulkan13Features structure corresponding to the VkPhysicalDeviceExtendedDynamicStateFeaturesEXT structure.

**Differences relative to VK_EXT_extended_dynamic_state2**

The optional dynamic state enumerants and entry points defined by VK_EXT_extended_dynamic_state2 for patch control points and logic op are not promoted in Vulkan 1.3. There are no members in the VkPhysicalDeviceVulkan13Features structure corresponding to the VkPhysicalDeviceExtendedDynamicState2FeaturesEXT structure.

**Differences relative to VK_EXT_texel_buffer_alignment**

The more specific alignment requirements defined by VkPhysicalDeviceTexelBufferAlignmentProperties are required in Vulkan 1.3. There are no members in the VkPhysicalDeviceVulkan13Features structure corresponding to the VkPhysicalDeviceTexelBufferAlignmentFeaturesEXT structure. The texelBufferAlignment feature is enabled if using a Vulkan 1.3 instance.

**Differences relative to VK_EXT_texture_compression_astc_hdr**

If the VK_EXT_texture_compression_astc_hdr extension is not supported, support for all formats defined by it are optional in Vulkan 1.3. The textureCompressionASTC_HDR member of VkPhysicalDeviceVulkan13Features indicates whether a Vulkan 1.3 implementation supports these formats.

**Differences relative to VK_EXT_ycbcr_2plane_444_formats**

If the VK_EXT_ycbcr_2plane_444_formats extension is not supported, support for all formats defined by it are optional in Vulkan 1.3. There are no members in the VkPhysicalDeviceVulkan13Features structure corresponding to the VkPhysicalDeviceYcbcr2Plane444FormatsFeaturesEXT structure.

**Additional Vulkan 1.3 Feature Support**

In addition to the promoted extensions described above, Vulkan 1.3 added required support for:

- SPIR-V version 1.6
SPIR-V 1.6 deprecates (but does not remove) the `WorkgroupSize` decoration.

- The `bufferDeviceAddress` feature which indicates support for accessing memory in shaders as storage buffers via `vkGetBufferDeviceAddress`.
- The `vulkanMemoryModel` and `vulkanMemoryModelDeviceScope` features, which indicate support for the corresponding Vulkan Memory Model capabilities.
- The `maxInlineUniformTotalSize` limit is added to provide the total size of all inline uniform block bindings in a pipeline layout.

### New Macros

- `VK_API_VERSION_1_3`

### New Base Types

- `VkFlags64`  

### New Object Types

- `VkPrivateDataSlot`  

### New Commands

- `vkCmdBeginRendering`
- `vkCmdBindVertexBuffers2`
- `vkCmdBlitImage2`
- `vkCmdCopyBuffer2`
- `vkCmdCopyBufferToImage2`
- `vkCmdCopyImage2`
- `vkCmdCopyImageToBuffer2`
- `vkCmdEndRendering`
- `vkCmdPipelineBarrier2`
- `vkCmdResetEvent2`
- `vkCmdResolveImage2`
- `vkCmdSetCullMode`
- `vkCmdSetDepthBiasEnable`
- `vkCmdSetDepthBoundsTestEnable`
- `vkCmdSetDepthCompareOp`
- `vkCmdSetDepthTestEnable`
- `vkCmdSetDepthWriteEnable`
- `vkCmdSetEvent2`
• vkCmdSetFrontFace
• vkCmdSetPrimitiveRestartEnable
• vkCmdSetPrimitiveTopology
• vkCmdSetRasterizerDiscardEnable
• vkCmdSetScissorWithCount
• vkCmdSetStencilOp
• vkCmdSetStencilTestEnable
• vkCmdSetViewportWithCount
• vkCmdWaitEvents2
• vkCmdWriteTimestamp2
• vkCreatePrivateDataSlot
• vkDestroyPrivateDataSlot
• vkGetDeviceBufferMemoryRequirements
• vkGetDeviceImageMemoryRequirements
• vkGetDeviceImageSparseMemoryRequirements
• vkGetPhysicalDeviceToolProperties
• vkGetPrivateData
• vkQueueSubmit2
• vkSetPrivateData
• vkSetPrivateData

New Structures
• VkBlitImageInfo2
• VkBufferCopy2
• VkBufferImageCopy2
• VkBufferMemoryBarrier2
• VkCommandBufferSubmitInfo
• VkCopyBufferInfo2
• VkCopyBufferToImageInfo2
• VkCopyImageInfo2
• VkCopyImageToBufferInfo2
• VkDependencyInfo
• VkDeviceBufferMemoryRequirements
• VkDeviceImageMemoryRequirements
• VkImageBlit2
• VkImageCopy2
- VkImageMemoryBarrier2
- VkImageResolve2
- VkPhysicalDeviceToolProperties
- VkPipelineCreationFeedback
- VkPrivateDataSlotCreateInfo
- VkRenderingAttachmentCreateInfo
- VkRenderingInfo
- VkResolveImageCreateInfo2
- VkSemaphoreSubmitCreateInfo
- VkSubmitInfo2
- Extending VkCommandBufferInheritanceInfo:
  - VkCommandBufferInheritanceRenderingInfo
- Extending VkDescriptorPoolCreateInfo:
  - VkDescriptorPoolInlineUniformBlockCreateInfo
- Extending VkDeviceCreateInfo:
  - VkDevicePrivateDataCreateInfo
- Extending VkFormatProperties2:
  - VkFormatProperties3
- Extending VkGraphicsPipelineCreateInfo:
  - VkPipelineRenderingCreateInfo
- Extending VkGraphicsPipelineCreateInfo, VkComputePipelineCreateInfo, VkRayTracingPipelineCreateInfoNV, VkRayTracingPipelineCreateInfoKHR:
  - VkPipelineCreationFeedbackCreateInfo
- Extending VkPhysicalDeviceFeatures2, VkDeviceCreateInfo:
  - VkPhysicalDeviceDynamicRenderingFeatures
  - VkPhysicalDeviceImageRobustnessFeatures
  - VkPhysicalDeviceInlineUniformBlockFeatures
  - VkPhysicalDeviceMaintenance4Features
  - VkPhysicalDevicePipelineCreationCacheControlFeatures
  - VkPhysicalDevicePrivateDataFeatures
  - VkPhysicalDeviceShaderDemoteToHelperInvocationFeatures
  - VkPhysicalDeviceShaderIntegerDotProductFeatures
  - VkPhysicalDeviceShaderTerminateInvocationFeatures
  - VkPhysicalDeviceSubgroupSizeControlFeatures
  - VkPhysicalDeviceSynchronization2Features
- VkPhysicalDeviceTextureCompressionASTCHDRFeatures
- VkPhysicalDeviceVulkan13Features
- VkPhysicalDeviceZeroInitializeWorkgroupMemoryFeatures

**Extending VkPhysicalDeviceProperties2:**
- VkPhysicalDeviceInlineUniformBlockProperties
- VkPhysicalDeviceMaintenance4Properties
- VkPhysicalDeviceShaderIntegerDotProductProperties
- VkPhysicalDeviceSubgroupSizeControlProperties
- VkPhysicalDeviceTexelBufferAlignmentProperties
- VkPhysicalDeviceVulkan13Properties

**Extending VkPipelineShaderStageCreateInfo, VkShaderCreateInfoEXT:**
- VkPipelineShaderStageRequiredSubgroupSizeCreateInfo

**Extending VkSubpassDependency2:**
- VkMemoryBarrier2

**Extending VkWriteDescriptorSet:**
- VkWriteDescriptorSetInlineUniformBlock

**New Enums**
- VkAccessFlagBits2
- VkFormatFeatureFlagBits2
- VkPipelineCreationFeedbackFlagBits
- VkPipelineStageFlagBits2
- VkRenderingFlagBits
- VkSubmitFlagBits
- VkToolPurposeFlagBits

**New Bitmasks**
- VkAccessFlags2
- VkFormatFeatureFlags2
- VkPipelineCreationFeedbackFlags
- VkPipelineStageFlags2
- VkPrivateDataSlotCreateFlags
- VkRenderingFlags
- VkSubmitFlags
- VkToolPurposeFlags
New Enum Constants

- Extending `VkAccessFlagBits`:
  - VK_ACCESS_NONE

- Extending `VkAttachmentStoreOp`:
  - VK_ATTACHMENT_STORE_OP_NONE

- Extending `VkDescriptorType`:
  - VK_DESCRIPTOR_TYPE_INLINE_UNIFORM_BLOCK

- Extending `VkDynamicState`:
  - VK_DYNAMIC_STATE_CULL_MODE
  - VK_DYNAMIC_STATE_DEPTH_BIAS_ENABLE
  - VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE
  - VK_DYNAMIC_STATE_DEPTHCOMPARE_OP
  - VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE
  - VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE
  - VK_DYNAMIC_STATE_FRONT_FACE
  - VK_DYNAMIC_STATE_PRIMITIVE_RESTART_ENABLE
  - VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY
  - VK_DYNAMIC_STATE_RASTERIZER_DISCARD_ENABLE
  - VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT
  - VK_DYNAMIC_STATE_STENCIL_OP
  - VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE
  - VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE
  - VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT

- Extending `VkEventCreateFlagBits`:
  - VK_EVENT_CREATE_DEVICE_ONLY_BIT

- Extending `VkFormat`:
  - VK_FORMAT_A4B4G4R4_UNORM_PACK16
  - VK_FORMAT_A4R4G4B4_UNORM_PACK16
  - VK_FORMAT_ASTC_10x10_SFLOAT_BLOCK
  - VK_FORMAT_ASTC_10x5_SFLOAT_BLOCK
  - VK_FORMAT_ASTC_10x6_SFLOAT_BLOCK
  - VK_FORMAT_ASTC_10x8_SFLOAT_BLOCK
  - VK_FORMAT_ASTC_12x10_SFLOAT_BLOCK
  - VK_FORMAT_ASTC_12x12_SFLOAT_BLOCK
• **Extending VkImageAspectFlagBits:**
  - VK_IMAGE_ASPECT_NONE

• **Extending VkImageLayout:**
  - VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL
  - VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL

• **Extending VkObjectType:**
  - VK_OBJECT_TYPE_PRIVATE_DATA_SLOT

• **Extending VkPipelineCacheCreateFlagBits:**
  - VK_PIPELINE_CACHE_CREATE_EXTERNALLY_SYNCHRONIZED_BIT

• **Extending VkPipelineCreateFlagBits:**
  - VK_PIPELINE_CREATE_EARLY_RETURN_ON_FAILURE_BIT
  - VK_PIPELINE_CREATE_FAIL_ON_PIPELINE_COMPILE_REQUIRED_BIT

• **Extending VkPipelineShaderStageCreateFlagBits:**
  - VK_PIPELINE_SHADER_STAGE_CREATE_ALLOW_VARYING_SUBGROUP_SIZE_BIT
  - VK_PIPELINE_SHADER_STAGE_CREATE_REQUIRE_FULL_SUBGROUPS_BIT

• **Extending VkPipelineStageFlagBits:**
  - VK_PIPELINE_STAGE_NONE

• **Extending VkResult:**
  - VK_PIPELINE_COMPILE_REQUIRED

• **Extending VkStructureType:**
  - VK_STRUCTURE_TYPE_BLIT_IMAGE_INFO_2
  - VK_STRUCTURE_TYPE_BUFFER_COPY_2
  - VK_STRUCTURE_TYPE_BUFFER_IMAGE_COPY_2
- VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER_2
- VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_RENDERING_INFO
- VK_STRUCTURE_TYPE_COMMAND_BUFFER_SUBMIT_INFO
- VK_STRUCTURE_TYPE_COPY_BUFFER_INFO_2
- VK_STRUCTURE_TYPE_COPY_BUFFER_TO_IMAGE_INFO_2
- VK_STRUCTURE_TYPE_COPY_IMAGE_INFO_2
- VK_STRUCTURE_TYPE_COPY_IMAGE_TO_BUFFER_INFO_2
- VK_STRUCTURE_TYPE_DEPENDENCY_INFO
- VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_INLINE_UNIFORM_BLOCK_CREATE_INFO
- VK_STRUCTURE_TYPE_DEVICE_BUFFER_MEMORY_REQUIREMENTS
- VK_STRUCTURE_TYPE_DEVICE_IMAGE_MEMORY_REQUIREMENTS
- VK_STRUCTURE_TYPE_DEVICE_PRIVATE_DATA_CREATE_INFO
- VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_3
- VK_STRUCTURE_TYPE_IMAGE_BLIT_2
- VK_STRUCTURE_TYPE_IMAGE_COPY_2
- VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER_2
- VK_STRUCTURE_TYPE_IMAGE_RESOLVE_2
- VK_STRUCTURE_TYPE_MEMORY_BARRIER_2
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DYNAMIC_RENDERING_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_ROBUSTNESS_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_INLINE_UNIFORM_BLOCK_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_4_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_4_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PIPELINE_CREATION_CACHE_CONTROL_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PRIVATE_DATA_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DEMOTE_TO_HELPER_INVOCATION_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_INTEGER_DOT_PRODUCT_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_TERMINATE_INVOCATION_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_SIZE_CONTROL_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_SIZE_CONTROL_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SYNCHRONIZATION_2_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXEL_BUFFER_ALIGNMENT_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TEXTURE_COMPRESSION_ASTC_HDR_FEATURES
Version 1.2

Vulkan Version 1.2 promoted a number of key extensions into the core API:

- VK_KHR_8bit_storage
- VK_KHR_buffer_device_address
- VK_KHR_create_renderpass2
- VK_KHR_depth_stencil_resolve
- VK_KHR_draw_indirect_count
- VK_KHR_driver_properties
- VK_KHR_image_format_list
- VK_KHR_imageless_framebuffer
- VK_KHR_sampler_mirror_clamp_to_edge
- VK_KHR_separate_depth_stencil_layouts
- VK_KHR_shader_atomic_int64
- VK_KHR_shader_float16_int8
- VK_KHR_shader_float_controls
- VK_KHR_shader_subgroup_extended_types
- VK_KHR_spirv_1_4
- VK_KHR_timeline_semaphore
All differences in behavior between these extensions and the corresponding Vulkan 1.2 functionality are summarized below.

**Differences relative to VK_KHR_8bit_storage**

If the VK_KHR_8bit_storage extension is not supported, support for the SPIR-V storageBuffer8BitAccess capability in shader modules is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::storageBuffer8BitAccess when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_KHR_draw_indirect_count**

If the VK_KHR_draw_indirect_count extension is not supported, support for the entry points vkCmdDrawIndirectCount and vkCmdDrawIndexedIndirectCount is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::drawIndirectCount when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_KHR_sampler_mirror_clamp_to_edge**

If the VK_KHR_sampler_mirror_clamp_to_edge extension is not supported, support for the VkSamplerAddressMode VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::samplerMirrorClampToEdge when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_EXT_descriptor_indexing**

If the VK_EXT_descriptor_indexing extension is not supported, support for the descriptorIndexing feature is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::descriptorIndexing when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_EXT_scalar_block_layout**

If the VK_EXT_scalar_block_layout extension is not supported, support for the scalarBlockLayout feature is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::scalarBlockLayout when queried via vkGetPhysicalDeviceFeatures2.
Differences relative to VK_EXT_shader_viewport_index_layer

The ShaderViewportIndexLayerEXT SPIR-V capability was replaced with the ShaderViewportIndex and ShaderLayer capabilities. Declaring both is equivalent to declaring ShaderViewportIndexLayerEXT SPIR-V capability. If the VK_EXT_shader_viewport_index_layer extension is not supported, support for the ShaderViewportIndexLayerEXT SPIR-V capability is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::shaderOutputViewportIndex and VkPhysicalDeviceVulkan12Features::shaderOutputLayer when queried via vkGetPhysicalDeviceFeatures2.

Differences relative to VK_KHR_buffer_device_address

If the VK_KHR_buffer_device_address extension is not supported, support for the bufferDeviceAddress feature is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::bufferDeviceAddress when queried via vkGetPhysicalDeviceFeatures2.

Differences relative to VK_KHR_shader_atomic_int64

If the VK_KHR_shader_atomic_int64 extension is not supported, support for the shaderBufferInt64Atomics feature is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::shaderBufferInt64Atomics when queried via vkGetPhysicalDeviceFeatures2.

Differences relative to VK_KHR_shader_float16_int8

If the VK_KHR_shader_float16_int8 extension is not supported, support for the shaderFloat16 and shaderInt8 features is optional. Support for these features are defined by VkPhysicalDeviceVulkan12Features::shaderFloat16 and VkPhysicalDeviceVulkan12Features::shaderInt8 when queried via vkGetPhysicalDeviceFeatures2.

Differences relative to VK_KHR_vulkan_memory_model

If the VK_KHR_vulkan_memory_model extension is not supported, support for the vulkanMemoryModel feature is optional. Support for this feature is defined by VkPhysicalDeviceVulkan12Features::vulkanMemoryModel when queried via vkGetPhysicalDeviceFeatures2.

Additional Vulkan 1.2 Feature Support

In addition to the promoted extensions described above, Vulkan 1.2 added support for:

- SPIR-V version 1.4.
- SPIR-V version 1.5.
- The samplerMirrorClampToEdge feature which indicates whether the implementation supports the VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE sampler address mode.
- The ShaderNonUniform capability in SPIR-V version 1.5.
- The shaderOutputViewportIndex feature which indicates that the ShaderViewportIndex capability can be used.
• The shaderOutputLayer feature which indicates that the ShaderLayer capability can be used.

• The subgroupBroadcastDynamicId feature which allows the “Id” operand of OpGroupNonUniformBroadcast to be dynamically uniform within a subgroup, and the “Index” operand of OpGroupNonUniformQuadBroadcast to be dynamically uniform within a derivative group, in shader modules of version 1.5 or higher.

• The drawIndirectCount feature which indicates whether the vkCmdDrawIndirectCount and vkCmdDrawIndexedIndirectCount functions can be used.

• The descriptorIndexing feature which indicates the implementation supports the minimum number of descriptor indexing features as defined in the Feature Requirements section.

• The samplerFilterMinmax feature which indicates whether the implementation supports the minimum number of image formats that support the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT feature bit as defined by the filterMinmaxSingleComponentFormats property minimum requirements.

• The framebufferIntegerColorSampleCounts limit which indicates the color sample counts that are supported for all framebuffer color attachments with integer formats.

New Macros

• VK_API_VERSION_1_2

New Commands

• vkCmdBeginRenderPass2
• vkCmdDrawIndexedIndirectCount
• vkCmdDrawIndirectCount
• vkCmdEndRenderPass2
• vkCmdNextSubpass2
• vkCreateRenderPass2
• vkGetBufferDeviceAddress
• vkGetBufferOpaqueCaptureAddress
• vkGetDeviceMemoryOpaqueCaptureAddress
• vkGetSemaphoreCounterValue
• vkResetQueryPool
• vkSignalSemaphore
• vkWaitSemaphores

New Structures

• VkAttachmentDescription2
• VkAttachmentReference2
• VkBufferDeviceAddressInfo
- VkConformanceVersion
- VkDeviceMemoryOpaqueCaptureAddressInfo
- VkFramebufferAttachmentImageInfo
- VkRenderPassCreateInfo2
- VkSemaphoreSignalInfo
- VkSemaphoreWaitInfo
- VkSubpassBeginInfo
- VkSubpassDependency2
- VkSubpassDescription2
- VkSubpassEndInfo
- Extending VkAttachmentDescription2:
  - VkAttachmentDescriptionStencilLayout
- Extending VkAttachmentReference2:
  - VkAttachmentReferenceStencilLayout
- Extending VkBufferCreateInfo:
  - VkBufferOpaqueCaptureAddressCreateInfo
- Extending VkDescriptorSetAllocateInfo:
  - VkDescriptorSetVariableDescriptorCountAllocateInfo
- Extending VkDescriptorSetLayoutCreateInfo:
  - VkDescriptorSetLayoutBindingFlagsCreateInfo
- Extending VkDescriptorSetLayoutSupport:
  - VkDescriptorSetVariableDescriptorCountLayoutSupport
- Extending VkFramebufferCreateInfo:
  - VkFramebufferAttachmentsCreateInfo
- Extending VkImageCreateInfo, VkPhysicalDeviceImageFormatInfo2:
  - VkImageStencilUsageCreateInfo
- Extending VkImageCreateInfo, VkSwapchainCreateInfoKHR, VkPhysicalDeviceImageFormatInfo2:
  - VkImageFormatListCreateInfo
- Extending VkMemoryAllocateInfo:
  - VkMemoryOpaqueCaptureAddressAllocateInfo
- Extending VkPhysicalDeviceFeatures2, VkDeviceCreateInfo:
  - VkPhysicalDevice8BitStorageFeatures
  - VkPhysicalDeviceBufferDeviceAddressFeatures
  - VkPhysicalDeviceDescriptorIndexingFeatures
  - VkPhysicalDeviceHostQueryResetFeatures
• VkPhysicalDeviceImagelessFramebufferFeatures
• VkPhysicalDeviceScalarBlockLayoutFeatures
• VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures
• VkPhysicalDeviceShaderAtomicInt64Features
• VkPhysicalDeviceShaderFloat16Int8Features
• VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures
• VkPhysicalDeviceTimelineSemaphoreFeatures
• VkPhysicalDeviceUniformBufferStandardLayoutFeatures
• VkPhysicalDeviceVulkan11Features
• VkPhysicalDeviceVulkan12Features
• VkPhysicalDeviceVulkanMemoryModelFeatures

• Extending VkPhysicalDeviceProperties2:
  • VkPhysicalDeviceDepthStencilResolveProperties
  • VkPhysicalDeviceDescriptorIndexingProperties
  • VkPhysicalDeviceDriverProperties
  • VkPhysicalDeviceFloatControlsProperties
  • VkPhysicalDeviceSamplerFilterMinmaxProperties
  • VkPhysicalDeviceTimelineSemaphoreProperties
  • VkPhysicalDeviceVulkan11Properties
  • VkPhysicalDeviceVulkan12Properties

• Extending VkRenderPassBeginInfo:
  • VkRenderPassAttachmentBeginInfo

• ExtendingVkSamplerCreateInfo:
  • VkSamplerReductionModeCreateInfo

• Extending VkSemaphoreCreateInfo, VkPhysicalDeviceExternalSemaphoreInfo:
  • VkSemaphoreTypeCreateInfo

• Extending VkSubmitInfo, VkBindSparseInfo:
  • VkTimelineSemaphoreSubmitInfo

• Extending VkSubpassDescription2:
  • VkSubpassDescriptionDepthStencilResolve

New Enums

• VkDescriptorBindingFlagBits
• VkDriverId
• VkResolveModeFlagBits
• VkSamplerReductionMode
• VkSemaphoreType
• VkSemaphoreWaitFlagBits
• VkShaderFloatControlsIndependence

New Bitmasks

• VkDescriptorBindingFlags
• VkResolveModeFlags
• VkSemaphoreWaitFlags

New Enum Constants

• VK_MAX_DRIVER_INFO_SIZE
• VK_MAX_DRIVER_NAME_SIZE

Extending VkBufferCreateFlagBits:
  ◦ VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT

Extending VkBufferUsageFlagBits:
  ◦ VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT

Extending VkDescriptorPoolCreateFlagBits:
  ◦ VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT

Extending VkDescriptorSetLayoutCreateFlagBits:
  ◦ VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT

Extending VkFormatFeatureFlagBits:
  ◦ VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT

Extending VkFramebufferCreateFlagBits:
  ◦ VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT

Extending VkImageLayout:
  ◦ VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL
  ◦ VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL
  ◦ VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL
  ◦ VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

Extending VkMemoryAllocateFlagBits:
  ◦ VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT
  ◦ VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT

Extending VkResult:
  ◦ VK_ERROR_FRAGMENTATION
- **VkErrorInvalidOpaqueCaptureAddress**

**Extending VkSamplerAddressMode:**
- **VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE**

**Extending VkStructureType:**
- **VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2**
- **VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_STENCIL_LAYOUT**
- **VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2**
- **VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_STENCIL_LAYOUT**
- **VK_STRUCTURE_TYPE_BUFFER_DEVICE_ADDRESS_INFO**
- **VK_STRUCTURE_TYPE_BUFFER_OPAQUE_CAPTURE_ADDRESS_CREATE_INFO**
- **VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_BINDING_FLAGS_CREATE_INFO**
- **VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_ALLOCATE_INFO**
- **VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_LAYOUT_SUPPORT**
- **VK_STRUCTURE_TYPE_DEVICE_MEMORY_OPAQUE_CAPTURE_ADDRESS_INFO**
- **VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO**
- **VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO**
- **VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO**
- **VK_STRUCTURE_TYPE_IMAGE_STENCIL_USAGE_CREATE_INFO**
- **VK_STRUCTURE_TYPE_MEMORY_OPAQUE_CAPTURE_ADDRESS_ALLOCATE_INFO**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_PROPERTIES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_HOST_QUERY_RESET_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_FILTER_MINMAX_PROPERTIES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SCALAR_BLOCK_LAYOUT_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES**
- **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_FEATURES**

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Version 1.1

Vulkan Version 1.1 promoted a number of key extensions into the core API:

- VK_KHR_16bit_storage
- VK_KHR_bind_memory2
- VK_KHR_dedicated_allocation
- VK_KHR_descriptor_update_template
- VK_KHR_device_group
- VK_KHR_device_group_creation
- VK_KHR_external_fence
- VK_KHR_external_fence_capabilities
- VK_KHR_external_memory
- VK_KHR_external_memory_capabilities
- VK_KHR_external_semaphore
All differences in behavior between these extensions and the corresponding Vulkan 1.1 functionality are summarized below.

**Differences relative to VK_KHR_16bit_storage**

If the VK_KHR_16bit_storage extension is not supported, support for the storageBuffer16BitAccess feature is optional. Support for this feature is defined by VkPhysicalDevice16BitStorageFeatures::storageBuffer16BitAccess or VkPhysicalDeviceVulkan11Features::storageBuffer16BitAccess when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_KHR_sampler_ycbcr_conversion**

If the VK_KHR_sampler_ycbcr_conversion extension is not supported, support for the samplerYcbcrConversion feature is optional. Support for this feature is defined by VkPhysicalDeviceSamplerYcbcrConversionFeatures::samplerYcbcrConversion or VkPhysicalDeviceVulkan11Features::samplerYcbcrConversion when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_KHR_shader_draw_parameters**

If the VK_KHR_shader_draw_parameters extension is not supported, support for the SPV_KHR_shader_draw_parameters SPIR-V extension is optional. Support for this feature is defined by VkPhysicalDeviceShaderDrawParametersFeatures::shaderDrawParameters or VkPhysicalDeviceVulkan11Features::shaderDrawParameters when queried via vkGetPhysicalDeviceFeatures2.

**Differences relative to VK_KHR_variable_pointers**

If the VK_KHR_variable_pointers extension is not supported, support for the variablePointersStorageBuffer feature is optional. Support for this feature is defined by
VkPhysicalDeviceVariablePointersFeatures::variablePointersStorageBuffer or VkPhysicalDeviceVulkan11Features::variablePointersStorageBuffer when queried via vkGetPhysicalDeviceFeatures2.

Additional Vulkan 1.1 Feature Support

In addition to the promoted extensions described above, Vulkan 1.1 added support for:

- The group operations and subgroup scope.
- The protected memory feature.
- A new command to enumerate the instance version: vkEnumerateInstanceVersion.
- The VkPhysicalDeviceShaderDrawParametersFeatures feature query struct (where the VK_KHR_shader_draw_parameters extension did not have one).

New Macros

- VK_API_VERSION_1_1

New Object Types

- VkDescriptorUpdateTemplate
- VkSamplerYcbcrConversion

New Commands

- vkBindBufferMemory2
- vkBindImageMemory2
- vkCmdDispatchBase
- vkCmdSetDeviceMask
- vkCreateDescriptorUpdateTemplate
- vkCreateSamplerYcbcrConversion
- vkDestroyDescriptorUpdateTemplate
- vkDestroySamplerYcbcrConversion
- vkEnumerateInstanceVersion
- vkEnumeratePhysicalDeviceGroups
- vkGetBufferMemoryRequirements2
- vkGetDescriptorSetLayoutSupport
- vkGetDeviceGroupPeerMemoryFeatures
- vkGetDeviceQueue2
- vkGetImageMemoryRequirements2
- vkGetImageSparseMemoryRequirements2
• vkGetPhysicalDeviceExternalBufferProperties
• vkGetPhysicalDeviceExternalFenceProperties
• vkGetPhysicalDeviceExternalSemaphoreProperties
• vkGetPhysicalDeviceFeatures2
• vkGetPhysicalDeviceFormatProperties2
• vkGetPhysicalDeviceImageFormatProperties2
• vkGetPhysicalDeviceMemoryProperties2
• vkGetPhysicalDeviceProperties2
• vkGetPhysicalDeviceQueueFamilyProperties2
• vkGetPhysicalDeviceSparseImageFormatProperties2
• vkTrimCommandPool
• vkUpdateDescriptorSetWithTemplate

New Structures

• VkBindBufferMemoryInfo
• VkBindImageMemoryInfo
• VkBufferMemoryRequirementsInfo2
• VkDescriptorSetLayoutSupport
• VkDescriptorUpdateTemplateCreateInfo
• VkDescriptorUpdateTemplateEntry
• VkDeviceQueueInfo2
• VkExternalBufferProperties
• VkExternalFenceProperties
• VkExternalMemoryProperties
• VkExternalSemaphoreProperties
• VkFormatProperties2
• VkImageFormatProperties2
• VkImageMemoryRequirementsInfo2
• VkImageSparseMemoryRequirementsInfo2
• VkInputAttachmentAspectReference
• VkMemoryRequirements2
• VkPhysicalDeviceExternalBufferInfo
• VkPhysicalDeviceExternalFenceInfo
• VkPhysicalDeviceExternalSemaphoreInfo
• VkPhysicalDeviceGroupProperties
• VkPhysicalDeviceImageFormatInfo2
• VkPhysicalDeviceMemoryProperties2
• VkPhysicalDeviceProperties2
• VkPhysicalDeviceSparseImageFormatInfo2
• VkQueueFamilyProperties2
• VkSamplerYcbcrConversionCreateInfo
• VkSparseImageFormatProperties2
• VkSparseImageMemoryRequirements2
• Extending VkBindBufferMemoryInfo:
  ◦ VkBindBufferMemoryDeviceGroupInfo
• Extending VkBindImageMemoryInfo:
  ◦ VkBindImageMemoryDeviceGroupInfo
  ◦ VkBindImagePlaneMemoryInfo
• Extending VkBindSparseInfo:
  ◦ VkDeviceGroupBindSparseInfo
• Extending VkBufferCreateInfo:
  ◦ VkExternalMemoryBufferCreateInfo
• Extending VkCommandBufferBeginInfo:
  ◦ VkDeviceGroupCommandBufferBeginInfo
• Extending VkDeviceCreateInfo:
  ◦ VkDeviceGroupDeviceCreateInfo
  ◦ VkPhysicalDeviceFeatures2
• Extending VkFenceCreateInfo:
  ◦ VkExportFenceCreateInfo
• Extending VkImageCreateInfo:
  ◦ VkExternalMemoryImageCreateInfo
• Extending VkImageFormatProperties2:
  ◦ VkExternalImageFormatProperties
  ◦ VkSamplerYcbcrConversionImageFormatProperties
• Extending VkImageMemoryRequirementsInfo2:
  ◦ VkImagePlaneMemoryRequirementsInfo
• Extending VkImageViewCreateInfo:
  ◦ VkImageViewUsageCreateInfo
• Extending VkMemoryAllocateInfo:
  ◦ VkExportMemoryAllocateInfo
- VkMemoryAllocateFlagsInfo
- VkMemoryDedicatedAllocateInfo

**Extending VkMemoryRequirements2:**
- VkMemoryDedicatedRequirements

**Extending VkPhysicalDeviceFeatures2, VkDeviceCreateInfo:**
- VkPhysicalDevice16BitStorageFeatures
- VkPhysicalDeviceMultiviewFeatures
- VkPhysicalDeviceProtectedMemoryFeatures
- VkPhysicalDeviceSamplerYcbcrConversionFeatures
- VkPhysicalDeviceShaderDrawParameterFeatures
- VkPhysicalDeviceShaderDrawParametersFeatures
- VkPhysicalDeviceVariablePointerFeatures
- VkPhysicalDeviceVariablePointersFeatures

**Extending VkPhysicalDeviceImageFormatInfo2:**
- VkPhysicalDeviceExternalImageFormatInfo

**Extending VkPhysicalDeviceProperties2:**
- VkPhysicalDeviceIDProperties
- VkPhysicalDeviceMaintenance3Properties
- VkPhysicalDeviceMultiviewProperties
- VkPhysicalDevicePointClippingProperties
- VkPhysicalDeviceProtectedMemoryProperties
- VkPhysicalDeviceSubgroupProperties

**Extending VkPipelineTessellationStateCreateInfo:**
- VkPipelineTessellationDomainOriginStateCreateInfo

**Extending VkRenderPassBeginInfo, VkRenderingInfo:**
- VkDeviceGroupRenderPassBeginInfo

**Extending VkRenderPassCreateInfo:**
- VkRenderPassInputAttachmentAspectCreateInfo
- VkRenderPassMultiviewCreateInfo

**Extending VkSamplerCreateInfo, VkImageViewCreateInfo:**
- VkSamplerYcbcrConversionInfo

**Extending VkSemaphoreCreateInfo:**
- VkExportSemaphoreCreateInfo

**Extending VkSubmitInfo:**
- VkDeviceGroupSubmitInfo
New Enums

- VkChromaLocation
- VkDescriptorUpdateTemplateType
- VkDeviceQueueCreateFlagBits
- VkExternalFenceFeatureFlagBits
- VkExternalFenceHandleTypeFlagBits
- VkExternalMemoryFeatureFlagBits
- VkExternalMemoryHandleTypeFlagBits
- VkExternalSemaphoreFeatureFlagBits
- VkExternalSemaphoreHandleTypeFlagBits
- VkFenceImportFlagBits
- VkMemoryAllocateFlagBits
- VkPeerMemoryFeatureFlagBits
- VkPointClippingBehavior
- VkSamplerYcbcrModelConversion
- VkSamplerYcbcrRange
- VkSemaphoreImportFlagBits
- VkSubgroupFeatureFlagBits
- VkTessellationDomainOrigin

New Bitmasks

- VkCommandPoolTrimFlags
- VkDescriptorUpdateTemplateCreateFlags
- VkExternalFenceFeatureFlags
- VkExternalFenceHandleTypeFlags
- VkExternalMemoryFeatureFlags
- VkExternalMemoryHandleTypeFlags
- VkExternalSemaphoreFeatureFlags
- VkExternalSemaphoreHandleTypeFlags
- VkFenceImportFlags
- VkMemoryAllocateFlags
- VkPeerMemoryFeatureFlags
- VkSemaphoreImportFlags
- VkSemaphoreImportFlags
New Enum Constants

- VkSubgroupFeatureFlags

Extending VkBufferCreateFlagBits:
  - VK_BUFFER_CREATE_PROTECTED_BIT

Extending VkCommandPoolCreateFlagBits:
  - VK_COMMAND_POOL_CREATE_PROTECTED_BIT

Extending VkDependencyFlagBits:
  - VK_DEPENDENCY_DEVICE_GROUP_BIT
  - VK_DEPENDENCY_VIEW_LOCAL_BIT

Extending VkDeviceQueueCreateFlagBits:
  - VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT

Extending VkFormat:
  - VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16
  - VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16
  - VK_FORMAT_B16G16R16G16_422_UNORM
  - VK_FORMAT_B8G8R8G8_422_UNORM
  - VK_FORMAT_G10X6B10X6R10X6_2PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16
  - VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16
  - VK_FORMAT_G16B16G16R16_422_UNORM
  - VK_FORMAT_G16_B16R16_2PLANE_420_UNORM
  - VK_FORMAT_G16_B16R16_2PLANE_422_UNORM
• Extending `VkFormatFeatureFlagBits`:
  - `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT`
  - `VK_FORMAT_FEATURE_DISJOINT_BIT`
  - `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT`
  - `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT`
  - `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT`
  - `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT`
  - `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT`
  - `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`
  - `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`

• Extending `VkImageAspectFlagBits`:
  - `VK_IMAGE_ASPECT_PLANE_0_BIT`
  - `VK_IMAGE_ASPECT_PLANE_1_BIT`
  - `VK_IMAGE_ASPECT_PLANE_2_BIT`

• Extending `VkImageCreateFlagBits`:
  - `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT`
  - `VK_IMAGE_CREATE_ALIAS_BIT`
  - `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT`
  - `VK_IMAGE_CREATE_DISJOINT_BIT`
- `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT`
- `VK_IMAGE_CREATE_PROTECTED_BIT`
- `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT`

**Extending `VkImageLayout`:**
- `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`
- `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`

**Extending `VkMemoryHeapFlagBits`:**
- `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT`

**Extending `VkMemoryPropertyFlagBits`:**
- `VK_MEMORY_PROPERTY_PROTECTED_BIT`

**Extending `VkObjectType`:**
- `VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE`
- `VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION`

**Extending `VkPipelineCreateFlagBits`:**
- `VK_PIPELINE_CREATE_DISPATCH_BASE`
- `VK_PIPELINE_CREATE_DISPATCH_BASE_BIT`
- `VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT`

**Extending `VkQueueFlagBits`:**
- `VK_QUEUE_PROTECTED_BIT`

**Extending `VkResult`:**
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`
- `VK_ERROR_OUT_OF_POOL_MEMORY`

**Extending `VkStructureType`:**
- `VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO`
- `VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO`
- `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO`
- `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO`
- `VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO`
- `VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2`
- `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT`
- `VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO`
- `VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO`
- `VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO`
- `VK_STRUCTURE_TYPEDEVICEGROUPDEVICECREATEINFO`
- `VK_STRUCTURE_TYPEDEVICEGROUPDEVICECREATEINFO`
- `VK_STRUCTURE_TYPEDEVICEGROUPRENDERPASSBEGININFO`
- VK_STRUCTURE_TYPEDEVICEGROUPSUBMITINFO
- VK_STRUCTURE_TYPEDEVICEQUEUEINFO2
- VK_STRUCTURE_TYPEEXPORTFENCECREATEINFO
- VK_STRUCTURE_TYPEEXPORTMEMORYALLOCATEINFO
- VK_STRUCTURE_TYPEEXPORTSEMAPHORECREATEINFO
- VK_STRUCTURE_TYPEEXTERNALBUFFERPROPERTIES
- VK_STRUCTURE_TYPEEXTERNALFENCEPROPERTIES
- VK_STRUCTURE_TYPEEXTERNALIMAGEFORMATPROPERTIES
- VK_STRUCTURE_TYPEEXTERNALMEMORYBUFFERCREATEINFO
- VK_STRUCTURE_TYPEEXTERNALMEMORYIMAGECREATEINFO
- VK_STRUCTURE_TYPEEXTERNALSEMAPHOREPROPERTIES
- VK_STRUCTURE_TYPEFORMATPROPERTIES2
- VK_STRUCTURE_TYPEIMAGEFORMATPROPERTIES2
- VK_STRUCTURE_TYPEIMAGEMEMORYREQUIREMENTSINFO2
- VK_STRUCTURE_TYPEIMAGEPLANEMEMORYREQUIREMENTSINFO
- VK_STRUCTURE_TYPEIMAGESPARSEMEMORYREQUIREMENTSINFO2
- VK_STRUCTURE_TYPEIMAGEVIEWUSAGECREATEINFO
- VK_STRUCTURE_TYPEMEMORYALLOCATEFLAGSINFO
- VK_STRUCTURE_TYPEMEMORYDEDICATEDALLOCATEINFO
- VK_STRUCTURE_TYPEMEMORYDEDICATEDREQUIREMENTS
- VK_STRUCTURE_TYPEMEMORYREQUIREMENTS2
- VK_STRUCTURE_TYPEPHYSICALDEVICE16BITSTORAGEFEATURES
- VK_STRUCTURE_TYPEPHYSICALDEVICEEXTERNALBUFFERINFO
- VK_STRUCTURE_TYPEPHYSICALDEVICEEXTERNALFENCEINFO
- VK_STRUCTURE_TYPEPHYSICALDEVICEEXTERNALIMAGEFORMATINFO
- VK_STRUCTURE_TYPEPHYSICALDEVICEEXTERNALSEMAPHOREINFO
- VK_STRUCTURE_TYPEPHYSICALDEVICEFEATURES2
- VK_STRUCTURE_TYPEPHYSICALDEVICEGROUPPROPERTIES
- VK_STRUCTURE_TYPEPHYSICALDEVICEIDPROPERTIES
- VK_STRUCTURE_TYPEPHYSICALDEVICEIMAGEFORMATINFO2
- VK_STRUCTURE_TYPEPHYSICALDEVICEMaintenance3PROPERTIES
- VK_STRUCTURE_TYPEPHYSICALDEVICEMEMORYPROPERTIES2
- VK_STRUCTURE_TYPEPHYSICALDEVICEMULTIVIEWFEATURES
- VK_STRUCTURE_TYPEPHYSICALDEVICEMULTIVIEWPROPERTIES
- VK_STRUCTURE_TYPEPHYSICALDEVICEPOINTCLIPPINGPROPERTIES
Version 1.0

Vulkan Version 1.0 was the initial release of the Vulkan API.

New Macros

- VK_API_VERSION
- VK_API_VERSION_1_0
- VK_API_VERSION_MAJOR
- VK_API_VERSION_MINOR
- VK_API_VERSION_PATCH
- VK_API_VERSION_VARIANT
- VK_DEFINE_HANDLE
- VK_DEFINE_NON_DISPATCHABLE_HANDLE
- VK_HEADER_VERSION
- VK_HEADER_VERSION_COMPLETE
- VK_MAKE_API_VERSION
- VK_MAKE_VERSION
- VK_NULL_HANDLE
- VK_USE_64_BIT_PTR_DEFINES
- VK_VERSION_MAJOR
- VK_VERSION_MINOR
- VK_VERSION_PATCH

**New Base Types**

- VkBool32
- VkDeviceAddress
- VkDeviceSize
- VkFlags
- VkSampleMask

**New Object Types**

- VkBuffer
- VkBufferView
- VkCommandBuffer
- VkCommandPool
- VkDescriptorPool
- VkDescriptorSet
- VkDescriptorSetLayout
- VkDevice
- VkDeviceMemory
- VkEvent
- VkFence
- VkFramebuffer
- VkImage
- VkImageView
- VkInstance
- VkPhysicalDevice
- VkPipeline
- VkPipelineCache
- VkPipelineLayout
• VkQueryPool
• VkQueue
• VkRenderPass
• VkSampler
• VkSemaphore
• VkShaderModule

**New Commands**

• vkAllocateCommandBuffers
• vkAllocateDescriptorSets
• vkAllocateMemory
• vkBeginCommandBuffer
• vkBindBufferMemory
• vkBindImageMemory
• vkCmdBeginQuery
• vkCmdBeginRenderPass
• vkCmdBindDescriptorSets
• vkCmdBindIndexBuffer
• vkCmdBindPipeline
• vkCmdBindVertexBuffers
• vkCmdBlitImage
• vkCmdClearAttachments
• vkCmdClearColorImage
• vkCmdClearDepthStencilImage
• vkCmdCopyBuffer
• vkCmdCopyBufferToImage
• vkCmdCopyImage
• vkCmdCopyImageToBuffer
• vkCmdCopyQueryPoolResults
• vkCmdDispatch
• vkCmdDispatchIndirect
• vkCmdDraw
• vkCmdDrawIndexed
• vkCmdDrawIndexedIndirect
• vkCmdDrawIndirect
• vkCmdEndQuery
• vkCmdEndRenderPass
• vkCmdExecuteCommands
• vkCmdFillBuffer
• vkCmdNextSubpass
• vkCmdPipelineBarrier
• vkCmdPushConstants
• vkCmdResetEvent
• vkCmdResetQueryPool
• vkCmdResolveImage
• vkCmdSetBlendConstants
• vkCmdSetDepthBias
• vkCmdSetDepthBounds
• vkCmdSetEvent
• vkCmdSetLineWidth
• vkCmdSetScissor
• vkCmdSetStencilCompareMask
• vkCmdSetStencilReference
• vkCmdSetStencilWriteMask
• vkCmdSetViewport
• vkCmdUpdateBuffer
• vkCmdWaitEvents
• vkCmdWriteTimestamp
• vkCreateBuffer
• vkCreateBufferView
• vkCreateCommandPool
• vkCreateComputePipelines
• vkCreateDescriptorPool
• vkCreateDescriptorSetLayout
• vkCreateDevice
• vkCreateEvent
• vkCreateFence
• vkCreateFramebuffer
• vkCreateGraphicsPipelines
• vkCreateImage
- vkCreateImageView
- vkCreateInstance
- vkCreatePipelineCache
- vkCreatePipelineLayout
- vkCreateQueryPool
- vkCreateRenderPass
- vkCreateSampler
- vkCreateSemaphore
- vkCreateShaderModule
- vkDestroyBuffer
- vkDestroyBufferView
- vkDestroyCommandPool
- vkDestroyDescriptorPool
- vkDestroyDescriptorSetLayout
- vkDestroyDevice
- vkDestroyEvent
- vkDestroyFence
- vkDestroyFramebuffer
- vkDestroyImage
- vkDestroyImageView
- vkDestroyInstance
- vkDestroyPipeline
- vkDestroyPipelineCache
- vkDestroyPipelineLayout
- vkDestroyQueryPool
- vkDestroyRenderPass
- vkDestroySampler
- vkDestroySemaphore
- vkDestroyShaderModule
- vkDeviceWaitIdle
- vkEndCommandBuffer
- vkEnumerateDeviceExtensionProperties
- vkEnumerateDeviceLayerProperties
- vkEnumerateInstanceExtensionProperties
- vkEnumerateInstanceLayerProperties
- vkEnumeratePhysicalDevices
- vkFlushMappedMemoryRanges
- vkFreeCommandBuffers
- vkFreeDescriptorSets
- vkFreeMemory
- vkGetBufferMemoryRequirements
- vkGetDeviceMemoryCommitment
- vkGetDeviceProcAddr
- vkGetDeviceQueue
- vkGetEventStatus
- vkGetFenceStatus
- vkGetImageMemoryRequirements
- vkGetImageSparseMemoryRequirements
- vkGetImageSubresourceLayout
- vkGetInstanceProcAddr
- vkGetPhysicalDeviceFeatures
- vkGetPhysicalDeviceFormatProperties
- vkGetPhysicalDeviceImageFormatProperties
- vkGetPhysicalDeviceMemoryProperties
- vkGetPhysicalDeviceProperties
- vkGetPhysicalDeviceQueueFamilyProperties
- vkGetPhysicalDeviceSparseImageFormatProperties
- vkGetPipelineCacheData
- vkGetQueryPoolResults
- vkGetRenderAreaGranularity
- vkInvalidateMappedMemoryRanges
- vkMapMemory
- vkMergePipelineCaches
- vkQueueBindSparse
- vkQueueSubmit
- vkQueueWaitIdle
- vkResetCommandBuffer
- vkResetCommandPool
- vkResetDescriptorPool
- vkResetEvent
• vkResetFences
• vkSetEvent
• vkUnmapMemory
• vkUpdateDescriptorSets
• vkWaitForFences

New Structures
• VkAllocationCallbacks
• VkApplicationInfo
• VkAttachmentDescription
• VkAttachmentReference
• VkBaseInStructure
• VkBaseOutStructure
• VkBindSparseInfo
• VkBufferCopy
• VkBufferCreateInfo
• VkBufferImageCopy
• VkBufferMemoryBarrier
• VkBufferViewCreateInfo
• VkClearAttachment
• VkClearDepthStencilValue
• VkClearRect
• VkCommandBufferAllocateInfo
• VkCommandBufferBeginInfo
• VkCommandBufferInheritanceInfo
• VkCommandPoolCreateInfo
• VkComponentMapping
• VkComputePipelineCreateInfo
• VkCopyDescriptorSet
• VkDescriptorBufferInfo
• VkDescriptorImageInfo
• VkDescriptorPoolCreateInfo
• VkDescriptorPoolSize
• VkDescriptorSetAllocateInfo
• VkDescriptorSetLayoutBinding
• VkPhysicalDeviceLimits
• VkPhysicalDeviceMemoryProperties
• VkPhysicalDeviceProperties
• VkPhysicalDeviceSparseProperties
• VkPipelineCacheCreateInfo
• VkPipelineCacheHeaderVersionOne
• VkPipelineColorBlendAttachmentState
• VkPipelineColorBlendStateCreateInfo
• VkPipelineDepthStencilStateCreateInfo
• VkPipelineDynamicStateCreateInfo
• VkPipelineInputAssemblyStateCreateInfo
• VkPipelineLayoutCreateInfo
• VkPipelineMultisampleStateCreateInfo
• VkPipelineRasterizationStateCreateInfo
• VkPipelineShaderStageCreateInfo
• VkPipelineTessellationStateCreateInfo
• VkPipelineVertexInputStateCreateInfo
• VkPipelineViewportStateCreateInfo
• VkPushConstantRange
• VkQueryPoolCreateInfo
• VkQueueFamilyProperties
• VkRect2D
• VkRenderPassBeginInfo
• VkRenderPassCreateInfo
• VkSamplerCreateInfo
• VkSemaphoreCreateInfo
• VkSparseBufferMemoryBindInfo
• VkSparseImageFormatProperties
• VkSparseImageMemoryBind
• VkSparseImageMemoryBindInfo
• VkSparseImageMemoryRequirements
• VkSparseImageOpaqueMemoryBindInfo
• VkSparseMemoryBind
• VkSpecializationInfo
• VkSpecializationMapEntry
- VkStencilOpState
- VkSubmitInfo
- VkSubpassDependency
- VkSubpassDescription
- VkSubresourceLayout
- VkVertexInputAttributeDescription
- VkVertexInputBindingDescription
- VkViewport
- VkWriteDescriptorSet
- Extending VkPipelineShaderStageCreateInfo:
  - VkShaderModuleCreateInfo

**New Unions**
- VkClearColorValue
- VkClearValue

**New Function Pointers**
- PFN_vkAllocationFunction
- PFN_vkFreeFunction
- PFN_vkInternalAllocationNotification
- PFN_vkInternalFreeNotification
- PFN_vkReallocationFunction
- PFN_vkVoidFunction

**New Enums**
- VkAccessFlagBits
- VkAttachmentDescriptionFlagBits
- VkAttachmentLoadOp
- VkAttachmentStoreOp
- VkBlendFactor
- VkBlendOp
- VkBorderColor
- VkBufferCreateFlagBits
- VkBufferUsageFlagBits
- VkColorComponentFlagBits
- VkCommandBufferLevel
- VkCommandBufferResetFlagBits
- VkCommandBufferUsageFlagBits
- VkCommandPoolCreateFlagBits
- VkCommandPoolResetFlagBits
- VkCompareOp
- VkComponentSwizzle
- VkCullModeFlagBits
- VkDependencyFlagBits
- VkDescriptorPoolCreateFlagBits
- VkDescriptorSetLayoutCreateFlagBits
- VkDescriptorType
- VkDynamicState
- VkEventCreateFlagBits
- VkFenceCreateFlagBits
- VkFilter
- VkFormat
- VkFormatFeatureFlagBits
- VkFramebufferCreateFlagBits
- VkFrontFace
- VkImageAspectFlagBits
- VkImageCreateFlagBits
- VkImageLayout
- VkImageTiling
- VkImageType
- VkImageUsageFlagBits
- VkImageViewCreateFlagBits
- VkImageViewType
- VkIndexType
- VkInstanceCreateFlagBits
- VkInternalAllocationType
- VkLogicOp
- VkMemoryHeapFlagBits
- VkMemoryPropertyFlagBits
- VkObjectType
- VkPhysicalDeviceType
- VkPipelineBindPoint
- VkPipelineCacheHeaderVersion
- VkPipelineCreateFlagBits
- VkPipelineShaderStageCreateFlagBits
- VkPipelineStageFlagBits
- VkPolygonMode
- VkPrimitiveTopology
- VkQueryControlFlagBits
- VkQueryPipelineStatisticFlagBits
- VkQueryResultFlagBits
- VkQueryType
- VkQueueFlagBits
- VkRenderPassCreateFlagBits
- VkResult
- VkSampleCountFlagBits
- VkSamplerAddressMode
- VkSamplerCreateFlagBits
- VkSamplerMipmapMode
- VkShaderStageFlagBits
- VkSharingMode
- VkSparseImageFormatFlagBits
- VkSparseMemoryBindFlagBits
- VkStencilFaceFlagBits
- VkStencilOp
- VkStructureType
- VkSubpassContents
- VkSubpassDescriptionFlagBits
- VkSystemAllocationScope
- VkVendorId
- VkVertexInputRate

**New Bitmasks**

- VkAccessFlags
- VkAttachmentDescriptionFlags
• VkBufferCreateFlags
• VkBufferUsageFlags
• VkBufferViewCreateFlags
• VkColorComponentFlags
• VkCommandBufferResetFlags
• VkCommandBufferUsageFlags
• VkCommandPoolCreateFlags
• VkCommandPoolResetFlags
• VkCullModeFlags
• VkDependencyFlags
• VkDescriptorPoolCreateFlags
• VkDescriptorPoolResetFlags
• VkDescriptorSetLayoutCreateFlags
• VkDeviceCreateFlags
• VkDeviceQueueCreateFlags
• VkEventCreateFlags
• VkFenceCreateFlags
• VkFormatFeatureFlags
• VkFramebufferCreateFlags
• VkImageAspectFlags
• VkImageCreateFlags
• VkImageUsageFlags
• VkImageViewCreateFlags
• VkInstanceCreateFlags
• VkMemoryHeapFlags
• VkMemoryMapFlags
• VkMemoryPropertyFlags
• VkPipelineCacheCreateFlags
• VkPipelineColorBlendStateCreateFlags
• VkPipelineCreateFlags
• VkPipelineDepthStencilStateCreateFlags
• VkPipelineDynamicStateCreateFlags
• VkPipelineInputAssemblyStateCreateFlags
• VkPipelineLayoutCreateFlags
• VkPipelineMultisampleStateCreateFlags
• VkPipelineRasterizationStateCreateFlags
• VkPipelineShaderStageCreateFlags
• VkPipelineStageFlags
• VkPipelineTessellationStateCreateFlags
• VkPipelineVertexInputStateCreateFlags
• VkPipelineViewportStateCreateFlags
• VkQueryControlFlags
• VkQueryPipelineStatisticFlags
• VkQueryPoolCreateFlags
• VkQueryResultFlags
• VkQueueFlags
• VkRenderPassCreateFlags
• VkSampleCountFlags
• VkSamplerCreateFlags
• VkSemaphoreCreateFlags
• VkShaderModuleCreateFlags
• VkShaderStageFlags
• VkSparseImageFormatFlags
• VkSparseMemoryBindFlags
• VkStencilFaceFlags
• VkSubpassDescriptionFlags

**New Headers**

• vk_platform

**New Enum Constants**

• VK_ATTACHMENT_UNUSED
• VK_FALSE
• VK_LOD_CLAMP_NONE
• VK_MAX_DESCRIPTION_SIZE
• VK_MAX_EXTENSION_NAME_SIZE
• VK_MAX_MEMORY_HEAPS
• VK_MAX_MEMORY_TYPES
• VK_MAX_PHYSICAL_DEVICE_NAME_SIZE
• VK_QUEUE_FAMILY_IGNORED
• VK_REMAINING_ARRAY_LAYERS
• VK_REMAINING_MIP_LEVELS
• VK_SUBPASS_EXTERNAL
• VK_TRUE
• VK_UUID_SIZE
• VK_WHOLE_SIZE
Appendix E: Layers & Extensions (Informative)

Extensions to the Vulkan API can be defined by authors, groups of authors, and the Khronos Vulkan Working Group. In order not to compromise the readability of the Vulkan Specification, the core Specification does not incorporate most extensions. The online Registry of extensions is available at URL

https://registry.khronos.org/vulkan/

and allows generating versions of the Specification incorporating different extensions.

Authors creating extensions and layers must follow the mandatory procedures described in the Vulkan Documentation and Extensions document when creating extensions and layers.

The remainder of this appendix documents a set of extensions chosen when this document was built. Versions of the Specification published in the Registry include:

- Core API + mandatory extensions required of all Vulkan implementations.
- Core API + all registered and published Khronos (KHR) extensions.
- Core API + all registered and published extensions.

Extensions are grouped as Khronos KHR, multivendor EXT, and then alphabetically by author ID. Within each group, extensions are listed in alphabetical order by their name.

Extension Dependencies

Extensions which have dependencies on specific core versions or on other extensions will list such dependencies.

For core versions, the specified version must be supported at runtime. All extensions implicitly require support for Vulkan 1.0.

For a device extension, use of any device-level functionality defined by that extension requires that any extensions that extension depends on be enabled.

For any extension, use of any instance-level functionality defined by that extension requires only that any extensions that extension depends on be supported at runtime.

List of Extensions
Appendix F: Vulkan Roadmap Milestones

Roadmap milestones are intended to be supported by mid-to-high-end smartphones, tablets, laptops, consoles, and desktop devices.

Each milestone indicates support for a set of extensions, features, limits, and formats across these devices, and should be supported by all such new hardware shipping by the end of the target year or shortly thereafter.

Roadmap 2022

The Roadmap 2022 milestone is intended to be supported by newer mid-to-high-end devices shipping in 2022 or shortly thereafter across mainstream smartphone, tablet, laptops, console and desktop devices.

Required API versions

This profile requires Vulkan 1.3.

Required Features

The following core optional features are required to be supported:

- Vulkan 1.0 Optional Features
  - fullDrawIndexUint32
  - imageCubeArray
  - independentBlend
  - sampleRateShading
  - drawIndirectFirstInstance
  - depthClamp
  - depthBiasClamp
  - samplerAnisotropy
  - occlusionQueryPrecise
  - fragmentStoresAndAtomics
  - shaderStorageImageExtendedFormats
  - shaderUniformBufferArrayDynamicIndexing
  - shaderSampledImageArrayDynamicIndexing
  - shaderStorageBufferArrayDynamicIndexing
  - shaderStorageImageArrayDynamicIndexing

- Vulkan 1.1 Optional Features
  - samplerYcbcrConversion
• Vulkan 1.2 Optional Features
  • samplerMirrorClampToEdge
  • descriptorIndexing
  • shaderUniformTexelBufferArrayDynamicIndexing
  • shaderStorageTexelBufferArrayDynamicIndexing
  • shaderUniformBufferArrayNonUniformIndexing
  • shaderSampledImageArrayNonUniformIndexing
  • shaderStorageBufferArrayNonUniformIndexing
  • shaderStorageImageArrayNonUniformIndexing
  • shaderUniformTexelBufferArrayNonUniformIndexing
  • descriptorBindingSampledImageUpdateAfterBind
  • descriptorBindingStorageImageUpdateAfterBind
  • descriptorBindingStorageBufferUpdateAfterBind
  • descriptorBindingUniformTexelBufferUpdateAfterBind
  • descriptorBindingStorageTexelBufferUpdateAfterBind
  • descriptorBindingUpdateUnusedWhilePending
  • descriptorBindingPartiallyBound
  • descriptorBindingVariableDescriptorCount
  • runtimeDescriptorArray
  • scalarBlockLayout

**Required Limits**

The following core increased limits are **required**

**Table 71. Vulkan 1.0 Limits**

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<td>Core Limit</td>
<td>Profile Limit</td>
<td>Limit Type</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>maxPerStageDescriptorUniformBuffers</td>
<td>-</td>
<td>12</td>
<td>15</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageBuffers</td>
<td>-</td>
<td>4</td>
<td>30</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorSampledImages</td>
<td>-</td>
<td>16</td>
<td>200</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageImages</td>
<td>-</td>
<td>4</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageResources</td>
<td>-</td>
<td>128</td>
<td>200</td>
<td>min</td>
</tr>
<tr>
<td>maxDescriptorSetSamplers</td>
<td>-</td>
<td>96</td>
<td>576</td>
<td>min, $n \times$ PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffers</td>
<td>-</td>
<td>72</td>
<td>90</td>
<td>min, $n \times$ PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffers</td>
<td>-</td>
<td>24</td>
<td>96</td>
<td>min, $n \times$ PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetSampledImages</td>
<td>-</td>
<td>96</td>
<td>1800</td>
<td>min, $n \times$ PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetStorageImages</td>
<td>-</td>
<td>24</td>
<td>144</td>
<td>min, $n \times$ PerStage</td>
</tr>
<tr>
<td>maxFragmentCombinedOutputResources</td>
<td>-</td>
<td>4</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxComputeWorkGroupInvocations</td>
<td>-</td>
<td>128</td>
<td>256</td>
<td>min</td>
</tr>
<tr>
<td>maxComputeWorkGroupSize</td>
<td>-</td>
<td>(128,128,64)</td>
<td>(256,256,64)</td>
<td>min</td>
</tr>
<tr>
<td>subTexelPrecisionBits</td>
<td>-</td>
<td>4</td>
<td>8</td>
<td>min</td>
</tr>
<tr>
<td>mipmapPrecisionBits</td>
<td>-</td>
<td>4</td>
<td>6</td>
<td>min</td>
</tr>
<tr>
<td>maxSamplerLodBias</td>
<td>-</td>
<td>2</td>
<td>14</td>
<td>min</td>
</tr>
<tr>
<td>pointSizeGranularity</td>
<td>0.0</td>
<td>1.0</td>
<td>0.125</td>
<td>max, fixed point increment</td>
</tr>
<tr>
<td>lineWidthGranularity</td>
<td>0.0</td>
<td>1.0</td>
<td>0.5</td>
<td>max, fixed point increment</td>
</tr>
<tr>
<td>standardSampleLocations</td>
<td>-</td>
<td>-</td>
<td>VK_TRUE</td>
<td>implementation-dependent</td>
</tr>
<tr>
<td>maxColorAttachments</td>
<td>-</td>
<td>4</td>
<td>7</td>
<td>min</td>
</tr>
</tbody>
</table>

Table 72. Vulkan 1.1 Limits
<table>
<thead>
<tr>
<th>Limit Name</th>
<th>Unsupported Limit</th>
<th>Core Limit</th>
<th>Profile Limit</th>
<th>Limit Type¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>subgroupSize</td>
<td>-</td>
<td>1/4</td>
<td>4</td>
<td>implementation-dependent</td>
</tr>
<tr>
<td>subgroupSupportedStages</td>
<td>-</td>
<td>VK_SHADER_STAGE_COMPUTE_BIT VK_SHADER_STAGE_FRAGMENT_BIT</td>
<td>implementation-dependent</td>
<td></td>
</tr>
<tr>
<td>subgroupSupportedOperations</td>
<td>-</td>
<td>VK_SUBGROUP_FEATURE_BASIC_BIT VK_SUBGROUP_FEATURE_VOTE_BIT VK_SUBGROUP_FEATURE_ARITHMETIC_BIT VK_SUBGROUP_FEATURE_BALLOT_BIT VK_SUBGROUP_FEATURE_SHUFFLE_BIT VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT VK_SUBGROUP_FEATURE_QUAD_BIT</td>
<td>implementation-dependent</td>
<td></td>
</tr>
</tbody>
</table>

Table 73. Vulkan 1.2 Limits

<table>
<thead>
<tr>
<th>Limit Name</th>
<th>Unsupported Limit</th>
<th>Core Limit</th>
<th>Profile Limit</th>
<th>Limit Type¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>shaderSignedZeroInfNanPreserveFloat16</td>
<td>-</td>
<td>-</td>
<td>VK_TRUE</td>
<td>implementation-dependent</td>
</tr>
<tr>
<td>shaderSignedZeroInfNanPreserveFloat32</td>
<td>-</td>
<td>-</td>
<td>VK_TRUE</td>
<td>implementation-dependent</td>
</tr>
<tr>
<td>maxPerStageDescriptorUpdateAfterBindInputAttachments</td>
<td>0</td>
<td>4</td>
<td>7</td>
<td>min</td>
</tr>
</tbody>
</table>

Table 74. Vulkan 1.3 Limits
<table>
<thead>
<tr>
<th>Limit Name</th>
<th>Unsupported Limit</th>
<th>Core Limit</th>
<th>Profile Limit</th>
<th>Limit Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxSubgroupSize</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
</tbody>
</table>

**Required extensions**

The following extensions are **required**

*VK_KHR_global_priority*
Appendix G: API Boilerplate

This appendix defines Vulkan API features that are infrastructure required for a complete functional description of Vulkan, but do not logically belong elsewhere in the Specification.

Vulkan Header Files

Vulkan is defined as an API in the C99 language. Khronos provides a corresponding set of header files for applications using the API, which may be used in either C or C++ code. The interface descriptions in the specification are the same as the interfaces defined in these header files, and both are derived from the `vk.xml` XML API Registry, which is the canonical machine-readable description of the Vulkan API. The Registry, scripts used for processing it into various forms, and documentation of the registry schema are available as described at [https://registry.khronos.org/vulkan/#apiregistry](https://registry.khronos.org/vulkan/#apiregistry).

Language bindings for other languages can be defined using the information in the Specification and the Registry. Khronos does not provide any such bindings, but third-party developers have created some additional bindings.

Vulkan Combined API Header `vulkan.h` (Informative)

Applications normally will include the header `vulkan.h`. In turn, `vulkan.h` always includes the following headers:

- `vk_platform.h`, defining platform-specific macros and headers.
- `vulkan_core.h`, defining APIs for the Vulkan core and all registered extensions other than window system-specific and provisional extensions, which are included in separate header files.

In addition, specific preprocessor macros defined at the time `vulkan.h` is included cause header files for the corresponding window system-specific and provisional interfaces to be included, as described below.

Vulkan Platform-Specific Header `vk_platform.h` (Informative)

Platform-specific macros and interfaces are defined in `vk_platform.h`. These macros are used to control platform-dependent behavior, and their exact definitions are under the control of specific platforms and Vulkan implementations.

Platform-Specific Calling Conventions

On many platforms the following macros are empty strings, causing platform- and compiler-specific default calling conventions to be used.

`VKAPI_ATTR` is a macro placed before the return type in Vulkan API function declarations. This macro controls calling conventions for C++11 and GCC/Clang-style compilers.

`VKAPI_CALL` is a macro placed after the return type in Vulkan API function declarations. This macro controls calling conventions for MSVC-style compilers.
**VKAPI_PTR** is a macro placed between the ‘(‘ and ‘*’ in Vulkan API function pointer declarations. This macro also controls calling conventions, and typically has the same definition as **VKAPI_ATTR** or **VKAPI_CALL**, depending on the compiler.

With these macros, a Vulkan function declaration takes the form of:

```c
VKAPI_ATTR <return_type> VKAPI_CALL <command_name>(<command_parameters>);
```

Additionally, a Vulkan function pointer type declaration takes the form of:

```c
typedef <return_type> (VKAPI_PTR *PFN_<command_name>)(<command_parameters>);
```

**Platform-Specific Header Control**

If the **VK_NO_STDINT_H** macro is defined by the application at compile time, extended integer types used by the Vulkan API, such as uint8_t, must also be defined by the application. Otherwise, the Vulkan headers will not compile. If **VK_NO_STDINT_H** is not defined, the system <stdint.h> is used to define these types. There is a fallback path when Microsoft Visual Studio version 2008 and earlier versions are detected at compile time.

If the **VK_NO_STDDEF_H** macro is defined by the application at compile time, size_t, must also be defined by the application. Otherwise, the Vulkan headers will not compile. If **VK_NO_STDDEF_H** is not defined, the system <stddef.h> is used to define this type.

**Vulkan Core API Header** **vulkan_core.h**

Applications that do not make use of window system-specific extensions may simply include **vulkan_core.h** instead of **vulkan.h**, although there is usually no reason to do so. In addition to the Vulkan API, **vulkan_core.h** also defines a small number of C preprocessor macros that are described below.

**Vulkan Header File Version Number**

**VK_HEADER_VERSION** is the version number of the **vulkan_core.h** header. This value is kept synchronized with the patch version of the released Specification.

```
// Provided by VK_VERSION_1_0
// Version of this file
#define VK_HEADER_VERSION 259
```

**VK_HEADER_VERSION_COMPLETE** is the complete version number of the **vulkan_core.h** header, comprising the major, minor, and patch versions. The major/minor values are kept synchronized with the complete version of the released Specification. This value is intended for use by automated tools to identify exactly which version of the header was used during their generation.

Applications should not use this value as their **VkApplicationInfo::apiVersion**. Instead applications
should explicitly select a specific fixed major/minor API version using, for example, one of the `VK_API_VERSION_*_values`.

```
// Provided by VK_VERSION_1_0
// Complete version of this file
#define VK_HEADER_VERSION_COMPLETE VK_MAKE_API_VERSION(0, 1, 3, VK_HEADER_VERSION)
```

`VK_API_VERSION` is now commented out of `vulkan_core.h` and cannot be used.

```
// Provided by VK_VERSION_1_0
// DEPRECATED: This define has been removed. Specific version defines (e.g. VK_API_VERSION_1_0), or the VK_MAKE_VERSION macro, should be used instead.
//#define VK_API_VERSION VK_MAKE_API_VERSION(0, 1, 0, 0) // Patch version should always be set to 0
```

**Vulkan Handle Macros**

`VK_DEFINE_HANDLE` defines a dispatchable handle type.

```
// Provided by VK_VERSION_1_0

#define VK_DEFINE_HANDLE(object) typedef struct object##_T* object;
```

- `object` is the name of the resulting C type.

The only dispatchable handle types are those related to device and instance management, such as `VkDevice`.

`VK_DEFINE_NON_DISPATCHABLE_HANDLE` defines a non-dispatchable handle type.

```
// Provided by VK_VERSION_1_0

#ifndef VK_DEFINE_NON_DISPATCHABLE_HANDLE
#if (VK_USE_64_BIT_PTR_DEFINES==1)
#define VK_DEFINE_NON_DISPATCHABLE_HANDLE(object) typedef struct object##_T* object;
#else
#define VK_DEFINE_NON_DISPATCHABLE_HANDLE(object) typedef uint64_t object;
#endif
#endif
```

- `object` is the name of the resulting C type.

Most Vulkan handle types, such as `VkBuffer`, are non-dispatchable.

**Note**
The *vulkan_core.h* header allows the `VK_DEFINE_NON_DISPATCHABLE_HANDLE` and `VK_NULL_HANDLE` definitions to be overridden by the application. If `VK_DEFINE_NON_DISPATCHABLE_HANDLE` is already defined when *vulkan_core.h* is compiled, the default definitions for `VK_DEFINE_NON_DISPATCHABLE_HANDLE` and `VK_NULL_HANDLE` are skipped. This allows the application to define a binary-compatible custom handle which *may* provide more type-safety or other features needed by the application. Applications *must* not define handles in a way that is not binary compatible - where binary compatibility is platform dependent.

`VK_NULL_HANDLE` is a reserved value representing a non-valid object handle. It may be passed to and returned from Vulkan commands only when *specifically allowed*.

```c
// Provided by VK_VERSION_1_0

#ifndef VK_DEFINE_NON_DISPATCHABLE_HANDLE
#ifdef VK_USE_64_BIT_PTR_DEFINES
    #if (VK_USE_64_BIT_PTR_DEFINES==1)
        #if (defined(__cplusplus) && (__cplusplus >= 201103L)) || (defined(_MSVC_LANG) && (_MSVC_LANG >= 201103L))
            #define VK_NULL_HANDLE nullptr
        #else
            #define VK_NULL_HANDLE ((void*)0)
        #endif
    #else
        #define VK_NULL_HANDLE 0ULL
    #endif
#endif
#else
    #define VK_NULL_HANDLE 0
#endif
#endif

// Provided by VK_VERSION_1_0

#ifndef VK_USE_64_BIT_PTR_DEFINES
    #if defined(__LP64__) || defined(_WIN64) || (defined(__x86_64__) && !defined(__ILP32__)) || defined(_M_X64) || defined(__ia64) || defined(_M_IA64) || defined(__aarch64__) || defined(__powerpc64__)
        #define VK_USE_64_BIT_PTR_DEFINES 1
    #else
        #define VK_USE_64_BIT_PTR_DEFINES 0
    #endif
#endif
```

`VK_USE_64_BIT_PTR_DEFINES` defines whether the default non-dispatchable handles are declared using either a 64-bit pointer type or a 64-bit unsigned integer type.

`VK_USE_64_BIT_PTR_DEFINES` is set to ‘1’ to use a 64-bit pointer type or any other value to use a 64-bit unsigned integer type.
The `vulkan_core.h` header allows the `VK_USE_64_BIT_PTR_DEFINES` definition to be overridden by the application. This allows the application to select either a 64-bit pointer type or a 64-bit unsigned integer type for non-dispatchable handles in the case where the predefined preprocessor check does not identify the desired configuration.

This macro was introduced starting with the Vulkan 1.2.174 headers, and its availability can be checked at compile time by requiring `VK_HEADER_VERSION >= 174`. It is not available if you are using older headers, such as may be shipped with an older Vulkan SDK. Developers requiring this functionality may wish to include a copy of the current Vulkan headers with their project in this case.

**Window System-Specific Header Control (Informative)**

To use a Vulkan extension supporting a platform-specific window system, header files for that window system **must** be included at compile time, or platform-specific types **must** be forward-declared. The Vulkan header files are unable to determine whether or not an external header is available at compile time, so platform-specific extensions are provided in separate headers from the core API and platform-independent extensions, allowing applications to decide which ones they need to be defined and how the external headers are included.

Extensions dependent on particular sets of platform headers, or that forward-declare platform-specific types, are declared in a header named for that platform. Before including these platform-specific Vulkan headers, applications **must** include both `vulkan_core.h` and any external native headers the platform extensions depend on.

As a convenience for applications that do not need the flexibility of separate platform-specific Vulkan headers, `vulkan.h` includes `vulkan_core.h`, and then conditionally includes platform-specific Vulkan headers and the external headers they depend on. Applications control which platform-specific headers are included by #defining macros before including `vulkan.h`.

The correspondence between platform-specific extensions, external headers they require, the platform-specific header which declares them, and the preprocessor macros which enable inclusion by `vulkan.h` are shown in the following table.

<table>
<thead>
<tr>
<th>Extension Name</th>
<th>Window System Name</th>
<th>Platform-specific Header</th>
<th>Required External Headers</th>
<th>Controlling <code>vulkan.h</code> Macro</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_KHR_android_surface</td>
<td>Android</td>
<td><code>vulkan_android.h</code></td>
<td>None</td>
<td><code>VK_USE_PLATFORM_ANDROID_KHR</code></td>
</tr>
<tr>
<td>VK_KHR_wayland_surface</td>
<td>Wayland</td>
<td><code>vulkan_wayland.h</code></td>
<td><code>&lt;wayland-client.h&gt;</code></td>
<td><code>VK_USE_PLATFORM_WAYLAND_KHR</code></td>
</tr>
<tr>
<td>Extension Name</td>
<td>Window System Name</td>
<td>Platform-specific Header</td>
<td>Required External Headers</td>
<td>Controlling Macro</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>VK_KHR_xcb_surface</td>
<td>X11 Xcb</td>
<td>vulkan_xcb.h</td>
<td>&lt;xcb/xcb.h&gt;</td>
<td>VK_USE_PLATFORM_XCB_KHR</td>
</tr>
<tr>
<td>VK_KHR_xlib_surface</td>
<td>X11 Xlib</td>
<td>vulkan_xlib.h</td>
<td>&lt;X11/Xlib.h&gt;</td>
<td>VK_USE_PLATFORM_XLIB_KHR</td>
</tr>
<tr>
<td>VK_EXT_directfb_surface</td>
<td>DirectFB</td>
<td>vulkan_directfb.h</td>
<td>&lt;directfb/directfb.h&gt;</td>
<td>VK_USE_PLATFORM_DIRECTFB_EXT</td>
</tr>
<tr>
<td>VK_EXT_acquire_xlib_display</td>
<td>X11 XRandR</td>
<td>vulkan_xlib_xrandr.h</td>
<td>&lt;X11/Xlib.h&gt;, &lt;X11/extensions/Xrandr.h&gt;</td>
<td>VK_USE_PLATFORM_XLIB_XRANDR_EXT</td>
</tr>
<tr>
<td>VK_GGP_stream_descriptor_surface, VK_GGP_frame_token</td>
<td>Google Games Platform</td>
<td>vulkan_ggp.h</td>
<td>&lt;ggp_c/vulkan_types.h&gt;</td>
<td>VK_USE_PLATFORM_GGP</td>
</tr>
<tr>
<td>VK_MVK_ios_surface</td>
<td>iOS</td>
<td>vulkan_ios.h</td>
<td>None</td>
<td>VK_USE_PLATFORM_IOS_MVK</td>
</tr>
<tr>
<td>VK_MVK_macos_surface</td>
<td>macOS</td>
<td>vulkan_macos.h</td>
<td>None</td>
<td>VK_USE_PLATFORM_MACOS_MVK</td>
</tr>
<tr>
<td>VK_NN_vi_surface</td>
<td>VI</td>
<td>vulkan_vi.h</td>
<td>None</td>
<td>VK_USE_PLATFORM_VI_NN</td>
</tr>
<tr>
<td>VK_FUCHSIA_imagepipe_surface</td>
<td>Fuchsia</td>
<td>vulkan_fuchsia.h</td>
<td>&lt;zircon/types.h&gt;</td>
<td>VK_USE_PLATFORM_FUCHSIA</td>
</tr>
<tr>
<td>VK_EXT_metal_surface</td>
<td>Metal on CoreAnimation</td>
<td>vulkan_metal.h</td>
<td>None</td>
<td>VK_USE_PLATFORM_METAL_EXT</td>
</tr>
<tr>
<td>VK_QNX_screen_surface</td>
<td>QNX Screen</td>
<td>vulkan_screen.h</td>
<td>&lt;screen/screen.h&gt;</td>
<td>VK_USE_PLATFORM_SCREEN_QNX</td>
</tr>
</tbody>
</table>

**Note**

This section describes the purpose of the headers independently of the specific underlying functionality of the window system extensions themselves. Each extension name will only link to a description of that extension when viewing a specification built with that extension included.
Provisional Extension Header Control (Informative)

Provisional extensions should not be used in production applications. The functionality defined by such extensions may change in ways that break backwards compatibility between revisions, and before final release of a non-provisional version of that extension.

Provisional extensions are defined in a separate provisional header, `vulkan_beta.h`, allowing applications to decide whether or not to include them. The mechanism is similar to window system-specific headers: before including `vulkan_beta.h`, applications must include `vulkan_core.h`.

Note

Sometimes a provisional extension will include a subset of its interfaces in `vulkan_core.h`. This may occur if the provisional extension is promoted from an existing vendor or EXT extension and some of the existing interfaces are defined as aliases of the provisional extension interfaces. All other interfaces of that provisional extension which are not aliased will be included in `vulkan_beta.h`.

As a convenience for applications, `vulkan.h` conditionally includes `vulkan_beta.h`. Applications can control inclusion of `vulkan_beta.h` by defining the macro `VK_ENABLE_BETA_EXTENSIONS` before including `vulkan.h`.

Note

Starting in version 1.2.171 of the Specification, all provisional enumerants are protected by the macro `VK_ENABLE_BETA_EXTENSIONS`. Applications needing to use provisional extensions must always define this macro, even if they are explicitly including `vulkan_beta.h`. This is a minor change to behavior, affecting only provisional extensions.

Note

This section describes the purpose of the provisional header independently of the specific provisional extensions which are contained in that header at any given time. The extension appendices for provisional extensions note their provisional status, and link back to this section for more information. Provisional extensions are intended to provide early access for bleeding-edge developers, with the understanding that extension interfaces may change in response to developer feedback. Provisional extensions are very likely to eventually be updated and released as non-provisional extensions, but there is no guarantee this will happen, or how long it will take if it does happen.

Video Std Headers

Performing video coding operations usually involves the application having to provide various parameters, data structures, or other syntax elements specific to the particular video compression standard used, and the associated semantics are covered by the specification of those.

The interface descriptions of these are available in the header files derived from the `video.xml` XML
file, which is the canonical machine-readable description of data structures and enumerations that are associated with the externally-provided video compression standards.

**Table 76. Video Std Headers**

<table>
<thead>
<tr>
<th>Video Std Header Name</th>
<th>Description</th>
<th>Header File</th>
<th>Related Extensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>vulkan_video_codecs_common</td>
<td>Codec-independent common definitions</td>
<td><code>&lt;vk_video/vulkan_video_codecs_common.h&gt;</code></td>
<td>-</td>
</tr>
<tr>
<td>vulkan_video_codec_h264std</td>
<td>ITU-T H.264 common definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h264std.h&gt;</code></td>
<td>VK_KHR_video_decode_h264, VK_EXT_video_encode_h264</td>
</tr>
<tr>
<td>vulkan_video_codec_h264std_decode</td>
<td>ITU-T H.264 decode-specific definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h264std_decode.h&gt;</code></td>
<td>VK_KHR_video_decode_h264</td>
</tr>
<tr>
<td>vulkan_video_codec_h264std_encode</td>
<td>ITU-T H.264 encode-specific definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h264std_encode.h&gt;</code></td>
<td>VK_EXT_video_encode_h264</td>
</tr>
<tr>
<td>vulkan_video_codec_h265std</td>
<td>ITU-T H.265 common definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h265std.h&gt;</code></td>
<td>VK_KHR_video_decode_h265, VK_EXT_video_encode_h265</td>
</tr>
<tr>
<td>vulkan_video_codec_h265std_decode</td>
<td>ITU-T H.265 decode-specific definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h265std_decode.h&gt;</code></td>
<td>VK_KHR_video_decode_h265</td>
</tr>
<tr>
<td>vulkan_video_codec_h265std_encode</td>
<td>ITU-T H.265 encode-specific definitions</td>
<td><code>&lt;vk_video/vulkan_video_codec_h265std_encode.h&gt;</code></td>
<td>VK_EXT_video_encode_h265</td>
</tr>
</tbody>
</table>
Appendix H: Invariance

The Vulkan specification is not pixel exact. It therefore does not guarantee an exact match between images produced by different Vulkan implementations. However, the specification does specify exact matches, in some cases, for images produced by the same implementation. The purpose of this appendix is to identify and provide justification for those cases that require exact matches.

Repeatability

The obvious and most fundamental case is repeated issuance of a series of Vulkan commands. For any given Vulkan and framebuffer state vector, and for any Vulkan command, the resulting Vulkan and framebuffer state must be identical whenever the command is executed on that initial Vulkan and framebuffer state. This repeatability requirement does not apply when using shaders containing side effects (image and buffer variable stores and atomic operations), because these memory operations are not guaranteed to be processed in a defined order.

One purpose of repeatability is avoidance of visual artifacts when a double-buffered scene is redrawn. If rendering is not repeatable, swapping between two buffers rendered with the same command sequence may result in visible changes in the image. Such false motion is distracting to the viewer. Another reason for repeatability is testability.

Repeatability, while important, is a weak requirement. Given only repeatability as a requirement, two scenes rendered with one (small) polygon changed in position might differ at every pixel. Such a difference, while within the law of repeatability, is certainly not within its spirit. Additional invariance rules are desirable to ensure useful operation.

Multi-pass Algorithms

Invariance is necessary for a whole set of useful multi-pass algorithms. Such algorithms render multiple times, each time with a different Vulkan mode vector, to eventually produce a result in the framebuffer. Examples of these algorithms include:

- “Erasing” a primitive from the framebuffer by redrawing it, either in a different color or using the XOR logical operation.
- Using stencil operations to compute capping planes.

Invariance Rules

For a given Vulkan device:

Rule 1 For any given Vulkan and framebuffer state vector, and for any given Vulkan command, the resulting Vulkan and framebuffer state must be identical each time the command is executed on that initial Vulkan and framebuffer state.

Rule 2 Changes to the following state values have no side effects (the use of any other state value is not affected by the change):
Required:

- Color and depth/stencil attachment contents
- Scissor parameters (other than enable)
- Write masks (color, depth, stencil)
- Clear values (color, depth, stencil)

Strongly suggested:

- Stencil parameters (other than enable)
- Depth test parameters (other than enable)
- Blend parameters (other than enable)
- Logical operation parameters (other than enable)

Corollary 1 Fragment generation is invariant with respect to the state values listed in Rule 2.

Rule 3 The arithmetic of each per-fragment operation is invariant except with respect to parameters that directly control it.

Corollary 2 Images rendered into different color attachments of the same framebuffer, either simultaneously or separately using the same command sequence, are pixel identical.

Rule 4 Identical pipelines will produce the same result when run multiple times with the same input. The wording “Identical pipelines” means VkPipeline objects that have been created with identical SPIR-V binaries and identical state, which are then used by commands executed using the same Vulkan state vector. Invariance is relaxed for shaders with side effects, such as performing stores or atomics.

Rule 5 All fragment shaders that either conditionally or unconditionally assign FragCoord.z to FragDepth are depth-invariant with respect to each other, for those fragments where the assignment to FragDepth actually is done.

If a sequence of Vulkan commands specifies primitives to be rendered with shaders containing side effects (image and buffer variable stores and atomic operations), invariance rules are relaxed. In particular, rule 1, corollary 2, and rule 4 do not apply in the presence of shader side effects.

The following weaker versions of rules 1 and 4 apply to Vulkan commands involving shader side effects:

Rule 6 For any given Vulkan and framebuffer state vector, and for any given Vulkan command, the contents of any framebuffer state not directly or indirectly affected by results of shader image or buffer variable stores or atomic operations must be identical each time the command is executed on that initial Vulkan and framebuffer state.

Rule 7 Identical pipelines will produce the same result when run multiple times with the same input as long as:

- shader invocations do not use image atomic operations;
• no framebuffer memory is written to more than once by image stores, unless all such stores write the same value; and

• no shader invocation, or other operation performed to process the sequence of commands, reads memory written to by an image store.

Note

The OpenGL specification has the following invariance rule: Consider a primitive p’ obtained by translating a primitive p through an offset (x, y) in window coordinates, where x and y are integers. As long as neither p’ nor p is clipped, it must be the case that each fragment f’ produced from p’ is identical to a corresponding fragment f from p except that the center of f’ is offset by (x, y) from the center of f.

This rule does not apply to Vulkan and is an intentional difference from OpenGL.

When any sequence of Vulkan commands triggers shader invocations that perform image stores or atomic operations, and subsequent Vulkan commands read the memory written by those shader invocations, these operations must be explicitly synchronized.

Tessellation Invariance

When using a pipeline containing tessellation evaluation shaders, the fixed-function tessellation primitive generator consumes the input patch specified by an application and emits a new set of primitives. The following invariance rules are intended to provide repeatability guarantees. Additionally, they are intended to allow an application with a carefully crafted tessellation evaluation shader to ensure that the sets of triangles generated for two adjacent patches have identical vertices along shared patch edges, avoiding “cracks” caused by minor differences in the positions of vertices along shared edges.

Rule 1 When processing two patches with identical outer and inner tessellation levels, the tessellation primitive generator will emit an identical set of point, line, or triangle primitives as long as the pipeline used to process the patch primitives has tessellation evaluation shaders specifying the same tessellation mode, spacing, vertex order, and point mode decorations. Two sets of primitives are considered identical if and only if they contain the same number and type of primitives and the generated tessellation coordinates for the vertex numbered m of the primitive numbered n are identical for all values of m and n.

Rule 2 The set of vertices generated along the outer edge of the subdivided primitive in triangle and quad tessellation, and the tessellation coordinates of each, depend only on the corresponding outer tessellation level and the spacing decorations in the tessellation shaders of the pipeline.

Rule 3 The set of vertices generated when subdividing any outer primitive edge is always symmetric. For triangle tessellation, if the subdivision generates a vertex with tessellation coordinates of the form (0, x, 1-x), (x, 0, 1-x), or (x, 1-x, 0), it will also generate a vertex with coordinates of exactly (0, 1-x, x), (1-x, 0, x), or (1-x, x, 0), respectively. For quad tessellation, if the subdivision generates a vertex with coordinates of (x, 0) or (0, x), it will also generate a vertex with coordinates of exactly (1-x, 0) or (0, 1-x), respectively. For isoline tessellation, if it generates vertices at (0, x) and (1, x) where x is not zero, it will also generate vertices at exactly (0, 1-x) and (1, 1-x), respectively.
Rule 4 The set of vertices generated when subdividing outer edges in triangular and quad tessellation must be independent of the specific edge subdivided, given identical outer tessellation levels and spacing. For example, if vertices at \((x, 1 - x, 0)\) and \((1-x, x, 0)\) are generated when subdividing the \(w = 0\) edge in triangular tessellation, vertices must be generated at \((x, 0, 1-x)\) and \((1-x, 0, x)\) when subdividing an otherwise identical \(v = 0\) edge. For quad tessellation, if vertices at \((x, 0)\) and \((1-x, 0)\) are generated when subdividing the \(v = 0\) edge, vertices must be generated at \((0, x)\) and \((0, 1-x)\) when subdividing an otherwise identical \(u = 0\) edge.

Rule 5 When processing two patches that are identical in all respects enumerated in rule 1 except for vertex order, the set of triangles generated for triangle and quad tessellation must be identical except for vertex and triangle order. For each triangle \(n_1\) produced by processing the first patch, there must be a triangle \(n_2\) produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in \(n_1\).

Rule 6 When processing two patches that are identical in all respects enumerated in rule 1 other than matching outer tessellation levels and/or vertex order, the set of interior triangles generated for triangle and quad tessellation must be identical in all respects except for vertex and triangle order. For each interior triangle \(n_1\) produced by processing the first patch, there must be a triangle \(n_2\) produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in \(n_1\). A triangle produced by the tessellator is considered an interior triangle if none of its vertices lie on an outer edge of the subdivided primitive.

Rule 7 For quad and triangle tessellation, the set of triangles connecting an inner and outer edge depends only on the inner and outer tessellation levels corresponding to that edge and the spacing decorations.

Rule 8 The value of all defined components of \(\text{TessCoord}\) will be in the range \([0, 1]\). Additionally, for any defined component \(x\) of \(\text{TessCoord}\), the results of computing \(1.0 - x\) in a tessellation evaluation shader will be exact. If any floating-point values in the range \([0, 1]\) fail to satisfy this property, such values must not be used as tessellation coordinate components.
Appendix I: Lexicon

This appendix defines terms, abbreviations, and API prefixes used in the Specification.

Glossary

The terms defined in this section are used consistently throughout the Specification and may be used with or without capitalization.

Accessible (Descriptor Binding)
A descriptor binding is accessible to a shader stage if that stage is included in the `stageFlags` of the descriptor binding. Descriptors using that binding can only be used by stages in which they are accessible.

Acquire Operation (Resource)
An operation that acquires ownership of an image subresource or buffer range.

Adjacent Vertex
A vertex in an adjacency primitive topology that is not part of a given primitive, but is accessible in geometry shaders.

Alias (API type/command)
An identical definition of another API type/command with the same behavior but a different name.

Aliased Range (Memory)
A range of a device memory allocation that is bound to multiple resources simultaneously.

Allocation Scope
An association of a host memory allocation to a parent object or command, where the allocation's lifetime ends before or at the same time as the parent object is freed or destroyed, or during the parent command.

Aspect (Image)
Some image types contain multiple kinds (called “aspects”) of data for each pixel, where each aspect is used in a particular way by the pipeline and may be stored differently or separately from other aspects. For example, the color components of an image format make up the color aspect of the image, and can be used as a framebuffer color attachment. Some operations, like depth testing, operate only on specific aspects of an image.

Attachment (Render Pass)
A zero-based integer index name used in render pass creation to refer to a framebuffer attachment that is accessed by one or more subpasses. The index also refers to an attachment description which includes information about the properties of the image view that will later be attached.
Availability Operation
An operation that causes the values generated by specified memory write accesses to become available for future access.

Available
A state of values written to memory that allows them to be made visible.

Back-Facing
See Facingness.

Batch
A single structure submitted to a queue as part of a queue submission command, describing a set of queue operations to execute.

Backwards Compatibility
A given version of the API is backwards compatible with an earlier version if an application, relying only on valid behavior and functionality defined by the earlier specification, is able to correctly run against each version without any modification. This assumes no active attempt by that application to not run when it detects a different version.

Binary Semaphore
A semaphore with a boolean payload indicating whether the semaphore is signaled or unsignaled. Represented by a VkSemaphore object created with a semaphore type of VK_SEMAPHORE_TYPE_BINARY.

Binding (Memory)
An association established between a range of a resource object and a range of a memory object. These associations determine the memory locations affected by operations performed on elements of a resource object. Memory bindings are established using the vkBindBufferMemory command for non-sparse buffer objects, using the vkBindImageMemory command for non-sparse image objects, and using the vkQueueBindSparse command for sparse resources.

Blend Constant
Four floating point (RGBA) values used as an input to blending.

Blending
Arithmetic operations between a fragment color value and a value in a color attachment that produce a final color value to be written to the attachment.

Buffer
A resource that represents a linear array of data in device memory. Represented by a VkBuffer object.

Buffer Device Address
A 64-bit value used in a shader to access buffer memory through the PhysicalStorageBuffer storage class.
Buffer View
An object that represents a range of a specific buffer, and state controlling how the contents are interpreted. Represented by a VkBufferView object.

Built-In Variable
A variable decorated in a shader, where the decoration makes the variable take values provided by the execution environment or values that are generated by fixed-function pipeline stages.

Built-In Interface Block
A block defined in a shader containing only variables decorated with built-in decorations, and is used to match against other shader stages.

Clip Coordinates
The homogeneous coordinate space in which vertex positions (Position decoration) are written by pre-rasterization shader stages.

Clip Distance
A built-in output from pre-rasterization shader stages defining a clip half-space against which the primitive is clipped.

Clip Volume
The intersection of the view volume with all clip half-spaces.

Color Attachment
A subpass attachment point, or image view, that is the target of fragment color outputs and blending.

Color Renderable Format
A VkFormat where VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT is set in one of the following, depending on the image’s tiling:

- VkFormatProperties::linearTilingFeatures
- VkFormatProperties::optimalTilingFeatures

Combined Image Sampler
A descriptor type that includes both a sampled image and a sampler.

Command Buffer
An object that records commands to be submitted to a queue. Represented by a VkCommandBuffer object.

Command Pool
An object that command buffer memory is allocated from, and that owns that memory. Command pools aid multithreaded performance by enabling different threads to use different allocators, without internal synchronization on each use. Represented by a VkCommandPool object.
Compatible Allocator
When allocators are compatible, allocations from each allocator can be freed by the other allocator.

Compatible Image Formats
When formats are compatible, images created with one of the formats can have image views created from it using any of the compatible formats. Also see Size-Compatible Image Formats.

Compatible Queues
Queues within a queue family. Compatible queues have identical properties.

Complete Mipmap Chain
The entire set of mip levels that can be provided for an image, from the largest application specified mip level size down to the minimum mip level size. See Image Mip Level Sizing.

Component (Format)
A distinct part of a format. Color components are represented with R, G, B, and A. Depth and stencil components are represented with D and S. Formats can have multiple instances of the same component. Some formats have other notations such as E or X which are not considered a component of the format.

Compressed Texel Block
An element of an image having a block-compressed format, comprising a rectangular block of texel values that are encoded as a single value in memory. Compressed texel blocks of a particular block-compressed format have a corresponding width, height, and depth defining the dimensions of these elements in units of texels, and a size in bytes of the encoding in memory.

Constant Integral Expressions
A SPIR-V constant instruction whose type is OpTypeInt. See Constant Instruction in section 2.2.1 “Instructions” of the Khronos SPIR-V Specification.

Coverage Index
The index of a sample in the coverage mask.

Coverage Mask
A bitfield associated with a fragment representing the samples that were determined to be covered based on the result of rasterization, and then subsequently modified by fragment operations or the fragment shader.

Cull Distance
A built-in output from pre-rasterization shader stages defining a cull half-space where the primitive is rejected if all vertices have a negative value for the same cull distance.

Cull Volume
The intersection of the view volume with all cull half-spaces.

Decoration (SPIR-V)
Auxiliary information such as built-in variables, stream numbers, invariance, interpolation type,
relaxed precision, etc., added to variables or structure-type members through decorations.

**Deprecated (feature)**

A feature is deprecated if it is no longer recommended as the correct or best way to achieve its intended purpose.

**Depth/Stencil Attachment**

A subpass attachment point, or image view, that is the target of depth and/or stencil test operations and writes.

**Depth/Stencil Format**

A *VkFormat* that includes depth and/or stencil components.

**Depth/Stencil Image (or ImageView)**

A *VkImage* (or *VkImageView*) with a depth/stencil format.

**Depth/Stencil Resolve Attachment**

A subpass attachment point, or image view, that is the target of a multisample resolve operation from the corresponding depth/stencil attachment at the end of the subpass.

**Derivative Group**

A set of fragment shader invocations that cooperate to compute derivatives, including implicit derivatives for sampled image operations.

**Descriptor**

Information about a resource or resource view written into a descriptor set that is used to access the resource or view from a shader.

**Descriptor Binding**

An entry in a descriptor set layout corresponding to zero or more descriptors of a single descriptor type in a set. Defined by a *VkDescriptorSetLayoutBinding* structure.

**Descriptor Pool**

An object that descriptor sets are allocated from, and that owns the storage of those descriptor sets. Descriptor pools aid multithreaded performance by enabling different threads to use different allocators, without internal synchronization on each use. Represented by a *VkDescriptorPool* object.

**Descriptor Set**

An object that resource descriptors are written into via the API, and that can be bound to a command buffer such that the descriptors contained within it can be accessed from shaders. Represented by a *VkDescriptorSet* object.

**Descriptor Set Layout**

An object defining the set of resources (types and counts) and their relative arrangement (in the binding namespace) within a descriptor set. Used when allocating descriptor sets and when creating pipeline layouts. Represented by a *VkDescriptorSetLayout* object.
Device
The processor(s) and execution environment that perform tasks requested by the application via the Vulkan API.

Device Group
A set of physical devices that support accessing each other's memory and recording a single command buffer that can be executed on all the physical devices.

Device Index
A zero-based integer that identifies one physical device from a logical device. A device index is valid if it is less than the number of physical devices in the logical device.

Device Mask
A bitmask where each bit represents one device index. A device mask value is valid if every bit that is set in the mask is at a bit position that is less than the number of physical devices in the logical device.

Device Memory
Memory accessible to the device. Represented by a VkDeviceMemory object.

Device-Level Command
Any command that is dispatched from a logical device, or from a child object of a logical device.

Device-Level Functionality
All device-level commands and objects, and their structures, enumerated types, and enumerants. Additionally, physical-device-level functionality defined by a device extension is also considered device-level functionality.

Device-Level Object
Logical device objects and their child objects. For example, VkDevice, VkQueue, and VkCommandBuffer objects are device-level objects.

Device-Local Memory
Memory that is connected to the device, and may be more performant for device access than host-local memory.

Direct Drawing Commands
Drawing commands that take all their parameters as direct arguments to the command (and not sourced via structures in buffer memory as the indirect drawing commands). Includes vkCmdDraw, and vkCmdDrawIndexed.

Disjoint
Disjoint planes are image planes to which memory is bound independently. A disjoint image consists of multiple disjoint planes, and is created with the VK_IMAGE_CREATE_DISJOINT_BIT bit set.

Dispatchable Command
A non-global command. The first argument to each dispatchable command is a dispatchable
handle type.

Dispatchable Handle
A handle of a pointer handle type which may be used by layers as part of intercepting API commands.

Dispatching Commands
Commands that provoke work using a compute pipeline. Includes `vkCmdDispatch` and `vkCmdDispatchIndirect`.

Drawing Commands
Commands that provoke work using a graphics pipeline. Includes `vkCmdDraw`, `vkCmdDrawIndexed`, `vkCmdDrawIndirectCount`, `vkCmdDrawIndexedIndirectCount`, `vkCmdDrawIndirect`, and `vkCmdDrawIndexedIndirect`.

Duration (Command)
The duration of a Vulkan command refers to the interval between calling the command and its return to the caller.

Dynamic Storage Buffer
A storage buffer whose offset is specified each time the storage buffer is bound to a command buffer via a descriptor set.

Dynamic Uniform Buffer
A uniform buffer whose offset is specified each time the uniform buffer is bound to a command buffer via a descriptor set.

Dynamically Uniform
See Dynamically Uniform in section 2.2 “Terms” of the Khronos SPIR-V Specification.

Element
Arrays are composed of multiple elements, where each element exists at a unique index within that array. Used primarily to describe data passed to or returned from the Vulkan API.

Explicitly-Enabled Layer
A layer enabled by the application by adding it to the enabled layer list in `vkCreateInstance` or `vkCreateDevice`.

Event
A synchronization primitive that is signaled when execution of previous commands completes through a specified set of pipeline stages. Events can be waited on by the device and polled by the host. Represented by a `VkEvent` object.

Executable State (Command Buffer)
A command buffer that has ended recording commands and can be executed. See also Initial State and Recording State.
Execution Dependency

A dependency that guarantees that certain pipeline stages’ work for a first set of commands has completed execution before certain pipeline stages’ work for a second set of commands begins execution. This is accomplished via pipeline barriers, subpass dependencies, events, or implicit ordering operations.

Execution Dependency Chain

A sequence of execution dependencies that transitively act as a single execution dependency.

Explicit chroma reconstruction

An implementation of sampler \(Y'CBC_R\) conversion which reconstructs reduced-resolution chroma samples to luma resolution and then separately performs texture sample interpolation. This is distinct from an implicit implementation, which incorporates chroma sample reconstruction into texture sample interpolation.

Extension Scope

The set of objects and commands that can be affected by an extension. Extensions are either device scope or instance scope.

Extending Structure

A structure type which may appear in the \(pNext\) chain of another structure, extending the functionality of the other structure. Extending structures may be defined by either core API versions or extensions.

External Handle

A resource handle which has meaning outside of a specific Vulkan device or its parent instance. External handles may be used to share resources between multiple Vulkan devices in different instances, or between Vulkan and other APIs. Some external handle types correspond to platform-defined handles, in which case the resource may outlive any particular Vulkan device or instance and may be transferred between processes, or otherwise manipulated via functionality defined by the platform for that handle type.

External synchronization

A type of synchronization required of the application, where parameters defined to be externally synchronized must not be used simultaneously in multiple threads.

Facingness (Polygon)

A classification of a polygon as either front-facing or back-facing, depending on the orientation (winding order) of its vertices.

Facingness (Fragment)

A fragment is either front-facing or back-facing, depending on the primitive it was generated from. If the primitive was a polygon (regardless of polygon mode), the fragment inherits the facingness of the polygon. All other fragments are front-facing.

Fence

A synchronization primitive that is signaled when a set of batches or sparse binding operations complete execution on a queue. Fences can be waited on by the host. Represented by a `VkFence`.
Flat Shading
A property of a vertex attribute that causes the value from a single vertex (the provoking vertex) to be used for all vertices in a primitive, and for interpolation of that attribute to return that single value unaltered.

Format Features
A set of features from VkFormatFeatureFlagBits that a VkFormat is capable of using for various commands. The list is determined by factors such as VkImageTiling.

Fragment
A rectangular framebuffer region with associated data produced by rasterization and processed by fragment operations including the fragment shader.

Fragment Area
The width and height, in pixels, of a fragment.

Fragment Input Attachment Interface
Variables with UniformConstant storage class and a decoration of InputAttachmentIndex that are statically used by a fragment shader’s entry point, which receive values from input attachments.

Fragment Output Interface
A fragment shader entry point’s variables with Output storage class, which output to color and/or depth/stencil attachments.

Framebuffer
A collection of image views and a set of dimensions that, in conjunction with a render pass, define the inputs and outputs used by drawing commands. Represented by a VkFramebuffer object.

Framebuffer Attachment
One of the image views used in a framebuffer.

Framebuffer Coordinates
A coordinate system in which adjacent pixels’ coordinates differ by 1 in x and/or y, with (0,0) in the upper left corner and pixel centers at half-integers.

Framebuffer-Space
Operating with respect to framebuffer coordinates.

Framebuffer-Local
A framebuffer-local dependency guarantees that only for a single framebuffer region, the first set of operations happens-before the second set of operations.

Framebuffer-Global
A framebuffer-global dependency guarantees that for all framebuffer regions, the first set of operations happens-before the second set of operations.
Framebuffer Region
A framebuffer region is a set of sample (x, y, layer, sample) coordinates that is a subset of the entire framebuffer.

Front-Facing
See Facingness.

Full Compatibility
A given version of the API is fully compatible with another version if an application, relying only on valid behavior and functionality defined by either of those specifications, is able to correctly run against each version without any modification. This assumes no active attempt by that application to not run when it detects a different version.

Global Command
A Vulkan command for which the first argument is not a dispatchable handle type.

Global Workgroup
A collection of local workgroups dispatched by a single dispatching command.

Handle
An opaque integer or pointer value used to refer to a Vulkan object. Each object type has a unique handle type.

Happen-after, happens-after
A transitive, irreflexive and antisymmetric ordering relation between operations. An execution dependency with a source of A and a destination of B enforces that B happens-after A. The inverse relation of happens-before.

Happen-before, happens-before
A transitive, irreflexive and antisymmetric ordering relation between operations. An execution dependency with a source of A and a destination of B enforces that A happens-before B. The inverse relation of happens-after.

Helper Invocation
A fragment shader invocation that is created solely for the purposes of evaluating derivatives for use in non-helper fragment shader invocations, and which does not have side effects.

Host
The processor(s) and execution environment that the application runs on, and that the Vulkan API is exposed on.

Host Mapped Device Memory
Device memory that is mapped for host access using vkMapMemory.

Host Memory
Memory not accessible to the device, used to store implementation data structures.
**Host-Accessible Subresource**
A buffer, or a linear image subresource in either the `VK_IMAGE_LAYOUT_PREINITIALIZED` or `VK_IMAGE_LAYOUT_GENERAL` layout. Host-accessible subresources have a well-defined addressing scheme which can be used by the host.

**Host-Local Memory**
Memory that is not local to the device, and **may** be less performant for device access than device-local memory.

**Host-Visible Memory**
Device memory that **can** be mapped on the host and **can** be read and written by the host.

**ICD**
Installable Client Driver. An ICD is represented as a `VkPhysicalDevice`.

**Identically Defined Objects**
Objects of the same type where all arguments to their creation or allocation functions, with the exception of `pAllocator`, are

1. Vulkan handles which refer to the same object or
2. identical scalar or enumeration values or
3. Host pointers which point to an array of values or structures which also satisfy these three constraints.

**Image**
A resource that represents a multi-dimensional formatted interpretation of device memory. Represented by a `VkImage` object.

**Image Subresource**
A specific mipmap level, layer, and set of aspects of an image.

**Image Subresource Range**
A set of image subresources that are contiguous mipmap levels and layers.

**Image View**
An object that represents an image subresource range of a specific image, and state controlling how the contents are interpreted. Represented by a `VkImageView` object.

**Immutable Sampler**
A sampler descriptor provided at descriptor set layout creation time for a specific binding. This sampler is then used for that binding in all descriptor sets allocated with the layout, and it **cannot** be changed.

**Implicit chroma reconstruction**
An implementation of sampler $Y'CbCr$ conversion which reconstructs the reduced-resolution chroma samples directly at the sample point, as part of the normal texture sampling operation. This is distinct from an **explicit chroma reconstruction** implementation, which reconstructs the reduced-resolution chroma samples to the resolution of the luma samples, then filters the result
as part of texture sample interpolation.

**Implicitly-Enabled Layer**
A layer enabled by a loader-defined mechanism outside the Vulkan API, rather than explicitly by the application during instance or device creation.

**Index Buffer**
A buffer bound via `vkCmdBindIndexBuffer` which is the source of index values used to fetch vertex attributes for a `vkCmdDrawIndexed` or `vkCmdDrawIndexedIndirect` command.

**Indexed Drawing Commands**
*Drawing commands* which use an index buffer as the source of index values used to fetch vertex attributes for a drawing command. Includes `vkCmdDrawIndexed`, `vkCmdDrawIndexedIndirectCount`, and `vkCmdDrawIndexedIndirect`.

**Indirect Commands**
Drawing or dispatching commands that source some of their parameters from structures in buffer memory. Includes `vkCmdDrawIndirect`, `vkCmdDrawIndirectCount`, `vkCmdDrawIndexedIndirectCount`, and `vkCmdDispatchIndirect`.

**Indirect Drawing Commands**
*Drawing commands* that source some of their parameters from structures in buffer memory. Includes `vkCmdDrawIndirect`, `vkCmdDrawIndirectCount`, `vkCmdDrawIndexedIndirectCount`, and `vkCmdDrawIndexedIndirect`.

**Initial State (Command Buffer)**
A command buffer that has not begun recording commands. See also Recording State and Executable State.

**Inline Uniform Block**
A descriptor type that represents uniform data stored directly in descriptor sets, and supports read-only access in a shader.

**Input Attachment**
A descriptor type that represents an image view, and supports unfiltered read-only access in a shader, only at the fragment's location in the view.

**Instance**
The top-level Vulkan object, which represents the application's connection to the implementation. Represented by a `VkInstance` object.

**Instance-Level Command**
Any command that is dispatched from an instance, or from a child object of an instance, except for physical devices and their children.

**Instance-Level Functionality**
All instance-level commands and objects, and their structures, enumerated types, and enumerants.
Instance-Level Object
High-level Vulkan objects, which are not physical devices, nor children of physical devices. For example, \texttt{VkInstance} is an instance-level object.

Instance (Memory)
In a logical device representing more than one physical device, some device memory allocations have the requested amount of memory allocated multiple times, once for each physical device in a device mask. Each such replicated allocation is an instance of the device memory.

Instance (Resource)
In a logical device representing more than one physical device, buffer and image resources exist on all physical devices but \texttt{can} be bound to memory differently on each. Each such replicated resource is an instance of the resource.

Internal Synchronization
A type of synchronization \texttt{required} of the implementation, where parameters not defined to be externally synchronized \texttt{may} require internal mutexing to avoid multithreaded race conditions.

Invocation (Shader)
A single execution of an entry point in a SPIR-V module. For example, a single vertex’s execution of a vertex shader or a single fragment’s execution of a fragment shader.

Invocation Group
A set of shader invocations that are executed in parallel and that \texttt{must} execute the same control flow path in order for control flow to be considered dynamically uniform.

Linear Resource
A resource is \texttt{linear} if it is one of the following:

- a \texttt{VkBuffer}
- a \texttt{VkImage} created with \texttt{VK_IMAGE_TILING_LINEAR}

A resource is \texttt{non-linear} if it is one of the following:

- a \texttt{VkImage} created with \texttt{VK_IMAGE_TILING_OPTIMAL}

Local Workgroup
A collection of compute shader invocations invoked by a single dispatching command, which share data via \texttt{WorkgroupLocal} variables and can synchronize with each other.

Logical Device
An object that represents the application’s interface to the physical device. The logical device is the parent of most Vulkan objects. Represented by a \texttt{VkDevice} object.

Logical Operation
Bitwise operations between a fragment color value and a value in a color attachment, that produce a final color value to be written to the attachment.
Lost Device
A state that a logical device **may** be in as a result of unrecoverable implementation errors, or other exceptional conditions.

Mappable
See Host-Visible Memory.

Memory Dependency
A memory dependency is an execution dependency which includes availability and visibility operations such that:

- The first set of operations happens-before the availability operation
- The availability operation happens-before the visibility operation
- The visibility operation happens-before the second set of operations

Memory Domain
A memory domain is an abstract place to which memory writes are made available by availability operations and memory domain operations. The memory domains correspond to the set of agents that the write can then be made visible to. The memory domains are **host**, **device**, **shader**, **workgroup instance** (for workgroup instance there is a unique domain for each compute workgroup) and **subgroup instance** (for subgroup instance there is a unique domain for each subgroup).

Memory Domain Operation
An operation that makes the writes that are available to one memory domain available to another memory domain.

Memory Heap
A region of memory from which device memory allocations **can** be made.

Memory Type
An index used to select a set of memory properties (e.g. mappable, cached) for a device memory allocation.

Minimum Mip Level Size
The smallest size that is permitted for a mip level. For conventional images this is 1x1x1. See Image Mip Level Sizing.

Mip Tail Region
The set of mipmap levels of a sparse residency texture that are too small to fill a sparse block, and that **must** all be bound to memory collectively and opaquely.

Multi-planar
A **multi-planar format** (or “planar format”) is an image format consisting of more than one **plane**, identifiable with a **_2PLANE** or **_3PLANE** component to the format name and listed in **Formats requiring sampler Y’CbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views**. A **multi-planar image** (or “planar image”) is an image of a multi-planar format.
Non-Dispatchable Handle
A handle of an integer handle type. Handle values may not be unique, even for two objects of the same type.

Non-Indexed Drawing Commands
Drawing commands for which the vertex attributes are sourced in linear order from the vertex input attributes for a drawing command (i.e. they do not use an index buffer). Includes vkCmdDraw, vkCmdDrawIndirectCount, and vkCmdDrawIndirect.

Normalized
A value that is interpreted as being in the range [0,1] as a result of being implicitly divided by some other value.

Normalized Device Coordinates
A coordinate space after perspective division is applied to clip coordinates, and before the viewport transformation converts them to framebuffer coordinates.

Obsoleted (feature)
A feature is obsolete if it can no longer be used.

Opaque Capture Address
A 64-bit value representing the device address of a buffer or memory object that is expected to be used by trace capture/replay tools in combination with the bufferDeviceAddress feature.

Overlapped Range (Aliased Range)
The aliased range of a device memory allocation that intersects a given image subresource of an image or range of a buffer.

Ownership (Resource)
If an entity (e.g. a queue family) has ownership of a resource, access to that resource is well-defined for access by that entity.

Packed Format
A format whose components are stored as a single texel block in memory, with their relative locations defined within that element.

Payload
Importable or exportable reference to the internal data of an object in Vulkan.

Peer Memory
An instance of memory corresponding to a different physical device than the physical device performing the memory access, in a logical device that represents multiple physical devices.

Physical Device
An object that represents a single device in the system. Represented by a VkPhysicalDevice object.
Physical-Device-Level Command

Any command that is dispatched from a physical device.

Physical-Device-Level Functionality

All physical-device-level commands and objects, and their structures, enumerated types, and enumerants.

Physical-Device-Level Object

Physical device objects. For example, VkPhysicalDevice is a physical-device-level object.

Pipeline

An object controlling how graphics or compute work is executed on the device. A pipeline includes one or more shaders, as well as state controlling any non-programmable stages of the pipeline. Represented by a VkPipeline object.

Pipeline Barrier

An execution and/or memory dependency recorded as an explicit command in a command buffer, that forms a dependency between the previous and subsequent commands.

Pipeline Cache

An object that can be used to collect and retrieve information from pipelines as they are created, and can be populated with previously retrieved information in order to accelerate pipeline creation. Represented by a VkPipelineCache object.

Pipeline Layout

An object defining the set of resources (via a collection of descriptor set layouts) and push constants used by pipelines that are created using the layout. Used when creating a pipeline and when binding descriptor sets and setting push constant values. Represented by a VkPipelineLayout object.

Pipeline Stage

A logically independent execution unit that performs some of the operations defined by an action command.

pNext Chain

A set of structures chained together through their pNext members.

Planar

See multi-planar.

Plane

An image plane is part of the representation of an image, containing a subset of the color components necessary to represent the texels in the image and with a contiguous mapping of coordinates to bound memory. Most images consist only of a single plane, but some formats spread the components across multiple image planes. The host-accessible properties of each image plane are accessible for a linear layout using vkGetImageSubresourceLayout. If a multi-planar image is created with the VK_IMAGE_CREATE_DISJOINT_BIT bit set, the image is described as disjoint, and its planes are therefore bound to memory independently.
Point Sampling (Rasterization)
A rule that determines whether a fragment sample location is covered by a polygon primitive by testing whether the sample location is in the interior of the polygon in framebuffer-space, or on the boundary of the polygon according to the tie-breaking rules.

Potential Format Features
The union of all VkFormatFeatureFlagBits that the implementation supports for a specified VkFormat, over all supported image tilings.

Pre-rasterization
Operations that execute before rasterization, and any state associated with those operations.

Preserve Attachment
One of a list of attachments in a subpass description that is not read or written by the subpass, but that is read or written on earlier and later subpasses and whose contents must be preserved through this subpass.

Primary Command Buffer
A command buffer that can execute secondary command buffers, and can be submitted directly to a queue.

Primitive Topology
State controlling how vertices are assembled into primitives, e.g. as lists of triangles, strips of lines, etc.

Promoted (feature)
A feature from an older extension is considered promoted if it is made available as part of a new core version or newer extension with wider support.

Protected Buffer
A buffer to which protected device memory can be bound.

Protected-capable Device Queue
A device queue to which protected command buffers can be submitted.

Protected Command Buffer
A command buffer which can be submitted to a protected-capable device queue.

Protected Device Memory
Device memory which can be visible to the device but must not be visible to the host.

Protected Image
An image to which protected device memory can be bound.

Provisional
A feature is released provisionally in order to get wider feedback on the functionality before it is finalized. Provisional features may change in ways that break backwards compatibility, and thus are not recommended for use in production applications.
**Provoking Vertex**

The vertex in a primitive from which flat shaded attribute values are taken. This is generally the “first” vertex in the primitive, and depends on the primitive topology.

**Push Constants**

A small bank of values writable via the API and accessible in shaders. Push constants allow the application to set values used in shaders without creating buffers or modifying and binding descriptor sets for each update.

**Push Constant Interface**

The set of variables with PushConstant storage class that are statically used by a shader entry point, and which receive values from push constant commands.

**Descriptor Update Template**

An object specifying a mapping from descriptor update information in host memory to elements in a descriptor set, which helps enable more efficient descriptor set updates.

**Query Pool**

An object containing a number of query entries and their associated state and results. Represented by a VkQueryPool object.

**Queue**

An object that executes command buffers and sparse binding operations on a device. Represented by a VkQueue object.

**Queue Family**

A set of queues that have common properties and support the same functionality, as advertised in VkQueueFamilyProperties.

**Queue Operation**

A unit of work to be executed by a specific queue on a device, submitted via a queue submission command. Each queue submission command details the specific queue operations that occur as a result of calling that command. Queue operations typically include work that is specific to each command, and synchronization tasks.

**Queue Submission**

Zero or more batches and an optional fence to be signaled, passed to a command for execution on a queue. See the Devices and Queues chapter for more information.

**Recording State (Command Buffer)**

A command buffer that is ready to record commands. See also Initial State and Executable State.

**Release Operation (Resource)**

An operation that releases ownership of an image subresource or buffer range.

**Render Pass**

An object that represents a set of framebuffer attachments and phases of rendering using those attachments. Represented by a VkRenderPass object.
**Render Pass Instance**

A use of a render pass in a command buffer.

**Required Extensions**

Extensions that **must** be enabled alongside extensions dependent on them (see Extension Dependencies).

**Reset (Command Buffer)**

Resetting a command buffer discards any previously recorded commands and puts a command buffer in the initial state.

**Residency Code**

An integer value returned by sparse image instructions, indicating whether any sparse unbound texels were accessed.

**Resolve Attachment**

A subpass attachment point, or image view, that is the target of a multisample resolve operation from the corresponding color attachment at the end of the subpass.

**Sample Index**

The index of a sample within a single set of samples.

**Sample Shading**

Invoking the fragment shader multiple times per fragment, with the covered samples partitioned among the invocations.

**Sampled Image**

A descriptor type that represents an image view, and supports filtered (sampled) and unfiltered read-only access in a shader.

**Sampler**

An object containing state controlling how sampled image data is sampled (or filtered) when accessed in a shader. Also a descriptor type describing the object. Represented by a VkSampler object.

**Secondary Command Buffer**

A command buffer that **can** be executed by a primary command buffer, and **must** not be submitted directly to a queue.

**Self-Dependency**

A subpass dependency from a subpass to itself, i.e. with srcSubpass equal to dstSubpass. A self-dependency is not automatically performed during a render pass instance, rather a subset of it **can** be performed via vkCmdPipelineBarrier during the subpass.

**Semaphore**

A synchronization primitive that supports signal and wait operations, and **can** be used to synchronize operations within a queue or across queues. Represented by a VkSemaphore object.
Shader
Instructions selected (via an entry point) from a shader module, which are executed in a shader stage.

Shader Code
A stream of instructions used to describe the operation of a shader.

Shader Module
A collection of shader code, potentially including several functions and entry points, that is used to create shaders in pipelines. Represented by a VkShaderModule object.

Shader Stage
A stage of the graphics or compute pipeline that executes shader code.

Side Effect
A store to memory or atomic operation on memory from a shader invocation.

Single-plane format
A format that is not multi-planar.

Size-Compatible Image Formats
When a compressed image format and an uncompressed image format are size-compatible, it means that the texel block size of the uncompressed format must equal the texel block size of the compressed format.

Sparse Block
An element of a sparse resource that can be independently bound to memory. Sparse blocks of a particular sparse resource have a corresponding size in bytes that they use in the bound memory.

Sparse Image Block
A sparse block in a sparse partially-resident image. In addition to the sparse block size in bytes, sparse image blocks have a corresponding width, height, and depth defining the dimensions of these elements in units of texels or compressed texel blocks, the latter being used in case of sparse images having a block-compressed format.

Sparse Unbound Texel
A texel read from a region of a sparse texture that does not have memory bound to it.

Static Use
An object in a shader is statically used by a shader entry point if any function in the entry point's call tree contains an instruction using the object. A reference in the entry point's interface list does not constitute a static use. Static use is used to constrain the set of descriptors used by a shader entry point.

Storage Buffer
A descriptor type that represents a buffer, and supports reads, writes, and atomics in a shader.
Storage Image
A descriptor type that represents an image view, and supports unfiltered loads, stores, and atomics in a shader.

Storage Texel Buffer
A descriptor type that represents a buffer view, and supports unfiltered, formatted reads, writes, and atomics in a shader.

Subgroup
A set of shader invocations that can synchronize and share data with each other efficiently. In compute shaders, the local workgroup is a superset of the subgroup.

Subgroup Mask
A bitmask for all invocations in the current subgroup with one bit per invocation, starting with the least significant bit in the first vector component, continuing to the last bit (less than SubgroupSize) in the last required vector component.

Subpass
A phase of rendering within a render pass, that reads and writes a subset of the attachments.

Subpass Dependency
An execution and/or memory dependency between two subpasses described as part of render pass creation, and automatically performed between subpasses in a render pass instance. A subpass dependency limits the overlap of execution of the pair of subpasses, and can provide guarantees of memory coherence between accesses in the subpasses.

Subpass Description
Lists of attachment indices for input attachments, color attachments, depth/stencil attachment, resolve attachments, depth/stencil resolve, and preserve attachments used by the subpass in a render pass.

Subset (Self-Dependency)
A subset of a self-dependency is a pipeline barrier performed during the subpass of the self-dependency, and whose stage masks and access masks each contain a subset of the bits set in the identically named mask in the self-dependency.

Texel Block
A single addressable element of an image with an uncompressed VkFormat, or a single compressed block of an image with a compressed VkFormat.

Texel Block Size
The size (in bytes) used to store a texel block of a compressed or uncompressed image.

Texel Coordinate System
One of three coordinate systems (normalized, unnormalized, integer) defining how texel coordinates are interpreted in an image or a specific mipmap level of an image.
Timeline Semaphore
A semaphore with a strictly increasing 64-bit unsigned integer payload indicating whether the semaphore is signaled with respect to a particular reference value. Represented by a VkSemaphore object created with a semaphore type of VK_SEMAPHORE_TYPE_TIMELINE.

Uniform Texel Buffer
A descriptor type that represents a buffer view, and supports unfiltered, formatted, read-only access in a shader.

Uniform Buffer
A descriptor type that represents a buffer, and supports read-only access in a shader.

Units in the Last Place (ULP)
A measure of floating-point error loosely defined as the smallest representable step in a floating-point format near a given value. For the precise definition see Precision and Operation of SPIR-V instructions or Jean-Michel Muller, “On the definition of ulp(x)”, RR-5504, INRIA. Other sources may also use the term “unit of least precision”.

Unnormalized
A value that is interpreted according to its conventional interpretation, and is not normalized.

Unprotected Buffer
A buffer to which unprotected device memory can be bound.

Unprotected Command Buffer
A command buffer which can be submitted to an unprotected device queue or a protected-capable device queue.

Unprotected Device Memory
Device memory which can be visible to the device and can be visible to the host.

Unprotected Image
An image to which unprotected device memory can be bound.

User-Defined Variable Interface
A shader entry point's variables with Input or Output storage class that are not built-in variables.

Vertex Input Attribute
A graphics pipeline resource that produces input values for the vertex shader by reading data from a vertex input binding and converting it to the attribute’s format.

Variable-Sized Descriptor Binding
A descriptor binding whose size will be specified when a descriptor set is allocated using this layout.

Vertex Input Binding
A graphics pipeline resource that is bound to a buffer and includes state that affects addressing calculations within that buffer.
**Vertex Input Interface**

A vertex shader entry point's variables with *Input* storage class, which receive values from vertex input attributes.

**View Mask**

When multiview is enabled, a view mask is a property of a subpass controlling which views the rendering commands are broadcast to.

**View Volume**

A subspace in homogeneous coordinates, corresponding to post-projection x and y values between -1 and +1, and z values between 0 and +1.

**Viewport Transformation**

A transformation from normalized device coordinates to framebuffer coordinates, based on a viewport rectangle and depth range.

**Visibility Operation**

An operation that causes available values to become visible to specified memory accesses.

**Visible**

A state of values written to memory that allows them to be accessed by a set of operations.

**Common Abbreviations**

The abbreviations and acronyms defined in this section are sometimes used in the Specification and the API where they are considered clear and commonplace.

**Src**

Source

**Dst**

Destination

**Min**

Minimum

**Max**

Maximum

**Rect**

Rectangle

**Info**

Information

**LOD**

Level of Detail
Log
  Logarithm

ID
  Identifier

UUID
  Universally Unique Identifier

Op
  Operation

R
  Red color component

G
  Green color component

B
  Blue color component

A
  Alpha color component

RTZ
  Round towards zero

RTE
  Round to nearest even

Prefixes

Prefixes are used in the API to denote specific semantic meaning of Vulkan names, or as a label to avoid name clashes, and are explained here:

VK/Vk/vk
  Vulkan namespace
  All types, commands, enumerants and defines in this specification are prefixed with these two characters.

PFN/pfn
  Function Pointer
  Denotes that a type is a function pointer, or that a variable is of a pointer type.

P
  Pointer
  Variable is a pointer.
vkCmd

Commands that record commands in command buffers
These API commands do not result in immediate processing on the device. Instead, they record
the requested action in a command buffer for execution when the command buffer is submitted
to a queue.

s

Structure
Used to denote the VK_STRUCTURE_TYPE* member of each structure in sType
Appendix J: Credits (Informative)

Vulkan 1.3 is the result of contributions from many people and companies participating in the Khronos Vulkan Working Group, as well as input from the Vulkan Advisory Panel.

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