Vulkan® 1.0.69 - A Specification

The Khronos Vulkan Working Group

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This specification contains substantially unmodified functionality from, and is a successor to, Khronos specifications including OpenGL, OpenGL ES and OpenCL.

Some parts of this Specification are purely informative and do not define requirements necessary for compliance and so are outside the Scope of this Specification. These parts of the Specification are marked by the “Note” icon or designated “Informative”.

Where this Specification uses terms, defined in the Glossary or otherwise, that refer to enabling technologies that are not expressly set forth as being required for compliance, those enabling technologies are outside the Scope of this Specification.

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Chapter 1. Introduction

This chapter is Informative except for the sections on Terminology and Normative References.

This document, referred to as the "Vulkan Specification" or just the "Specification" hereafter, describes the Vulkan graphics system: what it is, how it acts, and what is required to implement it. We assume that the reader has at least a rudimentary understanding of computer graphics. This means familiarity with the essentials of computer graphics algorithms and terminology as well as with modern GPUs (Graphic Processing Units).

The canonical version of the Specification is available in the official Vulkan Registry, located at URL

http://www.khronos.org/registry/vulkan/

1.1. What is the Vulkan Graphics System?

Vulkan is an API (Application Programming Interface) for graphics and compute hardware. The API consists of many commands that allow a programmer to specify shader programs, compute kernels, objects, and operations involved in producing high-quality graphical images, specifically color images of three-dimensional objects.

1.1.1. The Programmer's View of Vulkan

To the programmer, Vulkan is a set of commands that allow the specification of *shader programs* or *shaders*, *kernels*, data used by kernels or shaders, and state controlling aspects of Vulkan outside of shader execution. Typically, the data represents geometry in two or three dimensions and texture images, while the shaders and kernels control the processing of the data, rasterization of the geometry, and the lighting and shading of *fragments* generated by rasterization, resulting in the rendering of geometry into the framebuffer.

A typical Vulkan program begins with platform-specific calls to open a window or otherwise prepare a display device onto which the program will draw. Then, calls are made to open *queues* to which *command buffers* are submitted. The command buffers contain lists of commands which will be executed by the underlying hardware. The application **can** also allocate device memory, associate *resources* with memory and refer to these resources from within command buffers. Drawing commands cause application-defined shader programs to be invoked, which **can** then consume the data in the resources and use them to produce graphical images. To display the resulting images, further platform-specific commands are made to transfer the resulting image to a display device or window.

1.1.2. The Implementor's View of Vulkan

To the implementor, Vulkan is a set of commands that allow the construction and submission of command buffers to a device. Modern devices accelerate virtually all Vulkan operations, storing data and framebuffer images in high-speed memory and executing shaders in dedicated GPU processing resources.

The implementor's task is to provide a software library on the host which implements the Vulkan

API, while mapping the work for each Vulkan command to the graphics hardware as appropriate for the capabilities of the device.

1.1.3. Our View of Vulkan

We view Vulkan as a pipeline having some programmable stages and some state-driven fixed-function stages that are invoked by a set of specific drawing operations. We expect this model to result in a specification that satisfies the needs of both programmers and implementors. It does not, however, necessarily provide a model for implementation. An implementation **must** produce results conforming to those produced by the specified methods, but **may** carry out particular computations in ways that are more efficient than the one specified.

1.2. Filing Bug Reports

Issues with and bug reports on the Vulkan Specification and the API Registry **can** be filed in the Khronos Vulkan GitHub repository, located at URL

https://github.com/KhronosGroup/Vulkan-Docs

Please tag issues with appropriate labels, such as "Specification", "Ref Pages" or "Registry", to help us triage and assign them appropriately. Unfortunately, GitHub does not currently let users who do not have write access to the repository set GitHub labels on issues. In the meantime, they **can** be added to the title line of the issue set in brackets, e.g. "[Specification]".

1.3. Terminology

The key words **must**, **required**, **should**, **recommend**, **may**, and **optional** in this document are to be interpreted as described in RFC 2119:

http://www.ietf.org/rfc/rfc2119.txt

must

When used alone, this word, or the term **required**, means that the definition is an absolute requirement of the specification. When followed by **not** ("**must** not"), the phrase means that the definition is an absolute prohibition of the specification.

should

When used alone, this word means that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course. When followed by **not** ("**should** not"), the phrase means that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications **should** be understood and the case carefully weighed before implementing any behavior described with this label. In cases where grammatically appropriate, the terms **recommend** or **recommendation** may be used instead of **should**.

may

This word, or the adjective **optional**, means that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include a particular option must be prepared to interoperate with another implementation which does include the option, though perhaps with reduced functionality. In the same vein an implementation which does include a particular option must be prepared to interoperate with another implementation which does not include the option (except, of course, for the feature the option provides).

The additional terms **can** and **cannot** are to be interpreted as follows:

can

This word means that the particular behavior described is a valid choice for an application, and is never used to refer to implementation behavior.

cannot

This word means that the particular behavior described is not achievable by an application. For example, an entry point does not exist, or shader code is not capable of expressing an operation.

> *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.

1.4. Normative References

Normative references are references to external documents or resources to which implementers of Vulkan **must** comply.

IEEE Standard for Floating-Point Arithmetic, IEEE Std 754-2008, http://dx.doi.org/10.1109/IEEESTD.2008.4610935, August, 2008.

A. Garrard, *Khronos Data Format Specification, version 1.2*, https://www.khronos.org/registry/DataFormat/specs/1.2/dataformat.1.2.html, September, 2017.

J. Kessenich, *SPIR-V Extended Instructions for GLSL, Version 1.00*, https://www.khronos.org/registry/spir-v/, February 10, 2016.

J. Kessenich and B. Ouriel, *The Khronos SPIR-V Specification, Version 1.00*, https://www.khronos.org/registry/spir-v/, February 10, 2016.

J. Leech and T. Hector, *Vulkan Documentation and Extensions: Procedures and Conventions*, https://www.khronos.org/registry/vulkan/, July 11, 2016

Vulkan Loader Specification and Architecture Overview, https://github.com/KhronosGroup/Vulkan-LoaderAndValidationLayers/blob/master/loader/LoaderAndLayerInterface.md, August, 2016.

Chapter 2. 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.

2.1. Architecture Model

Vulkan is designed for, and the API is written for, CPU, GPU, and other hardware accelerator architectures with the following properties:

- 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.
- 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 **must** be identical for the host and the physical devices.

> *Note*
>
> Since a variety of data types and structures in Vulkan **may** be mapped back and forth between host and physical device memory, host and device architectures **must** both be able to access such data efficiently in order to write portable and performant applications.

2.2. 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 four types of functionality that queues **may** support: graphics, compute, transfer, and sparse memory management.

> *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.

A Vulkan application controls a set of devices through the submission of command buffers which have recorded device commands issued via Vulkan library calls. The content of command buffers is specific to the underlying hardware and is opaque to the application. Once constructed, a command buffer **can** be submitted once or many times to a queue for execution. Multiple command buffers **can** be built in parallel by employing multiple threads within the application.

Command buffers submitted to different queues **may** execute in parallel or even out of order with respect to one another. Command buffers submitted to a single queue respect submission order, as described further in synchronization chapter. Command buffer execution by the device is also asynchronous to host execution. Once a command buffer is submitted to a queue, control **may** return to the application immediately. Synchronization between the device and host, and between different queues is the responsibility of the application.

2.2.1. 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. These command buffers are then submitted to queues with a *queue submission* command for execution in a number of *batches*. Once submitted to a queue, these commands 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 optionally 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 operations on different queues have no implicit ordering constraints, and **may** execute in any order. Explicit ordering constraints between queues **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 either perform actions (draw, dispatch, clear, copy, query/timestamp operations, begin/end subpass operations), set state (bind pipelines, descriptor sets, and buffers, set dynamic state, push constants, set render pass/subpass state), or perform synchronization (set/wait events, pipeline barrier, render pass/subpass dependencies). Some commands perform more than one of these tasks. 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 that both the execution of certain pipeline stages in the later set occur 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.

The device executes queue operations asynchronously with respect to the host. Control is returned to an application immediately following command buffer submission to a queue. The application **must** synchronize work between the host and device as needed.

2.3. 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, and **may** encode object information directly in the handle rather than pointing to a software structure. Objects of a non-dispatchable type **may** not have unique handle values within a type or across types. 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.

2.3.1. 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` 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.

A `VkPipelineLayout` object **must** not be destroyed while any command buffer that uses it is in the recording state.

`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, descriptor set layouts **can** be destroyed any time they are not in use by an API command.

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`
- `VkBuffer`
- `VkBufferView`
- `VkImage`
- `VkImageView`
- `VkPipeline`
- `VkSampler`
- `VkDescriptorPool`
- `VkFramebuffer`
- `VkRenderPass`
- `VkCommandBuffer`
- `VkCommandPool`
- `VkDeviceMemory`
- `VkDescriptorSet`

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`
  - `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.

2.4. 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.

2.5. 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:

```
typedef uint32_t VkBool32;
```

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

VkDeviceSize represents device memory size and offset values:

```
typedef uint64_t VkDeviceSize;
```

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.

2.5.1. 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.

2.6. 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 software structures representing

Vulkan objects. A parameter declared as externally synchronized **may** have its software structures 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 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 effect.

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 such that they do not require external synchronization. One example of this is the use of a `VkPipelineCache` in `vkCreateGraphicsPipelines` and `vkCreateComputePipelines`, where external synchronization around such a heavyweight command would be impractical. The implementation **must** internally synchronize the cache in this example, and **may** be able to do so in the form of a much finer-grained mutex around the command. 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 `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` 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` 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

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 `pWaitSemaphores` member of each element of the `pSubmits` parameter in vkQueueSubmit
- Each element of the `pSignalSemaphores` member of each element of the `pSubmits` parameter in vkQueueSubmit
- Each element of the `pWaitSemaphores` member of each element of the `pBindInfo` parameter in vkQueueBindSparse
- Each element of the `pSignalSemaphores` member of each element of the `pBindInfo` parameter in vkQueueBindSparse
- The `buffer` member of each element of the `pBufferBinds` member of each element of the `pBindInfo` parameter in vkQueueBindSparse
- The `image` member of each element of the `pImageOpaqueBinds` member of each element of the `pBindInfo` parameter in vkQueueBindSparse
- The `image` member of each element of the `pImageBinds` member of each element of the `pBindInfo` parameter in vkQueueBindSparse
- Each element of the `pFences` parameter in vkResetFences
- Each element of the `pDescriptorSets` parameter in vkFreeDescriptorSets
- The `dstSet` member of each element of the `pDescriptorWrites` parameter in vkUpdateDescriptorSets
- The `dstSet` member of each element of the `pDescriptorCopies` parameter in vkUpdateDescriptorSets
- Each element of the `pCommandBuffers` parameter in vkFreeCommandBuffers

In addition, there are some implicit parameters that need to be externally synchronized. For example, all `commandBuffer` parameters that need to be externally synchronized imply that the `commandPool` that was passed in when creating that command buffer also needs to be externally synchronized. The implicit parameters and their associated object are listed below.

Implicit Externally Synchronized Parameters

- 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 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 vkCmdBindVertexBuffers
- 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

2.7. Errors

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.

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 (e.g. via robust buffer access).

> *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).

Applications **can** request stronger robustness guarantees by enabling the `robustBufferAccess` feature as described in Features, Limits, and Formats.

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.

2.7.1. Valid Usage

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

Some valid usage conditions have dependencies on run-time 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 draw command.

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

2.7.2. 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. A enumerant is valid if:

- The enumerant is defined as part of the enumerated type.
- The enumerant is not one of the special values defined for the enumerated type, which are suffixed with `_BEGIN_RANGE`, `_END_RANGE`, `_RANGE_SIZE` or `_MAX_ENUM`[1].

1

The meaning of these special tokens is not exposed in the Vulkan Specification. They are not part of the API, and they **should** not be used by applications. Their original intended use was for internal consumption by Vulkan implementations. Even that use will no longer be supported in the future, but they will be retained for backwards compatibility reasons.

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*
>
> This language is intended to accomodate 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.

Valid Usage for Flags

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

```
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 `Vk*Flags` type which is an alias of `VkFlags`, and whose name matches the corresponding `Vk*FlagBits` that are valid for that type, is used. These aliases are described in the Flag Types appendix of the Specification.

Any `Vk*Flags` 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. A bit flag is valid if:

- The bit flag is defined as part of the `Vk*FlagBits` 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.
- The flag is allowed in the context in which it is being used. For example, in some cases, certain bit flags or combinations of bit flags are mutually exclusive.

Any `Vk*Flags` 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*FlagBits` type. An application **cannot** rely on the state of these unspecified bits.

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.

Structure types supported by the Vulkan API include:

```
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_PIPELINE_SHADER_STAGE_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_TESSELLATION_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,
} VkStructureType;
```

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` of `VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO`, and thus its `sType` member **must** equal that when 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.

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 points to a valid structure defined by an extension, containing `sType` and `pNext` members as described in the Vulkan Documentation and Extensions document in the section "Extension Interactions". The set of structures connected by `pNext` pointers is referred to as a `pNext` *chain*. If that extension is supported by the implementation, then it **must** be enabled.

Each type of valid structure **must** not appear more than once in a `pNext` chain.

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 structures in the chain with `sType` values not defined by extensions supported by that component.

Extension structures are not described in the base Vulkan specification, but either in layered specifications incorporating those extensions, or in separate vendor-provided documents.

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.

2.7.3. 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 run time. All run time error codes are negative values.

All return codes in Vulkan are reported via VkResult return values. The possible codes are:

```c
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,
} 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

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
- `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_FRAGMENTED_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 accomodate the new allocation.

If a command returns a run time 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.

Out of memory errors do not damage any currently existing Vulkan objects. Objects that have already been successfully created **can** still be used by the application.

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

2.8. 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.

2.8.1. 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.

$1 \times x = x \times 1 = x.$

$x + 0 = 0 + x = x.$

$0^0 = 1.$

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 representable floating-point value 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. In IEEE 754 arithmetic, for example, providing a negative zero or a denormalized number to an Vulkan command **must** yield deterministic results, while providing a NaN or Inf yields unspecified results.

2.8.2. 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.

Any representable 16-bit floating-point value is legal as input to a Vulkan command that accepts 16-bit floating-point data. The result of providing a value that is not a floating-point number (such as Inf or NaN) to such a command is unspecified, but **must** not lead to Vulkan interruption or termination. Providing a denormalized number or negative zero to Vulkan **must** yield deterministic results.

2.8.3. 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.

When a floating-point value is converted to an unsigned 11-bit floating-point representation, finite values are rounded to the closest representable finite value.

While less accurate, implementations are allowed to always round in the direction of zero. This means negative values are converted to zero. Likewise, finite positive values greater than 65024 (the maximum finite representable unsigned 11-bit floating-point value) are converted to 65024. Additionally: negative infinity is converted to zero; positive infinity is converted to positive infinity; and both positive and negative NaN are converted to positive NaN.

Any representable unsigned 11-bit floating-point value is legal as input to a Vulkan command that accepts 11-bit floating-point data. The result of providing a value that is not a floating-point number (such as Inf or NaN) to such a command is unspecified, but **must** not lead to Vulkan interruption or termination. Providing a denormalized number to Vulkan **must** yield deterministic results.

2.8.4. 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.

When a floating-point value is converted to an unsigned 10-bit floating-point representation, finite values are rounded to the closest representable finite value.

While less accurate, implementations are allowed to always round in the direction of zero. This means negative values are converted to zero. Likewise, finite positive values greater than 64512 (the maximum finite representable unsigned 10-bit floating-point value) are converted to 64512. Additionally: negative infinity is converted to zero; positive infinity is converted to positive infinity; and both positive and negative NaN are converted to positive NaN.

Any representable unsigned 10-bit floating-point value is legal as input to a Vulkan command that accepts 10-bit floating-point data. The result of providing a value that is not a floating-point number (such as Inf or NaN) to such a command is unspecified, but **must** not lead to Vulkan interruption or termination. Providing a denormalized number to Vulkan **must** yield deterministic results.

2.8.5. General Requirements

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.

2.9. 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.

2.9.1. 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

$$f = \max\left(\frac{c}{2^{b-1} - 1}, -1.0\right)$$

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. Note that while zero is exactly expressible in this representation, one value (-128 in the example) is outside the representable range, and **must** be clamped before use. This equation is used everywhere that signed normalized fixed-point values are converted to floating-point.

2.9.2. 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 = convertFloatToUint(f × (2^b - 1), b)

where 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 = convertFloatToInt(f × (2^{b-1} - 1), b)

where 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.

2.10. API Version Numbers and Semantics

The Vulkan version number is used in several places in the API. In each such use, the API *major version number*, *minor version number*, and *patch version number* are packed into a 32-bit integer as follows:

- The major version number is a 10-bit integer packed into bits 31-22.
- 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.

Differences in any of the Vulkan version numbers indicates a change to the API in some way, with each part of the version number indicating a different scope of changes.

A difference in patch version numbers indicates that some usually small part of the specification or header has been modified, typically to fix a bug, and **may** have an impact on the behavior of existing functionality. Differences in this version number **should** not affect either *full compatibility* or *backwards compatibility* between two versions, or add additional interfaces to the API.

A difference in minor version numbers indicates that some amount of new functionality has been added. This will usually include new interfaces in the header, and **may** also include behavior changes and bug fixes. Functionality **may** be deprecated in a minor revision, but will not be removed. When a new minor version is introduced, the patch version is reset to 0, and each minor revision maintains its own set of patch versions. Differences in this version **should** not affect backwards compatibility, but will affect full compatibility.

A difference in major version numbers indicates a large set of changes to the API, potentially including new functionality and header interfaces, behavioral changes, removal of deprecated features, modification or outright replacement of any feature, and is thus very likely to break any and all compatibility. Differences in this version will typically require significant modification to an application in order for it to function.

C language macros for manipulating version numbers are defined in the Version Number Macros appendix.

2.11. 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*.

2.11.1. 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 offsets is defined by the structure:

```
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
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.

2.11.2. 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
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
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.

2.11.3. 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
typedef struct VkRect2D {
    VkOffset2D    offset;
    VkExtent2D    extent;
} VkRect2D;
```

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

Chapter 3. Initialization

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

3.1. Command Function Pointers

Vulkan commands are not necessarily exposed statically on a platform. Function pointers for all Vulkan commands **can** be obtained with the command:

```
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.

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

Table 1. vkGetInstanceProcAddr behavior

instance	pName	**return value**
*	NULL	undefined
invalid instance	*	undefined
NULL	vkEnumerateInstanceExtensionProperties	fp
NULL	vkEnumerateInstanceLayerProperties	fp
NULL	vkCreateInstance	fp
NULL	* (any pName not covered above)	NULL
instance	core Vulkan command	fp[1]
instance	enabled instance extension commands for instance	fp[1]

instance	pName	**return value**
instance	available device extension[2] commands for instance	fp[1]
instance	* (any pName not covered above)	NULL

1

The returned function pointer **must** only be called with a dispatchable object (the first parameter) that is instance or a child of instance.

2

An "available device extension" is a device extension supported by any physical device enumerated by instance.

Valid Usage (Implicit)

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

In order to support systems with multiple Vulkan implementations comprising heterogeneous collections of hardware and software, the function pointers returned by vkGetInstanceProcAddr **may** point to dispatch code, which calls a different real implementation for different VkDevice objects or their child objects. The overhead of this internal dispatch **can** be avoided for commands that dispatch from device-level objects by calling device-specific function pointers. Such function pointers **can** be obtained with the command:

```
PFN_vkVoidFunction vkGetDeviceProcAddr(
    VkDevice                                    device,
    const char*                                 pName);
```

The table below defines the various use cases for vkGetDeviceProcAddr and expected return value for each case.

The returned function pointer is of type PFN_vkVoidFunction, and must be cast to the type of the command being queried. The function pointer **must** only be called with a dispatchable object (the first parameter) that is device or a child of device.

Table 2. vkGetDeviceProcAddr behavior

device	pName	**return value**
NULL	*	undefined
invalid device	*	undefined
device	NULL	undefined

device	pName	**return value**
device	core device-level Vulkan command	fp
device	enabled device extension commands	fp
device	* (any pName not covered above)	NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pName **must** be a null-terminated UTF-8 string

The definition of PFN_vkVoidFunction is:

```
typedef void (VKAPI_PTR *PFN_vkVoidFunction)(void);
```

3.2. 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:

```
VK_DEFINE_HANDLE(VkInstance)
```

To create an instance object, call:

```
VkResult vkCreateInstance(
    const VkInstanceCreateInfo*                 pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkInstance*                                 pInstance);
```

- pCreateInfo points to an instance of VkInstanceCreateInfo 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

- All required extensions for each extension in the VkInstanceCreateInfo ::`ppEnabledExtensionNames` list **must** also be present in that list.

Valid Usage (Implicit)

- `pCreateInfo` **must** be a valid pointer to a valid `VkInstanceCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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:

```
typedef struct VkInstanceCreateInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkInstanceCreateFlags       flags;
    const VkApplicationInfo*    pApplicationInfo;
    uint32_t                    enabledLayerCount;
    const char* const*          ppEnabledLayerNames;
    uint32_t                    enabledExtensionCount;
    const char* const*          ppEnabledExtensionNames;
} VkInstanceCreateInfo;
```

- `sType` is the type of this structure.

- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- pApplicationInfo is NULL or a pointer to an instance of VkApplicationInfo. 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. 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)

- sType **must** be VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- If pApplicationInfo is not NULL, pApplicationInfo **must** be a valid pointer to a valid VkApplicationInfo structure
- If enabledLayerCount is not 0, ppEnabledLayerNames **must** be a valid pointer to an array of enabledLayerCount null-terminated UTF-8 strings
- If enabledExtensionCount is not 0, ppEnabledExtensionNames **must** be a valid pointer to an array of enabledExtensionCount null-terminated UTF-8 strings

```
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:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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 is the version of the Vulkan API against which the application expects to run, encoded as described in the API Version Numbers and Semantics section. If apiVersion is 0 the implementation **must** ignore it, otherwise if the implementation does not support the requested apiVersion, or an effective substitute for apiVersion, it **must** return VK_ERROR_INCOMPATIBLE_DRIVER. The patch version number specified in apiVersion is ignored when creating an instance object. Only the major and minor versions of the instance **must** match those requested in apiVersion.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_APPLICATION_INFO
- pNext **must** be NULL
- If pApplicationName is not NULL, pApplicationName **must** be a null-terminated UTF-8 string
- If pEngineName is not NULL, pEngineName **must** be a null-terminated UTF-8 string

To destroy an instance, call:

```
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

- All child objects created using `instance` **must** have been destroyed prior to destroying `instance`
- If `VkAllocationCallbacks` were provided when `instance` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `instance` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- If `instance` is not `NULL`, `instance` **must** be a valid `VkInstance` handle
- 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

Chapter 4. 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 device in a system (perhaps made up of several individual hardware devices working together), of which there are a finite number. A logical device represents an application's view of the device.

Physical devices are represented by `VkPhysicalDevice` handles:

```
VK_DEFINE_HANDLE(VkPhysicalDevice)
```

4.1. Physical Devices

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

```
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. If `pPhysicalDeviceCount` is smaller than the number of physical devices available, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available physical devices were returned.

Valid Usage (Implicit)

- instance **must** be a valid VkInstance handle
- pPhysicalDeviceCount **must** be a valid pointer to a uint32_t value
- If the value referenced by pPhysicalDeviceCount is not 0, and pPhysicalDevices is not NULL, pPhysicalDevices **must** be a valid pointer to an array of pPhysicalDeviceCount VkPhysicalDevice handles

Return Codes

Success

- VK_SUCCESS
- VK_INCOMPLETE

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_INITIALIZATION_FAILED

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

```
void vkGetPhysicalDeviceProperties(
    VkPhysicalDevice                            physicalDevice,
    VkPhysicalDeviceProperties*                 pProperties);
```

- physicalDevice is the handle to the physical device whose properties will be queried.
- pProperties points to an instance of the VkPhysicalDeviceProperties structure, that will be filled with returned information.

Valid Usage (Implicit)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- pProperties **must** be a valid pointer to a VkPhysicalDeviceProperties structure

The VkPhysicalDeviceProperties structure is defined as:

```c
typedef struct VkPhysicalDeviceProperties {
    uint32_t                            apiVersion;
    uint32_t                            driverVersion;
    uint32_t                            vendorID;
    uint32_t                            deviceID;
    VkPhysicalDeviceType                deviceType;
    char                                deviceName[VK_MAX_PHYSICAL_DEVICE_NAME_SIZE];
    uint8_t                             pipelineCacheUUID[VK_UUID_SIZE];
    VkPhysicalDeviceLimits              limits;
    VkPhysicalDeviceSparseProperties    sparseProperties;
} VkPhysicalDeviceProperties;
```

- `apiVersion` is the version of Vulkan supported by the device, encoded as described in the API Version Numbers and Semantics section.
- `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 a null-terminated UTF-8 string containing the name of the device.
- `pipelineCacheUUID` is an array of size `VK_UUID_SIZE`, containing 8-bit values that represent a universally unique identifier for the device.
- `limits` is the VkPhysicalDeviceLimits structure which specifies device-specific limits of the physical device. See Limits for details.
- `sparseProperties` is the VkPhysicalDeviceSparseProperties structure which specifies various sparse related properties of the physical device. See Sparse Properties for details.

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. In PCI-based implementations, the low sixteen bits of `vendorID` and `deviceID` **must** contain (respectively) the PCI vendor and device IDs associated with the hardware device, and the remaining bits **must** be set to zero. In non-PCI implementations, the choice of what values to return **may** be dictated by operating system or platform policies. It is otherwise at the discretion of the implementer, subject to the following constraints and guidelines:

- For purposes of physical device identification, the *vendor* of a physical device is the entity responsible for the most salient characteristics of the hardware represented by the physical device handle. In the case of a discrete GPU, this **should** be the GPU chipset vendor. In the case of a GPU or other accelerator integrated into a system-on-chip (SoC), this **should** be the supplier of the silicon IP used to create the GPU or other accelerator.
- If the vendor of the physical device has a valid PCI vendor ID issued by PCI-SIG, that ID **should** be used to construct `vendorID` as described above for PCI-based implementations. Implementations that do not return a PCI vendor ID in `vendorID` **must** return a valid Khronos vendor ID, obtained as described in the Vulkan Documentation and Extensions 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.

- The vendor of the physical device is responsible for selecting `deviceID`. The value selected **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.

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

```
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_PHYSICAL_DEVICE_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 properties of queues available on a physical device, call:

```
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. 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)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- pQueueFamilyPropertyCount **must** be a valid pointer to a uint32_t value
- 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 VkQueueFamilyProperties structures

The VkQueueFamilyProperties structure is defined as:

```
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.
- timestampValidBits is the unsigned integer count of meaningful bits in the timestamps written via vkCmdWriteTimestamp. The valid range for the count is 36..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) which indicates 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_x, 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_y, 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:

```
typedef enum VkQueueFlagBits {
    VK_QUEUE_GRAPHICS_BIT = 0x00000001,
    VK_QUEUE_COMPUTE_BIT = 0x00000002,
    VK_QUEUE_TRANSFER_BIT = 0x00000004,
    VK_QUEUE_SPARSE_BINDING_BIT = 0x00000008,
} VkQueueFlagBits;
```

- VK_QUEUE_GRAPHICS_BIT indicates that queues in this queue family support graphics operations.
- VK_QUEUE_COMPUTE_BIT indicates that queues in this queue family support compute operations.
- VK_QUEUE_TRANSFER_BIT indicates that queues in this queue family support transfer operations.
- VK_QUEUE_SPARSE_BINDING_BIT indicates 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.

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.

> *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.

```
typedef VkFlags VkQueueFlags;
```

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

4.2. 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. An application **must** create a separate logical device for each physical device it will use. 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.

4.2.1. Device Creation

Logical devices are represented by VkDevice handles:

```
VK_DEFINE_HANDLE(VkDevice)
```

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

```
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 points 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. 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.

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 the other errors). If that occurs, vkCreateDevice will return VK_ERROR_TOO_MANY_OBJECTS.

Valid Usage

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

Valid Usage (Implicit)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkDeviceCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
typedef struct VkDeviceCreateInfo {
    VkStructureType                    sType;
    const void*                        pNext;
    VkDeviceCreateFlags                flags;
    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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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 that contains boolean indicators of all the features to be enabled. Refer to the Features section for further details.

Valid Usage

- The queueFamilyIndex member of each element of pQueueCreateInfos **must** be unique within pQueueCreateInfos

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- pQueueCreateInfos **must** be a valid pointer to an array of queueCreateInfoCount valid VkDeviceQueueCreateInfo structures
- If enabledLayerCount is not 0, ppEnabledLayerNames **must** be a valid pointer to an array of enabledLayerCount null-terminated UTF-8 strings
- If enabledExtensionCount is not 0, ppEnabledExtensionNames **must** be a valid pointer to an array of enabledExtensionCount null-terminated UTF-8 strings
- If pEnabledFeatures is not NULL, pEnabledFeatures **must** be a valid pointer to a valid VkPhysicalDeviceFeatures structure
- queueCreateInfoCount **must** be greater than 0

```
typedef VkFlags VkDeviceCreateFlags;
```

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

4.2.2. 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.

4.2.3. Lost Device

A logical device **may** become *lost* because of hardware errors, execution timeouts, power management events and/or platform-specific events. This **may** cause pending and future command execution to fail and cause hardware resources to be corrupted. When this happens, certain commands will return VK_ERROR_DEVICE_LOST (see Error Codes for a list of such commands). 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 hardware, 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 their hardware has probably developed a fault or become physically disconnected, and **should** be investigated further. 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.

> *Note*
>
> Undefined behavior caused by an application error **may** cause a device to become lost. However, such undefined behavior **may** also cause unrecoverable damage to the process, and it is then not guaranteed that the API objects, including the VkPhysicalDevice or the VkInstance are still valid or that the error is recoverable.

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 commands that return a VkResult **may** return VK_ERROR_DEVICE_LOST. Commands that do not allow run-time 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.

4.2.4. Device Destruction

To destroy a device, call:

```
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

- All child objects created on device **must** have been destroyed prior to destroying device
- If VkAllocationCallbacks were provided when device was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when device was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- If device is not NULL, device **must** be a valid VkDevice handle
- 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

4.3. Queues

4.3.1. 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.

4.3.2. 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:

```
VK_DEFINE_HANDLE(VkQueue)
```

The `VkDeviceQueueCreateInfo` structure is defined as:

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

- `sType` is the type of this structure.

- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- queueFamilyIndex is an unsigned integer indicating the index of the queue family to create 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.
- pQueuePriorities is 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

- queueFamilyIndex **must** be less than pQueueFamilyPropertyCount returned by vkGetPhysicalDeviceQueueFamilyProperties
- queueCount **must** be less than or equal to the queueCount member of the VkQueueFamilyProperties structure, as returned by vkGetPhysicalDeviceQueueFamilyProperties in the pQueueFamilyProperties[queueFamilyIndex]
- Each element of pQueuePriorities **must** be between 0.0 and 1.0 inclusive

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- pQueuePriorities **must** be a valid pointer to an array of queueCount float values
- queueCount **must** be greater than 0

```
typedef VkFlags VkDeviceQueueCreateFlags;
```

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

To retrieve a handle to a VkQueue object, call:

```
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.

Valid Usage

- `queueFamilyIndex` **must** be one of the queue family indices specified when `device` was created, via the `VkDeviceQueueCreateInfo` structure
- `queueIndex` **must** be less than the number of queues created for the specified queue family index when `device` was created, via the `queueCount` member of the `VkDeviceQueueCreateInfo` structure

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pQueue` **must** be a valid pointer to a `VkQueue` handle

4.3.3. 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 Events) 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.

4.3.4. 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 make 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.

4.3.5. Queue Submission

Work is submitted to a queue via *queue submission* commands such as 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.

4.3.6. 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 5. 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:

```
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. Whenever the state of a command buffer is undefined, the application **must** set all relevant state on the command buffer before any state dependent commands such as draws and dispatches are recorded, otherwise the behavior of executing that command buffer is 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.

5.1. Command Buffer Lifecycle

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

Initial

When a command buffer is first allocated 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 - the device **may** be processing the commands recorded to it. Once execution of a command buffer completes, the command buffer reverts back to the executable 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 a command buffer into the *invalid state*. Command buffers in the invalid state **can** only be reset, moved to the *recording state*, or freed.

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 does any secondary recorded within it, and once all executions of each command buffer complete, they move to the executable state. If a secondary moves to any other state whilst it is recorded to another command buffer, the primary moves to the invalid state. A primary moving to any other state does not affect the state of the secondary. Resetting or freeing a primary command buffer removes the linkage to any secondary command buffers that were recorded to it.

5.2. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkCommandPool)
```

To create a command pool, call:

```
VkResult vkCreateCommandPool(
    VkDevice                                    device,
    const VkCommandPoolCreateInfo*              pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkCommandPool*                              pCommandPool);
```

- `device` is the logical device that creates the command pool.
- `pCreateInfo` contains information used to create the command pool.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pCommandPool` points to a `VkCommandPool` handle in which the created pool is returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkCommandPoolCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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:

```
typedef struct VkCommandPoolCreateInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkCommandPoolCreateFlags    flags;
    uint32_t                    queueFamilyIndex;
} VkCommandPoolCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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

- `queueFamilyIndex` **must** be the index of a queue family available in the calling command's `device` parameter

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be a valid combination of VkCommandPoolCreateFlagBits values

Bits which **can** be set in VkCommandPoolCreateInfo::`flags` to specify usage behavior for a command pool are:

```
typedef enum VkCommandPoolCreateFlagBits {
    VK_COMMAND_POOL_CREATE_TRANSIENT_BIT = 0x00000001,
    VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT = 0x00000002,
} VkCommandPoolCreateFlagBits;
```

- `VK_COMMAND_POOL_CREATE_TRANSIENT_BIT` indicates 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.

```
typedef VkFlags VkCommandPoolCreateFlags;
```

VkCommandPoolCreateFlags is a bitmask type for setting a mask of zero or more VkCommandPoolCreateFlagBits.

To reset a command pool, call:

```
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

- All VkCommandBuffer objects allocated from commandPool **must** not be in the pending state

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- commandPool **must** be a valid VkCommandPool handle
- flags **must** be a valid combination of VkCommandPoolResetFlagBits values
- 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_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

Bits which **can** be set in vkResetCommandPool::flags to control the reset operation are:

```
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.

```
typedef VkFlags VkCommandPoolResetFlags;
```

VkCommandPoolResetFlags is a bitmask type for setting a mask of zero or more VkCommandPoolResetFlagBits.

To destroy a command pool, call:

```
void vkDestroyCommandPool(
    VkDevice                                    device,
    VkCommandPool                               commandPool,
    const VkAllocationCallbacks*                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

- All `VkCommandBuffer` objects allocated from `commandPool` **must** not be in the pending state.
- If `VkAllocationCallbacks` were provided when `commandPool` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `commandPool` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `commandPool` is not VK_NULL_HANDLE, `commandPool` **must** be a valid `VkCommandPool` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `commandPool` is a valid handle, it **must** have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `commandPool` **must** be externally synchronized

5.3. Command Buffer Allocation and Management

To allocate command buffers, call:

```
VkResult vkAllocateCommandBuffers(
    VkDevice                                    device,
    const VkCommandBufferAllocateInfo*          pAllocateInfo,
    VkCommandBuffer*                            pCommandBuffers);
```

- `device` is the logical device that owns the command pool.
- `pAllocateInfo` is a pointer to an instance of the `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.

When command buffers are first allocated, they are in the initial state.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pAllocateInfo **must** be a valid pointer to a valid VkCommandBufferAllocateInfo structure
- pCommandBuffers **must** be a valid pointer to an array of pAllocateInfo::commandBufferCount VkCommandBuffer handles

Host Synchronization

- Host access to 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 VkCommandBufferAllocateInfo structure is defined as:

```
typedef struct VkCommandBufferAllocateInfo {
    VkStructureType         sType;
    const void*             pNext;
    VkCommandPool           commandPool;
    VkCommandBufferLevel    level;
    uint32_t                commandBufferCount;
} VkCommandBufferAllocateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- commandPool is the command pool from which the command buffers are allocated.
- level is an VkCommandBufferLevel value specifying the command buffer level.
- commandBufferCount is the number of command buffers to allocate from the pool.

Valid Usage

- commandBufferCount **must** be greater than 0

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO
- pNext **must** be NULL
- commandPool **must** be a valid VkCommandPool handle
- level **must** be a valid VkCommandBufferLevel value

Possible values of VkCommandBufferAllocateInfo::level, specifying the command buffer level, are:

```
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 command buffers, call:

```
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

- commandBuffer **must** not be in the pending state
- commandBuffer **must** have been allocated from a pool that was created with the VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- flags **must** be a valid combination of VkCommandBufferResetFlagBits values

Host Synchronization

- Host access to commandBuffer **must** be externally synchronized

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

Bits which **can** be set in vkResetCommandBuffer::flags to control the reset operation are:

```
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.

```
typedef VkFlags VkCommandBufferResetFlags;
```

VkCommandBufferResetFlags is a bitmask type for setting a mask of zero or more VkCommandBufferResetFlagBits.

To free command buffers, call:

```
void vkFreeCommandBuffers(
    VkDevice                                    device,
    VkCommandPool                               commandPool,
    uint32_t                                    commandBufferCount,
    const VkCommandBuffer*                      pCommandBuffers);
```

- device is the logical device that owns the command pool.
- commandPool is the command pool from which the command buffers were allocated.
- commandBufferCount is the length of the pCommandBuffers array.
- pCommandBuffers is 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

- All elements of pCommandBuffers **must** not be in the pending state
- 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)

- device **must** be a valid VkDevice handle
- commandPool **must** be a valid VkCommandPool handle
- commandBufferCount **must** be greater than 0
- commandPool **must** have been created, allocated, or retrieved from device
- 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

5.4. Command Buffer Recording

To begin recording a command buffer, call:

```
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 an instance of the VkCommandBufferBeginInfo structure, which defines additional information about how the command buffer begins recording.

Valid Usage

- commandBuffer **must** not be in the recording or pending state.
- 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.
- If commandBuffer is a secondary command buffer, the pInheritanceInfo member of pBeginInfo **must** be a valid VkCommandBufferInheritanceInfo structure
- If commandBuffer is a secondary command buffer and either the occlusionQueryEnable member of the pInheritanceInfo member of pBeginInfo is VK_FALSE, or the precise occlusion queries feature is not enabled, the queryFlags member of the pInheritanceInfo member pBeginInfo **must** not contain VK_QUERY_CONTROL_PRECISE_BIT

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- 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:

```
typedef struct VkCommandBufferBeginInfo {
    VkStructureType                          sType;
    const void*                              pNext;
    VkCommandBufferUsageFlags                flags;
    const VkCommandBufferInheritanceInfo*    pInheritanceInfo;
} VkCommandBufferBeginInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is a bitmask of VkCommandBufferUsageFlagBits specifying usage behavior for the command buffer.
- pInheritanceInfo is a pointer to a VkCommandBufferInheritanceInfo structure, which is used if commandBuffer is a secondary command buffer. If this is a primary command buffer, then this value is ignored.

Valid Usage

- If flags contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT, the renderPass member of pInheritanceInfo **must** be a valid VkRenderPass
- If flags contains VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT, the subpass member of pInheritanceInfo **must** be a valid subpass index within the renderPass member of pInheritanceInfo
- 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkCommandBufferUsageFlagBits values

Bits which **can** be set in VkCommandBufferBeginInfo::flags to specify usage behavior for a command buffer are:

```
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.

```
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:

```
typedef struct VkCommandBufferInheritanceInfo {
    VkStructureType                  sType;
    const void*                      pNext;
    VkRenderPass                     renderPass;
    uint32_t                         subpass;
    VkFramebuffer                    framebuffer;
    VkBool32                         occlusionQueryEnable;
    VkQueryControlFlags              queryFlags;
    VkQueryPipelineStatisticFlags    pipelineStatistics;
} VkCommandBufferInheritanceInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- renderPass is a VkRenderPass object defining which render passes the VkCommandBuffer will be compatible with and **can** be executed within. If the VkCommandBuffer will not be executed within a render pass instance, renderPass is ignored.
- subpass is the index of the subpass within the render pass instance that the VkCommandBuffer will be executed within. If the VkCommandBuffer will not be executed within a render pass instance, subpass is ignored.
- framebuffer optionally refers 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, or if the VkCommandBuffer will not be executed within a render pass instance.

> *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 indicates 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 indicates 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.

Valid Usage

- If the inherited queries feature is not enabled, occlusionQueryEnable **must** be VK_FALSE
- If the inherited queries feature is enabled, queryFlags **must** be a valid combination of VkQueryControlFlagBits values
- If the pipeline statistics queries feature is not enabled, pipelineStatistics **must** be 0

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO
- pNext **must** be NULL
- Both of framebuffer, and renderPass that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

If VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT was not set when creating a command buffer, that command buffer **must** not be submitted to a queue whilst it is already in the pending state. If VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT is not set on a secondary command buffer, that command buffer **must** not be used more than once in a given primary command buffer.

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.

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:

```
VkResult vkEndCommandBuffer(
    VkCommandBuffer                             commandBuffer);
```

- `commandBuffer` is the command buffer to complete recording.

If there was an error during recording, the application will be notified by an unsuccessful return code returned by `vkEndCommandBuffer`. If the application wishes to further use the command buffer, the command buffer **must** be reset. The command buffer **must** have been in the recording state, and is moved to the executable state.

Valid Usage

- `commandBuffer` **must** be in the recording state.
- If `commandBuffer` is a primary command buffer, there **must** not be an active render pass instance
- All queries made active during the recording of `commandBuffer` **must** have been made inactive

Valid Usage (Implicit)

- `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`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

When a command buffer is in the executable state, it **can** be submitted to a queue for execution.

5.5. Command Buffer Submission

To submit command buffers to a queue, call:

```
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.

> *Note*
>
> Submission can be a high overhead operation, and applications **should** attempt to batch work together into as few calls to `vkQueueSubmit` as possible.

`vkQueueSubmit` is a queue submission command, with each batch defined by an element of `pSubmits` as an instance of the VkSubmitInfo structure. 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 `pWaitDstStageMask` with synchronization are described in the semaphore wait operation section of the synchronization chapter.

The order that batches appear in `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 **may** overlap or otherwise execute out of order.

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 `vkQueueSubmit` 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 `vkQueueSubmit` fails in such a way that the implementation **can** not make that guarantee, the implementation **must** return

VK_ERROR_DEVICE_LOST. See Lost Device.

Valid Usage

- If fence is not VK_NULL_HANDLE, fence **must** be unsignaled
- 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
- Any calls to vkCmdSetEvent, vkCmdResetEvent or vkCmdWaitEvents that have been recorded into any of the command buffer elements of the pCommandBuffers member of any element of pSubmits, **must** not reference any 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 *pending state*.
- Any stage flag included in any element of the pWaitDstStageMask member of any element of pSubmits **must** be a pipeline stage supported by one of the capabilities of queue, as specified in the table of supported pipeline stages.
- Each element of the pSignalSemaphores member of any element of pSubmits **must** be unsignaled when the semaphore signal operation it defines is executed on the device
- When a semaphore unsignal operation defined by any element of the pWaitSemaphores member of any element of pSubmits executes on queue, no other queue **must** be waiting on the same semaphore.
- All elements of the pWaitSemaphores member of all elements of pSubmits **must** be semaphores that are signaled, or have semaphore signal operations previously 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.

Valid Usage (Implicit)

- `queue` **must** be a valid `VkQueue` handle
- If `submitCount` is not `0`, `pSubmits` **must** be a valid pointer to an array of `submitCount` valid `VkSubmitInfo` structures
- If `fence` is not VK_NULL_HANDLE, `fence` **must** be a valid `VkFence` handle
- Both of `fence`, and `queue` that are valid handles **must** have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `queue` **must** be externally synchronized
- Host access to `pSubmits`[].pWaitSemaphores[] **must** be externally synchronized
- Host access to `pSubmits`[].pSignalSemaphores[] **must** be externally synchronized
- Host access to `fence` **must** be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
-	-	Any	-

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:

```
typedef struct VkSubmitInfo {
    VkStructureType                sType;
    const void*                    pNext;
    uint32_t                       waitSemaphoreCount;
    const VkSemaphore*             pWaitSemaphores;
    const VkPipelineStageFlags*    pWaitDstStageMask;
    uint32_t                       commandBufferCount;
    const VkCommandBuffer*         pCommandBuffers;
    uint32_t                       signalSemaphoreCount;
    const VkSemaphore*             pSignalSemaphores;
} VkSubmitInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 semaphores 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 command buffers 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 semaphores 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

- Each element of pCommandBuffers **must** not have been allocated with VK_COMMAND_BUFFER_LEVEL_SECONDARY
- If the geometry shaders feature is not enabled, each element of pWaitDstStageMask **must** not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the tessellation shaders feature is not enabled, each element of pWaitDstStageMask **must** not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- Each element of pWaitDstStageMask **must** not include VK_PIPELINE_STAGE_HOST_BIT.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_SUBMIT_INFO
- pNext **must** be NULL
- If waitSemaphoreCount is not 0, pWaitSemaphores **must** be a valid pointer to an array of waitSemaphoreCount valid VkSemaphore handles
- If waitSemaphoreCount is not 0, pWaitDstStageMask **must** be a valid pointer to an array of waitSemaphoreCount valid combinations of VkPipelineStageFlagBits values
- Each element of pWaitDstStageMask **must** not be 0
- If commandBufferCount is not 0, pCommandBuffers **must** be a valid pointer to an array of commandBufferCount valid VkCommandBuffer handles
- If signalSemaphoreCount is not 0, pSignalSemaphores **must** be a valid pointer to an array of signalSemaphoreCount valid VkSemaphore handles
- Each of the elements of pCommandBuffers, the elements of pSignalSemaphores, and the elements of pWaitSemaphores that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

5.6. Queue Forward Progress

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, for every queued wait on a semaphore there **must** be a prior signal of that semaphore that will not be consumed by a different wait on the semaphore.

Command buffers in the submission **can** include vkCmdWaitEvents commands that wait on events that will not be signaled by earlier commands in the queue. Such events **must** be signaled by the application using vkSetEvent, and the vkCmdWaitEvents commands that wait upon them **must** not be inside a render pass instance. Implementations **may** have limits on how long the command buffer will wait, in order to avoid interfering with progress of other clients of the device. If the event is not signaled within these limits, results are undefined and **may** include device loss.

5.7. 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:

```
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 an array of secondary command buffer handles, which are recorded to execute in the primary command buffer in the order they are listed in the array.

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

- commandBuffer **must** have been allocated with a level of VK_COMMAND_BUFFER_LEVEL_PRIMARY
- Each element of pCommandBuffers **must** have been allocated with a level of VK_COMMAND_BUFFER_LEVEL_SECONDARY
- Each element of pCommandBuffers **must** be in the pending or executable state.
- 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, that primary command buffer **must** not be in the pending state
- 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.
- 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.
- 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.
- 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
- If vkCmdExecuteCommands is being called within a render pass instance, that render pass instance **must** have been begun with the contents parameter of vkCmdBeginRenderPass set to VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS
- 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
- If vkCmdExecuteCommands is being called within a render pass instance, 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
- If vkCmdExecuteCommands is being called within a render pass instance, the render passes specified in the pname::pBeginInfo::pInheritanceInfo::renderPass members of the vkBeginCommandBuffer commands used to begin recording each element of pCommandBuffers **must** be compatible with the current render pass.
- 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
- 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
- If the inherited queries feature is not enabled, commandBuffer **must** not have any queries active

- 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
- 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
- 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
- Each element of pCommandBuffers **must** not begin any query types that are active in commandBuffer

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- pCommandBuffers **must** be a valid pointer to an array of commandBufferCount valid VkCommandBuffer handles
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support transfer, graphics, or compute operations
- commandBuffer **must** be a primary VkCommandBuffer
- commandBufferCount **must** be greater than 0
- 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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary	Both	Transfer Graphics Compute	

Chapter 6. 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.

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.

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.

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.

6.1. 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 **A** and **B** be separate sets of operations.
- Let **S** be a synchronization command.
- Let $\mathbf{A_S}$ and $\mathbf{B_S}$ be the synchronization scopes of **S**.
- Let **A'** be the intersection of sets **A** and $\mathbf{A_S}$.
- Let **B'** be the intersection of sets **B** and $\mathbf{B_S}$.
- Submitting **A**, **S** and **B** for execution, in that order, will result in execution dependency **E** between **A'** and **B'**.
- Execution dependency **E** guarantees that **A'** happens-before **B'**.

An *execution dependency chain* is a sequence of execution dependencies that form a happens-before relation between the first dependency's **A'** and the final dependency's **B'**. For each consecutive pair of execution dependencies, a chain exists if the intersection of $\mathbf{B_S}$ in the first dependency and $\mathbf{A_S}$ 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 **S** be a set of synchronization commands that generate an execution dependency chain.
- Let $\mathbf{A_S}$ be the first synchronization scope of the first command in **S**.
- Let $\mathbf{B_S}$ be the second synchronization scope of the last command in **S**.

> *Note*
>
> An execution dependency is inherently also multiple execution dependencies - a dependency exists between each subset of **A'** and each subset of **B'**, and the same is true for execution dependency chains. For example, a synchronization command with multiple pipeline stages in its stage masks effectively generates one dependency between each source stage and each destination stage. This can be useful to think about when considering how execution chains are formed if they do not involve all parts of a synchronization command's dependency. Similarly, any set of adjacent dependencies in an execution dependency chain **can** be considered an execution dependency chain in its own right.

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.

Two additional types of operation are used to control memory access. *Availability operations* cause the values generated by specified memory write accesses to become *available* 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. *Visibility operations* cause any available values to become *visible* to specified memory accesses.

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 **A'** is made available. Any type of access that is in a memory dependency's second access scope and occurs in **B'** 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 **a** be the set of memory accesses performed by **A'**.
- Let **b** be the set of memory accesses performed by **B'**.
- Let $\mathbf{a}_S$ be the first access scope of the first command in **S**.
- Let $\mathbf{b}_S$ be the second access scope of the last command in **S**.
- Let **a'** be the intersection of sets **a** and $\mathbf{a}_S$.
- Let **b'** be the intersection of sets **b** and $\mathbf{b}_S$.
- Submitting **A**, **S** and **B** for execution, in that order, will result in a memory dependency **m** between **A'** and **B'**.
- Memory dependency **m** guarantees that:
  - Memory writes in **a'** are made available.
  - Available memory writes, including those from **a'**, are made visible to **b'**.

> *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.

6.1.1. 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. If the old layout does not match the new layout, a transition occurs. The old layout **must** match the current layout of the image subresource range, with one exception. The old layout **can** always be specified as `VK_IMAGE_LAYOUT_UNDEFINED`, though doing so invalidates the contents of the image subresource range.

> *Note*
>
> Setting the old layout to `VK_IMAGE_LAYOUT_UNDEFINED` implies that the contents of the image subresource need not be preserved. Implementations **may** use this information to avoid performing expensive data transition operations.

> *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.

6.1.2. Pipeline Stages

The work performed by an action command consists of multiple operations, which are performed by a sequence of logically independent execution units known as *pipeline stages*. The exact pipeline stages executed depend on the particular action command that is used, and current command buffer state when the action command was recorded. Drawing commands, dispatching commands, copy commands, and clear commands all execute in different sets of pipeline stages.

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, specifying pipeline stages, are:

```
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,
    VK_PIPELINE_STAGE_HOST_BIT = 0x00004000,
    VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT = 0x00008000,
    VK_PIPELINE_STAGE_ALL_COMMANDS_BIT = 0x00010000,
} VkPipelineStageFlagBits;
```

- `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` specifies the stage of the pipeline where any commands are initially received by the queue.
- `VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT` specifies the stage of the pipeline where Draw/DispatchIndirect 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 subpass 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 subpass 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 also includes subpass load and store operations and multisample resolve operations for framebuffer attachments with a color format.

- VK_PIPELINE_STAGE_TRANSFER_BIT specifies the execution of copy commands. This includes the operations resulting from all copy commands, clear commands (with the exception of vkCmdClearAttachments), and vkCmdCopyQueryPoolResults.
- VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT specifies the execution of a compute shader.
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT specifies the final stage in the pipeline where operations generated by all commands complete execution.
- 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_TOP_OF_PIPE_BIT
  - 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_BOTTOM_OF_PIPE_BIT
- VK_PIPELINE_STAGE_ALL_COMMANDS_BIT is equivalent to the logical OR of every other pipeline stage flag that is supported on the queue it is used with.

Note

An execution dependency with only VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT in the destination stage mask will only prevent that stage from executing in subsequently submitted commands. As this stage does not perform any actual execution, this is not observable - in effect, it does not delay processing of subsequent commands. Similarly an execution dependency with only VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT in the source stage mask will effectively not wait for any prior commands to complete.

When defining a memory dependency, using only VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT or VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT would never make any accesses available and/or visible because these stages do not access memory.

VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT and VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT are useful for accomplishing layout transitions and queue ownership operations when the required execution dependency is satisfied by other means - for example, semaphore operations between queues.

```
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 its first access scope only includes memory access performed by pipeline stages specified in that 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 its second access scope only includes memory access performed by pipeline stages specified in that mask.

> *Note*
>
> Including a particular pipeline stage in the first synchronization scope of a command implicitly includes logically earlier pipeline stages in the synchronization scope. Similarly, the second synchronization scope includes logically later pipeline stages.
>
> However, note that access scopes are not affected in this way - only the precise stages specified 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

Pipeline stage flag	Required queue capability flag
VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT	None required
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT	VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT	VK_QUEUE_COMPUTE_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT	VK_QUEUE_GRAPHICS_BIT, VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT	None required

Pipeline stage flag	Required queue capability flag
VK_PIPELINE_STAGE_HOST_BIT	None required
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT	VK_QUEUE_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT	None required

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 given stage in the source stage mask for a particular synchronization command also implies that any logically earlier stages are included in $\mathbf{A}_S$ 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 $\mathbf{B}_S$ 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.

The order of pipeline stages depends on the particular pipeline; graphics, compute, transfer or host.

For the graphics pipeline, the following stages occur in this order:

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
- 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_EARLY_FRAGMENT_TESTS_BIT
- VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
- VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT

- `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`
- `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT`

For the compute pipeline, the following stages occur in this order:

- `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT`
- `VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT`
- `VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT`
- `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT`

For the transfer pipeline, the following stages occur in this order:

- `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT`
- `VK_PIPELINE_STAGE_TRANSFER_BIT`
- `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT`

For host operations, only one pipeline stage occurs, so no order is guaranteed:

- `VK_PIPELINE_STAGE_HOST_BIT`

6.1.3. 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. Each access type corresponds to a bit flag in VkAccessFlagBits.

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.

Access types that **can** be set in an access mask include:

```
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,
    VK_ACCESS_HOST_WRITE_BIT = 0x00004000,
    VK_ACCESS_MEMORY_READ_BIT = 0x00008000,
    VK_ACCESS_MEMORY_WRITE_BIT = 0x00010000,
} VkAccessFlagBits;
```

- `VK_ACCESS_INDIRECT_COMMAND_READ_BIT` specifies read access to an indirect command structure read as part of an indirect drawing or dispatch command.
- `VK_ACCESS_INDEX_READ_BIT` specifies read access to an index buffer as part of an indexed drawing command, bound by vkCmdBindIndexBuffer.
- `VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT` specifies read access to a vertex buffer as part of a drawing command, bound by vkCmdBindVertexBuffers.
- `VK_ACCESS_UNIFORM_READ_BIT` specifies read access to a uniform buffer.
- `VK_ACCESS_INPUT_ATTACHMENT_READ_BIT` specifies read access to an input attachment within a render pass during fragment shading.
- `VK_ACCESS_SHADER_READ_BIT` specifies read access to a storage buffer, uniform texel buffer, storage texel buffer, sampled image, or storage image.
- `VK_ACCESS_SHADER_WRITE_BIT` specifies write access to a storage buffer, storage texel buffer, or storage image.
- `VK_ACCESS_COLOR_ATTACHMENT_READ_BIT` specifies read access to a color attachment, such as via blending, logic operations, or via certain subpass load operations.
- `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT` specifies write access to a color or resolve attachment during a render pass or via certain subpass load and store operations.
- `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT` specifies read access to a depth/stencil attachment, via depth or stencil operations or via certain subpass load operations.
- `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT` specifies write access to a depth/stencil attachment, via depth or stencil operations or via certain subpass load and store operations.
- `VK_ACCESS_TRANSFER_READ_BIT` specifies read access to an image or buffer in a copy operation.
- `VK_ACCESS_TRANSFER_WRITE_BIT` specifies write access to an image or buffer in a clear or copy

operation.

- 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.
- 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.
- VK_ACCESS_MEMORY_READ_BIT specifies read access via non-specific entities. These entities include the Vulkan device and host, but **may** also include entities external to the Vulkan device or otherwise not part of the core Vulkan pipeline. When included in a destination access mask, makes all available writes visible to all future read accesses on entities known to the Vulkan device.
- VK_ACCESS_MEMORY_WRITE_BIT specifies write access via non-specific entities. These entities include the Vulkan device and host, but **may** also include entities external to the Vulkan device or otherwise not part of the core Vulkan pipeline. When included in a source access mask, all writes that are performed by entities known to the Vulkan device are made available. When included in a destination access mask, makes all available writes visible to all future write accesses on entities known to the Vulkan device.

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

Access flag	Supported pipeline stages
VK_ACCESS_INDIRECT_COMMAND_READ_BIT	VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_ACCESS_INDEX_READ_BIT	VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT	VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_ACCESS_UNIFORM_READ_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, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT	VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
VK_ACCESS_SHADER_READ_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, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT

Access flag	Supported pipeline stages
VK_ACCESS_SHADER_WRITE_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, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT	VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT	VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT	VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT, or VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT	VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT, or VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_ACCESS_TRANSFER_READ_BIT	VK_PIPELINE_STAGE_TRANSFER_BIT
VK_ACCESS_TRANSFER_WRITE_BIT	VK_PIPELINE_STAGE_TRANSFER_BIT
VK_ACCESS_HOST_READ_BIT	VK_PIPELINE_STAGE_HOST_BIT
VK_ACCESS_HOST_WRITE_BIT	VK_PIPELINE_STAGE_HOST_BIT
VK_ACCESS_MEMORY_READ_BIT	N/A
VK_ACCESS_MEMORY_WRITE_BIT	N/A

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 visible to the VK_ACCESS_HOST_WRITE_BIT access type, where it **can** be further made available to the device by synchronization commands. Similarly, vkInvalidateMappedMemoryRanges **must** be called to guarantee that writes which are visible to the VK_ACCESS_HOST_READ_BIT access type 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 visible to the VK_ACCESS_HOST_WRITE_BIT access type. Similarly, writes made visible to the VK_ACCESS_HOST_READ_BIT access type are automatically made visible to the host.

Note

The vkQueueSubmit command automatically guarantees that host writes flushed to VK_ACCESS_HOST_WRITE_BIT are made available if they were flushed before the command executed, 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.

```
typedef VkFlags VkAccessFlags;
```

VkAccessFlags is a bitmask type for setting a mask of zero or more VkAccessFlagBits.

6.1.4. 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 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 `rasterizationSamples`, then a fragment **can** access any sample in the input attachment's pixel even if it only uses framebuffer-local dependencies. If the input attachment has the same number of samples, then the fragment **can** only access the covered samples in its input `SampleMask` (i.e. the fragment operations happen-after a framebuffer-local dependency for each sample the fragment covers). To access samples that are not covered, a framebuffer-global dependency is required.

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 optimal 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.

6.2. 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.

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 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, from lowest index to highest.
3. The order in which command buffers are specified in the `pCommandBuffers` member of

VkSubmitInfo, 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.

Action and synchronization commands recorded to a command buffer execute the `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` pipeline stage in submission order - forming an implicit execution dependency between this stage in each command.

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.

Query commands, 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.

6.3. Fences

Fences are a synchronization primitive that **can** be used to insert a dependency from a queue to the host. Fences have two states - signaled and unsignaled. A fence **can** be signaled as part of the execution of a queue submission command. Fences **can** be unsignaled on the host with vkResetFences. Fences **can** be waited on by the host with the vkWaitForFences command, and the current state **can** be queried with vkGetFenceStatus.

Fences are represented by `VkFence` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFence)
```

To create a fence, call:

```
VkResult vkCreateFence(
    VkDevice                                    device,
    const VkFenceCreateInfo*                    pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkFence*                                    pFence);
```

- device is the logical device that creates the fence.
- pCreateInfo is a pointer to an instance of the VkFenceCreateInfo structure which contains information about how the fence is to be created.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pFence points to a handle in which the resulting fence object is returned.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkFenceCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
typedef struct VkFenceCreateInfo {
    VkStructureType       sType;
    const void*           pNext;
    VkFenceCreateFlags    flags;
} VkFenceCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is a bitmask of VkFenceCreateFlagBits specifying the initial state and behavior of the fence.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_FENCE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkFenceCreateFlagBits values

```
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.

```
typedef VkFlags VkFenceCreateFlags;
```

VkFenceCreateFlags is a bitmask type for setting a mask of zero or more VkFenceCreateFlagBits.

To destroy a fence, call:

```
void vkDestroyFence(
    VkDevice                                    device,
    VkFence                                     fence,
    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

- All queue submission commands that refer to fence **must** have completed execution
- If VkAllocationCallbacks were provided when fence was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when fence was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `fence` is not VK_NULL_HANDLE, `fence` **must** be a valid `VkFence` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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:

```
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 5. Fence Object Status Codes

Status	Meaning
`VK_SUCCESS`	The fence specified by `fence` is signaled.
`VK_NOT_READY`	The fence specified by `fence` is unsignaled.
`VK_ERROR_DEVICE_LOST`	The device has been lost. See Lost Device.

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)

- `device` **must** be a valid `VkDevice` handle
- `fence` **must** be a valid `VkFence` handle
- `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:

```
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.

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

- 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)

- `device` **must** be a valid `VkDevice` handle
- `pFences` **must** be a valid pointer to an array of `fenceCount` valid `VkFence` handles
- `fenceCount` **must** be greater than `0`
- Each element of `pFences` **must** have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to each member of `pFences` **must** be externally synchronized

Return Codes

Success

- `VK_SUCCESS`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `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 additionally include in the first synchronization scope all previous queue submissions to the same queue via vkQueueSubmit.

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:

```
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 up to timeout nanoseconds for the condition to become satisfied.

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 specified timeout period expires before the condition is satisfied, vkWaitForFences returns VK_TIMEOUT. If the condition is satisfied before timeout nanoseconds has expired, vkWaitForFences returns VK_SUCCESS.

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)

- device **must** be a valid VkDevice handle
- pFences **must** be a valid pointer to an array of fenceCount valid VkFence handles
- fenceCount **must** be greater than 0
- Each element of pFences **must** have been created, allocated, or retrieved from device

Return Codes

Success

- VK_SUCCESS
- VK_TIMEOUT

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

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.

6.4. Semaphores

Semaphores are a synchronization primitive that **can** be used to insert a dependency between batches submitted to queues. Semaphores have two states - signaled and unsignaled. The state of a semaphore **can** be signaled after execution of a batch of commands is completed. A batch **can** wait for a semaphore to become signaled before it begins execution, and the semaphore is also unsignaled before the batch begins execution.

Semaphores are represented by `VkSemaphore` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSemaphore)
```

To create a semaphore, call:

```
VkResult vkCreateSemaphore(
    VkDevice                                    device,
    const VkSemaphoreCreateInfo*                pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkSemaphore*                                pSemaphore);
```

- device is the logical device that creates the semaphore.
- pCreateInfo is a pointer to an instance of the VkSemaphoreCreateInfo structure which contains information about how the semaphore is to be created.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pSemaphore points to a handle in which the resulting semaphore object is returned.

When created, the semaphore is in the unsignaled state.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkSemaphoreCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
typedef struct VkSemaphoreCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkSemaphoreCreateFlags    flags;
} VkSemaphoreCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0

```
typedef VkFlags VkSemaphoreCreateFlags;
```

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

To destroy a semaphore, call:

```
void vkDestroySemaphore(
    VkDevice                                    device,
    VkSemaphore                                 semaphore,
    const VkAllocationCallbacks*                pAllocator);
```

- 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

- All submitted batches that refer to semaphore **must** have completed execution
- If VkAllocationCallbacks were provided when semaphore was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when semaphore was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If semaphore is not VK_NULL_HANDLE, semaphore **must** be a valid VkSemaphore handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

6.4.1. 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.

The first synchronization scope includes every command submitted in the same batch. Semaphore signal operations that are defined by vkQueueSubmit additionally include all batches previously submitted to the same queue via vkQueueSubmit, including batches that are submitted in the same queue submission command, but at a lower index within the array of batches.

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.

6.4.2. Semaphore Waiting & Unsignaling

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 unsignal operations* which set the semaphores to the unsignaled state.

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`. Also, in the case of vkQueueSubmit, the second synchronization scope additionally includes all batches subsequently submitted to the same queue via vkQueueSubmit, including batches that are submitted in the same queue submission command, but at a higher index within the array of batches.

The first access scope is empty.

The second access scope includes all memory access performed by the device.

The semaphore unsignal 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 fences or events, the act of waiting for a semaphore also unsignals that semaphore. If two operations are separately specified to wait for the same semaphore, and there are no other execution dependencies between those operations, behaviour is undefined. An execution dependency **must** be present that guarantees that the semaphore unsignal operation for the first of those waits, happens-before the semaphore is signalled again, and before the second unsignal operation. Semaphore waits and signals should thus occur in discrete 1:1 pairs.

6.4.3. 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 and unsignal operation is submitted to a queue:

- The semaphore **must** be signaled, or have an associated semaphore signal operation that is pending execution.
- There **must** be no other queue waiting on the same semaphore when the operation executes.

6.5. 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 an event, or unsignal it, on either the host or the device. A device **can** 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkEvent)
```

To create an event, call:

```
VkResult vkCreateEvent(
    VkDevice                                    device,
    const VkEventCreateInfo*                    pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkEvent*                                    pEvent);
```

- `device` is the logical device that creates the event.
- `pCreateInfo` is a pointer to an instance of the `VkEventCreateInfo` structure which contains information about how the event is to be created.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

* pEvent points to a handle in which the resulting event object is returned.

When created, the event object is in the unsignaled state.

Valid Usage (Implicit)

* device **must** be a valid VkDevice handle
* pCreateInfo **must** be a valid pointer to a valid VkEventCreateInfo structure
* If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
* 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:

```
typedef struct VkEventCreateInfo {
    VkStructureType       sType;
    const void*           pNext;
    VkEventCreateFlags    flags;
} VkEventCreateInfo;
```

* sType is the type of this structure.
* pNext is NULL or a pointer to an extension-specific structure.
* flags is reserved for future use.

Valid Usage (Implicit)

* sType **must** be VK_STRUCTURE_TYPE_EVENT_CREATE_INFO
* pNext **must** be NULL
* flags **must** be 0

```
typedef VkFlags VkEventCreateFlags;
```

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

To destroy an event, call:

```
void vkDestroyEvent(
    VkDevice                                    device,
    VkEvent                                     event,
    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

- All submitted commands that refer to event **must** have completed execution
- If VkAllocationCallbacks were provided when event was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when event was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If event is not VK_NULL_HANDLE, event **must** be a valid VkEvent handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
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	Meaning
VK_EVENT_SET	The event specified by event is signaled.
VK_EVENT_RESET	The event specified by event is unsignaled.

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 (Implicit)

- device **must** be a valid VkDevice handle
- event **must** be a valid VkEvent handle
- 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:

```
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.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `event` **must** be a valid `VkEvent` handle
- `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`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

To set the state of an event to unsignaled from the host, call:

```
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

- `event` **must** not be waited on by a `vkCmdWaitEvents` command that is currently executing

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `event` **must** be a valid `VkEvent` handle
- `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`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The state of an event **can** also be updated on the device by commands inserted in command buffers.

To set the state of an event to signaled from a device, call:

```
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 when the `event` is signaled.

When vkCmdSetEvent is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and defines an event signal operation which sets the event to the signaled state.

The first synchronization scope includes every command previously submitted to the same queue, including those in the same command buffer and batch. The synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by `stageMask`.

The second synchronization scope includes only the event signal operation.

If `event` is already in the signaled state when vkCmdSetEvent is executed on the device, then vkCmdSetEvent has no effect, no event signal operation occurs, and no execution dependency is generated.

Valid Usage

- `stageMask` **must** not include `VK_PIPELINE_STAGE_HOST_BIT`
- If the geometry shaders feature is not enabled, `stageMask` **must** not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `stageMask` **must** not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `event` **must** be a valid `VkEvent` handle
- `stageMask` **must** be a valid combination of VkPipelineStageFlagBits values
- `stageMask` **must** not be `0`
- `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 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	

To set the state of an event to unsignaled from a device, call:

```
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.

When vkCmdResetEvent 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 every command previously submitted to the same queue, including those in the same command buffer and batch. The synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by `stageMask`.

The second synchronization scope includes only the event unsignal operation.

If `event` is already in the unsignaled state when vkCmdResetEvent is executed on the device, then vkCmdResetEvent has no effect, no event unsignal operation occurs, and no execution dependency is generated.

Valid Usage

- `stageMask` **must** not include `VK_PIPELINE_STAGE_HOST_BIT`
- If the geometry shaders feature is not enabled, `stageMask` **must** not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `stageMask` **must** not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`
- When this command executes, `event` **must** not be waited on by a `vkCmdWaitEvents` command that is currently executing

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `event` **must** be a valid `VkEvent` handle
- `stageMask` **must** be a valid combination of VkPipelineStageFlagBits values
- `stageMask` **must** not be `0`
- `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 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	

To wait for one or more events to enter the signaled state on a device, call:

```
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 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.

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 occuring 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 were previously submitted to the same queue 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 commands subsequently submitted to the same queue, including those in the same command buffer and batch. 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 access 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 access 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.

Note

vkCmdWaitEvents is used with vkCmdSetEvent 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 a vkCmdResetEvent command and a vkCmdWaitEvents command submitted after it, so some other execution dependency **must** be included between these commands (e.g. a semaphore).

Valid Usage

- `srcStageMask` **must** be the bitwise OR of the `stageMask` parameter used in previous calls to `vkCmdSetEvent` with any of the members of `pEvents` and `VK_PIPELINE_STAGE_HOST_BIT` if any of the members of `pEvents` was set using `vkSetEvent`
- If the geometry shaders feature is not enabled, `srcStageMask` **must** not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the geometry shaders feature is not enabled, `dstStageMask` **must** not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `srcStageMask` **must** not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `dstStageMask` **must** not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`
- If `pEvents` includes one or more events that will be signaled by `vkSetEvent` after `commandBuffer` has been submitted to a queue, then `vkCmdWaitEvents` **must** not be called inside a render pass instance
- Any pipeline stage included in `srcStageMask` or `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.
- Each element of `pMemoryBarriers`, `pBufferMemoryBarriers` or `pImageMemoryBarriers` **must** not have any access flag included in its `srcAccessMask` member if that bit is not supported by any of the pipeline stages in `srcStageMask`, as specified in the table of supported access types.
- Each element of `pMemoryBarriers`, `pBufferMemoryBarriers` or `pImageMemoryBarriers` **must** not have any access flag included in its `dstAccessMask` member if that bit is not supported by any of the pipeline stages in `dstStageMask`, as specified in the table of supported access types.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pEvents` **must** be a valid pointer to an array of `eventCount` valid `VkEvent` handles
- `srcStageMask` **must** be a valid combination of VkPipelineStageFlagBits values
- `srcStageMask` **must** not be `0`
- `dstStageMask` **must** be a valid combination of VkPipelineStageFlagBits values
- `dstStageMask` **must** not be `0`
- If `memoryBarrierCount` is not `0`, `pMemoryBarriers` **must** be a valid pointer to an array of `memoryBarrierCount` valid `VkMemoryBarrier` structures
- If `bufferMemoryBarrierCount` is not `0`, `pBufferMemoryBarriers` **must** be a valid pointer to an array of `bufferMemoryBarrierCount` valid `VkBufferMemoryBarrier` structures
- If `imageMemoryBarrierCount` is not `0`, `pImageMemoryBarriers` **must** be a valid pointer to an array of `imageMemoryBarrierCount` valid `VkImageMemoryBarrier` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations
- `eventCount` **must** be greater than `0`
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

6.6. Pipeline Barriers

vkCmdPipelineBarrier is a synchronization command that inserts a dependency between commands submitted to the same queue, or between commands in the same subpass.

To record a pipeline barrier, call:

```
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 stage mask.
- `dstStageMask` is a bitmask of VkPipelineStageFlagBits specifying the destination stage mask.
- `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.

When vkCmdPipelineBarrier is submitted to a queue, it defines a memory dependency between commands that were submitted before it, and those submitted after it.

If vkCmdPipelineBarrier was recorded outside a render pass instance, the first synchronization scope includes every command submitted to the same queue before it, including those in the same command buffer and batch. If vkCmdPipelineBarrier was recorded inside a render pass instance, the first synchronization scope includes only commands submitted before it 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 every command submitted to the same queue after it, including those in the same command buffer and batch. If vkCmdPipelineBarrier was recorded inside a render pass instance, the second synchronization scope includes only commands submitted after it 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 `dstStageMask`.

The first access scope is limited to access 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 access 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.

If dependencyFlags includes VK_DEPENDENCY_BY_REGION_BIT, then any dependency between framebuffer-space pipeline stages is framebuffer-local - otherwise it is framebuffer-global.

Valid Usage

- If the geometry shaders feature is not enabled, srcStageMask **must** not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the geometry shaders feature is not enabled, dstStageMask **must** not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the tessellation shaders feature is not enabled, srcStageMask **must** not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- If the tessellation shaders feature is not enabled, dstStageMask **must** not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- If vkCmdPipelineBarrier is called within a render pass instance, the render pass **must** have been created with a VkSubpassDependency instance in pDependencies that expresses a dependency from the current subpass to itself.
- If vkCmdPipelineBarrier is called within a render pass instance, srcStageMask **must** contain a subset of the bit values in the srcStageMask member of that instance of VkSubpassDependency
- If vkCmdPipelineBarrier is called within a render pass instance, dstStageMask **must** contain a subset of the bit values in the dstStageMask member of that instance of VkSubpassDependency
- If vkCmdPipelineBarrier is called within a render pass instance, the srcAccessMask of any element of pMemoryBarriers or pImageMemoryBarriers **must** contain a subset of the bit values the srcAccessMask member of that instance of VkSubpassDependency
- If vkCmdPipelineBarrier is called within a render pass instance, the dstAccessMask of any element of pMemoryBarriers or pImageMemoryBarriers **must** contain a subset of the bit values the dstAccessMask member of that instance of VkSubpassDependency
- If vkCmdPipelineBarrier is called within a render pass instance, dependencyFlags **must** be equal to the dependencyFlags member of that instance of VkSubpassDependency
- If vkCmdPipelineBarrier is called within a render pass instance, bufferMemoryBarrierCount **must** be 0
- If vkCmdPipelineBarrier is called within a render pass instance, the image member of any element of pImageMemoryBarriers **must** be equal to one of the elements of pAttachments that the current framebuffer was created with, that is also referred to by one of the elements of the pColorAttachments, pResolveAttachments or pDepthStencilAttachment members of the VkSubpassDescription instance that the current subpass was created with
- If vkCmdPipelineBarrier is called within a render pass instance, the oldLayout and newLayout members of any element of pImageMemoryBarriers **must** be equal to the layout member of an element of the pColorAttachments, pResolveAttachments or pDepthStencilAttachment members of the VkSubpassDescription instance that the current subpass was created with, that refers to the same image
- If vkCmdPipelineBarrier is called within a render pass instance, the oldLayout and newLayout members of an element of pImageMemoryBarriers **must** be equal

- If vkCmdPipelineBarrier is called within a render pass instance, the srcQueueFamilyIndex and dstQueueFamilyIndex members of any element of pImageMemoryBarriers **must** be VK_QUEUE_FAMILY_IGNORED
- Any pipeline stage included in srcStageMask or 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.
- Each element of pMemoryBarriers, pBufferMemoryBarriers and pImageMemoryBarriers **must** not have any access flag included in its srcAccessMask member if that bit is not supported by any of the pipeline stages in srcStageMask, as specified in the table of supported access types.
- Each element of pMemoryBarriers, pBufferMemoryBarriers and pImageMemoryBarriers **must** not have any access flag included in its dstAccessMask member if that bit is not supported by any of the pipeline stages in dstStageMask, as specified in the table of supported access types.

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- srcStageMask **must** be a valid combination of VkPipelineStageFlagBits values
- srcStageMask **must** not be 0
- dstStageMask **must** be a valid combination of VkPipelineStageFlagBits values
- dstStageMask **must** not be 0
- dependencyFlags **must** be a valid combination of VkDependencyFlagBits values
- If memoryBarrierCount is not 0, pMemoryBarriers **must** be a valid pointer to an array of memoryBarrierCount valid VkMemoryBarrier structures
- If bufferMemoryBarrierCount is not 0, pBufferMemoryBarriers **must** be a valid pointer to an array of bufferMemoryBarrierCount valid VkBufferMemoryBarrier structures
- If imageMemoryBarrierCount is not 0, pImageMemoryBarriers **must** be a valid pointer to an array of imageMemoryBarrierCount valid VkImageMemoryBarrier structures
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Transfer Graphics Compute	

Bits which **can** be set in vkCmdPipelineBarrier::dependencyFlags, specifying how execution and memory dependencies are formed, are:

```
typedef enum VkDependencyFlagBits {
    VK_DEPENDENCY_BY_REGION_BIT = 0x00000001,
} VkDependencyFlagBits;
```

- VK_DEPENDENCY_BY_REGION_BIT specifies that dependencies will be framebuffer-local.

```
typedef VkFlags VkDependencyFlags;
```

VkDependencyFlags is a bitmask type for setting a mask of zero or more VkDependencyFlagBits.

6.6.1. Subpass Self-dependency

If vkCmdPipelineBarrier is called inside a render pass instance, the following restrictions apply. For a given subpass to allow a pipeline barrier, the render pass **must** declare a *self-dependency* from that subpass to itself. That is, there **must** exist a VkSubpassDependency in the subpass dependency list for the render pass with srcSubpass and dstSubpass equal to that subpass index. More than one self-dependency **can** be declared for each subpass. Self-dependencies **must** only include pipeline stage bits that are graphics stages. Self-dependencies **must** not have any earlier pipeline stages depend on any later pipeline stages (according to the order of graphics pipeline stages), unless all of the stages are framebuffer-space stages. If the source and destination stage masks both include framebuffer-space stages, then dependencyFlags **must** include VK_DEPENDENCY_BY_REGION_BIT.

A vkCmdPipelineBarrier command inside a render pass instance **must** be a *subset* of one of the self-dependencies of the subpass it is used in, meaning that the stage masks and access masks **must** each include only a subset of the bits of the corresponding mask in that self-dependency. If the self-dependency has VK_DEPENDENCY_BY_REGION_BIT set, then so **must** the pipeline barrier. Pipeline barriers within a render pass instance **can** only be types VkMemoryBarrier or VkImageMemoryBarrier. If a VkImageMemoryBarrier is used, the image and image subresource range specified in the barrier **must** be a subset of one of the image views used by the framebuffer in the current subpass. Additionally, oldLayout **must** be equal to newLayout, and both the srcQueueFamilyIndex and dstQueueFamilyIndex **must** be VK_QUEUE_FAMILY_IGNORED.

6.7. 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.

6.7.1. Global Memory Barriers

Global memory barriers apply to memory accesses involving all memory objects that exist at the time of its execution.

The `VkMemoryBarrier` structure is defined as:

```
typedef struct VkMemoryBarrier {
    VkStructureType    sType;
    const void*        pNext;
    VkAccessFlags      srcAccessMask;
    VkAccessFlags      dstAccessMask;
} VkMemoryBarrier;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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)

- `sType` **must** be `VK_STRUCTURE_TYPE_MEMORY_BARRIER`
- `pNext` **must** be `NULL`
- `srcAccessMask` **must** be a valid combination of VkAccessFlagBits values
- `dstAccessMask` **must** be a valid combination of VkAccessFlagBits values

6.7.2. Buffer Memory Barriers

Buffer memory barriers only apply to memory accesses involving a specific buffer range. That is, a memory dependency formed from an 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 VkBufferMemoryBarrier structure is defined as:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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, 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 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, 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 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

- offset **must** be less than the size of buffer
- If size is not equal to VK_WHOLE_SIZE, size **must** be greater than 0
- If size is not equal to VK_WHOLE_SIZE, size **must** be less than or equal to than the size of buffer minus offset
- If buffer was created with a sharing mode of VK_SHARING_MODE_CONCURRENT, srcQueueFamilyIndex and dstQueueFamilyIndex **must** both be VK_QUEUE_FAMILY_IGNORED
- If buffer was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, srcQueueFamilyIndex and dstQueueFamilyIndex **must** either both be VK_QUEUE_FAMILY_IGNORED, or both be a valid queue family (see Queue Family Properties)
- If buffer was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, and srcQueueFamilyIndex and dstQueueFamilyIndex are not VK_QUEUE_FAMILY_IGNORED, at least one of them **must** be the same as the family of the queue that will execute this barrier

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER
- pNext **must** be NULL
- srcAccessMask **must** be a valid combination of VkAccessFlagBits values
- dstAccessMask **must** be a valid combination of VkAccessFlagBits values
- buffer **must** be a valid VkBuffer handle

6.7.3. 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 VkImageMemoryBarrier structure is defined as:

```c
typedef struct VkImageMemoryBarrier {
    VkStructureType            sType;
    const void*                pNext;
    VkAccessFlags              srcAccessMask;
    VkAccessFlags              dstAccessMask;
    VkImageLayout              oldLayout;
    VkImageLayout              newLayout;
    uint32_t                   srcQueueFamilyIndex;
    uint32_t                   dstQueueFamilyIndex;
    VkImage                    image;
    VkImageSubresourceRange    subresourceRange;
} VkImageMemoryBarrier;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 `oldLayout` is not equal to `newLayout`, then the memory barrier defines an image layout transition for the specified image subresource range.

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.

Valid Usage

- oldLayout **must** be VK_IMAGE_LAYOUT_UNDEFINED or the current layout of the image subresources affected by the barrier
- newLayout **must** not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED
- If image was created with a sharing mode of VK_SHARING_MODE_CONCURRENT, srcQueueFamilyIndex and dstQueueFamilyIndex **must** both be VK_QUEUE_FAMILY_IGNORED
- If image was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, srcQueueFamilyIndex and dstQueueFamilyIndex **must** either both be VK_QUEUE_FAMILY_IGNORED, or both be a valid queue family (see Queue Family Properties).
- If image was created with a sharing mode of VK_SHARING_MODE_EXCLUSIVE, and srcQueueFamilyIndex and dstQueueFamilyIndex are not VK_QUEUE_FAMILY_IGNORED, at least one of them **must** be the same as the family of the queue that will execute this barrier
- 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
- 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 has a depth/stencil format with both depth and stencil components, then the aspectMask member of subresourceRange **must** include both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT
- If either oldLayout or newLayout is VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL then image **must** have been created with VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT set
- If either 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 set
- If either 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 set
- If either 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 set
- If either oldLayout or newLayout is VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL then image **must** have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT set
- If either oldLayout or newLayout is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then image **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT set

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER
- pNext **must** be NULL
- srcAccessMask **must** be a valid combination of VkAccessFlagBits values
- dstAccessMask **must** be a valid combination of VkAccessFlagBits values
- oldLayout **must** be a valid VkImageLayout value
- newLayout **must** be a valid VkImageLayout value
- image **must** be a valid VkImage handle
- subresourceRange **must** be a valid VkImageSubresourceRange structure

6.7.4. 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. 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 subresource range. 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), 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. dstStageMask is ignored for such a barrier, such that no visibility operation is executed - the value of this mask does not affect the validity of the barrier. The release operation happens-after the availability operation.

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), on a queue from the destination 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. `srcStageMask` is ignored for such a barrier, such that no availability operation is executed - the value of this mask does not affect the validity of the barrier. The acquire operation 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 memory barrier **must** be equal to values of `oldLayout` and `newLayout` in the acquire 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 an `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.

6.8. Wait Idle Operations

To wait on the host for the completion of outstanding queue operations for a given queue, call:

```
VkResult vkQueueWaitIdle(
    VkQueue                                     queue);
```

- `queue` is the queue on which to wait.

vkQueueWaitIdle is equivalent to submitting a fence to a queue and waiting with an infinite timeout for that fence to signal.

Valid Usage (Implicit)

- queue **must** be a valid VkQueue handle

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
-	-	Any	-

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

To wait on the host for the completion of outstanding queue operations for all queues on a given logical device, call:

```
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)

- 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

6.9. Host Write Ordering Guarantees

When batches of command buffers are submitted to a queue via vkQueueSubmit, it defines a memory dependency with prior host operations, and execution of command buffers submitted to the queue.

The first synchronization scope is defined by the host execution model, but includes execution of vkQueueSubmit on the host and anything that happened-before it.

The second synchronization scope includes every command submitted in the same queue submission command, and all future submissions to the same queue.

The first access scope includes all host writes to mappable device memory that are either coherent, or have been flushed with vkFlushMappedMemoryRanges.

The second access scope includes all memory access performed by the device.

Chapter 7. Render Pass

A *render pass* represents a collection of attachments, subpasses, and dependencies between the subpasses, and describes how the attachments are used over the course of the subpasses. The use of a render pass in a command buffer is a *render pass instance*.

Render passes are represented by `VkRenderPass` handles:

```
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, or input attachment for that subpass (as determined by the `pColorAttachments`, `pDepthStencilAttachment`, `pResolveAttachments`, 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.

7.1. Render Pass Creation

To create a render pass, call:

```
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 an instance of the VkRenderPassCreateInfo structure that describes the parameters of the render pass.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pRenderPass` points to a `VkRenderPass` handle in which the resulting render pass object is returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkRenderPassCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- attachmentCount is the number of attachments used by this render pass, or zero indicating no attachments. Attachments are referred to by zero-based indices in the range [0,attachmentCount).
- pAttachments points to an array of attachmentCount number of VkAttachmentDescription structures describing properties of the attachments, or NULL if attachmentCount is zero.
- subpassCount is the number of subpasses to create for this render pass. Subpasses are referred to by zero-based indices in the range [0,subpassCount). A render pass **must** have at least one subpass.
- pSubpasses points to an array of subpassCount number of VkSubpassDescription structures describing properties of the subpasses.
- dependencyCount is the number of dependencies between pairs of subpasses, or zero indicating no dependencies.
- pDependencies points to an array of dependencyCount number of VkSubpassDependency structures describing dependencies between pairs of subpasses, or NULL if dependencyCount is zero.

Valid Usage

- 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
- 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 VkAttachmentDescription structures describing them **must** include VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT in flags
- 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, it **must** be less than attachmentCount
- The value of each element of the pPreserveAttachments member in each element of pSubpasses **must** not be VK_ATTACHMENT_UNUSED
- 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.
- 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.
- 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 source subpass.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- If attachmentCount is not 0, pAttachments **must** be a valid pointer to an array of attachmentCount valid VkAttachmentDescription structures
- pSubpasses **must** be a valid pointer to an array of subpassCount valid VkSubpassDescription structures
- If dependencyCount is not 0, pDependencies **must** be a valid pointer to an array of dependencyCount valid VkSubpassDependency structures
- subpassCount **must** be greater than 0

```
typedef VkFlags VkRenderPassCreateFlags;
```

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

The VkAttachmentDescription structure is defined as:

```
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 that will be used for the attachment.
- samples is the number of samples of the image as defined in VkSampleCountFlagBits.
- 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. During a render pass instance, an attachment **can** use a different layout in each subpass, if desired.

If the attachment uses a color format, then loadOp and storeOp are used, and stencilLoadOp and 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* that execute as part of the first subpass that uses the attachment. storeOp and stencilStoreOp define the *store operations* that execute as part of the last subpass that uses the attachment.

The load operation for each sample in an attachment happens-before any recorded command which accesses the sample in the first subpass where the attachment is used. 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 store operation for each sample in an attachment happens-after any recorded command which accesses the sample in the last subpass where the attachment is used. 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.

If an attachment is not used by any subpass, then loadOp, storeOp, stencilStoreOp, and stencilLoadOp are ignored, and the attachment's memory contents will not be modified by execution of a render pass instance.

During a render pass instance, input/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.

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.

Valid Usage

- finalLayout **must** not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

Valid Usage (Implicit)

- 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
- initialLayout **must** be a valid VkImageLayout value
- finalLayout **must** be a valid VkImageLayout value

Bits which **can** be set in VkAttachmentDescription::flags describing additional properties of the attachment are:

```
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.

Possible values of VkAttachmentDescription::loadOp and stencilLoadOp, specifying how the contents of the attachment are treated, are:

```
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. 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.

Possible values of VkAttachmentDescription::storeOp and stencilStoreOp, specifying how the contents of the attachment are treated, are:

```
typedef enum VkAttachmentStoreOp {
    VK_ATTACHMENT_STORE_OP_STORE = 0,
    VK_ATTACHMENT_STORE_OP_DONT_CARE = 1,
} VkAttachmentStoreOp;
```

- 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.

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. The precise set of valid scenarios is described in more detail below.

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`.

The `VkSubpassDescription` structure is defined as:

```
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 whether this is a compute or

graphics subpass. Currently, only graphics subpasses are supported.

- `inputAttachmentCount` is the number of input attachments.
- `pInputAttachments` is an array of VkAttachmentReference structures (defined below) that lists which of the render pass's attachments **can** be read in the fragment shader stage during the subpass, and what layout each attachment will be in during the subpass. Each element of the array corresponds to an input attachment unit number in the shader, i.e. if the shader declares an input variable `layout(input_attachment_index=X, set=Y, binding=Z)` then it uses the attachment provided in `pInputAttachments`[X]. Input attachments **must** also be bound to the pipeline with a descriptor set, with the input attachment descriptor written in the location (set=Y, binding=Z). Fragment shaders **can** use subpass input variables to access the contents of an input attachment at the fragment's (x, y, layer) framebuffer coordinates.
- `colorAttachmentCount` is the number of color attachments.
- `pColorAttachments` is an array of `colorAttachmentCount` VkAttachmentReference structures that lists which of the render pass's attachments will be used as color attachments in the subpass, and what layout each attachment will be in during the subpass. Each element of the array corresponds to a fragment shader output location, i.e. if the shader declared an output variable `layout(location=X)` then it uses the attachment provided in `pColorAttachments`[X].
- `pResolveAttachments` is `NULL` or an array of `colorAttachmentCount` VkAttachmentReference structures that lists which of the render pass's attachments are resolved to at the end of the subpass, and what layout each attachment will be in during the multisample resolve operation. 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. At the end of each subpass, multisample resolve operations read the subpass's color attachments, and resolve the samples for each pixel to the same pixel location in the corresponding resolve attachments, unless the resolve attachment index is `VK_ATTACHMENT_UNUSED`. If the first use of an attachment in a render pass is as a resolve attachment, then the `loadOp` is effectively ignored as the resolve is guaranteed to overwrite all pixels in the render area.
- `pDepthStencilAttachment` is a pointer to a VkAttachmentReference specifying which attachment will be used for depth/stencil data and the layout it will be in during the subpass. Setting the attachment index to `VK_ATTACHMENT_UNUSED` or leaving this pointer as `NULL` indicates that no depth/stencil attachment will be used in the subpass.
- `preserveAttachmentCount` is the number of preserved attachments.
- `pPreserveAttachments` is an array of `preserveAttachmentCount` render pass attachment indices describing the attachments that are not used by a subpass, but whose contents **must** be preserved throughout 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 $\mathbf{S_1}$ that uses or preserves the attachment, and a subpass dependency from $\mathbf{S_1}$ 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 $\mathbf{S_1}$ if those subpasses use or preserve the attachment.

Valid Usage

- pipelineBindPoint **must** be VK_PIPELINE_BIND_POINT_GRAPHICS
- colorAttachmentCount **must** be less than or equal to VkPhysicalDeviceLimits ::maxColorAttachments
- 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
- 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
- If pResolveAttachments is not NULL, the sample count of each element of pColorAttachments **must** be anything other than VK_SAMPLE_COUNT_1_BIT
- Each element of pResolveAttachments **must** have a sample count of VK_SAMPLE_COUNT_1_BIT
- Each element of pResolveAttachments **must** have the same VkFormat as its corresponding color attachment
- All attachments in pColorAttachments that are not VK_ATTACHMENT_UNUSED **must** have the same sample count
- If pDepthStencilAttachment is not VK_ATTACHMENT_UNUSED and any attachments in pColorAttachments are not VK_ATTACHMENT_UNUSED, they **must** have the same sample count
- If any input attachments are VK_ATTACHMENT_UNUSED, then any pipelines bound during the subpass **must** not access those input attachments from the fragment shader
- The attachment member of 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 as both an input attachment and a color or depth/stencil attachment, then each use **must** use the same layout

Valid Usage (Implicit)

- `flags` **must** be a valid combination of VkSubpassDescriptionFlagBits values
- `pipelineBindPoint` **must** be a valid VkPipelineBindPoint value
- If `inputAttachmentCount` is not `0`, `pInputAttachments` **must** be a valid pointer to an array of `inputAttachmentCount` valid `VkAttachmentReference` structures
- If `colorAttachmentCount` is not `0`, `pColorAttachments` **must** be a valid pointer to an array of `colorAttachmentCount` valid `VkAttachmentReference` structures
- If `colorAttachmentCount` is not `0`, and `pResolveAttachments` is not `NULL`, `pResolveAttachments` **must** be a valid pointer to an array of `colorAttachmentCount` valid `VkAttachmentReference` structures
- If `pDepthStencilAttachment` is not `NULL`, `pDepthStencilAttachment` **must** be a valid pointer to a valid `VkAttachmentReference` structure
- 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:

```
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.

```
typedef VkFlags VkSubpassDescriptionFlags;
```

`VkSubpassDescriptionFlags` is a bitmask type for setting a mask of zero or more VkSubpassDescriptionFlagBits.

The `VkAttachmentReference` structure is defined as:

```
typedef struct VkAttachmentReference {
    uint32_t         attachment;
    VkImageLayout    layout;
} VkAttachmentReference;
```

- `attachment` is the index of the attachment of the render pass, and corresponds to the index of the corresponding element in the `pAttachments` array of the `VkRenderPassCreateInfo` structure. If any color or depth/stencil attachments are `VK_ATTACHMENT_UNUSED`, then no writes occur for those attachments.

- layout is a VkImageLayout value specifying the layout the attachment uses during the subpass.

Valid Usage

- layout **must** not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED

Valid Usage (Implicit)

- layout **must** be a valid VkImageLayout value

The VkSubpassDependency structure is defined as:

```
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 describes a subpass self-dependency, and only constrains the pipeline barriers allowed within a subpass instance. Otherwise, when a render pass instance which includes a subpass dependency is submitted to a queue, it defines a memory dependency between the subpasses identified by srcSubpass and dstSubpass.

If srcSubpass is equal to VK_SUBPASS_EXTERNAL, the first synchronization scope includes commands submitted to the queue before the render pass instance began. 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 submitted after the render pass instance is ended. Otherwise, the second set of commands includes all commands submitted as part of the subpass instance identified by dstSubpass and any load, store or 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 access 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 access 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/dstAccessMask parameters) submitted as a part of a vkCmdPipelineBarrier (with matching srcStageMask/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 an 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

- If srcSubpass is not VK_SUBPASS_EXTERNAL, srcStageMask **must** not include VK_PIPELINE_STAGE_HOST_BIT
- If dstSubpass is not VK_SUBPASS_EXTERNAL, dstStageMask **must** not include VK_PIPELINE_STAGE_HOST_BIT
- If the geometry shaders feature is not enabled, srcStageMask **must** not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the geometry shaders feature is not enabled, dstStageMask **must** not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the tessellation shaders feature is not enabled, srcStageMask **must** not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- If the tessellation shaders feature is not enabled, dstStageMask **must** not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- 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
- srcSubpass and dstSubpass **must** not both be equal to VK_SUBPASS_EXTERNAL
- If srcSubpass is equal to dstSubpass, srcStageMask and dstStageMask **must** only contain one of VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, 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_BOTTOM_OF_PIPE_BIT, or VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
- If srcSubpass is equal to dstSubpass and not all of the stages in srcStageMask and dstStageMask are framebuffer-space stages, the logically latest pipeline stage in srcStageMask **must** be logically earlier than or equal to the logically earliest pipeline stage in dstStageMask
- 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.

Valid Usage (Implicit)

- srcStageMask **must** be a valid combination of VkPipelineStageFlagBits values
- srcStageMask **must** not be 0
- dstStageMask **must** be a valid combination of VkPipelineStageFlagBits values
- dstStageMask **must** not be 0
- 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

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 subpass dependency operates as if defined with the following parameters:

```
VkSubpassDependency implicitDependency = {
    .srcSubpass = VK_SUBPASS_EXTERNAL;
    .dstSubpass = firstSubpass; // First subpass attachment is used in
    .srcStageMask = VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT;
    .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 subpass dependency operates as if defined with the following parameters:

```
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_BOTTOM_OF_PIPE_BIT;
    .srcAccessMask = 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;
    .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.

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` happens-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` happens-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 in different layouts, and both layouts are read-only, 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:

```
// Used for input attachments
VkPipelineStageFlags inputAttachmentStages = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
VkAccessFlags inputAttachmentAccess = 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 depthStencilAttachmentAccess =
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT;

VkSubpassDependency implicitDependency = {
    .srcSubpass = firstSubpass;
    .dstSubpass = secondSubpass;
    .srcStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .dstStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .srcAccessMask = inputAttachmentAccess | depthStencilAttachmentAccess;
    .dstAccessMask = inputAttachmentAccess | depthStencilAttachmentAccess;
    .dependencyFlags = 0;
};
```

If a subpass uses the same attachment as both an input attachment and either a color attachment or a depth/stencil attachment, writes via the color or depth/stencil attachment are not automatically made visible to reads via the input attachment, causing a *feedback loop*, except in any of the following conditions:

- If the color components or depth/stencil components read by the input attachment are mutually exclusive with the components written by the color or depth/stencil attachments, then there is no feedback loop. This requires the graphics pipelines used by the subpass to disable writes to color components that are read as inputs via the `colorWriteMask`, and to disable writes to depth/stencil components that are read as inputs via `depthWriteEnable` or `stencilTestEnable`.
- If the attachment is used as an input attachment and depth/stencil attachment only, and the depth/stencil attachment is not written to.
- If a memory dependency is inserted between when the attachment is written and when it is subsequently read by later fragments. Pipeline barriers expressing a subpass self-dependency are the only way to achieve this, and one **must** be inserted every time a fragment will read values at a particular sample (x, y, layer, sample) coordinate, if those values have been written since the most recent pipeline barrier; or the since start of the subpass if there have been no pipeline barriers since the start of the subpass.

An attachment used as both an input attachment and a color attachment **must** be in the `VK_IMAGE_LAYOUT_GENERAL` layout. An attachment used as an input attachment and depth/stencil attachment **must** be in the `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_GENERAL` layout. An attachment **must** not be used as both a depth/stencil attachment and a color attachment.

To destroy a render pass, call:

```
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

- All submitted commands that refer to `renderPass` **must** have completed execution
- If `VkAllocationCallbacks` were provided when `renderPass` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `renderPass` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `renderPass` is not VK_NULL_HANDLE, `renderPass` **must** be a valid `VkRenderPass` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `renderPass` is a valid handle, it **must** have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `renderPass` **must** be externally synchronized

7.2. 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

A framebuffer is compatible with a render pass if it was created using the same render pass or a compatible render pass.

7.3. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFramebuffer)
```

To create a framebuffer, call:

```
VkResult vkCreateFramebuffer(
    VkDevice                                    device,
    const VkFramebufferCreateInfo*              pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkFramebuffer*                              pFramebuffer);
```

- `device` is the logical device that creates the framebuffer.
- `pCreateInfo` points to a VkFramebufferCreateInfo structure which describes additional information about framebuffer creation.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pFramebuffer` points to a `VkFramebuffer` handle in which the resulting framebuffer object is returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkFramebufferCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pFramebuffer` **must** be a valid pointer to a `VkFramebuffer` handle

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkFramebufferCreateInfo structure is defined as:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- renderPass is a render pass that defines what render passes the framebuffer will be compatible with. See Render Pass Compatibility for details.
- attachmentCount is the number of attachments.
- pAttachments is an array of VkImageView handles, each of which will be used as the corresponding attachment in a render pass instance.
- width, height and layers define the dimensions of the framebuffer.

Applications **must** ensure that all accesses to memory that backs image subresources used as attachments in a given renderpass instance either happen-before the load operations for those attachments, or happen-after the store operations for those attachments.

Note

This restriction means that the render pass has full knowledge of all uses of all of the attachments, so that the implementation is able to make correct decisions about when and how to perform layout transitions, when to overlap execution of subpasses, etc.

It is legal for a subpass to use no color or depth/stencil attachments, and rather 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 a given zero-attachment subpass **must** have the same value for VkPipelineMultisampleStateCreateInfo ::rasterizationSamples.

Valid Usage

- attachmentCount **must** be equal to the attachment count specified in renderPass
- 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
- 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
- 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
- Each element of pAttachments **must** have been created with an VkFormat value that matches the VkFormat specified by the corresponding VkAttachmentDescription in renderPass
- Each element of pAttachments **must** have been created with a samples value that matches the samples value specified by the corresponding VkAttachmentDescription in renderPass
- Each element of pAttachments **must** have dimensions at least as large as the corresponding framebuffer dimension
- Each element of pAttachments **must** only specify a single mip level
- 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 VkPhysicalDeviceLimits::maxFramebufferWidth
- height **must** be greater than 0.
- height **must** be less than or equal to VkPhysicalDeviceLimits::maxFramebufferHeight
- layers **must** be greater than 0.
- layers **must** be less than or equal to VkPhysicalDeviceLimits::maxFramebufferLayers

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_FRAMEBUFFER_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- `renderPass` **must** be a valid `VkRenderPass` handle
- If `attachmentCount` is not `0`, `pAttachments` **must** be a valid pointer to an array of `attachmentCount` valid `VkImageView` handles
- Both of `renderPass`, and the elements of `pAttachments` that are valid handles **must** have been created, allocated, or retrieved from the same `VkDevice`

```
typedef VkFlags VkFramebufferCreateFlags;
```

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

To destroy a framebuffer, call:

```
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

- All submitted commands that refer to `framebuffer` **must** have completed execution
- If `VkAllocationCallbacks` were provided when `framebuffer` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `framebuffer` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `framebuffer` is not VK_NULL_HANDLE, `framebuffer` **must** be a valid `VkFramebuffer` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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

7.4. 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 (defined below) which indicates 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

- 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 subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin **must** have been created with VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT set
- 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_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin **must** have been created with VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT set
- 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 subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin **must** have been created with VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT set
- 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 subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin **must** have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT set
- 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 subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT set
- If any of the initialLayout members 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 and 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.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pRenderPassBegin` **must** be a valid pointer to a valid `VkRenderPassBeginInfo` structure
- `contents` **must** be a valid VkSubpassContents value
- `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
- `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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary	Outside	Graphics	Graphics

The `VkRenderPassBeginInfo` structure is defined as:

```
typedef struct VkRenderPassBeginInfo {
    VkStructureType        sType;
    const void*            pNext;
    VkRenderPass           renderPass;
    VkFramebuffer          framebuffer;
    VkRect2D               renderArea;
    uint32_t               clearValueCount;
    const VkClearValue*    pClearValues;
} VkRenderPassBeginInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 an array of VkClearValue structures that contains 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, otherwise the pixels outside of the render area become undefined and shader side effects **may** occur for fragments outside the render area. The render area **must** be contained within the framebuffer dimensions.

> *Note*
>
> There **may** be a performance cost for using a render area smaller than the framebuffer, unless it matches the render area granularity for the render pass.

Valid Usage

- clearValueCount **must** be greater than the largest attachment index in renderPass that specifies a loadOp (or stencilLoadOp, if the attachment has a depth/stencil format) of VK_ATTACHMENT_LOAD_OP_CLEAR
- If clearValueCount is not 0, pClearValues **must** be a valid pointer to an array of clearValueCount valid VkClearValue unions
- renderPass **must** be compatible with the renderPass member of the VkFramebufferCreateInfo structure specified when creating framebuffer.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO
- pNext **must** be NULL
- renderPass **must** be a valid VkRenderPass handle
- framebuffer **must** be a valid VkFramebuffer handle
- Both of framebuffer, and renderPass **must** have been created, allocated, or retrieved from the same VkDevice

Possible values of vkCmdBeginRenderPass::contents, specifying how the commands in the first subpass will be provided, are:

```c
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 on the command buffer until vkCmdNextSubpass or vkCmdEndRenderPass.

To query the render area granularity, call:

```c
void vkGetRenderAreaGranularity(
    VkDevice                                    device,
    VkRenderPass                                renderPass,
    VkExtent2D*                                 pGranularity);
```

- `device` is the logical device that owns the render pass.
- `renderPass` is a handle to a render pass.
- `pGranularity` points 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` of the returned VkExtent2D (the vertical granularity).
- either the `offset.width` member in `renderArea` is a multiple of the horizontal granularity or `offset.x`+`offset.width` is equal to the `width` of the `framebuffer` in the VkRenderPassBeginInfo.
- either the `offset.height` member in `renderArea` is a multiple of the vertical granularity or `offset.y`+`offset.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)

- `device` **must** be a valid `VkDevice` handle
- `renderPass` **must** be a valid `VkRenderPass` handle
- `pGranularity` **must** be a valid pointer to a `VkExtent2D` structure
- `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:

```
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.

Moving to the next subpass automatically performs any multisample resolve operations in the subpass being ended. End-of-subpass multisample resolves are treated as color attachment writes for the purposes of synchronization. That is, they are considered to execute in the `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT` pipeline stage and their writes are synchronized with `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`. Synchronization between rendering within a subpass and any resolve operations at the end of the subpass occurs automatically, without need for explicit dependencies or pipeline barriers. However, if the resolve attachment is also used in a different subpass, an explicit dependency is needed.

After transitioning to the next subpass, the application **can** record the commands for that subpass.

Valid Usage

- The current subpass index **must** be less than the number of subpasses in the render pass minus one

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `contents` **must** be a valid VkSubpassContents value
- `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
- `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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary	Inside	Graphics	Graphics

To record a command to end a render pass instance after recording the commands for the last subpass, call:

```
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

- The current subpass index **must** be equal to the number of subpasses in the render pass minus one

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `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
- `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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary	Inside	Graphics	Graphics

Chapter 8. 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 vertex processing 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 that describe 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.

8.1. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkShaderModule)
```

To create a shader module, call:

```
VkResult vkCreateShaderModule(
    VkDevice                                    device,
    const VkShaderModuleCreateInfo*             pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkShaderModule*                             pShaderModule);
```

- `device` is the logical device that creates the shader module.
- `pCreateInfo` parameter is a pointer to an instance of the `VkShaderModuleCreateInfo` structure.

- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pShaderModule points 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 (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkShaderModuleCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
typedef struct VkShaderModuleCreateInfo {
    VkStructureType              sType;
    const void*                  pNext;
    VkShaderModuleCreateFlags    flags;
    size_t                       codeSize;
    const uint32_t*              pCode;
} VkShaderModuleCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- codeSize is the size, in bytes, of the code pointed to by pCode.
- pCode points 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

- codeSize **must** be greater than 0
- codeSize **must** be a multiple of 4
- pCode **must** point to valid SPIR-V code, formatted and packed as described by the Khronos SPIR-V Specification
- pCode **must** adhere to the validation rules described by the Validation Rules within a Module section of the SPIR-V Environment appendix
- pCode **must** declare the Shader capability for SPIR-V code
- 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
- If pCode declares any of the capabilities that are listed as not required by the implementation, the relevant feature **must** be enabled, as listed in the SPIR-V Environment appendix

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- pCode **must** be a valid pointer to an array of $\frac{codeSize}{4}$ uint32_t values

```
typedef VkFlags VkShaderModuleCreateFlags;
```

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

To destroy a shader module, call:

```
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

- If VkAllocationCallbacks were provided when shaderModule was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when shaderModule was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If shaderModule is not VK_NULL_HANDLE, shaderModule **must** be a valid VkShaderModule handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

8.2. 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 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.

8.3. 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 order of invocations of the same shader type are 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 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.

Stores issued to different memory locations within a single shader invocation **may** not be visible to other invocations, or **may** not become visible in the order they were performed.

The `OpMemoryBarrier` instruction **can** be used to provide stronger ordering of reads and writes performed by a single invocation. `OpMemoryBarrier` guarantees that any memory transactions issued by the shader invocation prior to the instruction complete prior to the memory transactions issued after the instruction. Memory barriers are needed for algorithms that require multiple invocations to access the same memory and require the operations to be performed in a partially-defined relative order. For example, if one shader invocation does a series of writes, followed by an `OpMemoryBarrier` instruction, followed by another write, then the results of the series of writes before the barrier become visible to other shader invocations at a time earlier or equal to when the results of the final write become visible to those invocations. In practice it means that another invocation that sees the results of the final write would also see the previous writes. Without the memory barrier, the final write **may** be visible before the previous writes.

Writes that are the result of shader stores through a variable decorated with `Coherent` automatically have available writes to the same buffer, buffer view, or image view made visible to them, and are themselves automatically made available to access by the same buffer, buffer view, or image view. Reads that are the result of shader loads through a variable decorated with `Coherent` automatically have available writes to the same buffer, buffer view, or image view made visible to them. The order that coherent writes to different locations become available is undefined, unless enforced by a memory barrier instruction or other memory dependency.

> *Note*
>
> Explicit memory dependencies **must** still be used to guarantee availability and visibility for access via other buffers, buffer views, or image views.

The built-in atomic memory transaction instructions **can** be used to read and write a given memory address atomically. While built-in atomic functions issued by multiple shader invocations are executed in undefined order relative to each other, these functions perform both a read and a write of a memory address and guarantee that no other memory transaction will write to the underlying memory between the read and write. Atomic operations ensure automatic availability and visibility for writes and reads in the same way as those to `Coherent` variables.

> *Note*
>
> Memory accesses performed on different resource descriptors with the same memory backing **may** not be well-defined even with the `Coherent` decoration or via atomics, due to things such as image layouts or ownership of the resource - as described in the Synchronization and Cache Control chapter.

> *Note*
>
> Atomics allow shaders to use shared global addresses for mutual exclusion or as counters, among other uses.

8.4. 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.

8.5. 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.

8.5.1. Vertex Shader Execution

A vertex shader **must** be executed at least once for each vertex specified by a draw command. 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 draw 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`).

8.6. 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`.

8.6.1. Tessellation Control Shader Execution

A tessellation control shader is invoked at least once for each *output* vertex in a patch.

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 attribute 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.

8.7. 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.

8.7.1. Tessellation Evaluation Shader Execution

A tessellation evaluation shader is invoked at least once for each unique vertex generated by the tessellator.

8.8. 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.

8.8.1. 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. The number of geometry shader invocations per input primitive is determined from the invocation count of the geometry shader specified by the `OpExecutionMode Invocations` in the geometry shader. If the invocation count is not specified, then a default of one invocation is executed.

8.9. Fragment Shaders

Fragment shaders are invoked as the result of rasterization 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.

8.9.1. Fragment Shader Execution

For each fragment generated by rasterization, a fragment shader **may** be invoked. A fragment shader **must** not be invoked if the Early Per-Fragment Tests cause it to have no coverage.

Furthermore, if it is determined that a fragment generated as the result of rasterizing a first primitive will have its outputs entirely overwritten by a fragment generated as the result of rasterizing a second primitive in the same subpass, and the fragment shader used for the fragment has no other side effects, then the fragment shader **may** not be executed for the fragment from the first primitive.

Relative ordering of execution of different fragment shader invocations is not defined.

When a primitive (partially or fully) covers a pixel, the number of times the fragment shader is invoked is implementation-dependent, but **must** obey the following constraints:

- Each covered sample is included in a single fragment shader invocation.
- When sample shading is not enabled, there is at least one fragment shader invocation.
- When sample shading is enabled, the minimum number of fragment shader invocations is as defined in Sample Shading.

When there is more than one fragment shader invocation per pixel, the association of samples to invocations is implementation-dependent.

In addition to the conditions outlined above for the invocation of a fragment shader, a fragment shader invocation **may** be produced as a *helper invocation*. A helper invocation is a fragment shader invocation that is created solely for the purposes of evaluating derivatives for use in non-helper fragment shader invocations. Stores and atomics performed by helper invocations **must** not have any effect on memory, and values returned by atomic instructions in helper invocations are undefined.

8.9.2. Early Fragment Tests

An explicit control is provided to allow fragment shaders to enable early fragment tests. If the fragment shader specifies the `EarlyFragmentTests` `OpExecutionMode`, the per-fragment tests described in Early Fragment Test Mode are performed prior to fragment shader execution. Otherwise, they are performed after fragment shader execution.

8.10. 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` 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.

8.11. Interpolation Decorations

Interpolation decorations control the behavior of attribute interpolation in the fragment shader stage. Interpolation decorations **can** be applied to `Input` storage class variables in the fragment shader stage's interface, and control the interpolation behavior of those variables.

Inputs that could be interpolated **can** be decorated by at most one of the following decorations:

- `Flat`: no interpolation
- `NoPerspective`: linear interpolation (for lines and polygons).

Fragment input variables decorated with neither `Flat` nor `NoPerspective` use perspective-correct interpolation (for lines and polygons).

The presence of and type of interpolation is controlled by the above interpolation decorations as well as the auxiliary decorations `Centroid` and `Sample`.

A variable decorated with `Flat` will not be interpolated. Instead, it will have the same value for every fragment within a triangle. This value will come from a single provoking vertex. A variable decorated with `Flat` **can** also be decorated with `Centroid` or `Sample`, which will mean the same thing as decorating it only as `Flat`.

For fragment shader input variables decorated with neither `Centroid` nor `Sample`, the assigned variable **may** be interpolated anywhere within the pixel and a single value **may** be assigned to each sample within the pixel.

`Centroid` and `Sample` **can** be used to control the location and frequency of the sampling of the decorated fragment shader input. If a fragment shader input is decorated with `Centroid`, a single value **may** be assigned to that variable for all samples in the pixel, but that value **must** be interpolated to a location that lies in both the pixel and in the primitive being rendered, including any of the pixel's samples covered by the primitive. Because the location at which the variable is interpolated **may** be different in neighboring pixels, and derivatives **may** be computed by computing differences between neighboring pixels, derivatives of centroid-sampled inputs **may** be less accurate than those for non-centroid interpolated variables. If a fragment shader input is decorated with `Sample`, a separate value **must** be assigned to that variable for each covered sample in the pixel, and that value **must** be sampled at the location of the individual sample. When `rasterizationSamples` is `VK_SAMPLE_COUNT_1_BIT`, the pixel center **must** be used for `Centroid`, `Sample`, and undecorated attribute interpolation.

Fragment shader inputs that are signed or unsigned integers, integer vectors, or any double-precision floating-point type **must** be decorated with `Flat`.

8.12. 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 that contains a memory instruction or image instruction with `x` as an `id` operand. See the "Memory Instructions" and "Image Instructions" subsections of section 3 "Binary Form" of the SPIR-V specification for the complete list of SPIR-V memory instructions.

Static use is not used to control the behavior of variables with `Input` and `Output` storage. The effects of those variables are applied based only on whether they are present in a shader entry point's interface.

8.13. Invocation and Derivative Groups

An *invocation group* (see the subsection "Control Flow" of section 2 of the SPIR-V specification) for a compute shader is the set of invocations in a single local workgroup. For graphics shaders, an invocation group is an implementation-dependent subset of the set of shader invocations of a given shader stage which are produced by a single drawing command. For indirect drawing commands with `drawCount` greater than one, invocations from separate draws are in distinct invocation groups.

> *Note*
>
> Because the partitioning of invocations into invocation groups is implementation-dependent and not observable, applications generally need to assume the worst case of all invocations in a draw belonging to a single invocation group.

A *derivative group* (see the subsection "Control Flow" of section 2 of the SPIR-V 1.00 Revision 4 specification) for a fragment shader is the set of invocations generated by a single primitive (point, line, or triangle), including any helper invocations generated by that primitive. Derivatives are undefined for a sampled image instruction if the instruction is in flow control that is not uniform across the derivative group.

Chapter 9. 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 framebuffer addresses and values using a two-dimensional description of a point, line segment, or triangle. Each *fragment* so produced is fed to the next stage (Fragment Shader) that performs operations on individual fragments before they finally alter the framebuffer. These operations include conditional updates into the framebuffer based on incoming and previously stored depth values (to effect depth buffering), blending of incoming fragment colors with stored colors, as well as masking, stenciling, and other logical operations on fragment values.

Framebuffer operations 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.

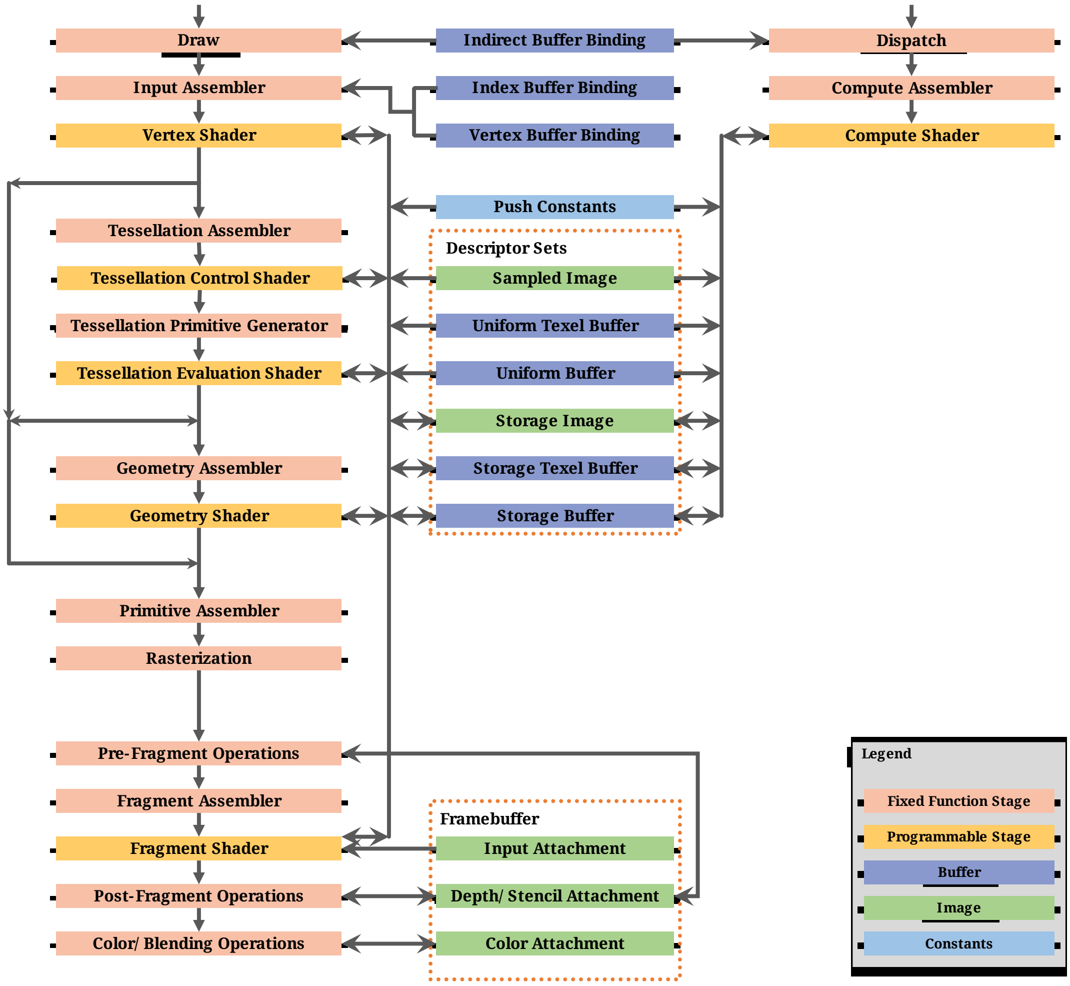

Figure 1. Block diagram of the Vulkan pipeline

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 device state in command buffers. Any pipeline object state that is marked as dynamic is not applied to the device state when the pipeline is bound. Dynamic state not set by binding the pipeline object **can** be modified at any time and persists for the lifetime of the command buffer, or until modified by another dynamic state command or another pipeline bind. No state, including dynamic state, is inherited from one command buffer to another. Only dynamic state that is **required** for the operations performed in the command buffer needs to be set. For example, if blending is disabled by the pipeline state then the dynamic color blend constants do not need to be specified in the command buffer, even if this state is marked as dynamic in the pipeline state object. If a new pipeline object is bound with state not marked as dynamic after a previous pipeline object with that same state as dynamic, the new pipeline object state will override the dynamic state. Modifying dynamic state that is not set as dynamic by the pipeline state object will lead to undefined results.

Compute and graphics pipelines are each represented by `VkPipeline` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipeline)
```

9.1. 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:

```
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 an array of `VkComputePipelineCreateInfo` structures.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pPipelines` is a pointer to an array in which the resulting compute pipeline objects are returned.

Valid Usage

- 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
- 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

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If pipelineCache is not VK_NULL_HANDLE, pipelineCache **must** be a valid VkPipelineCache handle
- 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:

```
typedef struct VkComputePipelineCreateInfo {
    VkStructureType                    sType;
    const void*                        pNext;
    VkPipelineCreateFlags              flags;
    VkPipelineShaderStageCreateInfo    stage;
    VkPipelineLayout                   layout;
    VkPipeline                         basePipelineHandle;
    int32_t                            basePipelineIndex;
} VkComputePipelineCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is a bitmask of VkPipelineCreateFlagBits specifying how the pipeline will be generated.
- `stage` is a VkPipelineShaderStageCreateInfo 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.

`stage` points to a structure of type `VkPipelineShaderStageCreateInfo`.

Valid Usage

- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineIndex is -1, basePipelineHandle **must** be a valid handle to a compute VkPipeline
- 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
- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineIndex is not -1, basePipelineHandle **must** be VK_NULL_HANDLE
- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineHandle is not VK_NULL_HANDLE, basePipelineIndex **must** be -1
- The stage member of stage **must** be VK_SHADER_STAGE_COMPUTE_BIT
- 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
- layout **must** be consistent with the layout of the compute shader specified in stage
- The number of resources in layout accessible to the compute shader stage **must** be less than or equal to VkPhysicalDeviceLimits::maxPerStageResources

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkPipelineCreateFlagBits values
- stage **must** be a valid VkPipelineShaderStageCreateInfo structure
- layout **must** be a valid VkPipelineLayout handle
- Both of basePipelineHandle, and layout that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

The VkPipelineShaderStageCreateInfo structure is defined as:

```
typedef struct VkPipelineShaderStageCreateInfo {
    VkStructureType                     sType;
    const void*                         pNext;
    VkPipelineShaderStageCreateFlags    flags;
    VkShaderStageFlagBits               stage;
    VkShaderModule                      module;
    const char*                         pName;
    const VkSpecializationInfo*         pSpecializationInfo;
} VkPipelineShaderStageCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- stage is a VkShaderStageFlagBits value specifying a single pipeline stage.
- module is a VkShaderModule object that contains the shader 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 VkSpecializationInfo, as described in Specialization Constants, and **can** be NULL.

Valid Usage

- If the geometry shaders feature is not enabled, stage **must** not be VK_SHADER_STAGE_GEOMETRY_BIT
- If the tessellation shaders feature is not enabled, stage **must** not be VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT or VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT
- stage **must** not be VK_SHADER_STAGE_ALL_GRAPHICS, or VK_SHADER_STAGE_ALL
- pName **must** be the name of an OpEntryPoint in module with an execution model that matches stage
- 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
- 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
- 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
- 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
- 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
- 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 that specifies a patch size with OutputVertices, the patch size **must** be greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize
- If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point **must** have an OpExecutionMode instruction that specifies a maximum output vertex count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryOutputVertices
- If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point **must** have an OpExecutionMode instruction that specifies an invocation count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryShaderInvocations
- If stage is 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
- If stage is 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
- If stage is VK_SHADER_STAGE_FRAGMENT_BIT, the identified entry point **must** not include any output variables in its interface decorated with CullDistance

- If stage is VK_SHADER_STAGE_FRAGMENT_BIT, and the identified entry point writes to FragDepth in any execution path, it **must** write to FragDepth in all execution paths

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- stage **must** be a valid VkShaderStageFlagBits value
- module **must** be a valid VkShaderModule handle
- pName **must** be a null-terminated UTF-8 string
- If pSpecializationInfo is not NULL, pSpecializationInfo **must** be a valid pointer to a valid VkSpecializationInfo structure

```
typedef VkFlags VkPipelineShaderStageCreateFlags;
```

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

Commands and structures which need to specify one or more shader stages do so using a bitmask whose bits correspond to stages. Bits which **can** be set to specify shader stages are:

```
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,
    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.

```
typedef VkFlags VkShaderStageFlags;
```

VkShaderStageFlags is a bitmask type for setting a mask of zero or more VkShaderStageFlagBits.

9.2. Graphics Pipelines

Graphics pipelines consist of multiple shader stages, multiple fixed-function pipeline stages, and a pipeline layout.

To create graphics pipelines, call:

```
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 an array of VkGraphicsPipelineCreateInfo structures.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pPipelines is a pointer to an array in which the resulting graphics pipeline objects are returned.

The VkGraphicsPipelineCreateInfo structure includes an array of shader create info structures containing all the desired active shader stages, as well as creation info to define all relevant fixed-function stages, and a pipeline layout.

Valid Usage

- 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
- 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

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If pipelineCache is not VK_NULL_HANDLE, pipelineCache **must** be a valid VkPipelineCache handle
- pCreateInfos **must** be a valid pointer to an array of createInfoCount valid VkGraphicsPipelineCreateInfo 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 VkGraphicsPipelineCreateInfo structure is defined as:

```
typedef struct VkGraphicsPipelineCreateInfo {
    VkStructureType                                  sType;
    const void*                                      pNext;
    VkPipelineCreateFlags                            flags;
    uint32_t                                         stageCount;
    const VkPipelineShaderStageCreateInfo*           pStages;
    const VkPipelineVertexInputStateCreateInfo*      pVertexInputState;
    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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 an array of size `stageCount` structures of type VkPipelineShaderStageCreateInfo describing the set of the shader stages to be included in the graphics pipeline.
- `pVertexInputState` is a pointer to an instance of the VkPipelineVertexInputStateCreateInfo structure.
- `pInputAssemblyState` is a pointer to an instance of the VkPipelineInputAssemblyStateCreateInfo structure which determines input assembly behavior, as described in Drawing Commands.
- `pTessellationState` is a pointer to an instance of the VkPipelineTessellationStateCreateInfo structure, and is ignored if the pipeline does not include a tessellation control shader stage and tessellation evaluation shader stage.
- `pViewportState` is a pointer to an instance of the VkPipelineViewportStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled.
- `pRasterizationState` is a pointer to an instance of the VkPipelineRasterizationStateCreateInfo structure.
- `pMultisampleState` is a pointer to an instance of the VkPipelineMultisampleStateCreateInfo, and is ignored if the pipeline has rasterization disabled.
- `pDepthStencilState` is a pointer to an instance of the VkPipelineDepthStencilStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled or if the subpass of the render pass the pipeline is created against does not use a depth/stencil attachment.

- `pColorBlendState` is a pointer to an instance of the VkPipelineColorBlendStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled or if the subpass of the render pass the pipeline is created against does not use any color attachments.
- `pDynamicState` is a pointer to VkPipelineDynamicStateCreateInfo and is used to indicate 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 an instance of any render pass 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.

`pStages` points to an array of VkPipelineShaderStageCreateInfo structures, which were previously described in Compute Pipelines.

`pDynamicState` points to a structure of type VkPipelineDynamicStateCreateInfo.

Valid Usage

- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineIndex` is -1, `basePipelineHandle` **must** be a valid handle to a graphics `VkPipeline`
- 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
- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineIndex` is not -1, `basePipelineHandle` **must** be VK_NULL_HANDLE
- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineHandle` is not VK_NULL_HANDLE, `basePipelineIndex` **must** be -1
- The `stage` member of each element of `pStages` **must** be unique
- The `stage` member of one element of `pStages` **must** be `VK_SHADER_STAGE_VERTEX_BIT`
- The `stage` member of each element of `pStages` **must** not be `VK_SHADER_STAGE_COMPUTE_BIT`
- If `pStages` includes a tessellation control shader stage, it **must** include a tessellation evaluation shader stage
- If `pStages` includes a tessellation evaluation shader stage, it **must** include a tessellation control shader stage
- If `pStages` includes a tessellation control shader stage and a tessellation evaluation shader stage, `pTessellationState` **must** be a valid pointer to a valid `VkPipelineTessellationStateCreateInfo` structure
- If `pStages` includes tessellation shader stages, the shader code of at least one stage **must** contain an `OpExecutionMode` instruction that specifies the type of subdivision in the pipeline
- If `pStages` includes tessellation shader stages, and the shader code of both stages contain an `OpExecutionMode` instruction that specifies the type of subdivision in the pipeline, they **must** both specify the same subdivision mode
- If `pStages` includes tessellation shader stages, the shader code of at least one stage **must** contain an `OpExecutionMode` instruction that specifies the output patch size in the pipeline
- If `pStages` includes tessellation shader stages, and the shader code of both contain an `OpExecutionMode` instruction that specifies the out patch size in the pipeline, they **must** both specify the same patch size
- If `pStages` includes tessellation shader stages, the `topology` member of `pInputAssembly` **must** be `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`
- If the `topology` member of `pInputAssembly` is `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`, `pStages` **must** include tessellation shader stages
- If `pStages` includes a geometry shader stage, and does not include any tessellation shader stages, its shader code **must** contain an `OpExecutionMode` instruction that specifies an input primitive type that is compatible with the primitive topology specified in `pInputAssembly`
- If `pStages` includes a geometry shader stage, and also includes tessellation shader stages, its shader code **must** contain an `OpExecutionMode` instruction that specifies an input

primitive type that is compatible with the primitive topology that is output by the tessellation stages

- If pStages includes a fragment shader stage and a geometry shader stage, 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
- If pStages includes a fragment shader stage, its shader code **must** not read from any input attachment that is defined as VK_ATTACHMENT_UNUSED in subpass
- The shader code for the entry points identified by pStages, and the rest of the state identified by this structure **must** adhere to the pipeline linking rules described in the Shader Interfaces chapter
- If rasterization is not disabled and subpass uses a depth/stencil attachment in renderPass that has a layout of VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL in the VkAttachmentReference defined by subpass, the depthWriteEnable member of pDepthStencilState **must** be VK_FALSE
- If rasterization is not disabled and subpass uses a depth/stencil attachment in renderPass that has a layout of VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL in the VkAttachmentReference defined by subpass, the failOp, passOp and depthFailOp members of each of the front and back members of pDepthStencilState **must** be VK_STENCIL_OP_KEEP
- If rasterization is not disabled and the subpass uses color attachments, then for each color attachment in the subpass the blendEnable member of the corresponding element of the pAttachment member of pColorBlendState **must** be VK_FALSE if the format of the attachment does not support color blend operations, as specified by the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT flag in VkFormatProperties ::linearTilingFeatures or VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties
- If rasterization is not disabled and the subpass uses color attachments, the attachmentCount member of pColorBlendState **must** be equal to the colorAttachmentCount used to create subpass
- If no element of the pDynamicStates member of pDynamicState is VK_DYNAMIC_STATE_VIEWPORT, the pViewports member of pViewportState **must** be a valid pointer to an array of pViewportState::viewportCount VkViewport structures
- If no element of the pDynamicStates member of pDynamicState is VK_DYNAMIC_STATE_SCISSOR, the pScissors member of pViewportState **must** be a valid pointer to an array of pViewportState::scissorCount VkRect2D structures
- If the wide lines feature is not enabled, and no element of the pDynamicStates member of pDynamicState is VK_DYNAMIC_STATE_LINE_WIDTH, the lineWidth member of pRasterizationState **must** be 1.0
- If the rasterizerDiscardEnable member of pRasterizationState is VK_FALSE, pViewportState **must** be a valid pointer to a valid VkPipelineViewportStateCreateInfo structure
- If the rasterizerDiscardEnable member of pRasterizationState is VK_FALSE, pMultisampleState **must** be a valid pointer to a valid VkPipelineMultisampleStateCreateInfo structure

- If the rasterizerDiscardEnable member of pRasterizationState is VK_FALSE, and subpass uses a depth/stencil attachment, pDepthStencilState **must** be a valid pointer to a valid VkPipelineDepthStencilStateCreateInfo structure
- If the rasterizerDiscardEnable member of pRasterizationState is VK_FALSE, and subpass uses color attachments, pColorBlendState **must** be a valid pointer to a valid VkPipelineColorBlendStateCreateInfo structure
- If the depth bias clamping 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
- If 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
- layout **must** be consistent with all shaders specified in pStages
- If subpass uses color and/or depth/stencil attachments, then the rasterizationSamples member of pMultisampleState **must** be the same as the sample count for those subpass attachments
- If 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
- subpass **must** be a valid subpass within renderPass
- 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkPipelineCreateFlagBits values
- pStages **must** be a valid pointer to an array of stageCount valid VkPipelineShaderStageCreateInfo structures
- pVertexInputState **must** be a valid pointer to a valid VkPipelineVertexInputStateCreateInfo structure
- pInputAssemblyState **must** be a valid pointer to a valid VkPipelineInputAssemblyStateCreateInfo structure
- pRasterizationState **must** be a valid pointer to a valid VkPipelineRasterizationStateCreateInfo structure
- If pDynamicState is not NULL, pDynamicState **must** be a valid pointer to a valid VkPipelineDynamicStateCreateInfo structure
- layout **must** be a valid VkPipelineLayout handle
- renderPass **must** be a valid VkRenderPass handle
- stageCount **must** be greater than 0
- Each of basePipelineHandle, layout, and renderPass that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

Possible values of the flags member of VkGraphicsPipelineCreateInfo and VkComputePipelineCreateInfo, specifying how a pipeline is created, are:

```
typedef enum VkPipelineCreateFlagBits {
    VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT = 0x00000001,
    VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT = 0x00000002,
    VK_PIPELINE_CREATE_DERIVATIVE_BIT = 0x00000004,
} 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 call to vkCreateGraphicsPipelines or vkCreateComputePipelines.
- VK_PIPELINE_CREATE_DERIVATIVE_BIT specifies that the pipeline to be created will be a child of a previously created parent pipeline.

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.

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- dynamicStateCount is the number of elements in the pDynamicStates array.
- pDynamicStates is 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 info.

Valid Usage

- Each element of pDynamicStates **must** be unique

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- pDynamicStates **must** be a valid pointer to an array of dynamicStateCount valid VkDynamicState values
- dynamicStateCount **must** be greater than 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:

```
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,
} VkDynamicState;
```

- `VK_DYNAMIC_STATE_VIEWPORT` specifies that the `pViewports` state in `VkPipelineViewportStateCreateInfo` will be ignored and **must** be set dynamically with vkCmdSetViewport before any draw 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 draw 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 draw 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 `depthBiasEnable` in `VkPipelineRasterizationStateCreateInfo` set to `VK_TRUE`.
- `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

9.2.1. 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, the results of fragment processing are undefined. Specifically, any fragment color outputs are considered to have undefined values, and the fragment depth is considered to be unmodified. 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

9.3. Pipeline destruction

To destroy a graphics or compute pipeline, call:

```
void vkDestroyPipeline(
    VkDevice                                    device,
    VkPipeline                                  pipeline,
    const VkAllocationCallbacks*                pAllocator);
```

- `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

- All submitted commands that refer to `pipeline` **must** have completed execution
- If `VkAllocationCallbacks` were provided when `pipeline` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `pipeline` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `pipeline` is not VK_NULL_HANDLE, `pipeline` **must** be a valid `VkPipeline` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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

9.4. 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 encouraged 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 (for example, due to out of memory errors), the `vkCreate*Pipelines` commands will return an error code. The implementation will attempt to create all pipelines, and only return VK_NULL_HANDLE values for those that actually failed.

9.5. 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 Vk*PipelineCreateInfo structure. If this is set, then exactly one of basePipelineHandle or basePipelineIndex members of the structure **must** have a valid handle/index, and indicates 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.

9.6. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineCache)
```

To create pipeline cache objects, call:

```
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 that contains the 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 `pAllocator`. 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.

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 `vkCreateGraphicsPipelines` and `vkCreateComputePipelines` commands.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkPipelineCacheCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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
typedef struct VkPipelineCacheCreateInfo {
    VkStructureType               sType;
    const void*                   pNext;
    VkPipelineCacheCreateFlags    flags;
    size_t                        initialDataSize;
    const void*                   pInitialData;
} VkPipelineCacheCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `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

- If `initialDataSize` is not `0`, it **must** be equal to the size of `pInitialData`, as returned by `vkGetPipelineCacheData` when `pInitialData` was originally retrieved
- If `initialDataSize` is not `0`, `pInitialData` **must** have been retrieved from a previous call to `vkGetPipelineCacheData`

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_PIPELINE_CACHE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- If `initialDataSize` is not `0`, `pInitialData` **must** be a valid pointer to an array of `initialDataSize` bytes

```c
typedef VkFlags VkPipelineCacheCreateFlags;
```

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

Pipeline cache objects **can** be merged using the command:

```
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 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

- `dstCache` **must** not appear in the list of source caches

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `dstCache` **must** be a valid `VkPipelineCache` handle
- `pSrcCaches` **must** be a valid pointer to an array of `srcCacheCount` valid `VkPipelineCache` handles
- `srcCacheCount` **must** be greater than `0`
- `dstCache` **must** have been created, allocated, or retrieved from `device`
- 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

Data **can** be retrieved from a pipeline cache object using the command:

```
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 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 vkGetPipelineCacheData will return VK_INCOMPLETE. 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.

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 initial bytes written to pData **must** be a header consisting of the following members:

Table 7. Layout for pipeline cache header version VK_PIPELINE_CACHE_HEADER_VERSION_ONE

Offset	Size	Meaning
0	4	length in bytes of the entire pipeline cache header written as a stream of bytes, with the least significant byte first
4	4	a VkPipelineCacheHeaderVersion value written as a stream of bytes, with the least significant byte first
8	4	a vendor ID equal to `VkPhysicalDeviceProperties::vendorID` written as a stream of bytes, with the least significant byte first
12	4	a device ID equal to `VkPhysicalDeviceProperties::deviceID` written as a stream of bytes, with the least significant byte first
16	`VK_UUID_SIZE`	a pipeline cache ID equal to `VkPhysicalDeviceProperties::pipelineCacheUUID`

The first four bytes encode the length of the entire pipeline cache header, in bytes. This value includes all fields in the header including the pipeline cache version field and the size of the length field.

The next four bytes encode the pipeline cache version, as described for VkPipelineCacheHeaderVersion. A consumer of the pipeline cache **should** use the cache version to interpret the remainder of the cache header.

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)

- `device` **must** be a valid `VkDevice` handle
- `pipelineCache` **must** be a valid `VkPipelineCache` handle
- `pDataSize` **must** be a valid pointer to a `size_t` value
- 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
- `pipelineCache` **must** have been created, allocated, or retrieved from `device`

Return Codes

Success

- `VK_SUCCESS`
- `VK_INCOMPLETE`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Possible values of the second group of four bytes in the header returned by vkGetPipelineCacheData, encoding the pipeline cache version, are:

```
typedef enum VkPipelineCacheHeaderVersion {
    VK_PIPELINE_CACHE_HEADER_VERSION_ONE = 1,
} VkPipelineCacheHeaderVersion;
```

- VK_PIPELINE_CACHE_HEADER_VERSION_ONE specifies version one of the pipeline cache.

To destroy a pipeline cache, call:

```
void vkDestroyPipelineCache(
    VkDevice                                    device,
    VkPipelineCache                             pipelineCache,
    const VkAllocationCallbacks*                pAllocator);
```

- device is the logical device that destroys the pipeline cache object.
- pipelineCache is the handle of the pipeline cache to destroy.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- If VkAllocationCallbacks were provided when pipelineCache was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when pipelineCache was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If pipelineCache is not VK_NULL_HANDLE, pipelineCache **must** be a valid VkPipelineCache handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

9.7. 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 instance of the `VkPipelineShaderStageCreateInfo` structure contains a parameter `pSpecializationInfo`, which **can** be `NULL` to indicate no specialization constants, or point to a `VkSpecializationInfo` structure.

The `VkSpecializationInfo` structure is defined as:

```
typedef struct VkSpecializationInfo {
    uint32_t                           mapEntryCount;
    const VkSpecializationMapEntry*    pMapEntries;
    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` which maps constant IDs to offsets in `pData`.
- `dataSize` is the byte size of the `pData` buffer.
- `pData` contains the actual constant values to specialize with.

`pMapEntries` points to a structure of type VkSpecializationMapEntry.

Valid Usage

- The `offset` member of each element of `pMapEntries` **must** be less than `dataSize`
- The `size` member of each element of `pMapEntries` **must** be less than or equal to `dataSize` minus `offset`
- If `mapEntryCount` is not `0`, `pMapEntries` **must** be a valid pointer to an array of `mapEntryCount` valid `VkSpecializationMapEntry` structures

Valid Usage (Implicit)

- If `dataSize` is not `0`, `pData` **must** be a valid pointer to an array of `dataSize` bytes

The VkSpecializationMapEntry structure is defined as:

```
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

- 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:

```
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 %wgsize BuiltIn WorkgroupSize ; decorate WorkgroupSize onto constant
%i32 = OpTypeInt 32 0 ; declare an unsigned 32-bit type
%uvec3 = OpTypeVector %i32 3 ; declare a 3 element vector type of unsigned 32-bit
%x = OpSpecConstant %i32 1 ; declare the .x component of WorkgroupSize
%y = OpSpecConstant %i32 1 ; declare the .y component of WorkgroupSize
%z = OpSpecConstant %i32 1 ; declare the .z component of WorkgroupSize
%wgsize = 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:

```
const VkSpecializationMapEntry entries[] =
{
    {
        13,                             // constantID
        0 * sizeof(uint32_t),           // offset
        sizeof(uint32_t)                // size
    },
    {
        42,                             // constantID
        1 * sizeof(uint32_t),           // offset
        sizeof(uint32_t)                // size
    },
    {
        3,                              // constantID
        2 * sizeof(uint32_t),           // offset
        sizeof(uint32_t)                // size
    }
};

const uint32_t data[] = { 16, 8, 4 }; // our workgroup size is 16x8x4

const VkSpecializationInfo info =
{
    3,                                  // mapEntryCount
    entries,                            // pMapEntries
    3 * sizeof(uint32_t),               // dataSize
    data,                               // pData
};
```

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:

```
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
%float = OpTypeFloat 32 ; declare a 32-bit floating-point type
%1 = OpSpecConstant %i32 -1 ; some signed 32-bit integer constant
%2 = OpSpecConstant %float 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.

Now to specialize the above via the specialization constants mechanism:

```
struct SpecializationData {
    int32_t data0;
    float data1;
};

const VkSpecializationMapEntry entries[] =
{
    {
        0,                                  // constantID
        offsetof(SpecializationData, data0),  // offset
        sizeof(SpecializationData::data0)     // size
    },
    {
        12,                                 // constantID
        offsetof(SpecializationData, data1),  // offset
        sizeof(SpecializationData::data1)     // size
    }
};

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 =
{
    2,                                  // mapEntryCount
    entries,                            // pMapEntries
    sizeof(data),                       // dataSize
    &data,                              // pData
};
```

It is legal for a SPIR-V module with specializations to be compiled into a pipeline where no specialization info 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.

9.8. Pipeline Binding

Once a pipeline has been created, it **can** be bound to the command buffer using the command:

```
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 whether to bind to the compute or graphics bind point. Binding one does not disturb the other.
- `pipeline` is the pipeline to be bound.

Once bound, a pipeline binding affects subsequent graphics or compute commands in the command buffer until a different pipeline is bound to the bind point. The pipeline bound to `VK_PIPELINE_BIND_POINT_COMPUTE` controls the behavior of vkCmdDispatch and vkCmdDispatchIndirect. The pipeline bound to `VK_PIPELINE_BIND_POINT_GRAPHICS` controls the behavior of all drawing commands. No other commands are affected by the pipeline state.

Valid Usage

- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, the `VkCommandPool` that `commandBuffer` was allocated from **must** support compute operations
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, the `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, `pipeline` **must** be a compute pipeline
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, `pipeline` **must** be a graphics pipeline
- If the variable multisample rate feature is not supported, `pipeline` is a graphics pipeline, the current subpass has 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)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pipelineBindPoint` **must** be a valid VkPipelineBindPoint value
- `pipeline` **must** be a valid `VkPipeline` handle
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

Possible values of vkCmdBindPipeline::`pipelineBindPoint`, specifying the bind point of a pipeline object, are:

```
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.

Chapter 10. Memory Allocation

Vulkan memory is broken up into two categories, *host memory* and *device memory*.

10.1. Host Memory

Host memory is memory needed by the Vulkan implementation for non-device-visible storage. This storage **may** be used for e.g. internal software structures.

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:

```
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 pointer to an application-defined memory allocation function of type PFN_vkAllocationFunction.
- `pfnReallocation` is a pointer to an application-defined memory reallocation function of type PFN_vkReallocationFunction.
- `pfnFree` is a pointer to an application-defined memory free function of type PFN_vkFreeFunction.
- `pfnInternalAllocation` is a pointer to an application-defined function that is called by the implementation when the implementation makes internal allocations, and it is of type PFN_vkInternalAllocationNotification.
- `pfnInternalFree` is a pointer to an application-defined function that is called by the implementation when the implementation frees internal allocations, and it is of type PFN_vkInternalFreeNotification.

Valid Usage

- pfnAllocation **must** be a valid pointer to a valid user-defined PFN_vkAllocationFunction
- pfnReallocation **must** be a valid pointer to a valid user-defined PFN_vkReallocationFunction
- pfnFree **must** be a valid pointer to a valid user-defined PFN_vkFreeFunction
- If either of pfnInternalAllocation or pfnInternalFree is not NULL, both **must** be valid callbacks

The type of pfnAllocation is:

```
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 run-time 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:

```
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 the same 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.

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 pfnAllocation or pfnReallocation. The application **should** free this memory.

The type of pfnInternalAllocation 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 pfnInternalFree 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* which defines 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:

```
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 an object of type `VkPipelineCache`, 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 `VkDevice` or `VkInstance`, the allocator will use an allocation scope of `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 `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 `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 *internal allocations* are allocated and freed. Upon allocation of executable memory, `pfnInternalAllocation` will be called. Upon freeing executable memory, `pfnInternalFree` will be called. An implementation will only call an informational callback for executable memory allocations and frees.

The `allocationType` parameter to the `pfnInternalAllocation` and `pfnInternalFree` functions **may** be one of the following values:

```
typedef enum VkInternalAllocationType {
    VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE = 0,
} VkInternalAllocationType;
```

* `VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE` specifies that the allocation is intended for execution by the host.

An implementation **must** only make calls into an application-provided allocator during the execution of an API command. An implementation **must** only make calls into an application-provided allocator from the same thread that called the provoking API command. The implementation **should** not synchronize calls to any of the callbacks. If synchronization is needed, the callbacks **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 an `VkAllocationCallbacks` structure between the time a `vkCreate*` command returns and the time a corresponding `vkDestroy*` command begins, that implementation **must** save a copy of the allocator before the `vkCreate*` command returns. The callback functions and any data structures they rely upon **must** remain valid for the lifetime of the object they are associated with.

If an allocator is provided to a `vkCreate*` command, a *compatible* allocator **must** be provided to the corresponding `vkDestroy*` command. Two `VkAllocationCallbacks` structures are compatible if memory allocated with `pfnAllocation` or `pfnReallocation` in each **can** be freed with `pfnReallocation` or `pfnFree` in the other. An allocator **must** not be provided to a `vkDestroy*` command if an allocator was not provided to the corresponding `vkCreate*` command.

If a non-`NULL` allocator is used, the `pfnAllocation`, `pfnReallocation` and `pfnFree` members **must** be non-`NULL` and point to valid implementations of the callbacks. An application **can** choose to not provide informational callbacks by setting both `pfnInternalAllocation` and `pfnInternalFree` to `NULL`. `pfnInternalAllocation` and `pfnInternalFree` **must** either both be `NULL` or both be non-`NULL`.

If pfnAllocation or pfnReallocation fail, the implementation **may** fail object creation and/or generate an VK_ERROR_OUT_OF_HOST_MEMORY error, as appropriate.

Allocation callbacks **must** not call any Vulkan commands.

The following sets of rules define when an implementation is permitted to call the allocator callbacks.

pfnAllocation or pfnReallocation **may** be called in the following situations:

- Allocations scoped to a VkDevice or VkInstance **may** be allocated from any API command.
- Allocations scoped to a command **may** be allocated from any API command.
- Allocations scoped to a VkPipelineCache **may** only be allocated from:
  - vkCreatePipelineCache
  - vkMergePipelineCaches for dstCache
  - vkCreateGraphicsPipelines for pipelineCache
  - vkCreateComputePipelines for pipelineCache
- Allocations scoped to a VkDescriptorPool **may** only be allocated from:
  - any command that takes the pool as a direct argument
  - vkAllocateDescriptorSets for the descriptorPool member of its pAllocateInfo parameter
  - vkCreateDescriptorPool
- Allocations scoped to a VkCommandPool **may** only be allocated from:
  - any command that takes the pool as a direct argument
  - vkCreateCommandPool
  - vkAllocateCommandBuffers for the commandPool member of its pAllocateInfo parameter
  - any vkCmd* command whose commandBuffer was allocated from that VkCommandPool
- Allocations scoped to any other object **may** only be allocated in that object's vkCreate* command.

pfnFree **may** be called in the following situations:

- Allocations scoped to a VkDevice or VkInstance **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.

10.2. 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.

Memory properties of a physical device describe the memory heaps and memory types available.

To query memory properties, call:

```
void vkGetPhysicalDeviceMemoryProperties(
    VkPhysicalDevice                            physicalDevice,
    VkPhysicalDeviceMemoryProperties*           pMemoryProperties);
```

* `physicalDevice` is the handle to the device to query.
* `pMemoryProperties` points to an instance of `VkPhysicalDeviceMemoryProperties` structure in which the properties are returned.

Valid Usage (Implicit)

* `physicalDevice` **must** be a valid `VkPhysicalDevice` handle
* `pMemoryProperties` **must** be a valid pointer to a `VkPhysicalDeviceMemoryProperties` structure

The `VkPhysicalDeviceMemoryProperties` structure is defined as:

```
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 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 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` | `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` | `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` | `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` | `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` | `VK_MEMORY_PROPERTY_HOST_CACHED_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` | `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` | `VK_MEMORY_PROPERTY_HOST_CACHED_BIT` | `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` | `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_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:

* either 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 the required 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 the required order.

This ordering requirement enables applications to use a simple search loop to select the desired memory type along the lines of:

```
// 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);
```

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,
} VkMemoryHeapFlagBits;
```

* VK_MEMORY_HEAP_DEVICE_LOCAL_BIT indicates 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.

```
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 heap, 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,
} VkMemoryPropertyFlagBits;
```

* VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT bit indicates 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 indicates that memory allocated with this type **can** be mapped for host access using vkMapMemory.
* VK_MEMORY_PROPERTY_HOST_COHERENT_BIT bit indicates 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 indicates 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 indicates 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.

```
typedef VkFlags VkMemoryPropertyFlags;
```

VkMemoryPropertyFlags is a bitmask type for setting a mask of zero or more VkMemoryPropertyFlagBits.

A Vulkan device operates on data in device memory via memory objects that are represented in the API by a VkDeviceMemory handle:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDeviceMemory)
```

To allocate memory objects, call:

```
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 an instance of the VkMemoryAllocateInfo structure describing parameters of the allocation. A successful 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.

The maximum number of valid memory allocations that **can** exist simultaneously within a VkDevice **may** be restricted by implementation- or platform-dependent limits. If a call to vkAllocateMemory would cause the total number of allocations to exceed these limits, such a call will fail and **must** return `VK_ERROR_TOO_MANY_OBJECTS`. The `maxMemoryAllocationCount` feature describes the number of allocations that **can** exist simultaneously before encountering these internal limits.

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

- `pAllocateInfo`\->`allocationSize` **must** be less than or equal to VkPhysicalDeviceMemoryProperties::`memoryHeaps`[`pAllocateInfo`\->`memoryTypeIndex`].`size` as returned by vkGetPhysicalDeviceMemoryProperties for the VkPhysicalDevice that `device` was created from.
- `pAllocateInfo`\->`memoryTypeIndex` **must** be less than VkPhysicalDeviceMemoryProperties ::`memoryTypeCount` as returned by vkGetPhysicalDeviceMemoryProperties for the VkPhysicalDevice that `device` was created from.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `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_TOO_MANY_OBJECTS`

The `VkMemoryAllocateInfo` structure is defined as:

```
typedef struct VkMemoryAllocateInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkDeviceSize       allocationSize;
    uint32_t           memoryTypeIndex;
} VkMemoryAllocateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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

Valid Usage

- `allocationSize` **must** be greater than `0`

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO`
- `pNext` **must** be `NULL`

To free a memory object, call:

```
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*. The memory **can** remain bound to images or buffers at the time the memory object is freed, but any further use of them (on host or device) for anything other than destroying those objects will result in undefined behavior. If there are still any bound images or buffers, the memory **may** not be immediately released by the implementation, but **must** be released by the time all bound images and buffers have been destroyed. Once memory is 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

- All submitted commands that refer to `memory` (via images or buffers) **must** have completed execution

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `memory` is not VK_NULL_HANDLE, `memory` **must** be a valid `VkDeviceMemory` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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

10.2.1. Host Access to Device Memory Objects

Memory objects created with 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:

```
VkResult vkMapMemory(
    VkDevice                                    device,
    VkDeviceMemory                              memory,
    VkDeviceSize                                offset,
    VkDeviceSize                                size,
    VkMemoryMapFlags                            flags,
    void**                                      ppData);
```

- device is the logical device that owns the memory.
- memory is the VkDeviceMemory object to be mapped.
- offset is a zero-based byte offset from the beginning of the memory object.
- size is the size of the memory range to map, or VK_WHOLE_SIZE to map from offset to the end of the allocation.
- flags is reserved for future use.
- ppData points to a pointer in which is returned a host-accessible pointer to the beginning of the mapped range. This pointer minus offset **must** be aligned to at least VkPhysicalDeviceLimits ::minMemoryMapAlignment.

It is an application error to call vkMapMemory on a memory object that is already 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 mapped for host access, 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

- memory **must** not be currently mapped
- offset **must** be less than the size of memory
- If size is not equal to VK_WHOLE_SIZE, size **must** be greater than 0
- If size is not equal to VK_WHOLE_SIZE, size **must** be less than or equal to the size of the memory minus offset
- memory **must** have been created with a memory type that reports VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- memory **must** be a valid VkDeviceMemory handle
- flags **must** be 0
- ppData **must** be a valid pointer to a pointer value
- 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

```
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.

To flush ranges of non-coherent memory from the host caches, call:

```
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 **can** be made available to device access, via availability operations from the VK_ACCESS_HOST_WRITE_BIT access type.

Unmapping non-coherent memory does not implicitly flush the 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)

- device **must** be a valid VkDevice handle
- pMemoryRanges **must** be a valid pointer to an array of memoryRangeCount valid VkMappedMemoryRange structures
- 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:

```
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 visible to 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.

> *Note*
>
> Mapping non-coherent memory does not implicitly invalidate the mapped memory, and device writes that have not been invalidated **must** be made visible before the host reads or overwrites them.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pMemoryRanges **must** be a valid pointer to an array of memoryRangeCount valid VkMappedMemoryRange structures
- 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:

```
typedef struct VkMappedMemoryRange {
    VkStructureType    sType;
    const void*        pNext;
    VkDeviceMemory     memory;
    VkDeviceSize       offset;
    VkDeviceSize       size;
} VkMappedMemoryRange;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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

- memory **must** be currently mapped
- If size is not equal to VK_WHOLE_SIZE, offset and size **must** specify a range contained within the currently mapped range of memory
- If size is equal to VK_WHOLE_SIZE, offset **must** be within the currently mapped range of memory
- If size is equal to VK_WHOLE_SIZE, the end of the current mapping of memory **must** be a multiple of VkPhysicalDeviceLimits::nonCoherentAtomSize bytes from the beginning of the memory object.
- offset **must** be a multiple of VkPhysicalDeviceLimits::nonCoherentAtomSize
- 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)

- sType **must** be VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE
- pNext **must** be NULL
- memory **must** be a valid VkDeviceMemory handle

To unmap a memory object once host access to it is no longer needed by the application, call:

```
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

- memory **must** be currently mapped

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- memory **must** be a valid VkDeviceMemory handle
- memory **must** have been created, allocated, or retrieved from device

Host Synchronization

- Host access to memory **must** be externally synchronized

10.2.2. 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:

```
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 **may** be out of date.

The implementation guarantees to allocate any committed memory from the heapIndex indicated by the memory type that the memory object was created with.

Valid Usage

- `memory` **must** have been created with a memory type that reports `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `memory` **must** be a valid `VkDeviceMemory` handle
- `pCommittedMemoryInBytes` **must** be a valid pointer to a `VkDeviceSize` value
- `memory` **must** have been created, allocated, or retrieved from `device`

Chapter 11. Resource Creation

Vulkan supports two primary resource types: *buffers* and *images*. Resources are views of memory with associated formatting and dimensionality. Buffers are essentially unformatted arrays of bytes whereas images contain format information, **can** be multidimensional and **may** have associated metadata.

11.1. 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 via certain commands, or by directly specifying them as parameters to certain commands.

Buffers are represented by `VkBuffer` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBuffer)
```

To create buffers, call:

```
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 an instance of the `VkBufferCreateInfo` structure containing parameters affecting creation of the buffer.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pBuffer` points to a `VkBuffer` handle in which the resulting buffer object is returned.

Valid Usage

- 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)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkBufferCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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 list of queue families that will access this buffer (ignored if sharingMode is not VK_SHARING_MODE_CONCURRENT).

Valid Usage

- size **must** be greater than 0
- If sharingMode is VK_SHARING_MODE_CONCURRENT, pQueueFamilyIndices **must** be a valid pointer to an array of queueFamilyIndexCount uint32_t values
- If sharingMode is VK_SHARING_MODE_CONCURRENT, queueFamilyIndexCount **must** be greater than 1
- If sharingMode is VK_SHARING_MODE_CONCURRENT, each element of pQueueFamilyIndices **must** be unique and **must** be less than pQueueFamilyPropertyCount returned by vkGetPhysicalDeviceQueueFamilyProperties for the physicalDevice that was used to create device
- If the sparse bindings feature is not enabled, flags **must** not contain VK_BUFFER_CREATE_SPARSE_BINDING_BIT
- If the sparse buffer residency feature is not enabled, flags **must** not contain VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse aliased residency feature is not enabled, flags **must** not contain VK_BUFFER_CREATE_SPARSE_ALIASED_BIT
- 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkBufferCreateFlagBits values
- usage **must** be a valid combination of VkBufferUsageFlagBits values
- usage **must** not be 0
- sharingMode **must** be a valid VkSharingMode value

Bits which **can** be set in VkBufferCreateInfo::usage, specifying usage behavior of a buffer, are:

```
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,
} VkBufferUsageFlagBits;
```

- VK_BUFFER_USAGE_TRANSFER_SRC_BIT specifies that the buffer **can** be used as the source of a *transfer command* (see the definition of VK_PIPELINE_STAGE_TRANSFER_BIT).
- VK_BUFFER_USAGE_TRANSFER_DST_BIT specifies that the buffer **can** be used as the destination of a transfer command.
- VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT 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.
- VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT 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.
- VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT 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.
- VK_BUFFER_USAGE_STORAGE_BUFFER_BIT 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.
- VK_BUFFER_USAGE_INDEX_BUFFER_BIT specifies that the buffer is suitable for passing as the buffer parameter to vkCmdBindIndexBuffer.
- VK_BUFFER_USAGE_VERTEX_BUFFER_BIT specifies that the buffer is suitable for passing as an element of the pBuffers array to vkCmdBindVertexBuffers.
- VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT specifies that the buffer is suitable for passing as the buffer parameter to vkCmdDrawIndirect, vkCmdDrawIndexedIndirect, or vkCmdDispatchIndirect.

```
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:

```c
typedef enum VkBufferCreateFlagBits {
    VK_BUFFER_CREATE_SPARSE_BINDING_BIT = 0x00000001,
    VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
    VK_BUFFER_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
} VkBufferCreateFlagBits;
```

- `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.

See Sparse Resource Features and Physical Device Features for details of the sparse memory features supported on a device.

```c
typedef VkFlags VkBufferCreateFlags;
```

`VkBufferCreateFlags` is a bitmask type for setting a mask of zero or more VkBufferCreateFlagBits.

To destroy a buffer, call:

```c
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

- All submitted commands that refer to `buffer`, either directly or via a `VkBufferView`, **must** have completed execution
- If `VkAllocationCallbacks` were provided when `buffer` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `buffer` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If buffer is not VK_NULL_HANDLE, buffer **must** be a valid VkBuffer handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

11.2. 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 interpreted as formatted data. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBufferView)
```

To create a buffer view, call:

```
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 an instance of the VkBufferViewCreateInfo structure containing parameters to be used to create the buffer.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pView points to a VkBufferView handle in which the resulting buffer view object is returned.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkBufferViewCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
typedef struct VkBufferViewCreateInfo {
    VkStructureType            sType;
    const void*                pNext;
    VkBufferViewCreateFlags    flags;
    VkBuffer                   buffer;
    VkFormat                   format;
    VkDeviceSize               offset;
    VkDeviceSize               range;
} VkBufferViewCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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 element size of format, then the nearest smaller multiple is used.

Valid Usage

- offset **must** be less than the size of buffer
- offset **must** be a multiple of VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment
- If range is not equal to VK_WHOLE_SIZE, range **must** be greater than 0
- If range is not equal to VK_WHOLE_SIZE, range **must** be a multiple of the element size of format
- If range is not equal to VK_WHOLE_SIZE, range divided by the element size of format **must** be less than or equal to VkPhysicalDeviceLimits::maxTexelBufferElements
- 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
- 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
- If buffer was created with usage containing VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT, format **must** be supported for uniform texel buffers, as specified by the VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT flag in VkFormatProperties::bufferFeatures returned by vkGetPhysicalDeviceFormatProperties
- If buffer was created with usage containing VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT, format **must** be supported for storage texel buffers, as specified by the VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT flag in VkFormatProperties::bufferFeatures returned by vkGetPhysicalDeviceFormatProperties
- If buffer is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_BUFFER_VIEW_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- buffer **must** be a valid VkBuffer handle
- format **must** be a valid VkFormat value

```
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:

```
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

- All submitted commands that refer to bufferView **must** have completed execution
- If VkAllocationCallbacks were provided when bufferView was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when bufferView was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If bufferView is not VK_NULL_HANDLE, bufferView **must** be a valid VkBufferView handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

11.3. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImage)
```

To create images, call:

```
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 an instance of the `VkImageCreateInfo` structure containing parameters to be used to create the image.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pImage` points to a `VkImage` handle in which the resulting image object is returned.

Valid Usage

- 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)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkImageCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 data elements 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 the number of sub-data element samples in the image as defined in VkSampleCountFlagBits. See Multisampling.
- `tiling` is a VkImageTiling value specifying the tiling arrangement of the data elements 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 list of queue families that will access this image (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

Implementations **may** support additional limits and capabilities beyond those listed above.

To query an implementation's specific capabilities for a given combination of format, imageType, tiling, usage, and flags, call vkGetPhysicalDeviceImageFormatProperties. The return value indicates whether that combination of image settings is supported. On success, the VkImageFormatProperties output parameter indicates the set of valid samples bits and the limits for extent, mipLevels, and arrayLayers.

To determine the set of valid usage bits for a given format, call vkGetPhysicalDeviceFormatProperties.

Valid Usage

- The combination of format, imageType, tiling, usage, and flags **must** be supported, as indicated by a VK_SUCCESS return value from vkGetPhysicalDeviceImageFormatProperties invoked with the same values passed to the corresponding parameters.
- If sharingMode is VK_SHARING_MODE_CONCURRENT, pQueueFamilyIndices **must** be a valid pointer to an array of queueFamilyIndexCount uint32_t values
- If sharingMode is VK_SHARING_MODE_CONCURRENT, queueFamilyIndexCount **must** be greater than 1
- If sharingMode is VK_SHARING_MODE_CONCURRENT, each element of pQueueFamilyIndices **must** be unique and **must** be less than pQueueFamilyPropertyCount returned by vkGetPhysicalDeviceQueueFamilyProperties for the physicalDevice that was used to create device
- format **must** not be VK_FORMAT_UNDEFINED
- extent::width **must** be greater than 0.
- extent::height **must** be greater than 0.
- extent::depth **must** be greater than 0.
- mipLevels **must** be greater than 0
- arrayLayers **must** be greater than 0
- If flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, imageType **must** be VK_IMAGE_TYPE_2D
- If imageType is VK_IMAGE_TYPE_1D, extent.width **must** be less than or equal to VkPhysicalDeviceLimits::maxImageDimension1D, or VkImageFormatProperties::maxExtent.width (as returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure) - whichever is higher
- If imageType is VK_IMAGE_TYPE_2D and flags does not contain VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, extent.width and extent.height **must** be less than or equal to VkPhysicalDeviceLimits::maxImageDimension2D, or VkImageFormatProperties ::maxExtent.width/height (as returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure) - whichever is higher
- If imageType is VK_IMAGE_TYPE_2D and flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, extent.width and extent.height **must** be less than or equal to VkPhysicalDeviceLimits ::maxImageDimensionCube, or VkImageFormatProperties::maxExtent.width/height (as returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure) - whichever is higher
- If imageType is VK_IMAGE_TYPE_2D and flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, extent.width and extent.height **must** be equal and arrayLayers **must** be greater than or equal to 6
- If imageType is VK_IMAGE_TYPE_3D, extent.width, extent.height and extent.depth **must** be less than or equal to VkPhysicalDeviceLimits::maxImageDimension3D, or VkImageFormatProperties ::maxExtent.width/height/depth (as returned by vkGetPhysicalDeviceImageFormatProperties

with format, imageType, tiling, usage, and flags equal to those in this structure) - whichever is higher

- If imageType is VK_IMAGE_TYPE_1D, both extent.height and extent.depth **must** be 1
- If imageType is VK_IMAGE_TYPE_2D, extent.depth **must** be 1
- mipLevels **must** be less than or equal to $\lfloor \log_2(\max($extent.width, extent.height, extent.depth$)) \rfloor + 1$.
- mipLevels **must** be less than or equal to VkImageFormatProperties::maxMipLevels (as returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure)
- arrayLayers **must** be less than or equal to VkImageFormatProperties::maxArrayLayers (as returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure)
- If imageType is VK_IMAGE_TYPE_3D, arrayLayers **must** be 1.
- If samples is not VK_SAMPLE_COUNT_1_BIT, imageType **must** be VK_IMAGE_TYPE_2D, flags **must** not contain VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, tiling **must** be VK_IMAGE_TILING_OPTIMAL, and mipLevels **must** be equal to 1
- 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
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT, extent.width **must** be less than or equal to VkPhysicalDeviceLimits::maxFramebufferWidth
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT, extent.height **must** be less than or equal to VkPhysicalDeviceLimits::maxFramebufferHeight
- 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.
- samples **must** be a bit value that is set in VkImageFormatProperties::sampleCounts returned by vkGetPhysicalDeviceImageFormatProperties with format, imageType, tiling, usage, and flags equal to those in this structure
- If the multisampled storage images feature is not enabled, and usage contains VK_IMAGE_USAGE_STORAGE_BIT, samples **must** be VK_SAMPLE_COUNT_1_BIT
- If the sparse bindings feature is not enabled, flags **must** not contain VK_IMAGE_CREATE_SPARSE_BINDING_BIT
- If imageType is VK_IMAGE_TYPE_1D, flags **must** not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for 2D images feature is not enabled, and imageType is VK_IMAGE_TYPE_2D, flags **must** not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for 3D images feature is not enabled, and imageType is

VK_IMAGE_TYPE_3D, flags **must** not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT

- If the sparse residency for images with 2 samples 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
- If the sparse residency for images with 4 samples 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
- If the sparse residency for images with 8 samples 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
- If the sparse residency for images with 16 samples 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
- If tiling is VK_IMAGE_TILING_LINEAR, format **must** be a format that has at least one supported feature bit present in the value of VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If tiling is VK_IMAGE_TILING_LINEAR, and VkFormatProperties::linearTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, usage **must** not contain VK_IMAGE_USAGE_SAMPLED_BIT
- If tiling is VK_IMAGE_TILING_LINEAR, and VkFormatProperties::linearTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT, usage **must** not contain VK_IMAGE_USAGE_STORAGE_BIT
- If tiling is VK_IMAGE_TILING_LINEAR, and VkFormatProperties::linearTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT, usage **must** not contain VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
- If tiling is VK_IMAGE_TILING_LINEAR, and VkFormatProperties::linearTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT, usage **must** not contain VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
- If tiling is VK_IMAGE_TILING_OPTIMAL, format **must** be a format that has at least one supported feature bit present in the value of VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If tiling is VK_IMAGE_TILING_OPTIMAL, and VkFormatProperties::optimalTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, usage **must** not contain VK_IMAGE_USAGE_SAMPLED_BIT
- If tiling is VK_IMAGE_TILING_OPTIMAL, and VkFormatProperties::optimalTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT, usage **must** not contain VK_IMAGE_USAGE_STORAGE_BIT
- If tiling is VK_IMAGE_TILING_OPTIMAL, and VkFormatProperties::optimalTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not

include VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT, usage **must** not contain VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT

- If tiling is VK_IMAGE_TILING_OPTIMAL, and VkFormatProperties::optimalTilingFeatures (as returned by vkGetPhysicalDeviceFormatProperties with the same value of format) does not include VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT, usage **must** not contain VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
- 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
- initialLayout **must** be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkImageCreateFlagBits values
- imageType **must** be a valid VkImageType value
- format **must** be a valid VkFormat value
- samples **must** be a valid VkSampleCountFlagBits value
- tiling **must** be a valid VkImageTiling value
- usage **must** be a valid combination of VkImageUsageFlagBits values
- usage **must** not be 0
- sharingMode **must** be a valid VkSharingMode value
- initialLayout **must** be a valid VkImageLayout value

Bits which **can** be set in VkImageCreateInfo::usage, specifying intended usage of an image, are:

```
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 attachment in a VkFramebuffer.
- VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT specifies that the memory bound to this image will have been allocated with the VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT (see Memory Allocation for more detail). 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.

```
typedef VkFlags VkImageUsageFlags;
```

VkImageUsageFlags is a bitmask type for setting a mask of zero or more VkImageUsageFlagBits.

Bits which **can** be set in VkImageCreateInfo::flags, specifying additional parameters of an image, are:

```
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,
} VkImageCreateFlagBits;
```

- 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.
- 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.

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.

See Sparse Resource Features and Sparse Physical Device Features for more details.

```
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:

```
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 data elements in an image, are:

```
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 optimal 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 host access layout of an image subresource, for an image created with linear tiling, call:

```
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 for the image subresource.
- pLayout points to a VkSubresourceLayout structure in which the layout is returned.

vkGetImageSubresourceLayout is invariant for the lifetime of a single image.

Valid Usage

- image **must** have been created with tiling equal to VK_IMAGE_TILING_LINEAR
- The aspectMask member of pSubresource **must** only have a single bit set
- The mipLevel member of pSubresource **must** be less than the mipLevels specified in VkImageCreateInfo when image was created
- The arrayLayer member of pSubresource **must** be less than the arrayLayers specified in VkImageCreateInfo when image was created

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- image **must** be a valid VkImage handle
- pSubresource **must** be a valid pointer to a valid VkImageSubresource structure
- pLayout **must** be a valid pointer to a VkSubresourceLayout structure
- image **must** have been created, allocated, or retrieved from device

The VkImageSubresource structure is defined as:

```
typedef struct VkImageSubresource {
    VkImageAspectFlags    aspectMask;
    uint32_t              mipLevel;
    uint32_t              arrayLayer;
} VkImageSubresource;
```

- aspectMask is a VkImageAspectFlags selecting the image *aspect*.

* `mipLevel` selects the mipmap level.
* `arrayLayer` selects the array layer.

Valid Usage (Implicit)

* `aspectMask` **must** be a valid combination of VkImageAspectFlagBits values
* `aspectMask` **must** not be `0`

Information about the layout of the image subresource is returned in a `VkSubresourceLayout` structure:

```
typedef struct VkSubresourceLayout {
    VkDeviceSize    offset;
    VkDeviceSize    size;
    VkDeviceSize    rowPitch;
    VkDeviceSize    arrayPitch;
    VkDeviceSize    depthPitch;
} VkSubresourceLayout;
```

* `offset` is the byte offset from the start of the image 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.

For images created with linear tiling, `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:

```
// (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.

```
// (x,y,z,layer) are in compressed texel block coordinates
address(x,y,z,layer) = layer*arrayPitch + z*depthPitch + y*rowPitch + x
*compressedTexelBlockByteSize + offset;
```

arrayPitch is undefined for images that were not created as arrays. depthPitch is defined only for 3D images.

For color formats, the aspectMask member of VkImageSubresource **must** be VK_IMAGE_ASPECT_COLOR_BIT. For depth/stencil formats, 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.

To destroy an image, call:

```
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

- All submitted commands that refer to image, either directly or via a VkImageView, **must** have completed execution
- If VkAllocationCallbacks were provided when image was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when image was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If image is not VK_NULL_HANDLE, image **must** be a valid VkImage handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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

11.4. 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). The image layout is per-image subresource, and separate image subresources of the same image **can** be in different layouts at the same time with one exception - depth and stencil aspects of a given image subresource **must** always be in the same layout.

> *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 images created with VK_IMAGE_TILING_LINEAR tiling 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
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,
} VkImageLayout;
```

The type(s) of device access supported by each layout are:

- `VK_IMAGE_LAYOUT_UNDEFINED` does not support device access. This layout **must** only be used as the `initialLayout` member of `VkImageCreateInfo` or `VkAttachmentDescription`, or as the `oldLayout` in an image transition. When transitioning out of this layout, the contents of the memory are not guaranteed to be preserved.
- `VK_IMAGE_LAYOUT_PREINITIALIZED` does not support device access. This layout **must** only be used as the `initialLayout` member of `VkImageCreateInfo` or `VkAttachmentDescription`, or as the `oldLayout` in an image transition. When transitioning out of this layout, the contents of the memory are preserved. 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 `VK_IMAGE_TILING_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_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` **must** only be used as a depth/stencil attachment in a `VkFramebuffer`. This layout is valid only for image subresources of images created with the `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` usage bit enabled.
- `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` **must** only be used as a read-only depth/stencil attachment in a `VkFramebuffer` and/or as a read-only image in a shader (which **can** be read as a sampled image, combined image/sampler and/or input attachment). This layout is valid only for image subresources of images created with the `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` usage bit enabled. Only image subresources of images created with `VK_IMAGE_USAGE_SAMPLED_BIT` **can** be used as a sampled image or combined image/sampler in a shader. Similarly, only image subresources of images created with `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` **can** be used as input attachments.
- `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL` **must** only be used as a read-only image in a shader (which **can** be read as a sampled image, combined image/sampler and/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 bit 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.

For each mechanism of accessing an image in the API, there is a parameter or structure member that controls the image layout used to access the image. 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). 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 the layout specified via the API controlling those accesses.

The image layout of each image subresource **must** be well-defined at each point in the image subresource's lifetime. This means that when performing a layout transition on the 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.

11.5. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImageView)
```

The types of image views that **can** be created are:

```
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;
```

The exact image view type is partially implicit, based on the image's type and sample count, as well as the view creation parameters as described in the image view compatibility table for vkCreateImageView. This table also shows which SPIR-V OpTypeImage Dim and Arrayed parameters correspond to each image view type.

To create an image view, call:

```
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 an instance of the 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 points to a VkImageView handle in which the resulting image view object is returned.

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 remaining parameters are contained in the pCreateInfo.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkImageViewCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- pView **must** be a valid pointer to a VkImageView handle

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkImageViewCreateInfo structure is defined as:

```
typedef struct VkImageViewCreateInfo {
    VkStructureType            sType;
    const void*                pNext;
    VkImageViewCreateFlags     flags;
    VkImage                    image;
    VkImageViewType            viewType;
    VkFormat                   format;
    VkComponentMapping         components;
    VkImageSubresourceRange    subresourceRange;
} VkImageViewCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `image` is a `VkImage` on which the view will be created.
- `viewType` is an VkImageViewType value specifying the type of the image view.
- `format` is a VkFormat describing the format and type used to interpret data elements in the image.
- `components` is a VkComponentMapping specifies a remapping of color components (or of depth or stencil components after they have been converted into color components).
- `subresourceRange` is a VkImageSubresourceRange selecting the set of mipmap levels and array layers to be accessible to the view.

If `image` was created with the `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` flag, `format` **can** be different from the image's format, but if 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.

> *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.

Table 8. Image and image view parameter compatibility requirements

Dim, Arrayed, MS	Image parameters	View parameters
	imageType = ci.imageType width = ci.extent.width height = ci.extent.height depth = ci.extent.depth arrayLayers = ci.arrayLayers samples = ci.samples flags = ci.flags where ci is the VkImageCreateInfo used to create image.	baseArrayLayer and layerCount are members of the subresourceRange member.
1D, 0, 0	imageType = VK_IMAGE_TYPE_1D width ≥ 1 height = 1 depth = 1 arrayLayers ≥ 1 samples = 1	viewType = VK_IMAGE_VIEW_TYPE_1D baseArrayLayer ≥ 0 layerCount = 1
1D, 1, 0	imageType = VK_IMAGE_TYPE_1D width ≥ 1 height = 1 depth = 1 arrayLayers ≥ 1 samples = 1	viewType = VK_IMAGE_VIEW_TYPE_1D_ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1
2D, 0, 0	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples = 1	viewType = VK_IMAGE_VIEW_TYPE_2D baseArrayLayer ≥ 0 layerCount = 1
2D, 1, 0	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples = 1	viewType = VK_IMAGE_VIEW_TYPE_2D_ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1
2D, 0, 1	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples > 1	viewType = VK_IMAGE_VIEW_TYPE_2D baseArrayLayer ≥ 0 layerCount = 1
2D, 1, 1	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples > 1	viewType = VK_IMAGE_VIEW_TYPE_2D_ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1

Dim, Arrayed, MS	Image parameters	View parameters
CUBE, 0, 0	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height = width depth = 1 arrayLayers ≥ 6 samples = 1 flags includes VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT	viewType = VK_IMAGE_VIEW_TYPE_CUBE baseArrayLayer ≥ 0 layerCount = 6
CUBE, 1, 0	imageType = VK_IMAGE_TYPE_2D width ≥ 1 height = width depth = 1 $N \geq 1$ arrayLayers ≥ $6 \times N$ samples = 1 flags includes VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT	viewType = VK_IMAGE_VIEW_TYPE_CUBE_ARRAY baseArrayLayer ≥ 0 layerCount = $6 \times N$, $N \geq 1$
3D, 0, 0	imageType = VK_IMAGE_TYPE_3D width ≥ 1 height ≥ 1 depth ≥ 1 arrayLayers = 1 samples = 1	viewType = VK_IMAGE_VIEW_TYPE_3D baseArrayLayer = 0 layerCount = 1

Valid Usage

- 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
- If the image cubemap arrays feature is not enabled, viewType **must** not be VK_IMAGE_VIEW_TYPE_CUBE_ARRAY
- If image was created with VK_IMAGE_TILING_LINEAR, format **must** be format that has at least one supported feature bit present in the value of VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- image **must** have been created with a usage value containing at least one of VK_IMAGE_USAGE_SAMPLED_BIT, VK_IMAGE_USAGE_STORAGE_BIT, VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
- If image was created with VK_IMAGE_TILING_LINEAR and usage contains VK_IMAGE_USAGE_SAMPLED_BIT, format **must** be supported for sampled images, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT flag in VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_LINEAR and usage contains VK_IMAGE_USAGE_STORAGE_BIT, format **must** be supported for storage images, as specified by the VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT flag in VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_LINEAR and usage contains VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, format **must** be supported for color attachments, as specified by the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag in VkFormatProperties ::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_LINEAR and usage contains VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, format **must** be supported for depth/stencil attachments, as specified by the VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT flag in VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_OPTIMAL, format **must** be format that has at least one supported feature bit present in the value of VkFormatProperties ::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_OPTIMAL and usage contains VK_IMAGE_USAGE_SAMPLED_BIT, format **must** be supported for sampled images, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_OPTIMAL and usage contains VK_IMAGE_USAGE_STORAGE_BIT, format **must** be supported for storage images, as specified by the VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format

- If image was created with VK_IMAGE_TILING_OPTIMAL and usage contains VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, format **must** be supported for color attachments, as specified by the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag in VkFormatProperties ::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- If image was created with VK_IMAGE_TILING_OPTIMAL and usage contains VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, format **must** be supported for depth/stencil attachments, as specified by the VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties with the same value of format
- 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
- 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 was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, format **must** be compatible with the format used to create image, as defined in Format Compatibility Classes
- If image was not created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, format **must** be identical to the format used to create image
- If image is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- subresourceRange and viewType **must** be compatible with the image, as described in the compatibility table

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- image **must** be a valid VkImage handle
- viewType **must** be a valid VkImageViewType value
- format **must** be a valid VkFormat value
- components **must** be a valid VkComponentMapping structure
- subresourceRange **must** be a valid VkImageSubresourceRange structure

```
typedef VkFlags VkImageViewCreateFlags;
```

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

The VkImageSubresourceRange structure is defined as:

```
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, behavior when indexing the last cube is undefined.

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. 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 using an imageView 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 and selects whether the imageView 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 imageView 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.

The components member is of type VkComponentMapping, and describes a remapping from components of the image to components of the vector returned by shader image instructions. This remapping **must** be identity for storage image descriptors, input attachment descriptors, and framebuffer attachments.

Valid Usage

- If levelCount is not VK_REMAINING_MIP_LEVELS, it **must** be greater than 0
- If layerCount is not VK_REMAINING_ARRAY_LAYERS, it **must** be greater than 0

Valid Usage (Implicit)

- aspectMask **must** be a valid combination of VkImageAspectFlagBits values
- aspectMask **must** not be 0

Bits which **can** be set in an aspect mask to specify aspects of an image for purposes such as identifying a subresource, are:

```
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,
} VkImageAspectFlagBits;
```

- 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 sparse resource operations.

```
typedef VkFlags VkImageAspectFlags;
```

VkImageAspectFlags is a bitmask type for setting a mask of zero or more VkImageAspectFlagBits.

The VkComponentMapping structure is defined as:

```c
typedef struct VkComponentMapping {
    VkComponentSwizzle    r;
    VkComponentSwizzle    g;
    VkComponentSwizzle    b;
    VkComponentSwizzle    a;
} VkComponentMapping;
```

- r is a VkComponentSwizzle specifying the component value placed in the R component of the output vector.
- g is a VkComponentSwizzle specifying the component value placed in the G component of the output vector.
- b is a VkComponentSwizzle specifying the component value placed in the B component of the output vector.
- a is a VkComponentSwizzle specifying the component value placed in the A component of the output vector.

Valid Usage (Implicit)

- r **must** be a valid VkComponentSwizzle value
- g **must** be a valid VkComponentSwizzle value
- b **must** be a valid VkComponentSwizzle value
- a **must** be a valid VkComponentSwizzle value

Possible values of the members of VkComponentMapping, specifying the component values placed in each component of the output vector, are:

```c
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;
```

- VK_COMPONENT_SWIZZLE_IDENTITY specifies that the component is set to the identity swizzle.
- VK_COMPONENT_SWIZZLE_ZERO specifies that the component is set to zero.
- 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 VkFormat.
- 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 9. Component Mappings Equivalent To VK_COMPONENT_SWIZZLE_IDENTITY

Component	Identity Mapping
components.r	VK_COMPONENT_SWIZZLE_R
components.g	VK_COMPONENT_SWIZZLE_G
components.b	VK_COMPONENT_SWIZZLE_B
components.a	VK_COMPONENT_SWIZZLE_A

To destroy an image view, call:

```
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

* All submitted commands that refer to imageView **must** have completed execution
* If VkAllocationCallbacks were provided when imageView was created, a compatible set of callbacks **must** be provided here
* If no VkAllocationCallbacks were provided when imageView was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `imageView` is not VK_NULL_HANDLE, `imageView` **must** be a valid `VkImageView` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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

11.6. Resource Memory Association

Resources are initially created as *virtual allocations* with no backing memory. Device memory is allocated separately (see 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 Sparse Resources.

Non-sparse resources **must** be bound completely and contiguously to a single `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.

To determine the memory requirements for a buffer resource, call:

```
void vkGetBufferMemoryRequirements(
    VkDevice                                    device,
    VkBuffer                                    buffer,
    VkMemoryRequirements*                       pMemoryRequirements);
```

- `device` is the logical device that owns the buffer.
- `buffer` is the buffer to query.
- `pMemoryRequirements` points to an instance of the VkMemoryRequirements structure in which the memory requirements of the buffer object are returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `buffer` **must** be a valid `VkBuffer` handle
- `pMemoryRequirements` **must** be a valid pointer to a `VkMemoryRequirements` structure
- `buffer` **must** have been created, allocated, or retrieved from `device`

To determine the memory requirements for an image resource, call:

```
void vkGetImageMemoryRequirements(
    VkDevice                                    device,
    VkImage                                     image,
    VkMemoryRequirements*                       pMemoryRequirements);
```

- `device` is the logical device that owns the image.
- `image` is the image to query.
- `pMemoryRequirements` points to an instance of the VkMemoryRequirements structure in which the memory requirements of the image object are returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `image` **must** be a valid `VkImage` handle
- `pMemoryRequirements` **must** be a valid pointer to a `VkMemoryRequirements` structure
- `image` **must** have been created, allocated, or retrieved from `device`

The `VkMemoryRequirements` structure is defined as:

```
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 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 a VkImage that was created with a VK_IMAGE_TILING_LINEAR value in the tiling member of the VkImageCreateInfo structure passed to vkCreateImage, 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.
- 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 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, 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.
- 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, 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, 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 vkGetImageMemoryRequirements::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.

To attach memory to a buffer object, call:

```
VkResult 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.

Valid Usage

- buffer **must** not already be backed by a memory object
- buffer **must** not have been created with any sparse memory binding flags
- memoryOffset **must** be less than the size of memory
- If buffer was created with the VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT or VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT, memoryOffset **must** be a multiple of VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment
- If buffer was created with the VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT, memoryOffset **must** be a multiple of VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment
- If buffer was created with the VK_BUFFER_USAGE_STORAGE_BUFFER_BIT, memoryOffset **must** be a multiple of VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment
- 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
- memoryOffset **must** be an integer multiple of the alignment member of the VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer
- 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

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `buffer` **must** be a valid `VkBuffer` handle
- `memory` **must** be a valid `VkDeviceMemory` handle
- `buffer` **must** have been created, allocated, or retrieved from `device`
- `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 an image object, call:

```
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.

Valid Usage

- `image` **must** not already be backed by a memory object
- `image` **must** not have been created with any sparse memory binding flags
- `memoryOffset` **must** be less than the size of `memory`
- `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`
- `memoryOffset` **must** be an integer multiple of the `alignment` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements` with `image`
- The `size` member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements` with `image` **must** be less than or equal to the size of `memory` minus `memoryOffset`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `image` **must** be a valid `VkImage` handle
- `memory` **must** be a valid `VkDeviceMemory` handle
- `image` **must** have been created, allocated, or retrieved from `device`
- `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`

Buffer-Image Granularity

There is an implementation-dependent limit, `bufferImageGranularity`, which 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 require such an additional granularity **may** report a 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 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.

11.7. 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:

```
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 same queue family at any given time. In order for a different queue family to be able to interpret the memory contents of a range or image subresource, the application **must** perform a queue family ownership transfer.

Upon creation, resources using VK_SHARING_MODE_EXCLUSIVE are not owned by any queue family. A buffer or image memory barrier is not required to acquire *ownership* when no queue family owns the resource - it is implicitly acquired upon first use within a queue.

> *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.

11.8. Memory Aliasing

A range of a VkDeviceMemory allocation is *aliased* if it is bound to multiple resources simultaneously, as described below, via vkBindImageMemory, vkBindBufferMemory, or via sparse memory bindings.

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.

> *Note*
>
> 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.

When an opaque, 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.

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 a 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.

Access to resources which alias memory from shaders using variables decorated with Coherent are not automatically coherent with each other.

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.

Chapter 12. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSampler)
```

To create a sampler object, call:

```
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 an instance of the VkSamplerCreateInfo structure specifying the state of the sampler object.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pSampler points to a VkSampler handle in which the resulting sampler object is returned.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkSamplerCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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
- VK_ERROR_TOO_MANY_OBJECTS

The VkSamplerCreateInfo structure is defined as:

```c
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `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 outside [0..1] range for U coordinate.
- `addressModeV` is a VkSamplerAddressMode value specifying the addressing mode for outside [0..1] range for V coordinate.
- `addressModeW` is a VkSamplerAddressMode value specifying the addressing mode for outside [0..1] range for W coordinate.
- `mipLodBias` is the bias to be added to mipmap LOD (level-of-detail) calculation and bias provided by image sampling functions in SPIR-V, as described in the Level-of-Detail 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 function to apply to fetched data before filtering as described in the Depth Compare Operation section.
- minLod and maxLod are the values used to clamp the computed LOD value, as described in the Level-of-Detail Operation section. maxLod **must** be greater than or equal to minLod.
- 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 dimensions for x, y and z. When set to VK_FALSE the range of image coordinates is zero to one. When unnormalizedCoordinates is VK_TRUE, samplers have the following requirements:
  - minFilter and magFilter **must** be equal.
  - mipmapMode **must** be VK_SAMPLER_MIPMAP_MODE_NEAREST.
  - minLod and maxLod **must** be zero.
  - addressModeU and addressModeV **must** each be either VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE or VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER.
  - anisotropyEnable **must** be VK_FALSE.
  - compareEnable **must** be VK_FALSE.
- 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 maxLod of zero would cause magnification to always be performed, and the 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 λ value to be non-zero and minification to be performed, while still always rounding down to the base level. If the minFilter and magFilter are equal, then using a maxLod of zero also works.

The maximum number of sampler objects which **can** be simultaneously created on a device is implementation-dependent and specified by the maxSamplerAllocationCount member of the VkPhysicalDeviceLimits structure. If maxSamplerAllocationCount is exceeded, vkCreateSampler will return VK_ERROR_TOO_MANY_OBJECTS.

Since VkSampler is a non-dispatchable handle type, implementations **may** return the same handle for sampler state vectors that are identical. In such cases, all such objects would only count once against the maxSamplerAllocationCount limit.

Valid Usage

- The absolute value of mipLodBias **must** be less than or equal to VkPhysicalDeviceLimits ::maxSamplerLodBias
- If the anisotropic sampling feature is not enabled, anisotropyEnable **must** be VK_FALSE
- If anisotropyEnable is VK_TRUE, maxAnisotropy **must** be between 1.0 and VkPhysicalDeviceLimits::maxSamplerAnisotropy, inclusive
- If unnormalizedCoordinates is VK_TRUE, minFilter and magFilter **must** be equal
- If unnormalizedCoordinates is VK_TRUE, mipmapMode **must** be VK_SAMPLER_MIPMAP_MODE_NEAREST
- If unnormalizedCoordinates is VK_TRUE, minLod and maxLod **must** be zero
- 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 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO
- pNext **must** be NULL
- 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

```
typedef VkFlags VkSamplerCreateFlags;
```

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

Possible values of the VkSamplerCreateInfo::magFilter and minFilter parameters, specifying filters used for texture lookups, are:

```
typedef enum VkFilter {
    VK_FILTER_NEAREST = 0,
    VK_FILTER_LINEAR = 1,
} VkFilter;
```

- 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:

```
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:

```
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,
    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 the VK_KHR_sampler_mirror_clamp_to_edge extension is enabled.

Possible values of VkSamplerCreateInfo::borderColor, specifying the border color used for texture lookups, are:

```
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,
    VK_BORDER_COLOR_INT_OPAQUE_WHITE = 5,
} VkBorderColor;
```

- VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK specifies a transparent, floating-point format, black color.
- VK_BORDER_COLOR_INT_TRANSPARENT_BLACK specifies a transparent, integer format, black color.
- VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK specifies an opaque, floating-point format, black color.
- VK_BORDER_COLOR_INT_OPAQUE_BLACK specifies an opaque, integer format, black color.
- VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE specifies an opaque, floating-point format, white color.
- VK_BORDER_COLOR_INT_OPAQUE_WHITE specifies an opaque, integer format, white color.

These colors are described in detail in Texel Replacement.

To destroy a sampler, call:

```
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

- All submitted commands that refer to sampler **must** have completed execution
- If VkAllocationCallbacks were provided when sampler was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when sampler was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `sampler` is not VK_NULL_HANDLE, `sampler` **must** be a valid `VkSampler` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `sampler` is a valid handle, it **must** have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `sampler` **must** be externally synchronized

Chapter 13. Resource Descriptors

Shaders access buffer and image resources by using special shader variables which are indirectly bound to buffer and image views via the API. These variables are organized into sets, where each set of bindings is represented by a *descriptor set* object in the API and a descriptor set is bound all at once. A *descriptor* is an opaque data structure representing a shader resource such as a buffer view, image view, sampler, or combined image sampler. The content of each set is determined by its *descriptor set layout* and the sequence of set layouts that **can** be used by resource variables in shaders within a pipeline is specified in a *pipeline layout*.

Each shader **can** use up to `maxBoundDescriptorSets` (see Limits) descriptor sets, and each descriptor set **can** include bindings for descriptors of all descriptor types. Each shader resource variable is assigned a tuple of (set number, binding number, array element) that defines its location within a descriptor set layout. In GLSL, the set number and binding number are assigned via layout qualifiers, and the array element is implicitly assigned consecutively starting with index equal to zero for the first element of an array (and array element is zero for non-array variables):

GLSL example

```
// Assign set number = M, binding number = N, array element = 0
layout (set=M, binding=N) uniform sampler2D variableName;

// Assign set number = M, binding number = N for all array elements, and
// array element = I for the I'th member of the array.
layout (set=M, binding=N) uniform sampler2D variableNameArray[I];
```

SPIR-V example

```
// Assign set number = M, binding number = N, array element = 0
               ...
          %1 = OpExtInstImport "GLSL.std.450"
               ...
               OpName %10 "variableName"
               OpDecorate %10 DescriptorSet M
               OpDecorate %10 Binding N
          %2 = OpTypeVoid
          %3 = OpTypeFunction %2
          %6 = OpTypeFloat 32
          %7 = OpTypeImage %6 2D 0 0 0 1 Unknown
          %8 = OpTypeSampledImage %7
          %9 = OpTypePointer UniformConstant %8
         %10 = OpVariable %9 UniformConstant
               ...

// Assign set number = M, binding number = N for all array elements, and
// array element = I for the I'th member of the array.
               ...
          %1 = OpExtInstImport "GLSL.std.450"
               ...
               OpName %13 "variableNameArray"
               OpDecorate %13 DescriptorSet M
               OpDecorate %13 Binding N
          %2 = OpTypeVoid
          %3 = OpTypeFunction %2
          %6 = OpTypeFloat 32
          %7 = OpTypeImage %6 2D 0 0 0 1 Unknown
          %8 = OpTypeSampledImage %7
          %9 = OpTypeInt 32 0
         %10 = OpConstant %9 I
         %11 = OpTypeArray %8 %10
         %12 = OpTypePointer UniformConstant %11
         %13 = OpVariable %12 UniformConstant
               ...
```

13.1. Descriptor Types

The following sections outline the various descriptor types supported by Vulkan. Each section defines a descriptor type, and each descriptor type has a manifestation in the shading language and SPIR-V as well as in descriptor sets. There is mostly a one-to-one correspondence between descriptor types and classes of opaque types in the shading language, where the opaque types in the shading language **must** refer to a descriptor in the pipeline layout of the corresponding descriptor type. But there is an exception to this rule as described in Combined Image Sampler.

13.1.1. Storage Image

A *storage image* (VK_DESCRIPTOR_TYPE_STORAGE_IMAGE) is a descriptor type that is used for load, store, and atomic operations on image memory from within shaders bound to pipelines.

Loads from storage images do not use samplers and are unfiltered and do not support coordinate wrapping or clamping. Loads are supported in all shader stages for image formats which report support for the VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT feature bit via vkGetPhysicalDeviceFormatProperties.

Stores to storage images are supported in compute shaders for image formats which report support for the VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT feature.

Storage images also support atomic operations in compute shaders for image formats which report support for the VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT feature.

Load and store operations on storage images **can** only be done on images in the VK_IMAGE_LAYOUT_GENERAL layout.

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.

Storage image declarations **must** specify the image format in the shader if the variable is used for atomic operations.

If the shaderStorageImageReadWithoutFormat feature is not enabled, storage image declarations **must** specify the image format in the shader if the variable is used for load operations.

If the shaderStorageImageWriteWithoutFormat feature is not enabled, storage image declarations **must** specify the image format in the shader if the variable is used for store operations.

Storage images are declared in GLSL shader source using uniform image variables of the appropriate dimensionality as well as a format layout qualifier (if necessary):

GLSL example

```
layout (set=m, binding=n, r32f) uniform image2D myStorageImage;
```

SPIR-V example

```
        ...
     %1 = OpExtInstImport "GLSL.std.450"
        ...
        OpName %9 "myStorageImage"
        OpDecorate %9 DescriptorSet m
        OpDecorate %9 Binding n
     %2 = OpTypeVoid
     %3 = OpTypeFunction %2
     %6 = OpTypeFloat 32
     %7 = OpTypeImage %6 2D 0 0 0 2 R32f
     %8 = OpTypePointer UniformConstant %7
     %9 = OpVariable %8 UniformConstant
        ...
```

13.1.2. Sampler

A *sampler* (`VK_DESCRIPTOR_TYPE_SAMPLER`) represents a set of parameters which control address calculations, filtering behavior, and other properties, that **can** be used to perform filtered loads from *sampled images* (see Sampled Image).

Samplers are declared in GLSL shader source using uniform `sampler` variables, where the sampler type has no associated texture dimensionality:

GLSL Example

```
layout (set=m, binding=n) uniform sampler mySampler;
```

SPIR-V example

```
        ...
     %1 = OpExtInstImport "GLSL.std.450"
        ...
        OpName %8 "mySampler"
        OpDecorate %8 DescriptorSet m
        OpDecorate %8 Binding n
     %2 = OpTypeVoid
     %3 = OpTypeFunction %2
     %6 = OpTypeSampler
     %7 = OpTypePointer UniformConstant %6
     %8 = OpVariable %7 UniformConstant
        ...
```

13.1.3. Sampled Image

A *sampled image* (`VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`) **can** be used (usually in conjunction with a sampler) to retrieve sampled image data. Shaders use a sampled image handle and a sampler handle to sample data, where the image handle generally defines the shape and format of the memory and the sampler generally defines how coordinate addressing is performed. The same sampler **can** be used to sample from multiple images, and it is possible to sample from the same sampled image with multiple samplers, each containing a different set of sampling parameters.

Sampled images are declared in GLSL shader source using uniform `texture` variables of the appropriate dimensionality:

GLSL example

```
layout (set=m, binding=n) uniform texture2D mySampledImage;
```

SPIR-V example

```
          ...
      %1 = OpExtInstImport "GLSL.std.450"
          ...
          OpName %9 "mySampledImage"
          OpDecorate %9 DescriptorSet m
          OpDecorate %9 Binding n
      %2 = OpTypeVoid
      %3 = OpTypeFunction %2
      %6 = OpTypeFloat 32
      %7 = OpTypeImage %6 2D 0 0 0 1 Unknown
      %8 = OpTypePointer UniformConstant %7
      %9 = OpVariable %8 UniformConstant
          ...
```

13.1.4. Combined Image Sampler

A *combined image sampler* (`VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`) represents a sampled image along with a set of sampling parameters. It is logically considered a sampled image and a sampler bound together.

> *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.

Combined image samplers are declared in GLSL shader source using uniform `sampler` variables of the appropriate dimensionality:

GLSL example

```
layout (set=m, binding=n) uniform sampler2D myCombinedImageSampler;
```

SPIR-V example

```
         ...
      %1 = OpExtInstImport "GLSL.std.450"
         ...
         OpName %10 "myCombinedImageSampler"
         OpDecorate %10 DescriptorSet m
         OpDecorate %10 Binding n
      %2 = OpTypeVoid
      %3 = OpTypeFunction %2
      %6 = OpTypeFloat 32
      %7 = OpTypeImage %6 2D 0 0 0 1 Unknown
      %8 = OpTypeSampledImage %7
      %9 = OpTypePointer UniformConstant %8
     %10 = OpVariable %9 UniformConstant
         ...
```

VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER descriptor set entries **can** also be accessed via separate sampler and sampled image shader variables. Such variables refer exclusively to the corresponding half of the descriptor, and **can** be combined in the shader with samplers or sampled images that **can** come from the same descriptor or from other combined or separate descriptor types. There are no additional restrictions on how a separate sampler or sampled image variable is used due to it originating from a combined descriptor.

13.1.5. Uniform Texel Buffer

A *uniform texel buffer* (VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER) represents a tightly packed array of homogeneous formatted data that is stored in a buffer and is made accessible to shaders. Uniform texel buffers are read-only.

Uniform texel buffers are declared in GLSL shader source using uniform samplerBuffer variables:

GLSL example

```
layout (set=m, binding=n) uniform samplerBuffer myUniformTexelBuffer;
```

SPIR-V example

```
        ...
%1 = OpExtInstImport "GLSL.std.450"
        ...
        OpName %9 "myUniformTexelBuffer"
        OpDecorate %9 DescriptorSet m
        OpDecorate %9 Binding n
%2 = OpTypeVoid
%3 = OpTypeFunction %2
%6 = OpTypeFloat 32
%7 = OpTypeImage %6 Buffer 0 0 0 1 Unknown
%8 = OpTypePointer UniformConstant %7
%9 = OpVariable %8 UniformConstant
        ...
```

13.1.6. Storage Texel Buffer

A *storage texel buffer* (`VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`) represents a tightly packed array of homogeneous formatted data that is stored in a buffer and is made accessible to shaders. Storage texel buffers differ from uniform texel buffers in that they support stores and atomic operations in shaders, **may** support a different maximum length, and **may** have different performance characteristics.

Storage texel buffers are declared in GLSL shader source using uniform `imageBuffer` variables:

GLSL example

```
layout (set=m, binding=n, r32f) uniform imageBuffer myStorageTexelBuffer;
```

SPIR-V example

```
        ...
%1 = OpExtInstImport "GLSL.std.450"
        ...
        OpName %9 "myStorageTexelBuffer"
        OpDecorate %9 DescriptorSet m
        OpDecorate %9 Binding n
%2 = OpTypeVoid
%3 = OpTypeFunction %2
%6 = OpTypeFloat 32
%7 = OpTypeImage %6 Buffer 0 0 0 2 R32f
%8 = OpTypePointer UniformConstant %7
%9 = OpVariable %8 UniformConstant
        ...
```

13.1.7. Uniform Buffer

A *uniform buffer* (VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER) is a region of structured storage that is made accessible for read-only access to shaders. It is typically used to store medium sized arrays of constants such as shader parameters, matrices and other related data.

Uniform buffers are declared in GLSL shader source using the uniform storage qualifier and block syntax:

GLSL example

```
layout (set=m, binding=n) uniform myUniformBuffer
{
    vec4 myElement[32];
};
```

SPIR-V example

```
          ...
     %1 = OpExtInstImport "GLSL.std.450"
          ...
          OpName %11 "myUniformBuffer"
          OpMemberName %11 0 "myElement"
          OpName %13 ""
          OpDecorate %10 ArrayStride 16
          OpMemberDecorate %11 0 Offset 0
          OpDecorate %11 Block
          OpDecorate %13 DescriptorSet m
          OpDecorate %13 Binding n
     %2 = OpTypeVoid
     %3 = OpTypeFunction %2
     %6 = OpTypeFloat 32
     %7 = OpTypeVector %6 4
     %8 = OpTypeInt 32 0
     %9 = OpConstant %8 32
    %10 = OpTypeArray %7 %9
    %11 = OpTypeStruct %10
    %12 = OpTypePointer Uniform %11
    %13 = OpVariable %12 Uniform
          ...
```

13.1.8. Storage Buffer

A *storage buffer* (VK_DESCRIPTOR_TYPE_STORAGE_BUFFER) is a region of structured storage that supports both read and write access for shaders. In addition to general read and write operations, some members of storage buffers **can** be used as the target of atomic operations. In general, atomic operations are only supported on members that have unsigned integer formats.

Storage buffers are declared in GLSL shader source using buffer storage qualifier and block syntax:

GLSL example

```
layout (set=m, binding=n) buffer myStorageBuffer
{
    vec4 myElement[];
};
```

SPIR-V example

```
          ...
     %1 = OpExtInstImport "GLSL.std.450"
          ...
          OpName %9 "myStorageBuffer"
          OpMemberName %9 0 "myElement"
          OpName %11 ""
          OpDecorate %8 ArrayStride 16
          OpMemberDecorate %9 0 Offset 0
          OpDecorate %9 BufferBlock
          OpDecorate %11 DescriptorSet m
          OpDecorate %11 Binding n
     %2 = OpTypeVoid
     %3 = OpTypeFunction %2
     %6 = OpTypeFloat 32
     %7 = OpTypeVector %6 4
     %8 = OpTypeRuntimeArray %7
     %9 = OpTypeStruct %8
    %10 = OpTypePointer Uniform %9
    %11 = OpVariable %10 Uniform
          ...
```

13.1.9. Dynamic Uniform Buffer

A *dynamic uniform buffer* (`VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`) differs from a uniform buffer only in how its address and length are specified. Uniform buffers bind a buffer address and length that is specified in the descriptor set update by a buffer handle, offset and range (see Descriptor Set Updates). With dynamic uniform buffers the buffer handle, offset and range specified in the descriptor set define the base address and length. The dynamic offset which is relative to this base address is taken from the `pDynamicOffsets` parameter to vkCmdBindDescriptorSets (see Descriptor Set Binding). The address used for a dynamic uniform buffer is the sum of the buffer base address and the relative offset. The length is unmodified and remains the range as specified in the descriptor update. The shader syntax is identical for uniform buffers and dynamic uniform buffers.

13.1.10. Dynamic Storage Buffer

A *dynamic storage buffer* (`VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`) differs from a storage buffer only in how its address and length are specified. The difference is identical to the difference between uniform buffers and dynamic uniform buffers (see Dynamic Uniform Buffer). The shader syntax is identical for storage buffers and dynamic storage buffers.

13.1.11. Input Attachment

An *input attachment* (VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT) is an image view that **can** be used for pixel local load operations from within fragment shaders bound to pipelines. Loads from input attachments are unfiltered. 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.

In the shader, input attachments **must** be decorated with their input attachment index in addition to descriptor set and binding numbers.

GLSL example

```
layout (input_attachment_index=i, set=m, binding=n) uniform subpassInput
myInputAttachment;
```

SPIR-V example

```
          ...
      %1 = OpExtInstImport "GLSL.std.450"
          ...
          OpName %9 "myInputAttachment"
          OpDecorate %9 DescriptorSet m
          OpDecorate %9 Binding n
          OpDecorate %9 InputAttachmentIndex i
      %2 = OpTypeVoid
      %3 = OpTypeFunction %2
      %6 = OpTypeFloat 32
      %7 = OpTypeImage %6 SubpassData 0 0 0 2 Unknown
      %8 = OpTypePointer UniformConstant %7
      %9 = OpVariable %8 UniformConstant
          ...
```

13.2. Descriptor Sets

Descriptors are grouped together into descriptor set objects. A descriptor set object is an opaque object that contains 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 hardware 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.

13.2.1. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSetLayout)
```

To create descriptor set layout objects, call:

```
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 an instance of the VkDescriptorSetLayoutCreateInfo structure specifying the state of the descriptor set layout object.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pSetLayout` points to a `VkDescriptorSetLayout` handle in which the resulting descriptor set layout object is returned.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkDescriptorSetLayoutCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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 an instance of the `VkDescriptorSetLayoutCreateInfo` structure:

```
typedef struct VkDescriptorSetLayoutCreateInfo {
    VkStructureType                        sType;
    const void*                            pNext;
    VkDescriptorSetLayoutCreateFlags       flags;
    uint32_t                               bindingCount;
    const VkDescriptorSetLayoutBinding*    pBindings;
} VkDescriptorSetLayoutCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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

- The VkDescriptorSetLayoutBinding::`binding` members of the elements of the `pBindings` array **must** each have different values.

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be a valid combination of VkDescriptorSetLayoutCreateFlagBits values
- 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` to specify options for descriptor set layout are:

```
typedef enum VkDescriptorSetLayoutCreateFlagBits {
} VkDescriptorSetLayoutCreateFlagBits;
```

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

```
typedef VkFlags VkDescriptorSetLayoutCreateFlags;
```

`VkDescriptorSetLayoutCreateFlags` is a bitmask type for setting a mask of zero or more

VkDescriptorSetLayoutCreateFlagBits.

The VkDescriptorSetLayoutBinding structure is defined as:

```
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. 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** be used by 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; later binding a sampler into an immutable sampler slot in a descriptor set is not allowed. If pImmutableSamplers is not NULL, then it is considered to be a pointer to an array of sampler handles that will be consumed by the set layout and used for the corresponding binding. If pImmutableSamplers is NULL, then the sampler slots 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 descriptorType is treated as 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

- 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
- If descriptorCount is not 0, stageFlags **must** be a valid combination of VkShaderStageFlagBits values
- 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)

- descriptorType **must** be a valid VkDescriptorType value

The following examples show a shader snippet using two descriptor sets, and application code that creates corresponding descriptor set layouts.

GLSL example

```
//
// 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

```
               ...
          %1 = OpExtInstImport "GLSL.std.450"
               ...
               OpName %9 "mySampledImage"
               OpName %14 "myArrayOfSampledImages"
               OpName %18 "myUniformBuffer"
               OpMemberName %18 0 "myElement"
               OpName %20 ""
               OpDecorate %9 DescriptorSet 0
               OpDecorate %9 Binding 0
               OpDecorate %14 DescriptorSet 0
               OpDecorate %14 Binding 1
               OpDecorate %17 ArrayStride 16
               OpMemberDecorate %18 0 Offset 0
               OpDecorate %18 Block
               OpDecorate %20 DescriptorSet 1
               OpDecorate %20 Binding 0
          %2 = OpTypeVoid
          %3 = OpTypeFunction %2
          %6 = OpTypeFloat 32
          %7 = OpTypeImage %6 2D 0 0 0 1 Unknown
          %8 = OpTypePointer UniformConstant %7
          %9 = OpVariable %8 UniformConstant
         %10 = OpTypeInt 32 0
         %11 = OpConstant %10 12
         %12 = OpTypeArray %7 %11
         %13 = OpTypePointer UniformConstant %12
         %14 = OpVariable %13 UniformConstant
         %15 = OpTypeVector %6 4
         %16 = OpConstant %10 32
         %17 = OpTypeArray %15 %16
         %18 = OpTypeStruct %17
         %19 = OpTypePointer Uniform %18
         %20 = OpVariable %19 Uniform
               ...
```

API example

```
VkResult myResult;

const VkDescriptorSetLayoutBinding myDescriptorSetLayoutBinding[] =
{
    // binding to a single image descriptor
    {
        0,                                      // binding
        VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,       // descriptorType
        1,                                      // descriptorCount
        VK_SHADER_STAGE_FRAGMENT_BIT,           // stageFlags
```

```
        NULL                                    // pImmutableSamplers
    },

    // binding to an array of image descriptors
    {
        1,                                      // binding
        VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,       // descriptorType
        12,                                     // descriptorCount
        VK_SHADER_STAGE_FRAGMENT_BIT,           // stageFlags
        NULL                                    // pImmutableSamplers
    },

    // binding to a single uniform buffer descriptor
    {
        0,                                      // binding
        VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER,      // descriptorType
        1,                                      // descriptorCount
        VK_SHADER_STAGE_FRAGMENT_BIT,           // stageFlags
        NULL                                    // pImmutableSamplers
    }
};

const VkDescriptorSetLayoutCreateInfo myDescriptorSetLayoutCreateInfo[] =
{
    // Create info for first descriptor set with two descriptor bindings
    {
        VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO,    // sType
        NULL,                                                   // pNext
        0,                                                      // flags
        2,                                                      // bindingCount
        &myDescriptorSetLayoutBinding[0]                        // pBindings
    },

    // Create info for second descriptor set with one descriptor binding
    {
        VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO,    // sType
        NULL,                                                   // pNext
        0,                                                      // flags
        1,                                                      // bindingCount
        &myDescriptorSetLayoutBinding[2]                        // pBindings
    }
};

VkDescriptorSetLayout myDescriptorSetLayout[2];

//
// Create first descriptor set layout
//
myResult = vkCreateDescriptorSetLayout(
    myDevice,
    &myDescriptorSetLayoutCreateInfo[0],
```

```
    NULL,
    &myDescriptorSetLayout[0]);

//
// Create second descriptor set layout
//
myResult = vkCreateDescriptorSetLayout(
    myDevice,
    &myDescriptorSetLayoutCreateInfo[1],
    NULL,
    &myDescriptorSetLayout[1]);
```

To destroy a descriptor set layout, call:

```
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

- If `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `descriptorSetLayout` is not VK_NULL_HANDLE, `descriptorSetLayout` **must** be a valid `VkDescriptorSetLayout` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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

13.2.2. 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 which describes 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineLayout)
```

To create a pipeline layout, call:

```
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 an instance of the VkPipelineLayoutCreateInfo structure specifying the state of the pipeline layout object.
- pAllocator controls host memory allocation as described in the Memory Allocation chapter.
- pPipelineLayout points to a VkPipelineLayout handle in which the resulting pipeline layout object is returned.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pCreateInfo **must** be a valid pointer to a valid VkPipelineLayoutCreateInfo structure
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- 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

- setLayoutCount **must** be less than or equal to VkPhysicalDeviceLimits::maxBoundDescriptorSets
- The total number of descriptors of the type 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 of the type 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 of the type 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 of the type 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 of the type 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 of the type 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 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 VkPhysicalDeviceLimits::maxDescriptorSetSamplers
- The total number of descriptors of the type VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER accessible across all shader stagess and and across all elements of pSetLayouts **must** be less than or equal to VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffers
- 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 VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffersDynamic
- 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 VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffers
- 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 VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffersDynamic

- The total number of descriptors of the type VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, 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 VkPhysicalDeviceLimits::maxDescriptorSetSampledImages
- 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 VkPhysicalDeviceLimits ::maxDescriptorSetStorageImages
- 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 VkPhysicalDeviceLimits::maxDescriptorSetInputAttachments
- Any two elements of pPushConstantRanges **must** not include the same stage in stageFlags

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- If setLayoutCount is not 0, pSetLayouts **must** be a valid pointer to an array of setLayoutCount valid VkDescriptorSetLayout handles
- If pushConstantRangeCount is not 0, pPushConstantRanges **must** be a valid pointer to an array of pushConstantRangeCount valid VkPushConstantRange structures

```
typedef VkFlags VkPipelineLayoutCreateFlags;
```

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

The VkPushConstantRange structure is defined as:

```
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 result in undefined data being read.
- 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

- `offset` **must** be less than `VkPhysicalDeviceLimits::maxPushConstantsSize`
- `offset` **must** be a multiple of `4`
- `size` **must** be greater than `0`
- `size` **must** be a multiple of `4`
- `size` **must** be less than or equal to `VkPhysicalDeviceLimits::maxPushConstantsSize` minus `offset`

Valid Usage (Implicit)

- `stageFlags` **must** be a valid combination of VkShaderStageFlagBits values
- `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 hardware resources or memory locations within a descriptor set. The assignment of hardware 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, or that are dead-code eliminated from any of the shaders. 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, or for which the variables have been dead-code eliminated from any of the shaders.

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 10. Pipeline Layout Resource Limits

Total Resources Available	Resource Types
`maxDescriptorSetSamplers`	sampler
	combined image sampler
`maxDescriptorSetSampledImages`	sampled image
	combined image sampler
	uniform texel buffer
`maxDescriptorSetStorageImages`	storage image
	storage texel buffer
`maxDescriptorSetUniformBuffers`	uniform buffer
	uniform buffer dynamic
`maxDescriptorSetUniformBuffersDynamic`	uniform buffer dynamic
`maxDescriptorSetStorageBuffers`	storage buffer
	storage buffer dynamic
`maxDescriptorSetStorageBuffersDynamic`	storage buffer dynamic
`maxDescriptorSetInputAttachments`	input attachment

To destroy a pipeline layout, call:

```
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

- If `VkAllocationCallbacks` were provided when `pipelineLayout` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `pipelineLayout` was created, `pAllocator` **must** be `NULL`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `pipelineLayout` is not VK_NULL_HANDLE, `pipelineLayout` **must** be a valid `VkPipelineLayout` handle
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- 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, if the previously bound descriptor sets for sets zero through N-1 were all bound using compatible pipeline layouts, then performing this binding does not disturb any of the lower numbered sets. If, additionally, the previous bound descriptor set for set N was bound using a pipeline layout compatible for set N, then the bindings in sets numbered greater than N are also not disturbed.

Similarly, when binding a pipeline, the pipeline **can** correctly access any previously bound descriptor sets which were bound with compatible pipeline layouts, as long as all lower numbered sets were also bound with compatible layouts.

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.

Implementor's Note

A consequence of layout compatibility is that when the implementation compiles a pipeline layout and assigns hardware units to resources, the mechanism to assign hardware units 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

```
const VkDescriptorSetLayout layouts[] = { layout1, layout2 };

const VkPushConstantRange ranges[] =
{
    {
        VK_PIPELINE_STAGE_VERTEX_SHADER_BIT,    // stageFlags
        0,                                      // offset
        4                                       // size
    },

    {
        VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT,  // stageFlags
        4,                                      // offset
        4                                       // size
    },
};

const VkPipelineLayoutCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO,  // sType
    NULL,                                           // pNext
    0,                                              // flags
    2,                                              // setLayoutCount
    layouts,                                        // pSetLayouts
    2,                                              // pushConstantRangeCount
    ranges                                          // pPushConstantRanges
};

VkPipelineLayout myPipelineLayout;
myResult = vkCreatePipelineLayout(
    myDevice,
    &createInfo,
    NULL,
    &myPipelineLayout);
```

13.2.3. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorPool)
```

To create a descriptor pool object, call:

```
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 an instance of the VkDescriptorPoolCreateInfo structure specifying the state of the descriptor pool object.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pDescriptorPool` points to a `VkDescriptorPool` handle in which the resulting descriptor pool object is returned.

`pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

The created descriptor pool is returned in `pDescriptorPool`.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pCreateInfo` **must** be a valid pointer to a valid `VkDescriptorPoolCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- `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 an instance of the VkDescriptorPoolCreateInfo structure:

```
typedef struct VkDescriptorPoolCreateInfo {
    VkStructureType                sType;
    const void*                    pNext;
    VkDescriptorPoolCreateFlags    flags;
    uint32_t                       maxSets;
    uint32_t                       poolSizeCount;
    const VkDescriptorPoolSize*    pPoolSizes;
} VkDescriptorPoolCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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 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.

Valid Usage

- maxSets **must** be greater than 0

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO
- pNext **must** be NULL
- flags **must** be a valid combination of VkDescriptorPoolCreateFlagBits values
- pPoolSizes **must** be a valid pointer to an array of poolSizeCount valid VkDescriptorPoolSize structures
- poolSizeCount **must** be greater than 0

Bits which **can** be set in VkDescriptorPoolCreateInfo::flags to enable operations on a descriptor pool are:

```
typedef enum VkDescriptorPoolCreateFlagBits {
    VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT = 0x00000001,
} VkDescriptorPoolCreateFlagBits;
```

- 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.

```
typedef VkFlags VkDescriptorPoolCreateFlags;
```

VkDescriptorPoolCreateFlags is a bitmask type for setting a mask of zero or more VkDescriptorPoolCreateFlagBits.

The VkDescriptorPoolSize structure is defined as:

```
typedef struct VkDescriptorPoolSize {
    VkDescriptorType    type;
    uint32_t            descriptorCount;
} VkDescriptorPoolSize;
```

- type is the type of descriptor.

* descriptorCount is the number of descriptors of that type to allocate.

Valid Usage

* descriptorCount **must** be greater than 0

Valid Usage (Implicit)

* type **must** be a valid VkDescriptorType value

To destroy a descriptor pool, call:

```
void vkDestroyDescriptorPool(
    VkDevice                                    device,
    VkDescriptorPool                            descriptorPool,
    const VkAllocationCallbacks*                pAllocator);
```

* device is the logical device that destroys the descriptor pool.
* descriptorPool is the descriptor pool to destroy.
* 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

* All submitted commands that refer to descriptorPool (via any allocated descriptor sets) **must** have completed execution
* If VkAllocationCallbacks were provided when descriptorPool was created, a compatible set of callbacks **must** be provided here
* If no VkAllocationCallbacks were provided when descriptorPool was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If descriptorPool is not VK_NULL_HANDLE, descriptorPool **must** be a valid VkDescriptorPool handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSet)
```

To allocate descriptor sets from a descriptor pool, call:

```
VkResult vkAllocateDescriptorSets(
    VkDevice                                    device,
    const VkDescriptorSetAllocateInfo*          pAllocateInfo,
    VkDescriptorSet*                            pDescriptorSets);
```

- device is the logical device that owns the descriptor pool.
- pAllocateInfo is a pointer to an instance of the 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. However, the descriptor set **can** be bound in a command buffer without causing errors or exceptions. All entries that are statically used by a pipeline in a drawing or dispatching command **must** have been populated before the descriptor set is bound for use by that command. Entries that are not statically used by a pipeline **can** have uninitialized descriptors or descriptors of resources that have been destroyed, and executing a draw or dispatch with such a descriptor set bound does not cause undefined behavior. This means applications need not populate unused entries with dummy descriptors.

If an allocation fails due to fragmentation, an indeterminate error is returned with an unspecified error code. Any returned error other than VK_ERROR_FRAGMENTED_POOL does not imply its usual meaning: applications **should** assume that the allocation failed due to fragmentation, and create a new descriptor pool.

> *Note*
>
> Applications **should** check for a negative return value when allocating new descriptor sets, assume that any error effectively means VK_ERROR_FRAGMENTED_POOL, and try to create a new descriptor pool. If VK_ERROR_FRAGMENTED_POOL is the actual return value, it adds certainty to that decision.
>
> The reason for this is that VK_ERROR_FRAGMENTED_POOL was only added in a later revision of the 1.0 specification, and so drivers **may** return other errors if they were written against earlier revisions. To ensure full compatibility with earlier patch revisions, these other errors are allowed.

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- pAllocateInfo **must** be a valid pointer to a valid VkDescriptorSetAllocateInfo structure
- pDescriptorSets **must** be a valid pointer to an array of pAllocateInfo::descriptorSetCount VkDescriptorSet handles

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

The VkDescriptorSetAllocateInfo structure is defined as:

```c
typedef struct VkDescriptorSetAllocateInfo {
    VkStructureType                 sType;
    const void*                     pNext;
    VkDescriptorPool                descriptorPool;
    uint32_t                        descriptorSetCount;
    const VkDescriptorSetLayout*    pSetLayouts;
} VkDescriptorSetAllocateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 an array of descriptor set layouts, with each member specifying how the corresponding descriptor set is allocated.

Valid Usage

- `descriptorSetCount` **must** not be greater than the number of sets that are currently available for allocation in `descriptorPool`
- `descriptorPool` **must** have enough free descriptor capacity remaining to allocate the descriptor sets of the specified layouts

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO`
- `pNext` **must** be `NULL`
- `descriptorPool` **must** be a valid `VkDescriptorPool` handle
- `pSetLayouts` **must** be a valid pointer to an array of `descriptorSetCount` valid `VkDescriptorSetLayout` handles
- `descriptorSetCount` **must** be greater than `0`
- Both of `descriptorPool`, and the elements of `pSetLayouts` **must** have been created, allocated, or retrieved from the same `VkDevice`

To free allocated descriptor sets, call:

```c
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 an array of handles to VkDescriptorSet objects.

After a successful call to vkFreeDescriptorSets, all descriptor sets in pDescriptorSets are invalid.

Valid Usage

- All submitted commands that refer to any element of pDescriptorSets **must** have completed execution
- 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
- Each valid handle in pDescriptorSets **must** have been allocated from descriptorPool
- descriptorPool **must** have been created with the VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT flag

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- descriptorPool **must** be a valid VkDescriptorPool handle
- descriptorSetCount **must** be greater than 0
- descriptorPool **must** have been created, allocated, or retrieved from device
- 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

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

To return all descriptor sets allocated from a given pool to the pool, rather than freeing individual descriptor sets, call:

```
VkResult vkResetDescriptorPool(
    VkDevice                                    device,
    VkDescriptorPool                            descriptorPool,
    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

- All uses of `descriptorPool` (via any allocated descriptor sets) **must** have completed execution

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `descriptorPool` **must** be a valid `VkDescriptorPool` handle
- `flags` **must** be `0`
- `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`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

```
typedef VkFlags VkDescriptorPoolResetFlags;
```

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

13.2.4. Descriptor Set Updates

Once allocated, descriptor sets **can** be updated with a combination of write and copy operations. To update descriptor sets, call:

```
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, that command buffer becomes invalid.

Valid Usage

- The dstSet member of each element of pDescriptorWrites or pDescriptorCopies **must** not be used by any command that was recorded to a command buffer which is in the pending state.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- If `descriptorWriteCount` is not `0`, `pDescriptorWrites` **must** be a valid pointer to an array of `descriptorWriteCount` valid `VkWriteDescriptorSet` structures
- If `descriptorCopyCount` is not `0`, `pDescriptorCopies` **must** be a valid pointer to an array of `descriptorCopyCount` valid `VkCopyDescriptorSet` structures

Host Synchronization

- Host access to `pDescriptorWrites`[].dstSet **must** be externally synchronized
- Host access to `pDescriptorCopies`[].dstSet **must** be externally synchronized

The `VkWriteDescriptorSet` structure is defined as:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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.
- `descriptorCount` is the number of descriptors to update (the number of elements in `pImageInfo`, `pBufferInfo`, or `pTexelBufferView`).
- `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 that specified in `VkDescriptorSetLayoutBinding` for `dstSet` at `dstBinding`. The type of the descriptor also controls which array the descriptors are taken from.
- `pImageInfo` points to an array of VkDescriptorImageInfo structures or is ignored, as described below.

- `pBufferInfo` points to an array of VkDescriptorBufferInfo structures or is ignored, as described below.
- `pTexelBufferView` points 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, 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.

Valid Usage

- 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
- dstBinding **must** be a binding with a non-zero descriptorCount
- All consecutive bindings updated via a single VkWriteDescriptorSet structure, except those with a descriptorCount of zero, **must** have identical descriptorType and stageFlags.
- 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.
- descriptorType **must** match the type of dstBinding within dstSet
- dstSet **must** be a valid VkDescriptorSet handle
- 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
- If descriptorType is VK_DESCRIPTOR_TYPE_SAMPLER, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, pImageInfo **must** be a valid pointer to an array of descriptorCount valid VkDescriptorImageInfo structures
- If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, pTexelBufferView **must** be a valid pointer to an array of descriptorCount valid VkBufferView handles
- 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
- 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
- If descriptorType is VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, the imageView and imageLayout members of each element of pImageInfo **must** be a valid VkImageView and VkImageLayout, respectively
- If descriptorType is VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, for each descriptor that will be accessed via load or store operations the imageLayout member for corresponding elements of pImageInfo **must** be VK_IMAGE_LAYOUT_GENERAL
- 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

- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- If descriptorType is VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, the imageLayout member of each element of pImageInfo **must** be VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- 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

- 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET
- pNext **must** be NULL
- descriptorType **must** be a valid VkDescriptorType value
- descriptorCount **must** be greater than 0
- Both of dstSet, and the elements of pTexelBufferView that are valid handles **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:

```
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,
} 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 storage image descriptor.
- VK_DESCRIPTOR_TYPE_STORAGE_IMAGE specifies a sampled 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 a input attachment descriptor.

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 sample 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.

The VkDescriptorBufferInfo structure is defined as:

```
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.

Valid Usage

- offset **must** be less than the size of buffer
- If range is not equal to VK_WHOLE_SIZE, range **must** be greater than 0
- If range is not equal to VK_WHOLE_SIZE, range **must** be less than or equal to the size of buffer minus offset

Valid Usage (Implicit)

- buffer **must** be a valid VkBuffer handle

The VkDescriptorImageInfo structure is defined as:

```
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

- imageLayout **must** match the actual VkImageLayout of each subresource accessible from imageView at the time this descriptor is accessed

Valid Usage (Implicit)

- Both of imageView, and sampler that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

The VkCopyDescriptorSet structure is defined as:

```
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 the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- srcSet, srcBinding, and srcArrayElement are the source set, binding, and array element, respectively.
- dstSet, dstBinding, and dstArrayElement are the destination set, binding, and array element, respectively.
- 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.

Valid Usage

- srcBinding **must** be a valid binding within srcSet
- 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
- dstBinding **must** be a valid binding within dstSet
- 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
- 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

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_COPY_DESCRIPTOR_SET
- pNext **must** be NULL
- srcSet **must** be a valid VkDescriptorSet handle
- dstSet **must** be a valid VkDescriptorSet handle
- Both of dstSet, and srcSet **must** have been created, allocated, or retrieved from the same VkDevice

13.2.5. Descriptor Set Binding

To bind one or more descriptor sets to a command buffer, call:

```
void vkCmdBindDescriptorSets(
    VkCommandBuffer                             commandBuffer,
    VkPipelineBindPoint                         pipelineBindPoint,
    VkPipelineLayout                            layout,
    uint32_t                                    firstSet,
    uint32_t                                    descriptorSetCount,
    const VkDescriptorSet*                      pDescriptorSets,
    uint32_t                                    dynamicOffsetCount,
    const uint32_t*                             pDynamicOffsets);
```

- commandBuffer is the command buffer that the descriptor sets will be bound to.
- pipelineBindPoint is a VkPipelineBindPoint indicating whether the descriptors will be used by graphics pipelines or compute pipelines. There is a separate set of bind points for each of graphics and compute, so binding one does not disturb the other.
- 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 an array of handles to VkDescriptorSet objects describing the descriptor sets to write 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 causes the sets numbered [firstSet.. firstSet+descriptorSetCount-1] to use the bindings stored in pDescriptorSets[0..descriptorSetCount-1] for subsequent rendering commands (either compute or graphics, according to the pipelineBindPoint). Any bindings that were previously applied via these sets are no longer valid.

Once bound, a descriptor set affects rendering of subsequent graphics or compute commands in the command buffer until a different set is bound to the same set number, or else until 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 draw or dispatch 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.

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 length 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 graphics or compute commands, as defined in the Pipeline Layout Compatibility section.

The descriptor set contents bound by a call to `vkCmdBindDescriptorSets` **may** be consumed during host execution of the command, or during shader execution of the resulting draws, or any time in between. Thus, the contents **must** not be altered (overwritten by an update command, or freed) between when the command is recorded 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

- 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`
- `dynamicOffsetCount` **must** be equal to the total number of dynamic descriptors in `pDescriptorSets`
- The sum of `firstSet` and `descriptorSetCount` **must** be less than or equal to `VkPipelineLayoutCreateInfo`::`setLayoutCount` provided when `layout` was created
- `pipelineBindPoint` **must** be supported by the `commandBuffer`'s parent `VkCommandPool`'s queue family
- Each element of `pDynamicOffsets` **must** satisfy the required alignment for the corresponding descriptor binding's descriptor type

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pipelineBindPoint` **must** be a valid VkPipelineBindPoint value
- `layout` **must** be a valid `VkPipelineLayout` handle
- `pDescriptorSets` **must** be a valid pointer to an array of `descriptorSetCount` valid `VkDescriptorSet` handles
- If `dynamicOffsetCount` is not `0`, `pDynamicOffsets` **must** be a valid pointer to an array of `dynamicOffsetCount` `uint32_t` values
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations
- `descriptorSetCount` **must** be greater than `0`
- Each of `commandBuffer`, `layout`, and the elements of `pDescriptorSets` **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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

13.2.6. 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.

The values of push constants are undefined at the start of a command buffer.

To update push constants, call:

```
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 an array of `size` bytes containing the new push constant values.

Valid Usage

- 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
- 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`
- `offset` **must** be a multiple of `4`
- `size` **must** be a multiple of `4`
- `offset` **must** be less than `VkPhysicalDeviceLimits`::`maxPushConstantsSize`
- `size` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxPushConstantsSize` minus `offset`

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- layout **must** be a valid VkPipelineLayout handle
- stageFlags **must** be a valid combination of VkShaderStageFlagBits values
- stageFlags **must** not be 0
- pValues **must** be a valid pointer to an array of size bytes
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics, or compute operations
- size **must** be greater than 0
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

Chapter 14. Shader Interfaces

When a pipeline is created, the set of shaders specified in the corresponding `Vk*PipelineCreateInfo` 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

Interface definitions make use of the following SPIR-V decorations:

- `DescriptorSet` and `Binding`
- `Location`, `Component`, and `Index`
- `Flat`, `NoPerspective`, `Centroid`, and `Sample`
- `Block` and `BufferBlock`
- `InputAttachmentIndex`
- `Offset`, `ArrayStride`, and `MatrixStride`
- `BuiltIn`

This specification describes valid uses for Vulkan of these decorations. Any other use of one of these decorations is invalid.

14.1. 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.

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. Generally, when non-shader stages are between shader stages, the user-defined variables, and most built-in variables, form an interface between the shader stages.

The variables forming the input or 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.

`Output` variables of a shader stage have undefined values until the shader writes to them or uses the `Initializer` operand when declaring the variable.

14.1.1. 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.

Built-ins only participate in interface matching if they are declared in such a block. They **must** not have any `Location` or `Component` decorations.

There **must** be no more than one built-in interface block per shader per interface.

14.1.2. User-defined Variable Interface

The remaining variables listed by `OpEntryPoint` with the `Input` or `Output` storage class form the *user-defined variable interface*. These variables **must** be identified with a `Location` decoration and **can** also be identified with a `Component` decoration.

14.1.3. Interface Matching

A user-defined output variable is considered to match an input variable in the subsequent stage if the two variables are declared with the same `Location` and `Component` decoration and match in type and decoration, except that interpolation decorations are not **required** to match. For the purposes of interface matching, variables declared without a `Component` decoration are considered to have a `Component` decoration of zero.

Variables or block members declared as structures are considered to match in type if and only if the structure members match in type, decoration, number, and declaration order. Variables or block members declared as arrays are considered to match in type only if both declarations specify the same element type and size.

Tessellation control shader per-vertex output variables and blocks, and tessellation control, tessellation evaluation, and geometry shader per-vertex input variables and blocks are required to be declared as arrays, with each element representing input or output values for a single vertex of a multi-vertex primitive. For the purposes of interface matching, the outermost array dimension of such variables and blocks is ignored.

At an interface between two non-fragment shader stages, the built-in interface block **must** match exactly, as described above. At an interface involving the fragment shader inputs, the presence or absence of any built-in output does not affect the interface matching.

At an interface between two shader stages, the user-defined variable interface **must** match exactly, as described above.

Any input value to a shader stage is well-defined as long as the preceding stages writes to a matching output, as described above.

Additionally, scalar and vector inputs are well-defined if there is a corresponding output satisfying all of the following conditions:

- the input and output match exactly in decoration,
- the output is a vector with the same basic type and has at least as many components as the input, and
- the common component type of the input and output is 32-bit integer or floating-point (64-bit component types are excluded).

In this case, the components of the input will be taken from the first components of the output, and any extra components of the output will be ignored.

14.1.4. Location Assignment

This section describes how many locations are consumed by a given type. As mentioned above, geometry shader inputs, tessellation control shader inputs and outputs, and tessellation evaluation inputs all 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 locations the type consumes.

The `Location` value specifies an interface slot comprised of a 32-bit four-component vector conveyed between stages. The `Component` specifies components within these vector locations. Only types with widths of 32 or 64 are supported in shader interfaces.

Inputs and outputs of the following types consume a single interface location:

- 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 locations.

If a declared input or output is an array of size n and each element takes m locations, it will be assigned $m \times n$ consecutive locations starting with the location specified.

If the declared input or output is an $n \times m$ 32- or 64-bit matrix, it will be assigned multiple locations starting with the location specified. The number of locations assigned for each matrix will be the same as for an n-element array of m-component vectors.

The layout of a structure type used as an `Input` or `Output` depends on whether it is also a `Block` (i.e. has a `Block` decoration).

If it is a not a `Block`, then the structure type **must** have a `Location` decoration. Its members are assigned consecutive locations in their declaration order, with the first member assigned to the location specified for the structure type. The members, and their nested types, **must** not themselves have `Location` decorations.

If the structure type is a `Block` but without a `Location`, then each of its members **must** have a `Location` decoration. If it is a `Block` with a `Location` decoration, then its members are assigned consecutive locations in declaration order, starting from the first member which is initially assigned the location specified for the Block. Any member with its own Location decoration is assigned that location. Each remaining member is assigned the location after the immediately preceding member in declaration order.

The locations 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, either explicitly or implicitly. Any two outputs listed as operands on the same OpEntryPoint **must** not be assigned the same location, either explicitly or implicitly.

The number of input and output locations available for a shader input or output interface are limited, and dependent on the shader stage as described in Shader Input and Output Locations.

Table 11. Shader Input and Output Locations

Shader Interface	Locations Available
vertex input	maxVertexInputAttributes
vertex output	maxVertexOutputComponents / 4
tessellation control input	maxTessellationControlPerVertexInputComponents / 4
tessellation control output	maxTessellationControlPerVertexOutputComponents / 4
tessellation evaluation input	maxTessellationEvaluationInputComponents / 4
tessellation evaluation output	maxTessellationEvaluationOutputComponents / 4
geometry input	maxGeometryInputComponents / 4
geometry output	maxGeometryOutputComponents / 4
fragment input	maxFragmentInputComponents / 4
fragment output	maxFragmentOutputAttachments

14.1.5. Component Assignment

The Component decoration allows the Location to be more finely specified for scalars and vectors, down to the individual components within a location that are consumed. The components within a location are 0, 1, 2, and 3. A variable or block member starting at component N will consume components N, N+1, N+2, … up through its size. For single precision types, it is invalid if this sequence of components gets larger than 3. A scalar 64-bit type will consume two of these components in sequence, and a two-component 64-bit vector type will consume all four components available within a location. A three- or four-component 64-bit vector type **must** not specify a Component decoration. A three-component 64-bit vector type will consume all four components of the first location and components 0 and 1 of the second location. This leaves components 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.

14.2. 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 locations 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.

14.3. Fragment Output Interface

When the fragment stage is present in a pipeline, the fragment shader outputs form an interface with the output attachments of the current subpass. The fragment shader output variables are matched by the `Location` and `Component` decorations to the color attachments specified in the `pColorAttachments` array of the VkSubpassDescription structure that describes the subpass that the fragment shader is executed in.

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 directed to the color attachment indicated by `pColorAttachments`[*i*], 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 locations is given by the `maxFragmentOutputAttachments` member of the `VkPhysicalDeviceLimits` structure.

Components of the output variables are assigned as described in Component Assignment. Output components 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). The input to blending or color attachment writes is undefined for components which do not correspond to a fragment shader output.

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.

No *component aliasing* of output variables is allowed, that is there **must** not be two output variables which have the same location, component, and index, 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. 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 result is undefined for those components.

14.4. 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 that describes 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, and a Sampled operand of 2.

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. 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 basic data type (floating-point, integer, unsigned integer) of the subpass input **must** match the basic format of the corresponding input attachment, or the values of subpass loads from these variables are undefined.

See Input Attachment for more details.

14.5. 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 resources that form the *shader resource interface* for a stage are the variables statically used by OpEntryPoint with the storage class of Uniform, UniformConstant, 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.

14.5.1. 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 variable in a push constant block **must** be placed at an Offset such that the entire constant value 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 variable in a push constant block **must** not cause the space required for that variable to extend outside the range [0, maxPushConstantsSize).

Any variable in a push constant block that is declared as an array **must** only be accessed with *dynamically uniform* indices.

14.5.2. Descriptor Set Interface

The *descriptor set interface* is comprised of the shader variables with the storage class of 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.

Variables identified with the UniformConstant storage class are used only as handles to refer to opaque resources. Such variables **must** be typed as OpTypeImage, OpTypeSampler, OpTypeSampledImage, or arrays of only these types. Variables of type OpTypeImage **must** have a Sampled operand of 1 (sampled image) or 2 (storage image).

Any array of these types **must** only be indexed with constant integral expressions, except under the following conditions:

- For arrays of OpTypeImage variables with Sampled operand of 2, if the shaderStorageImageArrayDynamicIndexing feature is enabled and the shader module declares the

StorageImageArrayDynamicIndexing capability, the array **must** only be indexed by dynamically uniform expressions.

- For arrays of OpTypeSampler, OpTypeSampledImage variables, or OpTypeImage variables with Sampled operand of 1, if the shaderSampledImageArrayDynamicIndexing feature is enabled and the shader module declares the SampledImageArrayDynamicIndexing capability, the array **must** only be indexed by dynamically uniform expressions.

The Sampled Type of an OpTypeImage declaration **must** match the same basic data type as the corresponding resource, or the values obtained by reading or sampling from this image are undefined.

The Image Format of an OpTypeImage declaration **must** not be **Unknown**, for variables which are used for OpImageRead or OpImageWrite operations, except under the following conditions:

- For OpImageWrite, if the shaderStorageImageWriteWithoutFormat feature is enabled and the shader module declares the StorageImageWriteWithoutFormat capability.
- For OpImageRead, if the shaderStorageImageReadWithoutFormat feature is enabled and the shader module declares the StorageImageReadWithoutFormat capability.

Variables identified with the Uniform storage class are used to access transparent buffer backed resources. Such variables **must** be:

- typed as OpTypeStruct, or arrays of only 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.

Any array of these types **must** only be indexed with constant integral expressions, except under the following conditions.

- For arrays of Block variables in the Uniform storage class, if the shaderUniformBufferArrayDynamicIndexing feature is enabled and the shader module declares the UniformBufferArrayDynamicIndexing capability, the array **must** only be indexed by dynamically uniform expressions.
- For arrays of BufferBlock variables in the Uniform storage class , if the shaderStorageBufferArrayDynamicIndexing feature is enabled and the shader module declares the StorageBufferArrayDynamicIndexing capability, the array **must** only be indexed by dynamically uniform expressions.

The Offset decoration for any variable in a Block **must** not cause the space required for that variable to extend outside the range [0, maxUniformBufferRange). The Offset decoration for any variable in a BufferBlock **must** not cause the space required for that variable to extend outside the range [0, maxStorageBufferRange).

Variables identified with a storage class of UniformConstant and a decoration of InputAttachmentIndex **must** be declared as described in Fragment Input Attachment Interface.

Each shader variable in the descriptor set interface **must** be of a type that corresponds to the descriptorType in the descriptor set layout binding that the variable is assigned to, as described in DescriptorSet and Binding Assignment. See Shader Resource and Descriptor Type Correspondence for the relationship between shader types and descriptor types.

Table 12. Shader Resource and Descriptor Type Correspondence

Resource type	Descriptor Type
sampler	VK_DESCRIPTOR_TYPE_SAMPLER or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
sampled image	VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
storage image	VK_DESCRIPTOR_TYPE_STORAGE_IMAGE
combined image sampler	VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
uniform texel buffer	VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER
storage texel buffer	VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER
uniform buffer	VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC
storage buffer	VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC
input attachment	VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT

Table 13. Shader Resource and Storage Class Correspondence

Resource type	Storage Class	Type	Decoration(s)[1]
sampler	UniformConstant	OpTypeSampler	
sampled image	UniformConstant	OpTypeImage (Sampled=1)	
storage image	UniformConstant	OpTypeImage (Sampled=2)	
combined image sampler	UniformConstant	OpTypeSampledImage	
uniform texel buffer	UniformConstant	OpTypeImage (Dim=Buffer, Sampled=1)	
storage texel buffer	UniformConstant	OpTypeImage (Dim=Buffer, Sampled=2)	
uniform buffer	Uniform	OpTypeStruct	Block, Offset, (ArrayStride), (MatrixStride)
storage buffer	Uniform	OpTypeStruct	BufferBlock, Offset, (ArrayStride), (MatrixStride)
input attachment	UniformConstant	OpTypeImage (Dim =SubpassData, Sampled=2)	InputAttachmentIndex

1

in addition to DescriptorSet and Binding

14.5.3. 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 size of the array declaration **must** be no larger than the descriptorCount of that VkDescriptorSetLayoutBinding. 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.

Not all descriptor sets and bindings specified in a pipeline layout need to be used in a particular shader stage or pipeline. If a variable assigned to a given DescriptorSet and Binding pair is statically used in the entry point being compiled, 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 descriptor set layout binding **must** be of a corresponding descriptor type, as defined in Shader Resource and Descriptor Type Correspondence.

It is valid for multiple shader variables to be assigned the same descriptor set and binding values, as long as all those that are statically used by the entry point being compiled are compatible with the descriptor type in the descriptor set layout binding.

Table 14. Shader Resource Limits

Resources per Stage	Resource Types
maxPerStageDescriptorSamplers	sampler
	combined image sampler
maxPerStageDescriptorSampledImages	sampled image
	combined image sampler
	uniform texel buffer
maxPerStageDescriptorStorageImages	storage image
	storage texel buffer
maxPerStageDescriptorUniformBuffers	uniform buffer
	uniform buffer dynamic
maxPerStageDescriptorStorageBuffers	storage buffer
	storage buffer dynamic
maxPerStageDescriptorInputAttachments	input attachment[1]

1

Input attachments **can** only be used in the fragment shader stage

14.5.4. Offset and Stride Assignment

All variables with a storage class of `PushConstant` or `Uniform` **must** be explicitly laid out using the `Offset`, `ArrayStride`, and `MatrixStride` decorations. There are two different layouts requirements depending on the specific resources.

Standard Uniform Buffer Layout

The *base alignment* of the type of an `OpTypeStruct` member of is defined recursively as follows:

- A scalar of size N has a base alignment of N.
- A two-component vector, with components of size N, has a base alignment of 2 N.
- A three- or four-component vector, with components of size N, has a base alignment of 4 N.
- An array has a base alignment equal to the base alignment of its element type, rounded up to a multiple of 16.
- A structure has a base alignment equal to the largest base alignment of any of its members, rounded up to a multiple of 16.
- A row-major matrix of C columns has a base alignment equal to the base alignment of a vector of C matrix components.
- A column-major matrix has a base alignment equal to the base alignment of the matrix column type.

Every member of an `OpTypeStruct` with storage class of `Uniform` and a decoration of `Block` (uniform buffers) **must** be laid out according to the following rules:

- The `Offset` decoration **must** be a multiple of its base alignment.
- Any `ArrayStride` or `MatrixStride` decoration **must** be an integer multiple of the base alignment of the array or matrix from above.
- The `Offset` decoration of a member **must** not place it between the end of a structure or an array and the next multiple of the base alignment of that structure or array.
- The numeric order of `Offset` decorations need not follow member declaration order.

> *Note*
>
> The **std140 layout** in GLSL satisfies these rules.

Standard Storage Buffer Layout

Member variables of an `OpTypeStruct` with a storage class of `PushConstant` (push constants), or a storage class of `Uniform` with a decoration of `BufferBlock` (storage buffers) **must** be laid out as above, except for array and structure base alignment which do not need to be rounded up to a multiple of 16.

> *Note*
>
> The **std430 layout** in GLSL satisfies these rules.

14.6. Built-In Variables

Built-in variables are accessed in shaders by declaring a variable decorated with a `BuiltIn` 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.

`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 point is outside the clip half-space.

The `ClipDistance` decoration **must** be used only within vertex, fragment, tessellation control, tessellation evaluation, and geometry shaders.

In vertex shaders, any variable decorated with `ClipDistance` **must** be declared using the `Output` storage class.

In fragment shaders, any variable decorated with `ClipDistance` **must** be declared using the `Input` storage class.

In tessellation control, tessellation evaluation, or geometry shaders, any variable decorated with `ClipDistance` **must** not be in a storage class other than `Input` or `Output`.

Any variable decorated with `ClipDistance` **must** be declared as an array of 32-bit floating-point values.

> *Note*
>
> The array variable decorated with `ClipDistance` is explicitly sized by the shader.

> *Note*
>
> In the last vertex processing 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 `ClipDistance` is then used by a fragment shader, `ClipDistance` contains these linearly interpolated values.

`CullDistance`

Decorating a variable with the `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.

The CullDistance decoration **must** be used only within vertex, fragment, tessellation control, tessellation evaluation, and geometry shaders.

In vertex shaders, any variable decorated with CullDistance **must** be declared using the Output storage class.

In fragment shaders, any variable decorated with CullDistance **must** be declared using the Input storage class.

In tessellation control, tessellation evaluation, or geometry shaders, any variable decorated with CullDistance **must** not be declared in a storage class other than input or output.

Any variable decorated with CullDistance **must** be declared as an array of 32-bit floating-point values.

> *Note*
>
> In fragment shaders, the values of the CullDistance array are linearly interpolated across each primitive.

> *Note*
>
> If CullDistance decorates an input variable, that variable will contain the corresponding value from the CullDistance decorated output variable from the previous shader stage.

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.

When sample shading is not enabled, the x and y components of FragCoord reflect the location of the center of the pixel, (0.5,0.5).

The z component of FragCoord is the interpolated depth value of the primitive.

The w component is the interpolated $\frac{1}{w}$.

The FragCoord decoration **must** be used only within fragment shaders.

The variable decorated with FragCoord **must** be declared using the Input storage class.

The Centroid interpolation decoration is ignored, but allowed, on FragCoord.

The variable decorated with FragCoord **must** be declared as a four-component vector of 32-bit floating-point values.

FragDepth

Decorating a variable with the FragDepth built-in decoration will make that variable contain the new depth value for all samples covered by the fragment. This value will be used for depth testing and, if the depth test passes, any subsequent write to the depth/stencil attachment.

To write to `FragDepth`, a shader **must** declare the `DepthReplacing` execution mode. If a shader declares the `DepthReplacing` execution mode and there is an execution path through the shader that does not set `FragDepth`, then the fragment's depth value is undefined for executions of the shader that take that path.

The `FragDepth` decoration **must** be used only within fragment shaders.

The variable decorated with `FragDepth` **must** be declared using the `Output` storage class.

The variable decorated with `FragDepth` **must** be declared as a scalar 32-bit floating-point value.

`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.

The `FrontFacing` decoration **must** be used only within fragment shaders.

The variable decorated with `FrontFacing` **must** be declared using the `Input` storage class.

The variable decorated with `FrontFacing` **must** be declared as a boolean.

`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`.

The `GlobalInvocationId` decoration **must** be used only within compute shaders.

The variable decorated with `GlobalInvocationId` **must** be declared using the `Input` storage class.

The variable decorated with `GlobalInvocationId` **must** be declared as a three-component vector of 32-bit integers.

`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 generation of derivatives.

The `HelperInvocation` decoration **must** be used only within fragment shaders.

The variable decorated with `HelperInvocation` **must** be declared using the `Input` storage class.

The variable decorated with `HelperInvocation` **must** be declared as a boolean.

> *Note*
>
> It is very likely that a helper invocation will have a value of SampleMask fragment shader input value that is zero.

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.

The InvocationId decoration **must** be used only within tessellation control and geometry shaders.

The variable decorated with InvocationId **must** be declared using the Input storage class.

The variable decorated with InvocationId **must** be declared as a scalar 32-bit integer.

InstanceIndex

Decorating a variable 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.

The InstanceIndex decoration **must** be used only within vertex shaders.

The variable decorated with InstanceIndex **must** be declared using the Input storage class.

The variable decorated with InstanceIndex **must** be declared as a scalar 32-bit integer.

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 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.

If the last active vertex processing stage shader entry point's interface does not include a variable decorated with Layer, then the first layer is used. If a vertex processing 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.

The Layer decoration **must** be used only within geometry, and fragment shaders.

In a geometry shader, any variable decorated with Layer **must** be declared using the Output storage class.

In a fragment shader, a variable decorated with `Layer` contains the layer index of the primitive that the fragment invocation belongs to.

In a fragment shader, any variable decorated with `Layer` **must** be declared using the `Input` storage class.

Any variable decorated with `Layer` **must** be declared as a scalar 32-bit integer.

`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.

The `LocalInvocationId` decoration **must** be used only within compute shaders.

The variable decorated with `LocalInvocationId` **must** be declared using the `Input` storage class.

The variable decorated with `LocalInvocationId` **must** be declared as a three-component vector of 32-bit integers.

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.

`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 dispatch commands.

The `NumWorkgroups` decoration **must** be used only within compute shaders.

The variable decorated with `NumWorkgroups` **must** be declared using the `Input` storage class.

The variable decorated with `NumWorkgroups` **must** be declared as a three-component vector of 32-bit integers.

`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. A single tessellation control or tessellation evaluation shader **can** read patches of differing sizes, so the value of the `PatchVertices` variable **may** differ between patches.

The `PatchVertices` decoration **must** be used only within tessellation control and tessellation evaluation shaders.

The variable decorated with PatchVertices **must** be declared using the Input storage class.

The variable decorated with PatchVertices **must** be declared as a scalar 32-bit integer.

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.

The PointCoord decoration **must** be used only within fragment shaders.

The variable decorated with PointCoord **must** be declared using the Input storage class.

The variable decorated with PointCoord **must** be declared as two-component vector of 32-bit floating-point values.

> *Note*
>
> Depending on how the point is rasterized, PointCoord **may** never reach (0,0) or (1,1).

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 PointSize by the last vertex processing stage in the pipeline is used as the framebuffer-space size of points produced by rasterization.

The PointSize decoration **must** be used only within vertex, tessellation control, tessellation evaluation, and geometry shaders.

In a vertex shader, any variable decorated with PointSize **must** be declared using the Output storage class.

In a tessellation control, tessellation evaluation, or geometry shader, any variable decorated with PointSize **must** be declared using either the Input or Output storage class.

Any variable decorated with PointSize **must** be declared as a scalar 32-bit floating-point value.

> *Note*
>
> When PointSize decorates a variable in the Input storage class, it contains the data written to the output variable decorated with PointSize from the previous shader stage.

Position

Decorating a variable with the Position built-in decoration will make that variable contain the position of the current vertex. In the last vertex processing stage, the value of the variable decorated with Position is used in subsequent primitive assembly, clipping, and rasterization operations.

The Position decoration **must** be used only within vertex, tessellation control, tessellation evaluation, and geometry shaders.

In a vertex shader, any variable decorated with Position **must** be declared using the Output storage class.

In a tessellation control, tessellation evaluation, or geometry shader, any variable decorated with Position **must** not be declared in a storage class other than Input or Output.

Any variable decorated with Position **must** be declared as a four-component vector of 32-bit floating-point values.

> *Note*
>
> When Position decorates a variable in the Input storage class, it contains the data written to the output variable decorated with Position from the previous shader stage.

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 correspond 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.

If a geometry shader is present and the fragment shader reads from an input variable decorated with PrimitiveId, then the geometry shader **must** write to an output variable decorated with PrimitiveId in all execution paths.

The PrimitiveId decoration **must** be used only within fragment, tessellation control, tessellation evaluation, and geometry shaders.

In a tessellation control or tessellation evaluation shader, any variable decorated with PrimitiveId **must** be declared using the Output storage class.

In a geometry shader, any variable decorated with `PrimitiveId` **must** be declared using either the `Input` or `Output` storage class.

In a fragment shader, any variable decorated with `PrimitiveId` **must** be declared using the `Input` storage class, and either the `Geometry` or `Tessellation` capability **must** also be declared.

Any variable decorated with `PrimitiveId` **must** be declared as a scalar 32-bit integer.

> *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.

`SampleId`

Decorating a variable with the `SampleId` built-in decoration will make that variable contain the zero-based index of the sample the invocation corresponds to. `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.

The `SampleId` decoration **must** be used only within fragment shaders.

The variable decorated with `SampleId` **must** be declared using the `Input` storage class.

The variable decorated with `SampleId` **must** be declared as a scalar 32-bit integer.

`SampleMask`

Decorating a variable with the `SampleMask` built-in decoration will make any variable contain the sample coverage 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 × M + B.

When state specifies multiple fragment shader invocations for a given fragment, the sample mask for any single fragment shader invocation specifies the subset of the covered samples for the fragment that correspond to the invocation. In this case, the bit corresponding to each covered sample will be set in exactly one fragment shader invocation.

A variable in the `Output` storage class decorated with `SampleMask` is an array of integers forming a bit array in a manner similar an input variable decorated with `SampleMask`, but where each bit represents coverage as computed by the shader. Modifying the sample mask by writing zero to a bit of `SampleMask` causes the sample to be considered uncovered. However, setting sample mask bits to one will never enable samples not covered by the original primitive. If the fragment shader is being evaluated at any frequency other than per-fragment, bits of the sample mask not corresponding to the current fragment shader invocation are ignored. This array **must** be sized in the fragment shader either implicitly or explicitly, 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.

The `SampleMask` decoration **must** be used only within fragment shaders.

Any variable decorated with `SampleMask` **must** be declared using either the `Input` or `Output` storage class.

Any variable decorated with `SampleMask` **must** be declared as an array of 32-bit integers.

`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.

The `SamplePosition` decoration **must** be used only within fragment shaders.

The variable decorated with `SamplePosition` **must** be declared using the `Input` storage class.

The variable decorated with `SamplePosition` **must** be declared as a two-component vector of 32-bit floating-point values.

`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.

The `TessCoord` decoration **must** be used only within tessellation evaluation shaders.

The variable decorated with `TessCoord` **must** be declared using the `Input` storage class.

The variable decorated with `TessCoord` **must** be declared as 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 which controls 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.

The `TessLevelOuter` decoration **must** be used only within tessellation control and tessellation evaluation shaders.

In a tessellation control shader, any variable decorated with `TessLevelOuter` **must** be declared using the `Output` storage class.

In a tessellation evaluation shader, any variable decorated with `TessLevelOuter` **must** be declared using the `Input` storage class.

Any 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, which controls 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.

The `TessLevelInner` decoration **must** be used only within tessellation control and tessellation evaluation shaders.

In a tessellation control shader, any variable decorated with `TessLevelInner` **must** be declared using the `Output` storage class.

In a tessellation evaluation shader, any variable decorated with `TessLevelInner` **must** be declared using the `Input` storage class.

Any 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.

The `VertexIndex` decoration **must** be used only within vertex shaders.

The variable decorated with `VertexIndex` **must** be declared using the `Input` storage class.

The variable decorated with `VertexIndex` **must** be declared as a scalar 32-bit integer.

> *Note*
>
> `VertexIndex` starts at the same starting value for each instance.

`ViewportIndex`

Decorating a variable with the `ViewportIndex` built-in decoration will make that variable contain the index of the viewport.

In a 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.

If the last active vertex processing stage shader entry point's interface does not include a variable decorated with `ViewportIndex`, then the first viewport is used. If a vertex processing 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.

The `ViewportIndex` decoration **must** be used only within geometry, and fragment shaders.

In a geometry shader, any variable decorated with `ViewportIndex` **must** be declared using the `Output` storage class.

In a fragment shader, the variable decorated with `ViewportIndex` contains the viewport index of the primitive that the fragment invocation belongs to.

In a fragment shader, any variable decorated with `ViewportIndex` **must** be declared using the `Input` storage class.

Any variable decorated with `ViewportIndex` **must** be declared as a scalar 32-bit integer.

`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 dispatch commands.

The `WorkgroupId` decoration **must** be used only within compute shaders.

The variable decorated with `WorkgroupId` **must** be declared using the `Input` storage class.

The variable decorated with `WorkgroupId` **must** be declared as a three-component vector of 32-bit integers.

`WorkgroupSize`

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 **must** take precedence over any execution mode set for `LocalSize`.

The `WorkgroupSize` decoration **must** be used only within compute shaders.

The object decorated with `WorkgroupSize` **must** be a specialization constant or a constant.

The object decorated with `WorkgroupSize` **must** be declared as a three-component vector of 32-bit integers.

Chapter 15. Image Operations

15.1. Image Operations Overview

Image Operations are steps performed by SPIR-V image instructions, where those instructions which take an OpTypeImage (representing a VkImageView) or OpTypeSampledImage (representing a (VkImageView, VkSampler) pair) and texel coordinates as operands, and return a value based on one or more neighboring texture elements (*texels*) in the image.

> *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.

SPIR-V Image Instructions include the following functionality:

- 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.
- Instructions with Dref in the name apply depth comparison on the texel values.
- Instructions with Sparse in the name additionally return a sparse residency code.

15.1.1. 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)

SPIR-V OpImageFetch, OpImageSparseFetch, OpImageRead, OpImageSparseRead, and OpImageWrite instructions use integer texel coordinates. 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), and the first four in that order have the same meanings as unnormalized texel coordinates. They are extracted from the SPIR-V operand in order (i, [,j], [,k], [,l]), 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 the sample index and is taken from the `Sample` image operand.

For all coordinate types, unused coordinates are assigned a value of zero.

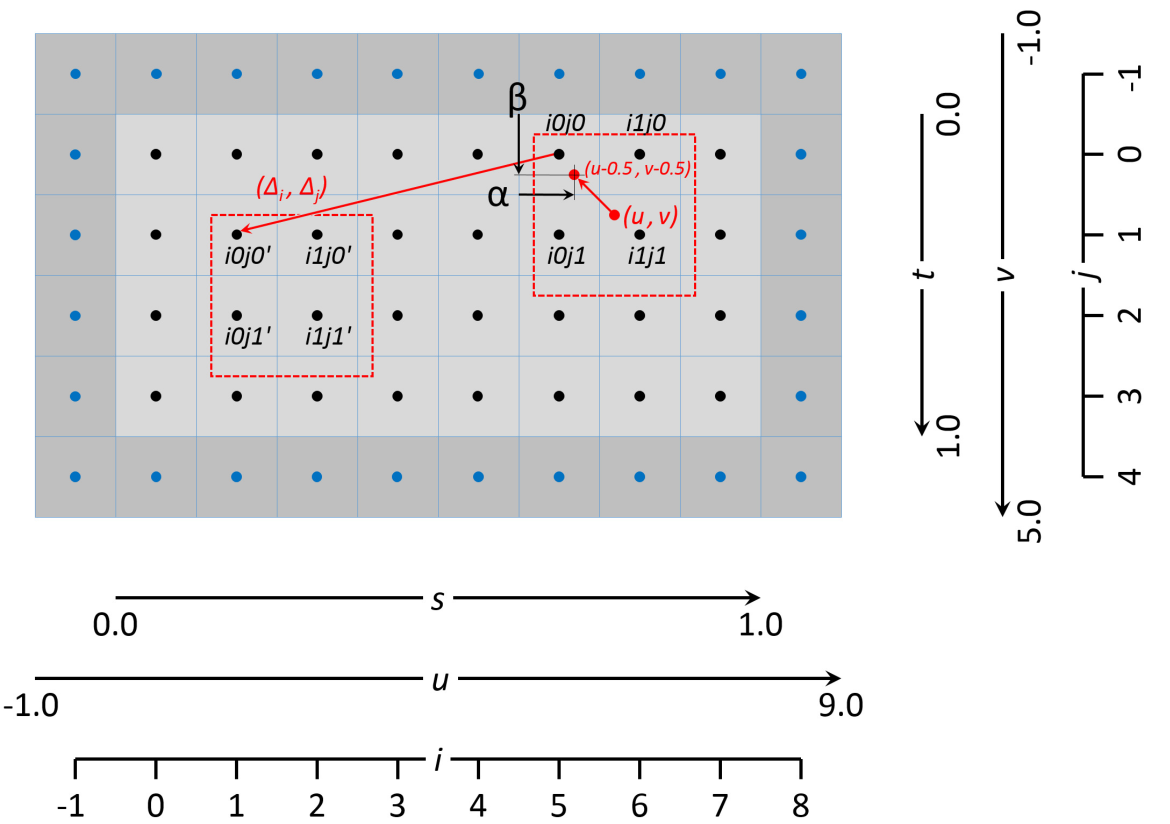

Figure 2. Texel Coordinate Systems

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, left to right.
  - The t coordinate goes from 0.0 to 1.0, top to bottom.
- Unnormalized texel coordinates:
  - The u coordinate goes from -1.0 to 9.0, left to right. The u coordinate within the range 0.0 to 8.0 is within the image, otherwise it is within the border.
  - The v coordinate goes from -1.0 to 5.0, top to bottom. The v coordinate within the range 0.0 to 4.0 is within the image, otherwise it is within the border.
- Integer texel coordinates:
  - The i coordinate goes from -1 to 8, left to right. The i coordinate within the range 0 to 7 addresses texels within the image, otherwise it addresses a border texel.
  - The j coordinate goes from -1 to 5, top to bottom. The j coordinate within the range 0 to 3 addresses texels within the image, otherwise it addresses a border texel.
- Also shown for linear filtering:
  - Given the unnormalized coordinates (u,v), the four texels selected are i_0j_0, i_1j_0, i_0j_1, and i_1j_1.
  - The weights α and β.

◦ Given the offset Δ_i and Δ_j, the four texels selected by the offset are $i_0j'_0$, $i_1j'_0$, $i_0j'_1$, and $i_1j'_1$.

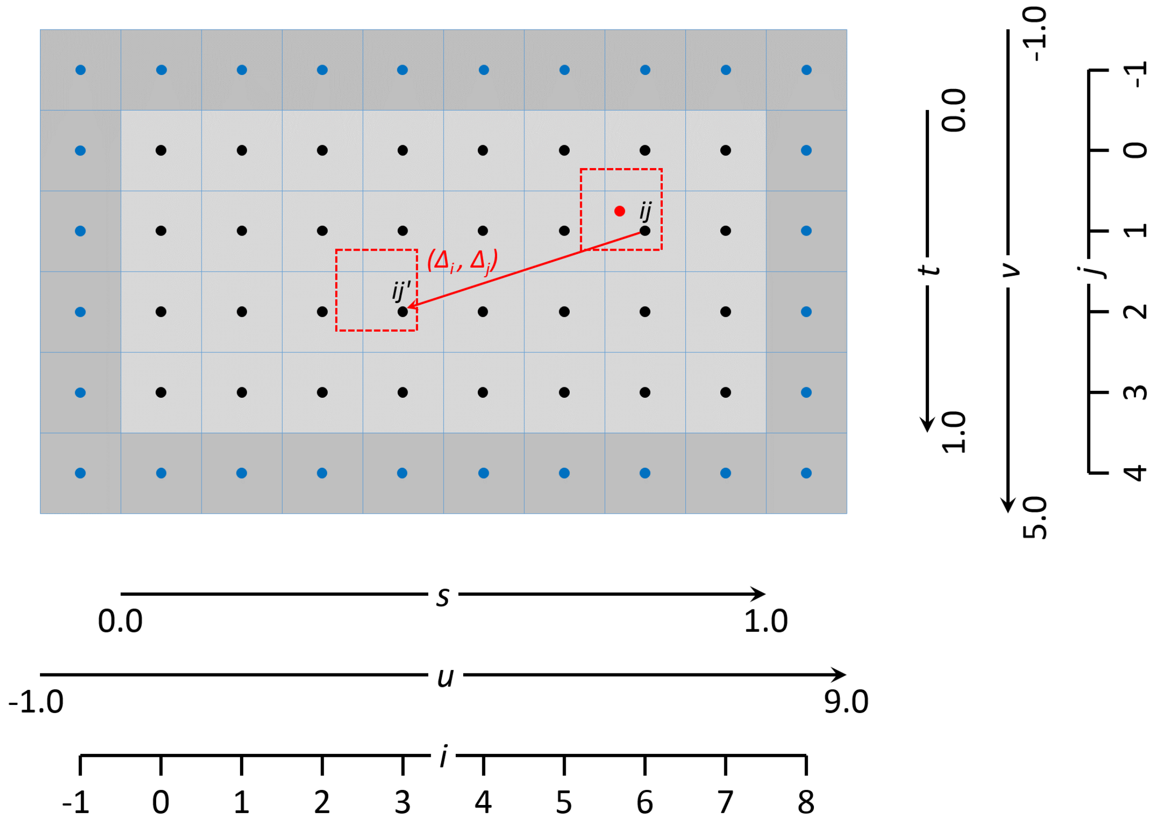

Figure 3. Texel Coordinate Systems

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 Δ_i and Δ_j, the texel selected by the offset is ij'.

15.2. Conversion Formulas

15.2.1. RGB to Shared Exponent Conversion

An RGB color (red, green, blue) is transformed to a shared exponent color (red_{shared}, $green_{shared}$, $blue_{shared}$, exp_{shared}) as follows:

First, the components (red, green, blue) are clamped to ($red_{clamped}$, $green_{clamped}$, $blue_{clamped}$) as:

$$red_{clamped} = \max(0, \min(sharedexp_{max}, red))$$

$$green_{clamped} = \max(0, \min(sharedexp_{max}, green))$$

$blue_{clamped} = max(0, min(sharedexp_{max}, blue))$

Where:

$$\begin{aligned} N &= 9 && \text{number of mantissa bits per component} \\ B &= 15 && \text{exponent bias} \\ E_{max} &= 31 && \text{maximum possible biased exponent value} \\ sharedexp_{max} &= \frac{(2^N - 1)}{2^N} \times 2^{(E_{max} - B)} \end{aligned}$$

> *Note*
>
> NaN, if supported, is handled as in IEEE 754-2008 `minNum()` and `maxNum()`. That is the result is a NaN is mapped to zero.

The largest clamped component, $max_{clamped}$ is determined:

$max_{clamped} = max(red_{clamped}, green_{clamped}, blue_{clamped})$

A preliminary shared exponent exp' is computed:

$$exp' = \begin{cases} \lfloor \log_2(max_{clamped}) \rfloor + (B + 1) & \text{for } max_{clamped} > 2^{-(B+1)} \\ 0 & \text{for } max_{clamped} \leq 2^{-(B+1)} \end{cases}$$

The shared exponent exp_{shared} is computed:

$$max_{shared} = \left\lfloor \frac{max_{clamped}}{2^{(exp' - B - N)}} + \frac{1}{2} \right\rfloor$$

$$exp_{shared} = \begin{cases} exp' & \text{for } 0 \leq max_{shared} < 2^N \\ exp' + 1 & \text{for } max_{shared} = 2^N \end{cases}$$

Finally, three integer values in the range 0 to 2^N are computed:

$$\begin{aligned} red_{shared} &= \left\lfloor \frac{red_{clamped}}{2^{(exp_{shared} - B - N)}} + \frac{1}{2} \right\rfloor \\ green_{shared} &= \left\lfloor \frac{green_{clamped}}{2^{(exp_{shared} - B - N)}} + \frac{1}{2} \right\rfloor \\ blue_{shared} &= \left\lfloor \frac{blue_{clamped}}{2^{(exp_{shared} - B - N)}} + \frac{1}{2} \right\rfloor \end{aligned}$$

15.2.2. Shared Exponent to RGB

A shared exponent color (red_{shared}, $green_{shared}$, $blue_{shared}$, exp_{shared}) is transformed to an RGB color (red, green, blue) as follows:

$$red = red_{shared} \times 2^{(exp_{shared} - B - N)}$$

$$green = green_{shared} \times 2^{(exp_{shared} - B - N)}$$

$$blue = blue_{shared} \times 2^{(exp_{shared} - B - N)}$$

Where:

N = 9 (number of mantissa bits per component)

B = 15 (exponent bias)

15.3. 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

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.

15.3.1. 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. There are a number of 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 VK_COMPONENT_SWIZZLE_IDENTITY.
- The VkImageLayout of any subresource in the image view does not match that specified in VkDescriptorImageInfo::imageLayout used to write the image descriptor.
- If the instruction is OpImageRead or OpImageSparseRead and the shaderStorageImageReadWithoutFormat feature is not enabled, or the instruction is OpImageWrite and the shaderStorageImageWriteWithoutFormat feature is not enabled, then the SPIR-V Image Format **must** be 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 and the image view format is not one of the depth/stencil formats with a depth component, or 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.

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

$0 \le i < w_s$

$0 \le j < h_s$

$0 \le k < d_s$

$0 \le l < layers$

$0 \le n < samples$

where:

w_s = width of the image level

h_s = height of the image level

d_s = depth of the image level

layers = number of layers in the image

samples = 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 on the borders along the edges and corners of a cube map image, and Cube map edge handling is performed.

Cube Map Edge Handling

If the texel coordinates lie on the borders along the edges and corners of a cube map image, the following steps are performed. Note that this only occurs when using `VK_FILTER_LINEAR` 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 along the border in either only i or only j

  then the texel lies along an edge, so 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 along the border in both i and j

  then the texel lies at a corner and 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, subject to the constraint that if the three available samples have the same value, the replacement texel also has 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.

15.3.2. 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 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.

15.3.3. 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 15. Border Color B

Sampler `borderColor`	**Corresponding Border Color**
`VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK`	B = (0.0, 0.0, 0.0, 0.0)
`VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK`	B = (0.0, 0.0, 0.0, 1.0)
`VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE`	B = (1.0, 1.0, 1.0, 1.0)
`VK_BORDER_COLOR_INT_TRANSPARENT_BLACK`	B = (0, 0, 0, 0)
`VK_BORDER_COLOR_INT_OPAQUE_BLACK`	B = (0, 0, 0, 1)
`VK_BORDER_COLOR_INT_OPAQUE_WHITE`	B = (1, 1, 1, 1)

> *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 16. Border Texel Components After Replacement

Texel Aspect or Format	**Component Assignment**
Depth aspect	$D = B_r$
Stencil aspect	$S = B_r$
One component color format	$C_r = B_r$

Texel Aspect or Format	Component Assignment
Two component color format	$C_{rg} = (B_r,B_g)$
Three component color format	$C_{rgb} = (B_r,B_g,B_b)$
Four component color format	$C_{rgba} = (B_r,B_g,B_b,B_a)$

If the read operation is from a buffer resource, and the `robustBufferAccess` feature is enabled, an invalid texel is replaced as described here.

If the `robustBufferAccess` feature is not enabled, the value of an invalid texel is undefined.

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 read **must** be safe, but the value of the sparse unbound texel is undefined.

15.3.4. Depth Compare Operation

If the image view has a depth/stencil format, the depth component is selected by the `aspectMask`, and the operation is a `Dref` instruction, a depth comparison is performed. The value of the result D is 1.0 if the result of the compare operation is true, and 0.0 otherwise. The compare operation is selected by the `compareOp` member of the sampler.

$$
\begin{array}{ll}
D = 1.0 & \begin{cases} D_{ref} \leq D & \text{for LEQUAL} \\ D_{ref} \geq D & \text{for GEQUAL} \\ D_{ref} < D & \text{for LESS} \\ D_{ref} > D & \text{for GREATER} \\ D_{ref} = D & \text{for EQUAL} \\ D_{ref} \neq D & \text{for NOTEQUAL} \\ true & \text{for ALWAYS} \\ false & \text{for NEVER} \end{cases} \\
D = 0.0 & \text{otherwise}
\end{array}
$$

where, in the depth comparison:

D_{ref} = shaderOp.D_{ref} (from **optional** SPIR-V operand)

D (texel depth value)

15.3.5. Conversion to RGBA

The texel is expanded from one, two, or three to four components based on the image base color:

Table 17. Texel Color After Conversion To RGBA

Texel Aspect or Format	RGBA Color
Depth aspect	$C_{rgba} = (D,0,0,one)$
Stencil aspect	$C_{rgba} = (S,0,0,one)$

Texel Aspect or Format	RGBA Color
One component color format	$C_{rgba} = (C_r,0,0,one)$
Two component color format	$C_{rgba} = (C_{rg},0,one)$
Three component color format	$C_{rgba} = (C_{rgb},one)$
Four component color format	$C_{rgba} = C_{rgba}$

where one = 1.0f for floating-point formats and depth aspects, and one = 1 for integer formats and stencil aspects.

15.3.6. 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.

The swizzle **can** rearrange the components of the texel, or substitute zero and one for any components. It is defined as follows for the R component, and operates similarly for the other components.

$$C'_{rgba}[R] = \begin{cases} C_{rgba}[R] & \text{for RED swizzle} \\ C_{rgba}[G] & \text{for GREEN swizzle} \\ C_{rgba}[B] & \text{for BLUE swizzle} \\ C_{rgba}[A] & \text{for ALPHA swizzle} \\ 0 & \text{for ZERO swizzle} \\ one & \text{for ONE swizzle} \\ C_{rgba}[R] & \text{for IDENTITY swizzle} \end{cases}$$

where:

$$\begin{aligned} &C_{rgba}[R] \text{is the RED component} \\ &C_{rgba}[G] \text{is the GREEN component} \\ &C_{rgba}[B] \text{is the BLUE component} \\ &C_{rgba}[A] \text{is the ALPHA component} \\ &one = 1.0\text{f} \quad \text{for floating point components} \\ &one = 1 \quad \text{for integer components} \end{aligned}$$

For each component this is applied to, the `VK_COMPONENT_SWIZZLE_IDENTITY` swizzle selects the corresponding component from C_{rgba}.

If the border color is one of the `VK_BORDER_COLOR_*_OPAQUE_BLACK` enums and the VkComponentSwizzle is not `VK_COMPONENT_SWIZZLE_IDENTITY` for all components (or the equivalent identity mapping), the value of the texel after swizzle is undefined.

15.3.7. 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.

15.4. 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
  - Coordinate validation
  - Sparse validation
- Texel output format conversion

15.4.1. 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 effect of the write on the image view's memory is undefined, but the write **must** not access memory outside of the image view.

15.4.2. 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.

15.4.3. 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 effect of the write is undefined but **must** be safe. In addition, the write **may** have a side effect that is visible to other image instructions, but **must** not be written to any device memory allocation.

15.4.4. Texel Output Format Conversion

Texels undergo a format conversion from the floating point, signed, or unsigned integer type of the texel data to the VkFormat of the image view. Any unused components are ignored.

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 and Fixed-

Point Data Conversion.

15.5. Derivative Operations

SPIR-V derivative instructions include `OpDPdx`, `OpDPdy`, `OpDPdxFine`, `OpDPdyFine`, `OpDPdxCoarse`, and `OpDPdyCoarse`. Derivative instructions are only available in a fragment shader.

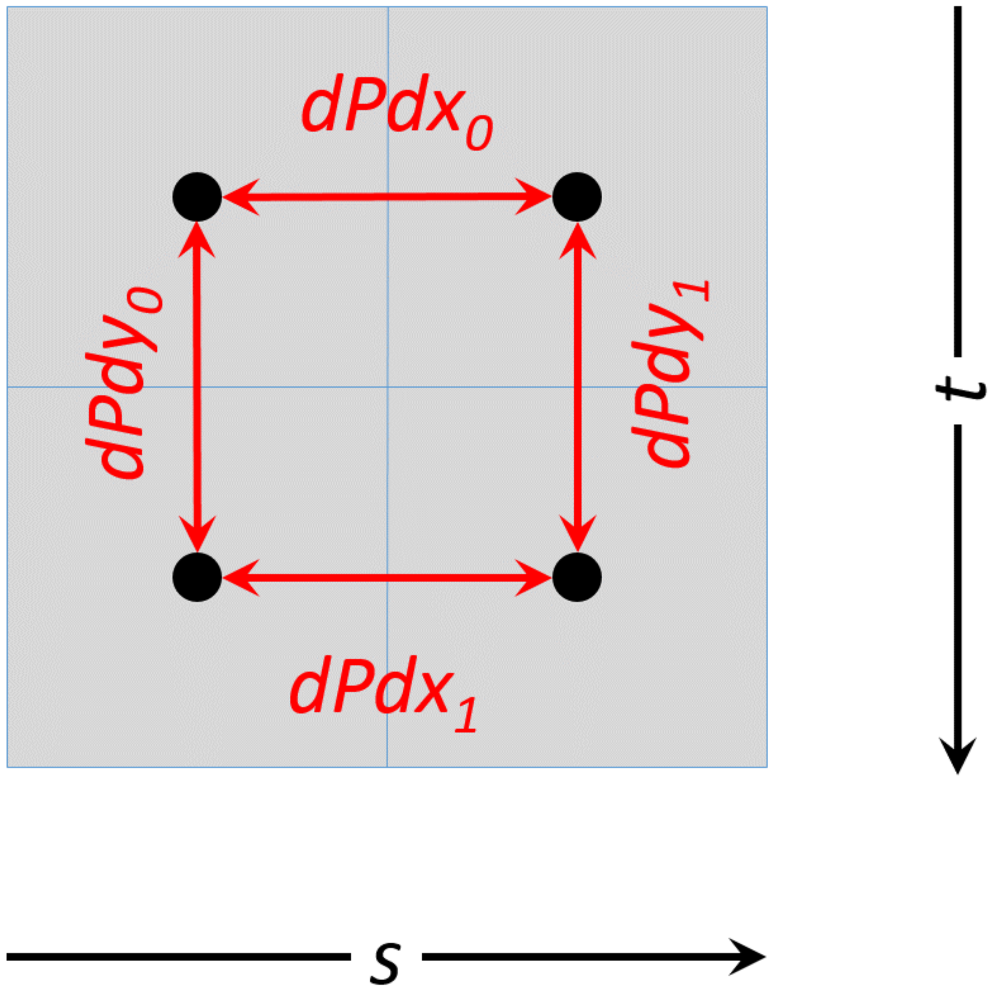

Figure 4. Implicit Derivatives

Derivatives are computed as if there is a 2×2 neighborhood of fragments for each fragment shader invocation. These neighboring fragments are used to compute derivatives with the assumption that the values of P in the neighborhood are piecewise linear. It is further assumed that the values of P in the neighborhood are locally continuous, therefore derivatives in non-uniform control flow are undefined.

$$
\begin{aligned}
dPdx_{i_1,\ j_0} = dPdx_{i_0,\ j_0} &= P_{i_1,\ j_0} - P_{i_0,\ j_0} \\
dPdx_{i_1,\ j_1} = dPdx_{i_0,\ j_1} &= P_{i_1,\ j_1} - P_{i_0,\ j_1} \\
dPdy_{i_0,\ j_1} = dPdy_{i_0,\ j_0} &= P_{i_0,\ j_1} - P_{i_0,\ j_0} \\
dPdy_{i_1,\ j_1} = dPdy_{i_1,\ j_0} &= P_{i_1,\ j_1} - P_{i_1,\ j_0}
\end{aligned}
$$

The `Fine` derivative instructions **must** return the values above, for a group of fragments in a 2×2 neighborhood. Coarse derivatives **may** return only two values. In this case, the values **should** be:

$$
dPdx = \begin{cases} dPdx_{i_0,\ j_0} & \text{preferred} \\ dPdx_{i_0,\ j_1} \end{cases}
$$

$$
dPdy = \begin{cases} dPdy_{i_0,\ j_0} & \text{preferred} \\ dPdy_{i_1,\ j_0} \end{cases}
$$

`OpDPdx` and `OpDPdy` **must** return the same result as either `OpDPdxFine` or `OpDPdxCoarse` and either `OpDPdyFine` or `OpDPdyCoarse`, respectively. Implementations **must** make the same choice of either coarse or fine for both `OpDPdx` and `OpDPdy`, and implementations **should** make the choice that is more efficient to compute.

15.6. Normalized Texel Coordinate Operations

If the image sampler instruction provides normalized texel coordinates, some of the following operations are performed.

15.6.1. 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:

$$
\begin{aligned}
s &= \frac{s}{q}, && \text{for 1D, 2D, or 3D image} \\
t &= \frac{t}{q}, && \text{for 2D or 3D image} \\
r &= \frac{r}{q}, && \text{for 3D image} \\
D_{ref} &= \frac{D_{ref}}{q}, && \text{if provided}
\end{aligned}
$$

15.6.2. 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 above. That is:

$$
\begin{aligned}
\partial s / \partial x &= dPdx(s), & \partial s / \partial y &= dPdy(s), && \text{for 1D, 2D, Cube, or 3D image} \\
\partial t / \partial x &= dPdx(t), & \partial t / \partial y &= dPdy(t), && \text{for 2D, Cube, or 3D image} \\
\partial u / \partial x &= dPdx(u), & \partial u / \partial y &= dPdy(u), && \text{for Cube or 3D image}
\end{aligned}
$$

Partial derivatives not defined above for certain image dimensionalities are set to zero.

For explicit LOD image instructions, if the **optional** SPIR-V operand 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 **optional** SPIR-V operand 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 λ_{base} as described in Level-of-Detail Operation.

15.6.3. 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_{face},t_{face}), The direction vector is also used to transform the derivatives to per-face derivatives.

15.6.4. 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 **must** have rules to disambiguate this situation.

The rules **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 **may** choose other rules, but the rules **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_c, t_c, r_c, and the selection of derivatives, are determined by the major axis direction as specified in the following two tables.

Table 18. Cube map face and coordinate selection

Major Axis Direction	Layer Number	Cube Map Face	s_c	t_c	r_c
$+r_x$	0	Positive X	$-r_z$	$-r_y$	r_x
$-r_x$	1	Negative X	$+r_z$	$-r_y$	r_x
$+r_y$	2	Positive Y	$+r_x$	$+r_z$	r_y
$-r_y$	3	Negative Y	$+r_x$	$-r_z$	r_y
$+r_z$	4	Positive Z	$+r_x$	$-r_y$	r_z
$-r_z$	5	Negative Z	$-r_x$	$-r_y$	r_z

Table 19. Cube map derivative selection

Major Axis Direction	$\partial s_c / \partial x$	$\partial s_c / \partial y$	$\partial t_c / \partial x$	$\partial t_c / \partial y$	$\partial r_c / \partial x$	$\partial r_c / \partial y$
$+r_x$	$-\partial r_z / \partial x$	$-\partial r_z / \partial y$	$-\partial r_y / \partial x$	$-\partial r_y / \partial y$	$+\partial r_x / \partial x$	$+\partial r_x / \partial y$
$-r_x$	$+\partial r_z / \partial x$	$+\partial r_z / \partial y$	$-\partial r_y / \partial x$	$-\partial r_y / \partial y$	$-\partial r_x / \partial x$	$-\partial r_x / \partial y$
$+r_y$	$+\partial r_x / \partial x$	$+\partial r_x / \partial y$	$+\partial r_z / \partial x$	$+\partial r_z / \partial y$	$+\partial r_y / \partial x$	$+\partial r_y / \partial y$
$-r_y$	$+\partial r_x / \partial x$	$+\partial r_x / \partial y$	$-\partial r_z / \partial x$	$-\partial r_z / \partial y$	$-\partial r_y / \partial x$	$-\partial r_y / \partial y$
$+r_z$	$+\partial r_x / \partial x$	$+\partial r_x / \partial y$	$-\partial r_y / \partial x$	$-\partial r_y / \partial y$	$+\partial r_z / \partial x$	$+\partial r_z / \partial y$
$-r_z$	$-\partial r_x / \partial x$	$-\partial r_x / \partial y$	$-\partial r_y / \partial x$	$-\partial r_y / \partial y$	$-\partial r_z / \partial x$	$-\partial r_z / \partial y$

15.6.5. Cube Map Coordinate Transformation

$$s_{face} = \frac{1}{2} \times \frac{s_c}{|r_c|} + \frac{1}{2}$$
$$t_{face} = \frac{1}{2} \times \frac{t_c}{|r_c|} + \frac{1}{2}$$

15.6.6. Cube Map Derivative Transformation

$$\frac{\partial s_{face}}{\partial x} = \frac{\partial}{\partial x}\left(\frac{1}{2} \times \frac{s_c}{|r_c|} + \frac{1}{2}\right)$$
$$\frac{\partial s_{face}}{\partial x} = \frac{1}{2} \times \frac{\partial}{\partial x}\left(\frac{s_c}{|r_c|}\right)$$
$$\frac{\partial s_{face}}{\partial x} = \frac{1}{2} \times \left(\frac{|r_c| \times \partial s_c / \partial x - s_c \times \partial r_c / \partial x}{(r_c)^2}\right)$$

$$\frac{\partial s_{face}}{\partial y} = \frac{1}{2} \times \left(\frac{|r_c| \times \partial s_c / \partial y - s_c \times \partial r_c / \partial y}{(r_c)^2}\right)$$
$$\frac{\partial t_{face}}{\partial x} = \frac{1}{2} \times \left(\frac{|r_c| \times \partial t_c / \partial x - t_c \times \partial r_c / \partial x}{(r_c)^2}\right)$$
$$\frac{\partial t_{face}}{\partial y} = \frac{1}{2} \times \left(\frac{|r_c| \times \partial t_c / \partial y - t_c \times \partial r_c / \partial y}{(r_c)^2}\right)$$

15.6.7. Scale Factor Operation, Level-of-Detail 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 implicit LOD selected **can** be queried using the SPIR-V instruction `OpImageQueryLod`, which gives access to the λ' and d_l values, defined below.

Scale Factor Operation

The magnitude of the derivatives are calculated by:

$m_{ux} = |\partial s/\partial x| \times w_{base}$

$m_{vx} = |\partial t/\partial x| \times h_{base}$

$m_{wx} = |\partial r/\partial x| \times d_{base}$

$m_{uy} = |\partial s/\partial y| \times w_{base}$

$m_{vy} = |\partial t/\partial y| \times h_{base}$

$m_{wy} = |\partial r/\partial y| \times d_{base}$

where:

$\partial t/\partial x = \partial t/\partial y = 0$ (for 1D images)

$\partial r/\partial x = \partial r/\partial y = 0$ (for 1D, 2D or Cube images)

and

w_{base} = image.w

h_{base} = image.h

d_{base} = image.d

(for the `baseMipLevel`, from the image descriptor).

A point sampled in screen space has an elliptical footprint in texture space. The minimum and maximum scale factors (ρ_{min}, ρ_{max}) **should** be the minor and major axes of this ellipse.

The *scale factors* ρ_x and ρ_y, calculated from the magnitude of the derivatives in x and y, are used to compute the minimum and maximum scale factors.

ρ_x and ρ_y **may** be approximated with functions f_x and f_y, subject to the following constraints:

$$f_x \text{ is continuous and monotonically increasing in each of } m_{ux}, m_{vx}, \text{ and } m_{wx}$$
$$f_y \text{ is continuous and monotonically increasing in each of } m_{uy}, m_{vy}, \text{ and } m_{wy}$$

$$\max(|m_{ux}|, |m_{vx}|, |m_{wx}|) \leq f_x \leq \sqrt{2}(|m_{ux}| + |m_{vx}| + |m_{wx}|)$$
$$\max(|m_{uy}|, |m_{vy}|, |m_{wy}|) \leq f_y \leq \sqrt{2}(|m_{uy}| + |m_{vy}| + |m_{wy}|)$$

The minimum and maximum scale factors (ρ_{min},ρ_{max}) are determined by:

$\rho_{max} = \max(\rho_x, \rho_y)$

$\rho_{min} = \min(\rho_x, \rho_y)$

The sampling rate is determined by:

$$N = \min(\lceil \rho_{max} / \rho_{min} \rceil, max_{Aniso})$$

where:

$sampler.max_{Aniso}$ = `maxAnisotropy` (from sampler descriptor)

$limits.max_{Aniso}$ = `maxSamplerAnisotropy` (from physical device limits)

$max_{Aniso} = \min(sampler.max_{Aniso}, limits.max_{Aniso})$

If $\rho_{max} = \rho_{min} = 0$, then all the partial derivatives are zero, the fragment's footprint in texel space is a point, and N **should** be treated as 1. If $\rho_{max} \neq 0$ and $\rho_{min} = 0$ then all partial derivatives along one axis are zero, the fragment's footprint in texel space is a line segment, and N **should** be treated as max_{Aniso}. However, anytime the footprint is small in texel space the implementation **may** use a smaller value of N, even when ρ_{min} is zero or close to zero.

An implementation **may** round N up to the nearest supported sampling rate.

If N = 1, sampling is isotropic. If N > 1, sampling is anisotropic.

Level-of-Detail Operation

The LOD parameter λ is computed as follows:

$$\lambda_{base}(x,y) = \begin{cases} shaderOp.Lod & \text{(from optional SPIR-V operand)} \\ \log_2\left(\frac{\rho_{max}}{N}\right) & \text{otherwise} \end{cases}$$

$$\lambda'(x,y) = \lambda_{base} + \text{clamp}(sampler.bias + shaderOp.bias, -maxSamplerLodBias, maxSamplerLodBias)$$

$$\lambda = \begin{cases} lod_{max}, & \lambda' > lod_{max} \\ \lambda', & lod_{min} \leq \lambda' \leq lod_{max} \\ lod_{min}, & \lambda' < lod_{min} \\ undefined, & lod_{min} > lod_{max} \end{cases}$$

where:

$$\begin{aligned} sampler.bias &= mipLodBias & \text{(from sampler descriptor)} \\ shaderOp.bias &= \begin{cases} Bias & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases} \\ sampler.lod_{min} &= minLod & \text{(from sampler descriptor)} \\ shaderOp.lod_{min} &= \begin{cases} MinLod & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases} \\ lod_{min} &= \max(sampler.lod_{min}, shaderOp.lod_{min}) \\ lod_{max} &= maxLod & \text{(from sampler descriptor)} \end{aligned}$$

and maxSamplerLodBias is the value of the VkPhysicalDeviceLimits feature `maxSamplerLodBias`.

Image Level(s) Selection

The image level(s) d, d_{hi}, and d_{lo} which texels are read from are determined by an image-level parameter d_l, which is computed based on the LOD parameter, as follows:

$$d_l = \begin{cases} nearest(d'), & \text{mipmapMode is VK\_SAMPLER\_MIPMAP\_MODE\_NEAREST} \\ d', & \text{otherwise} \end{cases}$$

where:

$$d' = level_{base} + \text{clamp}(\lambda, 0, q)$$

$$nearest(d') = \begin{cases} \lceil d' + 0.5 \rceil - 1, & \text{preferred} \\ \lfloor d' + 0.5 \rfloor, & \text{alternative} \end{cases}$$

and

$level_{base}$ = `baseMipLevel`

q = `levelCount` - 1

`baseMipLevel` and `levelCount` are taken from the `subresourceRange` of the image view.

If the sampler's `mipmapMode` is `VK_SAMPLER_MIPMAP_MODE_NEAREST`, then the level selected is $d = d_l$.

If the sampler's `mipmapMode` is `VK_SAMPLER_MIPMAP_MODE_LINEAR`, two neighboring levels are selected:

$$\begin{aligned} d_{hi} &= \lfloor d_l \rfloor \\ d_{lo} &= min(d_{hi} + 1, q) \\ \delta &= d_l - d_{hi} \end{aligned}$$

δ is the fractional value used for linear filtering between levels.

15.6.8. (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 (d or d_{hi} and d_{lo}) used in filtering.

$$\begin{aligned} u(x, y) &= s(x, y) \times width_{level} \\ v(x, y) &= \begin{cases} 0 & \text{for 1D images} \\ t(x, y) \times height_{level} & \text{otherwise} \end{cases} \\ w(x, y) &= \begin{cases} 0 & \text{for 2D or Cube images} \\ r(x, y) \times depth_{level} & \text{otherwise} \end{cases} \\ a(x, y) &= \begin{cases} a(x, y) & \text{for array images} \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

Operations then proceed to Unnormalized Texel Coordinate Operations.

15.7. Unnormalized Texel Coordinate Operations

15.7.1. (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 = clamp(RNE(a), 0, `layerCount` - 1) + `baseArrayLayer` where layerCount is the number of layers in the image subresource range of the image view, baseArrayLayer is the first layer from the subresource range, and where:

$$\mathrm{RNE}(a) = \begin{cases} \mathrm{roundTiesToEven}(a) & \text{preferred, from IEEE Std 754-2008 Floating-Point Arithmetic} \\ \lfloor a + 0.5 \rfloor & \text{alternative} \end{cases}$$

The sample index n is assigned the value zero.

Nearest filtering (VK_FILTER_NEAREST) computes the integer texel coordinates that the unnormalized coordinates lie within:

$$\begin{aligned} i &= \lfloor u \rfloor \\ j &= \lfloor v \rfloor \\ k &= \lfloor w \rfloor \end{aligned}$$

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 α, β, and γ.

$$\begin{aligned} i_0 &= \lfloor u - 0.5 \rfloor \\ i_1 &= i_0 + 1 \\ j_0 &= \lfloor v - 0.5 \rfloor \\ j_1 &= j_0 + 1 \\ k_0 &= \lfloor w - 0.5 \rfloor \\ k_1 &= k_0 + 1 \\ \alpha &= (u - 0.5) - i_0 \\ \beta &= (v - 0.5) - j_0 \\ \gamma &= (w - 0.5) - k_0 \end{aligned}$$

If the image instruction includes a ConstOffset operand, the constant offsets (Δ_i, Δ_j, Δ_k) are added to (i,j,k) components of the integer texel coordinates.

15.8. Integer Texel Coordinate Operations

The OpImageFetch and OpImageFetchSparse SPIR-V instructions **may** supply a LOD from which texels are to be fetched using the optional SPIR-V operand Lod. Other integer-coordinate operations **must** not. If the Lod is provided then it **must** be an integer.

The image level selected is:

$$d = level_{base} + \begin{cases} Lod & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases}$$

If d does not lie in the range [baseMipLevel, baseMipLevel + levelCount) then any values fetched are undefined.

15.9. Image Sample Operations

15.9.1. Wrapping Operation

Cube images ignore the wrap modes specified in the sampler. Instead, if VK_FILTER_NEAREST is used within a mip level then VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE is used, and if VK_FILTER_LINEAR is used within a mip level then sampling at the edges is performed as described earlier in the Cube map edge handling section.

The first integer texel coordinate i is transformed based on the `addressModeU` parameter of the sampler.

$$
i = \begin{cases} i \bmod size & \text{for repeat} \\ (size - 1) - \operatorname{mirror}((i \bmod (2 \times size)) - size) & \text{for mirrored repeat} \\ \operatorname{clamp}(i, 0, size - 1) & \text{for clamp to edge} \\ \operatorname{clamp}(i, -1, size) & \text{for clamp to border} \\ \operatorname{clamp}(\operatorname{mirror}(i), 0, size - 1) & \text{for mirror clamp to edge} \end{cases}
$$

where:

$$
\operatorname{mirror}(n) = \begin{cases} n & \text{for } n \geq 0 \\ -(1 + n) & \text{otherwise} \end{cases}
$$

j (for 2D and Cube image) and k (for 3D image) are similarly transformed based on the `addressModeV` and `addressModeW` parameters of the sampler, respectively.

15.9.2. Texel Gathering

SPIR-V instructions with `Gather` in the name return a vector derived from a 2×2 rectangular region of texels in the base level of the image view. The rules for the `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 `Component` value in the instruction from the swizzled color value of the four texels:

$$
\begin{aligned}
\tau[R] &= \tau_{i0\,j1}[level_{base}][comp] \\
\tau[G] &= \tau_{i1\,j1}[level_{base}][comp] \\
\tau[B] &= \tau_{i1\,j0}[level_{base}][comp] \\
\tau[A] &= \tau_{i0\,j0}[level_{base}][comp]
\end{aligned}
$$

where:

$$
\tau[level_{base}][comp] = \begin{cases} \tau[level_{base}][R], & \text{for } comp = 0 \\ \tau[level_{base}][G], & \text{for } comp = 1 \\ \tau[level_{base}][B], & \text{for } comp = 2 \\ \tau[level_{base}][A], & \text{for } comp = 3 \end{cases}
$$
$$
comp \text{ from SPIR-V operand Component}
$$

15.9.3. Texel Filtering

If λ 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 λ 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.

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.

$$\tau[level] = \begin{cases} \tau_{ijk}[level], & \text{for 3D image} \\ \tau_{ij}[level], & \text{for 2D or Cube image} \\ \tau_{i}[level], & \text{for 1D image} \end{cases}$$

Within a mip level, `VK_FILTER_LINEAR` filtering combines 8 (for 3D), 4 (for 2D or Cube), or 2 (for 1D) texel values, using the weights computed earlier:

$$\begin{aligned} \tau_{3D}[level] = reduce(&(1-\alpha)(1-\beta)(1-\gamma), \tau_{i0j0k0}[level], \\ &(\alpha)(1-\beta)(1-\gamma), \tau_{i1j0k0}[level], \\ &(1-\alpha)(\beta)(1-\gamma), \tau_{i0j1k0}[level], \\ &(\alpha)(\beta)(1-\gamma), \tau_{i1j1k0}[level], \\ &(1-\alpha)(1-\beta)(\gamma), \tau_{i0j0k1}[level], \\ &(\alpha)(1-\beta)(\gamma), \tau_{i1j0k1}[level], \\ &(1-\alpha)(\beta)(\gamma), \tau_{i0j1k1}[level], \\ &(\alpha)(\beta)(\gamma), \tau_{i1j1k1}[level]) \end{aligned}$$

$$\begin{aligned} \tau_{2D}[level] = reduce(&(1-\alpha)(1-\beta), \tau_{i0j0}[level], \\ &(\alpha)(1-\beta), \tau_{i1j0}[level], \\ &(1-\alpha)(\beta), \tau_{i0j1}[level], \\ &(\alpha)(\beta), \tau_{i1j1}[level]) \end{aligned}$$

$$\begin{aligned} \tau_{1D}[level] = reduce(&(1-\alpha), \tau_{i0}[level], \\ &(\alpha), \tau_{i1}[level]) \end{aligned}$$

$$\tau[level] = \begin{cases} \tau_{3D}[level], & \text{for 3D image} \\ \tau_{2D}[level], & \text{for 2D or Cube image} \\ \tau_{1D}[level], & \text{for 1D image} \end{cases}$$

The function reduce() is defined to operate on pairs of weights and texel values as follows. When using linear or anisotropic filtering, the values of multiple texels are combined using a weighted average to produce a filtered texture value.

Finally, mipmap filtering either selects a value from one mip level or computes a weighted average between neighboring mip levels:

$$\tau = \begin{cases} \tau[d], & \text{for mip mode BASE or NEAREST} \\ reduce((1-\delta), \tau[d_{hi}], \delta, \tau[d_{lo}]), & \text{for mip mode LINEAR} \end{cases}$$

15.9.4. 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.

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 be sampled within the image footprint of the image level d to approximate an anisotropic filter. The sum $\tau_{2Daniso}$ is defined using the single isotropic τ_{2D}(u,v) at level d.

$$\tau_{2Daniso} = \frac{1}{N}\sum_{i=1}^{N}\tau_{2D}\left(u\left(x - \frac{1}{2} + \frac{i}{N+1}, y\right), \left(v\left(x - \frac{1}{2} + \frac{i}{N+1}\right), y\right)\right), \qquad \text{when } \rho_x > \rho_y$$

$$\tau_{2Daniso} = \frac{1}{N}\sum_{i=1}^{N}\tau_{2D}\left(u\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right), \left(v\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right)\right)\right), \qquad \text{when } \rho_y \geq \rho_x$$

15.10. 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, Level-of-Detail 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.

Chapter 16. 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.

16.1. 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkQueryPool)
```

To create a query pool, call:

```
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 an instance of the `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)

- `device` **must** be a valid `VkDevice` handle
- `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
- `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:

```
typedef struct VkQueryPoolCreateInfo {
    VkStructureType                  sType;
    const void*                      pNext;
    VkQueryPoolCreateFlags           flags;
    VkQueryType                      queryType;
    uint32_t                         queryCount;
    VkQueryPipelineStatisticFlags    pipelineStatistics;
} VkQueryPoolCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific 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

- If the pipeline statistics queries feature is not enabled, queryType **must** not be VK_QUERY_TYPE_PIPELINE_STATISTICS
- If queryType is VK_QUERY_TYPE_PIPELINE_STATISTICS, pipelineStatistics **must** be a valid combination of VkQueryPipelineStatisticFlagBits values

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- queryType **must** be a valid VkQueryType value

```
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:

```
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

- All submitted commands that refer to queryPool **must** have completed execution
- If VkAllocationCallbacks were provided when queryPool was created, a compatible set of callbacks **must** be provided here
- If no VkAllocationCallbacks were provided when queryPool was created, pAllocator **must** be NULL

Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- If queryPool is not VK_NULL_HANDLE, queryPool **must** be a valid VkQueryPool handle
- If pAllocator is not NULL, pAllocator **must** be a valid pointer to a valid VkAllocationCallbacks structure
- 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:

```
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.

16.2. Query Operation

The operation of queries is controlled by the commands vkCmdBeginQuery, vkCmdEndQuery, vkCmdResetQueryPool, vkCmdCopyQueryPoolResults, and vkCmdWriteTimestamp.

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 sets the status to unavailable and makes the numerical results undefined. Performing a query operation with vkCmdBeginQuery and vkCmdEndQuery changes the status to available when the query finishes, and updates the numerical results. Both the availability status and numerical results are retrieved by calling either vkGetQueryPoolResults or vkCmdCopyQueryPoolResults.

Query commands, for the same query and submitted to the same queue, execute in their entirety in submission order, relative to each other. In effect there is an implicit execution dependency from each such query command to all query command previously submitted to the same queue. There is one significant exception to this; if the `flags` parameter of vkCmdCopyQueryPoolResults does not include `VK_QUERY_RESULT_WAIT_BIT`, execution of vkCmdCopyQueryPoolResults **may** happen-before the results of vkCmdEndQuery are available.

After query pool creation, each query is in an undefined state and **must** be reset prior to use. Queries **must** also be reset between uses. Using a query that has not been reset will result in undefined behavior.

To reset a range of queries in a query pool, call:

```
void vkCmdResetQueryPool(
    VkCommandBuffer                             commandBuffer,
    VkQueryPool                                 queryPool,
    uint32_t                                    firstQuery,
    uint32_t                                    queryCount);
```

- `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 [`firstQuery`, `firstQuery` + `queryCount` - 1] to unavailable.

Valid Usage

- `firstQuery` **must** be less than the number of queries in `queryPool`
- The sum of `firstQuery` and `queryCount` **must** be less than or equal to the number of queries in `queryPool`

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `queryPool` **must** be a valid `VkQueryPool` handle
- `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 `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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	

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 vkCmdBeginQuery command and a vkCmdEndQuery command within a specified command buffer, effectively scoping a set of drawing and/or compute 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 inherited queries 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 `occlusionQueryEnable`, `queryFlags`, and/or `pipelineStatistics` members of 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).

To begin a query, call:

```
void vkCmdBeginQuery(
    VkCommandBuffer                             commandBuffer,
    VkQueryPool                                 queryPool,
    uint32_t                                    query,
    VkQueryControlFlags                         flags);
```

- `commandBuffer` is the command buffer into which this command will be recorded.
- `queryPool` is the query pool that will manage the results of the query.
- `query` is the query index within the query pool that will contain the results.
- `flags` is a bitmask of VkQueryControlFlagBits specifying constraints on the types of queries that **can** be performed.

If the `queryType` of the pool is `VK_QUERY_TYPE_OCCLUSION` and `flags` contains `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.

Valid Usage

- The query identified by queryPool and query **must** currently not be active
- The query identified by queryPool and query **must** be unavailable
- If the precise occlusion queries 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
- queryPool **must** have been created with a queryType that differs from that of any other queries that have been made active, and are currently still active within commandBuffer
- query **must** be less than the number of queries in queryPool
- If the queryType used to create queryPool was VK_QUERY_TYPE_OCCLUSION, the VkCommandPool that commandBuffer was allocated from **must** support graphics operations
- 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
- 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

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- queryPool **must** be a valid VkQueryPool handle
- flags **must** be a valid combination of VkQueryControlFlagBits values
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics, or compute operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

Bits which **can** be set in vkCmdBeginQuery::flags, specifying constraints on the types of queries that **can** be performed, are:

```
typedef enum VkQueryControlFlagBits {
    VK_QUERY_CONTROL_PRECISE_BIT = 0x00000001,
} VkQueryControlFlagBits;
```

- VK_QUERY_CONTROL_PRECISE_BIT specifies the precision of occlusion queries.

```
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 draw or dispatch commands is executed, call:

```
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.

As queries operate asynchronously, ending a query does not immediately set the query's status to available. A query is considered *finished* when the final results of the query are ready to be retrieved by vkGetQueryPoolResults and vkCmdCopyQueryPoolResults, and this is when the query's status is set to available.

Once a query is ended the query **must** finish in finite time, unless the state of the query is changed using other commands, e.g. by issuing a reset of the query.

Valid Usage

- The query identified by queryPool and query **must** currently be active
- query **must** be less than the number of queries in queryPool

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- queryPool **must** be a valid VkQueryPool handle
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics, or compute operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics Compute	

An application **can** retrieve results either by requesting they be written into application-provided memory, or by requesting they be copied into a 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 stride bytes later.
- Each query's result is 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. Timestamps 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 integers corresponding to a single query, the values written to memory are undefined.

To retrieve status and results for a set of queries, call:

```
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. firstQuery and queryCount together define a range of queries. For pipeline statistics queries, each query index in the pool contains one integer value for each bit that is enabled in VkQueryPoolCreateInfo::pipelineStatistics when the pool is created.
- 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.

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. The behavior when not all queries are available, is described below.

If VK_QUERY_RESULT_64_BIT is not set and the result overflows a 32-bit value, the value **may** either wrap or saturate. Similarly, if VK_QUERY_RESULT_64_BIT is set and the result overflows a 64-bit value, the value **may** either wrap or saturate.

If VK_QUERY_RESULT_WAIT_BIT is set, Vulkan will wait for each query to be in the available state before retrieving the numerical results for that query. In this case, vkGetQueryPoolResults is guaranteed to succeed and return VK_SUCCESS if the queries become available in a finite time (i.e. if they have been issued and not reset). If queries will never finish (e.g. due to being reset but not issued), then vkGetQueryPoolResults **may** not return in finite time.

If VK_QUERY_RESULT_WAIT_BIT and VK_QUERY_RESULT_PARTIAL_BIT are both not set then no result values are written to pData for queries that are in the unavailable state at the time of the call, and vkGetQueryPoolResults returns VK_NOT_READY. However, availability state is still written to pData for those queries if VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is set.

> *Note*
>
> 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 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 the vkCmdResetQueryPool command has been executed since the last use of the query.

> *Note*
>
> 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.

If VK_QUERY_RESULT_PARTIAL_BIT is set, VK_QUERY_RESULT_WAIT_BIT is not set, and the query's status is unavailable, an intermediate result value between zero and the final result value is written to pData for that query.

VK_QUERY_RESULT_PARTIAL_BIT **must** not be used if the pool's queryType is VK_QUERY_TYPE_TIMESTAMP.

If VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is set, the final integer value written for each query is non-zero if the query's status was available or zero if the status was unavailable. When VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is used, implementations **must** guarantee that if they return a non-zero availability value then the numerical results **must** be valid, assuming the results are not reset by a subsequent command.

> *Note*
>
> Satisfying this guarantee **may** require careful ordering by the application, e.g. to read the availability status before reading the results.

Valid Usage

- `firstQuery` **must** be less than the number of queries in `queryPool`
- If `VK_QUERY_RESULT_64_BIT` is not set in `flags` then `pData` and `stride` **must** be multiples of `4`
- If `VK_QUERY_RESULT_64_BIT` is set in `flags` then `pData` and `stride` **must** be multiples of `8`
- The sum of `firstQuery` and `queryCount` **must** be less than or equal to the number of queries in `queryPool`
- `dataSize` **must** be large enough to contain the result of each query, as described here
- If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_TIMESTAMP`, `flags` **must** not contain `VK_QUERY_RESULT_PARTIAL_BIT`

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `queryPool` **must** be a valid `VkQueryPool` handle
- `pData` **must** be a valid pointer to an array of `dataSize` bytes
- `flags` **must** be a valid combination of VkQueryResultFlagBits values
- `dataSize` **must** be greater than `0`
- `queryPool` **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`

Bits which **can** be set in vkGetQueryPoolResults::`flags` and vkCmdCopyQueryPoolResults::`flags`, specifying how and when results are returned, are:

```
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.

```
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:

```
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.

vkCmdCopyQueryPoolResults is guaranteed to see the effect of previous uses of vkCmdResetQueryPool in the same queue, without any additional synchronization. Thus, the results will always reflect the most recent use of the query.

flags has the same possible values described above for the flags parameter of vkGetQueryPoolResults, but the different style of execution causes some subtle behavioral differences. Because vkCmdCopyQueryPoolResults executes in order with respect to other query commands, there is less ambiguity about which use of a query is being requested.

If no bits are set in flags, results for all requested queries in the available state are written as 32-bit unsigned integer values, and nothing is written for queries in the unavailable state.

If VK_QUERY_RESULT_64_BIT is set, the results are written as an array of 64-bit unsigned integer values as described for vkGetQueryPoolResults.

If VK_QUERY_RESULT_WAIT_BIT is set, the implementation will wait for each query's status to be in the available state before retrieving the numerical results for that query. This is guaranteed to reflect the most recent use of the query on the same queue, assuming that the query is not being simultaneously used by other queues. If the query does not become available in a finite amount of time (e.g. due to not issuing a query since the last reset), a VK_ERROR_DEVICE_LOST error **may** occur.

Similarly, if VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is set and VK_QUERY_RESULT_WAIT_BIT is not set, the availability is guaranteed to reflect the most recent use of the query on the same queue, assuming that the query is not being simultaneously used by other queues. As with vkGetQueryPoolResults, implementations **must** guarantee that if they return a non-zero availability value, then the numerical results are valid.

If VK_QUERY_RESULT_PARTIAL_BIT is set, VK_QUERY_RESULT_WAIT_BIT is not set, and the query's status is unavailable, an intermediate result value between zero and the final result value is written for that query.

VK_QUERY_RESULT_PARTIAL_BIT **must** not be used if the pool's queryType is VK_QUERY_TYPE_TIMESTAMP.

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

- dstOffset **must** be less than the size of dstBuffer
- firstQuery **must** be less than the number of queries in queryPool
- The sum of firstQuery and queryCount **must** be less than or equal to the number of queries in queryPool
- If VK_QUERY_RESULT_64_BIT is not set in flags then dstOffset and stride **must** be multiples of 4
- If VK_QUERY_RESULT_64_BIT is set in flags then dstOffset and stride **must** be multiples of 8
- dstBuffer **must** have enough storage, from dstOffset, to contain the result of each query, as described here
- 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
- If the queryType used to create queryPool was VK_QUERY_TYPE_TIMESTAMP, flags **must** not contain VK_QUERY_RESULT_PARTIAL_BIT

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- queryPool **must** be a valid VkQueryPool handle
- dstBuffer **must** be a valid VkBuffer handle
- flags **must** be a valid combination of VkQueryResultFlagBits 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
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	Transfer

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.

16.3. 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.

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.

16.4. 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 draw or dispatch commands while a pipeline statistics query is active. As such, pipeline statistics queries are available on queue families supporting either graphics or compute operations. Further, 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, that counter is undefined after the query has finished. At least one statistic counter relevant to the operations supported on the recording command buffer **must** be enabled.

Bits which **can** be set to individually enable pipeline statistics counters for query pools with VkQueryPoolCreateInfo::pipelineStatistics, and for secondary command buffers with VkCommandBufferInheritanceInfo::pipelineStatistics, are:

```
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_GEOMETRY_SHADER_INVOCATIONS_BIT = 0x00000008,
    VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT = 0x00000010,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT = 0x00000020,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT = 0x00000040,
    VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT = 0x00000080,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT = 0x00000100,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT =
0x00000200,
    VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x00000400,
} VkQueryPipelineStatisticFlagBits;
```

- 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 counter's value is incremented each time a primitive passes the primitive clipping stage. 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 vertex processing 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`).

```
typedef VkFlags VkQueryPipelineStatisticFlags;
```

`VkQueryPipelineStatisticFlags` is a bitmask type for setting a mask of zero or more VkQueryPipelineStatisticFlagBits.

16.5. 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, 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 one of the VkPipelineStageFlagBits, 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.

`vkCmdWriteTimestamp` latches the value of the timer when all previous commands have completed executing as far as the specified pipeline stage, and writes the timestamp value to memory. When the timestamp value is written, the availability status of the query is set to available.

> *Note*
>
> If an implementation is unable to detect completion and latch the timer at any specific stage of the pipeline, it **may** instead do so at any logically later stage.

vkCmdCopyQueryPoolResults **can** then be called to copy the timestamp value from the query pool into buffer memory, with ordering and synchronization behavior equivalent to how other queries operate. Timestamp values **can** also be retrieved from the query pool using vkGetQueryPoolResults. As with other queries, the query **must** be reset using vkCmdResetQueryPool before requesting the timestamp value be written to it.

While `vkCmdWriteTimestamp` **can** be called inside or outside of a render pass instance, vkCmdCopyQueryPoolResults **must** only be called outside of a render pass instance.

Timestamps **may** only be meaningfully compared if they are written by commands submitted to the same queue.

> *Note*
>
> An example of such a comparison is determining the execution time of a sequence of commands.

Valid Usage

- `queryPool` **must** have been created with a `queryType` of `VK_QUERY_TYPE_TIMESTAMP`
- The query identified by `queryPool` and `query` **must** be *unavailable*
- The command pool's queue family **must** support a non-zero `timestampValidBits`

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pipelineStage` **must** be a valid VkPipelineStageFlagBits value
- `queryPool` **must** be a valid `VkQueryPool` handle
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Transfer Graphics Compute	Transfer

Chapter 17. Clear Commands

17.1. 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:

```
void vkCmdClearColorImage(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     image,
    VkImageLayout                               imageLayout,
    const VkClearColorValue*                    pColor,
    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`.
- `pColor` is a pointer to a VkClearColorValue structure that contains the values the image subresource ranges will be cleared to (see Clear Values below).
- `rangeCount` is the number of image subresource range structures in `pRanges`.
- `pRanges` points to an array of VkImageSubresourceRange structures that describe a range of mipmap levels, array layers, and aspects to be cleared, as described in Image Views. The `aspectMask` of all image subresource ranges **must** only include `VK_IMAGE_ASPECT_COLOR_BIT`.

Each specified range in `pRanges` is cleared to the value specified by `pColor`.

Valid Usage

- image **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- If image is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- 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
- imageLayout **must** be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- 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 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 the arrayLayers specified in VkImageCreateInfo when image was created
- image **must** not have a compressed or depth/stencil format

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- image **must** be a valid VkImage handle
- imageLayout **must** be a valid VkImageLayout value
- pColor **must** be a valid pointer to a valid VkClearColorValue union
- pRanges **must** be a valid pointer to an array of rangeCount valid VkImageSubresourceRange structures
- 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
- rangeCount **must** be greater than 0
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	Transfer

To clear one or more subranges of a depth/stencil image, call:

```
void vkCmdClearDepthStencilImage(
    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 VkClearDepthStencilValue structure that contains the values 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` points to an array of VkImageSubresourceRange structures that describe a range of mipmap levels, array layers, and aspects to be cleared, as described in Image Views. The `aspectMask` of each image subresource range in `pRanges` **can** include `VK_IMAGE_ASPECT_DEPTH_BIT` if the image format has a depth component, and `VK_IMAGE_ASPECT_STENCIL_BIT` if the image format has a stencil component. `pDepthStencil` is a pointer to a `VkClearDepthStencilValue` structure that contains the values the image subresource ranges will be cleared to (see Clear Values below).

Valid Usage

- image **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- If image is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- 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
- imageLayout **must** be either of VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- 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 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 the arrayLayers specified in VkImageCreateInfo when image was created
- image **must** have a depth/stencil format

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
- 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
- rangeCount **must** be greater than 0
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics	Transfer

Clears outside render pass instances are treated as transfer operations for the purposes of memory barriers.

17.2. 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:

```
void vkCmdClearAttachments(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    attachmentCount,
    const VkClearAttachment*                    pAttachments,
    uint32_t                                    rectCount,
    const VkClearRect*                          pRects);
```

- `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` points to an array of VkClearRect structures defining regions within each selected attachment to clear.

`vkCmdClearAttachments` **can** clear multiple regions of each attachment used in the current subpass of a render pass instance. This command **must** be called only inside a render pass instance, and implicitly selects the images to clear based on the current framebuffer attachments and the command parameters.

Valid Usage

- If the aspectMask member of any element of pAttachments contains VK_IMAGE_ASPECT_COLOR_BIT, the colorAttachment member of that element **must** refer to a valid color attachment in the current subpass
- 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

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
- rectCount **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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Inside	Graphics	Graphics

The VkClearRect structure is defined as:

```
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 [`baseArrayLayer`, `baseArrayLayer + layerCount`) counting from the base layer of the attachment image view are cleared.

The `VkClearAttachment` structure is defined as:

```
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. `aspectMask` **can** include `VK_IMAGE_ASPECT_COLOR_BIT` for color attachments, `VK_IMAGE_ASPECT_DEPTH_BIT` for depth/stencil attachments with a depth component, and `VK_IMAGE_ASPECT_STENCIL_BIT` for depth/stencil attachments with a stencil component. If the subpass's depth/stencil attachment is `VK_ATTACHMENT_UNUSED`, then the clear has no effect.
- `colorAttachment` is only meaningful if `VK_IMAGE_ASPECT_COLOR_BIT` is set in `aspectMask`, in which case it is an index to the `pColorAttachments` array in the VkSubpassDescription structure of the current subpass which selects the color attachment to clear. If `colorAttachment` is `VK_ATTACHMENT_UNUSED` then the clear has no effect.
- `clearValue` is the color or depth/stencil value to clear the attachment to, as described in Clear Values below.

No memory barriers are needed between `vkCmdClearAttachments` and preceding or subsequent draw or attachment clear commands in the same subpass.

The `vkCmdClearAttachments` command is not affected by the bound pipeline state.

Attachments **can** also be cleared at the beginning of a render pass instance by setting `loadOp` (or `stencilLoadOp`) of VkAttachmentDescription to `VK_ATTACHMENT_LOAD_OP_CLEAR`, as described for vkCreateRenderPass.

Valid Usage

- If `aspectMask` includes `VK_IMAGE_ASPECT_COLOR_BIT`, it **must** not include `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`
- `aspectMask` **must** not include `VK_IMAGE_ASPECT_METADATA_BIT`
- `clearValue` **must** be a valid `VkClearValue` union

Valid Usage (Implicit)

- `aspectMask` **must** be a valid combination of VkImageAspectFlagBits values
- `aspectMask` **must** not be `0`

17.3. Clear Values

The `VkClearColorValue` structure is defined as:

```
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 formats in the Interpretation of Numeric Format table other than signed integer (`SINT`) or unsigned integer (`UINT`). 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 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 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
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

- `depth` **must** be between `0.0` and `1.0`, inclusive

The `VkClearValue` union is defined as:

```c
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.

Valid Usage

- `depthStencil` **must** be a valid `VkClearDepthStencilValue` structure

17.4. Filling Buffers

To clear buffer data, call:

```c
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 “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

- dstOffset **must** be less than the size of dstBuffer
- dstOffset **must** be a multiple of 4
- If size is not equal to VK_WHOLE_SIZE, size **must** be greater than 0
- If size is not equal to VK_WHOLE_SIZE, size **must** be less than or equal to the size of dstBuffer minus dstOffset
- If size is not equal to VK_WHOLE_SIZE, size **must** be a multiple of 4
- dstBuffer **must** have been created with VK_BUFFER_USAGE_TRANSFER_DST_BIT usage flag
- The VkCommandPool that commandBuffer was allocated from **must** support graphics or compute operations
- If dstBuffer is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `dstBuffer` **must** be a valid `VkBuffer` handle
- `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 `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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics Compute	Transfer

17.5. Updating Buffers

To update buffer data inline in a command buffer, call:

```
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 that they **should** not.

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 "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

- dstOffset **must** be less than the size of dstBuffer
- dataSize **must** be less than or equal to the size of dstBuffer minus dstOffset
- 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
- dstOffset **must** be a multiple of 4
- dataSize **must** be less than or equal to 65536
- dataSize **must** be a multiple of 4

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `dstBuffer` **must** be a valid `VkBuffer` handle
- `pData` **must** be a valid pointer to an array of `dataSize` bytes
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `dataSize` **must** be greater than `0`
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Transfer Graphics Compute	Transfer

Note

The `pData` parameter was of type `uint32_t`* instead of `void`* prior to revision 1.0.19 of the Specification and VK_HEADER_VERSION 19 of `vulkan.h`. This was a historical anomaly, as the source data may be of other types.

Chapter 18. Copy Commands

An application **can** copy buffer and image data using several methods depending on the type of data transfer. Data **can** be copied between buffer objects with `vkCmdCopyBuffer` and a portion of an image **can** be copied to another image with `vkCmdCopyImage`. Image data **can** also be copied to and from buffer memory using `vkCmdCopyImageToBuffer` and `vkCmdCopyBufferToImage`. Image data **can** be blitted (with or without scaling and filtering) with `vkCmdBlitImage`. Multisampled images **can** be resolved to a non-multisampled image with `vkCmdResolveImage`.

18.1. Common Operation

The following valid usage rules apply to all copy commands:

- Copy commands **must** be recorded outside of a render pass instance.
- The set of all bytes bound to all the source regions **must** not overlap the set of all bytes bound to the destination regions.
- The set of all bytes bound to each destination region **must** not overlap the set of all bytes bound to another destination region.
- Copy regions **must** be non-empty.
- Regions **must** not extend outside the bounds of the buffer or image level, except that regions of compressed images **can** extend as far as the dimension of the image level rounded up to a complete compressed texel block.
- Source image subresources **must** be in either the `VK_IMAGE_LAYOUT_GENERAL` or `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` layout. Destination image subresources **must** be in the `VK_IMAGE_LAYOUT_GENERAL` or `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` layout. As a consequence, if an image subresource is used as both source and destination of a copy, it **must** be in the `VK_IMAGE_LAYOUT_GENERAL` layout.
- Source images **must** have been created with the `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` usage bit enabled and destination images **must** have been created with the `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage bit enabled.
- Source buffers **must** have been created with the `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage bit enabled and destination buffers **must** have been created with the `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage bit enabled.

All copy commands are treated as “transfer” operations for the purposes of synchronization barriers.

18.2. Copying Data Between Buffers

To copy data between buffer objects, call:

```
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 region in `pRegions` is copied from the source buffer to the same region of the destination buffer. `srcBuffer` and `dstBuffer` **can** be the same buffer or alias the same memory, but the result is undefined if the copy regions overlap in memory.

Valid Usage

- The `size` member of each element of `pRegions` **must** be greater than `0`
- The `srcOffset` member of each element of `pRegions` **must** be less than the size of `srcBuffer`
- The `dstOffset` member of each element of `pRegions` **must** be less than the size of `dstBuffer`
- The `size` member of each element of `pRegions` **must** be less than or equal to the size of `srcBuffer` minus `srcOffset`
- 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)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `srcBuffer` **must** be a valid `VkBuffer` handle
- `dstBuffer` **must** be a valid `VkBuffer` handle
- `pRegions` **must** be a valid pointer to an array of `regionCount` `VkBufferCopy` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `regionCount` **must** be greater than `0`
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Transfer Graphics Compute	Transfer

The `VkBufferCopy` structure is defined as:

```
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.

18.3. Copying Data Between Images

vkCmdCopyImage performs image copies in a similar manner to a host memcpy. It does not perform general-purpose conversions such as scaling, resizing, blending, color-space conversion, or format conversions. Rather, it simply copies raw image data. vkCmdCopyImage **can** copy between images with different formats, provided the formats are compatible as defined below.

To copy data between image objects, call:

```
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 region in pRegions is copied from the source image to the same region of the destination image. srcImage and dstImage **can** be the same image or alias the same memory.

The formats of srcImage and dstImage **must** be compatible. Formats are considered compatible if their element size is the same between both formats. For example, VK_FORMAT_R8G8B8A8_UNORM is compatible with VK_FORMAT_R32_UINT because both texels are 4 bytes in size. Depth/stencil formats **must** match exactly.

vkCmdCopyImage allows copying between size-compatible compressed and uncompressed internal formats. Formats are size-compatible if the element size of the uncompressed format is equal to the element size (compressed texel block size) of the compressed format. Such a copy does not perform on-the-fly compression or decompression. When copying from an uncompressed format to a compressed format, each texel of uncompressed data of the source image is copied as a raw value to the corresponding compressed texel block of the destination image. When copying from a compressed format to an uncompressed format, each compressed texel block of the source image is copied as a raw value to the corresponding texel of uncompressed data in the destination image. Thus, for example, it is legal to copy between a 128-bit uncompressed format and a compressed format which has a 128-bit sized compressed texel block representing 4×4 texels (using 8 bits per texel), or between a 64-bit uncompressed format and a compressed format which has a 64-bit sized compressed texel block representing 4×4 texels (using 4 bits per texel).

When copying between compressed and uncompressed formats the `extent` members represent the texel dimensions of the source image and not the destination. When copying from a compressed image to an uncompressed image the image texel dimensions written to the uncompressed image will be source extent divided by the compressed texel block dimensions. When copying from an uncompressed image to a compressed image the image texel dimensions written to the compressed image will be the source extent multiplied by the compressed texel block dimensions. In both cases the number of bytes read and the number of bytes written will be identical.

Copying to or from block-compressed images is typically done in multiples of the compressed texel block size. For this reason the `extent` **must** be a multiple of the compressed texel block dimension. There is one exception to this rule which is **required** to handle compressed images created with dimensions that are not a multiple of the compressed texel block dimensions: if the `srcImage` is compressed, then:

- If `extent.width` is not a multiple of the compressed texel block width, then (`extent.width` + `srcOffset.x`) **must** equal the image subresource width.
- If `extent.height` is not a multiple of the compressed texel block height, then (`extent.height` + `srcOffset.y`) **must** equal the image subresource height.
- If `extent.depth` is not a multiple of the compressed texel block depth, then (`extent.depth` + `srcOffset.z`) **must** equal the image subresource depth.

Similarly, if the `dstImage` is compressed, then:

- If `extent.width` is not a multiple of the compressed texel block width, then (`extent.width` + `dstOffset.x`) **must** equal the image subresource width.
- If `extent.height` is not a multiple of the compressed texel block height, then (`extent.height` + `dstOffset.y`) **must** equal the image subresource height.
- If `extent.depth` is not a multiple of the compressed texel block depth, then (`extent.depth` + `dstOffset.z`) **must** equal the image subresource depth.

This allows the last compressed texel block of the image in each non-multiple dimension to be included as a source or destination of the copy.

`vkCmdCopyImage` **can** be used to copy image data between multisample images, but both images **must** have the same number of samples.

Valid Usage

- The source region specified by each element of pRegions **must** be a region that is contained within srcImage
- The destination region specified by each element of pRegions **must** be a region that is contained within dstImage
- 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** have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag
- If srcImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- srcImageLayout **must** specify the layout of the image subresources of srcImage specified in pRegions at the time this command is executed on a VkDevice
- srcImageLayout **must** be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- dstImage **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- If dstImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- 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
- The VkFormat of each of srcImage and dstImage **must** be compatible, as defined below
- The sample count of srcImage and dstImage **must** match
- The srcSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when srcImage was created
- The dstSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when dstImage was created
- 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
- 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
- The srcOffset and 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 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

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- srcImage **must** be a valid VkImage handle
- srcImageLayout **must** be a valid VkImageLayout value
- dstImage **must** be a valid VkImage handle
- dstImageLayout **must** be a valid VkImageLayout value
- pRegions **must** be a valid pointer to an array of regionCount valid VkImageCopy structures
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- regionCount **must** be greater than 0
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Transfer Graphics Compute	Transfer

The VkImageCopy structure is defined as:

```
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`.

Copies are done layer by layer starting with `baseArrayLayer` member of `srcSubresource` for the source and `dstSubresource` for the destination. `layerCount` layers are copied to the destination image.

Valid Usage

- The aspectMask member of srcSubresource and dstSubresource **must** match
- The layerCount member of srcSubresource and dstSubresource **must** match
- If either of the calling command's srcImage or dstImage parameters are of VkImageType VK_IMAGE_TYPE_3D, the baseArrayLayer and layerCount members of both srcSubresource and dstSubresource **must** be 0 and 1, respectively
- The aspectMask member of srcSubresource **must** specify aspects present in the calling command's srcImage
- The aspectMask member of dstSubresource **must** specify aspects present in the calling command's dstImage
- srcOffset.x and (extent.width + srcOffset.x) **must** both be greater than or equal to 0 and less than or equal to the source image subresource width
- srcOffset.y and (extent.height + srcOffset.y) **must** both be greater than or equal to 0 and less than or equal to the source image subresource height
- If the calling command's srcImage is of type VK_IMAGE_TYPE_1D, then srcOffset.y **must** be 0 and extent.height **must** be 1.
- srcOffset.z and (extent.depth + srcOffset.z) **must** both be greater than or equal to 0 and less than or equal to the source image subresource depth
- If the calling command's srcImage is of type VK_IMAGE_TYPE_1D, then srcOffset.z **must** be 0 and extent.depth **must** be 1.
- If the calling command's dstImage is of type VK_IMAGE_TYPE_1D, then dstOffset.z **must** be 0 and extent.depth **must** be 1.
- If the calling command's srcImage is of type VK_IMAGE_TYPE_2D, then srcOffset.z **must** be 0.
- If the calling command's dstImage is of type VK_IMAGE_TYPE_2D, then dstOffset.z **must** be 0.
- If the calling command's srcImage or dstImage is of type VK_IMAGE_TYPE_2D, then extent.depth **must** be 1.
- dstOffset.x and (extent.width + dstOffset.x) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource width
- dstOffset.y and (extent.height + dstOffset.y) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource height
- If the calling command's dstImage is of type VK_IMAGE_TYPE_1D, then dstOffset.y **must** be 0 and extent.height **must** be 1.
- dstOffset.z and (extent.depth + dstOffset.z) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource depth
- If the calling command's srcImage is a compressed image, all members of srcOffset **must** be a multiple of the corresponding dimensions of the compressed texel block
- If the calling command's srcImage is a compressed image, extent.width **must** be a multiple of the compressed texel block width or (extent.width + srcOffset.x) **must** equal the source image subresource width

- If the calling command's srcImage is a compressed image, extent.height **must** be a multiple of the compressed texel block height or (extent.height + srcOffset.y) **must** equal the source image subresource height
- If the calling command's srcImage is a compressed image, extent.depth **must** be a multiple of the compressed texel block depth or (extent.depth + srcOffset.z) **must** equal the source image subresource depth
- If the calling command's dstImage is a compressed format image, all members of dstOffset **must** be a multiple of the corresponding dimensions of the compressed texel block
- If the calling command's dstImage is a compressed format image, extent.width **must** be a multiple of the compressed texel block width or (extent.width + dstOffset.x) **must** equal the destination image subresource width
- If the calling command's dstImage is a compressed format image, extent.height **must** be a multiple of the compressed texel block height or (extent.height + dstOffset.y) **must** equal the destination image subresource height
- If the calling command's dstImage is a compressed format image, extent.depth **must** be a multiple of the compressed texel block depth or (extent.depth + dstOffset.z) **must** equal the destination image subresource depth

Valid Usage (Implicit)

- srcSubresource **must** be a valid VkImageSubresourceLayers structure
- dstSubresource **must** be a valid VkImageSubresourceLayers structure

The VkImageSubresourceLayers structure is defined as:

```
typedef struct VkImageSubresourceLayers {
    VkImageAspectFlags    aspectMask;
    uint32_t              mipLevel;
    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 from.
- baseArrayLayer and layerCount are the starting layer and number of layers to copy.

Valid Usage

- 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`
- `aspectMask` **must** not contain `VK_IMAGE_ASPECT_METADATA_BIT`
- `layerCount` **must** be greater than 0

Valid Usage (Implicit)

- `aspectMask` **must** be a valid combination of VkImageAspectFlagBits values
- `aspectMask` **must** not be `0`

18.4. Copying Data Between Buffers and Images

To copy data from a buffer object to an image object, call:

```
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 region in `pRegions` is copied from the specified region of the source buffer to the specified region of the destination image.

Valid Usage

- The buffer region specified by each element of pRegions **must** be a region that is contained within srcBuffer
- The image region specified by each element of pRegions **must** be a region that is contained within dstImage
- 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
- 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
- If dstImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- dstImage **must** have a sample count equal to VK_SAMPLE_COUNT_1_BIT
- 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
- The imageSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when dstImage 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 dstImage was created
- The imageOffset and 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

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `srcBuffer` **must** be a valid `VkBuffer` handle
- `dstImage` **must** be a valid `VkImage` handle
- `dstImageLayout` **must** be a valid VkImageLayout value
- `pRegions` **must** be a valid pointer to an array of `regionCount` valid `VkBufferImageCopy` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `regionCount` **must** be greater than `0`
- 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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Transfer Graphics Compute	Transfer

To copy data from an image object to a buffer object, call:

```
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 region in pRegions is copied from the specified region of the source image to the specified region of the destination buffer.

Valid Usage

- The image region specified by each element of pRegions **must** be a region that is contained within srcImage
- The buffer region specified by each element of pRegions **must** be a region that is contained within dstBuffer
- 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** have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag
- If srcImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- srcImage **must** have a sample count equal to VK_SAMPLE_COUNT_1_BIT
- srcImageLayout **must** specify the layout of the image subresources of srcImage specified in pRegions at the time this command is executed on a VkDevice
- srcImageLayout **must** be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- 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
- 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 imageOffset and 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

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `srcImage` **must** be a valid `VkImage` handle
- `srcImageLayout` **must** be a valid VkImageLayout value
- `dstBuffer` **must** be a valid `VkBuffer` handle
- `pRegions` **must** be a valid pointer to an array of `regionCount` valid `VkBufferImageCopy` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `regionCount` **must** be greater than `0`
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Transfer Graphics Compute	Transfer

For both vkCmdCopyBufferToImage and vkCmdCopyImageToBuffer, each element of `pRegions` is a structure defined as:

```c
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 the data in buffer memory as a subregion of a larger two- or three-dimensional image, and control the addressing calculations of data in buffer memory. 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`.

When copying to or from a depth or stencil aspect, the data in buffer memory uses a layout that is a (mostly) tightly packed representation of the depth or stencil data. Specifically:

- data copied to or from the stencil aspect of any depth/stencil format is tightly packed with one `VK_FORMAT_S8_UINT` value per texel.
- data copied to or from the depth aspect of a `VK_FORMAT_D16_UNORM` or `VK_FORMAT_D16_UNORM_S8_UINT` format is tightly packed with one `VK_FORMAT_D16_UNORM` value per texel.
- data copied to or from the depth aspect of a `VK_FORMAT_D32_SFLOAT` or `VK_FORMAT_D32_SFLOAT_S8_UINT` format is tightly packed with one `VK_FORMAT_D32_SFLOAT` value per texel.
- data copied to or from the depth aspect of a `VK_FORMAT_X8_D24_UNORM_PACK32` or `VK_FORMAT_D24_UNORM_S8_UINT` format is packed with one 32-bit word per texel with the D24 value in the LSBs of the word, and undefined values in the eight MSBs.

> *Note*
>
> To copy both the depth and stencil aspects of a depth/stencil format, two entries in `pRegions` **can** be used, where one specifies the depth aspect in `imageSubresource`, and the other specifies the stencil aspect.

Because depth or stencil aspect buffer to image copies **may** require format conversions on some implementations, they are not supported on queues that do not support graphics. When copying to a depth aspect, the data in buffer memory **must** be in the the range [0,1] or undefined results occur.

Copies are done layer by layer starting with image layer `baseArrayLayer` member of `imageSubresource`. `layerCount` layers are copied from the source image or to the destination image.

Valid Usage

- If the calling command's VkImage parameter's format is not a depth/stencil format, then bufferOffset **must** be a multiple of the format's element size
- bufferOffset **must** be a multiple of 4
- bufferRowLength **must** be 0, or greater than or equal to the width member of imageExtent
- bufferImageHeight **must** be 0, or greater than or equal to the height member of imageExtent
- imageOffset.x and (imageExtent.width + imageOffset.x) **must** both be greater than or equal to 0 and less than or equal to the image subresource width
- imageOffset.y and (imageExtent.height + imageOffset.y) **must** both be greater than or equal to 0 and less than or equal to the image subresource height
- If the calling command's srcImage (vkCmdCopyImageToBuffer) or dstImage (vkCmdCopyBufferToImage) is of type VK_IMAGE_TYPE_1D, then imageOffset.y **must** be 0 and imageExtent.height **must** be 1.
- imageOffset.z and (imageExtent.depth + imageOffset.z) **must** both be greater than or equal to 0 and less than or equal to the image subresource depth
- If the calling command's srcImage (vkCmdCopyImageToBuffer) or dstImage (vkCmdCopyBufferToImage) is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then imageOffset.z **must** be 0 and imageExtent.depth **must** be 1
- If the calling command's VkImage parameter is a compressed image, bufferRowLength **must** be a multiple of the compressed texel block width
- If the calling command's VkImage parameter is a compressed image, bufferImageHeight **must** be a multiple of the compressed texel block height
- If the calling command's VkImage parameter is a compressed image, all members of imageOffset **must** be a multiple of the corresponding dimensions of the compressed texel block
- If the calling command's VkImage parameter is a compressed image, bufferOffset **must** be a multiple of the compressed texel block size in bytes
- If the calling command's VkImage parameter is a compressed image, imageExtent.width **must** be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) **must** equal the image subresource width
- If the calling command's VkImage parameter is a compressed image, imageExtent.height **must** be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) **must** equal the image subresource height
- If the calling command's VkImage parameter is a compressed image, imageExtent.depth **must** be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) **must** equal the image subresource depth
- The aspectMask member of imageSubresource **must** specify aspects present in the calling command's VkImage parameter
- The aspectMask member of imageSubresource **must** only have a single bit set

- If the calling command's VkImage parameter is of VkImageType VK_IMAGE_TYPE_3D, the baseArrayLayer and layerCount members of imageSubresource **must** be 0 and 1, respectively
- When copying to the depth aspect of an image subresource, the data in the source buffer **must** be in the range [0,1]

Valid Usage (Implicit)

- imageSubresource **must** be a valid VkImageSubresourceLayers structure

Pseudocode for image/buffer addressing is:

```
rowLength = region->bufferRowLength;
if (rowLength == 0)
    rowLength = region->imageExtent.width;

imageHeight = region->bufferImageHeight;
if (imageHeight == 0)
    imageHeight = region->imageExtent.height;

elementSize = <element size of the format of the src/dstImage>;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x)
* elementSize;

where x,y,z range from (0,0,0) to region->imageExtent.{width,height,depth}.
```

Note that imageOffset does not affect addressing calculations for buffer memory. Instead, bufferOffset **can** be used to select the starting address in buffer memory.

For block-compression formats, all parameters are still specified in texels rather than compressed texel blocks, but the addressing math operates on whole compressed texel blocks. Pseudocode for compressed copy addressing is:

```
rowLength = region->bufferRowLength;
if (rowLength == 0)
    rowLength = region->imageExtent.width;

imageHeight = region->bufferImageHeight;
if (imageHeight == 0)
    imageHeight = region->imageExtent.height;

compressedTexelBlockSizeInBytes = <compressed texel block size taken from the src
/dstImage>;
rowLength /= compressedTexelBlockWidth;
imageHeight /= compressedTexelBlockHeight;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x)
* compressedTexelBlockSizeInBytes;

where x,y,z range from (0,0,0) to region->imageExtent.{width/
compressedTexelBlockWidth,height/compressedTexelBlockHeight,depth/compressedTexelBlock
Depth}.
```

Copying to or from block-compressed images is typically done in multiples of the compressed texel block size. For this reason the `imageExtent` **must** be a multiple of the compressed texel block dimension. There is one exception to this rule which is **required** to handle compressed images created with dimensions that are not a multiple of the compressed texel block dimensions:

- If `imageExtent.width` is not a multiple of the compressed texel block width, then (`imageExtent.width` + `imageOffset.x`) **must** equal the image subresource width.
- If `imageExtent.height` is not a multiple of the compressed texel block height, then (`imageExtent.height` + `imageOffset.y`) **must** equal the image subresource height.
- If `imageExtent.depth` is not a multiple of the compressed texel block depth, then (`imageExtent.depth` + `imageOffset.z`) **must** equal the image subresource depth.

This allows the last compressed texel block of the image in each non-multiple dimension to be included as a source or destination of the copy.

18.5. Image Copies with Scaling

To copy regions of a source image into a destination image, potentially performing format conversion, arbitrary scaling, and filtering, call:

```
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:

  $u_{base} = i + ½$

  $v_{base} = j + ½$

  $w_{base} = k + ½$

- These base coordinates are then offset by the first destination offset:

  $u_{offset} = u_{base} - x_{dst0}$

  $v_{offset} = v_{base} - y_{dst0}$

  $w_{offset} = w_{base} - z_{dst0}$

  $a_{offset} = a - \texttt{baseArrayCount}_{dst}$

- The scale is determined from the source and destination regions, and applied to the offset coordinates:

  $scale\_u = (x_{src1} - x_{src0}) / (x_{dst1} - x_{dst0})$

  $scale\_v = (y_{src1} - y_{src0}) / (y_{dst1} - y_{dst0})$

  $scale\_w = (z_{src1} - z_{src0}) / (z_{dst1} - z_{dst0})$

  $u_{scaled} = u_{offset} * scale_u$

  $v_{scaled} = v_{offset} * scale_v$

  $w_{scaled} = w_{offset} * scale_w$

- Finally the source offset is added to the scaled coordinates, to determine the final unnormalized coordinates used to sample from `srcImage`:

  $u = u_{scaled} + x_{src0}$

  $v = v_{scaled} + y_{src0}$

  $w = w_{scaled} + z_{src0}$

  q = `mipLevel`

  a = a_{offset} + `baseArrayCount`$_{src}$

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.

3D textures are blitted slice by slice. Slices in the source region bounded by `srcOffsets`[0].`z` and `srcOffsets`[1].`z` are copied to slices in the destination region bounded by `dstOffsets`[0].`z` and `dstOffsets`[1].`z`. For each destination slice, a source **z** coordinate is linearly interpolated between `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. If `filter` parameter is `VK_FILTER_NEAREST` then value sampled from the source image is taken from the single nearest slice (with undefined 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, unscaled 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

- The source region specified by each element of pRegions **must** be a region that is contained within srcImage
- The destination region specified by each element of pRegions **must** be a region that is contained within dstImage
- 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
- srcImage **must** use a format that supports VK_FORMAT_FEATURE_BLIT_SRC_BIT, which is indicated by VkFormatProperties::linearTilingFeatures (for linearly tiled images) or VkFormatProperties::optimalTilingFeatures (for optimally tiled images) - as returned by vkGetPhysicalDeviceFormatProperties
- srcImage **must** have been created with VK_IMAGE_USAGE_TRANSFER_SRC_BIT usage flag
- If srcImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- srcImageLayout **must** specify the layout of the image subresources of srcImage specified in pRegions at the time this command is executed on a VkDevice
- srcImageLayout **must** be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- dstImage **must** use a format that supports VK_FORMAT_FEATURE_BLIT_DST_BIT, which is indicated by VkFormatProperties::linearTilingFeatures (for linearly tiled images) or VkFormatProperties::optimalTilingFeatures (for optimally tiled images) - as returned by vkGetPhysicalDeviceFormatProperties
- dstImage **must** have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- If dstImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- 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
- The sample count of srcImage and dstImage **must** both be equal to VK_SAMPLE_COUNT_1_BIT
- 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
- 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
- If either of srcImage or dstImage was created with a depth/stencil format, the other **must** have exactly the same format
- If srcImage was created with a depth/stencil format, filter **must** be VK_FILTER_NEAREST
- srcImage **must** have been created with a samples value of VK_SAMPLE_COUNT_1_BIT
- dstImage **must** have been created with a samples value of VK_SAMPLE_COUNT_1_BIT
- If filter is VK_FILTER_LINEAR, srcImage **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in

VkFormatProperties::linearTilingFeatures (for a linear image) or VkFormatProperties::optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties

- The srcSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when srcImage was created
- The dstSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when dstImage was created
- 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
- 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)

- commandBuffer **must** be a valid VkCommandBuffer handle
- srcImage **must** be a valid VkImage handle
- srcImageLayout **must** be a valid VkImageLayout value
- dstImage **must** be a valid VkImage handle
- dstImageLayout **must** be a valid VkImageLayout value
- pRegions **must** be a valid pointer to an array of regionCount valid VkImageBlit structures
- filter **must** be a valid VkFilter value
- 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
- regionCount **must** be greater than 0
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics	Transfer

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 an array of two VkOffset3D structures specifying the bounds of the source region within srcSubresource.
- dstSubresource is the subresource to blit into.
- dstOffsets is 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 the specified source and destination regions.

Valid Usage

- The `aspectMask` member of `srcSubresource` and `dstSubresource` **must** match
- The `layerCount` member of `srcSubresource` and `dstSubresource` **must** match
- If either of the calling command's `srcImage` or `dstImage` parameters are of VkImageType `VK_IMAGE_TYPE_3D`, the `baseArrayLayer` and `layerCount` members of both `srcSubresource` and `dstSubresource` **must** be `0` and `1`, respectively
- The `aspectMask` member of `srcSubresource` **must** specify aspects present in the calling command's `srcImage`
- The `aspectMask` member of `dstSubresource` **must** specify aspects present in the calling command's `dstImage`
- `srcOffset`[0].`x` and `srcOffset`[1].`x` **must** both be greater than or equal to `0` and less than or equal to the source image subresource width
- `srcOffset`[0].`y` and `srcOffset`[1].`y` **must** both be greater than or equal to `0` and less than or equal to the source image subresource height
- If the calling command's `srcImage` is of type `VK_IMAGE_TYPE_1D`, then `srcOffset`[0].y **must** be `0` and `srcOffset`[1].y **must** be `1`.
- `srcOffset`[0].`z` and `srcOffset`[1].`z` **must** both be greater than or equal to `0` and less than or equal to the source image subresource depth
- If the calling command's `srcImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `srcOffset`[0].z **must** be `0` and `srcOffset`[1].z **must** be `1`.
- `dstOffset`[0].`x` and `dstOffset`[1].`x` **must** both be greater than or equal to `0` and less than or equal to the destination image subresource width
- `dstOffset`[0].`y` and `dstOffset`[1].`y` **must** both be greater than or equal to `0` and less than or equal to the destination image subresource height
- If the calling command's `dstImage` is of type `VK_IMAGE_TYPE_1D`, then `dstOffset`[0].y **must** be `0` and `dstOffset`[1].y **must** be `1`.
- `dstOffset`[0].`z` and `dstOffset`[1].`z` **must** both be greater than or equal to `0` and less than or equal to the destination image subresource depth
- If the calling command's `dstImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `dstOffset`[0].z **must** be `0` and `dstOffset`[1].z **must** be `1`.

Valid Usage (Implicit)

- `srcSubresource` **must** be a valid `VkImageSubresourceLayers` structure
- `dstSubresource` **must** be a valid `VkImageSubresourceLayers` structure

18.6. Resolving Multisample Images

To resolve a multisample image to a non-multisample image, call:

```
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.

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

- The source region specified by each element of pRegions **must** be a region that is contained within srcImage
- The destination region specified by each element of pRegions **must** be a region that is contained within dstImage
- The union of all source regions, and the union of all destination regions, specified by the elements of pRegions, **must** not overlap in memory
- If srcImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- srcImage **must** have a sample count equal to any valid sample count value other than VK_SAMPLE_COUNT_1_BIT
- If dstImage is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- dstImage **must** have a sample count equal to VK_SAMPLE_COUNT_1_BIT
- srcImageLayout **must** specify the layout of the image subresources of srcImage specified in pRegions at the time this command is executed on a VkDevice
- srcImageLayout **must** be VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- 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
- If dstImage was created with tiling equal to VK_IMAGE_TILING_LINEAR, dstImage **must** have been created with a format that supports being a color attachment, as specified by the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag in VkFormatProperties::linearTilingFeatures returned by vkGetPhysicalDeviceFormatProperties
- If dstImage was created with tiling equal to VK_IMAGE_TILING_OPTIMAL, dstImage **must** have been created with a format that supports being a color attachment, as specified by the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties
- srcImage and dstImage **must** have been created with the same image format
- The srcSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when srcImage was created
- The dstSubresource.mipLevel member of each element of pRegions **must** be less than the mipLevels specified in VkImageCreateInfo when dstImage was created
- 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
- 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)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `srcImage` **must** be a valid `VkImage` handle
- `srcImageLayout` **must** be a valid VkImageLayout value
- `dstImage` **must** be a valid `VkImage` handle
- `dstImageLayout` **must** be a valid VkImageLayout value
- `pRegions` **must** be a valid pointer to an array of `regionCount` valid `VkImageResolve` 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 outside of a render pass instance
- `regionCount` **must** be greater than `0`
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Graphics	Transfer

The `VkImageResolve` structure is defined as:

```
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

- The aspectMask member of srcSubresource and dstSubresource **must** only contain VK_IMAGE_ASPECT_COLOR_BIT
- The layerCount member of srcSubresource and dstSubresource **must** match
- If either of the calling command's srcImage or dstImage parameters are of VkImageType VK_IMAGE_TYPE_3D, the baseArrayLayer and layerCount members of both srcSubresource and dstSubresource **must** be 0 and 1, respectively
- srcOffset.x and (extent.width + srcOffset.x) **must** both be greater than or equal to 0 and less than or equal to the source image subresource width
- srcOffset.y and (extent.height + srcOffset.y) **must** both be greater than or equal to 0 and less than or equal to the source image subresource height
- If the calling command's srcImage is of type VK_IMAGE_TYPE_1D, then srcOffset.y **must** be 0 and extent.height **must** be 1.
- srcOffset.z and (extent.depth + srcOffset.z) **must** both be greater than or equal to 0 and less than or equal to the source image subresource depth
- If the calling command's srcImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then srcOffset.z **must** be 0 and extent.depth **must** be 1.
- dstOffset.x and (extent.width + dstOffset.x) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource width
- dstOffset.y and (extent.height + dstOffset.y) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource height
- If the calling command's dstImage is of type VK_IMAGE_TYPE_1D, then dstOffset.y **must** be 0 and extent.height **must** be 1.
- dstOffset.z and (extent.depth + dstOffset.z) **must** both be greater than or equal to 0 and less than or equal to the destination image subresource depth
- If the calling command's dstImage is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then dstOffset.z **must** be 0 and extent.depth **must** be 1.

Valid Usage (Implicit)

- srcSubresource **must** be a valid VkImageSubresourceLayers structure
- dstSubresource **must** be a valid VkImageSubresourceLayers structure

Chapter 19. 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 currently 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`:

```
typedef struct VkPipelineInputAssemblyStateCreateInfo {
    VkStructureType                            sType;
    const void*                                pNext;
    VkPipelineInputAssemblyStateCreateFlags    flags;
    VkPrimitiveTopology                        topology;
    VkBool32                                   primitiveRestartEnable;
} VkPipelineInputAssemblyStateCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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

- 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`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`, `primitiveRestartEnable` **must** be `VK_FALSE`
- If the geometry shaders 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`
- If the tessellation shaders feature is not enabled, `topology` **must** not be `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- `topology` **must** be a valid VkPrimitiveTopology value

```
typedef VkFlags VkPipelineInputAssemblyStateCreateFlags;
```

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

19.1. Primitive Topologies

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 use) and depends on the execution modes of those shaders. Supported topologies are defined by VkPrimitiveTopology and include:

```c
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;
```

Each primitive topology, and its construction from a list of vertices, is summarized below.

> *Note*
>
> The terminology “the vertex i ” means “the vertex with index i in the ordered list of vertices defining this primitive”.

19.1.1. Points

A series of individual points are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_POINT_LIST`. Each vertex defines a separate point.

19.1.2. Separate Lines

Individual line segments, each defined by a pair of vertices, are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_LINE_LIST`. The first two vertices define the first segment, with subsequent pairs of vertices each defining one more segment. If the number of vertices is odd, then the last vertex is ignored.

19.1.3. Line Strips

A series of one or more connected line segments are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP`. In this case, the first vertex specifies the first segment’s start point while the second vertex specifies the first segment’s endpoint and the second segment’s start point. In general, vertex i (for i > 0) specifies the beginning of the ith segment and the end of the previous segment. The last vertex specifies the end of the last segment. If only one vertex is specified, then no primitive is generated.

19.1.4. Triangle Strips

A triangle strip is a series of triangles connected along shared edges, and is specified with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`. In this case, the first three vertices define the first triangle, and their order is significant. Each subsequent vertex defines a new triangle using that point along with the last two vertices from the previous triangle, as shown in figure Triangle strips, fans, and lists. If fewer than three vertices are specified, no primitive is produced. The order of vertices in successive triangles changes as shown in the figure, so that all triangle faces have the same orientation.

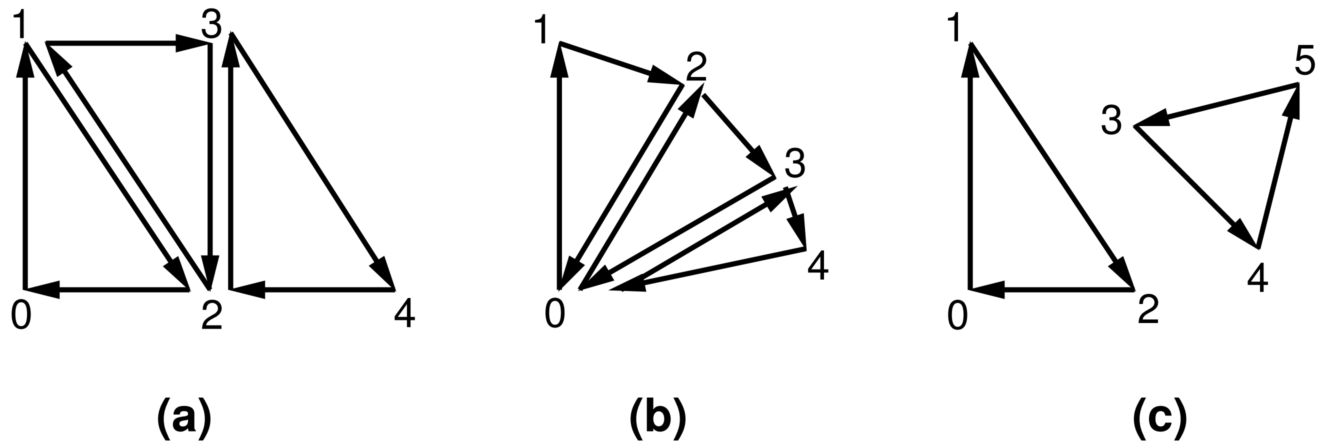

Figure 5. Triangle strips, fans, and lists

> **Caption**
>
> In the Triangle strips, fans, and lists diagram, the sub-sections represent:
>
> - (a) A triangle strip.
> - (b) A triangle fan.
> - (c) Independent triangles.
>
> The numbers give the sequencing of the vertices in order within the vertex arrays. Note that in (a) and (b) triangle edge ordering is determined by the first triangle, while in (c) the order of each triangle's edges is independent of the other triangles.

19.1.5. Triangle Fans

A triangle fan is specified with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`. It is similar to a triangle strip, but changes the vertex replaced from the previous triangle as shown in figure Triangle strips, fans, and lists, so that all triangles in the fan share a common vertex.

19.1.6. Separate Triangles

Separate triangles are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, as shown in figure Triangle strips, fans, and lists. In this case, vertices 3 i, 3 i + 1, and 3 i + 2 (in that order) determine a triangle for each i = 0, 1, …, n-1, where there are 3 n + k vertices drawn. k is either 0, 1, or 2; if k is not zero, the final k vertices are ignored.

19.1.7. Lines With Adjacency

Lines with adjacency are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY`, and are independent line segments where each endpoint has a corresponding *adjacent* vertex that is accessible in a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored.

A line segment is drawn from vertex 4 i + 1 to vertex 4 i + 2 for each i = 0, 1, …, n-1, where there are 4 n + k vertices. k is either 0, 1, 2, or 3; if k is not zero, the final k vertices are ignored. For line segment i, vertices 4 i and 4 i + 3 vertices are considered adjacent to vertices 4 i + 1 and 4 i + 2, respectively, as shown in figure Lines with adjacency.

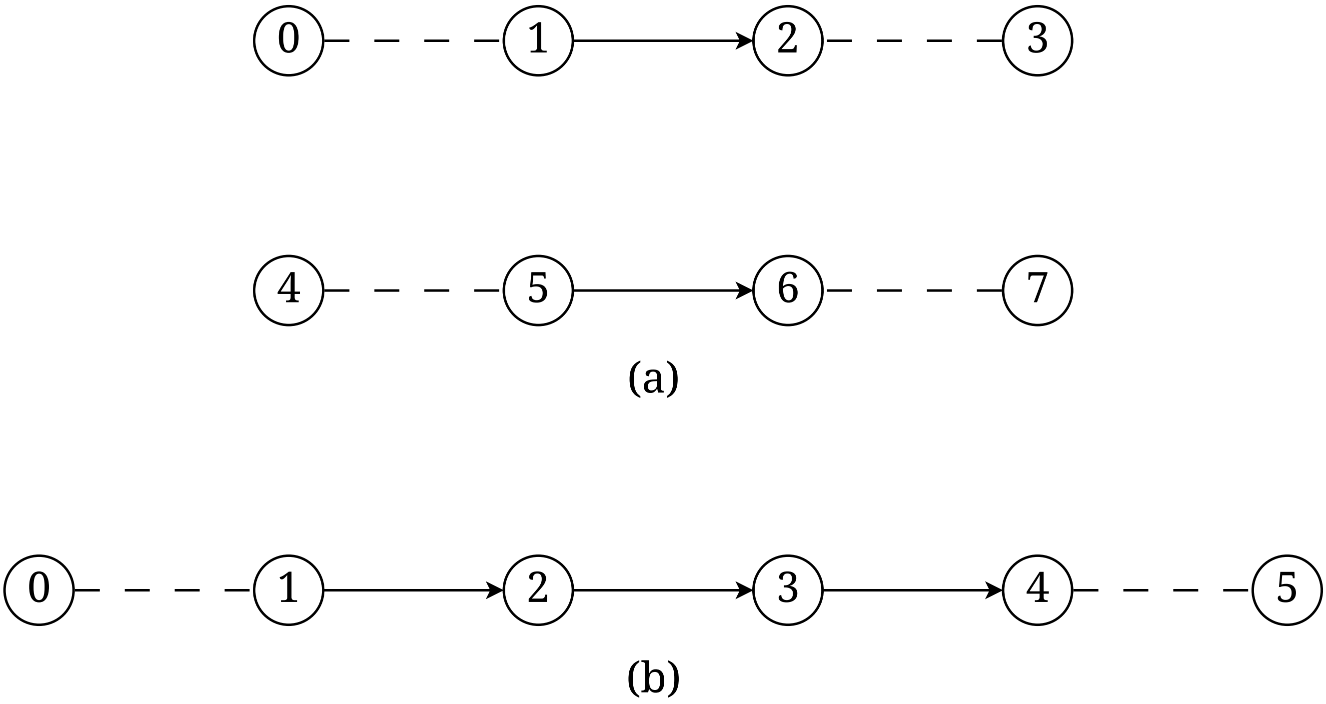

Figure 6. Lines with adjacency

> **Caption**
>
> In the Lines with adjacency diagram, the sub-sections represent:
>
> - (a) Lines with adjacency.
> - (b) Line strips with adjacency.
>
> The vertices connected with solid lines belong to the main primitives. The vertices connected by dashed lines are the adjacent vertices that are accessible in a geometry shader.

19.1.8. Line Strips With Adjacency

Line strips with adjacency are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY` and are similar to line strips, except that each line segment has a pair of adjacent vertices that are accessible in a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored.

A line segment is drawn from vertex i + 1 vertex to vertex i + 2 for each i = 0, 1, …, n-1, where there are n + 3 vertices. If there are fewer than four vertices, all vertices are ignored. For line segment i, vertices i and i + 3 are considered adjacent to vertices i + 1 and i + 2, respectively, as shown in figure Lines with adjacency.

19.1.9. Triangle List With Adjacency

Triangles with adjacency are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY`, and are similar to separate triangles except that each triangle edge has an adjacent vertex that is accessible in a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored.

Vertices 6 i, 6 i + 2, and 6 i + 4 (in that order) determine a triangle for each i = 0, 1, …, n-1, where there are 6 n+k vertices. k is either 0, 1, 2, 3, 4, or 5; if k is non-zero, the final k vertices are ignored. For triangle i, vertices 6 i + 1, 6 i + 3, and 6 i + 5 vertices are considered adjacent to edges from vertex 6 i to 6 i + 2, from 6 i + 2 to 6 i + 4, and from 6 i + 4 to 6 i vertices, respectively, as shown in figure Triangles with adjacency.

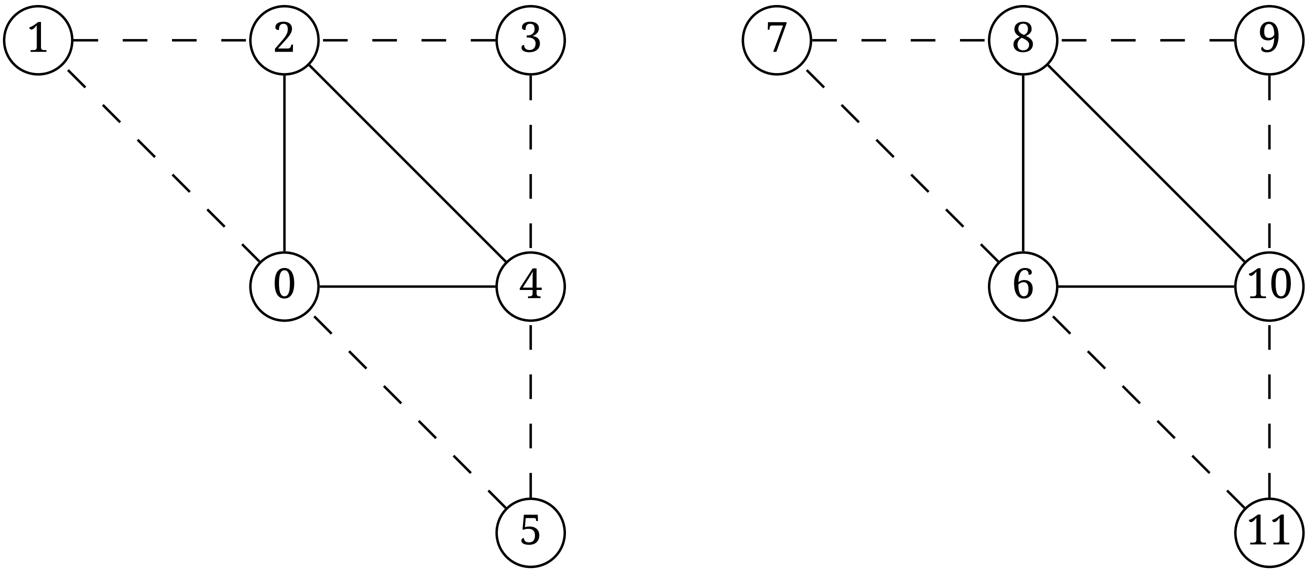

Figure 7. Triangles with adjacency

Caption

In the Triangles with adjacency diagram, the vertices connected with solid lines belong to the main primitive. The vertices connected by dashed lines are the adjacent vertices that are accessible in a geometry shader.

19.1.10. Triangle Strips With Adjacency

Triangle strips with adjacency are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY`, and are similar to triangle strips except that each triangle edge has an adjacent vertex that is accessible in a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored.

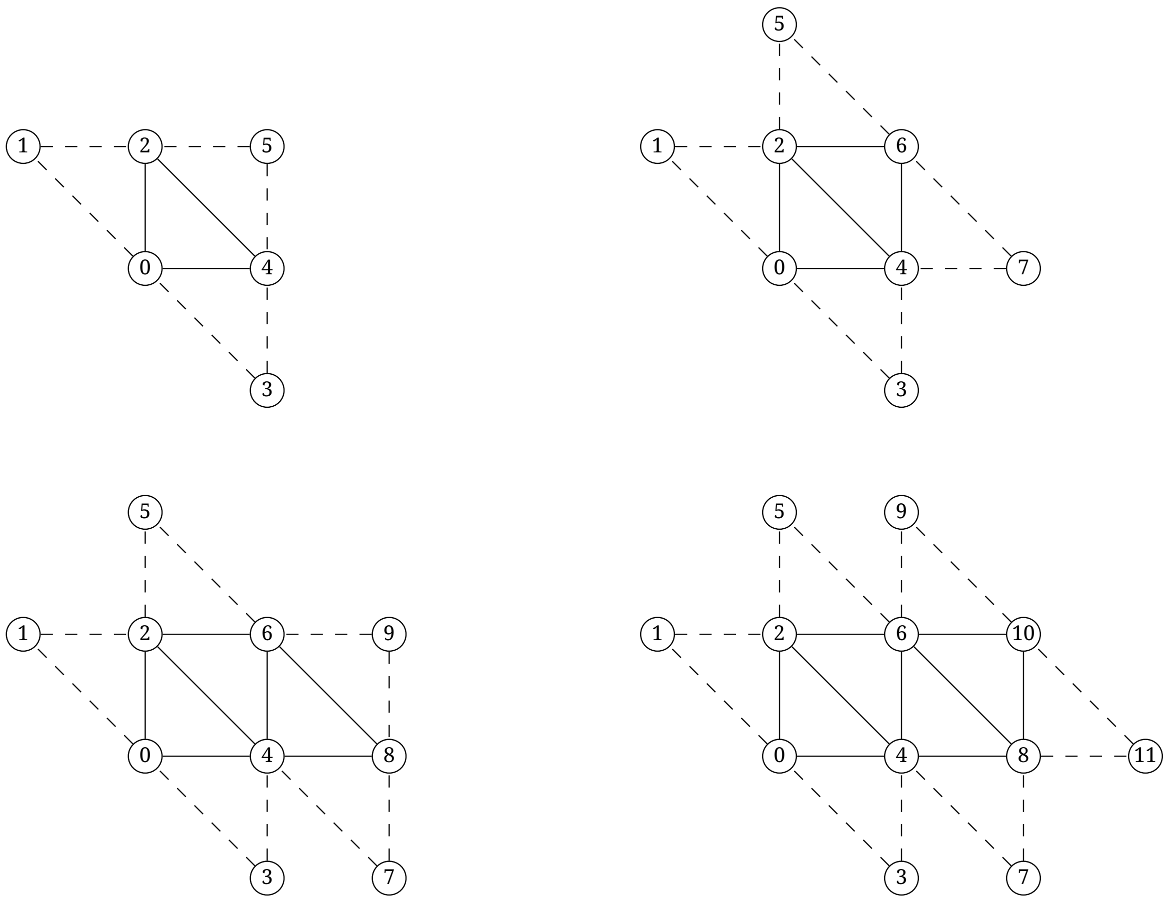

Figure 8. Triangle strips with adjacency

> **Caption**
>
> In the Triangle strips with adjacency diagram, the vertices connected with solid lines belong to the main primitive; the vertices connected by dashed lines are the adjacent vertices that are accessible in a geometry shader.

In triangle strips with adjacency, n triangles are drawn where there are 2 (n + 2) + k vertices. k is either 0 or 1; if k is 1, the final vertex is ignored. If there are fewer than 6 vertices, the entire primitive is ignored. Table Triangles generated by triangle strips with adjacency. describes the vertices and order used to draw each triangle, and which vertices are considered adjacent to each edge of the triangle, as shown in figure Triangle strips with adjacency.

Table 20. Triangles generated by triangle strips with adjacency.

	Primitive Vertices			**Adjacent Vertices**		
Primitive	1st	2nd	3rd	1/2	2/3	3/1
only (i = 0, n = 1)	0	2	4	1	5	3
first (i = 0)	0	2	4	1	6	3
middle (i odd)	2 i + 2	2 i	2 i + 4	2 i-2	2 i + 3	2 i + 6

	Primitive Vertices			Adjacent Vertices		
middle (i even)	2 i	2 i + 2	2 i + 4	2 i-2	2 i + 6	2 i + 3
last (i=n-1, i odd)	2 i + 2	2 i	2 i + 4	2 i-2	2 i + 3	2 i + 5
last (i=n-1, i even)	2 i	2 i + 2	2 i + 4	2 i-2	2 i + 5	2 i + 3

Caption

In the Triangles generated by triangle strips with adjacency table, each triangle is drawn using the vertices whose numbers are in the **1st**, **2nd**, and **3rd** columns under **Primitive Vertices**, in that order. The vertices in the 1/2, 2/3, and 3/1 columns under **Adjacent Vertices** are considered adjacent to the edges from the first to the second, from the second to the third, and from the third to the first vertex of the triangle, respectively. The six rows correspond to six cases: the first and only triangle (i = 0, n = 1), the first triangle of several (i = 0, n > 0), *odd* middle triangles (i = 1, 3, 5 …), *even* middle triangles (i = 2, 4, 6, …), and special cases for the last triangle, when i is either even or odd. For the purposes of this table, both the first vertex and first triangle are numbered 0.

19.1.11. Separate Patches

Separate patches are specified with `topology` `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`. A patch is an ordered collection of vertices used for primitive tessellation. The vertices comprising a patch have no implied geometric ordering, and are used by tessellation shaders and the fixed-function tessellator to generate new point, line, or triangle primitives.

Each patch in the series has a fixed number of vertices, specified by the `patchControlPoints` member of the VkPipelineTessellationStateCreateInfo structure passed to vkCreateGraphicsPipelines. Once assembled and vertex shaded, these patches are provided as input to the tessellation control shader stage.

If the number of vertices in a patch is given by v, vertices v × i through v × i + v - 1 (in that order) determine a patch for each i = 0, 1, …, n-1, where there are v × n + k vertices. k is in the range [0, v - 1]; if k is not zero, the final k vertices are ignored.

19.1.12. General Considerations For Polygon Primitives

Depending on the polygon mode, a *polygon primitive* generated from a drawing command with `topology` `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY`, or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY` is rendered in one of several ways, such as outlining its border or filling its interior. The order of vertices in such a primitive is significant during polygon rasterization and fragment shading.

19.2. 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 draw 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 draw 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 draw 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.

19.3. 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 undefined 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 `vertexIndex` and the `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 `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 `vertexIndex`, as well as binding vertex buffers containing those attributes to a command buffer). These commands are:
  - vkCmdDraw
  - vkCmdDrawIndirect
- Indexed drawing commands read index values from an *index buffer* and use this to compute the

vertexIndex value for the vertex shader. These commands are:

- vkCmdDrawIndexed
- vkCmdDrawIndexedIndirect

To bind an index buffer to a command buffer, call:

```
void vkCmdBindIndexBuffer(
    VkCommandBuffer                             commandBuffer,
    VkBuffer                                    buffer,
    VkDeviceSize                                offset,
    VkIndexType                                 indexType);
```

- commandBuffer is the command buffer into which the command is recorded.
- buffer is the buffer being bound.
- offset is the starting offset in bytes within buffer used in index buffer address calculations.
- indexType is a VkIndexType value specifying whether indices are treated as 16 bits or 32 bits.

Valid Usage

- offset **must** be less than the size of buffer
- 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
- buffer **must** have been created with the VK_BUFFER_USAGE_INDEX_BUFFER_BIT flag
- If buffer is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- buffer **must** be a valid VkBuffer handle
- indexType **must** be a valid VkIndexType value
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

Possible values of vkCmdBindIndexBuffer::`indexType`, specifying the size of indices, are:

```
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 Robust Buffer Access feature.

To record a non-indexed draw, call:

```
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 currently bound graphics pipeline.

Valid Usage

- The current render pass **must** be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline currently 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 currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS.
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_GRAPHICS, 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 the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_GRAPHICS, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have valid buffers bound
- 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
- A valid graphics pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_GRAPHICS
- If the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS requires any dynamic state, that state **must** have been set on the current command buffer
- Every input attachment used by the current subpass **must** be bound to the pipeline via a descriptor set
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties ::linearTilingFeatures (for a linear image) or VkFormatProperties:: optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties
- Image subresources used as attachments in the current render pass **must** not be accessed in any way other than as an attachment by this command.

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- 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

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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Inside	Graphics	Graphics

To record an indexed draw, call:

```c
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 currently 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 currently bound graphics pipeline.

Valid Usage

- The current render pass **must** be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline currently 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 currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS.
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_GRAPHICS, 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 the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_GRAPHICS, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have valid buffers bound
- 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
- A valid graphics pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_GRAPHICS
- If the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS requires any dynamic state, that state **must** have been set on the current command buffer
- (indexSize * (firstIndex + indexCount) + offset) **must** be less than or equal to the size of the currently bound index buffer, with indexSize being based on the type specified by indexType, where the index buffer, indexType, and offset are specified via vkCmdBindIndexBuffer
- Every input attachment used by the current subpass **must** be bound to the pipeline via a descriptor set
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties ::linearTilingFeatures (for a linear image) or VkFormatProperties:: optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties
- Image subresources used as attachments in the current render pass **must** not be accessed in any way other than as an attachment by this command.

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- 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

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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Inside	Graphics	Graphics

To record a non-indexed indirect draw, call:

```
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

- 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
- If drawCount is greater than 1, stride **must** be a multiple of 4 and **must** be greater than or equal to sizeof(VkDrawIndirectCommand)
- If the multi-draw indirect feature is not enabled, drawCount **must** be 0 or 1
- If the drawIndirectFirstInstance feature is not enabled, all the firstInstance members of the VkDrawIndirectCommand structures accessed by this command **must** be 0
- The current render pass **must** be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline currently 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 currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS.
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_GRAPHICS, 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 the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_GRAPHICS, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have valid buffers bound
- A valid graphics pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_GRAPHICS
- If the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS requires any dynamic state, that state **must** have been set on the current command buffer
- 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
- drawCount **must** be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount

- Every input attachment used by the current subpass **must** be bound to the pipeline via a descriptor set
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties::linearTilingFeatures (for a linear image) or VkFormatProperties::optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties
- Image subresources used as attachments in the current render pass **must** not be accessed in any way other than as an attachment by this command.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `buffer` **must** be a valid `VkBuffer` handle
- `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
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Inside	Graphics	Graphics

The `VkDrawIndirectCommand` structure is defined as:

```
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

- 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 drawIndirectFirstInstance feature is not enabled, `firstInstance` **must** be `0`

To record an indexed indirect draw, call:

```
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.

`vkCmdDrawIndexedIndirect` 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

- 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
- If drawCount is greater than 1, stride **must** be a multiple of 4 and **must** be greater than or equal to sizeof(VkDrawIndexedIndirectCommand)
- If the multi-draw indirect feature is not enabled, drawCount **must** be 0 or 1
- If the drawIndirectFirstInstance feature is not enabled, all the firstInstance members of the VkDrawIndexedIndirectCommand structures accessed by this command **must** be 0
- The current render pass **must** be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline currently 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 currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS.
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_GRAPHICS, 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 the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_GRAPHICS, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have valid buffers bound
- A valid graphics pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_GRAPHICS
- If the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS requires any dynamic state, that state **must** have been set on the current command buffer
- If drawCount is equal to 1, (offset + sizeof(VkDrawIndexedIndirectCommand)) **must** be less than or equal to the size of buffer
- If drawCount is greater than 1, (stride × (drawCount - 1) + offset + sizeof (VkDrawIndexedIndirectCommand)) **must** be less than or equal to the size of buffer
- drawCount **must** be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount

- Every input attachment used by the current subpass **must** be bound to the pipeline via a descriptor set
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_GRAPHICS accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties::linearTilingFeatures (for a linear image) or VkFormatProperties::optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties
- Image subresources used as attachments in the current render pass **must** not be accessed in any way other than as an attachment by this command.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `buffer` **must** be a valid `VkBuffer` handle
- `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
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Inside	Graphics	Graphics

The `VkDrawIndexedIndirectCommand` structure is defined as:

```
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

- 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
- (indexSize * (firstIndex + indexCount) + offset) **must** be less than or equal to the size of the currently bound index buffer, with indexSize being based on the type specified by indexType, where the index buffer, indexType, and offset are specified via vkCmdBindIndexBuffer
- If the drawIndirectFirstInstance feature is not enabled, firstInstance **must** be 0

Chapter 20. Fixed-Function Vertex Processing

Some implementations have specialized fixed-function hardware for fetching and format-converting vertex input data from buffers, rather than performing the fetch as part of the vertex shader. Vulkan includes a vertex attribute fetch stage in the graphics pipeline in order to take advantage of this.

20.1. 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

```
// 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

```
        ...
   %1 = OpExtInstImport "GLSL.std.450"
        ...
        OpName %9 "variableName"
        OpName %15 "variableNameArray"
        OpDecorate %18 BuiltIn VertexIndex
        OpDecorate %19 BuiltIn InstanceIndex
        OpDecorate %9 Location M
        OpDecorate %9 Component 2
        OpDecorate %15 Location N
        ...
   %2 = OpTypeVoid
   %3 = OpTypeFunction %2
   %6 = OpTypeFloat 32
   %7 = OpTypeVector %6 2
   %8 = OpTypePointer Input %7
   %9 = OpVariable %8 Input
  %10 = OpTypeVector %6 4
  %11 = OpTypeInt 32 0
  %12 = OpConstant %11 L
  %13 = OpTypeArray %10 %12
  %14 = OpTypePointer Input %13
  %15 = OpVariable %14 Input
        ...
```

20.1.1. Attribute Location and Component Assignment

Vertex shaders allow `Location` and `Component` decorations on input variable declarations. The `Location` decoration specifies which vertex input attribute is used to read and interpret the data that a variable will consume. The `Component` decoration allows the location to be more finely specified for scalars and vectors, down to the individual components within a location that are consumed. The components within a location are 0, 1, 2, and 3. A variable starting at component N will consume components N, N+1, N+2, … up through its size. For single precision types, it is invalid if the sequence of components gets larger than 3.

When a vertex shader input variable declared using a scalar or vector 32-bit 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 32-bit input variables. Any 32-bit scalar or vector input will consume a single location. For 32-bit data types, missing components are filled in with default values as described below.

Table 21. Input attribute components accessed by 32-bit input variables

32-bit data type	`Component` decoration	Components consumed
scalar	0 or unspecified	(x, o, o, o)
scalar	1	(o, y, o, o)
scalar	2	(o, o, z, o)
scalar	3	(o, o, o, w)
two-component vector	0 or unspecified	(x, y, o, o)
two-component vector	1	(o, y, z, o)
two-component vector	2	(o, o, z, w)
three-component vector	0 or unspecified	(x, y, z, o)
three-component vector	1	(o, y, z, w)
four-component vector	0 or unspecified	(x, y, z, w)

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 22. Input attributes accessed by 32-bit input matrix variables

Data type	Column vector type	Locations consumed	Components consumed
mat2	two-component vector	i, i+1	(x, y, o, o), (x, y, o, o)
mat2x3	three-component vector	i, i+1	(x, y, z, o), (x, y, z, o)
mat2x4	four-component vector	i, i+1	(x, y, z, w), (x, y, z, w)
mat3x2	two-component vector	i, i+1, i+2	(x, y, o, o), (x, y, o, o), (x, y, o, o)
mat3	three-component vector	i, i+1, i+2	(x, y, z, o), (x, y, z, o), (x, y, z, o)
mat3x4	four-component vector	i, i+1, i+2	(x, y, z, w), (x, y, z, w), (x, y, z, w)
mat4x2	two-component vector	i, i+1, i+2, i+3	(x, y, o, o), (x, y, o, o), (x, y, o, o), (x, y, o, o)
mat4x3	three-component vector	i, i+1, i+2, i+3	(x, y, z, o), (x, y, z, o), (x, y, z, o), (x, y, z, o)
mat4	four-component vector	i, i+1, i+2, i+3	(x, y, z, w), (x, y, z, w), (x, y, z, w), (x, y, z, w)

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 (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 locations and components 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. Input attributes which have one- or two-component 64-bit formats will consume a single location. Input attributes which have three- or four-component 64-bit formats will consume two consecutive locations. A 64-bit scalar data type will consume two components, and a 64-bit two-component vector data type will consume all four components available within a location. A three- or four-component 64-bit data type **must** not specify a component. A three-component 64-bit data type will consume all four components of the first location and components 0 and 1 of the second location. This leaves components 2 and 3 available for other component-qualified declarations. A four-component 64-bit data type will consume all four components of the first location and all four components of the second location. It is invalid for a scalar or two-component 64-bit data type to specify a component of 1 or 3.

Table 23. Input attribute locations and components accessed by 64-bit input variables

Input format	Locations consumed	64-bit data type	`Location` decoration	`Component` decoration	32-bit components consumed
R64	i	scalar	i	0 or unspecified	(x, y, -, -)
R64G64	i	scalar	i	0 or unspecified	(x, y, o, o)
		scalar	i	2	(o, o, z, w)
		two-component vector	i	0 or unspecified	(x, y, z, w)
R64G64B64	i, i+1	scalar	i	0 or unspecified	(x, y, o, o), (o, o, -, -)
		scalar	i	2	(o, o, z, w), (o, o, -, -)
		scalar	i+1	0 or unspecified	(o, o, o, o), (x, y, -, -)
		two-component vector	i	0 or unspecified	(x, y, z, w), (o, o, -, -)
		three-component vector	i	unspecified	(x, y, z, w), (x, y, -, -)

Input format	Locations consumed	64-bit data type	`Location` decoration	`Component` decoration	32-bit components consumed
R64G64B64A64	i, i+1	scalar	i	0 or unspecified	(x, y, o, o), (o, o, o, o)
		scalar	i	2	(o, o, z, w), (o, o, o, o)
		scalar	i+1	0 or unspecified	(o, o, o, o), (x, y, o, o)
		scalar	i+1	2	(o, o, o, o), (o, o, z, w)
		two-component vector	i	0 or unspecified	(x, y, z, w), (o, o, o, o)
		two-component vector	i+1	0 or unspecified	(o, o, o, o), (x, y, z, w)
		three-component vector	i	unspecified	(x, y, z, w), (x, y, o, o)
		four-component vector	i	unspecified	(x, y, z, w), (x, y, z, w)

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 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 location immediately following the last 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 `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. *Location aliasing* is causing two variables to have the same location number. *Component aliasing* is assigning the same (or overlapping) component number for two location aliases. Location aliasing is allowed only if it does not cause component aliasing. Further, when location aliasing, the aliases sharing the location **must** all have the same SPIR-V floating-point component type or all have the same width integer-type components.

20.2. Vertex Input Description

Applications specify vertex input attribute and vertex input binding descriptions as part of graphics pipeline creation. The VkGraphicsPipelineCreateInfo::pVertexInputState points to a structure of type VkPipelineVertexInputStateCreateInfo.

The VkPipelineVertexInputStateCreateInfo structure is defined as:

```
typedef struct VkPipelineVertexInputStateCreateInfo {
    VkStructureType                             sType;
    const void*                                 pNext;
    VkPipelineVertexInputStateCreateFlags       flags;
    uint32_t                                    vertexBindingDescriptionCount;
    const VkVertexInputBindingDescription*      pVertexBindingDescriptions;
    uint32_t                                    vertexAttributeDescriptionCount;
    const VkVertexInputAttributeDescription*    pVertexAttributeDescriptions;
} VkPipelineVertexInputStateCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- vertexBindingDescriptionCount is the number of vertex binding descriptions provided in pVertexBindingDescriptions.
- 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

- vertexBindingDescriptionCount **must** be less than or equal to VkPhysicalDeviceLimits ::maxVertexInputBindings
- vertexAttributeDescriptionCount **must** be less than or equal to VkPhysicalDeviceLimits ::maxVertexInputAttributes
- For every binding specified by each element of pVertexAttributeDescriptions, a VkVertexInputBindingDescription **must** exist in pVertexBindingDescriptions with the same value of binding
- All elements of pVertexBindingDescriptions **must** describe distinct binding numbers
- All elements of pVertexAttributeDescriptions **must** describe distinct attribute locations

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- If vertexBindingDescriptionCount is not 0, pVertexBindingDescriptions **must** be a valid pointer to an array of vertexBindingDescriptionCount valid VkVertexInputBindingDescription structures
- 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 an instance of the VkVertexInputBindingDescription structure.

The VkVertexInputBindingDescription structure is 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 distance in bytes between two 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

- binding **must** be less than VkPhysicalDeviceLimits::maxVertexInputBindings
- stride **must** be less than or equal to VkPhysicalDeviceLimits::maxVertexInputBindingStride

Valid Usage (Implicit)

- inputRate **must** be a valid VkVertexInputRate value

Possible values of VkVertexInputBindingDescription::inputRate, specifying the rate at which vertex attributes are pulled from buffers, are:

```
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 an instance of the VkVertexInputAttributeDescription structure.

The VkVertexInputAttributeDescription structure is defined as:

```
typedef struct VkVertexInputAttributeDescription {
    uint32_t    location;
    uint32_t    binding;
    VkFormat    format;
    uint32_t    offset;
} VkVertexInputAttributeDescription;
```

- location is the shader binding 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

- location **must** be less than VkPhysicalDeviceLimits::maxVertexInputAttributes
- binding **must** be less than VkPhysicalDeviceLimits::maxVertexInputBindings
- offset **must** be less than or equal to VkPhysicalDeviceLimits::maxVertexInputAttributeOffset
- format **must** be allowed as a vertex buffer format, as specified by the VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT flag in VkFormatProperties::bufferFeatures returned by vkGetPhysicalDeviceFormatProperties

Valid Usage (Implicit)

- format **must** be a valid VkFormat value

To bind vertex buffers to a command buffer for use in subsequent draw commands, call:

```
void vkCmdBindVertexBuffers(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    firstBinding,
    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 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]. All vertex input attributes that use each of these bindings will use these updated addresses in their address calculations for subsequent draw commands.

Valid Usage

- firstBinding **must** be less than VkPhysicalDeviceLimits::maxVertexInputBindings
- The sum of firstBinding and bindingCount **must** be less than or equal to VkPhysicalDeviceLimits::maxVertexInputBindings
- All elements of pOffsets **must** be less than the size of the corresponding element in pBuffers
- All elements of pBuffers **must** have been created with the VK_BUFFER_USAGE_VERTEX_BUFFER_BIT flag
- Each element of pBuffers that is non-sparse **must** be bound completely and contiguously to a single VkDeviceMemory object

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- pBuffers **must** be a valid pointer to an array of bindingCount valid VkBuffer handles
- pOffsets **must** be a valid pointer to an array of bindingCount VkDeviceSize values
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics operations
- bindingCount **must** be greater than 0
- Both of commandBuffer, and the elements of pBuffers **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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

The address of each attribute for each vertexIndex and instanceIndex is calculated as follows:

- Let attribDesc be the member of VkPipelineVertexInputStateCreateInfo::pVertexAttributeDescriptions with VkVertexInputAttributeDescription::location equal to the vertex input attribute number.
- Let bindingDesc be the member of VkPipelineVertexInputStateCreateInfo::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 for vkCmdDrawIndexed), and let instanceIndex be the instance number of the draw (a value between firstInstance and firstInstance+instanceCount).

```
bufferBindingAddress = buffer[binding].baseAddress + offset[binding];

if (bindingDesc.inputRate == VK_VERTEX_INPUT_RATE_VERTEX)
    vertexOffset = vertexIndex * bindingDesc.stride;
else
    vertexOffset = instanceIndex * bindingDesc.stride;

attribAddress = bufferBindingAddress + vertexOffset + attribDesc.offset;
```

For each attribute, raw data is extracted starting at attribAddress and is converted from the VkVertexInputAttributeDescription's format to either to floating-point, unsigned integer, or signed integer based on the base type of the format; the base type of the format **must** match the base type of the input variable in the shader. 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). If the format does not include G, B, or A components, then those are filled with (0,0,1) as needed (using either 1.0f or integer 1 based on the format) for attributes that are not 64-bit data types. 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.

20.3. Example

To create a graphics pipeline that uses the following vertex description:

```
struct Vertex
{
    float   x, y, z, w;
    uint8_t u, v;
};
```

The application could use the following set of structures:

```
const VkVertexInputBindingDescription binding =
{
    0,                                          // binding
    sizeof(Vertex),                             // stride
    VK_VERTEX_INPUT_RATE_VERTEX                 // inputRate
};

const VkVertexInputAttributeDescription attributes[] =
{
    {
        0,                                      // location
        binding.binding,                        // binding
        VK_FORMAT_R32G32B32A32_SFLOAT,          // format
        0                                       // offset
    },
    {
        1,                                      // location
        binding.binding,                        // binding
        VK_FORMAT_R8G8_UNORM,                   // format
        4 * sizeof(float)                       // offset
    }
};

const VkPipelineVertexInputStateCreateInfo viInfo =
{
    VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_CREATE_INFO,    // sType
    NULL,                            // pNext
    0,                               // flags
    1,                               // vertexBindingDescriptionCount
    &binding,                        // pVertexBindingDescriptions
    2,                               // vertexAttributeDescriptionCount
    &attributes[0]                   // pVertexAttributeDescriptions
};
```

Chapter 21. 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.

21.1. 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 `TessLevelOuter` and `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 `OpExecutionMode` instruction in the tessellation evaluation or tessellation control shader using one of execution modes `Triangles`, `Quads`, and `IsoLines`. Other tessellation-related execution modes **can** also be specified in either the tessellation control or tessellation evaluation shaders, and if they are specified in both then the modes **must** be the same.

Tessellation execution modes include:

- `Triangles`, `Quads`, and `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.
- `VertexOrderCw` and `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.
- `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.
- `SpacingEqual`, `SpacingFractionalEven`, and `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.
- `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 figure Domain parameterization for tessellation primitive modes (upper-left origin). The domain space has an upper-left origin.

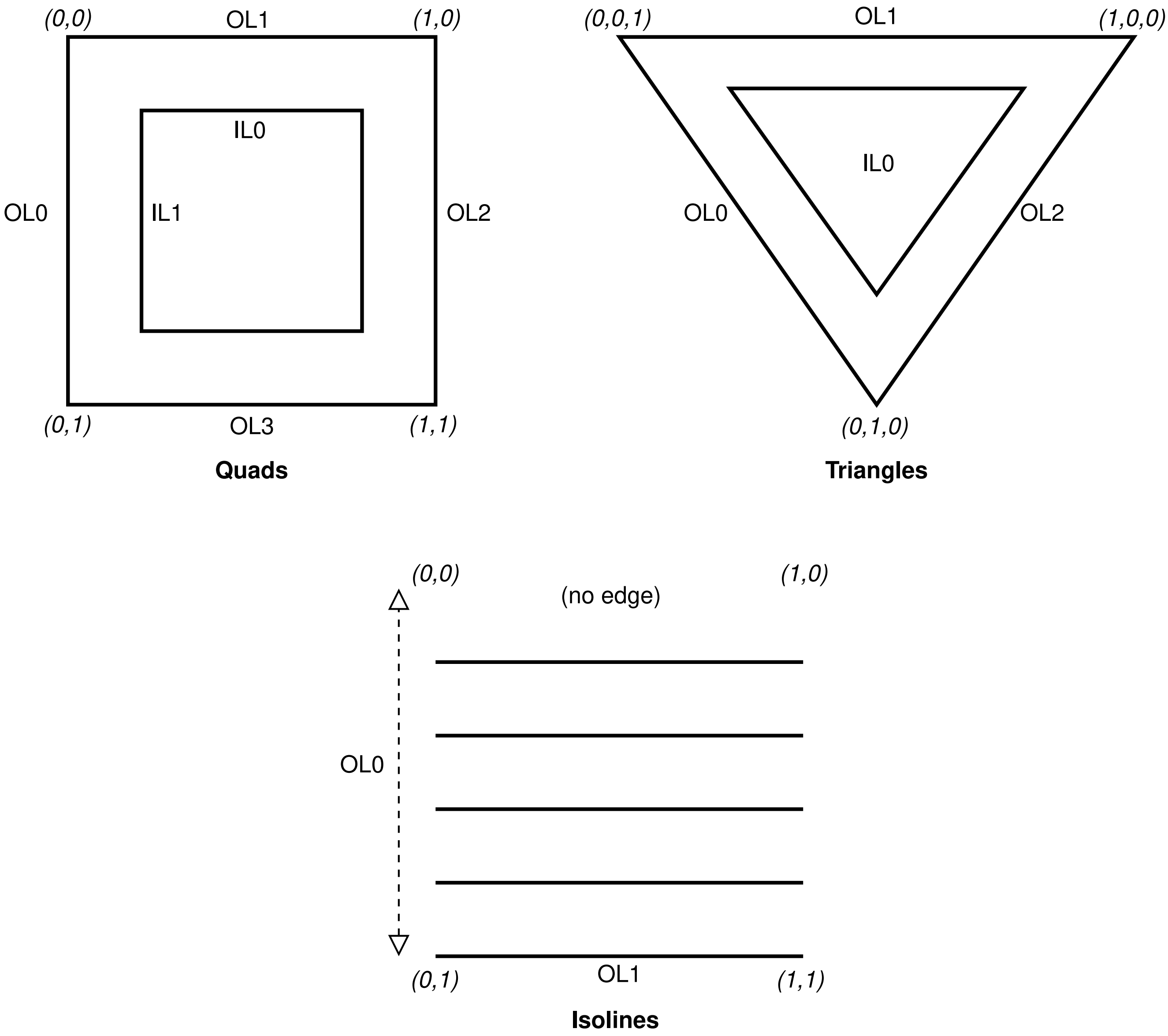

Figure 9. Domain parameterization for tessellation primitive modes (upper-left origin)

Caption

In the domain parameterization diagrams, the coordinates illustrate the value of `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.

21.2. 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.

21.3. 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, `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, `maxLevel`] and then rounded up to the nearest even integer n. If `SpacingFractionalOdd` is used, the tessellation level is clamped to [1, `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 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.

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 ith vertex of the triangle.

> *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.

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. Otherwise, the tessellator will produce a collection of line segments or triangles according to the primitive mode. When tessellating triangles or quads in 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.

21.4. 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.

21.5. 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 + ε 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 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.

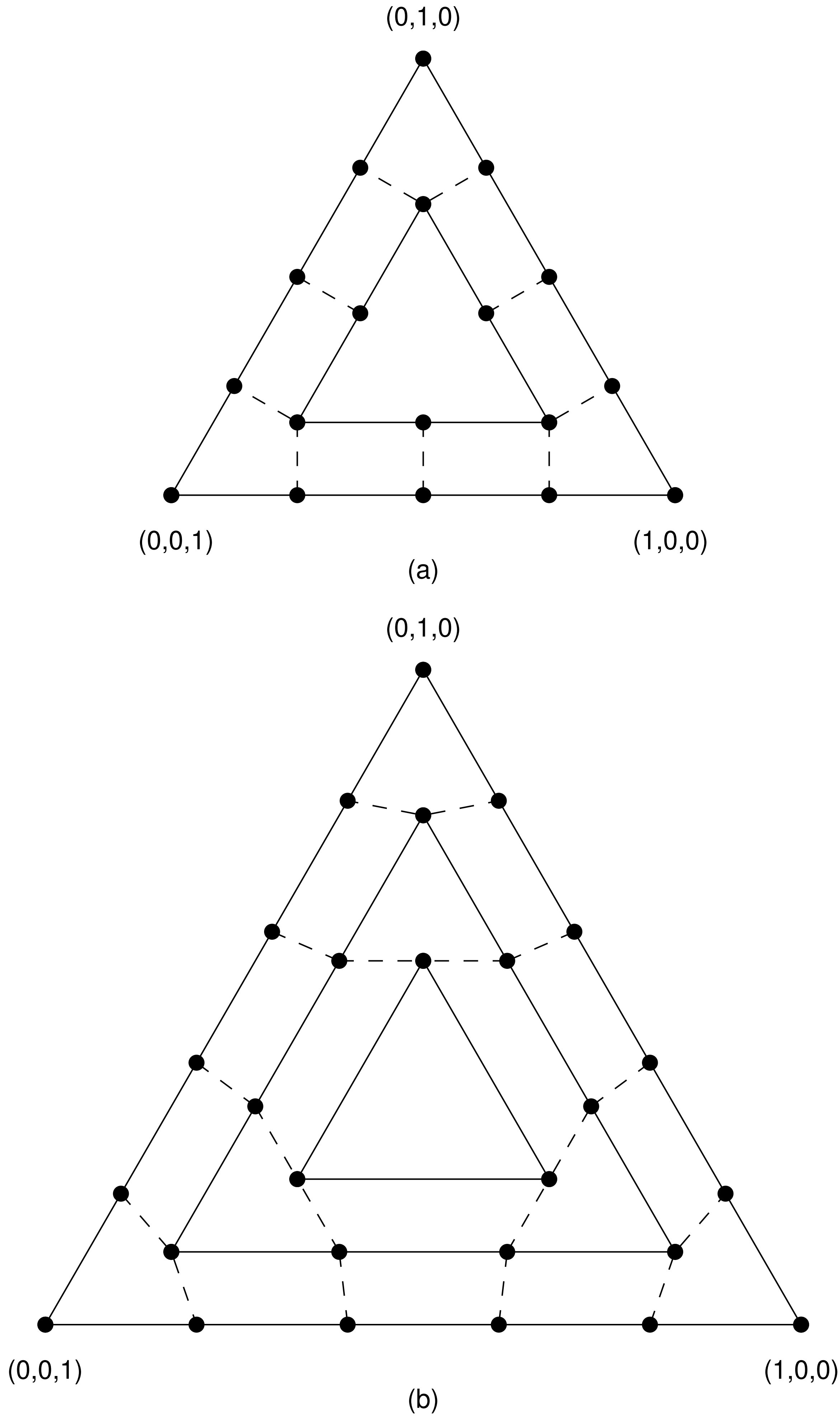

Figure 10. Inner Triangle Tessellation

Caption

In the Inner Triangle Tessellation diagram, inner tessellation levels of (a) five and (b) four 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.

The order in which the vertices for a given output triangle is generated is implementation-dependent. However, when depicted in a manner similar to Inner Triangle Tessellation, the order of the vertices in each generated triangle will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

21.6. 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 were originally specified as 1 + ε 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.

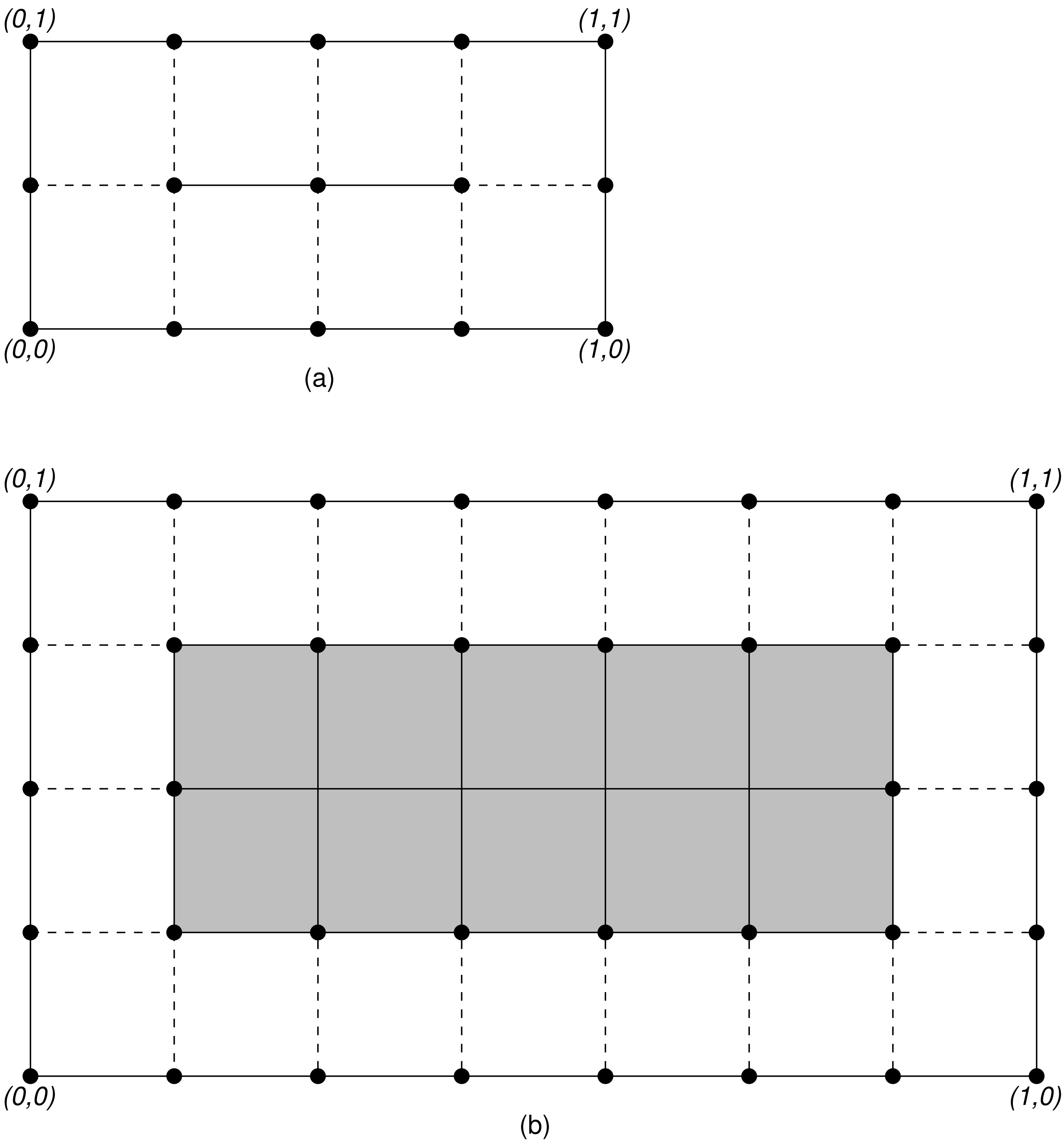

Figure 11. Inner Quad Tessellation

Caption

In the Inner Quad Tessellation diagram, inner quad tessellation levels of (a) (4,2) and (b) (7,4) are shown. Gray regions 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 on the top figure 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 triangle. 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.

The order in which the vertices for a given output triangle is generated is implementation-dependent. However, when depicted in a manner similar to Inner Quad Tessellation, the order of the vertices in each generated triangle will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

21.7. 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, $\frac{1}{n}, \frac{2}{n}, \ldots, \frac{n-1}{n}$.

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.

The order in which the vertices for a given output line is generated is implementation-dependent.

21.8. Tessellation Pipeline State

The `pTessellationState` member of VkGraphicsPipelineCreateInfo points to a structure of type `VkPipelineTessellationStateCreateInfo`.

The `VkPipelineTessellationStateCreateInfo` structure is defined as:

```
typedef struct VkPipelineTessellationStateCreateInfo {
    VkStructureType                           sType;
    const void*                               pNext;
    VkPipelineTessellationStateCreateFlags    flags;
    uint32_t                                  patchControlPoints;
} VkPipelineTessellationStateCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- patchControlPoints number of control points per patch.

Valid Usage

- patchControlPoints **must** be greater than zero and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0

```
typedef VkFlags VkPipelineTessellationStateCreateFlags;
```

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

Chapter 22. 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.

22.1. 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** be compatible with the primitive topology used by primitive assembly (if tessellation is not in use) or **must** match the type of primitive generated by the tessellation primitive generator (if tessellation is in use). Compatibility is defined below, with each input primitive type. The input primitive types accepted by a geometry shader are:

Points

Geometry shaders that operate on points use an `OpExecutionMode` instruction specifying the `InputPoints` input mode. Such a shader is valid only when the pipeline primitive topology is `VK_PRIMITIVE_TOPOLOGY_POINT_LIST` (if tessellation is not in use) or if tessellation is in use and the tessellation evaluation shader uses `PointMode`. There is only a single input vertex available for each geometry shader invocation. However, inputs to the geometry shader are still presented as an array, but this array has a length of one.

Lines

Geometry shaders that operate on line segments are generated by including an `OpExecutionMode` instruction with the `InputLines` mode. Such a shader is valid only for the `VK_PRIMITIVE_TOPOLOGY_LINE_LIST`, and `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP` primitive topologies (if tessellation is not in use) or if tessellation is in use and the tessellation mode is `Isolines`. There are two input vertices available for each geometry shader invocation. The first vertex refers to the vertex at the beginning of the line segment and the second vertex refers to the vertex at the end of the line segment.

Lines with Adjacency

Geometry shaders that operate on line segments with adjacent vertices are generated by including an `OpExecutionMode` instruction with the `InputLinesAdjacency` mode. Such a shader is valid only for the `VK_PRIMITIVE_TOPOLOGY_LINES_WITH_ADJACENCY` and `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY` primitive topologies and **must** not be used when tessellation is in use.

In this mode, there are four vertices available for each geometry shader invocation. The second vertex refers to attributes of the vertex at the beginning of the line segment and the third vertex refers to the vertex at the end of the line segment. The first and fourth vertices refer to the vertices adjacent to the beginning and end of the line segment, respectively.

Triangles

Geometry shaders that operate on triangles are created by including an OpExecutionMode instruction with the Triangles mode. Such a shader is valid when the pipeline topology is VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP, or VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN (if tessellation is not in use) or when tessellation is in use and the tessellation mode is Triangles or Quads.

In this mode, there are three vertices available for each geometry shader invocation. The first, second, and third vertices refer to attributes of the first, second, and third vertex of the triangle, respectively.

Triangles with Adjacency

Geometry shaders that operate on triangles with adjacent vertices are created by including an OpExecutionMode instruction with the InputTrianglesAdjacency mode. Such a shader is valid when the pipeline topology is VK_PRIMITIVE_TOPOLOGY_TRIANGLES_WITH_ADJACENCY or VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY, and **must** not be used when tessellation is in use.

In this mode, there are six vertices available for each geometry shader invocation. The first, third and fifth vertices refer to attributes of the first, second and third vertex of the triangle, respectively. The second, fourth and sixth vertices refer to attributes of the vertices adjacent to the edges from the first to the second vertex, from the second to the third vertex, and from the third to the first vertex, respectively.

22.2. 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.

22.3. 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 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`.

22.4. 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 23. Fixed-Function Vertex Post-Processing

After programmable vertex processing, 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.

23.1. 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. The provoking vertex depends on the primitive topology, and is generally the “first” vertex of the primitive. For primitives not processed by tessellation or geometry shaders, the provoking vertex is selected from the input vertices according to the following table.

Table 24. Provoking vertex selection

Primitive type of primitive i	Provoking vertex number
VK_PRIMITIVE_TOPOLOGY_POINT_LIST	i
VK_PRIMITIVE_TOPOLOGY_LINE_LIST	2 i
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP	i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST	3 i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP	i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN	i + 1
VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY	4 i + 1
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY	i + 1
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY	6 i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY	2 i

Caption

The Provoking vertex selection table defines the output values used for flat shading the i^{th} primitive generated by drawing commands with the indicated primitive type, derived from the corresponding values of the vertex whose index is shown in the table. Primitives and vertices are numbered starting from zero.

Flat shading is applied to those vertex attributes that match fragment input attributes which are decorated as `Flat`.

If a geometry shader is active, the output primitive topology is either points, line strips, or triangle strips, and the selection of the provoking vertex behaves according to the corresponding row of the table. If a tessellation evaluation shader is active and a geometry shader is not active, the provoking vertex is undefined but **must** be one of the vertices of the primitive.

23.2. 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:

$$-w_c \le x_c \le w_c$$
$$-w_c \le y_c \le w_c$$
$$0 \le z_c \le w_c$$

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

$$c_i(\mathbf{P}) \geq 0$$

where $c_i(\mathbf{P})$ is the clip distance i at point **P**. For point primitives, $c_i(\mathbf{P})$ 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. If depth clamping is enabled, the plane equation

$$0 \leq z_c \leq w_c$$

(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.

If a point's vertex lies outside of the clip volume, the entire primitive **may** be discarded.

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 original vertices' coordinates are $\mathbf{P}_1$ and $\mathbf{P}_2$, then t is given by

$$\mathbf{P} = t\,\mathbf{P}_1 + (1-t)\,\mathbf{P}_2.$$

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 lie entirely inside the clip volume, and it is discarded if every one of its edges lie entirely outside the clip volume. 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.

23.3. 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 $\mathbf{P}_1$ and $\mathbf{P}_2$ of an unclipped edge be $\mathbf{c}_1$ and $\mathbf{c}_2$. The value of t (see Primitive Clipping) for a clipped point **P** is used to obtain the output value associated with **P** as

$$\mathbf{c} = t\ \mathbf{c}_1 + (1-t)\ \mathbf{c}_2.$$

(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_c, 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 `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 **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 $\mathbf{c}_1$ or $\mathbf{c}_2$, since flat shading has already occurred and the two values are identical.

23.4. Coordinate Transformations

Clip coordinates for a vertex result from shader execution, which yields a vertex coordinate `Position`.

Perspective division on clip coordinates yields *normalized device coordinates*, followed by a *viewport* transformation (see Controlling the Viewport) to convert these coordinates into *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

$$\begin{pmatrix} x_d \\ y_d \\ z_d \end{pmatrix} = \begin{pmatrix} \frac{x_c}{w_c} \\ \frac{y_c}{w_c} \\ \frac{z_c}{w_c} \end{pmatrix}$$

23.5. 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

$x_f = (p_x / 2)\ x_d + o_x$

$y_f = (p_y / 2)\ y_d + o_y$

$z_f = p_z \times z_d + o_z$

Multiple viewports are available, numbered zero up to `VkPhysicalDeviceLimits`::`maxViewports` minus one. The number of viewports used by a pipeline is controlled by the `viewportCount` member of the `VkPipelineViewportStateCreateInfo` structure used in pipeline creation.

The `VkPipelineViewportStateCreateInfo` structure is defined as:

```
typedef struct VkPipelineViewportStateCreateInfo {
    VkStructureType                       sType;
    const void*                           pNext;
    VkPipelineViewportStateCreateFlags    flags;
    uint32_t                              viewportCount;
    const VkViewport*                     pViewports;
    uint32_t                              scissorCount;
    const VkRect2D*                       pScissors;
} VkPipelineViewportStateCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.

- flags is reserved for future use.
- viewportCount is the number of viewports used by the pipeline.
- pViewports is a pointer to an array of VkViewport structures, defining the viewport transforms. If the viewport state is dynamic, this member is ignored.
- scissorCount is the number of scissors and **must** match the number of viewports.
- pScissors is a pointer to an array of VkRect2D structures which define the rectangular bounds of the scissor for the corresponding viewport. If the scissor state is dynamic, this member is ignored.

Valid Usage

- If the multiple viewports feature is not enabled, viewportCount **must** be 1
- If the multiple viewports feature is not enabled, scissorCount **must** be 1
- viewportCount **must** be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
- scissorCount **must** be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
- scissorCount and viewportCount **must** be identical

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- viewportCount **must** be greater than 0
- scissorCount **must** be greater than 0

```
typedef VkFlags VkPipelineViewportStateCreateFlags;
```

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

If a geometry shader is active and has an output variable decorated with ViewportIndex, the viewport transformation uses the viewport corresponding to the value assigned to ViewportIndex 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 geometry shader did not assign a value to ViewportIndex for all vertices of a primitive due to flow control, the results of the viewport transformation of the vertices of such primitives are undefined. If no geometry shader is active, or if the geometry shader 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.

If the bound pipeline state object was not created with the VK_DYNAMIC_STATE_VIEWPORT dynamic state enabled, viewport transformation parameters are specified using the pViewports member of VkPipelineViewportStateCreateInfo in the pipeline state object. If the pipeline state object was created with the VK_DYNAMIC_STATE_VIEWPORT dynamic state enabled, the viewport transformation parameters are dynamically set and changed with the command:

```
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.

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

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_VIEWPORT dynamic state enabled
- firstViewport **must** be less than VkPhysicalDeviceLimits::maxViewports
- The sum of firstViewport and viewportCount **must** be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
- If the multiple viewports feature is not enabled, firstViewport **must** be 0
- If the multiple viewports feature is not enabled, viewportCount **must** be 1

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- pViewports **must** be a valid pointer to an array of viewportCount VkViewport structures
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support graphics operations
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

Both VkPipelineViewportStateCreateInfo and vkCmdSetViewport use `VkViewport` to set the viewport transformation parameters.

The `VkViewport` structure is defined as:

```
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. It is valid for `minDepth` to be greater than or equal to `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 ∈ { 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` + `width` / 2

o_y = `y` + `height` / 2

o_z = `minDepth`

p_x = `width`

p_y = `height`

p_z = `maxDepth` - `minDepth`.

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

- `width` **must** be greater than `0.0`
- `width` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxViewportDimensions`[0]
- `height` **must** be greater than `0.0`
- The absolute value of `height` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxViewportDimensions`[1]
- `x` **must** be greater than or equal to `viewportBoundsRange`[0]
- (`x` + `width`) **must** be less than or equal to `viewportBoundsRange`[1]
- `y` **must** be greater than or equal to `viewportBoundsRange`[0]
- (`y` + `height`) **must** be less than or equal to `viewportBoundsRange`[1]
- `minDepth` **must** be between `0.0` and `1.0`, inclusive
- `maxDepth` **must** be between `0.0` and `1.0`, inclusive

Chapter 24. Rasterization

Rasterization is the process by which a primitive is converted to a two-dimensional image. Each point 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 subpixel 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 the early per-fragment tests, if enabled.

Several factors affect rasterization, including the members of `VkPipelineRasterizationStateCreateInfo` and `VkPipelineMultisampleStateCreateInfo`.

The `VkPipelineRasterizationStateCreateInfo` structure is defined as:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.

- depthClampEnable controls whether to clamp the fragment's depth values instead of clipping primitives to the z planes of the frustum, 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

- If the depth clamping feature is not enabled, depthClampEnable **must** be VK_FALSE
- If the non-solid fill modes feature is not enabled, polygonMode **must** be VK_POLYGON_MODE_FILL

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- polygonMode **must** be a valid VkPolygonMode value
- cullMode **must** be a valid combination of VkCullModeFlagBits values
- frontFace **must** be a valid VkFrontFace value

```
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:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `rasterizationSamples` is a VkSampleCountFlagBits specifying the number of samples per pixel 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 bitmask of static coverage information that is ANDed with the coverage information generated during rasterization, as described in Sample Mask.
- `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.

Valid Usage

- If the sample rate shading feature is not enabled, `sampleShadingEnable` **must** be `VK_FALSE`
- If the alpha to one feature is not enabled, `alphaToOneEnable` **must** be `VK_FALSE`
- `minSampleShading` **must** be in the range [0,1]

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- `rasterizationSamples` **must** be a valid VkSampleCountFlagBits value
- If `pSampleMask` is not `NULL`, `pSampleMask` **must** be a valid pointer to an array of $\lceil \frac{rasterizationSamples}{32} \rceil$ `VkSampleMask` values

```
typedef VkFlags VkPipelineMultisampleStateCreateFlags;
```

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

Rasterization only produces fragments corresponding to pixels in the framebuffer. 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 early per-fragment tests described in Early Per-Fragment Tests.

Surviving fragments are processed by fragment shaders. Fragment shaders determine associated data for fragments, and **can** also modify or replace their assigned depth values.

If the subpass for which this pipeline is being created uses color and/or depth/stencil attachments, then `rasterizationSamples` **must** be the same as the sample count for those subpass attachments.

If the subpass for which this pipeline is being created does not use color or depth/stencil attachments, `rasterizationSamples` **must** follow the rules for a zero-attachment subpass.

24.1. 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.

24.2. 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. Scissor test
2. Sample mask generation
3. Depth bounds test

4. Stencil test, stencil op and stencil write
5. Depth test and depth write
6. Sample counting for occlusion queries
7. coverage reduction
8. Blending, logic operations, and color writes

Each of these operations is atomically executed for each primitive and sample location.

Execution of these operations for each primitive in a subpass occurs in primitive order.

24.3. 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 pixel.

Each fragment includes a coverage value with `rasterizationSamples` bits (see Sample Mask). Each fragment includes `rasterizationSamples` depth values and sets of associated data. An implementation **may** choose to assign the same associated data to more than one sample. The location for evaluating such associated data **may** be anywhere within the pixel including the pixel center or any of the sample locations. When `rasterizationSamples` is `VK_SAMPLE_COUNT_1_BIT`, the pixel center **must** be used. The different associated data values need not all be evaluated at the same location. Each pixel fragment thus consists of integer x and y grid coordinates, `rasterizationSamples` depth values and sets of associated data, and a coverage value with `rasterizationSamples` bits.

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.

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 ith entry in the table corresponding to bit i in the sample masks. `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 pixel.

Table 25. Standard sample locations

VK_SAMPLE_COUNT_1_BIT	VK_SAMPLE_COUNT_2_BIT	VK_SAMPLE_COUNT_4_BIT	VK_SAMPLE_COUNT_8_BIT	VK_SAMPLE_COUNT_16_BIT
(0.5,0.5)	(0.25,0.25) (0.75,0.75)	(0.375, 0.125) (0.875, 0.375) (0.125, 0.625) (0.625, 0.875)	(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)	(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)

24.4. 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** provide a minimum of max(minSampleShadingFactor × totalSamples , 1) unique associated data for each fragment, where minSampleShadingFactor is the minimum fraction of sample shading and totalSamples is the value of VkPipelineMultisampleStateCreateInfo::pname.rasterizationSamples specified at pipeline creation time. These are associated with the samples in an implementation-dependent manner. When minSampleShadingFactor is 1.0, a separate set of associated data are evaluated for each sample, and each set of values is evaluated at the sample location.

Sample shading is enabled for a graphics pipeline:

- If the interface of the fragment shader entry point of the graphics pipeline includes an input variable decorated with SampleId or SamplePosition. In this case minSampleShadingFactor takes the value 1.0.
- Else if the sampleShadingEnable member of the VkPipelineMultisampleStateCreateInfo structure specified when creating the graphics pipeline is set to VK_TRUE. In this case minSampleShadingFactor takes the value of VkPipelineMultisampleStateCreateInfo::minSampleShading.

Otherwise, sample shading is considered disabled.

24.5. 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 that controls the width/height of that square. The point size is taken from the (potentially clipped) shader built-in PointSize written by:

- the geometry shader, if active;
- the tessellation evaluation shader, if active and no geometry shader is active;
- the tessellation control shader, if active and no geometry or tessellation evaluation shader is active; or
- the vertex shader, otherwise

and clamped to the implementation-dependent point size range [pointSizeRange[0], pointSizeRange[1]]. If the value written to PointSize is less than or equal to zero, or if no value was written to PointSize, results are undefined.

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 pointSizeRange and pointSizeGranularity 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 size 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.

24.5.1. Basic Point Rasterization

Point rasterization produces a fragment for each framebuffer pixel 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 top-to-bottom, respectively. The following formulas are used to evaluate s and t:

$$s = \frac{1}{2} + \frac{\left(x_p - x_f\right)}{\text{size}}$$

$$t = \frac{1}{2} + \frac{\left(y_p - y_f\right)}{\text{size}}$$

where 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 pixel center (i.e. at the half-integer) or the location of a sample, and (x_f,y_f) is the exact, unrounded framebuffer coordinate of the vertex for the point. When rasterizationSamples is VK_SAMPLE_COUNT_1_BIT, the pixel center **must** be used.

24.6. Line Segments

A line is drawn by generating a set of fragments overlapping a rectangle centered on the line segment. Each line segment has an associated width that controls the width of that rectangle.

The line width is specified by the VkPipelineRasterizationStateCreateInfo::lineWidth property of the currently active pipeline, if the pipeline was not created with VK_DYNAMIC_STATE_LINE_WIDTH enabled.

Otherwise, the line width is set by calling vkCmdSetLineWidth:

```
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.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_LINE_WIDTH dynamic state enabled
- If the wide lines feature is not enabled, lineWidth **must** be 1.0

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- commandBuffer **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

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 size 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.

24.6.1. 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 $\mathbf{p}_r = (x_d, y_d)$ be the framebuffer coordinates at which associated data are evaluated. This **may** be the pixel center of a fragment or the location of a sample within the fragment. When `rasterizationSamples` is `VK_SAMPLE_COUNT_1_BIT`, the pixel center **must** be used. Let $\mathbf{p}_a = (x_a, y_a)$ and $\mathbf{p}_b = (x_b, y_b)$ 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 **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.)

The value of an associated datum f for the fragment, whether it be a shader output or the clip w coordinate, **must** be determined using *perspective interpolation*:

$$f = \frac{(1-t) f_a / w_a + t f_b / w_b}{(1-t) / w_a + t / w_b}$$

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 segments, respectively.

Depth values for lines **must** be determined using *linear interpolation*:

$$z = (1 - t)\, z_a + t\, z_b$$

where z_a and z_b are the depth values of the starting and ending endpoints of the segment, respectively.

The `NoPerspective` and `Flat` interpolation decorations **can** be used with fragment shader inputs to declare how they are interpolated. When neither decoration is applied, perspective interpolation is performed as described above. When the `NoPerspective` decoration is used, linear interpolation is performed in the same fashion as for depth values, as described above. When the `Flat` decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the provoking vertex corresponding to that primitive.

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.

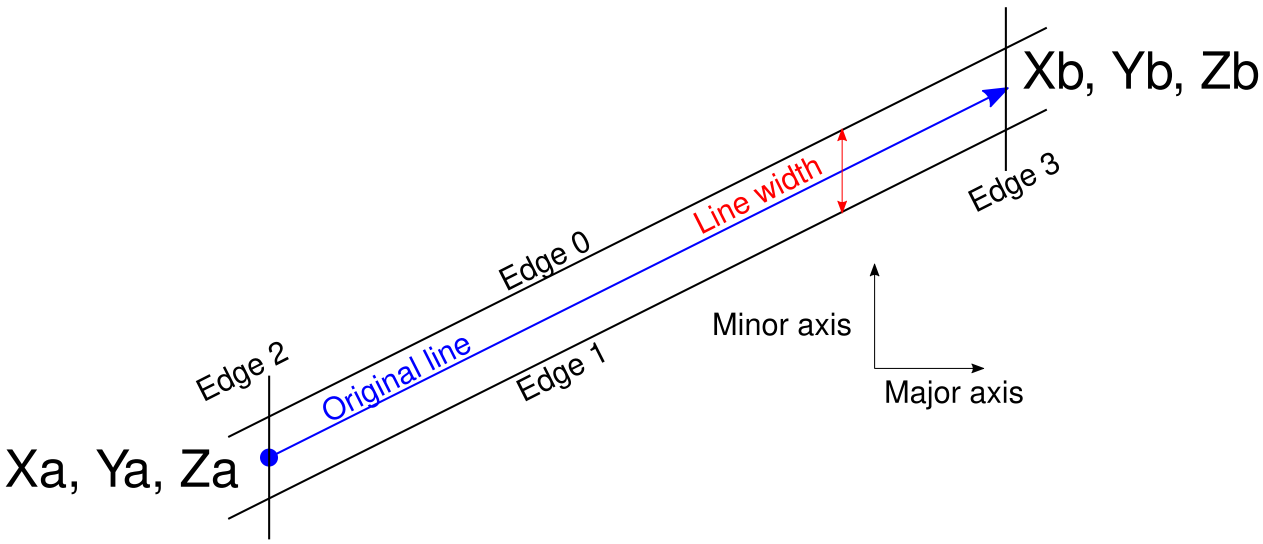

Figure 12. Non strict lines

24.7. 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.

24.7.1. 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:

$$a = -\frac{1}{2}\sum_{i=0}^{n-1} x_f^i y_f^{i\oplus 1} - x_f^{i\oplus 1} y_f^i$$

where x_f^i and y_f^i are the x and y framebuffer coordinates of the ith vertex of the n-vertex polygon (vertices are numbered starting at zero for the purposes of this computation) and i ⊕ 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:

```
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.

Once the orientation of triangles is determined, they are culled according to the VkPipelineRasterizationStateCreateInfo::cullMode property of the currently active pipeline. Possible values are:

```
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.

```
typedef VkFlags VkCullModeFlags;
```

VkCullModeFlags is a bitmask type for setting a mask of zero or more VkCullModeFlagBits.

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 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. Define *barycentric coordinates* for 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:

$$a = \frac{A(p p_b p_c)}{A(p_a p_b p_c)}, \quad b = \frac{A(p p_a p_c)}{A(p_a p_b p_c)}, \quad c = \frac{A(p p_a p_b)}{A(p_a p_b p_c)},$$

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.

The value of an associated datum f for a fragment produced by rasterizing a triangle, whether it be a shader output or the clip w coordinate, **must** be determined using perspective interpolation:

$$f = \frac{a f_a / w_a + b f_b / w_b + c f_c / w_c}{a / w_a + b / w_b + c / w_c}$$

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 - this **must** be a pixel center or the location of a sample. When `rasterizationSamples` is `VK_SAMPLE_COUNT_1_BIT`, the pixel center **must** be used.

Depth values for triangles **must** be determined using linear interpolation:

$z = a\, z_a + b\, z_b + c\, z_c$

where z_a, z_b, and z_c are the depth values of p_a, p_b, and p_c, respectively.

The `NoPerspective` and `Flat` interpolation decorations **can** be used with fragment shader inputs to declare how they are interpolated. When neither decoration is applied, perspective interpolation is performed as described above. When the `NoPerspective` decoration is used, linear interpolation is performed in the same fashion as for depth values, as described above. When the `Flat` decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the provoking vertex corresponding to that primitive.

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, $0 \le a_i \le 1$ 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 $j \ne i$.

> *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 equation [triangle_perspective_interpolation] are iterated independently and a division performed for each fragment).

24.7.2. Polygon Mode

Possible values of the VkPipelineRasterizationStateCreateInfo::`polygonMode` property of the currently active pipeline, specifying the method of rasterization for polygons, are:

```
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.

24.7.3. Depth Bias

The depth values of all fragments generated by the rasterization of a polygon **can** be offset by a single value that is computed for that polygon. This behavior is controlled by the `depthBiasEnable`, `depthBiasConstantFactor`, `depthBiasClamp`, and `depthBiasSlopeFactor` members of VkPipelineRasterizationStateCreateInfo, or by the corresponding parameters to the `vkCmdSetDepthBias` command if depth bias state is dynamic.

```
void vkCmdSetDepthBias(
    VkCommandBuffer                             commandBuffer,
    float                                       depthBiasConstantFactor,
    float                                       depthBiasClamp,
    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.

If depthBiasEnable is VK_FALSE, no depth bias is applied and the fragment's depth values are unchanged.

depthBiasSlopeFactor scales the maximum depth slope of the polygon, and depthBiasConstantFactor scales an implementation-dependent constant that relates to the usable resolution of the depth buffer. The resulting values are summed to produce the depth bias value which is then clamped to a minimum or maximum value specified by depthBiasClamp. depthBiasSlopeFactor, depthBiasConstantFactor, and depthBiasClamp **can** each be positive, negative, or zero.

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_f, y_f, z_f) is a point on the triangle. m **may** be approximated as

$$m = \max\left(\left|\frac{\partial z_f}{\partial x_f}\right|, \left|\frac{\partial z_f}{\partial y_f}\right|\right).$$

The minimum resolvable difference r is an implementation-dependent parameter that depends on the depth buffer representation. It is the smallest difference in framebuffer coordinate z values that is guaranteed to remain distinct throughout polygon rasterization and in the depth buffer. 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 buffer representations, r is constant throughout the range of the entire depth buffer. For floating-point depth buffers, 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

$$r = 2^{e-n}$$

If no depth buffer is present, r is undefined.

The bias value o for a polygon is

$$o = \begin{cases} m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor & depthBiasClamp = 0 \text{ or } NaN \\ \min(m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor, depthBiasClamp) & depthBiasClamp > 0 \\ \max(m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor, depthBiasClamp) & depthBiasClamp < 0 \end{cases}$$

m is computed as described above. If the depth buffer 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.

For fixed-point depth buffers, fragment depth values are always limited to the range [0,1] by clamping after depth bias addition is performed. Fragment depth values are clamped even when the depth buffer uses a floating-point representation.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the `VK_DYNAMIC_STATE_DEPTH_BIAS` dynamic state enabled
- If the depth bias clamping feature is not enabled, `depthBiasClamp` **must** be `0.0`

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `commandBuffer` **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

Chapter 25. Fragment Operations

Fragment operations execute on a per-fragment or per-sample basis, affecting whether or how a fragment or sample is written to the framebuffer. Some operations execute before fragment shading, and others after. Fragment operations always adhere to rasterization order.

25.1. Early Per-Fragment Tests

Once fragments are produced by rasterization, a number of per-fragment operations are performed prior to fragment shader execution. If a fragment is discarded during any of these operations, it will not be processed by any subsequent stage, including fragment shader execution.

The scissor test and sample mask generation are both always performed during early fragment tests.

Fragment operations are performed in the following order:

- the scissor test (see Scissor Test)
- multisample fragment operations (see Sample Mask)

If early per-fragment operations are enabled by the fragment shader, these operations are also performed:

- Depth bounds test
- Stencil test
- Depth test
- Sample counting for occlusion queries

25.2. Scissor Test

The scissor test determines if a fragment's framebuffer coordinates (x_f,y_f) lie within the scissor rectangle corresponding to the viewport index (see Controlling the Viewport) used by the primitive that generated the fragment. If the pipeline state object is created without `VK_DYNAMIC_STATE_SCISSOR` enabled then the scissor rectangles are set by the VkPipelineViewportStateCreateInfo state of the pipeline state object. Otherwise, to dynamically set the scissor rectangles call:

```
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).

Each scissor rectangle is described by a VkRect2D structure, with the offset.x and offset.y values determining the upper left corner of the scissor rectangle, and the extent.width and extent.height values determining the size in pixels.

Valid Usage

* The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_SCISSOR dynamic state enabled
* firstScissor **must** be less than VkPhysicalDeviceLimits::maxViewports
* The sum of firstScissor and scissorCount **must** be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
* If the multiple viewports feature is not enabled, firstScissor **must** be 0
* If the multiple viewports feature is not enabled, scissorCount **must** be 1
* The x and y members of offset **must** be greater than or equal to 0
* Evaluation of (offset.x + extent.width) **must** not cause a signed integer addition overflow
* Evaluation of (offset.y + extent.height) **must** not cause a signed integer addition overflow

Valid Usage (Implicit)

* commandBuffer **must** be a valid VkCommandBuffer handle
* pScissors **must** be a valid pointer to an array of scissorCount VkRect2D structures
* commandBuffer **must** be in the recording state
* The VkCommandPool that commandBuffer was allocated from **must** support graphics operations
* 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

If `offset.x` ≤ x_f < `offset.x` + `extent.width` and `offset.y` ≤ y_f < `offset.y` + `extent.height` for the selected scissor rectangle, then the scissor test passes. Otherwise, the test fails and the fragment is discarded. For points, lines, and polygons, the scissor rectangle for a primitive is selected in the same manner as the viewport (see Controlling the Viewport). The scissor rectangles test only applies to drawing commands, not to other commands like clears or copies.

It is legal for `offset.x` + `extent.width` or `offset.y` + `extent.height` to exceed the dimensions of the framebuffer - the scissor test still applies as defined above. Rasterization does not produce fragments outside of the framebuffer, so such fragments never have the scissor test performed on them.

The scissor test is always performed. Applications **can** effectively disable the scissor test by specifying a scissor rectangle that encompasses the entire framebuffer.

25.3. Sample Mask

This step modifies fragment coverage values based on the values in the `pSampleMask` array member of VkPipelineMultisampleStateCreateInfo, as described previously in section Graphics Pipelines.

`pSampleMask` contains an array of static coverage information that is `ANDed` with the coverage information generated during rasterization. Bits that are zero disable coverage for the corresponding sample. Bit B of mask word M corresponds to sample 32 × M + B. The array is sized to a length of ⌈ `rasterizationSamples` / 32 ⌉ words. If `pSampleMask` is `NULL`, it is treated as if the mask has all bits enabled, i.e. no coverage is removed from fragments.

The elements of the sample mask array are of type `VkSampleMask`, each representing 32 bits of coverage information:

```
typedef uint32_t VkSampleMask;
```

25.4. Early Fragment Test Mode

The depth bounds test, stencil test, depth test, and occlusion query sample counting are performed before fragment shading if and only if early fragment tests are enabled by the fragment shader (see Early Fragment Tests). When early per-fragment operations are enabled, these operations are performed prior to fragment shader execution, and the stencil buffer, depth buffer, and occlusion query sample counts will be updated accordingly; these operations will not be performed again after fragment shader execution.

If a pipeline's fragment shader has early fragment tests disabled, these operations are performed only after fragment program execution, in the order described below. If a pipeline does not contain a fragment shader, these operations are performed only once.

If early fragment tests are enabled, any depth value computed by the fragment shader has no effect. Additionally, the depth test (including depth writes), stencil test (including stencil writes) and sample counting operations are performed even for fragments or samples that would be discarded after fragment shader execution due to per-fragment operations such as alpha-to-coverage tests, or due to the fragment being discarded by the shader itself.

25.5. Late Per-Fragment Tests

After programmable fragment processing, per-fragment operations are performed before blending and color output to the framebuffer.

A fragment is produced by rasterization with framebuffer coordinates of (x_f,y_f) and depth z, as described in Rasterization. The fragment is then modified by programmable fragment processing, which adds associated data as described in Shaders. The fragment is then further modified, and possibly discarded by the late per-fragment operations described in this chapter. Finally, if the fragment was not discarded, it is used to update the framebuffer at the fragment's framebuffer coordinates for any samples that remain covered.

The depth bounds test, stencil test, and depth test are performed for each pixel sample, rather than just once for each fragment. Stencil and depth operations are performed for a pixel sample only if that sample's fragment coverage bit is a value of 1 when the fragment executes the corresponding stage of the graphics pipeline. If the corresponding coverage bit is 0, no operations are performed for that sample. Failure of the depth bounds, stencil, or depth test results in termination of the processing of that sample by means of disabling coverage for that sample, rather than discarding of the fragment. If, at any point, a fragment's coverage becomes zero for all samples, then the fragment is discarded. All operations are performed on the depth and stencil values stored in the depth/stencil attachment of the framebuffer. The contents of the color attachments are not modified at this point.

The depth bounds test, stencil test, depth test, and occlusion query operations described in Depth Bounds Test, Stencil Test, Depth Test, Sample Counting are instead performed prior to fragment processing, as described in Early Fragment Test Mode, if requested by the fragment shader.

25.6. Multisample Coverage

If a fragment shader is active and its entry point's interface includes a built-in output variable decorated with `SampleMask`, the fragment coverage is `ANDed` with the bits of the sample mask to generate a new fragment coverage value. If such a fragment shader did not assign a value to `SampleMask` due to flow of control, the value `ANDed` with the fragment coverage is undefined. If no fragment shader is active, or if the active fragment shader does not include `SampleMask` in its interface, the fragment coverage is not modified.

Next, the fragment alpha and coverage values 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 value with `rasterizationSamples` bits is generated where each bit is determined by the fragment's alpha value. The temporary coverage value is then ANDed with the fragment coverage value to generate a new fragment coverage value.

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 pixel locations.

> *Note*
>
> Using different algorithms at different pixel location **may** help to avoid artifacts caused by regular coverage sample locations.

Next, if `alphaToOneEnable` is enabled, each alpha value is replaced by the maximum representable alpha value for fixed-point color buffers, or by 1.0 for floating-point buffers. Otherwise, the alpha values are not changed.

25.7. 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:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 the comparison operator used in the depth test.
- depthBoundsTestEnable controls whether depth bounds testing is enabled.
- stencilTestEnable controls whether stencil testing is enabled.
- front and back control the parameters of the stencil test.
- minDepthBounds and maxDepthBounds define the range of values used in the depth bounds test.

Valid Usage

- If the depth bounds testing feature is not enabled, depthBoundsTestEnable **must** be VK_FALSE

Valid Usage (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO
- pNext **must** be NULL
- flags **must** be 0
- depthCompareOp **must** be a valid VkCompareOp value
- front **must** be a valid VkStencilOpState structure
- back **must** be a valid VkStencilOpState structure

```
typedef VkFlags VkPipelineDepthStencilStateCreateFlags;
```

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

25.8. Depth Bounds Test

The depth bounds test conditionally disables coverage of a sample based on the outcome of a comparison between the value z_a in the depth attachment at location (x_f,y_f) (for the appropriate sample) and a range of values. The test is enabled or disabled by the depthBoundsTestEnable member of VkPipelineDepthStencilStateCreateInfo: If the pipeline state object is created without the VK_DYNAMIC_STATE_DEPTH_BOUNDS dynamic state enabled then the range of values used in the depth bounds test are defined by the minDepthBounds and maxDepthBounds members of the VkPipelineDepthStencilStateCreateInfo structure. Otherwise, to dynamically set the depth bounds range values call:

```
void vkCmdSetDepthBounds(
    VkCommandBuffer                             commandBuffer,
    float                                       minDepthBounds,
    float                                       maxDepthBounds);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `minDepthBounds` is the lower bound of the range of depth values used in the depth bounds test.
- `maxDepthBounds` is the upper bound of the range.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the `VK_DYNAMIC_STATE_DEPTH_BOUNDS` dynamic state enabled
- `minDepthBounds` **must** be between `0.0` and `1.0`, inclusive
- `maxDepthBounds` **must** be between `0.0` and `1.0`, inclusive

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `commandBuffer` **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

If `minDepthBounds` ≤ z_a ≤ `maxDepthBounds`}, then the depth bounds test passes. Otherwise, the test fails and the sample's coverage bit is cleared in the fragment. If there is no depth framebuffer attachment or if the depth bounds test is disabled, it is as if the depth bounds test always passes.

25.9. Stencil Test

The stencil test conditionally disables coverage of a sample based on the outcome of a comparison between the stencil value in the depth/stencil attachment at location (x_f,y_f) (for the appropriate sample) and a reference value. The stencil test also updates the value in the stencil attachment, depending on the test state, the stencil value and the stencil write masks. The test is enabled or disabled by the stencilTestEnable member of VkPipelineDepthStencilStateCreateInfo.

When disabled, the stencil test and associated modifications are not made, and the sample's coverage is not modified.

The stencil test is controlled with the front and back members of VkPipelineDepthStencilStateCreateInfo which are of type VkStencilOpState.

The VkStencilOpState structure is defined as:

```
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 reference value that is used in the unsigned stencil comparison.

Valid Usage (Implicit)

- failOp **must** be a valid VkStencilOp value
- passOp **must** be a valid VkStencilOp value
- depthFailOp **must** be a valid VkStencilOp value
- compareOp **must** be a valid VkCompareOp value

There are two sets of stencil-related state, the front stencil state set and the back stencil state set. Stencil tests and writes use the front set of stencil state when processing front-facing fragments and use the back set of stencil state when processing back-facing fragments. Fragments rasterized from non-polygon primitives (points and lines) are always considered front-facing. Fragments rasterized from polygon primitives inherit their facingness from the polygon, even if the polygon is rasterized as points or lines due to the current VkPolygonMode. Whether a polygon is front- or back-facing is determined in the same manner used for face culling (see Basic Polygon Rasterization).

The operation of the stencil test is also affected by the compareMask, writeMask, and reference members of VkStencilOpState set in the pipeline state object if the pipeline state object is created without the VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK, VK_DYNAMIC_STATE_STENCIL_WRITE_MASK, and VK_DYNAMIC_STATE_STENCIL_REFERENCE dynamic states enabled, respectively.

If the pipeline state object is created with the VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK dynamic state enabled, then to dynamically set the stencil compare mask call:

```
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.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK dynamic state enabled

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `faceMask` **must** be a valid combination of VkStencilFaceFlagBits values
- `faceMask` **must** not be `0`
- `commandBuffer` **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

Bits which **can** be set in the vkCmdSetStencilCompareMask::`faceMask` parameter, and similar parameters of other commands specifying which stencil state to update stencil masks for, are:

```
typedef enum VkStencilFaceFlagBits {
    VK_STENCIL_FACE_FRONT_BIT = 0x00000001,
    VK_STENCIL_FACE_BACK_BIT = 0x00000002,
    VK_STENCIL_FRONT_AND_BACK = 0x00000003,
} 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_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.

```
typedef VkFlags VkStencilFaceFlags;
```

`VkStencilFaceFlags` is a bitmask type for setting a mask of zero or more VkStencilFaceFlagBits.

If the pipeline state object is created with the VK_DYNAMIC_STATE_STENCIL_WRITE_MASK dynamic state enabled, then to dynamically set the stencil write mask call:

```
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.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_STENCIL_WRITE_MASK dynamic state enabled

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- faceMask **must** be a valid combination of VkStencilFaceFlagBits values
- faceMask **must** not be 0
- commandBuffer **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

If the pipeline state object is created with the VK_DYNAMIC_STATE_STENCIL_REFERENCE dynamic state enabled, then to dynamically set the stencil reference value call:

```
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.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_STENCIL_REFERENCE dynamic state enabled

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- faceMask **must** be a valid combination of VkStencilFaceFlagBits values
- faceMask **must** not be 0
- commandBuffer **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

reference is an integer reference value that is used in the unsigned stencil comparison. The reference value used by stencil comparison must be within the range $[0,2^s-1]$, where s is the number of bits in the stencil framebuffer attachment, otherwise the reference value is considered undefined. The s least significant bits of compareMask are bitwise ANDed with both the reference and the stored stencil value, and the resulting masked values are those that participate in the comparison controlled by compareOp. Let R be the masked reference value and S be the masked stored stencil value.

Possible values of VkStencilOpState::compareOp, specifying the stencil comparison function, are:

```
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 test never passes.
- VK_COMPARE_OP_LESS specifies that the test passes when R < S.
- VK_COMPARE_OP_EQUAL specifies that the test passes when R = S.
- VK_COMPARE_OP_LESS_OR_EQUAL specifies that the test passes when R ≤ S.
- VK_COMPARE_OP_GREATER specifies that the test passes when R > S.
- VK_COMPARE_OP_NOT_EQUAL specifies that the test passes when R ≠ S.
- VK_COMPARE_OP_GREATER_OR_EQUAL specifies that the test passes when R ≥ S.
- VK_COMPARE_OP_ALWAYS specifies that the test always passes.

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:

```
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.

If the stencil test fails, the sample's coverage bit is cleared in the fragment. If there is no stencil framebuffer attachment, stencil modification **cannot** occur, and it is as if the stencil tests always pass.

If the stencil test passes, the writeMask member of the VkStencilOpState structures controls how the updated stencil value is written to the stencil framebuffer attachment.

The least significant s bits of writeMask, where s is the number of bits in the stencil framebuffer attachment, specify an integer mask. Where a 1 appears in this mask, the corresponding bit in the stencil value in the depth/stencil attachment is written; where a 0 appears, the bit is not written. The writeMask value uses either the front-facing or back-facing state based on the facingness of the fragment. Fragments generated by front-facing primitives use the front mask and fragments generated by back-facing primitives use the back mask.

25.10. Depth Test

The depth test conditionally disables coverage of a sample based on the outcome of a comparison between the fragment's depth value at the sample location and the sample's depth value in the depth/stencil attachment at location (x_f,y_f). The comparison is enabled or disabled with the depthTestEnable member of the VkPipelineDepthStencilStateCreateInfo structure. When disabled, the depth comparison and subsequent possible updates to the value of the depth component of the depth/stencil attachment are bypassed and the fragment is passed to the next operation. The stencil value, however, **can** be modified as indicated above as if the depth test passed. If enabled, the comparison takes place and the depth/stencil attachment value **can** subsequently be modified.

The comparison is specified with the depthCompareOp member of VkPipelineDepthStencilStateCreateInfo. Let z_f be the incoming fragment's depth value for a sample, and let z_a be the depth/stencil attachment value in memory for that sample. The depth test passes under the following conditions:

- VK_COMPARE_OP_NEVER: the test never passes.
- VK_COMPARE_OP_LESS: the test passes when $z_f < z_a$.
- VK_COMPARE_OP_EQUAL: the test passes when $z_f = z_a$.

- VK_COMPARE_OP_LESS_OR_EQUAL: the test passes when $z_f \leq z_a$.
- VK_COMPARE_OP_GREATER: the test passes when $z_f > z_a$.
- VK_COMPARE_OP_NOT_EQUAL: the test passes when $z_f \neq z_a$.
- VK_COMPARE_OP_GREATER_OR_EQUAL: the test passes when $z_f \geq z_a$.
- VK_COMPARE_OP_ALWAYS: the test always passes.

If depth clamping (see Primitive Clipping) is enabled, before the incoming fragment's z_f is compared to z_a, z_f is clamped to [min(n,f),max(n,f)], where n and f are the minDepth and maxDepth depth range values of the viewport used by this fragment, respectively.

If the depth test fails, the sample's coverage bit is cleared in the fragment. The stencil value at the sample's location is updated according to the function currently in effect for depth test failure.

If the depth test passes, the sample's (possibly clamped) z_f value is conditionally written to the depth framebuffer attachment based on the depthWriteEnable member of VkPipelineDepthStencilStateCreateInfo. If depthWriteEnable is VK_TRUE the value is written, and if it is VK_FALSE the value is not written. The stencil value at the sample's location is updated according to the function currently in effect for depth test success.

If there is no depth framebuffer attachment, it is as if the depth test always passes.

25.11. 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.

25.12. Coverage Reduction

Coverage reduction generates a *color sample mask* from the coverage mask, with one bit for each sample in the color attachment(s) for the subpass. If a bit in the color sample mask is 0, then blending and writing to the framebuffer are not performed for that sample.

Each color sample is associated with a unique rasterization sample, and the value of the coverage mask is assigned to the color sample mask.

Chapter 26. The Framebuffer

26.1. 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 pixel sample, 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.

Blending applies only to fixed-point and floating-point color attachments. If the color attachment has an integer format, blending is not applied.

The pipeline blend state is included in the `VkPipelineColorBlendStateCreateInfo` structure during graphics pipeline creation:

The `VkPipelineColorBlendStateCreateInfo` structure is defined as:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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`.

This value **must** equal the `colorAttachmentCount` for the subpass in which this pipeline is used.

- `pAttachments`: is a pointer to array of per target attachment states.
- `blendConstants` is 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.

Each element of the `pAttachments` array is a VkPipelineColorBlendAttachmentState structure specifying per-target blending state for each individual color attachment. If the independent blending feature is not enabled on the device, all VkPipelineColorBlendAttachmentState elements in the `pAttachments` array **must** be identical.

Valid Usage

- If the independent blending feature is not enabled, all elements of `pAttachments` **must** be identical
- If the logic operations feature is not enabled, `logicOpEnable` **must** be `VK_FALSE`
- If `logicOpEnable` is `VK_TRUE`, `logicOp` **must** be a valid VkLogicOp value

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- If `attachmentCount` is not `0`, `pAttachments` **must** be a valid pointer to an array of `attachmentCount` valid `VkPipelineColorBlendAttachmentState` structures

```
typedef VkFlags VkPipelineColorBlendStateCreateFlags;
```

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

The `VkPipelineColorBlendAttachmentState` structure is defined as:

```
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 use 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

- If the dual source blending 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
- If the dual source blending 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
- If the dual source blending 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
- If the dual source blending 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)

- srcColorBlendFactor **must** be a valid VkBlendFactor value
- dstColorBlendFactor **must** be a valid VkBlendFactor value
- colorBlendOp **must** be a valid VkBlendOp value
- srcAlphaBlendFactor **must** be a valid VkBlendFactor value
- dstAlphaBlendFactor **must** be a valid VkBlendFactor value
- alphaBlendOp **must** be a valid VkBlendOp value
- colorWriteMask **must** be a valid combination of VkColorComponentFlagBits values

26.1.1. Blend Factors

The source and destination color and alpha blending factors are selected from the enum:

```
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,
    VK_BLEND_FACTOR_SRC1_COLOR = 15,
    VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR = 16,
    VK_BLEND_FACTOR_SRC1_ALPHA = 17,
    VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA = 18,
} VkBlendFactor;
```

The semantics of each enum value is described in the table below:

Table 26. Blend Factors

VkBlendFactor	RGB Blend Factors (S_r,S_g,S_b) or (D_r,D_g,D_b)	Alpha Blend Factor (S_a or D_a)
VK_BLEND_FACTOR_ZERO	(0,0,0)	0
VK_BLEND_FACTOR_ONE	(1,1,1)	1
VK_BLEND_FACTOR_SRC_COLOR	(R_{s0},G_{s0},B_{s0})	A_{s0}
VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR	(1-R_{s0},1-G_{s0},1-B_{s0})	1-A_{s0}
VK_BLEND_FACTOR_DST_COLOR	(R_d,G_d,B_d)	A_d
VK_BLEND_FACTOR_ONE_MINUS_DST_COLOR	(1-R_d,1-G_d,1-B_d)	1-A_d
VK_BLEND_FACTOR_SRC_ALPHA	(A_{s0},A_{s0},A_{s0})	A_{s0}
VK_BLEND_FACTOR_ONE_MINUS_SRC_ALPHA	(1-A_{s0},1-A_{s0},1-A_{s0})	1-A_{s0}
VK_BLEND_FACTOR_DST_ALPHA	(A_d,A_d,A_d)	A_d
VK_BLEND_FACTOR_ONE_MINUS_DST_ALPHA	(1-A_d,1-A_d,1-A_d)	1-A_d
VK_BLEND_FACTOR_CONSTANT_COLOR	(R_c,G_c,B_c)	A_c
VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_COLOR	(1-R_c,1-G_c,1-B_c)	1-A_c

VkBlendFactor	RGB Blend Factors (S_r,S_g,S_b) or (D_r,D_g,D_b)	Alpha Blend Factor (S_a or D_a)
VK_BLEND_FACTOR_CONSTANT_ALPHA	(A_c,A_c,A_c)	A_c
VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_ALPHA	(1-A_c,1-A_c,1-A_c)	1-A_c
VK_BLEND_FACTOR_SRC_ALPHA_SATURATE	(f,f,f); f = min(A_{s0},1-A_d)	1
VK_BLEND_FACTOR_SRC1_COLOR	(R_{s1},G_{s1},B_{s1})	A_{s1}
VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR	(1-R_{s1},1-G_{s1},1-B_{s1})	1-A_{s1}
VK_BLEND_FACTOR_SRC1_ALPHA	(A_{s1},A_{s1},A_{s1})	A_{s1}
VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA	(1-A_{s1},1-A_{s1},1-A_{s1})	1-A_{s1}

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.

If the pipeline state object is created without the VK_DYNAMIC_STATE_BLEND_CONSTANTS dynamic state enabled then the *blend constant* (R_c,G_c,B_c,A_c) is specified via the blendConstants member of VkPipelineColorBlendStateCreateInfo.

Otherwise, to dynamically set and change the blend constant, call:

```
void vkCmdSetBlendConstants(
    VkCommandBuffer                             commandBuffer,
    const float                                 blendConstants[4]);
```

- commandBuffer is the command buffer into which the command will be recorded.
- blendConstants is an array of four values specifying the R, G, B, and A components of the blend constant color used in blending, depending on the blend factor.

Valid Usage

- The currently bound graphics pipeline **must** have been created with the VK_DYNAMIC_STATE_BLEND_CONSTANTS dynamic state enabled

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `commandBuffer` **must** be in the recording state
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Both	Graphics	

26.1.2. Dual-Source Blending

Blend factors that use the secondary color input (R_{s1},G_{s1},B_{s1},A_{s1}) (`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 hardware 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.

26.1.3. 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
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 each basic blend operations is described in the table below:

Table 27. Basic Blend Operations

VkBlendOp	RGB Components	Alpha Component
VK_BLEND_OP_ADD	$R = R_{s0} \times S_r + R_d \times D_r$ $G = G_{s0} \times S_g + G_d \times D_g$ $B = B_{s0} \times S_b + B_d \times D_b$	$A = A_{s0} \times S_a + A_d \times D_a$
VK_BLEND_OP_SUBTRACT	$R = R_{s0} \times S_r - R_d \times D_r$ $G = G_{s0} \times S_g - G_d \times D_g$ $B = B_{s0} \times S_b - B_d \times D_b$	$A = A_{s0} \times S_a - A_d \times D_a$
VK_BLEND_OP_REVERSE_SUBTRACT	$R = R_d \times D_r - R_{s0} \times S_r$ $G = G_d \times D_g - G_{s0} \times S_g$ $B = B_d \times D_b - B_{s0} \times S_b$	$A = A_d \times D_a - A_{s0} \times S_a$
VK_BLEND_OP_MIN	$R = \min(R_{s0},R_d)$ $G = \min(G_{s0},G_d)$ $B = \min(B_{s0},B_d)$	$A = \min(A_{s0},A_d)$
VK_BLEND_OP_MAX	$R = \max(R_{s0},R_d)$ $G = \max(G_{s0},G_d)$ $B = \max(B_{s0},B_d)$	$A = \max(A_{s0},A_d)$

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.
- 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_{s0}, G_{s0}, B_{s0} and A_{s0}, 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 $EOTF^{-1}$” section of the Khronos Data Format Specification.

If the framebuffer color attachment numeric format is not sRGB encoded then the resulting c_s 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. Framebuffer color attachments greater than or equal to VkSubpassDescription ::colorAttachmentCount perform no writes.

26.2. 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:

```
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

- ¬ is bitwise invert,
- ∧ is bitwise and,
- ∨ is bitwise or,
- ⊕ 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 28. Logical Operations

Mode	Operation
VK_LOGIC_OP_CLEAR	0
VK_LOGIC_OP_AND	s ∧ d
VK_LOGIC_OP_AND_REVERSE	s ∧ ¬ d
VK_LOGIC_OP_COPY	s
VK_LOGIC_OP_AND_INVERTED	¬ s ∧ d
VK_LOGIC_OP_NO_OP	d
VK_LOGIC_OP_XOR	s ⊕ d
VK_LOGIC_OP_OR	s ∨ d
VK_LOGIC_OP_NOR	¬ (s ∨ d)
VK_LOGIC_OP_EQUIVALENT	¬ (s ⊕ d)
VK_LOGIC_OP_INVERT	¬ d
VK_LOGIC_OP_OR_REVERSE	s ∨ ¬ d
VK_LOGIC_OP_COPY_INVERTED	¬ s
VK_LOGIC_OP_OR_INVERTED	¬ s ∨ d
VK_LOGIC_OP_NAND	¬ (s ∧ d)
VK_LOGIC_OP_SET	all 1s

The result of the logical operation is then written to the color attachment as controlled by the component write mask, described in Blend Operations.

26.3. Color Write Mask

Bits which **can** be set in VkPipelineColorBlendAttachmentState::colorWriteMask to determine whether the final color values R, G, B and A are written to the framebuffer attachment are:

```
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.

```
typedef VkFlags VkColorComponentFlags;
```

`VkColorComponentFlags` is a bitmask type for setting a mask of zero or more VkColorComponentFlagBits.

Chapter 27. 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 currently bound compute pipeline. A compute pipeline **must** be bound to a command buffer before any dispatch commands are recorded in that command buffer.

To record a dispatch, call:

```
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

- groupCountX **must** be less than or equal to VkPhysicalDeviceLimits ::maxComputeWorkGroupCount[0]
- groupCountY **must** be less than or equal to VkPhysicalDeviceLimits ::maxComputeWorkGroupCount[1]
- groupCountZ **must** be less than or equal to VkPhysicalDeviceLimits ::maxComputeWorkGroupCount[2]
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_COMPUTE, with a VkPipelineLayout that is compatible for set *n*, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- A valid compute pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_COMPUTE
- For each push constant that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_COMPUTE, with a VkPipelineLayout that is compatible for push constants with the one used to create the current VkPipeline, as described in Pipeline Layout Compatibility
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_COMPUTE accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_COMPUTE accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound

descriptor set

* Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties::linearTilingFeatures (for a linear image) or VkFormatProperties::optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties

Valid Usage (Implicit)

* commandBuffer **must** be a valid VkCommandBuffer handle
* commandBuffer **must** be in the recording state
* The VkCommandPool that commandBuffer was allocated from **must** support compute 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Compute	Compute

To record an indirect command dispatch, call:

```
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

- If buffer is non-sparse then it **must** be bound completely and contiguously to a single VkDeviceMemory object
- For each set *n* that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE, a descriptor set **must** have been bound to *n* at VK_PIPELINE_BIND_POINT_COMPUTE, with a VkPipelineLayout that is compatible for set *n*, 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 if they are statically used by the currently bound VkPipeline object, specified via vkCmdBindPipeline
- A valid compute pipeline **must** be bound to the current command buffer with VK_PIPELINE_BIND_POINT_COMPUTE
- buffer **must** have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set
- offset **must** be a multiple of 4
- The sum of offset and the size of VkDispatchIndirectCommand **must** be less than or equal to the size of buffer
- For each push constant that is statically used by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE, a push constant value **must** have been set for VK_PIPELINE_BIND_POINT_COMPUTE, with a VkPipelineLayout that is compatible for push constants with the one used to create the current VkPipeline, as described in Pipeline Layout Compatibility
- If any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 any VkSampler object that is accessed from a shader by the VkPipeline currently bound to VK_PIPELINE_BIND_POINT_COMPUTE uses unnormalized coordinates, it **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 robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_COMPUTE accesses a uniform buffer, it **must** not access values outside of the range of that buffer specified in the currently bound descriptor set
- If the robust buffer access feature is not enabled, and any shader stage in the VkPipeline object currently bound to VK_PIPELINE_BIND_POINT_COMPUTE accesses a storage buffer, it **must** not access values outside of the range of that buffer specified in the currently bound

descriptor set

- Any VkImageView being sampled with VK_FILTER_LINEAR as a result of this command **must** be of a format which supports linear filtering, as specified by the VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT flag in VkFormatProperties::linearTilingFeatures (for a linear image) or VkFormatProperties::optimalTilingFeatures(for an optimally tiled image) returned by vkGetPhysicalDeviceFormatProperties

Valid Usage (Implicit)

- commandBuffer **must** be a valid VkCommandBuffer handle
- buffer **must** be a valid VkBuffer handle
- commandBuffer **must** be in the recording state
- The VkCommandPool that commandBuffer was allocated from **must** support compute operations
- This command **must** only be called outside of a render pass instance
- 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

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
Primary Secondary	Outside	Compute	Compute

The VkDispatchIndirectCommand structure is defined as:

```
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

- `x` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxComputeWorkGroupCount`[0]
- `y` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxComputeWorkGroupCount`[1]
- `z` **must** be less than or equal to `VkPhysicalDeviceLimits`::`maxComputeWorkGroupCount`[2]

Chapter 28. 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.

28.1. 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.

- Sparse binding is the base feature, 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:
  - sparseResidencyBuffer: Support for creating VkBuffer objects with the VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidencyImage2D: Support for creating 2D single-sampled VkImage objects with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidencyImage3D: Support for creating 3D VkImage objects with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidency2Samples: Support for creating 2D VkImage objects with 2 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidency4Samples: Support for creating 2D VkImage objects with 4 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidency8Samples: Support for creating 2D VkImage objects with 8 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
  - sparseResidency16Samples: 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 is not **required** for sparse 3D and MSAA images and is 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.

- Sparse aliasing 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.

28.2. 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.

28.2.1. 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.

28.3. 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.

28.4. 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.

28.4.1. 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.

Formatted accesses to 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 hardware 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 of causing a hardware fault.
>
> Given that reads of unbound regions are undefined in this scenario, implementations **may** use the same physical memory for unbound regions of multiple resources within the same process.

28.4.2. 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.

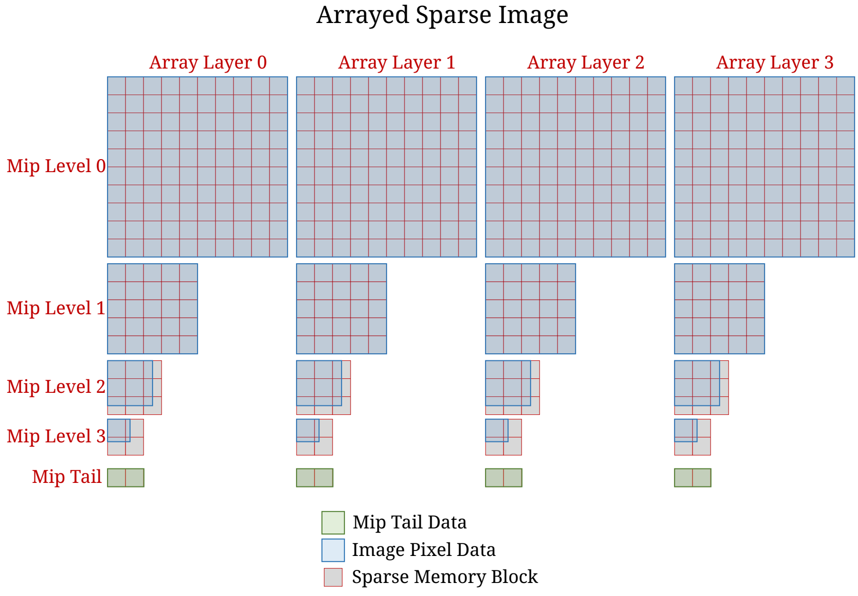

Figure 13. Sparse Image

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.

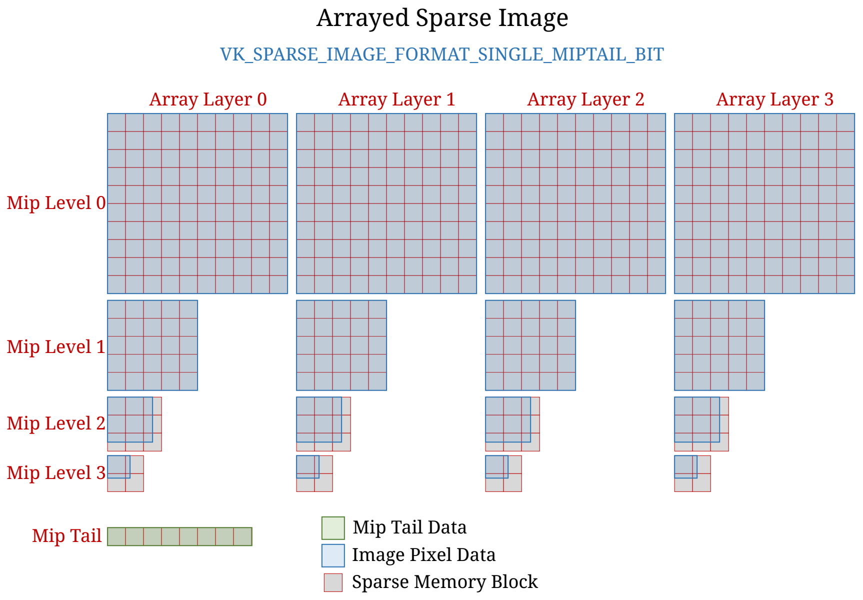

Figure 14. Sparse Image with Single Mip Tail

When `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` is present all array layers will share a single mip tail region.

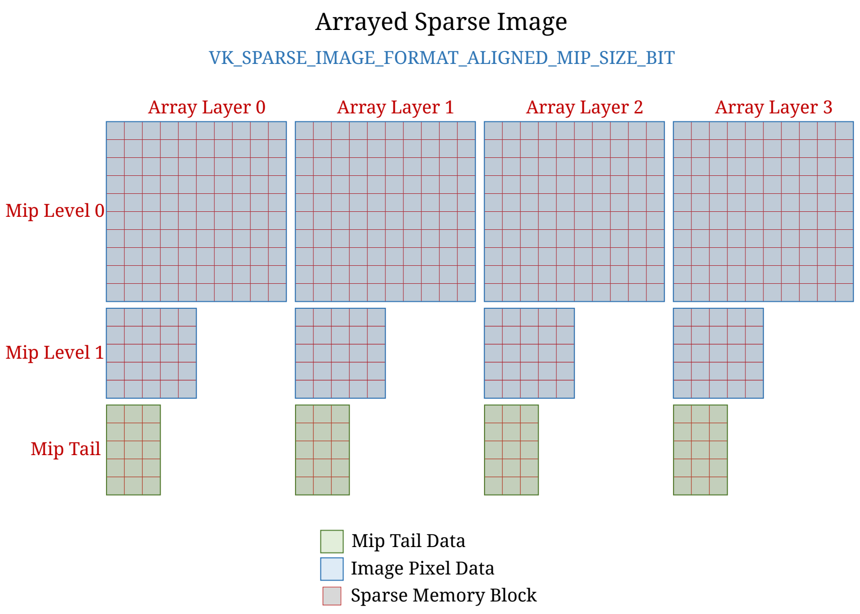

Figure 15. Sparse Image with Aligned Mip Size

> *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.

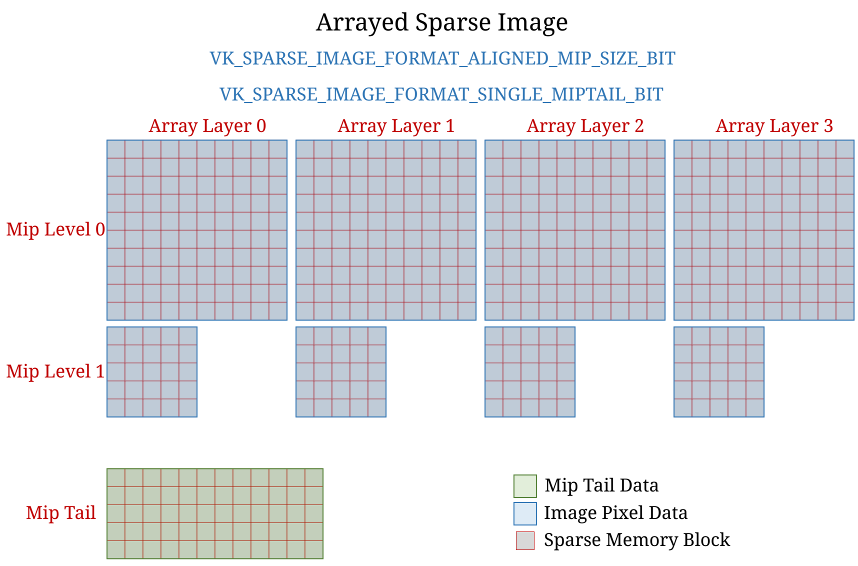

Figure 16. Sparse Image with Aligned Mip Size and Single Mip Tail

> *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.

28.4.3. 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 29. Standard Sparse Image Block Shapes (Single Sample)

TEXEL SIZE (bits)	Block Shape (2D)	Block Shape (3D)
8-Bit	256 × 256 × 1	64 × 32 × 32
16-Bit	256 × 128 × 1	32 × 32 × 32
32-Bit	128 × 128 × 1	32 × 32 × 16
64-Bit	128 × 64 × 1	32 × 16 × 16
128-Bit	64 × 64 × 1	16 × 16 × 16

Table 30. Standard Sparse Image Block Shapes (MSAA)

TEXEL SIZE (bits)	Block Shape (2X)	Block Shape (4X)	Block Shape (8X)	Block Shape (16X)
8-Bit	128 × 256 × 1	128 × 128 × 1	64 × 128 × 1	64 × 64 × 1
16-Bit	128 × 128 × 1	128 × 64 × 1	64 × 64 × 1	64 × 32 × 1
32-Bit	64 × 128 × 1	64 × 64 × 1	32 × 64 × 1	32 × 32 × 1
64-Bit	64 × 64 × 1	64 × 32 × 1	32 × 32 × 1	32 × 16 × 1
128-Bit	32 × 64 × 1	32 × 32 × 1	16 × 32 × 1	16 × 16 × 1

Implementations that support the standard sparse image block shape for all applicable formats **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.

28.4.4. 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.

28.4.5. 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:

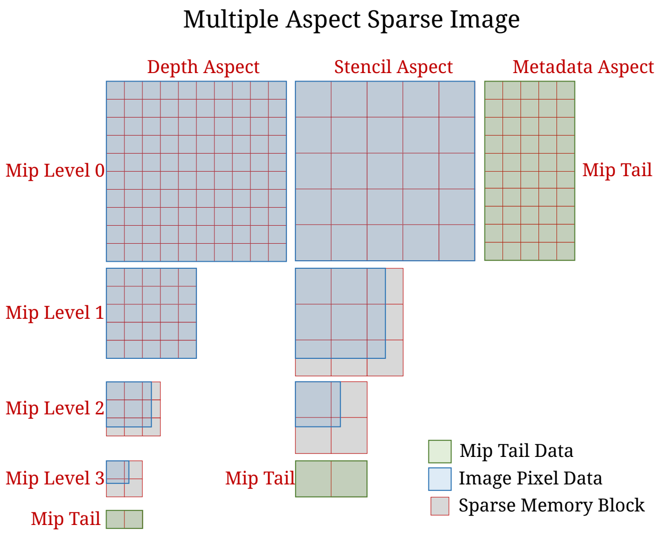

Figure 17. Multiple Aspect Sparse Image

> *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 ¼ the size of the depth data, hence the stencil sparse blocks include 4 × the number of texels. The sparse block size in bytes for all of the aspects is identical and defined by `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.

28.5. Sparse Memory Aliasing

By default sparse resources have the same aliasing rules as non-sparse resources. See Memory Aliasing for more information.

`VkDevice` objects that have the sparseResidencyAliased feature enabled are able to use the

VK_BUFFER_CREATE_SPARSE_ALIASED_BIT and 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 VK_BUFFER_CREATE_SPARSE_ALIASED_BIT / 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.

28.6. Sparse Resource Implementation Guidelines

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 sparse residency features allow sparse resources to be used even when not all pages are bound to memory. Hardware that supports 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 the cache implementation of the hardware this **may** not always be possible.

Hardware that does not fault, but does not guarantee correct read values will not require dummy pages, but also **must** not support residencyNonResidentStrict.

Hardware 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) "dummy" 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 dummy 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 hardware requires "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 does not require any sophisticated logic to determine what device virtual address to bind. The cost is that the application **can** 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 denotes 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 values makes it easiest for the implementation to derive the correct device virtual address.

28.7. 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

28.7.1. Physical Device Features

Some sparse-resource related features are reported and enabled in VkPhysicalDeviceFeatures. These features **must** be supported and enabled on the 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 VkBuffer and VkImage objects with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT and VK_IMAGE_CREATE_SPARSE_BINDING_BIT flags, respectively.
- sparseResidencyBuffer: Support for creating VkBuffer objects with the VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT flag.
- sparseResidencyImage2D: Support for creating 2D single-sampled VkImage objects with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidencyImage3D: Support for creating 3D VkImage objects with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidency2Samples: Support for creating 2D VkImage objects with 2 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidency4Samples: Support for creating 2D VkImage objects with 4 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidency8Samples: Support for creating 2D VkImage objects with 8 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidency16Samples: Support for creating 2D VkImage objects with 16 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
- sparseResidencyAliased: Support for creating VkBuffer and VkImage objects with the VK_BUFFER_CREATE_SPARSE_ALIASED_BIT and VK_IMAGE_CREATE_SPARSE_ALIASED_BIT flags, respectively.

28.7.2. 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 structure of type VkPhysicalDeviceSparseProperties.

The VkPhysicalDeviceSparseProperties structure is defined as:

```
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 were populated with 0; writes to non-resident regions will be discarded.

28.7.3. 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
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 **can** be set in VkSparseImageFormatProperties::flags, specifying additional information about the sparse resource, are:

```c
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.

```c
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 capabilities.
- format is the image format.
- type is the dimensionality of image.
- samples is the number of samples per texel as defined in VkSampleCountFlagBits.
- usage is a bitmask describing the intended usage of the image.
- tiling is the tiling arrangement of the data elements 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

- 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)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- format **must** be a valid VkFormat value
- type **must** be a valid VkImageType value
- samples **must** be a valid VkSampleCountFlagBits value
- usage **must** be a valid combination of VkImageUsageFlagBits values
- usage **must** not be 0
- tiling **must** be a valid VkImageTiling value
- pPropertyCount **must** be a valid pointer to a uint32_t value
- 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

28.7.4. 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) at CreateDevice time. 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).

28.7.5. 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 denotes 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 denotes 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:

```
typedef struct VkSparseImageMemoryRequirements {
    VkSparseImageFormatProperties    formatProperties;
    uint32_t                         imageMipTailFirstLod;
    VkDeviceSize                     imageMipTailSize;
    VkDeviceSize                     imageMipTailOffset;
    VkDeviceSize                     imageMipTailStride;
} VkSparseImageMemoryRequirements;
```

- formatProperties.aspectMask is the set of aspects of the image that this sparse memory requirement applies to. This will usually have a single aspect specified. However, depth/stencil images **may** have depth and stencil data interleaved in the same sparse block, in which case both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT would be present.
- formatProperties.imageGranularity describes the dimensions of a single bindable sparse image block in texel units. For aspect VK_IMAGE_ASPECT_METADATA_BIT, all dimensions will be zero. All metadata is located in the mip tail region.
- formatProperties.flags is a bitmask of VkSparseImageFormatFlagBits:
  - If VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT is set the image uses a single mip tail region for all array layers.
  - If VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT is set the dimensions of mip levels **must** be integer multiples of the corresponding dimensions of the sparse image block for levels not located in the mip tail.
  - If VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT is set the image uses non-standard sparse image block dimensions. The formatProperties.imageGranularity values do not match the standard sparse image block dimension corresponding to the image's 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:

```
void vkGetImageSparseMemoryRequirements(
    VkDevice                                    device,
    VkImage                                     image,
    uint32_t*                                   pSparseMemoryRequirementCount,
    VkSparseImageMemoryRequirements*            pSparseMemoryRequirements);
```

- device is the logical device that owns the image.
- image is the VkImage object to get the memory requirements for.
- 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 VkSparseImageMemoryRequirements structures.

If pSparseMemoryRequirements is NULL, then the number of sparse memory requirements available is returned in pSparseMemoryRequirementCount. Otherwise, pSparseMemoryRequirementCount **must** point to a variable set by the user to the number of elements in the pSparseMemoryRequirements array, and on return the variable is overwritten with the number of structures actually written to pSparseMemoryRequirements. If pSparseMemoryRequirementCount is less than the number of sparse memory requirements available, at most pSparseMemoryRequirementCount structures will be written.

If the image was not created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT then pSparseMemoryRequirementCount will be set to zero and pSparseMemoryRequirements will not be written to.

> *Note*
>
> It is legal for an implementation to report a larger value in VkMemoryRequirements::size than would be obtained by adding together memory sizes for all VkSparseImageMemoryRequirements returned by vkGetImageSparseMemoryRequirements. This **may** occur when the hardware requires unused padding in the address range describing the resource.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `image` **must** be a valid `VkImage` handle
- `pSparseMemoryRequirementCount` **must** be a valid pointer to a `uint32_t` value
- If the value referenced by `pSparseMemoryRequirementCount` is not `0`, and `pSparseMemoryRequirements` is not `NULL`, `pSparseMemoryRequirements` **must** be a valid pointer to an array of `pSparseMemoryRequirementCount` `VkSparseImageMemoryRequirements` structures
- `image` **must** have been created, allocated, or retrieved from `device`

28.7.6. 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. Access to resources that are bound to memory objects that have been freed will result in undefined behavior, potentially including application termination.
>
> Implementations **must** ensure that no access to physical memory owned by the system or another process will occur in this scenario. In other words, accessing resources bound to freed memory **may** result in application termination, but **must** not result in system termination or in reading non-process-accessible memory.

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. Accessing memory in a range while it is being rebound results in undefined behavior. It is valid to 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:

```
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:

metadataRegion = [base, base + imageMipTailSize)

base = imageMipTailOffset + imageMipTailStride × 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,VkMemoryRequirements::size).

Valid Usage

- 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
- 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
- size **must** be greater than 0
- resourceOffset **must** be less than the size of the resource
- size **must** be less than or equal to the size of the resource minus resourceOffset
- memoryOffset **must** be less than the size of memory
- size **must** be less than or equal to the size of memory minus memoryOffset

Valid Usage (Implicit)

- If memory is not VK_NULL_HANDLE, memory **must** be a valid VkDeviceMemory handle
- 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:

```
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.

```
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:

```
typedef struct VkSparseBufferMemoryBindInfo {
    VkBuffer                     buffer;
    uint32_t                     bindCount;
    const VkSparseMemoryBind*    pBinds;
} 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 array of VkSparseMemoryBind structures.

Valid Usage (Implicit)

- buffer **must** be a valid VkBuffer handle
- pBinds **must** be a valid pointer to an array of bindCount valid VkSparseMemoryBind structures
- 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:

```
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 array of VkSparseMemoryBind structures.

Valid Usage

- 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)

- image **must** be a valid VkImage handle
- pBinds **must** be a valid pointer to an array of bindCount valid VkSparseMemoryBind structures
- 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:

```
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 array of VkSparseImageMemoryBind structures

Valid Usage

- The subresource.mipLevel member of each element of pBinds **must** be less than the mipLevels specified in VkImageCreateInfo when image was created
- The subresource.arrayLayer member of each element of pBinds **must** be less than the arrayLayers specified in VkImageCreateInfo when image was created

Valid Usage (Implicit)

- image **must** be a valid VkImage handle
- pBinds **must** be a valid pointer to an array of bindCount valid VkSparseImageMemoryBind structures
- bindCount **must** be greater than 0

The VkSparseImageMemoryBind structure is defined as:

```
typedef struct VkSparseImageMemoryBind {
    VkImageSubresource          subresource;
    VkOffset3D                  offset;
    VkExtent3D                  extent;
    VkDeviceMemory              memory;
    VkDeviceSize                memoryOffset;
    VkSparseMemoryBindFlags     flags;
} VkSparseImageMemoryBind;
```

- subresource is the aspectMask 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

- If the sparse aliased residency 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
- `memory` and `memoryOffset` **must** match the memory requirements of the calling command's `image`, as described in section Resource Memory Association
- `subresource` **must** be a valid image subresource for `image` (see Image Views)
- `offset.x` **must** be a multiple of the sparse image block width (`VkSparseImageFormatProperties`::`imageGranularity.width`) of the image
- `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
- `offset.y` **must** be a multiple of the sparse image block height (`VkSparseImageFormatProperties`::`imageGranularity.height`) of the image
- `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
- `offset.z` **must** be a multiple of the sparse image block depth (`VkSparseImageFormatProperties`::`imageGranularity.depth`) of the image
- `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

Valid Usage (Implicit)

- `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:

```
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 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 an instance of the 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

- If fence is not VK_NULL_HANDLE, fence **must** be unsignaled
- 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
- 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
- When a semaphore unsignal operation defined by any element of the pWaitSemaphores member of any element of pBindInfo executes on queue, no other queue **must** be waiting on the same semaphore.
- All elements of the pWaitSemaphores member of all elements of pBindInfo **must** be semaphores that are signaled, or have semaphore signal operations previously submitted for execution.

Valid Usage (Implicit)

- queue **must** be a valid VkQueue handle
- If bindInfoCount is not 0, pBindInfo **must** be a valid pointer to an array of bindInfoCount valid VkBindSparseInfo structures
- If fence is not VK_NULL_HANDLE, fence **must** be a valid VkFence handle
- The queue **must** support sparse binding operations
- Both of fence, and queue that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to `queue` **must** be externally synchronized
- Host access to `pBindInfo`[].pWaitSemaphores[] **must** be externally synchronized
- Host access to `pBindInfo`[].pSignalSemaphores[] **must** be externally synchronized
- Host access to `pBindInfo`[].pBufferBinds[].buffer **must** be externally synchronized
- Host access to `pBindInfo`[].pImageOpaqueBinds[].image **must** be externally synchronized
- Host access to `pBindInfo`[].pImageBinds[].image **must** be externally synchronized
- Host access to `fence` **must** be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types	Pipeline Type
-	-	SPARSE_BINDING	-

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:

```
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 the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific 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 (Implicit)

- sType **must** be VK_STRUCTURE_TYPE_BIND_SPARSE_INFO
- pNext **must** be NULL
- If waitSemaphoreCount is not 0, pWaitSemaphores **must** be a valid pointer to an array of waitSemaphoreCount valid VkSemaphore handles
- If bufferBindCount is not 0, pBufferBinds **must** be a valid pointer to an array of bufferBindCount valid VkSparseBufferMemoryBindInfo structures
- If imageOpaqueBindCount is not 0, pImageOpaqueBinds **must** be a valid pointer to an array of imageOpaqueBindCount valid VkSparseImageOpaqueMemoryBindInfo structures
- If imageBindCount is not 0, pImageBinds **must** be a valid pointer to an array of imageBindCount valid VkSparseImageMemoryBindInfo structures
- If signalSemaphoreCount is not 0, pSignalSemaphores **must** be a valid pointer to an array of signalSemaphoreCount valid VkSemaphore handles
- Both of the elements of pSignalSemaphores, and the elements of pWaitSemaphores that are valid handles **must** have been created, allocated, or retrieved from the same VkDevice

28.8. Examples

The following examples illustrate basic creation of sparse images and binding them to physical memory.

28.8.1. Basic Sparse Resources

This basic example creates a normal VkImage object but uses fine-grained memory allocation to back the resource with multiple memory ranges.

```
VkDevice                device;
VkQueue                 queue;
VkImage                 sparseImage;
VkAllocationCallbacks*  pAllocator = NULL;
VkMemoryRequirements    memoryRequirements = {};
VkDeviceSize            offset = 0;
VkSparseMemoryBind      binds[MAX_CHUNKS] = {}; // MAX_CHUNKS is NOT part of Vulkan
uint32_t                bindCount = 0;

// ...

// Allocate image object
const VkImageCreateInfo sparseImageInfo =
{
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO,        // sType
    NULL,                                       // pNext
    VK_IMAGE_CREATE_SPARSE_BINDING_BIT | ...,   // flags
```

```
    ...
};
vkCreateImage(device, &sparseImageInfo, pAllocator, &sparseImage);

// Get memory requirements
vkGetImageMemoryRequirements(
    device,
    sparseImage,
    &memoryRequirements);

// Bind memory in fine-grained fashion, find available memory ranges
// from potentially multiple VkDeviceMemory pools.
// (Illustration purposes only, can be optimized for perf)
while (memoryRequirements.size && bindCount < MAX_CHUNKS)
{
    VkSparseMemoryBind* pBind = &binds[bindCount];
    pBind->resourceOffset = offset;

    AllocateOrGetMemoryRange(
        device,
        &memoryRequirements,
        &pBind->memory,
        &pBind->memoryOffset,
        &pBind->size);

    // memory ranges must be sized as multiples of the alignment
    assert(IsMultiple(pBind->size, memoryRequirements.alignment));
    assert(IsMultiple(pBind->memoryOffset, memoryRequirements.alignment));

    memoryRequirements.size -= pBind->size;
    offset                  += pBind->size;
    bindCount++;
}

// Ensure all image has backing
if (memoryRequirements.size)
{
    // Error condition - too many chunks
}

const VkSparseImageOpaqueMemoryBindInfo opaqueBindInfo =
{
    sparseImage,                                // image
    bindCount,                                  // bindCount
    binds                                       // pBinds
};

const VkBindSparseInfo bindSparseInfo =
{
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO,         // sType
    NULL,                                       // pNext
```

```
    ...
    1,                                          // imageOpaqueBindCount
    &opaqueBindInfo,                            // pImageOpaqueBinds
    ...
};

// vkQueueBindSparse is externally synchronized per queue object.
AcquireQueueOwnership(queue);

// Actually bind memory
vkQueueBindSparse(queue, 1, &bindSparseInfo, VK_NULL_HANDLE);

ReleaseQueueOwnership(queue);
```

28.8.2. Advanced Sparse Resources

This more advanced example creates an arrayed color attachment / texture image and binds only LOD zero and the **required** metadata to physical memory.

```
VkDevice                            device;
VkQueue                             queue;
VkImage                             sparseImage;
VkAllocationCallbacks*              pAllocator = NULL;
VkMemoryRequirements                memoryRequirements = {};
uint32_t                            sparseRequirementsCount = 0;
VkSparseImageMemoryRequirements*    pSparseReqs = NULL;
VkSparseMemoryBind                  binds[MY_IMAGE_ARRAY_SIZE] = {};
VkSparseImageMemoryBind             imageBinds[MY_IMAGE_ARRAY_SIZE] = {};
uint32_t                            bindCount = 0;

// Allocate image object (both renderable and sampleable)
const VkImageCreateInfo sparseImageInfo =
{
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO,        // sType
    NULL,                                       // pNext
    VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT | ..., // flags
    ...
    VK_FORMAT_R8G8B8A8_UNORM,                   // format
    ...
    MY_IMAGE_ARRAY_SIZE,                        // arrayLayers
    ...
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT |
    VK_IMAGE_USAGE_SAMPLED_BIT,                 // usage
    ...
};
vkCreateImage(device, &sparseImageInfo, pAllocator, &sparseImage);

// Get memory requirements
vkGetImageMemoryRequirements(
    device,
```

```
    sparseImage,
    &memoryRequirements);

// Get sparse image aspect properties
vkGetImageSparseMemoryRequirements(
    device,
    sparseImage,
    &sparseRequirementsCount,
    NULL);

pSparseReqs = (VkSparseImageMemoryRequirements*)
    malloc(sparseRequirementsCount * sizeof(VkSparseImageMemoryRequirements));

vkGetImageSparseMemoryRequirements(
    device,
    sparseImage,
    &sparseRequirementsCount,
    pSparseReqs);

// Bind LOD level 0 and any required metadata to memory
for (uint32_t i = 0; i < sparseRequirementsCount; ++i)
{
    if (pSparseReqs[i].formatProperties.aspectMask &
        VK_IMAGE_ASPECT_METADATA_BIT)
    {
        // Metadata must not be combined with other aspects
        assert(pSparseReqs[i].formatProperties.aspectMask ==
               VK_IMAGE_ASPECT_METADATA_BIT);

        if (pSparseReqs[i].formatProperties.flags &
            VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT)
        {
            VkSparseMemoryBind* pBind = &binds[bindCount];
            pBind->memorySize = pSparseReqs[i].imageMipTailSize;
            bindCount++;

            // ... Allocate memory range

            pBind->resourceOffset = pSparseReqs[i].imageMipTailOffset;
            pBind->memoryOffset = /* allocated memoryOffset */;
            pBind->memory = /* allocated memory */;
            pBind->flags = VK_SPARSE_MEMORY_BIND_METADATA_BIT;

        }
        else
        {
            // Need a mip tail region per array layer.
            for (uint32_t a = 0; a < sparseImageInfo.arrayLayers; ++a)
            {
                VkSparseMemoryBind* pBind = &binds[bindCount];
                pBind->memorySize = pSparseReqs[i].imageMipTailSize;
```

```
                bindCount++;

                // ... Allocate memory range

                pBind->resourceOffset = pSparseReqs[i].imageMipTailOffset +
                                        (a * pSparseReqs[i].imageMipTailStride);

                pBind->memoryOffset = /* allocated memoryOffset */;
                pBind->memory = /* allocated memory */
                pBind->flags = VK_SPARSE_MEMORY_BIND_METADATA_BIT;
            }
        }
    }
    else
    {
        // resource data
        VkExtent3D lod0BlockSize =
        {
            AlignedDivide(
                sparseImageInfo.extent.width,
                pSparseReqs[i].formatProperties.imageGranularity.width);
            AlignedDivide(
                sparseImageInfo.extent.height,
                pSparseReqs[i].formatProperties.imageGranularity.height);
            AlignedDivide(
                sparseImageInfo.extent.depth,
                pSparseReqs[i].formatProperties.imageGranularity.depth);
        }
        size_t totalBlocks =
            lod0BlockSize.width *
            lod0BlockSize.height *
            lod0BlockSize.depth;

        // Each block is the same size as the alignment requirement,
        // calculate total memory size for level 0
        VkDeviceSize lod0MemSize = totalBlocks * memoryRequirements.alignment;

        // Allocate memory for each array layer
        for (uint32_t a = 0; a < sparseImageInfo.arrayLayers; ++a)
        {
            // ... Allocate memory range

            VkSparseImageMemoryBind* pBind = &imageBinds[a];
            pBind->subresource.aspectMask = pSparseReqs[i].formatProperties.
aspectMask;
            pBind->subresource.mipLevel = 0;
            pBind->subresource.arrayLayer = a;

            pBind->offset = (VkOffset3D){0, 0, 0};
            pBind->extent = sparseImageInfo.extent;
            pBind->memoryOffset = /* allocated memoryOffset */;
```

```
            pBind->memory = /* allocated memory */;
            pBind->flags = 0;
        }
    }

    free(pSparseReqs);
}

const VkSparseImageOpaqueMemoryBindInfo opaqueBindInfo =
{
    sparseImage,                                // image
    bindCount,                                  // bindCount
    binds                                       // pBinds
};

const VkSparseImageMemoryBindInfo imageBindInfo =
{
    sparseImage,                                // image
    sparseImageInfo.arrayLayers,                // bindCount
    imageBinds                                  // pBinds
};

const VkBindSparseInfo bindSparseInfo =
{
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO,         // sType
    NULL,                                       // pNext
    ...
    1,                                          // imageOpaqueBindCount
    &opaqueBindInfo,                            // pImageOpaqueBinds
    1,                                          // imageBindCount
    &imageBindInfo,                             // pImageBinds
    ...
};

// vkQueueBindSparse is externally synchronized per queue object.
AcquireQueueOwnership(queue);

// Actually bind memory
vkQueueBindSparse(queue, 1, &bindSparseInfo, VK_NULL_HANDLE);

ReleaseQueueOwnership(queue);
```

Chapter 29. Extended Functionality

Additional functionality **may** be provided by layers or extensions. A layer **cannot** add or modify Vulkan commands, while an extension **may** do so.

The set of layers to enable is specified when creating an instance, and those layers are able to intercept any Vulkan command dispatched to that instance or any of its child objects.

Extensions can operate at either the instance or device *extension scope*. Enabled instance extensions are able to affect the operation of the instance and any of its child objects, while device extensions **may** only be available on a subset of physical devices, **must** be individually enabled per-device, and only affect the operation of the devices where they are enabled.

Examples of these might be:

- Whole API validation is an example of a layer.
- Debug capabilities might make a good instance extension.
- A layer that provides hardware-specific performance telemetry and analysis could be a layer that is only active for devices created from compatible physical devices.
- Functions to allow an application to use additional hardware features beyond the core would be a good candidate for a device extension.

29.1. Layers

When a layer is enabled, it inserts itself into the call chain for Vulkan commands the layer is interested in. A common use of layers is to validate application behavior during development. For example, the implementation will not check that Vulkan 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.

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 "Vulkan Loader Specification and Architecture Overview" document for additional information.

To query the available layers, call:

```
VkResult vkEnumerateInstanceLayerProperties(
    uint32_t*                                   pPropertyCount,
    VkLayerProperties*                          pProperties);
```

- `pPropertyCount` is a pointer to an integer related to the number of layer properties available or queried, as described below.
- `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. If pPropertyCount is smaller than the number of layers available, VK_INCOMPLETE will be returned instead of VK_SUCCESS, to indicate that not all the available layer 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)

- pPropertyCount **must** be a valid pointer to a uint32_t value
- 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:

```
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 a null-terminated UTF-8 string specifying 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 the API Version Numbers and Semantics section.

- implementationVersion is the version of this layer. It is an integer, increasing with backward compatible changes.
- description is a null-terminated UTF-8 string providing additional details that **can** be used by the application to identify the layer.

To enable a layer, the name of the layer **should** be added to the ppEnabledLayerNames member of VkInstanceCreateInfo when creating a VkInstance.

Loader implementations **may** provide mechanisms outside the Vulkan API for enabling specific layers. Layers enabled through such a mechanism are *implicitly enabled*, while layers enabled by including the layer name in the ppEnabledLayerNames member of VkInstanceCreateInfo are *explicitly enabled*. Except where otherwise specified, implicitly enabled and explicitly enabled layers differ only in the way they are enabled. Explicitly enabling a layer that is implicitly enabled has no additional effect.

29.1.1. 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 VkInstance and VkPhysicalDevice, except they were not able to intercept 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 **should** still enumerate and enable device layers. The behavior of vkEnumerateDeviceLayerProperties and valid usage of the ppEnabledLayerNames member of VkDeviceCreateInfo maximizes compatibility with applications written to work with the previous requirements.

To enumerate device layers, call:

```
VkResult vkEnumerateDeviceLayerProperties(
    VkPhysicalDevice                            physicalDevice,
    uint32_t*                                   pPropertyCount,
    VkLayerProperties*                          pProperties);
```

- 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. If pPropertyCount is smaller than the number of layers available, VK_INCOMPLETE will be returned instead of VK_SUCCESS, to indicate that not all the available layer 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.

Valid Usage (Implicit)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- pPropertyCount **must** be a valid pointer to a uint32_t value
- 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.

29.2. 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.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 "Vulkan Loader Specification and Architecture Overview" document for additional information.

To query the available instance extensions, call:

```
VkResult vkEnumerateInstanceExtensionProperties(
    const char*                                 pLayerName,
    uint32_t*                                   pPropertyCount,
    VkExtensionProperties*                      pProperties);
```

- 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, as described below.
- 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. If pPropertyCount is smaller than the number of extensions available, 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.

Valid Usage (Implicit)

- If pLayerName is not NULL, pLayerName **must** be a null-terminated UTF-8 string
- pPropertyCount **must** be a valid pointer to a uint32_t value
- 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

To enable an instance extension, the name of the extension **should** be added to the ppEnabledExtensionNames member of VkInstanceCreateInfo when creating a VkInstance.

Enabling an extension does not change 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.

To query the extensions available to a given physical device, call:

```
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.

Valid Usage (Implicit)

- `physicalDevice` **must** be a valid `VkPhysicalDevice` handle
- If `pLayerName` is not `NULL`, `pLayerName` **must** be a null-terminated UTF-8 string
- `pPropertyCount` **must** be a valid pointer to a `uint32_t` value
- 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:

```
typedef struct VkExtensionProperties {
    char        extensionName[VK_MAX_EXTENSION_NAME_SIZE];
    uint32_t    specVersion;
} VkExtensionProperties;
```

- `extensionName` is a null-terminated string specifying the name of the extension.
- `specVersion` is the version of this extension. It is an integer, incremented with backward compatible changes.

29.2.1. Instance Extensions and Device Extensions

This section provides some guidelines and rules for when to expose new functionality as an instance extension, as a device extension, or as both. The decision depends on the scope of the new functionality; such as whether it extends instance-level or device-level functionality. All Vulkan commands, structures, and enumerants are considered either instance-level, physical-device-level, or device-level.

Commands that are dispatched from instances (`VkInstance`) are considered instance-level commands. Any structure, enumerated type, and enumerant that is used with instance-level commands are considered instance-level objects. New instance-level extension functionality **must** be structured within an instance extension.

Any command or object that **must** be used after calling vkCreateDevice is a device-level command or object. These objects include all children of VkDevice objects, such as queues (VkQueue) and command buffers (VkCommandBuffer). New device-level extension functionality **may** be structured within a device extension.

Commands that are dispatched from physical devices (VkPhysicalDevice) are considered physical-device-level commands. Any structure, enumerated type, and enumerant that is used with physical-device-level commands, and not used with instance-level commands, are considered physical-device-level objects. Vulkan 1.0 requires all new physical-device-level extension functionality to be structured within an instance extension.

29.3. Extension Dependencies

Some extensions are dependent on other extensions to function. To use extensions with dependencies, such *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.

> *Note*
>
> The Specification does not currently include required extensions in Valid Usage statements for individual commands and structures, although it might do so in the future. Nonetheless, applications **must** not use any extension functionality if dependencies of that extension are not enabled.

29.4. Extension Compatibility

By default, all extensions are considered compatible with each other and any core API version, unless otherwise stated. Thus enabling such extensions does not otherwise alter the behavior of the application.

Each extension that is mutually exclusive or otherwise incompatible with another extension or set of extensions documents them in the appendix summarizing that extension and has a corresponding Valid Usage statement disallowing enabling such an incompatible combination of extensions at VkInstance creation time or VkDevice creation time, depending on the type of extensions participating in the interaction.

Chapter 30. Features, Limits, and Formats

Vulkan is designed to support a wide range of hardware and as such there are a number of features, limits, and formats which are not supported on all hardware. Features describe functionality that is not **required** and which **must** be explicitly enabled. Limits describe implementation-dependent minimums, maximums, and other device characteristics that an application **may** need to be aware of. 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.

> *Note*
>
> The features and limits are reported via basic structures (that is VkPhysicalDeviceFeatures and VkPhysicalDeviceLimits), as well as extensible structures (`VkPhysicalDeviceFeatures2KHR` and `VkPhysicalDeviceProperties2KHR`) which were added in `[VK_KHR_get_physical_device_properties2]`. When new features or limits are added in future Vulkan version or extensions, each extension **should** introduce one new feature structure and/or limit structure (as needed). These structures **can** be added to the `pNext` chain of the `VkPhysicalDeviceFeatures2KHR` and `VkPhysicalDeviceProperties2KHR` structures, respectively.

30.1. Features

The Specification defines a set of fine-grained features that are not **required**, but **may** be supported by a Vulkan implementation. Support for features is reported and enabled on a per-feature basis. Features are properties of the physical device.

To query supported features, call:

```
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` indicates that the feature is supported on this physical device, and `VK_FALSE` indicates that the feature is not supported.

Valid Usage (Implicit)

- `physicalDevice` **must** be a valid `VkPhysicalDevice` handle
- `pFeatures` **must** be a valid pointer to a `VkPhysicalDeviceFeatures` structure

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. If an application uses a feature without enabling it at VkDevice creation time, the device behavior is undefined. The validation layer will warn if features are used without being enabled.

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.

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 is equivalent to setting all members of the structure to VK_FALSE.

> *Note*
>
> Some features, such as robustBufferAccess, **may** incur a run-time performance cost. Application writers **should** carefully consider the implications of enabling all supported features.

The VkPhysicalDeviceFeatures structure is defined as:

```
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;
    VkBool32    samplerAnisotropy;
    VkBool32    textureCompressionETC2;
    VkBool32    textureCompressionASTC_LDR;
    VkBool32    textureCompressionBC;
    VkBool32    occlusionQueryPrecise;
    VkBool32    pipelineStatisticsQuery;
    VkBool32    vertexPipelineStoresAndAtomics;
```

```
    VkBool32    fragmentStoresAndAtomics;
    VkBool32    shaderTessellationAndGeometryPointSize;
    VkBool32    shaderImageGatherExtended;
    VkBool32    shaderStorageImageExtendedFormats;
    VkBool32    shaderStorageImageMultisample;
    VkBool32    shaderStorageImageReadWithoutFormat;
    VkBool32    shaderStorageImageWriteWithoutFormat;
    VkBool32    shaderUniformBufferArrayDynamicIndexing;
    VkBool32    shaderSampledImageArrayDynamicIndexing;
    VkBool32    shaderStorageBufferArrayDynamicIndexing;
    VkBool32    shaderStorageImageArrayDynamicIndexing;
    VkBool32    shaderClipDistance;
    VkBool32    shaderCullDistance;
    VkBool32    shaderFloat64;
    VkBool32    shaderInt64;
    VkBool32    shaderInt16;
    VkBool32    shaderResourceResidency;
    VkBool32    shaderResourceMinLod;
    VkBool32    sparseBinding;
    VkBool32    sparseResidencyBuffer;
    VkBool32    sparseResidencyImage2D;
    VkBool32    sparseResidencyImage3D;
    VkBool32    sparseResidency2Samples;
    VkBool32    sparseResidency4Samples;
    VkBool32    sparseResidency8Samples;
    VkBool32    sparseResidency16Samples;
    VkBool32    sparseResidencyAliased;
    VkBool32    variableMultisampleRate;
    VkBool32    inheritedQueries;
} VkPhysicalDeviceFeatures;
```

The members of the `VkPhysicalDeviceFeatures` structure describe the following features:

- `robustBufferAccess` indicates 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.

> *Note*
>
> If a SPIR-V `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.

    ▪ If any buffer access in a given SPIR-V block is determined to be out of bounds, then any other access of the same type (load, store, or atomic) in the same SPIR-V block that accesses an address less than 16 bytes away from the out of bounds address **may** also be considered out of bounds.

  ◦ Out-of-bounds buffer loads will return any of the following values:

    ▪ 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).

    ▪ Zero values, or (0,0,0,x) vectors for vector reads where x is a valid value represented in the type of the vector components and **may** be any of:

      ▪ 0, 1, or the maximum representable positive integer value, for signed or unsigned integer components

      ▪ 0.0 or 1.0, for floating-point components

  ◦ Out-of-bounds writes **may** modify values within the memory range(s) bound to the buffer, but **must** not modify any other memory.

  ◦ Out-of-bounds atomics **may** modify values within the memory range(s) bound to the buffer, but **must** not modify any other memory, and return an undefined value.

  ◦ 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:

    ▪ `vertexBufferRangeSize`, if `bindingStride` == 0; or

    ▪ (`vertexBufferRangeSize` - (`vertexBufferRangeSize` % `bindingStride`))

    where `vertexBufferRangeSize` is the byte size of the memory range bound to the vertex buffer binding and `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, out of bounds accesses **may** corrupt any memory within the process and cause undefined behavior up to and including application termination.

- fullDrawIndexUint32 indicates 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 indicates 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 indicates 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 indicates 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 indicates whether shader modules **can** declare the Geometry capability.
- tessellationShader indicates 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 indicates whether shader modules **can** declare the Tessellation capability.
- sampleRateShading indicates 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 indicates whether shader modules **can** declare the SampleRateShading capability.
- dualSrcBlend indicates 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 indicates 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 indicates 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 indicates whether indirect draw 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates whether the implementation is able to replace the alpha value of the color fragment output from the fragment shader with the maximum representable alpha value for fixed-point colors or 1.0 for floating-point colors. 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 indicates 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. Similarly, the viewportCount parameter to the vkCmdSetViewport command and the scissorCount parameter to the vkCmdSetScissor command **must** be 1, and the firstViewport parameter to the vkCmdSetViewport command and the firstScissor parameter to the vkCmdSetScissor command **must** be 0.
- samplerAnisotropy indicates whether anisotropic filtering is supported. If this feature is not enabled, the anisotropyEnable member of the VkSamplerCreateInfo structure **must** be VK_FALSE.
- textureCompressionETC2 indicates 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

vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties **can** be used to check for additional supported properties of individual formats.

- textureCompressionASTC_LDR indicates 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_10x5_UNORM_BLOCK
  - VK_FORMAT_ASTC_10x5_SRGB_BLOCK
  - VK_FORMAT_ASTC_10x6_UNORM_BLOCK
  - VK_FORMAT_ASTC_10x6_SRGB_BLOCK
  - VK_FORMAT_ASTC_10x8_UNORM_BLOCK
  - VK_FORMAT_ASTC_10x8_SRGB_BLOCK
  - VK_FORMAT_ASTC_10x10_UNORM_BLOCK
  - VK_FORMAT_ASTC_10x10_SRGB_BLOCK
  - VK_FORMAT_ASTC_12x10_UNORM_BLOCK
  - VK_FORMAT_ASTC_12x10_SRGB_BLOCK
  - VK_FORMAT_ASTC_12x12_UNORM_BLOCK

- VK_FORMAT_ASTC_12x12_SRGB_BLOCK

vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties **can** be used to check for additional supported properties of individual formats.

- textureCompressionBC indicates 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
  - VK_FORMAT_BC6H_UFLOAT_BLOCK
  - VK_FORMAT_BC6H_SFLOAT_BLOCK
  - VK_FORMAT_BC7_UNORM_BLOCK
  - VK_FORMAT_BC7_SRGB_BLOCK

  vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties **can** be used to check for additional supported properties of individual formats.

- occlusionQueryPrecise indicates 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 indicates 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 indicates 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 buffers, and storage buffer variables used by these stages in shader modules **must** be decorated with the NonWriteable decoration (or the readonly

memory qualifier in GLSL).

- fragmentStoresAndAtomics indicates 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 buffers, and storage buffer variables used by the fragment stage in shader modules **must** be decorated with the NonWriteable decoration (or the readonly memory qualifier in GLSL).
- shaderTessellationAndGeometryPointSize indicates 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 indicates 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 indicates 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 indicates whether shader modules **can** declare the ImageGatherExtended capability.
- shaderStorageImageExtendedFormats indicates whether the extended storage image formats are available in shader code. If this feature is not enabled, the formats requiring the StorageImageExtendedFormats capability are not supported for storage images. This also indicates whether shader modules **can** declare the StorageImageExtendedFormats capability.
- shaderStorageImageMultisample indicates 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 indicates whether shader modules **can** declare the StorageImageMultisample capability.
- shaderStorageImageReadWithoutFormat indicates whether storage images require a format qualifier to be specified when reading from storage images. If this feature is not enabled, the OpImageRead instruction **must** not have an OpTypeImage of Unknown. This also indicates whether shader modules **can** declare the StorageImageReadWithoutFormat capability.
- shaderStorageImageWriteWithoutFormat indicates whether storage images require a format qualifier to be specified when writing to storage images. If this feature is not enabled, the OpImageWrite instruction **must** not have an OpTypeImage of Unknown. This also indicates whether shader modules **can** declare the StorageImageWriteWithoutFormat capability.
- shaderUniformBufferArrayDynamicIndexing indicates 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 indicates whether shader modules **can** declare the UniformBufferArrayDynamicIndexing capability.
- shaderSampledImageArrayDynamicIndexing indicates 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 indicates whether shader modules **can** declare the SampledImageArrayDynamicIndexing capability.

- shaderStorageBufferArrayDynamicIndexing indicates 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 indicates whether shader modules **can** declare the StorageBufferArrayDynamicIndexing capability.
- shaderStorageImageArrayDynamicIndexing indicates 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 indicates whether shader modules **can** declare the StorageImageArrayDynamicIndexing capability.
- shaderClipDistance indicates 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 indicates whether shader modules **can** declare the ClipDistance capability.
- shaderCullDistance indicates 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 indicates whether shader modules **can** declare the CullDistance capability.
- shaderFloat64 indicates 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 indicates whether shader modules **can** declare the Float64 capability.
- shaderInt64 indicates 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 indicates whether shader modules **can** declare the Int64 capability.
- shaderInt16 indicates 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 indicates whether shader modules **can** declare the Int16 capability.
- shaderResourceResidency indicates 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 indicates whether shader modules **can** declare the SparseResidency capability. The feature requires at least one of the sparseResidency* features to be supported.
- shaderResourceMinLod indicates whether image operations that specify 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 indicates whether shader modules **can** declare the MinLod capability.
- sparseBinding indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates whether all pipelines that will be bound to a command buffer during a subpass with no attachments **must** have the same value for VkPipelineMultisampleStateCreateInfo::rasterizationSamples. If set to VK_TRUE, the implementation supports variable multisample rates in a subpass with 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` indicates whether a secondary command buffer **may** be executed while a query is active.

30.1.1. Feature Requirements

All Vulkan graphics implementations **must** support the following features:

- `robustBufferAccess`.

All other features are not **required** by the Specification.

30.2. Limits

There are a variety of implementation-dependent limits.

The `VkPhysicalDeviceLimits` are properties of the physical device. These are available in the `limits` member of the VkPhysicalDeviceProperties structure which is returned from vkGetPhysicalDeviceProperties.

The `VkPhysicalDeviceLimits` structure is defined as:

```
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              maxPerStageDescriptorSampledImages;
    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              maxDescriptorSetSampledImages;
    uint32_t              maxDescriptorSetStorageImages;
    uint32_t              maxDescriptorSetInputAttachments;
    uint32_t              maxVertexInputAttributes;
    uint32_t              maxVertexInputBindings;
    uint32_t              maxVertexInputAttributeOffset;
    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;
    VkSampleCountFlags    framebufferNoAttachmentsSampleCounts;
    uint32_t              maxColorAttachments;
    VkSampleCountFlags    sampledImageColorSampleCounts;
    VkSampleCountFlags    sampledImageIntegerSampleCounts;
    VkSampleCountFlags    sampledImageDepthSampleCounts;
    VkSampleCountFlags    sampledImageStencilSampleCounts;
    VkSampleCountFlags    storageImageSampleCounts;
    uint32_t              maxSampleMaskWords;
    VkBool32              timestampComputeAndGraphics;
    float                 timestampPeriod;
    uint32_t              maxClipDistances;
    uint32_t              maxCullDistances;
    uint32_t              maxCombinedClipAndCullDistances;
    uint32_t              discreteQueuePriorities;
    float                 pointSizeRange[2];
    float                 lineWidthRange[2];
    float                 pointSizeGranularity;
    float                 lineWidthGranularity;
    VkBool32              strictLines;
    VkBool32              standardSampleLocations;
    VkDeviceSize          optimalBufferCopyOffsetAlignment;
    VkDeviceSize          optimalBufferCopyRowPitchAlignment;
    VkDeviceSize          nonCoherentAtomSize;
} VkPhysicalDeviceLimits;
```

- `maxImageDimension1D` is the maximum dimension (`width`) supported for all images created with an `imageType` of `VK_IMAGE_TYPE_1D`.
- `maxImageDimension2D` is the maximum dimension (`width` or `height`) supported for all images created with an `imageType` of `VK_IMAGE_TYPE_2D` and without `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT` set in `flags`.
- `maxImageDimension3D` is the maximum dimension (`width`, `height`, or `depth`) supported for all images created with an `imageType` of `VK_IMAGE_TYPE_3D`.
- `maxImageDimensionCube` is the maximum dimension (`width` or `height`) supported for all images created with an `imageType` of `VK_IMAGE_TYPE_2D` and with `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT` set in `flags`.
- `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 any

VkDescriptorBufferInfo structures passed to a call 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 any VkDescriptorBufferInfo structures passed to a call 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 size 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. 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. 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. 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. 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. 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. 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. 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 descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_SAMPLER or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER count against this limit. See Sampler and Combined Image Sampler.
- maxDescriptorSetUniformBuffers is the maximum number of uniform buffers that **can** be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC 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 descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC count against this limit. See Dynamic Uniform Buffer.
- maxDescriptorSetStorageBuffers is the maximum number of storage buffers that **can** be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC 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 descriptor bindings in a pipeline layout across all pipeline shader stages and

descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC count against this limit. See Dynamic Storage Buffer.

- maxDescriptorSetSampledImages is the maximum number of sampled images that **can** be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. 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. See Combined Image Sampler, Sampled Image, and Uniform Texel Buffer.
- maxDescriptorSetStorageImages is the maximum number of storage images that **can** be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER count against this limit. See Storage Image, and Storage Texel Buffer.
- maxDescriptorSetInputAttachments is the maximum number of input attachments that **can** be included in descriptor bindings in a pipeline layout across all pipeline shader stages and descriptor set numbers. Descriptors with a type of VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT 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. 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, 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 buffers which **can** be used in the fragment shader stage.
- `maxComputeSharedMemorySize` is the maximum total storage size, in bytes, of all variables declared with the `WorkgroupLocal` 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 dispatch 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 dispatch 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 execution mode in shader modules and 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 specified by the LocalSize execution mode and 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. The filtering hardware will snap to these locations when computing 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.

> *Note*
>
> For example, if this value is 2 bits then when linearly filtering between two levels, each level could: contribute: 0%, 33%, 66%, or 100% (this is just an example and the amount of contribution **should** be covered by different equations in the spec).

* 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 fullDrawIndexUint32.
* maxDrawIndirectCount is the maximum draw count that is supported for indirect draw 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 [-maxSamplerLodBias,+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 [minimum, maximum] range that the corners of a viewport **must** be contained in. This range **must** be at least [-2 × size, 2 × size - 1], where size = max(maxViewportDimensions[0], 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 [-size + 1, 2 × 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.
- minTexelBufferOffsetAlignment is the minimum **required** alignment, in bytes, for the offset member of the VkBufferViewCreateInfo structure for texel buffers. When a buffer view is created for a buffer which was created with VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT or VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT set in the usage member of the VkBufferCreateInfo structure, the offset **must** be an integer multiple of this limit.
- 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.
- 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.
- 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 or ConstOffsets image operands of any of the OpImage*Gather image instructions.
- maxTexelGatherOffset is the maximum offset value for the Offset or ConstOffsets image operands of any of the OpImage*Gather image instructions.
- minInterpolationOffset is the minimum negative offset value for the offset operand of the

InterpolateAtOffset extended instruction.

- maxInterpolationOffset is the maximum positive offset value for the offset operand of the InterpolateAtOffset extended instruction.
- subPixelInterpolationOffsetBits is the number of subpixel 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[1] of VkSampleCountFlagBits indicating the color sample counts that are supported for all framebuffer color attachments with floating- or fixed-point formats. There is no limit that indicates the color sample counts that are supported for all color attachments with integer formats.
- framebufferDepthSampleCounts is a bitmask[1] 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[1] 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 framebuffer with 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 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 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 indicates 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 [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 [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 indicates 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 indicates 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 vkCmdCopyBufferToImage and vkCmdCopyImageToBuffer. The per texel alignment requirements are enforced, but applications **should** use the optimal alignment for optimal performance and power use.

- optimalBufferCopyRowPitchAlignment is the optimal buffer row pitch alignment in bytes for vkCmdCopyBufferToImage 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.
- nonCoherentAtomSize is the size and alignment in bytes that bounds concurrent access to host-mapped device memory.

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:

```
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.

```
typedef VkFlags VkSampleCountFlags;
```

VkSampleCountFlags is a bitmask type for setting a mask of zero or more VkSampleCountFlagBits.

30.2.1. 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 31. Required Limit Types

Type	Limit	Feature
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	sparseBinding
uint32_t	maxBoundDescriptorSets	-
uint32_t	maxPerStageDescriptorSamplers	-
uint32_t	maxPerStageDescriptorUniformBuffers	-
uint32_t	maxPerStageDescriptorStorageBuffers	-
uint32_t	maxPerStageDescriptorSampledImages	-
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	maxDescriptorSetSampledImages	-
uint32_t	maxDescriptorSetStorageImages	-
uint32_t	maxDescriptorSetInputAttachments	-
uint32_t	maxVertexInputAttributes	-
uint32_t	maxVertexInputBindings	-
uint32_t	maxVertexInputAttributeOffset	-
uint32_t	maxVertexInputBindingStride	-

Type	Limit	Feature
uint32_t	maxVertexOutputComponents	-
uint32_t	maxTessellationGenerationLevel	tessellationShader
uint32_t	maxTessellationPatchSize	tessellationShader
uint32_t	maxTessellationControlPerVertexInputComponents	tessellationShader
uint32_t	maxTessellationControlPerVertexOutputComponents	tessellationShader
uint32_t	maxTessellationControlPerPatchOutputComponents	tessellationShader
uint32_t	maxTessellationControlTotalOutputComponents	tessellationShader
uint32_t	maxTessellationEvaluationInputComponents	tessellationShader
uint32_t	maxTessellationEvaluationOutputComponents	tessellationShader
uint32_t	maxGeometryShaderInvocations	geometryShader
uint32_t	maxGeometryInputComponents	geometryShader
uint32_t	maxGeometryOutputComponents	geometryShader
uint32_t	maxGeometryOutputVertices	geometryShader
uint32_t	maxGeometryTotalOutputComponents	geometryShader
uint32_t	maxFragmentInputComponents	-
uint32_t	maxFragmentOutputAttachments	-
uint32_t	maxFragmentDualSrcAttachments	dualSrcBlend
uint32_t	maxFragmentCombinedOutputResources	-
uint32_t	maxComputeSharedMemorySize	-
3 × uint32_t	maxComputeWorkGroupCount	-
uint32_t	maxComputeWorkGroupInvocations	-
3 × uint32_t	maxComputeWorkGroupSize	-
uint32_t	subPixelPrecisionBits	-
uint32_t	subTexelPrecisionBits	-
uint32_t	mipmapPrecisionBits	-
uint32_t	maxDrawIndexedIndexValue	fullDrawIndexUint32
uint32_t	maxDrawIndirectCount	multiDrawIndirect
float	maxSamplerLodBias	-
float	maxSamplerAnisotropy	samplerAnisotropy
uint32_t	maxViewports	multiViewport
2 × uint32_t	maxViewportDimensions	-
2 × float	viewportBoundsRange	-
uint32_t	viewportSubPixelBits	-
size_t	minMemoryMapAlignment	-
VkDeviceSize	minTexelBufferOffsetAlignment	-
VkDeviceSize	minUniformBufferOffsetAlignment	-
VkDeviceSize	minStorageBufferOffsetAlignment	-
int32_t	minTexelOffset	-

Type	Limit	Feature
uint32_t	maxTexelOffset	-
int32_t	minTexelGatherOffset	shaderImageGatherExtended
uint32_t	maxTexelGatherOffset	shaderImageGatherExtended
float	minInterpolationOffset	sampleRateShading
float	maxInterpolationOffset	sampleRateShading
uint32_t	subPixelInterpolationOffsetBits	sampleRateShading
uint32_t	maxFramebufferWidth	-
uint32_t	maxFramebufferHeight	-
uint32_t	maxFramebufferLayers	-
VkSampleCountFlags	framebufferColorSampleCounts	-
VkSampleCountFlags	framebufferDepthSampleCounts	-
VkSampleCountFlags	framebufferStencilSampleCounts	-
VkSampleCountFlags	framebufferNoAttachmentsSampleCounts	-
uint32_t	maxColorAttachments	-
VkSampleCountFlags	sampledImageColorSampleCounts	-
VkSampleCountFlags	sampledImageIntegerSampleCounts	-
VkSampleCountFlags	sampledImageDepthSampleCounts	-
VkSampleCountFlags	sampledImageStencilSampleCounts	-
VkSampleCountFlags	storageImageSampleCounts	shaderStorageImageMultisample
uint32_t	maxSampleMaskWords	-
VkBool32	timestampComputeAndGraphics	-
float	timestampPeriod	-
uint32_t	maxClipDistances	shaderClipDistance
uint32_t	maxCullDistances	shaderCullDistance
uint32_t	maxCombinedClipAndCullDistances	shaderCullDistance
uint32_t	discreteQueuePriorities	-
2 × float	pointSizeRange	largePoints
2 × float	lineWidthRange	wideLines
float	pointSizeGranularity	largePoints
float	lineWidthGranularity	wideLines
VkBool32	strictLines	-

Type	Limit	Feature
VkBool32	standardSampleLocations	-
VkDeviceSize	optimalBufferCopyOffsetAlignment	-
VkDeviceSize	optimalBufferCopyRowPitchAlignment	-
VkDeviceSize	nonCoherentAtomSize	-

Table 32. Required Limits

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
maxImageDimension1D	-	4096	min
maxImageDimension2D	-	4096	min
maxImageDimension3D	-	256	min
maxImageDimensionCube	-	4096	min
maxImageArrayLayers	-	256	min
maxTexelBufferElements	-	65536	min
maxUniformBufferRange	-	16384	min
maxStorageBufferRange	-	2^{27}	min
maxPushConstantsSize	-	128	min
maxMemoryAllocationCount	-	4096	min
maxSamplerAllocationCount	-	4000	min
bufferImageGranularity	-	131072	max
sparseAddressSpaceSize	0	2^{31}	min
maxBoundDescriptorSets	-	4	min
maxPerStageDescriptorSamplers	-	16	min
maxPerStageDescriptorUniformBuffers	-	12	min
maxPerStageDescriptorStorageBuffers	-	4	min
maxPerStageDescriptorSampledImages	-	16	min
maxPerStageDescriptorStorageImages	-	4	min
maxPerStageDescriptorInputAttachments	-	4	min
maxPerStageResources	-	128 [2]	min
maxDescriptorSetSamplers	-	96 [8]	min, $n \times$ PerStage
maxDescriptorSetUniformBuffers	-	72 [8]	min, $n \times$ PerStage
maxDescriptorSetUniformBuffersDynamic	-	8	min
maxDescriptorSetStorageBuffers	-	24 [8]	min, $n \times$ PerStage
maxDescriptorSetStorageBuffersDynamic	-	4	min

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
maxDescriptorSetSampledImages	-	96 [8]	min, *n* × PerStage
maxDescriptorSetStorageImages	-	24 [8]	min, *n* × PerStage
maxDescriptorSetInputAttachments	-	4	min
maxVertexInputAttributes	-	16	min
maxVertexInputBindings	-	16	min
maxVertexInputAttributeOffset	-	2047	min
maxVertexInputBindingStride	-	2048	min
maxVertexOutputComponents	-	64	min
maxTessellationGenerationLevel	0	64	min
maxTessellationPatchSize	0	32	min
maxTessellationControlPerVertexInputComponents	0	64	min
maxTessellationControlPerVertexOutputComponents	0	64	min
maxTessellationControlPerPatchOutputComponents	0	120	min
maxTessellationControlTotalOutputComponents	0	2048	min
maxTessellationEvaluationInputComponents	0	64	min
maxTessellationEvaluationOutputComponents	0	64	min
maxGeometryShaderInvocations	0	32	min
maxGeometryInputComponents	0	64	min
maxGeometryOutputComponents	0	64	min
maxGeometryOutputVertices	0	256	min
maxGeometryTotalOutputComponents	0	1024	min
maxFragmentInputComponents	-	64	min
maxFragmentOutputAttachments	-	4	min
maxFragmentDualSrcAttachments	0	1	min
maxFragmentCombinedOutputResources	-	4	min
maxComputeSharedMemorySize	-	16384	min
maxComputeWorkGroupCount	-	(65535,65535,65535)	min
maxComputeWorkGroupInvocations	-	128	min
maxComputeWorkGroupSize	-	(128,128,64)	min
subPixelPrecisionBits	-	4	min
subTexelPrecisionBits	-	4	min
mipmapPrecisionBits	-	4	min
maxDrawIndexedIndexValue	2^{24}-1	2^{32}-1	min

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
maxDrawIndirectCount	1	2^{16}-1	min
maxSamplerLodBias	-	2	min
maxSamplerAnisotropy	1	16	min
maxViewports	1	16	min
maxViewportDimensions	-	(4096,4096) [3]	min
viewportBoundsRange	-	(-8192,8191) [4]	(max,min)
viewportSubPixelBits	-	0	min
minMemoryMapAlignment	-	64	min
minTexelBufferOffsetAlignment	-	256	max
minUniformBufferOffsetAlignment	-	256	max
minStorageBufferOffsetAlignment	-	256	max
minTexelOffset	-	-8	max
maxTexelOffset	-	7	min
minTexelGatherOffset	0	-8	max
maxTexelGatherOffset	0	7	min
minInterpolationOffset	0.0	-0.5 [5]	max
maxInterpolationOffset	0.0	0.5 - (1 ULP) [5]	min
subPixelInterpolationOffsetBits	0	4 [5]	min
maxFramebufferWidth	-	4096	min
maxFramebufferHeight	-	4096	min
maxFramebufferLayers	-	256	min
framebufferColorSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
framebufferDepthSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
framebufferStencilSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
framebufferNoAttachmentsSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
maxColorAttachments	-	4	min

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
sampledImageColorSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
sampledImageIntegerSampleCounts	-	VK_SAMPLE_COUNT_1_BIT	min
sampledImageDepthSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
sampledImageStencilSampleCounts	-	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
storageImageSampleCounts	VK_SAMPLE_COUNT_1_BIT	(VK_SAMPLE_COUNT_1_BIT | VK_SAMPLE_COUNT_4_BIT)	min
maxSampleMaskWords	-	1	min
timestampComputeAndGraphics	-	-	implementation dependent
timestampPeriod	-	-	duration
maxClipDistances	0	8	min
maxCullDistances	0	8	min
maxCombinedClipAndCullDistances	0	8	min
discreteQueuePriorities	-	2	min
pointSizeRange	(1.0,1.0)	(1.0,64.0 - ULP)[6]	(max,min)
lineWidthRange	(1.0,1.0)	(1.0,8.0 - ULP)[7]	(max,min)
pointSizeGranularity	0.0	1.0 [6]	max, fixed point increment
lineWidthGranularity	0.0	1.0 [7]	max, fixed point increment
strictLines	-	-	implementation dependent
standardSampleLocations	-	-	implementation dependent
optimalBufferCopyOffsetAlignment	-	-	recommendation
optimalBufferCopyRowPitchAlignment	-	-	recommendation
nonCoherentAtomSize	-	256	max

1

The **Limit Type** column indicates the limit is either the minimum limit all implementations **must** support or the maximum limit 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: [minInterpolationOffset, 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].

7

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].

8

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).

30.3. Formats

The features for the set of formats (VkFormat) supported by the implementation are queried individually using the vkGetPhysicalDeviceFormatProperties command.

30.3.1. Format Definition

Image formats which **can** be passed to, and **may** be returned from Vulkan commands, are:

```
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_B8G8R8A8_UNORM = 44,
```

```
    VK_FORMAT_B8G8R8A8_SNORM = 45,
    VK_FORMAT_B8G8R8A8_USCALED = 46,
    VK_FORMAT_B8G8R8A8_SSCALED = 47,
    VK_FORMAT_B8G8R8A8_UINT = 48,
    VK_FORMAT_B8G8R8A8_SINT = 49,
    VK_FORMAT_B8G8R8A8_SRGB = 50,
    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_SSCALED_PACK32 = 61,
    VK_FORMAT_A2R10G10B10_UINT_PACK32 = 62,
    VK_FORMAT_A2R10G10B10_SINT_PACK32 = 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,
    VK_FORMAT_R16_UNORM = 70,
    VK_FORMAT_R16_SNORM = 71,
    VK_FORMAT_R16_USCALED = 72,
    VK_FORMAT_R16_SSCALED = 73,
    VK_FORMAT_R16_UINT = 74,
    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,
    VK_FORMAT_R16G16_SFLOAT = 83,
    VK_FORMAT_R16G16B16_UNORM = 84,
    VK_FORMAT_R16G16B16_SNORM = 85,
    VK_FORMAT_R16G16B16_USCALED = 86,
    VK_FORMAT_R16G16B16_SSCALED = 87,
    VK_FORMAT_R16G16B16_UINT = 88,
    VK_FORMAT_R16G16B16_SINT = 89,
    VK_FORMAT_R16G16B16_SFLOAT = 90,
    VK_FORMAT_R16G16B16A16_UNORM = 91,
    VK_FORMAT_R16G16B16A16_SNORM = 92,
    VK_FORMAT_R16G16B16A16_USCALED = 93,
    VK_FORMAT_R16G16B16A16_SSCALED = 94,
    VK_FORMAT_R16G16B16A16_UINT = 95,
```

```
    VK_FORMAT_R16G16B16A16_SINT = 96,
    VK_FORMAT_R16G16B16A16_SFLOAT = 97,
    VK_FORMAT_R32_UINT = 98,
    VK_FORMAT_R32_SINT = 99,
    VK_FORMAT_R32_SFLOAT = 100,
    VK_FORMAT_R32G32_UINT = 101,
    VK_FORMAT_R32G32_SINT = 102,
    VK_FORMAT_R32G32_SFLOAT = 103,
    VK_FORMAT_R32G32B32_UINT = 104,
    VK_FORMAT_R32G32B32_SINT = 105,
    VK_FORMAT_R32G32B32_SFLOAT = 106,
    VK_FORMAT_R32G32B32A32_UINT = 107,
    VK_FORMAT_R32G32B32A32_SINT = 108,
    VK_FORMAT_R32G32B32A32_SFLOAT = 109,
    VK_FORMAT_R64_UINT = 110,
    VK_FORMAT_R64_SINT = 111,
    VK_FORMAT_R64_SFLOAT = 112,
    VK_FORMAT_R64G64_UINT = 113,
    VK_FORMAT_R64G64_SINT = 114,
    VK_FORMAT_R64G64_SFLOAT = 115,
    VK_FORMAT_R64G64B64_UINT = 116,
    VK_FORMAT_R64G64B64_SINT = 117,
    VK_FORMAT_R64G64B64_SFLOAT = 118,
    VK_FORMAT_R64G64B64A64_UINT = 119,
    VK_FORMAT_R64G64B64A64_SINT = 120,
    VK_FORMAT_R64G64B64A64_SFLOAT = 121,
    VK_FORMAT_B10G11R11_UFLOAT_PACK32 = 122,
    VK_FORMAT_E5B9G9R9_UFLOAT_PACK32 = 123,
    VK_FORMAT_D16_UNORM = 124,
    VK_FORMAT_X8_D24_UNORM_PACK32 = 125,
    VK_FORMAT_D32_SFLOAT = 126,
    VK_FORMAT_S8_UINT = 127,
    VK_FORMAT_D16_UNORM_S8_UINT = 128,
    VK_FORMAT_D24_UNORM_S8_UINT = 129,
    VK_FORMAT_D32_SFLOAT_S8_UINT = 130,
    VK_FORMAT_BC1_RGB_UNORM_BLOCK = 131,
    VK_FORMAT_BC1_RGB_SRGB_BLOCK = 132,
    VK_FORMAT_BC1_RGBA_UNORM_BLOCK = 133,
    VK_FORMAT_BC1_RGBA_SRGB_BLOCK = 134,
    VK_FORMAT_BC2_UNORM_BLOCK = 135,
    VK_FORMAT_BC2_SRGB_BLOCK = 136,
    VK_FORMAT_BC3_UNORM_BLOCK = 137,
    VK_FORMAT_BC3_SRGB_BLOCK = 138,
    VK_FORMAT_BC4_UNORM_BLOCK = 139,
    VK_FORMAT_BC4_SNORM_BLOCK = 140,
    VK_FORMAT_BC5_UNORM_BLOCK = 141,
    VK_FORMAT_BC5_SNORM_BLOCK = 142,
    VK_FORMAT_BC6H_UFLOAT_BLOCK = 143,
    VK_FORMAT_BC6H_SFLOAT_BLOCK = 144,
    VK_FORMAT_BC7_UNORM_BLOCK = 145,
    VK_FORMAT_BC7_SRGB_BLOCK = 146,
```

```
    VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK = 147,
    VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK = 148,
    VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK = 149,
    VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK = 150,
    VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK = 151,
    VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK = 152,
    VK_FORMAT_EAC_R11_UNORM_BLOCK = 153,
    VK_FORMAT_EAC_R11_SNORM_BLOCK = 154,
    VK_FORMAT_EAC_R11G11_UNORM_BLOCK = 155,
    VK_FORMAT_EAC_R11G11_SNORM_BLOCK = 156,
    VK_FORMAT_ASTC_4x4_UNORM_BLOCK = 157,
    VK_FORMAT_ASTC_4x4_SRGB_BLOCK = 158,
    VK_FORMAT_ASTC_5x4_UNORM_BLOCK = 159,
    VK_FORMAT_ASTC_5x4_SRGB_BLOCK = 160,
    VK_FORMAT_ASTC_5x5_UNORM_BLOCK = 161,
    VK_FORMAT_ASTC_5x5_SRGB_BLOCK = 162,
    VK_FORMAT_ASTC_6x5_UNORM_BLOCK = 163,
    VK_FORMAT_ASTC_6x5_SRGB_BLOCK = 164,
    VK_FORMAT_ASTC_6x6_UNORM_BLOCK = 165,
    VK_FORMAT_ASTC_6x6_SRGB_BLOCK = 166,
    VK_FORMAT_ASTC_8x5_UNORM_BLOCK = 167,
    VK_FORMAT_ASTC_8x5_SRGB_BLOCK = 168,
    VK_FORMAT_ASTC_8x6_UNORM_BLOCK = 169,
    VK_FORMAT_ASTC_8x6_SRGB_BLOCK = 170,
    VK_FORMAT_ASTC_8x8_UNORM_BLOCK = 171,
    VK_FORMAT_ASTC_8x8_SRGB_BLOCK = 172,
    VK_FORMAT_ASTC_10x5_UNORM_BLOCK = 173,
    VK_FORMAT_ASTC_10x5_SRGB_BLOCK = 174,
    VK_FORMAT_ASTC_10x6_UNORM_BLOCK = 175,
    VK_FORMAT_ASTC_10x6_SRGB_BLOCK = 176,
    VK_FORMAT_ASTC_10x8_UNORM_BLOCK = 177,
    VK_FORMAT_ASTC_10x8_SRGB_BLOCK = 178,
    VK_FORMAT_ASTC_10x10_UNORM_BLOCK = 179,
    VK_FORMAT_ASTC_10x10_SRGB_BLOCK = 180,
    VK_FORMAT_ASTC_12x10_UNORM_BLOCK = 181,
    VK_FORMAT_ASTC_12x10_SRGB_BLOCK = 182,
    VK_FORMAT_ASTC_12x12_UNORM_BLOCK = 183,
    VK_FORMAT_ASTC_12x12_SRGB_BLOCK = 184,
} VkFormat;
```

- `VK_FORMAT_UNDEFINED` indicates 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_R5G6B5_UNORM_PACK16 specifies a three-component, 16-bit packed unsigned normalized format that has a 5-bit R component in bits 11..15, a 6-bit G component in bits 5..10, and a 5-bit B component in bits 0..4.
- VK_FORMAT_B5G6R5_UNORM_PACK16 specifies a three-component, 16-bit packed unsigned normalized format that has a 5-bit B component in bits 11..15, a 6-bit G component in bits 5..10, and a 5-bit R component in bits 0..4.
- 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_SRGB 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.
- 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_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.
- `VK_FORMAT_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

- VK_FORMAT_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.
- VK_FORMAT_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.
- VK_FORMAT_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.
- VK_FORMAT_A2B10G10R10_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 B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R 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 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_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, 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 4×4 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 4×4 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_BC4_UNORM_BLOCK specifies a one-component, block-compressed format where each 64-bit compressed texel block encodes a 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.
- VK_FORMAT_ETC2_R8G8B8A8_UNORM_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.
- 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_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_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_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_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_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_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_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 with sRGB nonlinear encoding applied to the RGB components.

* 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_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_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_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_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.
* 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_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.

Packed Formats

For the purposes of address alignment when accessing buffer memory containing vertex attribute or texel data, the following formats are considered *packed* - whole texels or attributes are stored in a single data element, rather than individual components occupying a single data element:

* 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_UNORM_PACK16
  - VK_FORMAT_R5G5B5A1_UNORM_PACK16
  - VK_FORMAT_B5G5R5A1_UNORM_PACK16
  - VK_FORMAT_A1R5G5B5_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_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_A2B10G10R10_UNORM_PACK32
  - VK_FORMAT_A2B10G10R10_SNORM_PACK32
  - VK_FORMAT_A2B10G10R10_USCALED_PACK32
  - VK_FORMAT_A2B10G10R10_SSCALED_PACK32
  - VK_FORMAT_A2B10G10R10_UINT_PACK32
  - VK_FORMAT_A2B10G10R10_SINT_PACK32
  - VK_FORMAT_B10G11R11_UFLOAT_PACK32
  - VK_FORMAT_E5B9G9R9_UFLOAT_PACK32
  - VK_FORMAT_X8_D24_UNORM_PACK32

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 specifies 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 33. Interpretation of Numeric Format

Numeric format	Description
UNORM	The components are unsigned normalized values in the range [0,1]
SNORM	The components are signed normalized values in the range [-1,1]
USCALED	The components are unsigned integer values that get converted to floating-point in the range $[0,2^n-1]$
SSCALED	The components are signed integer values that get converted to floating-point in the range $[-2^{n-1},2^{n-1}-1]$
UINT	The components are unsigned integer values in the range $[0,2^n-1]$
SINT	The components are signed integer values in the range $[-2^{n-1},2^{n-1}-1]$
UFLOAT	The components are unsigned floating-point numbers (used by packed, shared exponent, and some compressed formats)
SFLOAT	The components are signed floating-point numbers
SRGB	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

The suffix _PACKnn indicates that the format is 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 34. Interpretation of Compression Scheme

Compression scheme	Description
BC	Block Compression. See Block-Compressed Image Formats.
ETC2	Ericsson Texture Compression. See ETC Compressed Image Formats.
EAC	ETC2 Alpha Compression. See ETC Compressed Image Formats.
ASTC	Adaptive Scalable Texture Compression (LDR Profile). See ASTC Compressed Image Formats.

Representation

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 an *element size*, the number of bytes used to stored one element or one compressed block, with the value of the element size listed in VkFormat.

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 35. Byte mappings for non-packed/compressed color formats

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	← Byte
R																VK_FORMAT_R8_*
R	G															VK_FORMAT_R8G8_*
R	G	B														VK_FORMAT_R8G8B8_*
B	G	R														VK_FORMAT_B8G8R8_*
R	G	B	A													VK_FORMAT_R8G8B8A8_*
B	G	R	A													VK_FORMAT_B8G8R8A8_*
R																VK_FORMAT_R16_*
R		G														VK_FORMAT_R16G16_*
R		G		B												VK_FORMAT_R16G16B16_*
R		G		B		A										VK_FORMAT_R16G16B16A16_*
R																VK_FORMAT_R32_*
R				G												VK_FORMAT_R32G32_*
R				G				B								VK_FORMAT_R32G32B32_*
R				G				B				A				VK_FORMAT_R32G32B32A32_*
R																VK_FORMAT_R64_*
R								G								VK_FORMAT_R64G64_*
VK_FORMAT_R64G64B64_* **as** VK_FORMAT_R64G64_* **but with B in bytes 16-23**																
VK_FORMAT_R64G64B64A64_* **as** VK_FORMAT_R64G64B64_* **but with A in bytes 24-31**																

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 36. Bit mappings for packed 8-bit formats

Bit							
7	6	5	4	3	2	1	0
VK_FORMAT_R4G4_UNORM_PACK8							
R				**G**			
3	2	1	0	3	2	1	0

Table 37. Bit mappings for packed 16-bit formats

Bit															
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
VK_FORMAT_R4G4B4A4_UNORM_PACK16															
R				**G**				**B**				**A**			
3	2	1	0	3	2	1	0	3	2	1	0	3	2	1	0
VK_FORMAT_B4G4R4A4_UNORM_PACK16															
B				**G**				**R**				**A**			

Bit															
3	2	1	0	3	2	1	0	3	2	1	0	3	2	1	0
VK_FORMAT_R5G6B5_UNORM_PACK16															
R					G						B				
4	3	2	1	0	5	4	3	2	1	0	4	3	2	1	0
VK_FORMAT_B5G6R5_UNORM_PACK16															
B					G						R				
4	3	2	1	0	5	4	3	2	1	0	4	3	2	1	0
VK_FORMAT_R5G5B5A1_UNORM_PACK16															
R					G					B					A
4	3	2	1	0	4	3	2	1	0	4	3	2	1	0	0
VK_FORMAT_B5G5R5A1_UNORM_PACK16															
B					G					R					A
4	3	2	1	0	4	3	2	1	0	4	3	2	1	0	0
VK_FORMAT_A1R5G5B5_UNORM_PACK16															
A	R					G					B				
0	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0

Table 38. Bit mappings for packed 32-bit formats

Bit																															
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
VK_FORMAT_A8B8G8R8_*_PACK32																															
A								B								G								R							
7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
VK_FORMAT_A2R10G10B10_*_PACK32																															
A		R										G										B									
1	0	9	8	7	6	5	4	3	2	1	0	9	8	7	6	5	4	3	2	1	0	9	8	7	6	5	4	3	2	1	0
VK_FORMAT_A2B10G10R10_*_PACK32																															
A		B										G										R									
1	0	9	8	7	6	5	4	3	2	1	0	9	8	7	6	5	4	3	2	1	0	9	8	7	6	5	4	3	2	1	0
VK_FORMAT_B10G11R11_UFLOAT_PACK32																															
B										G											R										
9	8	7	6	5	4	3	2	1	0	10	9	8	7	6	5	4	3	2	1	0	10	9	8	7	6	5	4	3	2	1	0
VK_FORMAT_E5B9G9R9_UFLOAT_PACK32																															
E					B									G									R								
4	3	2	1	0	8	7	6	5	4	3	2	1	0	8	7	6	5	4	3	2	1	0	8	7	6	5	4	3	2	1	0
VK_FORMAT_X8_D24_UNORM_PACK32																															
X								D																							
7	6	5	4	3	2	1	0	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

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 that described in the format (e.g. D16 **must** not be implemented as D24 or D32).

Format Compatibility Classes

Uncompressed color formats are *compatible* with each other if they occupy the same number of bits per data element. Compressed color formats are compatible with each other if the only difference between them is the numerical type of the uncompressed pixels (e.g. signed vs. unsigned, or SRGB vs. UNORM encoding). Each depth/stencil format is only compatible with itself. In the following table, all the formats in the same row are compatible.

Table 39. Compatible formats

Class	Formats
8-bit	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
16-bit	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

Class	Formats
24-bit	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

Class	Formats
32-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, 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_A2B10G10R10_UNORM_PACK32, VK_FORMAT_A2B10G10R10_SNORM_PACK32, VK_FORMAT_A2B10G10R10_USCALED_PACK32, VK_FORMAT_A2B10G10R10_SSCALED_PACK32, VK_FORMAT_A2B10G10R10_UINT_PACK32, VK_FORMAT_A2B10G10R10_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

Class	Formats
48-bit	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
64-bit	VK_FORMAT_R16G16B16A16_UNORM, VK_FORMAT_R16G16B16A16_SNORM, VK_FORMAT_R16G16B16A16_USCALED, VK_FORMAT_R16G16B16A16_SSCALED, VK_FORMAT_R16G16B16A16_UINT, VK_FORMAT_R16G16B16A16_SINT, VK_FORMAT_R16G16B16A16_SFLOAT, VK_FORMAT_R32G32_UINT, VK_FORMAT_R32G32_SINT, VK_FORMAT_R32G32_SFLOAT, VK_FORMAT_R64_UINT, VK_FORMAT_R64_SINT, VK_FORMAT_R64_SFLOAT
96-bit	VK_FORMAT_R32G32B32_UINT, VK_FORMAT_R32G32B32_SINT, VK_FORMAT_R32G32B32_SFLOAT
128-bit	VK_FORMAT_R32G32B32A32_UINT, VK_FORMAT_R32G32B32A32_SINT, VK_FORMAT_R32G32B32A32_SFLOAT, VK_FORMAT_R64G64_UINT, VK_FORMAT_R64G64_SINT, VK_FORMAT_R64G64_SFLOAT
192-bit	VK_FORMAT_R64G64B64_UINT, VK_FORMAT_R64G64B64_SINT, VK_FORMAT_R64G64B64_SFLOAT
256-bit	VK_FORMAT_R64G64B64A64_UINT, VK_FORMAT_R64G64B64A64_SINT, VK_FORMAT_R64G64B64A64_SFLOAT
BC1_RGB	VK_FORMAT_BC1_RGB_UNORM_BLOCK, VK_FORMAT_BC1_RGB_SRGB_BLOCK
BC1_RGBA	VK_FORMAT_BC1_RGBA_UNORM_BLOCK, VK_FORMAT_BC1_RGBA_SRGB_BLOCK
BC2	VK_FORMAT_BC2_UNORM_BLOCK, VK_FORMAT_BC2_SRGB_BLOCK
BC3	VK_FORMAT_BC3_UNORM_BLOCK, VK_FORMAT_BC3_SRGB_BLOCK
BC4	VK_FORMAT_BC4_UNORM_BLOCK, VK_FORMAT_BC4_SNORM_BLOCK

Class	Formats
BC5	VK_FORMAT_BC5_UNORM_BLOCK, VK_FORMAT_BC5_SNORM_BLOCK
BC6H	VK_FORMAT_BC6H_UFLOAT_BLOCK, VK_FORMAT_BC6H_SFLOAT_BLOCK
BC7	VK_FORMAT_BC7_UNORM_BLOCK, VK_FORMAT_BC7_SRGB_BLOCK
ETC2_RGB	VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK
ETC2_RGBA	VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK
ETC2_EAC_RGBA	VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK
EAC_R	VK_FORMAT_EAC_R11_UNORM_BLOCK, VK_FORMAT_EAC_R11_SNORM_BLOCK
EAC_RG	VK_FORMAT_EAC_R11G11_UNORM_BLOCK, VK_FORMAT_EAC_R11G11_SNORM_BLOCK
ASTC_4x4	VK_FORMAT_ASTC_4x4_UNORM_BLOCK, VK_FORMAT_ASTC_4x4_SRGB_BLOCK
ASTC_5x4	VK_FORMAT_ASTC_5x4_UNORM_BLOCK, VK_FORMAT_ASTC_5x4_SRGB_BLOCK
ASTC_5x5	VK_FORMAT_ASTC_5x5_UNORM_BLOCK, VK_FORMAT_ASTC_5x5_SRGB_BLOCK
ASTC_6x5	VK_FORMAT_ASTC_6x5_UNORM_BLOCK, VK_FORMAT_ASTC_6x5_SRGB_BLOCK
ASTC_6x6	VK_FORMAT_ASTC_6x6_UNORM_BLOCK, VK_FORMAT_ASTC_6x6_SRGB_BLOCK
ASTC_8x5	VK_FORMAT_ASTC_8x5_UNORM_BLOCK, VK_FORMAT_ASTC_8x5_SRGB_BLOCK
ASTC_8x6	VK_FORMAT_ASTC_8x6_UNORM_BLOCK, VK_FORMAT_ASTC_8x6_SRGB_BLOCK
ASTC_8x8	VK_FORMAT_ASTC_8x8_UNORM_BLOCK, VK_FORMAT_ASTC_8x8_SRGB_BLOCK
ASTC_10x5	VK_FORMAT_ASTC_10x5_UNORM_BLOCK, VK_FORMAT_ASTC_10x5_SRGB_BLOCK
ASTC_10x6	VK_FORMAT_ASTC_10x6_UNORM_BLOCK, VK_FORMAT_ASTC_10x6_SRGB_BLOCK
ASTC_10x8	VK_FORMAT_ASTC_10x8_UNORM_BLOCK, VK_FORMAT_ASTC_10x8_SRGB_BLOCK
ASTC_10x10	VK_FORMAT_ASTC_10x10_UNORM_BLOCK, VK_FORMAT_ASTC_10x10_SRGB_BLOCK
ASTC_12x10	VK_FORMAT_ASTC_12x10_UNORM_BLOCK, VK_FORMAT_ASTC_12x10_SRGB_BLOCK

Class	Formats
ASTC_12x12	VK_FORMAT_ASTC_12x12_UNORM_BLOCK, VK_FORMAT_ASTC_12x12_SRGB_BLOCK
D16	VK_FORMAT_D16_UNORM
D24	VK_FORMAT_X8_D24_UNORM_PACK32
D32	VK_FORMAT_D32_SFLOAT
S8	VK_FORMAT_S8_UINT
D16S8	VK_FORMAT_D16_UNORM_S8_UINT
D24S8	VK_FORMAT_D24_UNORM_S8_UINT
D32S8	VK_FORMAT_D32_SFLOAT_S8_UINT

30.3.2. Format Properties

To query supported format features which are properties of the physical device, call:

```
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)

- physicalDevice **must** be a valid VkPhysicalDevice handle
- format **must** be a valid VkFormat value
- pFormatProperties **must** be a valid pointer to a VkFormatProperties structure

The VkFormatProperties structure is defined as:

```
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, then the only possible use would be image transfers - which alone are not useful. As such, 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-compression format, then buffers **must** not support any features for the format.

Bits which **can** be set in the VkFormatProperties features linearTilingFeatures, optimalTilingFeatures, and bufferFeatures are:

```
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,
} VkFormatFeatureFlagBits;
```

The following bits **may** be set in linearTilingFeatures and optimalTilingFeatures, specifying that the features are supported by images or image views 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 images.
- 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 and as an input attachment.
- 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 vkCmdBlitImage command.
- VK_FORMAT_FEATURE_BLIT_DST_BIT specifies that an image **can** be used as dstImage for the vkCmdBlitImage command.
- 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 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 indicates 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. If this bit is not present, linear filtering with depth compare disabled is unsupported and linear filtering with depth compare enabled is supported, but **may** compute the filtered value 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.

The following bits **may** be set in bufferFeatures, specifying that the features are supported by buffers or buffer views created with the queried vkGetPhysicalDeviceProperties::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).

```
typedef VkFlags VkFormatFeatureFlags;
```

VkFormatFeatureFlags is a bitmask type for setting a mask of zero or more VkFormatFeatureFlagBits.

30.3.3. 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.

The following tables show which feature bits **must** be supported for each format.

Table 40. Key for format feature tables

✓	This feature **must** be supported on the named format
†	This feature **must** be supported on at least some of the named formats, with more information in the table where the symbol appears

Table 41. Feature bits in `optimalTilingFeatures`

`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`

Table 42. 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 43. Mandatory format support: sub-byte channels

Format	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_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
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
VK_FORMAT_UNDEFINED													
VK_FORMAT_R4G4_UNORM_PACK8													
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	✓	✓	✓			✓	✓	✓					

Table 44. Mandatory format support: 1-3 byte-sized channels

Format	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_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
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													
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_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													

Table 45. Mandatory format support: 4 byte-sized channels

Format	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_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
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	✓	✓	✓			✓	✓	✓					

Table 46. Mandatory format support: 10-bit channels

Format	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_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
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_A2B10G10R10_UNORM_PACK32	✓	✓	✓			✓	✓	✓		✓	✓		
VK_FORMAT_A2B10G10R10_SNORM_PACK32													
VK_FORMAT_A2B10G10R10_USCALED_PACK32													
VK_FORMAT_A2B10G10R10_SSCALED_PACK32													
VK_FORMAT_A2B10G10R10_UINT_PACK32	✓	✓				✓	✓				✓		
VK_FORMAT_A2B10G10R10_SINT_PACK32													

Table 47. Mandatory format support: 16-bit channels

Format	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_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
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	✓	✓	✓			✓	✓	✓		✓	✓		
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_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													
VK_FORMAT_R16G16B16A16_UNORM										✓			
VK_FORMAT_R16G16B16A16_SNORM										✓			
VK_FORMAT_R16G16B16A16_USCALED													
VK_FORMAT_R16G16B16A16_SSCALED													
VK_FORMAT_R16G16B16A16_UINT	✓	✓		✓		✓	✓			✓	✓	✓	
VK_FORMAT_R16G16B16A16_SINT	✓	✓		✓		✓	✓			✓	✓	✓	
VK_FORMAT_R16G16B16A16_SFLOAT	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	

Table 48. Mandatory format support: 32-bit channels

Format	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_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
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_R32G32B32_UINT										✓			
VK_FORMAT_R32G32B32_SINT										✓			
VK_FORMAT_R32G32B32_SFLOAT										✓			
VK_FORMAT_R32G32B32A32_UINT	✓	✓		✓		✓	✓			✓	✓	✓	
VK_FORMAT_R32G32B32A32_SINT	✓	✓		✓		✓	✓			✓	✓	✓	
VK_FORMAT_R32G32B32A32_SFLOAT	✓	✓		✓		✓	✓			✓	✓	✓	

Table 49. Mandatory format support: 64-bit/uneven channels

Format	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_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
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
VK_FORMAT_R64_UINT													
VK_FORMAT_R64_SINT													
VK_FORMAT_R64_SFLOAT													
VK_FORMAT_R64G64_UINT													
VK_FORMAT_R64G64_SINT													
VK_FORMAT_R64G64_SFLOAT													
VK_FORMAT_R64G64B64_UINT													
VK_FORMAT_R64G64B64_SINT													
VK_FORMAT_R64G64B64_SFLOAT													
VK_FORMAT_R64G64B64A64_UINT													
VK_FORMAT_R64G64B64A64_SINT													
VK_FORMAT_R64G64B64A64_SFLOAT													
VK_FORMAT_B10G11R11_UFLOAT_PACK32	✓	✓	✓							✓			
VK_FORMAT_E5B9G9R9_UFLOAT_PACK32	✓	✓	✓										

Table 50. Mandatory format support: depth/stencil with VkImageType VK_IMAGE_TYPE_2D

VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT

Format	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_VERTEX_BUFFER_BIT	VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT	VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT	
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
VK_FORMAT_D16_UNORM	✓	✓							✓				
VK_FORMAT_X8_D24_UNORM_PACK32									†				
VK_FORMAT_D32_SFLOAT	✓	✓							†				
VK_FORMAT_S8_UINT													
VK_FORMAT_D16_UNORM_S8_UINT													
VK_FORMAT_D24_UNORM_S8_UINT									†				
VK_FORMAT_D32_SFLOAT_S8_UINT									†				

VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT 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 51. Mandatory format support: BC compressed formats with VkImageType VK_IMAGE_TYPE_2D and VK_IMAGE_TYPE_3D

Format	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_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
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	†	†	†										
VK_FORMAT_BC6H_UFLOAT_BLOCK	†	†	†										
VK_FORMAT_BC6H_SFLOAT_BLOCK	†	†	†										
VK_FORMAT_BC7_UNORM_BLOCK	†	†	†										
VK_FORMAT_BC7_SRGB_BLOCK	†	†	†										

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: ETC2 and EAC compressed formats with VkImageType VK_IMAGE_TYPE_2D, or Mandatory format support: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D.

Table 52. Mandatory format support: ETC2 and EAC compressed formats with VkImageType VK_IMAGE_TYPE_2D

Format	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_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
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	†	†	†										

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: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D.

Table 53. Mandatory format support: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D

Format	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_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
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
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_10x5_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x5_SRGB_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x6_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x6_SRGB_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x8_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x8_SRGB_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x10_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_10x10_SRGB_BLOCK	†	†	†										

VK_FORMAT_ASTC_12x10_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_12x10_SRGB_BLOCK	†	†	†										
VK_FORMAT_ASTC_12x12_UNORM_BLOCK	†	†	†										
VK_FORMAT_ASTC_12x12_SRGB_BLOCK	†	†	†										

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.

30.4. Additional Image Capabilities

In addition to the minimum capabilities described in the previous sections (Limits and Formats), implementations **may** support additional capabilities for certain types of images. For example, larger dimensions or additional sample counts for certain image types, or additional capabilities for *linear* tiling format images.

To query additional capabilities specific to image types, call:

```
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 points to an instance of the 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:

```
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** either be equal to 1 (valid only if tiling is VK_IMAGE_TILING_LINEAR) or be equal to ⌈$\log_2$(max(width, height, depth))⌉ + 1. width, height, and depth are taken from the corresponding members of maxExtent.
- maxArrayLayers is the maximum number of array layers. maxArrayLayers **must** either be equal to 1 or be greater than or equal to the maxImageArrayLayers member of VkPhysicalDeviceLimits. A value of 1 is valid only if tiling is VK_IMAGE_TILING_LINEAR or if type is VK_IMAGE_TYPE_3D.
- 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 or the image will be invalid. 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.

> *Note*
>
> Filling VkImageFormatProperties 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.

30.4.1. 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

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_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a depth aspect, a superset of VkPhysicalDeviceLimits::framebufferDepthSampleCounts
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a stencil aspect, a superset of VkPhysicalDeviceLimits::framebufferStencilSampleCounts
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a color aspect, a superset of VkPhysicalDeviceLimits::sampledImageColorSampleCounts
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a depth aspect, 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.

30.4.2. Allowed Extent Values Based On Image Type

Implementations **may** support extent values larger than the required minimum/maximum values for certain types of images 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`

Chapter 31. 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.

```
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,
} VkObjectType;
```

Table 54. VkObjectType and Vulkan Handle Relationship

VkObjectType	Vulkan Handle Type
VK_OBJECT_TYPE_UNKNOWN	Unknown/Undefined Handle
VK_OBJECT_TYPE_INSTANCE	VkInstance
VK_OBJECT_TYPE_PHYSICAL_DEVICE	VkPhysicalDevice
VK_OBJECT_TYPE_DEVICE	VkDevice
VK_OBJECT_TYPE_QUEUE	VkQueue
VK_OBJECT_TYPE_SEMAPHORE	VkSemaphore

VkObjectType	Vulkan Handle Type
VK_OBJECT_TYPE_COMMAND_BUFFER	VkCommandBuffer
VK_OBJECT_TYPE_FENCE	VkFence
VK_OBJECT_TYPE_DEVICE_MEMORY	VkDeviceMemory
VK_OBJECT_TYPE_BUFFER	VkBuffer
VK_OBJECT_TYPE_IMAGE	VkImage
VK_OBJECT_TYPE_EVENT	VkEvent
VK_OBJECT_TYPE_QUERY_POOL	VkQueryPool
VK_OBJECT_TYPE_BUFFER_VIEW	VkBufferView
VK_OBJECT_TYPE_IMAGE_VIEW	VkImageView
VK_OBJECT_TYPE_SHADER_MODULE	VkShaderModule
VK_OBJECT_TYPE_PIPELINE_CACHE	VkPipelineCache
VK_OBJECT_TYPE_PIPELINE_LAYOUT	VkPipelineLayout
VK_OBJECT_TYPE_RENDER_PASS	VkRenderPass
VK_OBJECT_TYPE_PIPELINE	VkPipeline
VK_OBJECT_TYPE_DESCRIPTOR_SET_LAYOUT	VkDescriptorSetLayout
VK_OBJECT_TYPE_SAMPLER	VkSampler
VK_OBJECT_TYPE_DESCRIPTOR_POOL	VkDescriptorPool
VK_OBJECT_TYPE_DESCRIPTOR_SET	VkDescriptorSet
VK_OBJECT_TYPE_FRAMEBUFFER	VkFramebuffer
VK_OBJECT_TYPE_COMMAND_POOL	VkCommandPool

If this Specification was generated with any such extensions included, they will be described in the remainder of this chapter.

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 1.0 implementation **must** support the 1.0 version 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

Implementations **must** support the following capability operands declared by `OpCapability`:

- `Matrix`
- `Shader`
- `InputAttachment`
- `Sampled1D`
- `Image1D`
- `SampledBuffer`
- `ImageBuffer`
- `ImageQuery`
- `DerivativeControl`

Implementations **may** support features that are not **required** by the Specification, as described in the Features chapter. If such a feature is supported, then any capability operand(s) corresponding to that feature **must** also be supported.

Table 55. SPIR-V Capabilities which are not **required***, and corresponding feature or extension names*

SPIR-V OpCapability	Vulkan feature or extension name
`Geometry`	geometryShader
`Tessellation`	tessellationShader
`Float64`	shaderFloat64
`Int64`	shaderInt64
`Int16`	shaderInt16
`TessellationPointSize`	shaderTessellationAndGeometryPointSize
`GeometryPointSize`	shaderTessellationAndGeometryPointSize
`ImageGatherExtended`	shaderImageGatherExtended

SPIR-V OpCapability	Vulkan feature or extension name
StorageImageMultisample	shaderStorageImageMultisample
UniformBufferArrayDynamicIndexing	shaderUniformBufferArrayDynamicIndexing
SampledImageArrayDynamicIndexing	shaderSampledImageArrayDynamicIndexing
StorageBufferArrayDynamicIndexing	shaderStorageBufferArrayDynamicIndexing
StorageImageArrayDynamicIndexing	shaderStorageImageArrayDynamicIndexing
ClipDistance	shaderClipDistance
CullDistance	shaderCullDistance
ImageCubeArray	imageCubeArray
SampleRateShading	sampleRateShading
SparseResidency	shaderResourceResidency
MinLod	shaderResourceMinLod
SampledCubeArray	imageCubeArray
ImageMSArray	shaderStorageImageMultisample
StorageImageExtendedFormats	shaderStorageImageExtendedFormats
InterpolationFunction	sampleRateShading
StorageImageReadWithoutFormat	shaderStorageImageReadWithoutFormat
StorageImageWriteWithoutFormat	shaderStorageImageWriteWithoutFormat
MultiViewport	multiViewport

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.

Validation Rules within a Module

A SPIR-V module passed to vkCreateShaderModule **must** conform to the following rules:

- Every entry point **must** have no return value and accept no arguments.
- Recursion: The static function-call graph for an entry point **must** not contain cycles.
- The **Logical** addressing model **must** be selected.
- **Scope** for execution **must** be limited to:
  - **Workgroup**
  - **Subgroup**
- **Scope** for memory **must** be limited to:
  - **Device**

◦ **Workgroup**
◦ **Invocation**

- **Storage Class must** be limited to:
  ◦ **UniformConstant**
  ◦ **Input**
  ◦ **Uniform**
  ◦ **Output**
  ◦ **Workgroup**
  ◦ **Private**
  ◦ **Function**
  ◦ **PushConstant**
  ◦ **Image**
- Memory semantics **must** obey the following rules:
  ◦ **Acquire must** not be used with `OpAtomicStore`.
  ◦ **Release must** not be used with `OpAtomicLoad`.
  ◦ **AcquireRelease must** not be used with `OpAtomicStore` or `OpAtomicLoad`.
  ◦ Sequentially consistent atomics and barriers are not supported and **SequentiallyConsistent** is treated as **AcquireRelease**. **SequentiallyConsistent should** not be used.
  ◦ `OpMemoryBarrier` **must** use one of **Acquire**, **Release**, **AcquireRelease**, or **SequentiallyConsistent** and **must** include at least one storage class.
  ◦ If the semantics for `OpControlBarrier` includes one of **Acquire**, **Release**, **AcquireRelease**, or **SequentiallyConsistent**, then it **must** include at least one storage class.
  ◦ **SubgroupMemory**, **CrossWorkgroupMemory**, and **AtomicCounterMemory** are ignored.
- Any `OpVariable` with an `Initializer` operand **must** have one of the following as its `Storage Class` operand:
  ◦ **Output**
  ◦ **Private**
  ◦ **Function**
- 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.
- Images
  ◦ `OpTypeImage` **must** declare a scalar 32-bit float 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.)
  ◦ `OpSampledImage` **must** only consume an “Image” operand whose type has its “Sampled”

operand set to 1.

  - 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.
  - The "Depth" operand of OpTypeImage is ignored.

- Decorations
  - The GLSLShared and GLSLPacked decorations **must** not be used.
  - The Flat, NoPerspective, Sample, and Centroid decorations **must** not be used on variables with storage class other than Input or on variables used in the interface of non-fragment shader entry points.
  - The Patch decoration **must** not be used on variables in the interface of a vertex, geometry, or fragment shader stage's entry point.
- OpTypeRuntimeArray **must** only be used for the last member of an OpTypeStruct that is in the Uniform storage class decorated as BufferBlock.
- Linkage: See Shader Interfaces for additional linking and validation rules.
- Compute Shaders
  - For each compute shader entry point, either a LocalSize execution mode or an object decorated with the WorkgroupSize decoration **must** be specified.
- Atomic instructions **must** declare a scalar 32-bit integer type for the "Result Type".

Precision and Operation of SPIR-V Instructions

The following rules apply to both 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.
- Any denormalized value input into a shader or potentially generated by any instruction in a shader **may** be flushed to 0.
- The rounding mode **cannot** be set and is undefined.
- NaNs **may** not be generated. Instructions that operate on a NaN **may** not result in a NaN.
- Support for signaling NaNs is **optional** and exceptions are never raised.

The precision of double-precision instructions is at least that of single precision. For single precision (32 bit) instructions, precisions are **required** to be at least as follows, unless decorated with RelaxedPrecision:

Table 56. Precision of core SPIR-V Instructions

Instruction	Precision
OpFAdd	Correctly rounded.
OpFSub	Correctly rounded.

Instruction	Precision
OpFMul	Correctly rounded.
OpFOrdEqual, OpFUnordEqual	Correct result.
OpFOrdLessThan, OpFUnordLessThan	Correct result.
OpFOrdGreaterThan, OpFUnordGreaterThan	Correct result.
OpFOrdLessThanEqual, OpFUnordLessThanEqual	Correct result.
OpFOrdGreaterThanEqual, OpFUnordGreaterThanEqual	Correct result.
OpFDiv	2.5 ULP for b in the range [2^{-126}, 2^{126}].
conversions between types	Correctly rounded.

Table 57. Precision of GLSL.std.450 Instructions

Instruction	Precision
fma()	Inherited from OpFMul followed by OpFAdd.
exp(x), exp2(x)	3 + 2 × |x| ULP.
log(), log2()	3 ULP outside the range [0.5, 2.0]. Absolute error < 2^{-21} inside the range [0.5, 2.0].
pow(x, y)	Inherited from exp2(y × log2(x)).
sqrt()	Inherited from 1.0 / inversesqrt().
inversesqrt()	2 ULP.

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. These include, for example, the trigonometric functions and determinant.

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.

Compatibility Between SPIR-V Image Formats And Vulkan Formats

Images which are read from or written to by shaders **must** have SPIR-V image formats compatible with the Vulkan image formats backing the image under the circumstances described for texture image validation. The compatibile formats are:

Table 58. SPIR-V and Vulkan Image Format Compatibility

SPIR-V Image Format	Compatible Vulkan Format
Rgba32f	VK_FORMAT_R32G32B32A32_SFLOAT
Rgba16f	VK_FORMAT_R16G16B16A16_SFLOAT
R32f	VK_FORMAT_R32_SFLOAT

SPIR-V Image Format	Compatible Vulkan Format
Rgba8	VK_FORMAT_R8G8B8A8_UNORM
Rgba8Snorm	VK_FORMAT_R8G8B8A8_SNORM
Rg32f	VK_FORMAT_R32G32_SFLOAT
Rg16f	VK_FORMAT_R16G16_SFLOAT
R11fG11fB10f	VK_FORMAT_B10G11R11_UFLOAT_PACK32
R16f	VK_FORMAT_R16_SFLOAT
Rgba16	VK_FORMAT_R16G16B16A16_UNORM
Rgb10A2	VK_FORMAT_A2B10G10R10_UNORM_PACK32
Rg16	VK_FORMAT_R16G16_UNORM
Rg8	VK_FORMAT_R8G8_UNORM
R16	VK_FORMAT_R16_UNORM
R8	VK_FORMAT_R8_UNORM
Rgba16Snorm	VK_FORMAT_R16G16B16A16_SNORM
Rg16Snorm	VK_FORMAT_R16G16_SNORM
Rg8Snorm	VK_FORMAT_R8G8_SNORM
R16Snorm	VK_FORMAT_R16_SNORM
R8Snorm	VK_FORMAT_R8_SNORM
Rgba32i	VK_FORMAT_R32G32B32A32_SINT
Rgba16i	VK_FORMAT_R16G16B16A16_SINT
Rgba8i	VK_FORMAT_R8G8B8A8_SINT
R32i	VK_FORMAT_R32_SINT
Rg32i	VK_FORMAT_R32G32_SINT
Rg16i	VK_FORMAT_R16G16_SINT
Rg8i	VK_FORMAT_R8G8_SINT
R16i	VK_FORMAT_R16_SINT
R8i	VK_FORMAT_R8_SINT
Rgba32ui	VK_FORMAT_R32G32B32A32_UINT
Rgba16ui	VK_FORMAT_R16G16B16A16_UINT
Rgba8ui	VK_FORMAT_R8G8B8A8_UINT
R32ui	VK_FORMAT_R32_UINT
Rgb10a2ui	VK_FORMAT_A2B10G10R10_UINT_PACK32
Rg32ui	VK_FORMAT_R32G32_UINT
Rg16ui	VK_FORMAT_R16G16_UINT
Rg8ui	VK_FORMAT_R8G8_UINT
R16ui	VK_FORMAT_R16_UINT
R8ui	VK_FORMAT_R8_UINT

Appendix B: Compressed Image Formats

The compressed texture formats used by Vulkan are described in the specifically identified sections of the Khronos Data Format Specification, version 1.1.

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

Table 59. Mapping of Vulkan BC formats to descriptions

VkFormat	Khronos Data Format Specification description
Formats described in the "S3TC Compressed Texture Image Formats" chapter	
VK_FORMAT_BC1_RGB_UNORM_BLOCK	BC1 with no alpha
VK_FORMAT_BC1_RGB_SRGB_BLOCK	BC1 with no alpha, sRGB-encoded
VK_FORMAT_BC1_RGBA_UNORM_BLOCK	BC1 with alpha
VK_FORMAT_BC1_RGBA_SRGB_BLOCK	BC1 with alpha, sRGB-encoded
VK_FORMAT_BC2_UNORM_BLOCK	BC2
VK_FORMAT_BC2_SRGB_BLOCK	BC2, sRGB-encoded
VK_FORMAT_BC3_UNORM_BLOCK	BC3
VK_FORMAT_BC3_SRGB_BLOCK	BC3, sRGB-encoded
Formats described in the "RGTC Compressed Texture Image Formats" chapter	
VK_FORMAT_BC4_UNORM_BLOCK	BC4 unsigned
VK_FORMAT_BC4_SNORM_BLOCK	BC4 signed
VK_FORMAT_BC5_UNORM_BLOCK	BC5 unsigned
VK_FORMAT_BC5_SNORM_BLOCK	BC5 signed
Formats described in the "BPTC Compressed Texture Image Formats" chapter	
VK_FORMAT_BC6H_UFLOAT_BLOCK	BC6H (unsigned version)
VK_FORMAT_BC6H_SFLOAT_BLOCK	BC6H (signed version)
VK_FORMAT_BC7_UNORM_BLOCK	BC7
VK_FORMAT_BC7_SRGB_BLOCK	BC7, sRGB-encoded

ETC Compressed Image Formats

The following formats are described in the “ETC2 Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

Table 60. Mapping of Vulkan ETC formats to descriptions

VkFormat	Khronos Data Format Specification description
VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK	RGB ETC2
VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK	RGB ETC2 with sRGB encoding
VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK	RGB ETC2 with punch-through alpha
VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK	RGB ETC2 with punch-through alpha and sRGB
VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK	RGBA ETC2
VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK	RGBA ETC2 with sRGB encoding
VK_FORMAT_EAC_R11_UNORM_BLOCK	Unsigned R11 EAC
VK_FORMAT_EAC_R11_SNORM_BLOCK	Signed R11 EAC
VK_FORMAT_EAC_R11G11_UNORM_BLOCK	Unsigned RG11 EAC
VK_FORMAT_EAC_R11G11_SNORM_BLOCK	Signed RG11 EAC

ASTC Compressed Image Formats

ASTC formats are described in the “ASTC Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

Table 61. Mapping of Vulkan ASTC formats to descriptions

VkFormat	Compressed texel block dimensions	sRGB-encoded
VK_FORMAT_ASTC_4x4_UNORM_BLOCK	4 × 4	No
VK_FORMAT_ASTC_4x4_SRGB_BLOCK	4 × 4	Yes
VK_FORMAT_ASTC_5x4_UNORM_BLOCK	5 × 4	No
VK_FORMAT_ASTC_5x4_SRGB_BLOCK	5 × 4	Yes
VK_FORMAT_ASTC_5x5_UNORM_BLOCK	5 × 5	No
VK_FORMAT_ASTC_5x5_SRGB_BLOCK	5 × 5	Yes
VK_FORMAT_ASTC_6x5_UNORM_BLOCK	6 × 5	No
VK_FORMAT_ASTC_6x5_SRGB_BLOCK	6 × 5	Yes
VK_FORMAT_ASTC_6x6_UNORM_BLOCK	6 × 6	No
VK_FORMAT_ASTC_6x6_SRGB_BLOCK	6 × 6	Yes
VK_FORMAT_ASTC_8x5_UNORM_BLOCK	8 × 5	No
VK_FORMAT_ASTC_8x5_SRGB_BLOCK	8 × 5	Yes
VK_FORMAT_ASTC_8x6_UNORM_BLOCK	8 × 6	No
VK_FORMAT_ASTC_8x6_SRGB_BLOCK	8 × 6	Yes
VK_FORMAT_ASTC_8x8_UNORM_BLOCK	8 × 8	No
VK_FORMAT_ASTC_8x8_SRGB_BLOCK	8 × 8	Yes
VK_FORMAT_ASTC_10x5_UNORM_BLOCK	10 × 5	No
VK_FORMAT_ASTC_10x5_SRGB_BLOCK	10 × 5	Yes
VK_FORMAT_ASTC_10x6_UNORM_BLOCK	10 × 6	No
VK_FORMAT_ASTC_10x6_SRGB_BLOCK	10 × 6	Yes
VK_FORMAT_ASTC_10x8_UNORM_BLOCK	10 × 8	No
VK_FORMAT_ASTC_10x8_SRGB_BLOCK	10 × 8	Yes
VK_FORMAT_ASTC_10x10_UNORM_BLOCK	10 × 10	No
VK_FORMAT_ASTC_10x10_SRGB_BLOCK	10 × 10	Yes
VK_FORMAT_ASTC_12x10_UNORM_BLOCK	12 × 10	No
VK_FORMAT_ASTC_12x10_SRGB_BLOCK	12 × 10	Yes
VK_FORMAT_ASTC_12x12_UNORM_BLOCK	12 × 12	No
VK_FORMAT_ASTC_12x12_SRGB_BLOCK	12 × 12	Yes

Appendix C: Layers & Extensions

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

http://www.khronos.org/registry/vulkan/

and allows generating versions of the Specification incorporating different extensions.

Most of the content previously in this appendix does not specify **use** of specific Vulkan extensions and layers, but rather specifies the processes by which extensions and layers are created. As of version 1.0.21 of the Vulkan Specification, this content has been migrated to the Vulkan Documentation and Extensions document. Authors creating extensions and layers **must** follow the mandatory procedures in that document.

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`, Khronos `KHX`, multivendor `EXT`, and then alphabetically by author ID. Within each group, extensions are listed in alphabetical order by their name.

> *Note*
>
> The `KHX` author ID indicates that an extension is experimental, and is being considered for standardization in future `KHR` or core Vulkan API versions. Developers are encouraged to experiment with them and provide feedback, but **should** not use them as the basis for production applications. `KHX` extensions are expected to be supported for a limited time only. They **may** change their interfaces and behavior in significant ways as a result of feedback, and **may** be withdrawn or replaced with stable `KHR` or core functionality at any time. Implementations of these extensions receive limited or no testing when submitted to the Khronos conformance process.
>
> Some vendors may use an alternate author ID ending in `X` for some of their extensions. The exact meaning of such an author ID is defined by each vendor, and may not be equivalent to `KHX`, but it is likely to indicate a lesser degree of interface stability than a non-`X` extension from the same vendor.

VK_KHR_sampler_mirror_clamp_to_edge

Name String

`VK_KHR_sampler_mirror_clamp_to_edge`

Extension Type

Device extension

Registered Extension Number

15

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0

Contact

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Last Modified Date

2016-02-16

Contributors

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`VK_KHR_sampler_mirror_clamp_to_edge` extends the set of sampler address modes to include an additional mode (`VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE`) that effectively uses a texture map twice as large as the original image in which the additional half of the new image is a mirror image of the original image.

This new mode relaxes the need to generate images whose opposite edges match by using the original image to generate a matching "mirror image". This mode allows the texture to be mirrored only once in the negative s, t, and r directions.

New Enum Constants

- Extending VkSamplerAddressMode:
  - `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE`

Example

Creating a sampler with the new address mode in each dimension

```
VkSamplerCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO // sType
    // Other members set to application-desired values
};

createInfo.addressModeU = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;
createInfo.addressModeV = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;
createInfo.addressModeW = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;

VkSampler sampler;
VkResult result = vkCreateSampler(
    device,
    &createInfo,
    &sampler);
```

Version History

- Revision 1, 2016-02-16 (Tobias Hector)
  - Initial draft

Appendix D: 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.

Macro Definitions in vulkan.h

The supplied vulkan.h header defines a small number of C preprocessor macros that are described below.

Vulkan Version Number Macros

API Version Numbers are packed into integers. These macros manipulate version numbers in useful ways.

`VK_VERSION_MAJOR` extracts the API major version number from a packed version number:

```
#define VK_VERSION_MAJOR(version) ((uint32_t)(version) >> 22)
```

`VK_VERSION_MINOR` extracts the API minor version number from a packed version number:

```
#define VK_VERSION_MINOR(version) (((uint32_t)(version) >> 12) & 0x3ff)
```

`VK_VERSION_PATCH` extracts the API patch version number from a packed version number:

```
#define VK_VERSION_PATCH(version) ((uint32_t)(version) & 0xfff)
```

`VK_API_VERSION_1_0` returns the API version number for Vulkan 1.0. The patch version number in this macro will always be zero. The supported patch version for a physical device **can** be queried with vkGetPhysicalDeviceProperties.

```
// Vulkan 1.0 version number
#define VK_API_VERSION_1_0 VK_MAKE_VERSION(1, 0, 0)// Patch version should always be
set to 0
```

`VK_API_VERSION` is now commented out of vulkan.h and **cannot** be used.

```
// 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_VERSION(1, 0, 0) // Patch version should always be
set to 0
```

`VK_MAKE_VERSION` constructs an API version number.

```
#define VK_MAKE_VERSION(major, minor, patch) \
    (((major) << 22) | ((minor) << 12) | (patch))
```

- `major` is the major version number.
- `minor` is the minor version number.
- `patch` is the patch version number.

This macro **can** be used when constructing the VkApplicationInfo::`apiVersion` parameter passed to vkCreateInstance.

Vulkan Header File Version Number

`VK_HEADER_VERSION` is the version number of the vulkan.h header. This value is currently kept synchronized with the release number of the Specification. However, it is not guaranteed to remain synchronized, since most Specification updates have no effect on vulkan.h.

```
// Version of this file
#define VK_HEADER_VERSION 69
```

Vulkan Handle Macros

`VK_DEFINE_HANDLE` defines a dispatchable handle type.

```
#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.

```
#if !defined(VK_DEFINE_NON_DISPATCHABLE_HANDLE)
#if defined(__LP64__) || defined(_WIN64) || (defined(__x86_64__) && !defined(
__ILP32__) ) || defined(_M_X64) || defined(__ia64) || defined (_M_IA64) || defined
(__aarch64__) || defined(__powerpc64__)
        #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.h header allows the VK_DEFINE_NON_DISPATCHABLE_HANDLE definition to be overridden by the application. If VK_DEFINE_NON_DISPATCHABLE_HANDLE is already defined when the vulkan.h header is compiled the default definition is 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. Behavior is undefined if the application defines a non-binary-compatible handle and **may** result in memory corruption or application termination. Binary compatibility is platform dependent so the application **must** be careful if it overrides the default VK_DEFINE_NON_DISPATCHABLE_HANDLE definition.

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.

```
#define VK_NULL_HANDLE 0
```

Platform-Specific Macro Definitions in vk_platform.h

Additional platform-specific macros and interfaces are defined using the included vk_platform.h file. 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:

```
VKAPI_ATTR <return_type> VKAPI_CALL <command_name>(<command_parameters>);
```

Additionaly, a Vulkan function pointer type declaration takes the form of:

```
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 vulkan.h, such as uint8_t, **must** also be defined by the application. Otherwise, vulkan.h will not compile. If VK_NO_STDINT_H is not defined, the system <stdint.h> is used to define these types, or there is a fallback path when Microsoft Visual Studio version 2008 and earlier versions are detected at compile time.

Window System-Specific Header Control

To use a Vulkan extension supporting a platform-specific window system, header files for that window systems **must** be included at compile time. The Vulkan header files cannot determine whether or not an external header is available at compile time, so applications wishing to use such an extension **must** #define a macro causing such headers to be included. If this is not done, the corresponding extension interfaces will not be defined and they will be unusable.

The extensions, **required** compile time symbols to enable them, window systems they correspond to, and external header files that are included when the macro is #defined are shown in the following table.

Table 62. Window System Extensions and Required Compile Time Symbol Definitions

Extension Name	Required Compile Time Symbol	Window System Name	External Header Files Used
[VK_KHR_android_surface]	VK_USE_PLATFORM_ANDROID_KHR	Android Native	<android/native_window.h>
[VK_KHR_mir_surface]	VK_USE_PLATFORM_MIR_KHR	Mir	<mir_toolkit/client_types.h>
[VK_KHR_wayland_surface]	VK_USE_PLATFORM_WAYLAND_KHR	Wayland	<wayland-client.h>
[VK_KHR_win32_surface]	VK_USE_PLATFORM_WIN32_KHR	Microsoft Windows	<windows.h>
[VK_KHR_xcb_surface]	VK_USE_PLATFORM_XCB_KHR	X Window System Xcb library	<xcb/xcb.h>
[VK_KHR_xlib_surface]	VK_USE_PLATFORM_XLIB_KHR	X Window System Xlib library	<X11/Xlib.h>

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.

Appendix E: 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 spec 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, depends 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 n1 produced by processing the first patch, there **must** be a triangle n2 produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in n1.*

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 n1 produced by processing the first patch, there **must** be a triangle n2 produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in n1. 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* `TessCoord` *will be in the range [0, 1]. Additionally, for any defined component x of* `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.*

Glossary

The terms defined in this section are used consistently throughout this 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.

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.

API Order

A set of ordering rules that govern how primitives in draw commands affect the framebuffer.

Aspect (Image)

An image **may** contain multiple kinds, or 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 **may** be used as a framebuffer color attachment. Some operations, like depth testing, operate only on specific aspects of an image. Others operations, like image/buffer copies, only operate on one aspect at a time.

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.

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.

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 View

An object that represents a range of a specific buffer, and state that controls 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 that contains only variables decorated with built-in decorations, and is used to match against other shader stages.

Clip Coordinates

The homogeneous coordinate space that vertex positions (`Position` decoration) are written in by vertex processing stages.

Clip Distance

A built-in output from vertex processing stages that defines 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 the `optimalTilingFeatures` or `linearTilingFeatures` field of VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties, depending on the tiling used.

Color Sample Mask

A bitfield associated with a fragment, with one bit for each sample in the color attachment(s). Samples are considered to be covered based on the result of the Coverage Reduction stage. Uncovered samples do not write to color attachments.

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.

Compatible Queues

Queues within a queue family. Compatible queues have identical properties.

Component (Format)

A distinct part of a format. Depth, stencil, and color channels (e.g. R, G, B, A), are all separate components.

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 that define the dimensions of these elements in units of texels, and a size in bytes of the encoding in memory.

Coverage

A bitfield associated with a fragment, where each bit is associated to a rasterization sample. Samples are initially considered to be covered based on the result of rasterization, and then coverage can subsequently be turned on or off by other fragment operations or the fragment shader. Uncovered samples do not write to framebuffer attachments.

Cull Distance

A built-in output from vertex processing stages that defines 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.

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.

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 that defines 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 Memory

Memory accessible to the device. Represented by a VkDeviceMemory object.

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.

Dispatchable Handle

A handle of a pointer handle type which **may** be used by layers as part of intercepting API commands. The first argument to each Vulkan command is a dispatchable handle type.

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, 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 Size

The size (in bytes) used to store one element of an uncompressed format or the size (in bytes) used to store one block of a block-compressed format.

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 complete 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.

Extension Scope

The set of objects and commands that **can** be affected by an extension. Extensions are either device scope or instance scope.

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 object.

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.

Fragment Input Attachment Interface

A fragment shader entry point's variables with `UniformConstant` storage class and a decoration of `InputAttachmentIndex`, 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.

Global Workgroup

A collection of local workgroups dispatched by a single dispatch 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

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

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 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.

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. CPU 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 and layer 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 that controls how the contents are interpreted. Represented by a VkImageView object.

Immutable Sampler

A sampler descriptor provided at descriptor set layout creation time, and that is used for that binding in all descriptor sets allocated from the layout, and cannot be changed.

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, and vkCmdDrawIndexedIndirect.

Indirect Commands

Drawing or dispatching commands that source some of their parameters from structures in buffer memory. Includes vkCmdDrawIndirect, vkCmdDrawIndexedIndirect, and vkCmdDispatchIndirect.

Indirect Drawing Commands

Drawing commands that source some of their parameters from structures in buffer memory. Includes vkCmdDrawIndirect, and vkCmdDrawIndexedIndirect.

Initial State (Command Buffer)

A command buffer that has not begun recording commands. See also Recorded State and Executable State.

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 Object

High-level Vulkan objects, which are not logical devices, nor children of logical devices. For example, VkInstance and VkPhysicalDevice objects are instance-level objects.

Internal Synchronization

A type of synchronization **required** of the implementation, where parameters not defined to be externally synchronized **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 **must** execute the same control flow path in order for control flow to be considered dynamically uniform.

Linear Resource

A resource is *linear* if it is a VkBuffer, or a VkImage created with `VK_IMAGE_TILING_LINEAR`. A resource is *non-linear* if it is a VkImage created with `VK_IMAGE_TILING_OPTIMAL`.

Local Workgroup

A collection of compute shader invocations invoked by a single dispatch command, which share shared memory 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 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 hardware 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 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.

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.

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, 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 to framebuffer coordinates.

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 data element in memory, with their relative locations defined within that element.

Physical Device

An object that represents a single device in the system. Represented by a VkPhysicalDevice object.

Pipeline

An object that controls 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 that defines 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.

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.

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 that controls how vertices are assembled into primitives, e.g. as lists of triangles, strips of lines, etc..

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.

Query Pool

An object that contains 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 which **must** be enabled to use a specific enabled extension (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.

Retired Swapchain

A swapchain that has been used as the `oldSwapchain` parameter to vkCreateSwapchainKHR. Images cannot be acquired from a retired swapchain, however images that were acquired (but not presented) before the swapchain was retired **can** be presented.

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 that contains state that controls 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.

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 that define 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. 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.

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, 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 Coordinate System

One of three coordinate systems (normalized, unnormalized, integer) that define how texel coordinates are interpreted in an image or a specific mipmap level of an image.

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.

Unnormalized

A value that is interpreted according to its conventional interpretation, and is not normalized.

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.

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.

Vertex Processing Stages

A set of shader stages that comprises the vertex shader, tessellation control shader, tessellation evaluation shader, and geometry shader stages.

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

Abbreviations and acronyms are sometimes used in the Specification and the API where they are considered clear and commonplace, and are defined here:

Src
: Source

Dst
: Destination

Min
: Minimum

Max
: Maximum

Rect
: Rectangle

Info
: Information

LOD
: Level of Detail

ID
: Identifier

UUID
: Universally Unique Identifier

Op
: Operation

R
: Red color component

G
: Green color component

B
: Blue color component

A
: Alpha color component

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 F: Credits

Vulkan 1.0 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.

Members of the Working Group, including the company that they represented at the time of their contributions, are listed below. Some specific contributions made by individuals are listed together with their name.

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- Adam Śmigielski, Mobica
- Alex Bourd, Qualcomm Technologies, Inc.
- Alexander Galazin, ARM
- Allen Hux, Intel
- Alon Or-bach, Samsung Electronics (WSI technical sub-group chair)
- Andrew Cox, Samsung Electronics
- Andrew Garrard, Samsung Electronics (format wrangler)
- Andrew Poole, Samsung Electronics
- Andrew Rafter, Samsung Electronics
- Andrew Richards, Codeplay Software Ltd.
- Andrew Woloszyn, Google
- Antoine Labour, Google
- Aras Pranckevičius, Unity
- Ashwin Kolhe, NVIDIA
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- Benj Lipchak
- Bill Hollings, The Brenwill Workshop
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- Brent E. Insko, Intel
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- Christophe Riccio, Unity

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- Dan Ginsburg, Valve
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- Graeme Leese, Broadcom
- Graham Connor, Imagination Technologies
- Graham Sellers, AMD
- Hwanyong Lee, Kyungpook National University
- Ian Elliott, LunarG
- Ian Romanick, Intel
- James Jones, NVIDIA
- James Hughes, Oculus VR
- Jan Hermes, Continental Corporation
- Jan-Harald Fredriksen, ARM
- Jason Ekstrand, Intel
- Jeff Bolz, NVIDIA (extensive contributions, exhaustive review and rewrites for technical correctness)
- Jeff Juliano, NVIDIA
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- Jens Owen, LunarG
- Jeremy Hayes, LunarG
- Jesse Barker, Unity
- Jesse Hall, Google

- Johannes van Waveren, Oculus VR
- John Kessenich, Google (SPIR-V and GLSL for Vulkan spec author)
- John McDonald, Valve
- Jon Ashburn, LunarG
- Jon Leech, Independent (XML toolchain, normative language, release wrangler)
- Jonas Gustavsson, Sony Mobile
- Jonathan Hamilton, Imagination Technologies
- Jungwoo Kim, Samsung Electronics
- Kenneth Benzie, Codeplay Software Ltd.
- Kerch Holt, NVIDIA (SPIR-V technical sub-group chair)
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- Mark Callow
- Mark Lobodzinski, LunarG
- Mateusz Przybylski, Intel
- Mathias Heyer, NVIDIA
- Mathias Schott, NVIDIA
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- Nick Penwarden, Epic Games
- Niklas Smedberg, Unity

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- Pat Brown, NVIDIA
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- Pierre Boudier, NVIDIA
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- Piers Daniell, NVIDIA (dynamic state, copy commands, memory types)
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- Pyry Haulos, Google (Vulkan conformance test subcommittee chair)
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- Rob Stepinski, Transgaming
- Robert J. Simpson, Qualcomm Technologies, Inc.
- Rolando Caloca Olivares, Epic Games
- Roy Ju, Mediatek
- Rufus Hamede, Imagination Technologies
- Sean Ellis, ARM
- Sean Harmer, KDAB
- Shannon Woods, Google
- Slawomir Cygan, Intel
- Slawomir Grajewski, Intel
- Stefanus Du Toit, Google
- Steve Hill, Broadcom
- Steve Viggers, Core Avionics & Industrial Inc.
- Stuart Smith, Imagination Technologies
- Tim Foley, Intel
- Timo Suoranta, AMD
- Timothy Lottes, AMD
- Tobias Hector, Imagination Technologies (validity language and toolchain)
- Tobin Ehlis, LunarG
- Tom Olson, ARM (working group chair)
- Tomasz Kubale, Intel
- Tony Barbour, LunarG
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- Zhenghong Wang, Mediatek

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