Vulkan 1.0.26 - A Specification

Contents

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 the scope of shaders. 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

http://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**, **shall 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, or the adjective **recommended**, 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.

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 1.1*, https://www.khronos.org/registry/dataformat/specs/1.1/dataformat.1.1.html, June, 2016.

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

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.

Where the Specification leaves choices open that would affect Application Binary Interface compatibility on a given platform supporting Vulkan, those choices are usually made to be compliant to the preferred ABI defined by the platform vendor. Some choices, such as function calling conventions, may be made in platform-specific portions of the `vk_platform.h` header file.

> **Note**
> For example, the Android ABI is defined by Google, and the Linux ABI is defined by a combination of gcc defaults, distribution vendor choices, and external standards such as the Linux Standard Base.

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 the submission order, as described further in Queue Operation. 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 must always adhere to command order and API order, 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 implicit 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 events and pipeline barriers.

There are a few implicit ordering constraints between commands within a command buffer, but only covering a subset of execution. Additional explicit ordering constraints can be expressed with events, pipeline barriers and subpass dependencies.

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 otherwise forbidden by the specification, action commands may overlap execution or execute out of order, and may not see the side effects of each other’s memory accesses.

The execution order of an action command with respect to any synchronization commands that affect that action command must match the recording and submission order, within submissions to a single queue.

API order sorts primitives:

- First, by the action command that generates them.
- Second, by the order they are processed by primitive assembly.

Within this order, implementations also sort primitives:

- Third, by an implementation-dependent ordering of new primitives generated by tessellation, if a tessellation shader is active.
- Fourth, by the order new primitives are generated by geometry shading, if geometry shading is active.
- Fifth, by an implementation-dependent ordering of primitives generated due to the polygon mode.

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.

Application-owned memory is immediately consumed by any Vulkan command it is passed into. The application can alter or free this memory as soon as the commands that consume 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 `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 recording or pending execution:

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

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 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;
```

`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.

2.4.1 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.

2.5 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.

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* member of the *pAllocateInfo* parameter in `vkAllocateDescriptorSets`
- The *descriptorPool* parameter in `vkFreeDescriptorSets`
- The *framebuffer* parameter in `vkDestroyFramebuffer`
- The *renderPass* parameter in `vkDestroyRenderPass`
- The *commandPool* parameter in `vkDestroyCommandPool`
- The *commandPool* parameter in `vkResetCommandPool`
- The *commandPool* member of the *pAllocateInfo* parameter in `vkAllocateCommandBuffers`
- The *commandPool* parameter in `vkFreeCommandBuffers`
- The *commandBuffer* parameter in `vkBeginCommandBuffer`
- The *commandBuffer* parameter in `vkEndCommandBuffer`
- The *commandBuffer* parameter in `vkResetCommandBuffer`
- The *commandBuffer* parameter in `vkCmdBindPipeline`
- The *commandBuffer* parameter in `vkCmdSetViewport`
- The *commandBuffer* parameter in `vkCmdSetScissor`
- The *commandBuffer* parameter in `vkCmdSetLineWidth`
- The *commandBuffer* parameter in `vkCmdSetDepthBias`
- The *commandBuffer* parameter in `vkCmdSetBlendConstants`
- The *commandBuffer* parameter in `vkCmdSetDepthBounds`
- The *commandBuffer* parameter in `vkCmdSetStencilCompareMask`
- The *commandBuffer* parameter in `vkCmdSetStencilWriteMask`
- The *commandBuffer* parameter in `vkCmdSetStencilReference`
- The *commandBuffer* parameter in `vkCmdBindDescriptorSets`

- The *commandBuffer* parameter in `vkCmdBindIndexBuffer`
- The *commandBuffer* parameter in `vkCmdBindVertexBuffers`
- The *commandBuffer* parameter in `vkCmdDraw`
- The *commandBuffer* parameter in `vkCmdDrawIndexed`
- The *commandBuffer* parameter in `vkCmdDrawIndirect`
- The *commandBuffer* parameter in `vkCmdDrawIndexedIndirect`
- The *commandBuffer* parameter in `vkCmdDispatch`
- The *commandBuffer* parameter in `vkCmdDispatchIndirect`
- The *commandBuffer* parameter in `vkCmdCopyBuffer`
- The *commandBuffer* parameter in `vkCmdCopyImage`
- The *commandBuffer* parameter in `vkCmdBlitImage`
- The *commandBuffer* parameter in `vkCmdCopyBufferToImage`
- The *commandBuffer* parameter in `vkCmdCopyImageToBuffer`
- The *commandBuffer* parameter in `vkCmdUpdateBuffer`
- The *commandBuffer* parameter in `vkCmdFillBuffer`
- The *commandBuffer* parameter in `vkCmdClearColorImage`
- The *commandBuffer* parameter in `vkCmdClearDepthStencilImage`
- The *commandBuffer* parameter in `vkCmdClearAttachments`
- The *commandBuffer* parameter in `vkCmdResolveImage`
- The *commandBuffer* parameter in `vkCmdSetEvent`
- The *commandBuffer* parameter in `vkCmdResetEvent`
- The *commandBuffer* parameter in `vkCmdWaitEvents`
- The *commandBuffer* parameter in `vkCmdPipelineBarrier`
- The *commandBuffer* parameter in `vkCmdBeginQuery`
- The *commandBuffer* parameter in `vkCmdEndQuery`
- The *commandBuffer* parameter in `vkCmdResetQueryPool`
- The *commandBuffer* parameter in `vkCmdWriteTimestamp`
- The *commandBuffer* parameter in `vkCmdCopyQueryPoolResults`
- The *commandBuffer* parameter in `vkCmdPushConstants`
- The *commandBuffer* parameter in `vkCmdBeginRenderPass`
- The *commandBuffer* parameter in `vkCmdNextSubpass`
- The *commandBuffer* parameter in `vkCmdEndRenderPass`
- The *commandBuffer* parameter in `vkCmdExecuteCommands`

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 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`

2.6 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, and does not allow one application to access data belonging to another application. Applications can request stronger robustness guarantees by enabling the *`robustBufferAccess`* feature as described in Chapter 30.

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.

2.6.1 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.

Certain usage rules apply to all commands in the API unless explicitly denoted differently for a command. These rules are as follows.

2.6.1.1 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 handle `VK_NULL_HANDLE` can be passed in place of valid object handles when *explicitly called out in the specification*. Any command that creates an object successfully must not return `VK_NULL_HANDLE`. It is valid to pass `VK_NULL_HANDLE` to any **`vkDestroy*`** or **`vkFree*`** command, which will silently ignore these values.

2.6.1.2 Valid Usage for Pointers

Any parameter that is a pointer must be a valid pointer. 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.

2.6.1.3 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`.

2.6.1.4 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 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.

2.6.1.5 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. As a general rule, the name of this value is obtained by taking the structure name, 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 must have a *sType* value of VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO.

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.

The list of supported structure types is defined in an appendix.

2.6.1.6 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”. If that extension is supported by the implementation, then it must be enabled. 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 chained structures 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.

2.6.1.7 Valid Usage for Nested Structures

The above rules 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.

2.6.2 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:

```
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 requested pool allocation has failed due to fragmentation of the pool's memory.

If a command returns a run time error, it will leave any result pointers unmodified, unless other behavior is explicitly defined in the specification.

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`**.

2.7 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.

2.7.1 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}. $x \cdot 0 = 0 \cdot x = 0$ for any non-infinite and non-NaN x. $1 \cdot x = x \cdot 1 = x$. $x + 0 = 0 + x = x$. $0^0 = 1$.

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 Infs and NaNs 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.

2.7.2 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.

2.7.3 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.

2.7.4 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.

2.7.5 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.

2.8 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.

2.8.1 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.

2.8.2 Conversion from Floating-Point to Normalized Fixed-Point

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

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

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

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

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

where $\mathrm{convertFloatToInt}(r,b)$ 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.

2.9 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.

2.10 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*.

2.10.1 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:

```c
typedef struct VkOffset2D {
    int32_t    x;
    int32_t    y;
} VkOffset2D;
```

A three-dimensional offset is defined by the structure:

```c
typedef struct VkOffset3D {
    int32_t    x;
    int32_t    y;
    int32_t    z;
} VkOffset3D;
```

2.10.2 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;
```

A three-dimensional extent is defined by the structure:

```c
typedef struct VkExtent3D {
    uint32_t    width;
    uint32_t    height;
    uint32_t    depth;
} VkExtent3D;
```

2.10.3 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;
```

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. Loaders are encouraged to export function symbols for all other core Vulkan commands as well; if this is done, then applications that use only the core Vulkan commands have no need to use **`vkGetInstanceProcAddr`**.

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 3.1: vkGetInstanceProcAddr behavior

instance	***pName***	**return value**
*	NULL	undefined
invalid instance	*	undefined

Table 3.1: (continued)

instance	*pName*	return value
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	available device extension commands for *instance*	fp[1,2]
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*. e.g. VkInstance, VkPhysicalDevice, VkDevice, VkQueue, or VkCommandBuffer.

2

An “available extension” is an extension function supported by any of the loader, driver or layer.

Valid Usage

- If *instance* is not NULL, *instance* must be a valid VkInstance handle
- *pName* must be a null-terminated 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 (and objects created from them). The overhead of this internal dispatch can be avoided by obtaining device-specific function pointers for any commands that use a device or device-child object as their dispatchable object. Such function pointers can be obtained with the command:

```
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.

Table 3.2: vkGetDeviceProcAddr behavior

device	***pName***	**return value**
NULL	*	undefined
invalid device	*	undefined
device	NULL	undefined
device	core Vulkan command[1]	fp
device	enabled extension commands[1]	fp
device	* (any *pName* not covered above)	NULL

1
The returned function pointer must only be called with a dispatchable object (the first parameter) that is *device* or a child of *device*. e.g. `VkDevice`, `VkQueue`, or `VkCommandBuffer`.

Valid Usage

- *device* must be a valid `VkDevice` handle
- *pName* must be a null-terminated 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 creates the instance, then enables and initializes global layers and extensions requested by the application. If an extension is provided by a layer, both the layer and extension must be specified at **vkCreateInstance** time. If a specified layer cannot be found, no `VkInstance` will be created and the function will return `VK_ERROR_LAYER_NOT_PRESENT`. Likewise, if a specified extension cannot be found the call will return `VK_ERROR_EXTENSION_NOT_PRESENT`.

Valid Usage

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

- *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 pointer to a valid VkApplicationInfo structure
- If *enabledLayerCount* is not 0, *ppEnabledLayerNames* must be a pointer to an array of *enabledLayerCount* null-terminated strings
- If *enabledExtensionCount* is not 0, *ppEnabledExtensionNames* must be a pointer to an array of *enabledExtensionCount* null-terminated strings

The *pApplicationInfo* member of VkInstanceCreateInfo can point to an instance of VkApplicationInfo.

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 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 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* 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

- *sType* must be VK_STRUCTURE_TYPE_APPLICATION_INFO
- *pNext* must be NULL
- If *pApplicationName* is not NULL, *pApplicationName* must be a null-terminated string
- If *pEngineName* is not NULL, *pEngineName* must be a null-terminated string
- *apiVersion* must be zero, or otherwise it must be a version that the implementation supports, or supports an effective substitute for

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

- If *instance* is not NULL, *instance* must be a valid VkInstance handle
- If *pAllocator* is not NULL, *pAllocator* must be a pointer to a valid VkAllocationCallbacks structure
- 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

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 structures 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

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

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

The `VkPhysicalDeviceProperties` structure is defined as:

```
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 devices types 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

- *physicalDevice* must be a valid VkPhysicalDevice handle
- *pQueueFamilyPropertyCount* must be a pointer to a uint32_t value
- If the value referenced by *pQueueFamilyPropertyCount* is not 0, and *pQueueFamilyProperties* is not NULL, *pQueueFamilyProperties* must be a 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* contains flags indicating the 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 bits specified in *queueFlags* 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;
```

- if VK_QUEUE_GRAPHICS_BIT is set, then the queues in this queue family support graphics operations.
- if VK_QUEUE_COMPUTE_BIT is set, then the queues in this queue family support compute operations.
- if VK_QUEUE_TRANSFER_BIT is set, then the queues in this queue family support transfer operations.
- if VK_QUEUE_SPARSE_BINDING_BIT is set, then the 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.

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.
- (Ax,Ay,Az) where Ax, Ay, and Az 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 Ax, Ay, and Az, respectively.
  - *width* of a `VkExtent3D` parameter must be an integer multiple of Ax, 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 Ay, 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 Az, 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.

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.

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

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

- *sType* must be `VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO`
- *pNext* must be `NULL`
- *flags* must be `0`
- *pQueueCreateInfos* must be a pointer to an array of *queueCreateInfoCount* valid `VkDeviceQueueCreateInfo` structures
- If *enabledLayerCount* is not `0`, *ppEnabledLayerNames* must be a pointer to an array of *enabledLayerCount* null-terminated strings
- If *enabledExtensionCount* is not `0`, *ppEnabledExtensionNames* must be a pointer to an array of *enabledExtensionCount* null-terminated strings
- If *pEnabledFeatures* is not `NULL`, *pEnabledFeatures* must be a pointer to a valid `VkPhysicalDeviceFeatures` structure
- *queueCreateInfoCount* must be greater than `0`
- The *queueFamilyIndex* member of any given element of *pQueueCreateInfos* must be unique within *pQueueCreateInfos*

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 pending execution, 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

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

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, this is a recommendation to implementations and 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

- *sType* must be `VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO`

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

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

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

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 Section 6.3) 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 explicit scheduling 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.

4.3.5.1 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 memory barriers. This is true within a command buffer, and across command buffers submitted to a given queue. See Section 6.3, Section 6.5 and Section 6.5.3 about synchronization primitives suitable to guarantee execution order and side-effect visibility between commands on a given queue.

Each command buffer is always in one of three states:

- *Initial state*: Before `vkBeginCommandBuffer`. Either `vkBeginCommandBuffer` has never been called, or the command buffer has been reset since it last recorded commands.
- *Recording state*: Between `vkBeginCommandBuffer` and `vkEndCommandBuffer`. The command buffer is in a state where it can record commands.

- *Executable state*: After `vkEndCommandBuffer`. The command buffer is in a state where it has finished recording commands and can be executed.

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).

5.1 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 application-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

- *`device`* must be a valid `VkDevice` handle
- *`pCreateInfo`* must be a pointer to a valid `VkCommandPoolCreateInfo` structure
- If *`pAllocator`* is not `NULL`, *`pAllocator`* must be a pointer to a valid `VkAllocationCallbacks` structure
- *`pCommandPool`* must be a 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 indicating usage behavior for the pool and command buffers allocated from it. Bits which can be set include:

```
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 controls whether command buffers allocated from the pool can be individually reset. If this flag is set, individual command buffers allocated from the pool can be reset either explicitly, by calling **vkResetCommandBuffer**, or implicitly, by calling **vkBeginCommandBuffer** on an executable command buffer. If this flag is not set, then **vkResetCommandBuffer** and **vkBeginCommandBuffer** (on an executable command buffer) must not be called on the command buffers allocated from the pool, and they can only be reset in bulk by calling **vkResetCommandPool**.

- *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

- *sType* must be `VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO`
- *pNext* must be `NULL`
- *flags* must be a valid combination of `VkCommandPoolCreateFlagBits` values
- *queueFamilyIndex* must be the index of a queue family available in the calling command's *device* parameter

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* contains additional flags controlling the behavior of the reset. Bits which can be set include:

  ```
  typedef enum VkCommandPoolResetFlagBits {
      VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
  } VkCommandPoolResetFlagBits;
  ```

  If *flags* includes `VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT`, resetting a command pool recycles all of the resources from the command pool back to the system.

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.

Valid Usage

- *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*
- All `VkCommandBuffer` objects allocated from *commandPool* must not currently be pending execution

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

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 implicitly freed and become invalid. Command buffers allocated from a given pool do not need to be freed before destroying that command pool.

Valid Usage

- *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 pointer to a valid VkAllocationCallbacks structure
- If *commandPool* is a valid handle, it must have been created, allocated, or retrieved from *device*
- All VkCommandBuffer objects allocated from *commandPool* must not be pending execution

- 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`

Host Synchronization

- Host access to *commandPool* must be externally synchronized

5.2 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.

Valid Usage

- *device* must be a valid `VkDevice` handle
- *pAllocateInfo* must be a pointer to a valid `VkCommandBufferAllocateInfo` structure
- *pCommandBuffers* must be a 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 name of the command pool that the command buffers allocate their memory from.
- *level* determines whether the command buffers are primary or secondary command buffers. Possible values include:

```
typedef enum VkCommandBufferLevel {
    VK_COMMAND_BUFFER_LEVEL_PRIMARY = 0,
    VK_COMMAND_BUFFER_LEVEL_SECONDARY = 1,
} VkCommandBufferLevel;
```

- *commandBufferCount* is the number of command buffers to allocate from the pool.

Valid Usage

- *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
- *commandBufferCount* must be greater than 0

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, and is put in the initial state.
- *flags* is a bitmask controlling the reset operation. Bits which can be set include:

```
typedef enum VkCommandBufferResetFlagBits {
    VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
} VkCommandBufferResetFlagBits;
```

  If *flags* includes VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT, then 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.

Valid Usage

- *commandBuffer* must be a valid VkCommandBuffer handle
- *flags* must be a valid combination of VkCommandBufferResetFlagBits values
- *commandBuffer* must not currently be pending execution
- *commandBuffer* must have been allocated from a pool that was created with the VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT

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

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 handle of the command pool that the command buffers were allocated from.
- *commandBufferCount* is the length of the *pCommandBuffers* array.
- *pCommandBuffers* is an array of handles of command buffers to free.

Valid Usage

- *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*
- All elements of *pCommandBuffers* must not be pending execution
- *pCommandBuffers* must be a pointer to an array of *commandBufferCount* VkCommandBuffer handles, each element of which must either be a valid handle or VK_NULL_HANDLE

Host Synchronization

- Host access to *commandPool* must be externally synchronized
- Host access to each member of *pCommandBuffers* must be externally synchronized

5.3 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 be a valid `VkCommandBuffer` handle
- *pBeginInfo* must be a pointer to a valid `VkCommandBufferBeginInfo` structure
- *commandBuffer* must not be in the recording state
- *commandBuffer* must not currently be pending execution
- 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`

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

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 indicating usage behavior for the command buffer. Bits which can be set include:

```
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 indicates 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 indicates 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.
  - Setting VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT allows the command buffer to be resubmitted to a queue or recorded into a primary command buffer while it is pending execution.
- *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

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

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;
```

- *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 *renderPass* 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. If this is a primary command buffer, then this value is ignored.
- *pipelineStatistics* indicates 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

- *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 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**

A primary command buffer is considered to be pending execution from the time it is submitted via **vkQueueSubmit** until that submission completes.

A secondary command buffer is considered to be pending execution from the time its execution is recorded into a primary buffer (via **vkCmdExecuteCommands**) until the final time that primary buffer's submission to a queue completes. If, after the primary buffer completes, the secondary command buffer is recorded to execute on a different primary buffer, the first primary buffer must not be resubmitted until after it is reset with vkResetCommandBuffer unless the secondary command buffer was recorded with VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT.

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. Furthermore, if a secondary command buffer without VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT set is recorded to execute in a primary command buffer with VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT set, the primary command buffer must not be pending execution more than once at a time.

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 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. It then puts the command buffer in 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. The command buffer must have been in the recording state, and is moved to the executable state.

If there was an error during recording, the application will be notified by an unsuccessful return code returned by **`vkEndCommandBuffer`**. If the application wishes to further use the command buffer, the command buffer must be reset.

Valid Usage

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

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

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

5.4 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. 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.

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.

Valid Usage

- *queue* must be a valid VkQueue handle
- If *submitCount* is not 0, *pSubmits* must be a 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
- 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

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
-	-	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. The command buffers submitted in a batch begin execution in the order they appear in *pCommandBuffers*, but may complete out of order.
- *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.

Valid Usage

- *sType* must be VK_STRUCTURE_TYPE_SUBMIT_INFO

- *pNext* must be NULL
- If *waitSemaphoreCount* is not 0, *pWaitSemaphores* must be a pointer to an array of *waitSemaphoreCount* valid VkSemaphore handles
- If *waitSemaphoreCount* is not 0, *pWaitDstStageMask* must be a 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 pointer to an array of *commandBufferCount* valid VkCommandBuffer handles
- If *signalSemaphoreCount* is not 0, *pSignalSemaphores* must be a 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
- Any given element of *pSignalSemaphores* must currently be unsignaled
- Any given element of *pCommandBuffers* must either have been recorded with the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT, or not currently be executing on the device
- Any given element of *pCommandBuffers* must be in the executable state
- If any given element of *pCommandBuffers* contains commands that execute secondary command buffers, those secondary command buffers must have been recorded with the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT, or not currently be executing on the device
- If any given element of *pCommandBuffers* was recorded with VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT, it must not have been previously submitted without re-recording that command buffer
- If any given element of *pCommandBuffers* contains commands that execute secondary command buffers recorded with VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT, each such secondary command buffer must not have been previously submitted without re-recording that command buffer
- Any given element of *pCommandBuffers* must not contain commands that execute a secondary command buffer, if that secondary command buffer has been recorded in another primary command buffer after it was recorded into this VkCommandBuffer
- Any given element of *pCommandBuffers* must have been allocated from a VkCommandPool that was created for the same queue family that the calling command's *queue* belongs to
- Any given element of *pCommandBuffers* must not have been allocated with VK_COMMAND_BUFFER_LEVEL_SECONDARY
- Any given element of VkSemaphore in *pWaitSemaphores* must refer to a prior signal of that VkSemaphore that will not be consumed by any other wait on that semaphore
- If the geometry shaders feature is not enabled, any given element of *pWaitDstStageMask* must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the tessellation shaders feature is not enabled, any given element of *pWaitDstStageMask* must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT

5.5 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.

5.6 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.

Once **vkCmdExecuteCommands** has been called, any prior executions of the secondary command buffers specified by *pCommandBuffers* in any other primary command buffer become invalidated, unless those secondary command buffers were recorded with `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`.

Valid Usage

- *commandBuffer* must be a valid `VkCommandBuffer` handle
- *pCommandBuffers* must be a 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
- *commandBuffer* must have been allocated with a *level* of VK_COMMAND_BUFFER_LEVEL_PRIMARY
- Any given element of *pCommandBuffers* must have been allocated with a *level* of VK_COMMAND_BUFFER_LEVEL_SECONDARY
- Any given element of *pCommandBuffers* must not be already pending execution in *commandBuffer*, or appear twice in *pCommandBuffers*, unless it was recorded with the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT flag
- Any given element of *pCommandBuffers* must not be already pending execution in any other VkCommandBuffer, unless it was recorded with the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT flag
- Any given element of *pCommandBuffers* must be in the executable state
- Any given 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, any given 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, any given 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, any given element of *pCommandBuffers* must have been recorded with a render pass that is compatible with the current render pass - see Section 7.2
- If **vkCmdExecuteCommands** is being called within a render pass instance, and any given 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, any given 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
- Any given element of *pCommandBuffers* must not begin any query types that are active in *commandBuffer*

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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, there are four forms of concurrency during execution: between the host and device, between the queues, between queue submissions, and between commands within a command buffer. Vulkan provides the application with a set of synchronization primitives for these purposes. Further, memory caches and other optimizations mean that the normal flow of command execution does not guarantee that all memory transactions from a command are immediately visible to other agents with views into a given range of memory. Vulkan also provides barrier operations to ensure this type of synchronization.

Four synchronization primitive types are exposed by Vulkan. These are:

- Fences
- Semaphores
- Events
- Barriers

Each is covered in detail in its own subsection of this chapter. Fences are used to communicate completion of execution of command buffer submissions to queues back to the application. Fences can therefore be used as a coarse-grained synchronization mechanism. Semaphores are generally associated with resources or groups of resources and can be used to marshal ownership of shared data. Their status is not visible to the host. Events provide a finer-grained synchronization primitive which can be signaled at command level granularity by both device and host, and can be waited upon by either. Barriers provide execution and memory synchronization between sets of commands.

6.1 Fences

Fences can be used by the host to determine completion of execution of *queue operations*.

A fence's status is always either *signaled* or *unsignaled*. The host can poll the status of a single fence, or wait for any or all of a group of fences to become signaled.

Fences are represented by `VkFence` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFence)
```

To create a new fence object, use the command

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

- *device* is the logical device that creates the fence.
- *pCreateInfo* points to a `VkFenceCreateInfo` structure specifying the state of the fence object.
- *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

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

- `flags` defines the initial state and behavior of the fence. Bits which can be set include:

```
typedef enum VkFenceCreateFlagBits {
    VK_FENCE_CREATE_SIGNALED_BIT = 0x00000001,
} VkFenceCreateFlagBits;
```

  If `flags` contains `VK_FENCE_CREATE_SIGNALED_BIT` then the fence object is created in the signaled state. Otherwise it is created in the unsignaled state.

Valid Usage

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

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

- `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 pointer to a valid `VkAllocationCallbacks` structure
- If `fence` is a valid handle, it must have been created, allocated, or retrieved from `device`
- `fence` must not be associated with any queue command that has not yet completed execution on that queue
- 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`

Host Synchronization

- Host access to *fence* must be externally synchronized

To query the status of a fence from the host, use the command

```
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, which is one of:

- VK_SUCCESS indicates that the fence is signaled.
- VK_NOT_READY indicates that the fence is unsignaled.

Valid Usage

- *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 reset the status of one or more fences to the unsignaled state, use the command:

```
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 *fenceCount* fence handles to reset.

If a fence is already in the unsignaled state, then resetting it has no effect.

Valid Usage

- *device* must be a valid `VkDevice` handle
- *pFences* must be a 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*
- Any given element of *pFences* must not currently be associated with any queue command that has not yet completed execution on that queue

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`

Fences can be signaled by including them in a queue submission command, defining a queue operation to signal that fence. This *fence signal operation* defines the first half of a memory dependency, guaranteeing that all memory accesses defined by the queue submission are made available, and that queue operations described by that submission have completed execution. This half of the memory dependency does not include host availability of memory accesses. The second half of the dependency can be defined by `vkWaitForFences`.

Fence signal operations for `vkQueueSubmit` additionally include all queue operations previously submitted via `vkQueueSubmit` in their half of a memory dependency.

To cause the host to wait until any one or all of a group of fences is signaled, use the command:

```
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`.

`vkWaitForFences` defines the second half of a memory dependency with the host, for each fence being waited on. The memory dependency defined by signaling a fence and waiting on the host does not guarantee that the results of memory accesses will be visible to the host, or that the memory is available. To provide that guarantee, the application must insert a memory barrier between the device writes and the end of the submission that will signal the fence, with *`dstAccessMask`* having the `VK_ACCESS_HOST_READ_BIT` bit set, with *`dstStageMask`* having the `VK_PIPELINE_STAGE_HOST_BIT` bit set, and with the appropriate *`srcStageMask`* and *`srcAccessMask`* members set to guarantee completion of the writes. If the memory was allocated without the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` set, then **`vkInvalidateMappedMemoryRanges`** must be called after the fence is signaled in order to ensure the writes are visible to the host, as described in Host Access to Device Memory Objects.

Valid Usage

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

6.2 Semaphores

Semaphores are used to coordinate queue operations both within a queue and between different queues. A semaphore's status is always either *signaled* or *unsignaled*.

Semaphores are represented by `VkSemaphore` handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSemaphore)
```

To create a new semaphore object, use the command

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

- *device* is the logical device that creates the semaphore.
- *pCreateInfo* points to a `VkSemaphoreCreateInfo` structure specifying the state of the semaphore object.
- *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. The semaphore is created in the unsignaled state.

Valid Usage

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

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

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *semaphore* is a valid handle, it must have been created, allocated, or retrieved from *device*
- *semaphore* must not be associated with any queue command that has not yet completed execution on that queue
- 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`

Host Synchronization

- Host access to *semaphore* must be externally synchronized

Semaphores can be signaled by including them in a batch as part of a queue submission command, defining a queue operation to signal that semaphore. This *semaphore signal operation* defines the first half of a memory dependency, guaranteeing that all memory accesses defined by the submitted queue operations in the batch are made available, and that those queue operations have completed execution.

Semaphore signal operations for `vkQueueSubmit` additionally include all queue operations previously submitted via `vkQueueSubmit` in their half of a memory dependency, and all batches that are stored at a lower index in the same *`pSubmits`* array.

Signaling of semaphores can be waited on by similarly including them in a batch, defining a queue operation to wait for a signal. A semaphore wait operation defines the second half of a memory dependency for the semaphores being waited on. This half of the memory dependency guarantees that the first half has completed execution, and also guarantees that all available memory accesses are made visible to the queue operations in the batch.

Semaphore wait operations for `vkQueueSubmit` additionally include all queue operations subsequently submitted via `vkQueueSubmit` in their half of a memory dependency, and all batches that are stored at a higher index in the same *`pSubmits`* array.

When queue execution reaches a semaphore wait operation, the queue will stall execution of queue operations in the batch until each semaphore becomes signaled. Once all semaphores are signaled, the semaphores will be reset to the unsignaled state, and subsequent queue operations will be permitted to execute.

Semaphore wait operations defined by `vkQueueSubmit` only wait at specific pipeline stages, rather than delaying all of each command buffer's execution, with the pipeline stages determined by the corresponding element of the *`pWaitDstStageMask`* member of `VkSubmitInfo`. Execution of work by those stages in subsequent commands is stalled until the corresponding semaphore reaches the signaled state.

Note

A common scenario for using *pWaitDstStageMask* with values other than VK_PIPELINE_STAGE_ALL_COMMANDS_BIT is when synchronizing a window system presentation operation against subsequent command buffers which render the next frame. In this case, a presentation image must not be overwritten until the presentation operation completes, but other pipeline stages can execute without waiting. A mask of VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT prevents subsequent color attachment writes from executing until the semaphore signals. Some implementations may be able to execute transfer operations and/or vertex processing work before the semaphore is signaled.

If an image layout transition needs to be performed on a swapchain image before it is used in a framebuffer, that can be performed as the first operation submitted to the queue after acquiring the image, and should not prevent other work from overlapping with the presentation operation. For example, a VkImageMemoryBarrier could use:

- *srcStageMask* = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
- *srcAccessMask* = VK_ACCESS_MEMORY_READ_BIT
- *dstStageMask* = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
- *dstAccessMask* = VK_ACCESS_COLOR_ATTACHMENT_READ_BIT | VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT.
- *oldLayout* = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR
- *newLayout* = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

Alternatively, *oldLayout* can be VK_IMAGE_LAYOUT_UNDEFINED, if the image's contents need not be preserved.

This barrier accomplishes a dependency chain between previous presentation operations and subsequent color attachment output operations, with the layout transition performed in between, and does not introduce a dependency between previous work and any vertex processing stages. More precisely, the semaphore signals after the presentation operation completes, then the semaphore wait stalls the VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT stage, then there is a dependency from that same stage to itself with the layout transition performed in between.

(The primary use case for this example is with the presentation extensions, thus the VK_IMAGE_LAYOUT_PRESENT_SRC_KHR token is used even though it is not defined in the core Vulkan specification.)

6.3 Events

Events represent a fine-grained synchronization primitive that can be used to gauge progress through a sequence of commands executed on a queue by Vulkan. An event is initially in the unsignaled state. It can be signaled by a device, using commands inserted into the command buffer, or by the host. It can also be reset to the unsignaled state by a device or the host. The host can query the state of an event. A device can wait for one or more events to become signaled.

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

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

- *flags* is reserved for future use.

Valid Usage

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

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *event* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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 6.1: 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 pending execution, 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

- *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.

Valid Usage

- *`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.

Valid Usage

- *device* must be a valid VkDevice handle
- *event* must be a valid VkEvent handle
- *event* must have been created, allocated, or retrieved from *device*
- *event* must not be waited on by a **vkCmdWaitEvents** command that is currently executing

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 pipeline stage at which the state of *event* is updated as described below.

Valid Usage

- *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
- 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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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 reset.
- *stageMask* specifies the pipeline stage at which the state of *event* is updated as described below.

Valid Usage

- *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
- 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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS COMPUTE

For both **vkCmdSetEvent** and **vkCmdResetEvent**, the status of *event* is updated once the pipeline stages specified by *stageMask* (see Section 6.5.2) have completed executing prior commands. The command modifying the event is passed through the pipeline bound to the command buffer at time of execution.

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* (see Section 6.5.2) is the bitwise OR of the pipeline stages used to signal the event object handles in *pEvents*.
- *dstStageMask* is the pipeline stages at which the wait will occur.
- *pMemoryBarriers* is a pointer to an array of *memoryBarrierCount* `VkMemoryBarrier` structures.
- *pBufferMemoryBarriers* is a pointer to an array of *bufferMemoryBarrierCount* `VkBufferMemoryBarrier` structures.
- *pImageMemoryBarriers* is a pointer to an array of *imageMemoryBarrierCount* `VkImageMemoryBarrier` structures. See Section 6.5.3 for more details about memory barriers.

vkCmdWaitEvents waits for events set by either **vkSetEvent** or **vkCmdSetEvent** to become signaled. Logically, it has three phases:

1. Wait at the pipeline stages specified by *dstStageMask* (see Section 6.5.2) until the *eventCount* event objects specified by *pEvents* become signaled. Implementations may wait for each event object to become signaled in sequence (starting with the first event object in *pEvents*, and ending with the last), or wait for all of the event objects to become signaled at the same time.
2. Execute the memory barriers specified by *pMemoryBarriers*, *pBufferMemoryBarriers* and *pImageMemoryBarriers* (see Section 6.5.3).
3. Resume execution of pipeline stages specified by *dstStageMask*

Implementations may not execute commands in a pipelined manner, so **vkCmdWaitEvents** may not observe the results of a subsequent **vkCmdSetEvent** or **vkCmdResetEvent** command, even if the stages in *dstStageMask* occur after the stages in *srcStageMask*.

Commands that update the state of events in different pipeline stages may execute out of order, unless the ordering is enforced by execution dependencies.

Note
Applications should be careful to avoid race conditions when using events. For example, an event should only be reset if no **vkCmdWaitEvents** command is executing that waits upon that event.

Valid Usage

- *commandBuffer* must be a valid `VkCommandBuffer` handle
- *pEvents* must be a 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 pointer to an array of *memoryBarrierCount* valid `VkMemoryBarrier` structures
- If *bufferMemoryBarrierCount* is not `0`, *pBufferMemoryBarriers* must be a pointer to an array of *bufferMemoryBarrierCount* valid `VkBufferMemoryBarrier` structures
- If *imageMemoryBarrierCount* is not `0`, *pImageMemoryBarriers* must be a 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`
- *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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS COMPUTE

An act of setting or resetting an event in one queue may not affect or be visible to other queues. For cross-queue synchronization, semaphores can be used.

6.4 Execution And Memory Dependencies

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. The two sets can be:

- First set: commands before a `vkCmdSetEvent` command.

  Second set: commands after a `vkCmdWaitEvents` command in the same queue, using the same event.

- First set: commands in a lower numbered subpass (or before a render pass instance).

  Second set: commands in a higher numbered subpass (or after a render pass instance), where there is a subpass dependency between the two subpasses (or between a subpass and `VK_SUBPASS_EXTERNAL`).

- First set: commands before a pipeline barrier.

  Second set: commands after that pipeline barrier in the same queue (possibly limited to within the same subpass).

An *execution dependency* is a single dependency between a set of source and destination pipeline stages, which guarantees that all work performed by the set of pipeline stages included in *`srcStageMask`* (see Pipeline Stage Flags) of the first set of commands completes before any work performed by the set of pipeline stages included in *`dstStageMask`* of the second set of commands begins.

An *execution dependency chain* from a set of source pipeline stages *A* to a set of destination pipeline stages *B* is a sequence of execution dependencies submitted to a queue in order between a first set of commands and a second set of commands, satisfying the following conditions:

- the first dependency includes *A* or `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT` or `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT` in the *`srcStageMask`*. And,
- the final dependency includes *B* or `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` or `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT` in the *`dstStageMask`*. And,
- for each dependency in the sequence (except the first) at least one of the following conditions is true:
  - *`srcStageMask`* of the current dependency includes at least one bit *C* that is present in the *`dstStageMask`* of the previous dependency. Or,
  - *`srcStageMask`* of the current dependency includes `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT` or `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT`. Or,

  - `dstStageMask` of the previous dependency includes `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT` or `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT`. Or,
  - `srcStageMask` of the current dependency includes `VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT`, and `dstStageMask` of the previous dependency includes at least one graphics pipeline stage. Or,
  - `dstStageMask` of the previous dependency includes `VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT`, and `srcStageMask` of the current dependency includes at least one graphics pipeline stage.

- for each dependency in the sequence (except the first), at least one of the following conditions is true:
  - the current dependency is a **vkCmdSetEvent/vkCmdWaitEvents** pair (where the **vkCmdWaitEvents** may be inside or outside a render pass instance), or a **vkCmdPipelineBarrier** outside of a render pass instance, or a subpass dependency with `srcSubpass` equal to `VK_SUBPASS_EXTERNAL` for a render pass instance that begins with a **vkCmdBeginRenderPass** command, and the previous dependency is any of:
    * a **vkCmdSetEvent/vkCmdWaitEvents** pair or a **vkCmdPipelineBarrier**, either one outside of a render pass instance, that precedes the current dependency in the queue execution order. Or,
    * a subpass dependency, with `dstSubpass` equal to `VK_SUBPASS_EXTERNAL`, for a renderpass instance that was ended with a **vkCmdEndRenderPass** command that precedes the current dependency in the queue execution order.
  - the current dependency is a subpass dependency for a render pass instance, and the previous dependency is any of:
    * another dependency for the same render pass instance, with a `dstSubpass` equal to the `srcSubpass` of the current dependency. Or,
    * a **vkCmdPipelineBarrier** of the same render pass instance, recorded for the subpass indicated by the `srcSubpass` of the current dependency. Or,
    * a **vkCmdSetEvent/vkCmdWaitEvents** pair, where the **vkCmdWaitEvents** is inside the same render pass instance, recorded for the subpass indicated by the `srcSubpass` of the current dependency.
  - the current dependency is a **vkCmdPipelineBarrier** inside a subpass of a render pass instance, and the previous dependency is any of:
    * a subpass dependency for the same render pass instance, with a `dstSubpass` equal to the subpass of the **vkCmdPipelineBarrier**. Or,
    * a **vkCmdPipelineBarrier** of the same render pass instance, recorded for the same subpass, before the current dependency. Or,
    * a **vkCmdSetEvent/vkCmdWaitEvents** pair, where the **vkCmdWaitEvents** is inside the same render pass instance, recorded for the same subpass, before the current dependency.

A pair of consecutive execution dependencies in an execution dependency chain accomplishes a dependency between the stages *A* and *B* via intermediate stages *C*, even if no work is executed between them that uses the pipeline stages included in *C*.

An execution dependency chain guarantees that the work performed by the pipeline stages *A* in the first set of commands completes before the work performed by pipeline stages *B* in the second set of commands begins.

A command C_1 is said to *happen-before* an execution dependency D_2 for a pipeline stage *S* if all the following conditions are true:

- C_1 is in the first set of commands for an execution dependency D_1 that includes *S* in its `srcStageMask`. And,
- there exists an execution dependency chain that includes D_1 and D_2, where D_2 follows D_1 in the execution dependency sequence.

Similarly, a command C_2 is said to *happen-after* an execution dependency D_1 for a pipeline stage *S* if all the following conditions are true:

- C_2 is in the second set of commands for an execution dependency D_2 that includes S in its *dstStageMask*. And,
- there exists an execution dependency chain that includes D_1 and D_2, where D_2 follows D_1 in the execution dependency sequence.

An execution dependency is *by-region* if its *dependencyFlags* parameter includes VK_DEPENDENCY_BY_REGION_BIT. Such a barrier describes a per-region (x,y,layer) dependency. That is, for each region, the implementation must ensure that the source stages for the first set of commands complete execution before any destination stages begin execution in the second set of commands for the same region. Since fragment shader invocations are not specified to run in any particular groupings, the size of a region is implementation-dependent, not known to the application, and must be assumed to be no larger than a single pixel. If *dependencyFlags* does not include VK_DEPENDENCY_BY_REGION_BIT, it describes a global dependency, that is for all pixel regions, the source stages must have completed for preceding commands before any destination stages starts for subsequent commands.

Memory dependencies are coupled to execution dependencies, and synchronize accesses to memory between two sets of commands. They operate according to two "halves" of a dependency to synchronize two sets of commands, the commands that happen-before the execution dependency for the *srcStageMask* vs the commands that happen-after the execution dependency for the *dstStageMask*, as described above. The first half of the dependency makes memory accesses using the set of access types in *srcAccessMask* performed in pipeline stages in *srcStageMask* by the first set of commands complete and writes be *available* for subsequent commands. The second half of the dependency makes any available writes from previous commands *visible* to pipeline stages in *dstStageMask* using the set of access types in *dstAccessMask* for the second set of commands, if those writes have been made available with the first half of the same or a previous dependency. The two halves of a memory dependency can either be expressed as part of a single command, or can be part of separate barriers as long as there is an execution dependency chain between them. The application must use memory dependencies to make writes visible before subsequent reads can rely on them, and before subsequent writes can overwrite them. Failure to do so causes the result of the reads to be undefined, and the order of writes to be undefined.

Global memory barriers apply to all resources owned by the device. Buffer and image memory barriers apply to the buffer range(s) or image subresource(s) included in the command. For accesses to a byte of a buffer or image subresource of an image to be synchronized between two sets of commands, the byte or image subresource must be included in both the first and second halves of the dependencies described above, but need not be included in each step of the execution dependency chain between them.

An execution dependency chain is *by-region* if all stages in all dependencies in the chain are framebuffer-space pipeline stages, and if the VK_DEPENDENCY_BY_REGION_BIT bit is included in all dependencies in the chain. Otherwise, the execution dependency chain is not by-region. The two halves of a memory dependency form a by-region dependency if **all** execution dependency chains between them are by-region. In other words, if there is any execution dependency between two sets of commands that is not by-region, then the memory dependency is not by-region.

When an image memory barrier includes a layout transition, the barrier first makes writes via *srcStageMask* and *srcAccessMask* available, then performs the layout transition, then makes the contents of the image subresource(s) in the new layout visible to memory accesses in *dstStageMask* and *dstAccessMask*, as if there is an execution and memory dependency between the source masks and the transition, as well as between the transition and the destination masks. Any writes that have previously been made available are included in the layout transition, but any previous writes that have not been made available may become lost or corrupt the image.

All dependencies must include at least one bit in each of the *srcStageMask* and *dstStageMask*.

Memory dependencies are used to solve data hazards, e.g. to ensure that write operations are visible to subsequent read operations (read-after-write hazard), as well as write-after-write hazards. Write-after-read and read-after-read hazards only require execution dependencies to synchronize.

6.5 Pipeline Barriers

A *pipeline barrier* inserts an execution dependency and a set of memory dependencies between a set of commands earlier in the command buffer and a set of commands later in the command buffer.

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 a set of source pipeline stages (see Section 6.5.2).
- *dstStageMask* is a bitmask specifying a set of destination pipeline stages.

  The pipeline barrier specifies an execution dependency such that all work performed by the set of pipeline stages included in *srcStageMask* of the first set of commands completes before any work performed by the set of pipeline stages included in *dstStageMask* of the second set of commands begins.
- *dependencyFlags* is a bitmask of `VkDependencyFlagBits`. The execution dependency is by-region if the mask includes `VK_DEPENDENCY_BY_REGION_BIT`.
- *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.

Each element of the *pMemoryBarriers*, *pBufferMemoryBarriers* and *pImageMemoryBarriers* arrays specifies two halves of a memory dependency, as defined above. Specifics of each type of memory barrier and the memory access types are defined further in Memory Barriers.

If **vkCmdPipelineBarrier** is called outside a render pass instance, then the first set of commands is all prior commands submitted to the queue and recorded in the command buffer and the second set of commands is all subsequent commands recorded in the command buffer and submitted to the queue. If **vkCmdPipelineBarrier** is called inside a render pass instance, then the first set of commands is all prior commands in the same subpass and the second set of commands is all subsequent commands in the same subpass.

Valid Usage

- *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 pointer to an array of *memoryBarrierCount* valid `VkMemoryBarrier` structures
- If *bufferMemoryBarrierCount* is not `0`, *pBufferMemoryBarriers* must be a pointer to an array of *bufferMemoryBarrierCount* valid `VkBufferMemoryBarrier` structures
- If *imageMemoryBarrierCount* is not `0`, *pImageMemoryBarriers* must be a 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
- 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. Additionally:
  - *srcStageMask* must contain a subset of the bit values in the *srcStageMask* member of that instance of `VkSubpassDependency`
  - *dstStageMask* must contain a subset of the bit values in the *dstStageMask* member of that instance of `VkSubpassDependency`
  - 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`
  - 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`
  - *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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	TRANSFER GRAPHICS COMPUTE

6.5.1 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. More precisely, this means that whatever is the last pipeline stage in *srcStageMask* must be no later than whatever is the first pipeline stage in *dstStageMask* (the latest source stage can be equal to the earliest destination stage). 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.

6.5.2 Pipeline Stage Flags

Several of the event commands, **vkCmdPipelineBarrier**, and VkSubpassDependency depend on being able to specify where in the logical pipeline events can be signaled, or the source and destination of an execution dependency. These pipeline stages are specified using a bitmask:

```
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;
```

The meaning of each bit is:

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT: Stage of the pipeline where commands are initially received by the queue.
- VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT: Stage of the pipeline where Draw/DispatchIndirect data structures are consumed.
- VK_PIPELINE_STAGE_VERTEX_INPUT_BIT: Stage of the pipeline where vertex and index buffers are consumed.
- VK_PIPELINE_STAGE_VERTEX_SHADER_BIT: Vertex shader stage.
- VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT: Tessellation control shader stage.
- VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT: Tessellation evaluation shader stage.
- VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT: Geometry shader stage.

- VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT: Fragment shader stage.
- VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT: Stage of the pipeline where early fragment tests (depth and stencil tests before fragment shading) are performed.
- VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT: Stage of the pipeline where late fragment tests (depth and stencil tests after fragment shading) are performed.
- VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT: Stage of the pipeline after blending where the final color values are output from the pipeline. This stage also includes resolve operations that occur at the end of a subpass. Note that this does not necessarily indicate that the values have been committed to memory.
- VK_PIPELINE_STAGE_TRANSFER_BIT: Execution of copy commands. This includes the operations resulting from all transfer commands. The set of transfer commands comprises **vkCmdCopyBuffer**, **vkCmdCopyImage**, **vkCmdBlitImage**, **vkCmdCopyBufferToImage**, **vkCmdCopyImageToBuffer**, **vkCmdUpdateBuffer**, **vkCmdFillBuffer**, **vkCmdClearColorImage**, **vkCmdClearDepthStencilImage**, **vkCmdResolveImage**, and **vkCmdCopyQueryPoolResults**.
- VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT: Execution of a compute shader.
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT: Final stage in the pipeline where commands complete execution.
- VK_PIPELINE_STAGE_HOST_BIT: A pseudo-stage indicating execution on the host of reads/writes of device memory.
- VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT: Execution of all graphics pipeline stages.
- VK_PIPELINE_STAGE_ALL_COMMANDS_BIT: Execution of all stages supported on the queue.

Note

The VK_PIPELINE_STAGE_ALL_COMMANDS_BIT and VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT differ from VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT in that they correspond to all (or all graphics) stages, rather than to a specific stage at the end of the pipeline. An execution dependency with only VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT in *dstStageMask* will not delay subsequent commands, while including either of the other two bits will. Similarly, when defining a memory dependency, if the stage mask(s) refer to all stages, then the indicated access types from all stages will be made available and/or visible, but using only VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT would not make any accesses available and/or visible because this stage does not access memory. The VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT is useful for accomplishing memory barriers and layout transitions when the next accesses will be done in a different queue or by a presentation engine; in these cases subsequent commands in the same queue do not need to wait, but the barrier or transition must complete before semaphores associated with the batch signal.

Note

If an implementation is unable to update the state of an event at any specific stage of the pipeline, it may instead update the event at any logically later stage. 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. In the limit, an event may be signaled after all graphics stages complete. If an implementation is unable to wait on an event at any specific stage of the pipeline, it may instead wait on it at any logically earlier stage.

Similarly, if an implementation is unable to implement an execution dependency at specific stages of the pipeline, it may implement the dependency in a way where additional source pipeline stages complete and/or where additional destination pipeline stages' execution is blocked to satisfy the dependency.

If an implementation makes such a substitution, it must not affect the semantics of execution or memory dependencies or image and buffer memory barriers.

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 6.2: Supported pipeline stage flags

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

6.5.3 Memory Barriers

Memory barriers express the two halves of a memory dependency between an earlier set of memory accesses against a later set of memory accesses. Vulkan provides three types of memory barriers: global memory, buffer memory, and image memory.

6.5.4 Global Memory Barriers

The global memory barrier type is specified with an instance of the `VkMemoryBarrier` structure. This type of barrier applies 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 the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- *dstAccessMask* is a bitmask of the classes of memory accesses performed by the second set of commands that will participate in the dependency.

srcAccessMask and *dstAccessMask*, along with *srcStageMask* and *dstStageMask* from `vkCmdPipelineBarrier`, define the two halves of a memory dependency and an execution dependency. Memory accesses using the set of access types in *srcAccessMask* performed in pipeline stages in *srcStageMask* by the first set of commands must complete and be available to later commands. The side effects of the first set of commands will be visible to memory accesses using the set of access types in *dstAccessMask* performed in pipeline stages in *dstStageMask* by the second set of commands. If the barrier is by-region, these requirements only apply to invocations within the same framebuffer-space region, for pipeline stages that perform framebuffer-space work. The execution dependency guarantees that execution of work by the destination stages of the second set of commands will not begin until execution of work by the source stages of the first set of commands has completed.

A common type of memory dependency is to avoid a read-after-write hazard. In this case, the source access mask and stages will include writes from a particular stage, and the destination access mask and stages will indicate how those writes will be read in subsequent commands. However, barriers can also express write-after-read dependencies and write-after-write dependencies, and are even useful to express read-after-read dependencies across an image layout change.

Bits which can be set in `VkMemoryBarrier`::*srcAccessMask* and `VkMemoryBarrier`::*dstAccessMask* 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` indicates that the access is an indirect command structure read as part of an indirect drawing command.
- `VK_ACCESS_INDEX_READ_BIT` indicates that the access is an index buffer read.
- `VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT` indicates that the access is a read via the vertex input bindings.
- `VK_ACCESS_UNIFORM_READ_BIT` indicates that the access is a read via a uniform buffer or dynamic uniform buffer descriptor.
- `VK_ACCESS_INPUT_ATTACHMENT_READ_BIT` indicates that the access is a read via an input attachment descriptor.
- `VK_ACCESS_SHADER_READ_BIT` indicates that the access is a read from a shader via any other descriptor type.
- `VK_ACCESS_SHADER_WRITE_BIT` indicates that the access is a write or atomic from a shader via the same descriptor types as in `VK_ACCESS_SHADER_READ_BIT`.
- `VK_ACCESS_COLOR_ATTACHMENT_READ_BIT` indicates that the access is a read via a color attachment.
- `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT` indicates that the access is a write via a color or resolve attachment.
- `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT` indicates that the access is a read via a depth/stencil attachment.
- `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT` indicates that the access is a write via a depth/stencil attachment.
- `VK_ACCESS_TRANSFER_READ_BIT` indicates that the access is a read from a transfer (copy, blit, resolve, etc.) operation. For the complete set of transfer operations, see VK_PIPELINE_STAGE_TRANSFER_BIT.
- `VK_ACCESS_TRANSFER_WRITE_BIT` indicates that the access is a write from a transfer (copy, blit, resolve, etc.) operation. For the complete set of transfer operations, see VK_PIPELINE_STAGE_TRANSFER_BIT.
- `VK_ACCESS_HOST_READ_BIT` indicates that the access is a read via the host.
- `VK_ACCESS_HOST_WRITE_BIT` indicates that the access is a write via the host.
- `VK_ACCESS_MEMORY_READ_BIT` indicates that the access is a read via a non-specific unit attached to the memory. This unit may be external to the Vulkan device or otherwise not part of the core Vulkan pipeline. When included in *`dstAccessMask`*, all writes using access types in *`srcAccessMask`* performed by pipeline stages in *`srcStageMask`* must be visible in memory.
- `VK_ACCESS_MEMORY_WRITE_BIT` indicates that the access is a write via a non-specific unit attached to the memory. This unit may be external to the Vulkan device or otherwise not part of the core Vulkan pipeline. When included in *`srcAccessMask`*, all access types in *`dstAccessMask`* from pipeline stages in *`dstStageMask`* will observe the side effects of commands that executed before the barrier. When included in *`dstAccessMask`* all writes using access types in *`srcAccessMask`* performed by pipeline stages in *`srcStageMask`* must be visible in memory.

Color attachment reads and writes are automatically (without memory or execution dependencies) coherent and ordered against themselves and each other for a given sample within a subpass of a render pass instance, executing in rasterization order. Similarly, depth/stencil attachment reads and writes are automatically coherent and ordered against themselves and each other in the same circumstances.

Shader reads and/or writes through two variables (in the same or different shader invocations) decorated with **`Coherent`** and which use the same image view or buffer view are automatically coherent with each other, but require execution dependencies if a specific order is desired. Similarly, shader atomic operations are coherent with each other and with **`Coherent`** variables. Non-**`Coherent`** shader memory accesses require memory dependencies for writes to be available and reads to be visible.

Certain memory access types are only supported on queues that support a particular set of operations. The following table lists, for each access 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 access type 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 6.3: Supported access flags

Access flag	**Required queue capability flag**
`VK_ACCESS_INDIRECT_COMMAND_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`
`VK_ACCESS_INDEX_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_UNIFORM_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`
`VK_ACCESS_INPUT_ATTACHMENT_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_SHADER_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`
`VK_ACCESS_SHADER_WRITE_BIT`	`VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`
`VK_ACCESS_COLOR_ATTACHMENT_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`	`VK_QUEUE_GRAPHICS_BIT`
`VK_ACCESS_TRANSFER_READ_BIT`	`VK_QUEUE_GRAPHICS_BIT`, `VK_QUEUE_COMPUTE_BIT` or `VK_QUEUE_TRANSFER_BIT`
`VK_ACCESS_TRANSFER_WRITE_BIT`	`VK_QUEUE_GRAPHICS_BIT`, `VK_QUEUE_COMPUTE_BIT` or `VK_QUEUE_TRANSFER_BIT`
`VK_ACCESS_HOST_READ_BIT`	None
`VK_ACCESS_HOST_WRITE_BIT`	None
`VK_ACCESS_MEMORY_READ_BIT`	None
`VK_ACCESS_MEMORY_WRITE_BIT`	None

Valid Usage

- *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

6.5.5 Buffer Memory Barriers

The buffer memory barrier type is specified with an instance of the `VkBufferMemoryBarrier` structure. This type of barrier only applies to memory accesses involving a specific range of the specified buffer object. That is, a memory dependency formed from a buffer memory barrier is scoped to the specified range of the buffer. It is also used to transfer ownership of a buffer range from one queue family to another, as described in the Resource Sharing section.

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 the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- *dstAccessMask* is a bitmask of the classes of memory accesses performed by the second set of commands that will participate in the dependency.
- *srcQueueFamilyIndex* is the queue family that is relinquishing ownership of the range of *buffer* to another queue, or `VK_QUEUE_FAMILY_IGNORED` if there is no transfer of ownership.
- *dstQueueFamilyIndex* is the queue family that is acquiring ownership of the range of *buffer* from another queue, or `VK_QUEUE_FAMILY_IGNORED` if there is no transfer of ownership.
- *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.

Valid Usage

- *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
- *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 Section 4.3.1)
- If *buffer* was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and *srcQueueFamilyIndex* and *dstQueueFamilyIndex* are valid queue families, at least one of them must be the same as the family of the queue that will execute this barrier

6.5.6 Image Memory Barriers

The image memory barrier type is specified with an instance of the `VkImageMemoryBarrier` structure. This type of barrier only applies to memory accesses involving a specific image subresource range of the specified image object. That is, a memory dependency formed from an image memory barrier is scoped to the specified image subresources of the image. It is also used to perform a layout transition for an image subresource range, or to transfer ownership of an image subresource range from one queue family to another as described in the Resource Sharing section.

The `VkImageMemoryBarrier` structure is defined as:

```
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 the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- *dstAccessMask* is a bitmask of the classes of memory accesses performed by the second set of commands that will participate in the dependency.
- *oldLayout* describes the current layout of the image subresource(s).
- *newLayout* describes the new layout of the image subresource(s).
- *srcQueueFamilyIndex* is the queue family that is relinquishing ownership of the image subresource(s) to another queue, or VK_QUEUE_FAMILY_IGNORED if there is no transfer of ownership).
- *dstQueueFamilyIndex* is the queue family that is acquiring ownership of the image subresource(s) from another queue, or VK_QUEUE_FAMILY_IGNORED if there is no transfer of ownership).
- *image* is a handle to the image whose backing memory is affected by the barrier.
- *subresourceRange* describes an area of the backing memory for *image* (see Section 11.5 for the description of VkImageSubresourceRange), as well as the set of image subresources whose image layouts are modified.

If *oldLayout* differs from *newLayout*, a layout transition occurs as part of the image memory barrier, affecting the data contained in the region of the image defined by the *subresourceRange*. If *oldLayout* is VK_IMAGE_LAYOUT_UNDEFINED, then the data is undefined after the layout transition. This may allow a more efficient transition, since the data may be discarded. The layout transition must occur after all operations using the old layout are completed and before all operations using the new layout are started. This is achieved by ensuring that there is a memory dependency between previous accesses and the layout transition, as well as between the layout transition and subsequent accesses, where the layout transition occurs between the two halves of a memory dependency in an image memory barrier.

Layout transitions that are performed via image memory barriers are automatically ordered against other layout transitions, including those that occur as part of a render pass instance.

Note
See Section 11.4 for details on available image layouts and their usages.

Valid Usage

- *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
- `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 Section 4.3.1)
- If `image` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are valid queue families, at least one of them must be the same as the family of the queue that will execute this barrier
- `subresourceRange` must be a valid image subresource range for the image (see Section 11.5)
- If `image` has a depth/stencil format with both depth and stencil components, then `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

6.5.7 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

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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
-	-	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

- *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

6.6 Host Write Ordering Guarantees

When submitting batches of command buffers to a queue via vkQueueSubmit, it is guaranteed that:

- Host writes to mappable device memory that occurred before the call to **vkQueueSubmit** are visible to the queue operation resulting from that submission, if the device memory is coherent or if the memory range was flushed with vkFlushMappedMemoryRanges.

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 do resolve operations to others as *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. 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 ordering restrictions between pairs of subpasses. If no dependencies are specified, implementations may reorder or overlap portions (e.g., certain shader stages) of the execution of subpasses.

Dependencies limit the extent of overlap or reordering, and are defined using masks of pipeline stages and memory access types. Each dependency acts as an execution and memory dependency, similarly to how pipeline barriers are defined. Dependencies are needed if two subpasses operate on attachments with overlapping ranges of the same `VkDeviceMemory` object and at least one subpass writes to that range.

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.

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. 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

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

- *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 pointer to an array of *attachmentCount* valid `VkAttachmentDescription` structures
- *pSubpasses* must be a pointer to an array of *subpassCount* valid `VkSubpassDescription` structures
- If *dependencyCount* is not `0`, *pDependencies* must be a pointer to an array of *dependencyCount* valid `VkSubpassDependency` structures
- *subpassCount* must be greater than `0`
- 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 given 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 given element of *pSubpasses* is not `VK_ATTACHMENT_UNUSED`, it must be less than *attachmentCount*
- The value of any element of the *pPreserveAttachments* member in any given element of *pSubpasses* must not be `VK_ATTACHMENT_UNUSED`

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 describing additional properties of the attachment. Bits which can be set include:

```
typedef enum VkAttachmentDescriptionFlagBits {
    VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT = 0x00000001,
```

```
} VkAttachmentDescriptionFlagBits;
```

- *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* specifies how the contents of color and depth components of the attachment are treated at the beginning of the subpass where it is first used:

```
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 means the contents within the render area will be preserved.
  – VK_ATTACHMENT_LOAD_OP_CLEAR means the contents within the render area will be cleared to a uniform value, which is specified when a render pass instance is begun.
  – VK_ATTACHMENT_LOAD_OP_DONT_CARE means the contents within the area need not be preserved; the contents of the attachment will be undefined inside the render area.

- *storeOp* specifies how the contents of color and depth components of the attachment are treated at the end of the subpass where it is last used:

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

  – VK_ATTACHMENT_STORE_OP_STORE means the contents within the render area are written to memory and will be available for reading after the render pass instance completes once the writes have been synchronized with VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT (for color attachments) or VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT (for depth/stencil attachments).
  – VK_ATTACHMENT_STORE_OP_DONT_CARE means 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.

- *stencilLoadOp* specifies how the contents of stencil components of the attachment are treated at the beginning of the subpass where it is first used, and must be one of the same values allowed for *loadOp* above.
- *stencilStoreOp* specifies how the contents of stencil components of the attachment are treated at the end of the last subpass where it is used, and must be one of the same values allowed for *storeOp* above.
- *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.

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 stored or resolved 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

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

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.

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. Those 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. This valid scenario 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. 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`.

Note
The exact set of attachment indices that alias with each other is not known until a framebuffer is created using the render pass, so the above conditions cannot be validated at render pass creation time.

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 reserved for future use.
- *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 shader 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).
- *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 resolve. If *pResolveAttachments* is not `NULL`, each of its elements corresponds to a color attachment (the element in *pColorAttachments* at the same index). At the end of each subpass, the subpass's color attachments are resolved to corresponding resolve attachments, unless the resolve attachment index is `VK_ATTACHMENT_UNUSED` or *pResolveAttachments* is `NULL`. 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 S1 that uses or preserves the attachment, and a subpass dependency from S1 to S.
- The attachment is not used or preserved in subpass S.

Once the contents of an attachment become undefined in subpass S, they remain undefined for subpasses in subpass dependency chains starting with subpass S until they are written again. However, they remain valid for subpasses in other subpass dependency chains starting with subpass S1 if those subpasses use or preserve the attachment.

Valid Usage

- *flags* must be `0`
- *pipelineBindPoint* must be a valid `VkPipelineBindPoint` value
- If *inputAttachmentCount* is not `0`, *pInputAttachments* must be a pointer to an array of *inputAttachmentCount* valid `VkAttachmentReference` structures
- If *colorAttachmentCount* is not `0`, *pColorAttachments* must be a pointer to an array of *colorAttachmentCount* valid `VkAttachmentReference` structures
- If *colorAttachmentCount* is not `0`, and *pResolveAttachments* is not `NULL`, *pResolveAttachments* must be a pointer to an array of *colorAttachmentCount* valid `VkAttachmentReference` structures
- If *pDepthStencilAttachment* is not `NULL`, *pDepthStencilAttachment* must be a pointer to a valid `VkAttachmentReference` structure
- If *preserveAttachmentCount* is not `0`, *pPreserveAttachments* must be a pointer to an array of *preserveAttachmentCount* `uint32_t` values

- *pipelineBindPoint* must be VK_PIPELINE_BIND_POINT_GRAPHICS
- *colorCount* 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
- Any given element of *pResolveAttachments* must have a sample count of VK_SAMPLE_COUNT_1_BIT
- Any given element of *pResolveAttachments* must have the same VkFormat as its corresponding color attachment
- All attachments in *pColorAttachments* and *pDepthStencilAttachment* that are not VK_ATTACHMENT_UNUSED 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 any element of *pPreserveAttachments* must not be VK_ATTACHMENT_UNUSED
- Any given 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*

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. The implementation will automatically perform layout transitions as needed between subpasses to make each subpass use the requested layouts.

Valid Usage

- *layout* must be a valid `VkImageLayout` value
- *layout* must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`

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* and *dstSubpass* are the subpass indices of the producer and consumer subpasses, respectively. *srcSubpass* and *dstSubpass* can also have the special value `VK_SUBPASS_EXTERNAL`. The source subpass must always be a lower numbered subpass than the destination subpass (excluding external subpasses and self-dependencies), so that the order of subpass descriptions is a valid execution ordering, avoiding cycles in the dependency graph.
- *srcStageMask*, *dstStageMask*, *srcAccessMask*, *dstAccessMask*, and *dependencyFlags* describe an execution and memory dependency between subpasses. The bits that can be included in *dependencyFlags* are:

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

  - If *dependencyFlags* contains `VK_DEPENDENCY_BY_REGION_BIT`, then the dependency is by-region as defined in Execution And Memory Dependencies.

Each subpass dependency defines an execution and memory dependency between two sets of commands, with the second set depending on the first set. When *srcSubpass* does not equal *dstSubpass* then the first set of commands is:

- All commands in the subpass indicated by *srcSubpass*, if *srcSubpass* is not `VK_SUBPASS_EXTERNAL`.
- All commands before the render pass instance, if *srcSubpass* is `VK_SUBPASS_EXTERNAL`.

While the corresponding second set of commands is:

- All commands in the subpass indicated by *dstSubpass*, if *dstSubpass* is not `VK_SUBPASS_EXTERNAL`.
- All commands after the render pass instance, if *dstSubpass* is `VK_SUBPASS_EXTERNAL`.

When *srcSubpass* equals *dstSubpass* then the first set consists of commands in the subpass before a call to `vkCmdPipelineBarrier` and the second set consists of commands in the subpass following that same call as described in the Subpass Self-dependency section.

The *srcStageMask*, *dstStageMask*, *srcAccessMask*, *dstAccessMask*, and *dependencyFlags* parameters of the dependency are interpreted the same way as for other dependencies, as described in Synchronization and Cache Control.

Valid Usage

- *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 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*, the highest bit value included in *srcStageMask* must be less than or equal to the lowest bit value in *dstStageMask*

Automatic image layout transitions between subpasses also interact with the subpass dependencies. If two subpasses are connected by a dependency and those two subpasses use the same attachment in a different layout, then the layout transition will occur after the memory accesses via *srcAccessMask* have completed in all pipeline stages included in *srcStageMask* in the source subpass, and before any memory accesses via *dstAccessMask* occur in any pipeline stages included in *dstStageMask* in the destination subpass.

The automatic image layout transitions from *initialLayout* to the first used layout (if it is different) are performed according to the following rules:

- If the attachment does not include the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT bit and there is no subpass dependency from VK_SUBPASS_EXTERNAL to the first subpass that uses the attachment, then it is as if there were such a dependency with *srcStageMask* = *srcAccessMask* = 0 and *dstStageMask* and *dstAccessMask* including all relevant bits (all graphics pipeline stages and all access types that use image resources), with the transition executing as part of that dependency. In other words, it may overlap work before the render pass instance and is complete before the subpass begins.
- If the attachment does not include the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT bit and there is a subpass dependency from VK_SUBPASS_EXTERNAL to the first subpass that uses the attachment, then the transition executes as part of that dependency and according to its stage and access masks. It must not overlap work that came before the render pass instance that is included in the source masks, but it may overlap work in previous subpasses.
- If the attachment includes the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT bit, then the transition executes according to all the subpass dependencies with *dstSubpass* equal to the first subpass index that the attachment is used in. That is, it occurs after all memory accesses in the source stages and masks from all the source subpasses have completed and are available, and before the union of all the destination stages begin, and the new layout is visible to the union of all the destination access types. If there are no incoming subpass dependencies, then this case follows the first rule.

Similar rules apply for the transition to the *finalLayout*, using dependencies with *dstSubpass* equal to VK_SUBPASS_EXTERNAL

If an attachment specifies the VK_ATTACHMENT_LOAD_OP_CLEAR load operation, then it will logically be cleared at the start of the first subpass where it is used.

> **Note**
> Implementations may move clears earlier as long as it does not affect the operation of a render pass instance. For example, an implementation may choose to clear all attachments at the start of the render pass instance. If an attachment has the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT flag set, then the clear must occur at the start of subpass where the attachment is first used, in order to preserve the operation of the render pass instance.

The first use of an attachment must not specify a layout equal to VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL if the attachment specifies that the *loadOp* is VK_ATTACHMENT_LOAD_OP_CLEAR. If a subpass uses the same attachment as both an input attachment and either a color attachment or a depth/stencil attachment, then both uses must observe the result of the clear.

Similarly, if an attachment specifies that the *storeOp* is VK_ATTACHMENT_STORE_OP_STORE, then it will logically be stored at the end of the last subpass where it is used.

> **Note**
> Implementations may move stores later as long as it does not affect the operation of a render pass instance. If an attachment has the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT flag set, then the store must occur at the end of the highest numbered subpass that uses the attachment.

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

It will be common for a render pass to consist of a simple linear graph of dependencies, where subpass N depends on subpass N-1 for all N, and the operation of the memory barriers and layout transitions is fairly straightforward to reason about for those simple cases. But for more complex graphs, there are some rules that govern when there must be dependencies between subpasses.

As stated earlier, render passes must include subpass dependencies which (either directly or via a subpass dependency chain) separate any two subpasses that operate on the same attachment or aliasing attachments, if at least one of those subpasses writes to the attachment. If an image layout changes between those two subpasses, the implementation uses the stageMasks and accessMasks indicated by the subpass dependency as the masks that control when the layout transition must occur. If there is not a layout change on the attachment, or if an implementation treats the two layouts identically, then it may treat the dependency as a simple execution/memory barrier.

If two subpasses use the same attachment in different layouts but both uses are read-only (i.e. input attachment, or read-only depth/stencil attachment), the application does not need to express a dependency between the two subpasses. Implementations that treat the two layouts differently may deduce and insert a dependency between the subpasses, with the implementation choosing the appropriate stage masks and access masks based on whether the attachment is used as an input or depth/stencil attachment, and may insert the appropriate layout transition along with the execution/memory barrier. Implementations that treat the two layouts identically need not insert a barrier, and the two subpasses may execute simultaneously. The stage masks and access masks are chosen as follows:

- for input attachments, stage mask = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, access mask = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT.
- for depth/stencil attachments, stage mask = VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT | VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT, access mask = VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT

where *srcStageMask* and *srcAccessMask* are taken based on usage in the source subpass and *dstStageMask* and *dstAccessMask* are taken based on usage in the destination subpass.

If a subpass uses the same attachment as both an input attachment and either a color attachment or a depth/stencil attachment, reads from the input attachment are not automatically coherent with writes through the color or depth/stencil attachment. In order to achieve well-defined results, one of two criteria must be satisfied. First, 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 attachment then there is no *feedback loop* and the reads and writes both function normally, with the reads observing values from the previous subpass(es) or from memory. This option 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*.

Second, if the input attachment reads components that are written by the color or depth/stencil attachment, then there is a feedback loop and a pipeline barrier must be used between when the attachment is written and when it is subsequently read by later fragments. This pipeline barrier must follow the rules of a self-dependency as described in Subpass Self-dependency, where the barrier's flags include:

- *dstStageMask* = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT,
- *dstAccessMask* = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT, and
- *srcAccessMask* = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT (for color attachments) or *srcAccessMask* = VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT (for depth/stencil attachments).
- *srcStageMask* = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT (for color attachments) or *srcStageMask* = VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT | VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT (for depth/stencil attachments).

- *dependencyFlags* = VK_DEPENDENCY_BY_REGION_BIT.

A pipeline barrier is needed each time a fragment will read a particular (x,y,layer,sample) location if that location has been written since the most recent pipeline barrier, or since the 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 color attachment must be in the VK_IMAGE_LAYOUT_GENERAL layout. An attachment used as both an input attachment and depth/stencil attachment must be in either the VK_IMAGE_LAYOUT_GENERAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL layout. Since an attachment in the VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL layout is read-only, this situation is not a feedback loop.

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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *renderPass* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

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 that contain only a single subpass are compatible if their corresponding color, input, resolve, and depth/stencil attachment references are compatible.

If two render passes contain more than one subpass, they are compatible if they are 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

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

Image subresources used as attachments must not be used via any non-attachment usage for the duration of a render pass instance.

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

- *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 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`
- *attachmentCount* must be equal to the attachment count specified in *renderPass*
- Any given 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`
- Any given 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`
- Any given 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`
- Any given element of *pAttachments* must have been created with an `VkFormat` value that matches the `VkFormat` specified by the corresponding `VkAttachmentDescription` in *renderPass*
- Any given element of *pAttachments* must have been created with a *samples* value that matches the *samples* value specified by the corresponding `VkAttachmentDescription` in *renderPass*

- Any given element of *pAttachments* must have dimensions at least as large as the corresponding framebuffer dimension
- Any given element of *pAttachments* must only specify a single mip level
- Any given element of *pAttachments* must have been created with the identity swizzle
- *width* must be less than or equal to `VkPhysicalDeviceLimits`::*maxFramebufferWidth*
- *height* must be less than or equal to `VkPhysicalDeviceLimits`::*maxFramebufferHeight*
- *layers* must be less than or equal to `VkPhysicalDeviceLimits`::*maxFramebufferLayers*

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *framebuffer* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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* specifies how the commands in the first subpass will be provided, and is one of the values:

  ```
  typedef enum VkSubpassContents {
      VK_SUBPASS_CONTENTS_INLINE = 0,
      VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS = 1,
  } VkSubpassContents;
  ```

  If *contents* is `VK_SUBPASS_CONTENTS_INLINE`, 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. If *contents* is `VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS`, 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`**.

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

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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary	Outside	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 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

- *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
- If *clearValueCount* is not 0, *pClearValues* must be a pointer to an array of *clearValueCount* VkClearValue unions
- Both of *framebuffer*, and *renderPass* must have been created, allocated, or retrieved from the same VkDevice
- *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

To query the render area granularity, call:

```
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. Similarly, pipeline barriers are valid even if their effect extends outside the render area.

Valid Usage

- *device* must be a valid `VkDevice` handle
- *renderPass* must be a valid `VkRenderPass` handle
- *pGranularity* must be a 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

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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary	Inside	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

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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary	Inside	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

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

- *sType* must be `VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO`
- *pNext* must be `NULL`
- *flags* must be `0`
- *pCode* must be a pointer to an array of $\frac{codeSize}{4}$ `uint32_t` values
- *codeSize* must be greater than 0
- *codeSize* must be a multiple of 4. If the `VK_NV_glsl_shader extension` is enabled and *pCode* references GLSL code *codeSize* can be a multiple of 1
- *pCode* must point to valid SPIR-V code, formatted and packed as described by the [Khronos SPIR-V Specification]. If the `VK_NV_glsl_shader` extension is enabled *pCode* can instead reference valid GLSL code and must be written to the `GL_KHR_vulkan_glsl` extension specification
- *pCode* must adhere to the validation rules described by the Validation Rules within a Module section of the SPIR-V Environment appendix. If the `VK_NV_glsl_shader` extension is enabled *pCode* can be valid GLSL code with respect to the `GL_KHR_vulkan_glsl` GLSL extension specification
- *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

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

- `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 pointer to a valid `VkAllocationCallbacks` structure
- If `shaderModule` is a valid handle, it must have been created, allocated, or retrieved from `device`
- 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`

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 primitive 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 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.

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.

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.

The number of fragment shader invocations produced per-pixel is determined as follows:

- If per-sample shading is enabled, the fragment shader is invoked once per covered sample.
- Otherwise, the fragment shader is invoked at least once per fragment but no more than once per covered sample.

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.

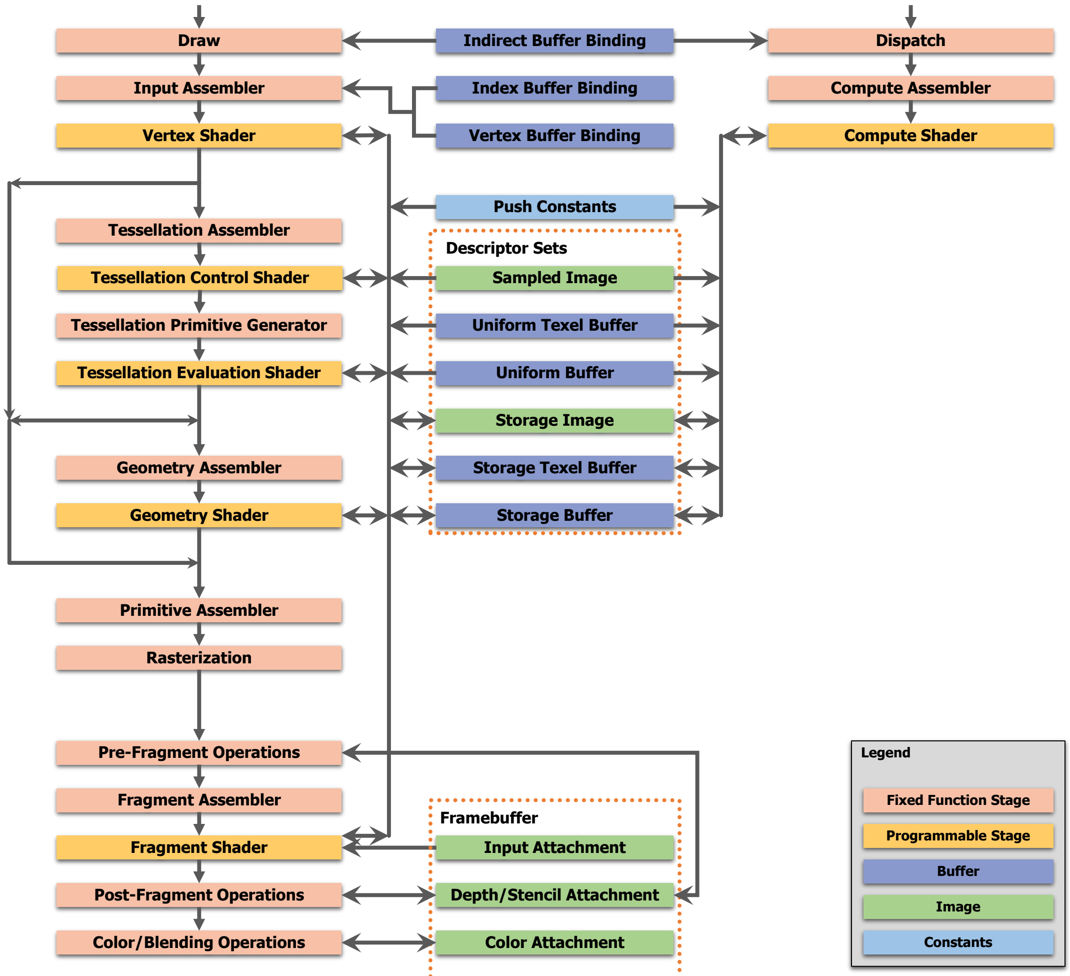


Figure 9.1: Block diagram of the Vulkan pipeline

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

- *`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 pointer to an array of *createInfoCount* valid VkComputePipelineCreateInfo structures
- If *pAllocator* is not NULL, *pAllocator* must be a pointer to a valid VkAllocationCallbacks structure
- *pPipelines* must be a 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*
- If the *flags* member of any given 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

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* provides options for pipeline creation, and is of type VkPipelineCreateFlagBits.
- *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

- *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`
- 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 *basePipelineIndex* is not `-1`, it must be a valid index into the calling command's *pCreateInfos* parameter
- If *flags* contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and *basePipelineHandle* is not `VK_NULL_HANDLE`, *basePipelineIndex* must be `-1`
- If *flags* contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and *basePipelineHandle* is not `VK_NULL_HANDLE`, *basePipelineHandle* must be a valid `VkPipeline` handle
- If *flags* contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and *basePipelineHandle* is not `VK_NULL_HANDLE`, it must be a valid handle to a compute `VkPipeline`
- 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 all shaders specified in *pStages*

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* names a single pipeline stage. Bits which can be set include:

```
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;
```

- *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

- *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 string
- If *pSpecializationInfo* is not NULL, *pSpecializationInfo* must be a pointer to a valid VkSpecializationInfo structure
- 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

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

- *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 pointer to an array of *createInfoCount* valid `VkGraphicsPipelineCreateInfo` structures
- If *pAllocator* is not `NULL`, *pAllocator* must be a pointer to a valid `VkAllocationCallbacks` structure
- *pPipelines* must be a 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*
- If the *flags* member of any given 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

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` controlling how the pipeline will be generated, as described below.
- *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, or `NULL` 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, or `NULL` 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`, or `NULL` if the pipeline has rasterization disabled.
- *pDepthStencilState* is a pointer to an instance of the `VkPipelineDepthStencilStateCreateInfo` structure, or `NULL` 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, or NULL 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 can 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 *renderPass* 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.

Bits which can be set in *flags* 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.
* 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.

pDynamicState points to a structure of type VkPipelineDynamicStateCreateInfo.

Valid Usage

* *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 pointer to an array of *stageCount* valid VkPipelineShaderStageCreateInfo structures
- *pVertexInputState* must be a pointer to a valid VkPipelineVertexInputStateCreateInfo structure
- *pInputAssemblyState* must be a pointer to a valid VkPipelineInputAssemblyStateCreateInfo structure
- *pRasterizationState* must be a pointer to a valid VkPipelineRasterizationStateCreateInfo structure
- If *pDynamicState* is not NULL, *pDynamicState* must be a 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
- 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 *basePipelineIndex* is not -1, it must be a valid index into the calling command's *pCreateInfos* parameter
- If *flags* contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and *basePipelineHandle* is not VK_NULL_HANDLE, *basePipelineIndex* must be -1
- If *flags* contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and *basePipelineHandle* is not VK_NULL_HANDLE, *basePipelineHandle* must be a valid VkPipeline handle
- If *flags* contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and *basePipelineHandle* is not VK_NULL_HANDLE, it must be a valid handle to a graphics VkPipeline
- 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 any given 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 not be NULL
- 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 *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*, and *pDepthStencilState* is not NULL, the *depthWriteEnable* member of *pDepthStencilState* must be VK_FALSE

- If *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*, and *pDepthStencilState* is not NULL, the *failOp*, *passOp* and *depthFailOp* members of each of the *front* and *back* members of *pDepthStencilState* must be VK_STENCIL_OP_KEEP

- If *pColorBlendState* is not NULL, the *blendEnable* member of each element of the *pAttachment* member of *pColorBlendState* must be VK_FALSE if the *format* of the attachment referred to in *subpass* of *renderPass* 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 *pColorBlendState* is not NULL, 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 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 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 pointer to a valid VkPipelineViewportStateCreateInfo structure
- If the *rasterizerDiscardEnable* member of *pRasterizationState* is VK_FALSE, *pMultisampleState* must be a 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 pointer to a valid VkPipelineDepthStencilStateCreateInfo structure
- If the *rasterizerDiscardEnable* member of *pRasterizationState* is VK_FALSE, and *subpass* uses color attachments, *pColorBlendState* must be a 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 *pDepthStencil* is VK_TRUE, the *depthBiasClamp* member of *pDepthStencil* must be 0.0
- If no element of the *pDynamicStates* member of *pDynamicState* is VK_DYNAMIC_STATE_DEPTH_BOUNDS, and the *depthBoundsTestEnable* member of *pDepthStencil* is VK_TRUE, the *minDepthBounds* and *maxDepthBounds* members of *pDepthStencil* 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 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 enums which indicate which pieces of pipeline state will use the values from dynamic state commands rather than from the pipeline state creation info.

Valid Usage

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

The source of difference pieces of dynamic state is determined by the VkPipelineDynamicStateCreateInfo::*pDynamicStates* property of the currently active pipeline, which takes the following 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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 indicates 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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *pipeline* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

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

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

```
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

- *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 pointer to an array of *initialDataSize* bytes
- 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**

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

- *device* must be a valid VkDevice handle
- *dstCache* must be a valid VkPipelineCache handle
- *pSrcCaches* must be a 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*
- *dstCache* must not appear in the list of source caches

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 *pipelineCache* is passed to another command between them, or a pipeline created using *pipelineCache* is destroyed.

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 9.1: 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 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. This field is interpreted as a VkPipelineCacheHeaderVersion value, and must have one of the following values:

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

- *device* must be a valid `VkDevice` handle
- *pipelineCache* must be a valid `VkPipelineCache` handle
- *pDataSize* must be a pointer to a `size_t` value
- If the value referenced by *pDataSize* is not `0`, and *pData* is not `NULL`, *pData* must be a 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`

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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *pipelineCache* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

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

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

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* specifies the bind point, and must have one of the values

```
typedef enum VkPipelineBindPoint {
    VK_PIPELINE_BIND_POINT_GRAPHICS = 0,
    VK_PIPELINE_BIND_POINT_COMPUTE = 1,
} VkPipelineBindPoint;
```

  specifying whether *pipeline* will be bound as a compute (VK_PIPELINE_BIND_POINT_COMPUTE) or graphics (VK_PIPELINE_BIND_POINT_GRAPHICS) pipeline. There are separate bind points for each of graphics and compute, so 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 vkCmdDraw, vkCmdDrawIndexed, vkCmdDrawIndirect, and vkCmdDrawIndexedIndirect. No other commands are affected by the pipeline state.

Valid Usage

- *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
- 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

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS COMPUTE

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 pointer to a valid user-defined PFN_vkAllocationFunction
- *pfnReallocation* must be a pointer to a valid user-defined PFN_vkReallocationFunction
- *pfnFree* must be a 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 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 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 $\min(\text{original size}, \text{new size}) - 1$ 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 the requested type of an allocation.
- *allocationScope* is a VkSystemAllocationScope value specifying the 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 the requested type of an allocation.
- *allocationScope* is a VkSystemAllocationScope value specifying the scope of the lifetime of the allocation, as described here.

Each allocation has a *scope* which defines its lifetime and which object it is associated with. The scope is provided in the *allocationScope* parameter passed to callbacks defined in VkAllocationCallbacks. Possible values for this parameter are defined by VkSystemAllocationScope:

```
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 - The allocation is scoped to the duration of the Vulkan command.

- VK_SYSTEM_ALLOCATION_SCOPE_OBJECT - The allocation is scoped to the lifetime of the Vulkan object that is being created or used.
- VK_SYSTEM_ALLOCATION_SCOPE_CACHE - The allocation is scoped to the lifetime of a VkPipelineCache object.
- VK_SYSTEM_ALLOCATION_SCOPE_DEVICE - The allocation is scoped to the lifetime of the Vulkan device.
- VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE - 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 a 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 scope available:

- If an allocation is scoped to the duration of a command, the allocator will use the VK_SYSTEM_ALLOCATION_SCOPE_COMMAND 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 scope. The most specific allocator available is used (pipeline 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 a 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 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 a 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 - The allocation is intended for execution by the host.

An implementation must only make calls into an application-provided allocator from within the scope 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:

- Host memory scoped to the lifetime of a `VkDevice` or `VkInstance` may be allocated from any API command.
- Host memory scoped to the duration of a command may be allocated from any API command.
- Host memory scoped to the lifetime of a `VkPipelineCache` may only be allocated from:
  - **`vkCreatePipelineCache`**
  - **`vkMergePipelineCaches`** for *`dstCache`*
  - **`vkCreateGraphicsPipelines`** for *`pPipelineCache`*
  - **`vkCreateComputePipelines`** for *`pPipelineCache`*
- Host memory scoped to the lifetime of 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`**
- Host memory scoped to the lifetime of 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`

- Host memory scoped to the lifetime of any other object may only be allocated in that object's **`vkCreate*`** command.

`pfnFree` may be called in the following situations:

- Host memory scoped to the lifetime of a `VkDevice` or `VkInstance` may be freed from any API command.
- Host memory scoped to the duration of a command must be freed by any API command which allocates such memory.
- Host memory scoped to the lifetime of a `VkPipelineCache` may be freed from **`vkDestroyPipelineCache`**.
- Host memory scoped to the lifetime of a `VkDescriptorPool` may be freed from
  - any command that takes the pool as a direct argument
- Host memory scoped to the lifetime of a `VkCommandPool` may be freed from:
  - any command that takes the pool as a direct argument
  - **`vkResetCommandBuffer`** whose *`commandBuffer`* was allocated from that `VkCommandPool`
- Host memory scoped to the lifetime of 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 opaque images that can be natively used by the device, or uniform buffer objects that reside in on-device memory.

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

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

The `VkPhysicalDeviceMemoryProperties` structure is defined as:

```c
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 *pMemoryRanges* 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 *pMemoryRanges* 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*.

The memory types are sorted according to a preorder which serves to aid in easily selecting an appropriate memory type. Given two memory types X and Y, the preorder defines $X \leq Y$ if:

- the memory property bits set for X are a strict subset of the memory property bits set for Y. Or,
- the memory property bits set for X are the same as the memory property bits set for Y, and X uses a memory heap with greater or equal performance (as determined in an implementation-specific manner).

Memory types are ordered in the list such that X is assigned a lesser *memoryTypeIndex* than Y if $X \leq Y \wedge \neg(Y \leq X)$ according to the preorder. Note that the list of all allowed memory property flag combinations above satisfies this preorder, but other orders would as well. The goal of this ordering is to enable applications to use a simple search loop in selecting the proper memory type, along the lines of:

```
// Find a memory type in "memoryTypeBits" that includes all of "properties"
int32_t FindProperties(uint32_t memoryTypeBits, VkMemoryPropertyFlags properties)
{
    for (int32_t i = 0; i < memoryTypeCount; ++i)
    {
        if ((memoryTypeBits & (1 << i)) &&
            ((memoryTypes[i].propertyFlags & properties) == properties))
            return i;
    }
    return -1;
}

// Try to find an optimal memory type, or if it does not exist
// find any compatible memory type
VkMemoryRequirements memoryRequirements;
vkGetImageMemoryRequirements(device, image, &memoryRequirements);
int32_t memoryType = FindProperties(memoryRequirements.memoryTypeBits,  ↩
    optimalProperties);
if (memoryType == -1)
    memoryType = FindProperties(memoryRequirements.memoryTypeBits, requiredProperties) ↩
        ;
```

The loop will find the first supported memory type that has all bits requested in **properties** set. If there is no exact match, it will find a closest match (i.e. a memory type with the fewest additional bits set), which has some additional bits set but which are not detrimental to the behaviors requested by **properties**. The application can first search for the optimal properties, e.g. a memory type that is device-local or supports coherent cached accesses, as appropriate for the intended usage, and if such a memory type is not present can fallback to searching for a less optimal but guaranteed set of properties such as "0" or "host-visible and coherent".

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 attribute flags for the heap. The bits specified in *flags* are:

```
typedef enum VkMemoryHeapFlagBits {
    VK_MEMORY_HEAP_DEVICE_LOCAL_BIT = 0x00000001,
} VkMemoryHeapFlagBits;
```

  – if *flags* contains VK_MEMORY_HEAP_DEVICE_LOCAL_BIT, it means 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.

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 properties for this memory type. The bits specified in *propertyFlags* 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;
```

  – if *propertyFlags* has the VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT bit set, memory allocated with this type is the most efficient for device access. This property will only be set for memory types belonging to heaps with the VK_MEMORY_HEAP_DEVICE_LOCAL_BIT set.
  – if *propertyFlags* has the VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT bit set, memory allocated with this type can be mapped using vkMapMemory so that it can be accessed on the host.
  – if *propertyFlags* has the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT bit set, host cache management commands **vkFlushMappedMemoryRanges** and **vkInvalidateMappedMemoryRanges** are not needed to make host writes visible to the device or device writes visible to the host, respectively.
  – if *propertyFlags* has the VK_MEMORY_PROPERTY_HOST_CACHED_BIT bit set, 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.
  – if *propertyFlags* has the VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT bit set, 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.

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

Memory objects are represented by VkDeviceMemory handles:

```
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 by 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.

There is an implementation-dependent maximum number of memory allocations which can be simultaneously created on a device. This is specified by the maxMemoryAllocationCount member of the VkPhysicalDeviceLimits structure. If *maxMemoryAllocationCount* is exceeded, **vkAllocateMemory** will return VK_ERROR_TOO_MANY_OBJECTS.

Note
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 should be returned.

Valid Usage

- *device* must be a valid VkDevice handle
- *pAllocateInfo* must be a pointer to a valid VkMemoryAllocateInfo structure
- If *pAllocator* is not NULL, *pAllocator* must be a pointer to a valid VkAllocationCallbacks structure
- *pMemory* must be a pointer to a VkDeviceMemory handle
- The number of currently valid memory objects, allocated from *device*, must be less than VkPhysicalDeviceLimits::*maxMemoryAllocationCount*

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 the memory type index, which selects the properties of the memory to be allocated, as well as the heap the memory will come from.

Valid Usage

- *sType* must be VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO
- *pNext* must be NULL
- *allocationSize* must be less than or equal to the amount of memory available to the VkMemoryHeap specified by *memoryTypeIndex* and the calling command's VkDevice
- *allocationSize* must be greater than 0

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 queued for execution. 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.

Valid Usage

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *memory* is a valid handle, it must have been created, allocated, or retrieved from *device*
- All submitted commands that refer to *memory* (via images or buffers) must have completed execution

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.

`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

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

- *memory* must be a valid VkDeviceMemory handle
- *flags* must be 0
- *ppData* must be a pointer to a pointer
- *memory* must have been created, allocated, or retrieved from *device*
- *memory* must not currently be 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

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

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 performance cost.

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` must be used to guarantee that host writes to non-coherent memory are visible to the device. It must be called after the host writes to non-coherent memory have completed and before command buffers that will read or write any of those memory locations are submitted to a queue.

Valid Usage

- *`device`* must be a valid `VkDevice` handle
- *`pMemoryRanges`* must be a 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 must be used to guarantee that device writes to non-coherent memory are visible to the host. It must be called after command buffers that execute and flush (via memory barriers) the device writes have completed, and before the host will read or write any of those locations. If a range of non-coherent memory is written by the host and then invalidated without first being flushed, its contents are undefined.

Valid Usage

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

- *sType* must be VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE
- *pNext* must be NULL
- *memory* must be a valid VkDeviceMemory handle
- *memory* must currently be 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*
- *offset* must be a multiple of VkPhysicalDeviceLimits::*nonCoherentAtomSize*
- If *size* is not equal to VK_WHOLE_SIZE, *size* must be a multiple of VkPhysicalDeviceLimits::*nonCoherentAtomSize*

Host-visible memory types that advertise the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT property still require memory barriers between host and device in order to be coherent, but do not require additional cache management operations to achieve coherency. For host writes to be seen by subsequent command buffer operations, a pipeline barrier from a source of VK_ACCESS_HOST_WRITE_BIT and VK_PIPELINE_STAGE_HOST_BIT to a destination of the relevant device pipeline stages and access types must be performed. Note that such a barrier is performed implicitly upon each command buffer submission, so an explicit barrier is only rarely needed (e.g. if a command buffer waits upon an event signaled by the host, where the host wrote some data after submission). For device writes to be seen by subsequent host reads, a pipeline barrier is required to make the writes visible.

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

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

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

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

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

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

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 describing additional parameters of the buffer. See `VkBufferCreateFlagBits` below for a description of the supported bits.
- `size` is the size in bytes of the buffer to be created.
- `usage` is a bitmask describing the allowed usages of the buffer. See `VkBufferUsageFlagBits` below for a description of the supported bits.

- *sharingMode* is the sharing mode of the buffer when it will be accessed by multiple queue families, see `VkSharingMode` in the Resource Sharing section below for supported values.
- *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`).

Bits which can be set in *usage* 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` indicates 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` indicates that the buffer can be used as the destination of a transfer command.
- `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT` indicates 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` indicates 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` indicates 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` indicates 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` indicates that the buffer is suitable for passing as the *buffer* parameter to **vkCmdBindIndexBuffer**.
- `VK_BUFFER_USAGE_VERTEX_BUFFER_BIT` indicates that the buffer is suitable for passing as an element of the *pBuffers* array to **vkCmdBindVertexBuffers**.
- `VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT` indicates that the buffer is suitable for passing as the *buffer* parameter to **vkCmdDrawIndirect**, **vkCmdDrawIndexedIndirect**, or **vkCmdDispatchIndirect**.

Any combination of bits can be specified for *usage*, but at least one of the bits must be set in order to create a valid buffer.

Bits which can be set in *flags* are:

```
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;
```

These bits have the following meanings:

- `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` indicates that the buffer will be backed using sparse memory binding.
- `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` indicates 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` indicates 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.

Valid Usage

- *`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
- *`size`* must be greater than `0`
- If *`sharingMode`* is `VK_SHARING_MODE_CONCURRENT`, *`pQueueFamilyIndices`* must be a pointer to an array of *`queueFamilyIndexCount`* `uint32_t` values
- If *`sharingMode`* is `VK_SHARING_MODE_CONCURRENT`, *`queueFamilyIndexCount`* must be greater than `1`
- 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`

To destroy a buffer, call:

```
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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *buffer* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

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

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

- *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
- *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`
  - *range* must be a multiple of the element size of *format*
  - *range* divided by the size of an element of *format*, must be less than or equal to `VkPhysicalDeviceLimits`::*maxTexelBufferElements*
  - 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**

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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *bufferView* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

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

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

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkImageCreateInfo structure is defined as:

```
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 describing additional parameters of the image. See VkImageCreateFlagBits below for a description of the supported bits.
- *imageType* is a VkImageType specifying the basic dimensionality of the image, as described below. 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 specifying the tiling arrangement of the data elements in memory, as described below.
- *usage* is a bitmask describing the intended usage of the image. See VkImageUsageFlagBits below for a description of the supported bits.
- *sharingMode* is the sharing mode of the image when it will be accessed by multiple queue families, and must be one of the values described for VkSharingMode in the Resource Sharing section below.
- *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* selects the initial VkImageLayout state of all image subresources of the image. See Image Layouts. *initialLayout* must be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

Valid limits for the image *extent*, *mipLevels*, *arrayLayers* and *samples* members are queried with the vkGetPhysicalDeviceImageFormatProperties command.

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 determine the specific capabilities of an implementation, query the valid *usage* bits by calling vkGetPhysicalDeviceFormatProperties and the valid limits for *mipLevels* and *arrayLayers* by calling vkGetPhysicalDeviceImageFormatProperties.

Valid Usage

- *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
- If *sharingMode* is `VK_SHARING_MODE_CONCURRENT`, *pQueueFamilyIndices* must be a pointer to an array of *queueFamilyIndexCount* `uint32_t` values
- If *sharingMode* is `VK_SHARING_MODE_CONCURRENT`, *queueFamilyIndexCount* must be greater than `1`
- *format* must not be `VK_FORMAT_UNDEFINED`
- The *width*, *height*, and *depth* members of *extent* must all 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*, *type*, *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*, *type*, *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*, *type*, *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*, *type*, *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 $\lfloor \log_2(\max(extent.width, extent.height, extent.depth)) \rfloor + 1$
- If any of `extent.width`, `extent.height`, or `extent.depth` are greater than the equivalently named members of `VkPhysicalDeviceLimits`::`maxImageDimension3D`, `mipLevels` must be less than or equal to `VkImageFormatProperties`::`maxMipLevels` (as returned by **vkGetPhysicalDeviceImageFormatProperties** with `format`, `type`, `tiling`, `usage`, and `flags` equal to those in this structure)
- `arrayLayers` must be less than or equal to `VkPhysicalDeviceLimits`::`maxImageArrayLayers`, or `VkImageFormatProperties`::`maxArrayLayers` (as returned by **vkGetPhysicalDeviceImageFormatProperties** with `format`, `type`, `tiling`, `usage`, and `flags` equal to those in this structure) - whichever is higher
- 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` mustnot: 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`
- `samples` must be a bit value that is set in `VkImageFormatProperties`::`sampleCounts` returned by **vkGetPhysicalDeviceImageFormatProperties** with `format`, `type`, `tiling`, `usage`, and `flags` equal to those in this structure
- If the ETC2 texture compression feature is not enabled, `format` must not be `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`, or `VK_FORMAT_EAC_R11G11_SNORM_BLOCK`
- If the ASTC LDR texture compression feature is not enabled, `format` must not be `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, or VK_FORMAT_ASTC_12x12_SRGB_BLOCK

- If the BC texture compression feature is not enabled, *format* must not be 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, or VK_FORMAT_BC7_SRGB_BLOCK
- 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 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

The intended usage of an image is specified by the bitmask VkImageCreateInfo::*usage*. Bits which can be set include:

```
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;
```

These bits have the following meanings:

- VK_IMAGE_USAGE_TRANSFER_SRC_BIT indicates that the image can be used as the source of a transfer command.
- VK_IMAGE_USAGE_TRANSFER_DST_BIT indicates that the image can be used as the destination of a transfer command.
- VK_IMAGE_USAGE_SAMPLED_BIT indicates 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 indicates 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 indicates 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 indicates 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 indicates that the memory bound to this image will have been allocated with the VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT (see Chapter 10 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 indicates 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.

Additional parameters of an image are specified by VkImageCreateInfo::*flags*. Bits which can be set include:

```
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;
```

These bits have the following meanings:

- VK_IMAGE_CREATE_SPARSE_BINDING_BIT indicates that the image will be backed using sparse memory binding.
- VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT indicates 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 indicates 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 indicates that the image can be used to create a VkImageView with a different format from the image.
- VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT indicates 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.

The basic dimensionality of an image is specified by `VkImageCreateInfo`::*`imageType`*, which must be one of the values

```
typedef enum VkImageType {
    VK_IMAGE_TYPE_1D = 0,
    VK_IMAGE_TYPE_2D = 1,
    VK_IMAGE_TYPE_3D = 2,
} VkImageType;
```

These values specify one-, two-, or three-dimensional images, respectively.

The tiling arrangement of data elements in an image is specified by `VkImageCreateInfo`::*`tiling`*, which must be one of the values

```
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), and `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

- *`device`* must be a valid `VkDevice` handle
- *`image`* must be a valid `VkImage` handle

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

- *aspectMask* must be a valid combination of `VkImageAspectFlagBits` values
- *aspectMask* must not be `0`
- *mipLevel* must be less than the *mipLevels* specified in `VkImageCreateInfo` when the image was created
- *arrayLayer* must be less than the *arrayLayers* specified in `VkImageCreateInfo` when the image was created

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*texelSize + ↩
    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

- *`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 pointer to a valid `VkAllocationCallbacks` structure
- If *`image`* is a valid handle, it must have been created, allocated, or retrieved from *`device`*
- 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`

Host Synchronization

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

11.4 Image Layouts

Images are stored in implementation-dependent opaque layouts in memory. Implementations may support several opaque layouts, and the layout used at any given time is determined by the `VkImageLayout` state of the image subresource. Each layout has limitations on what kinds of operations are supported for image subresources using the layout. 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 Section 6.5.6), or as part of a subpass dependency within a render pass (see `VkSubpassDependency`). The image layout state 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:

```
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`: Supports no 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`: Supports no 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.

* `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 Chapter 17 and Chapter 18). 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 Section 13.2.4). 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 table below. 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. The remaining parameters are contained in the *pCreateInfo*.

Valid Usage

- *device* must be a valid `VkDevice` handle
- *pCreateInfo* must be a pointer to a valid `VkImageViewCreateInfo` structure
- If *pAllocator* is not `NULL`, *pAllocator* must be a pointer to a valid `VkAllocationCallbacks` structure
- *pView* must be a 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 the type of the image view.
- *format* is a `VkFormat` describing the format and type used to interpret data elements in the image.
- *components* specifies a remapping of color components (or of depth or stencil components after they have been converted into color components). See `VkComponentMapping`.
- *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.

Table 11.1: Image and image view parameter compatibility requirements

Dim, Arrayed, MS	**Image parameters**	**View parameters**
1D, 0, 0	imageType = `VK_IMAGE_TYPE_1D` width >= 1 height = 1 depth = 1 arrayLayers >= 1 samples = 1	viewType = `VK_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_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_VIEW_TYPE_2D` baseArrayLayer >= 0 layerCount = 1

Table 11.1: (continued)

Dim, Arrayed, MS	Image parameters	View parameters
2D, 1, 0	imageType = VK_IMAGE_TYPE_2D width >= 1 height >= 1 depth = 1 arrayLayers >= 1 samples = 1	viewType = VK_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_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_VIEW_TYPE_2D_ARRAY baseArrayLayer >= 0 layerCount >= 1
CUBE, 0, 0	imageType = VK_IMAGE_TYPE_2D width >= 1 height = width depth = 1 arrayLayers >= 6 samples = 1 flags include VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT	viewType = VK_VIEW_TYPE_CUBE baseArrayLayer >= 0 layerCount = 6
CUBE, 1, 0	imageType = VK_IMAGE_TYPE_2D width >= 1 height = width depth = 1 N >= 1 arrayLayers >= $6 \times N$ samples = 1 flags include VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT	viewType = VK_VIEW_TYPE_CUBE_ARRAY baseArrayLayer >= 0 N >= 1 layerCount = $6 \times N$
3D, 0, 0	imageType = VK_IMAGE_TYPE_3D width >= 1 height >= 1 depth >= 1 arrayLayers = 1 samples = 1	viewType = VK_VIEW_TYPE_3D baseArrayLayer = 0 layerCount = 1

Valid Usage

- *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
- 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 the ETC2 texture compression feature is not enabled, *format* must not be 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, or VK_FORMAT_EAC_R11G11_SNORM_BLOCK
- If the ASTC LDR texture compression feature is not enabled, *format* must not be 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, or VK_FORMAT_ASTC_12x12_SRGB_BLOCK
- If the BC texture compression feature is not enabled, *format* must not be 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, or VK_FORMAT_BC7_SRGB_BLOCK
- 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*

- If *image* was created with VK_IMAGE_TILING_LINEAR and *usage* containing 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* containing 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* containing 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* containing 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* containing 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* containing 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* containing 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* containing 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* must be a valid image subresource range for *image* (see Section 11.5)
- 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*

- *subResourceRange* and *viewType* must be compatible with the image, as described in the compatibility table

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 indicating which aspect(s) of the image are included in the view. See `VkImageAspectFlagBits`.
- *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 is a bitmask indicating the format being used. Bits which may be set include:

```
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;
```

The mask 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

- *aspectMask* must be a valid combination of VkImageAspectFlagBits values
- *aspectMask* must not be 0
- If *levelCount* is not VK_REMAINING_MIP_LEVELS, $(baseMipLevel + levelCount)$ must be less than or equal to the *mipLevels* specified in VkImageCreateInfo when the image was created
- If *layerCount* is not VK_REMAINING_ARRAY_LAYERS, $(baseArrayLayer + layerCount)$ must be less than or equal to the *arrayLayers* specified in VkImageCreateInfo when the image was created

The VkComponentMapping structure is defined as:

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

- *r* determines the component value placed in the R component of the output vector.
- *g* determines the component value placed in the G component of the output vector.
- *b* determines the component value placed in the B component of the output vector.
- *a* determines the component value placed in the A component of the output vector.

Each of *r*, *g*, *b*, and *a* is one of the values:

```
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: the component is set to the identity swizzle.
- VK_COMPONENT_SWIZZLE_ZERO: the component is set to zero.

- `VK_COMPONENT_SWIZZLE_ONE`: 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`: the component is set to the value of the R component of the image.
- `VK_COMPONENT_SWIZZLE_G`: the component is set to the value of the G component of the image.
- `VK_COMPONENT_SWIZZLE_B`: the component is set to the value of the B component of the image.
- `VK_COMPONENT_SWIZZLE_A`: 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 11.2: 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`

Valid Usage

- *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

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *imageView* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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 Section 10.2) 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 Chapter 28.

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

- `device` must be a valid `VkDevice` handle
- `buffer` must be a valid `VkBuffer` handle
- `pMemoryRequirements` must be a 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

- `device` must be a valid `VkDevice` handle
- `image` must be a valid `VkImage` handle
- `pMemoryRequirements` must be a 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`, 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 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**.
- The *memoryTypeBits* member is identical for all `VkImage` objects created with the same combination of values for the *tiling* member and 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.
- `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

- `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`
- `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*

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 a VkDeviceMemory object describing the device memory to attach.

* *memoryOffset* is the start offset of the region of *memory* which is to be bound to the image. The number of bytes returned in the VkMemoryRequirements::*size* member in *memory*, starting from *memoryOffset* bytes, will be bound to the specified image.

Valid Usage

* *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*
* *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*

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 buffer, linear image and optimal image resources must be placed in adjacent memory locations to avoid aliasing. Two resources which do not satisfy this granularity requirement are said to alias. Linear image resource are images created with VK_IMAGE_TILING_LINEAR and optimal image resources are those created with VK_IMAGE_TILING_OPTIMAL. *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**
> *bufferImageGranularity* is really a granularity between "linear" resources, including buffers and images with linear tiling, vs. "optimal" resources, i.e. images with optimal tiling. It would have been better named "linearOptimalGranularity".

Given resourceA at the lower memory offset and resourceB at the higher memory offset in the same VkDeviceMemory object, where one of the resources is a buffer or a linear image and the other is an optimal image, 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 buffer or a linear image is at adjacent memory location with an optimal image and both will be used simultaneously. Adjacent buffers' or adjacent images' memory ranges 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 transfer exclusive ownership of the range or image subresource between the source and destination queue families with the following sequence of operations:

1. Release exclusive ownership from the source queue family to the destination queue family.
2. Use semaphores to ensure proper execution control for the ownership transfer.
3. Acquire exclusive ownership for the destination queue family from the source queue family.

To release exclusive ownership of a range of a buffer or image subresource of an image object, the application must execute a buffer or image memory barrier, respectively (see `VkBufferMemoryBarrier` and `VkImageMemoryBarrier`) 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.

To acquire exclusive ownership, the application must execute the same buffer or image memory barrier on a queue from the destination queue family.

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. However, images still require a layout transition from `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED` before being used on the first queue. This layout transition can either be accomplished by an image memory barrier or by use in a render pass instance.

Once a queue family has used a range or image subresource of an `VK_SHARING_MODE_EXCLUSIVE` resource, its contents are undefined to other queue families unless ownership is transferred. The contents may also become undefined for other reasons, e.g. as a result of writes to an image subresource that aliases the same memory. A queue family can take ownership of a range or image subresource without an ownership transfer in the same way as for a resource that was just created, however doing so means any contents written by other queue families or via incompatible aliases are undefined.

11.8 Memory Aliasing

A range of a `VkDeviceMemory` allocation is *aliased* if it is bound to multiple resources simultaneously, via `vkBindImageMemory`, `vkBindBufferMemory`, or via sparse memory bindings. A memory range aliased between two images or two buffers is defined to be the intersection of the memory ranges bound to the two resources. A memory range aliased between two resources where one is a buffer or a linear image, and the other is an optimal image, is defined to be the intersection of the memory ranges bound to the two resources, where each range is first padded to be aligned to the *bufferImageGranularity*. 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. Opaque images and linear image subresources in other layouts are not host-accessible.

If two aliases are both host-accessible, then they interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

If either of two aliases is not host-accessible, then 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

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

```
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 the magnification filter to apply to lookups, and is of type:

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

- *minFilter* is the minification filter to apply to lookups, and is of type `VkFilter`.

- *mipmapMode* is the mipmap filter to apply to lookups as described in the Texel Filtering section, and is of type:

```
typedef enum VkSamplerMipmapMode {
    VK_SAMPLER_MIPMAP_MODE_NEAREST = 0,
    VK_SAMPLER_MIPMAP_MODE_LINEAR = 1,
} VkSamplerMipmapMode;
```

- *addressModeU* is the addressing mode for outside [0..1] range for U coordinate. See `VkSamplerAddressMode`.
- *addressModeV* is the addressing mode for outside [0..1] range for V coordinate. See `VkSamplerAddressMode`.
- *addressModeW* is the addressing mode for outside [0..1] range for W coordinate. See `VkSamplerAddressMode`.
- *mipLodBias* is the bias to be added to mipmap LOD calculation and bias provided by image sampling functions in SPIR-V, as described in the 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.
- *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 the comparison function to apply to fetched data before filtering as described in the Depth Compare Operation section. See `VkCompareOp`.
- *minLod* and *maxLod* are the values used to clamp the computed level-of-detail value, as described in the Level-of-Detail Operation section. *maxLod* must be greater than or equal to *minLod*.
- *borderColor* is the predefined border color to use, as described in the Texel Replacement section, and is of type:

```
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;
```

- *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.

---

addressModeU, *addressModeV*, and *addressModeW* must each have one of the following values:

```
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;
```

These values control 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.

- VK_SAMPLER_ADDRESS_MODE_REPEAT indicates that the repeat wrap mode will be used.
- VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT indicates that the mirrored repeat wrap mode will be used.
- VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE indicates that the clamp to edge wrap mode will be used.
- VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER indicates that the clamp to border wrap mode will be used.
- VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE indicates that the mirror clamp to edge wrap mode will be used. This is only valid if the VK_KHR_mirror_clamp_to_edge extension is enabled.

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

- *`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
- 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

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *sampler* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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 `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 %10 "myUniformTexelBuffer"
              OpDecorate %10 DescriptorSet m
              OpDecorate %10 Binding n
         %2 = OpTypeVoid
         %3 = OpTypeFunction %2
         %6 = OpTypeFloat 32
         %7 = OpTypeImage %6 Buffer 0 0 0 1 Unknown
         %8 = OpTypeSampledImage %7
         %9 = OpTypePointer UniformConstant %8
        %10 = OpVariable %9 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

- *device* must be a valid `VkDevice` handle
- *pCreateInfo* must be a pointer to a valid `VkDescriptorSetLayoutCreateInfo` structure
- If *pAllocator* is not `NULL`, *pAllocator* must be a pointer to a valid `VkAllocationCallbacks` structure
- *pSetLayout* must be a 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 reserved for future use.
- *bindingCount* is the number of elements in *pBindings*.
- *pBindings* is a pointer to an array of `VkDescriptorSetLayoutBinding` structures.

Valid Usage

- *sType* must be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO`
- *pNext* must be `NULL`
- *flags* must be `0`
- If *bindingCount* is not `0`, *pBindings* must be a pointer to an array of *bindingCount* valid `VkDescriptorSetLayoutBinding` structures

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. 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. However, all binding numbers between 0 and the maximum binding number 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

- `descriptorType` must be a valid `VkDescriptorType` value
- 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 pointer to an array of `descriptorCount` valid `VkSampler` handles
- If `descriptorCount` is not `0`, `stageFlags` must be a valid combination of `VkShaderStageFlagBits` values

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *descriptorSetLayout* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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

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

- *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 pointer to an array of *setLayoutCount* valid VkDescriptorSetLayout handles
- If *pushConstantRangeCount* is not 0, *pPushConstantRanges* must be a pointer to an array of *pushConstantRangeCount* valid VkPushConstantRange structures
- *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 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

- `stageFlags` must be a valid combination of `VkShaderStageFlagBits` values
- `stageFlags` must not be `0`
- `offset` must be less than `VkPhysicalDeviceLimits`::`maxPushConstantsSize`
- `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`

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 13.1: 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

Table 13.1: (continued)

Total Resources Available	Resource Types
	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

- *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 pointer to a valid VkAllocationCallbacks structure
- If *pipelineLayout* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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

Host Synchronization

- Host access to *pipelineLayout* must be externally synchronized

13.2.2.1 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 matching (the same, or 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

- *device* must be a valid `VkDevice` handle
- *pCreateInfo* must be a pointer to a valid `VkDescriptorPoolCreateInfo` structure
- If *pAllocator* is not `NULL`, *pAllocator* must be a pointer to a valid `VkAllocationCallbacks` structure
- *pDescriptorPool* must be a 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* specifies certain supported operations on the pool. Bits which can be set include:

  ```
  typedef enum VkDescriptorPoolCreateFlagBits {
      VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT = 0x00000001,
  } VkDescriptorPoolCreateFlagBits;
  ```

  If *flags* includes `VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT`, then 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.

- *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

- *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 pointer to an array of *poolSizeCount* valid VkDescriptorPoolSize structures
- *poolSizeCount* must be greater than 0
- *maxSets* must be greater than 0

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

- *type* must be a valid `VkDescriptorType` value
- *descriptorCount* must be greater than `0`

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *descriptorPool* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

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 array must be at least the length specified by the *descriptorSetCount* member of *pAllocateInfo*.

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

- *device* must be a valid `VkDevice` handle
- *pAllocateInfo* must be a pointer to a valid `VkDescriptorSetAllocateInfo` structure
- *pDescriptorSets* must be a 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:

```
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

- *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 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
- *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

To free allocated descriptor sets, call:

```
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

- *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*
- All submitted commands that refer to any element of *pDescriptorSets* must have completed execution
- *pDescriptorSets* must be a 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

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

- *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*
- All uses of *descriptorPool* (via any allocated descriptor sets) must have completed execution

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

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.

Valid Usage

- *device* must be a valid VkDevice handle
- If *descriptorWriteCount* is not 0, *pDescriptorWrites* must be a pointer to an array of *descriptorWriteCount* valid VkWriteDescriptorSet structures
- If *descriptorCopyCount* is not 0, *pDescriptorCopies* must be a 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. This behavior applies recursively, with the update affecting consecutive bindings as needed to update all *descriptorCount* descriptors. All consecutive bindings updated via a single `VkWriteDescriptorSet` structure must have identical *descriptorType* and *stageFlags*, and must all either use immutable samplers or must all not use immutable samplers.

Valid Usage

- *sType* must be `VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET`
- *pNext* must be `NULL`
- *dstSet* must be a valid `VkDescriptorSet` handle
- *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`
- *dstBinding* must be a valid binding point within *dstSet*
- *descriptorType* must match the type of *dstBinding* 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 *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 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 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 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 any given 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 any given element of *pImageInfo* must be a valid `VkImageView` and `VkImageLayout`, respectively

- If *descriptorType* is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, the *offset* member of any given 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 any given element of *pBufferInfo* must be a multiple of VkPhysicalDeviceLimits::*minStorageBufferOffsetAlignment*
- If *descriptorType* is VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, the *buffer* member of any given 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 any given 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 any given 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 any given 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 any given 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 any given 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 any given element of *pImageInfo* must have been created with the identity swizzle

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;
```

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, the elements of the VkWriteDescriptorSet::*pBufferInfo* array of VkDescriptorBufferInfo structures will be used to update the descriptors, and other arrays will be ignored.

If *descriptorType* is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, the VkWriteDescriptorSet::*pTexelBufferView* array will be used to update the descriptors, and other arrays will be ignored.

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, the elements of the VkWriteDescriptorSet::*pImageInfo* array of VkDescriptorImageInfo structures will be used to update the descriptors, and other arrays will be ignored.

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 using 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

- *buffer* must be a valid VkBuffer handle
- *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*

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 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

- 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

* *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`
* *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

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

- *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 pointer to an array of *descriptorSetCount* valid `VkDescriptorSet` handles
- If *dynamicOffsetCount* is not `0`, *pDynamicOffsets* must be a 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`
- Any given element of *pDescriptorSets* must have been allocated with a `VkDescriptorSetLayout` that matches (is the same as, or defined identically to) 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
- Any given element of *pDynamicOffsets* must satisfy the required alignment for the corresponding descriptor binding's descriptor type

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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

- *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 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
- *stageFlags* must match exactly the shader stages used in *layout* for the range specified by *offset* and *size*

- `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`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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

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 Table 14.1.

Table 14.1: 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

Table 14.1: (continued)

Shader Interface	Locations Available
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 Section 20.1.1 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 Section 26.1, 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 Section 2.8.1; otherwise no type conversion is applied. 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 Section 13.1.11 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, 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, 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 declaration must refer to the same type of resource as is indicated by the *descriptorType*. See Shader Resource and Descriptor Type Correspondence for the relationship between shader declarations and descriptor types.

Table 14.2: Shader Resource and Descriptor Type Correspondence

Resource type	Descriptor Type
sampler	VK_DESCRIPTOR_TYPE_SAMPLER
sampled image	VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE
storage image	VK_DESCRIPTOR_TYPE_STORAGE_IMAGE

Table 14.2: (continued)

Resource type	**Descriptor Type**
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 VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC
storage buffer	VK_DESCRIPTOR_TYPE_STORAGE_BUFFER VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC
input attachment	VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT

Table 14.3: 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 identified 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.

The range of descriptor sets is between zero and *`maxBoundDescriptorSets`* minus one. If a descriptor set value is statically used by an entry-point there must be an associated *`pSetLayout`* in the corresponding pipeline layout as described in Pipeline Layouts consistency.

If the **`Binding`** decoration is used with an array, the entire array is identified with 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.

The binding can be any 32-bit unsigned integer value, as described in Section 13.2.1. Each descriptor set has its own binding name space.

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.

If multiple entry-points in the same pipeline refer to the same set and binding, all variable definitions with that **`DescriptorSet`** and **`Binding`** must have the same basic type.

Not all descriptor sets and bindings specified in a pipeline layout need to be used in a particular shader stage or pipeline, but if a **`DescriptorSet`** and **`Binding`** decoration is specified for a variable that is statically used in that shader there must be a pipeline layout entry identified with that descriptor set and *`binding`* and the corresponding *`stageFlags`* must specify the appropriate `VkShaderStageFlagBits` for that stage.

Table 14.4: 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

Member variables 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, computed 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 vector of *C* matrix components
  - a column-major matrix has a base alignment equal to the base alignment of the matrix column type
- 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 immediately following a structure or an array must be greater than or equal to the next multiple of the base alignment of that structure or array.

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 the sample 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 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 a primitive is front or back facing. This variable is non-zero if the current fragment is considered to be part of a front-facing primitive and is zero if the fragment is considered to be part of a back-facing 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 the geometry shader will be directed. If a geometry shader entry-point's interface does not include a variable decorated with **Layer**, then the first layer is used. If a geometry 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.

In a fragment shader, a variable decorated with **Layer** contains the layer index of the primitive that the fragment invocation belongs to.

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, 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 parameters passed into `vkCmdDispatch` or read from the `VkDispatchIndirectCommand` structure read through a call to `vkCmdDispatchIndirect`.

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 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.

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 fragment, 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.

Any variable decorated with **PrimitiveId** must be declared as 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**, per-sample shading is enabled for draws that use that fragment shader.

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 $32 \times M + B$.

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`**, per-sample shading is enabled for draws that use that fragment shader.

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 the geometry shader will be directed. The selected viewport index is used to select the viewport transform and scissor rectangle. If a geometry shader entry-point's interface does not include a variable decorated with **`ViewportIndex`**, then the first viewport is used. If a geometry shader entry-point's interface includes a variable decorated with **`ViewportIndex`**, it must write the same value to **`ViewportIndex`** for all output vertices of a given primitive.

In a fragment shader, the variable decorated with **`ViewportIndex`** contains the viewport index of the primitive that the fragment invocation belongs to.

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, 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 zero to the values of the parameters passed into `vkCmdDispatch` or read from the `VkDispatchIndirectCommand` structure read through a call to `vkCmdDispatchIndirect`.

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 a variable with the **WorkgroupSize** built-in decoration will make that variable 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 level of detail used in the sampling operation based on the coordinates used in neighboring fragments.
  - Instructions with **`ExplicitLod`** in the name determine the level of detail 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.

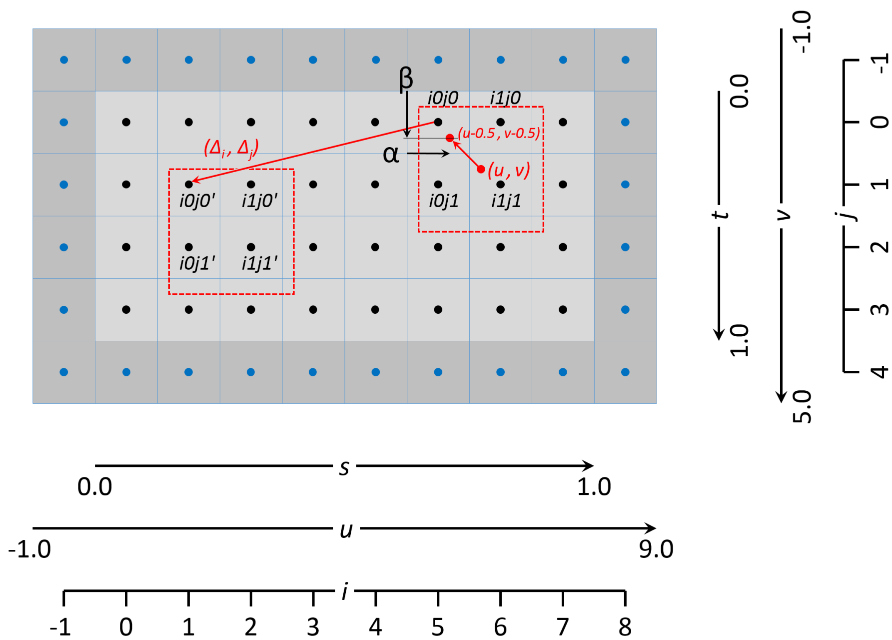
Unnormalized texel coordinates are referred to as (u, v, w, a), with the coordinates having the following meanings:

- 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.

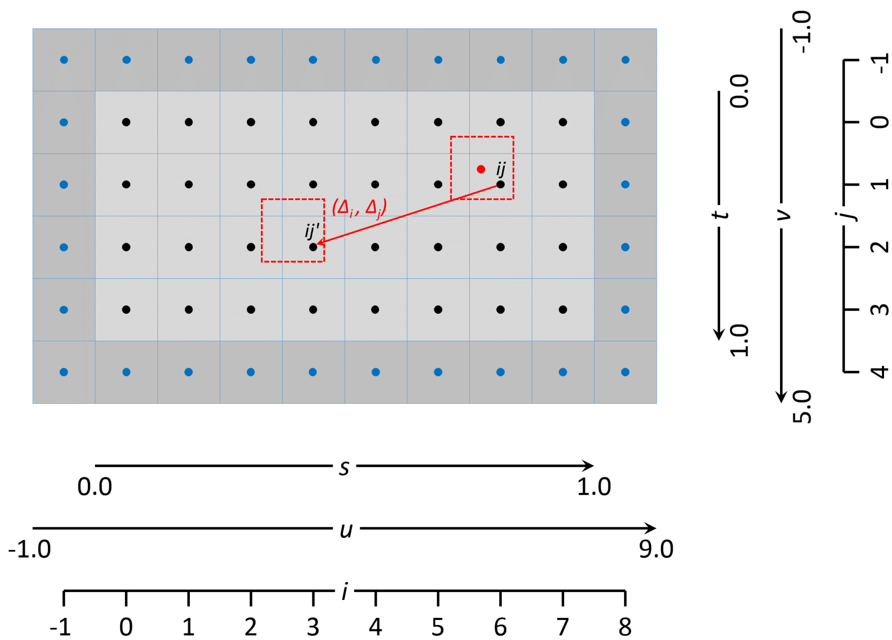
Integer texel coordinates are referred to as (i, j, k, l, n), and the first four in that order have the same meanings as unnormalized texel coordinates. They are extracted from the SPIR-V operand in order (i, [,j], [,k], [,l]), with j and k conditionally present based on the **Dim** of the image, and 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.



The Texel Coordinate Systems - For the example shown of an 8x4 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 i0j0, i1j0, i0j1 and i1j1.
  - The weights α and β.
  - Given the offset Δ_i and Δ_j, the four texels selected by the offset are i0j0’, i1j0’, i0j1’ and i1j1’.



The Texel Coordinate Systems - For the example shown of an 8x4 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:

$N = 9$	number of mantissa bits per component
$B = 15$	exponent bias
$E_{max} = 31$	maximum possible biased exponent value
$sharedexp_{max} = \frac{(2^N - 1)}{2^N} \times 2^{(E_{max} - B)}$	

> **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:

$$red_{shared} = \left\lfloor \frac{red_{clamped}}{2^{(exp_{shared}-B-N)}} + \frac{1}{2} \right\rfloor$$
$$green_{shared} = \left\lfloor \frac{green_{clamped}}{2^{(exp_{shared}-B-N)}} + \frac{1}{2} \right\rfloor$$
$$blue_{shared} = \left\lfloor \frac{blue_{clamped}}{2^{(exp_{shared}-B-N)}} + \frac{1}{2} \right\rfloor$$

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
- 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.

15.3.1.1 Instruction/Sampler/Image Validation

There are a number of cases where a SPIR-V instruction can mismatch with the sampler, the image, or both. There are a number of cases where the sampler can mismatch with the image. In such cases the value of the texel returned is undefined.

These cases include:

- The sampler `borderColor` is an integer type and the image `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 `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 `VkComponentSwizzle` for any of the `VkComponentMapping` components is not `VK_COMPONENT_SWIZZLE_IDENTITY`.
- 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 *format* is not one of the depth/stencil formats with a depth component, or the image 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.

15.3.1.2 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 satisfy any of the conditions

$$\begin{aligned} i &< 0 & i &\geq w_s \\ j &< 0 & j &\geq h_s \\ k &< 0 & k &\geq d_s \\ l &< 0 & l &\geq layers \\ n &< 0 & n &\geq samples \end{aligned}$$

where:

$$\begin{aligned} w_s &= \text{width of the image level} \\ h_s &= \text{height of the image level} \\ d_s &= \text{depth of the image level} \\ layers &= \text{number of layers in the image} \\ samples &= \text{number of samples per texel in the image} \end{aligned}$$

then the texel fails integer texel coordinate validation.

There are four cases to consider:

- 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.
- 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.
- 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.
- 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.

15.3.1.3 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 the 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.

15.3.1.4 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 “KHR_DF_TRANSFER_SRGB” 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, or
- 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 15.1: 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 15.2: 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	$C_r = (B_r)$
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` property *residencyNonResidentStrict* is 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 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.

$$
\begin{aligned}
D &= 1.0 \quad \begin{cases} D_{ref} \leq D & \text{for LEQUAL} \\ D_{ref} \geq D & \text{for GEQUAL} \\ D_{ref} < D & \text{for LESS} \\ D_{ref} > D & \text{for GREATER} \\ D_{ref} = D & \text{for EQUAL} \\ D_{ref} \neq D & \text{for NOTEQUAL} \\ true & \text{for ALWAYS} \\ false & \text{for NEVER} \end{cases} \\
D &= 0.0 \quad \text{otherwise}
\end{aligned}
$$

where, in the depth comparison:

$$D_{ref} = shaderOp.D_{ref} \quad \text{(from optional SPIR-V operand)}$$
$$D \quad \text{texel depth value}$$

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 15.3: Texel Color After Conversion To RGBA

Texel Aspect or Format	**RGBA Color**
Depth aspect	$C_{rgba} = (D, 0, 0, one)$
Stencil aspect	$C_{rgba} = (S, 0, 0, one)$
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:

$C_{rgba}[R]$is the RED component
$C_{rgba}[G]$is the GREEN component
$C_{rgba}[B]$is the BLUE component
$C_{rgba}[A]$is the ALPHA component
$one = 1.0\text{f}$ for floating point components
$one = 1$ for integer components

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.

15.4.1.1 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` property *`residencyNonResidentStrict`* 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.

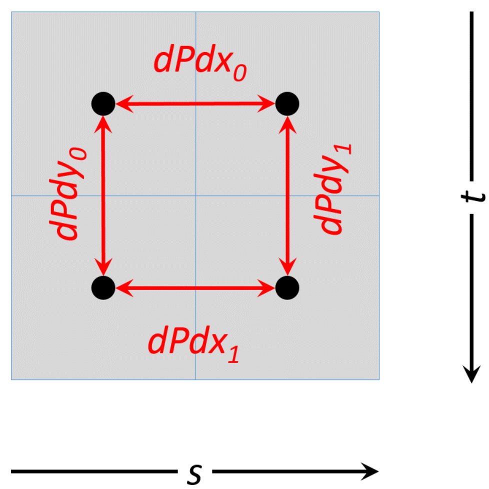
15.4.4 Texel Output Format Conversion

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.



Derivatives are computed as if there is a 2x2 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 2x2 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:

$$s = \frac{s}{q}, \qquad \text{for 1D, 2D, or 3D image}$$

$$t = \frac{t}{q}, \qquad \text{for 2D or 3D image}$$

$$r = \frac{r}{q}, \qquad \text{for 3D image}$$

$$D_{ref} = \frac{D_{ref}}{q}, \qquad \text{if provided}$$

15.6.2 Derivative Image Operations

Derivatives are used for level-of-detail 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 level-of-detail 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 15.4: Cube map face and coordinate selection

Major Axis Direction	**Layer Number**	**Cube Map Face**	s_c	t_c	r_c
$+r_x$	0	*PositiveX*	$-r_z$	$-r_y$	r_x
$-r_x$	1	*NegativeX*	$+r_z$	$-r_y$	r_x
$+r_y$	2	*PositiveY*	$+r_x$	$+r_z$	r_y
$-r_y$	3	*NegativeY*	$+r_x$	$-r_z$	r_y
$+r_z$	4	*PositiveZ*	$+r_x$	$-r_y$	r_z
$-r_z$	5	*NegativeZ*	$-r_x$	$-r_y$	r_z

Table 15.5: 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

Level-of-detail selection can be either explicit (provided explicitly by the image instruction) or implicit (determined from a scale factor calculated from the derivatives).

15.6.7.1 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:

$$\begin{aligned}
\partial t/\partial x = \partial t/\partial y = 0 & \qquad \text{(for 1D image)} \\
\partial r/\partial x = \partial r/\partial y = 0 & \qquad \text{(for 1D, 2D or Cube image)}
\end{aligned}$$

$$\begin{aligned}
w_{base} &= image.w \\
h_{base} &= image.h \\
d_{base} &= image.d \\
&\text{of the } baseMipLevel \qquad \text{(from image descriptor)}
\end{aligned}$$

The *scale factors* $(\rho_x, \rho y)$ should be calculated by:

$$\begin{aligned}
\rho_x &= \sqrt{m_{ux}^2 + m_{vx}^2 + m_{wx}^2} \\
\rho_y &= \sqrt{m_{uy}^2 + m_{vy}^2 + m_{wy}^2}
\end{aligned}$$

The ideal functions ρ_x and ρ_y may be approximated with functions f_x and f_y, subject to the following constraints:

$$\begin{aligned}
&f_x \text{ is continuous and monotonically increasing in each of } m_{ux}, m_{vx}, \text{ and } m_{wx} \\
&f_y \text{ is continuous and monotonically increasing in each of } m_{uy}, m_{vy}, \text{ and } m_{wy}
\end{aligned}$$

$$\begin{aligned}
\max\left(|m_{ux}|, |m_{vx}|, |m_{wx}|\right) \le & f_x \le |m_{ux}| + |m_{vx}| + |m_{wx}| \\
\max\left(|m_{uy}|, |m_{vy}|, |m_{wy}|\right) \le & f_y \le |m_{uy}| + |m_{vy}| + |m_{wy}|
\end{aligned}$$

The minimum and maximum scale factors (ρ_{min}, ρ_{max}) are determined by:

$$\begin{aligned}
\rho_{max} &= \max(\rho_x, \rho_y) \\
\rho_{min} &= \min(\rho_x, \rho_y)
\end{aligned}$$

The sampling rate is determined by:

$$N = \min\left(\left\lceil \frac{\rho_{max}}{\rho_{min}} \right\rceil, max_{Aniso}\right)$$

where:

$$\begin{aligned}
sampler.max_{Aniso} &= maxAnisotropy & \text{(from sampler descriptor)} \\
limits.max_{Aniso} &= maxSamplerAnisotropy & \text{(from physical device limits)} \\
max_{Aniso} &= \min\left(sampler.max_{Aniso}, limits.max_{Aniso}\right)
\end{aligned}$$

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.

15.6.7.2 Level-of-Detail Operation

The *level-of-detail* 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:

$$sampler.bias = mipLodBias \qquad \text{(from sampler descriptor)}$$

$$shaderOp.bias = \begin{cases} Bias & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases}$$

$$sampler.lod_{min} = minLod \qquad \text{(from sampler descriptor)}$$

$$shaderOp.lod_{min} = \begin{cases} MinLod & \text{(from optional SPIR-V operand)} \\ 0 & \text{otherwise} \end{cases}$$

$$lod_{min} = \max(sampler.lod_{min}, shaderOp.lod_{min})$$

$$lod_{max} = maxLod \qquad \text{(from sampler descriptor)}$$

and *maxSamplerLodBias* is the value of the `VkPhysicalDeviceLimits` feature maxSamplerLodBias.

15.6.7.3 Image Level(s) Selection

The image level(s) $d, d_{hi},$ and d_{lo} which texels are read from are selected based on the level-of-detail parameter, as follows. If the sampler's *`mipmapMode`* is `VK_SAMPLER_MIPMAP_MODE_NEAREST`, then level d is used:

$$d = \begin{cases} level_{base}, & \lambda \leq \frac{1}{2} \\ nearest(\lambda), & \lambda > \frac{1}{2}, level_{base} + \lambda \leq q + \frac{1}{2} \\ q, & \lambda > \frac{1}{2}, level_{base} + \lambda > q + \frac{1}{2} \end{cases}$$

where:

$$nearest(\lambda) = \begin{cases} \left\lceil level_{base} + \lambda + \frac{1}{2} \right\rceil - 1, & \text{preferred} \\ \left\lfloor level_{base} + \lambda + \frac{1}{2} \right\rfloor, & \text{alternative} \end{cases}$$

and

$q = levelCount - 1$

`levelCount` is taken from the *`subresourceRange`* of the image view.

If the sampler's *`mipmapMode`* is `VK_SAMPLER_MIPMAP_MODE_LINEAR`, two neighboring levels are selected:

$$d_{hi} = \begin{cases} q, & level_{base} + \lambda \geq q \\ \left\lfloor level_{base} + \lambda \right\rfloor, & \text{otherwise} \end{cases}$$

$$d_{lo} = \begin{cases} q, & level_{base} + \lambda \geq q \\ d_{hi} + 1, & \text{otherwise} \end{cases}$$

δ is the fractional value used for linear filtering between levels.

$$\delta = \text{frac}(\lambda)$$

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.

$$\begin{aligned}
u(x,y) &= s(x,y) \times width_{level} \\
v(x,y) &= \begin{cases} 0 & \text{for 1D images} \\ t(x,y) \times height_{level} & \text{otherwise} \end{cases} \\
w(x,y) &= \begin{cases} 0 & \text{for 2D or Cube images} \\ r(x,y) \times depth_{level} & \text{otherwise} \end{cases}
\end{aligned}$$

$$a(x,y) = \begin{cases} a(x,y) & \text{for array images} \\ 0 & \text{otherwise} \end{cases}$$

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:

$$l = \text{clamp}(\text{RNE}(a), 0, layerCount - 1) + baseArrayLayer$$

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:

$$\text{RNE}(a) = \begin{cases} \text{roundTiesToEven}(a) & \text{preferred, from IEEE Std 754-2008 Floating-Point Arithmetic} \\ \lfloor a + \frac{1}{2} \rfloor & \text{alternative} \end{cases}$$

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 $\alpha, \beta, and \gamma$.

$$
\begin{aligned}
i_0 &= \left\lfloor u - \frac{1}{2} \right\rfloor & i_1 &= i_0 + 1 \\
j_0 &= \left\lfloor v - \frac{1}{2} \right\rfloor & j_1 &= j_0 + 1 \\
k_0 &= \left\lfloor w - \frac{1}{2} \right\rfloor & k_1 &= k_0 + 1
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= \operatorname{frac}\left(u - \frac{1}{2}\right) \\
\beta &= \operatorname{frac}\left(v - \frac{1}{2}\right) \\
\gamma &= \operatorname{frac}\left(w - \frac{1}{2}\right)
\end{aligned}
$$

If the image instruction includes a $ConstOffset$ operand, the constant offsets $(\Delta_i, \Delta_j, \Delta_k)$ are added to (i, j, k) components of the integer texel coordinates.

15.8 Image Sample Operations

15.8.1 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.

15.8.2 Texel Gathering

SPIR-V instructions with **Gather** in the name return a vector derived from a 2x2 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:

$$\begin{aligned}
\tau[R] &= \tau_{i0j1}[level_{base}][comp] \\
\tau[G] &= \tau_{i1j1}[level_{base}][comp] \\
\tau[B] &= \tau_{i1j0}[level_{base}][comp] \\
\tau[A] &= \tau_{i0j0}[level_{base}][comp]
\end{aligned}$$

where:

$$\tau[level_{base}][comp] = \begin{cases} \tau[level_{base}][R], & \text{for } comp = 0 \\ \tau[level_{base}][G], & \text{for } comp = 1 \\ \tau[level_{base}][B], & \text{for } comp = 2 \\ \tau[level_{base}][A], & \text{for } comp = 3 \end{cases}$$

$$comp \text{ from SPIR-V operand Component}$$

15.8.3 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 computes a weighted average of 8 (for 3D), 4 (for 2D or Cube), or 2 (for 1D) texel values, using the weights computed earlier:

$$\begin{aligned}
\tau_{3D}[level] = &(1-\alpha)(1-\beta)(1-\gamma)\tau_{i0j0k0}[level] \\
&+ (\alpha)(1-\beta)(1-\gamma)\tau_{i1j0k0}[level] \\
&+ (1-\alpha)(\beta)(1-\gamma)\tau_{i0j1k0}[level] \\
&+ (\alpha)(\beta)(1-\gamma)\tau_{i1j1k0}[level] \\
&+ (1-\alpha)(1-\beta)(\gamma)\tau_{i0j0k1}[level] \\
&+ (\alpha)(1-\beta)(\gamma)\tau_{i1j0k1}[level] \\
&+ (1-\alpha)(\beta)(\gamma)\tau_{i0j1k1}[level] \\
&+ (\alpha)(\beta)(\gamma)\tau_{i1j1k1}[level]
\end{aligned}$$

$$\begin{aligned}
\tau_{2D}[level] = &(1-\alpha)(1-\beta)\tau_{i0j0}[level] \\
&+ (\alpha)(1-\beta)\tau_{i1j0}[level] \\
&+ (1-\alpha)(\beta)\tau_{i0j1}[level] \\
&+ (\alpha)(\beta)\tau_{i1j1}[level]
\end{aligned}$$

$$\begin{aligned}
\tau_{1D}[level] = &(1-\alpha)\tau_{i0}[level] \\
&+ (\alpha)\tau_{i1}[level]
\end{aligned}$$

$$\tau[level] = \begin{cases} \tau_{3D}[level], & \text{for 3D image} \\ \tau_{2D}[level], & \text{for 2D or Cube image} \\ \tau_{1D}[level], & \text{for 1D image} \end{cases}$$

Finally, mipmap filtering either selects a value from one mip level or computes a weighted average between neighboring mip levels:

$$\tau = \begin{cases} \tau[d], & \text{for mip mode BASE or NEAREST} \\ (1-\delta)\tau[d_{hi}] + \delta\tau[d_{lo}], & \text{for mip mode LINEAR} \end{cases}$$

15.8.4 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.

$$\tau_{2Daniso} = \frac{1}{N}\sum_{i=1}^{N} \tau_{2D}\left(u\left(x - \frac{1}{2} + \frac{i}{N+1}, y\right), \left(v\left(x - \frac{1}{2} + \frac{i}{N+1}\right), y\right)\right), \qquad \text{when } \rho_x > \rho_y$$

$$\tau_{2Daniso} = \frac{1}{N}\sum_{i=1}^{N} \tau_{2D}\left(u\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right), \left(v\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right)\right)\right), \qquad \text{when } \rho_y \geq \rho_x$$

15.9 Image Operation Steps

Each step described in this chapter is performed by a subset of the image instructions:

- Texel Input Validation Operations, Format Conversion, Texel Replacement, Conversion to RGBA, and Component Swizzle: Performed by all instructions except **`OpImageWrite`**.
- Depth Comparison: Performed by **`OpImage`***__`Dref`__ instructions.
- All Texel output operations: Performed by **`OpImageWrite`**.
- Projection: Performed by all **`OpImage`***__`Proj`__ instructions.
- Derivative Image Operations, Cube Map Operations, Scale Factor Operation, 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

- *device* must be a valid `VkDevice` handle
- *pCreateInfo* must be a pointer to a valid `VkQueryPoolCreateInfo` structure
- If *pAllocator* is not `NULL`, *pAllocator* must be a pointer to a valid `VkAllocationCallbacks` structure
- *pQueryPool* must be a 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 the type of queries managed by the pool, and must be one of the values

  ```
  typedef enum VkQueryType {
      VK_QUERY_TYPE_OCCLUSION = 0,
      VK_QUERY_TYPE_PIPELINE_STATISTICS = 1,
      VK_QUERY_TYPE_TIMESTAMP = 2,
  } VkQueryType;
  ```

- *queryCount* is the number of queries managed by the pool.

- *pipelineStatistics* is a bitmask indicating which counters will be returned in queries on the new pool, as described below in Section 16.4. *pipelineStatistics* is ignored if *queryType* is not `VK_QUERY_TYPE_PIPELINE_STATISTICS`.

Valid Usage

- *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
- 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

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

- *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 pointer to a valid `VkAllocationCallbacks` structure
- If *queryPool* is a valid handle, it must have been created, allocated, or retrieved from *device*
- 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`

Host Synchronization

- Host access to *queryPool* must be externally synchronized

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`.

All query commands execute in order and are guaranteed to see the effects of each other's memory accesses, with one significant exception: **vkCmdCopyQueryPoolResults** may execute before the results of **vkCmdEndQuery** are available. However, if `VK_QUERY_RESULT_WAIT_BIT` is used, then **vkCmdCopyQueryPoolResults** must reflect the result of any previously executed queries. Other sequences of commands, such as **vkCmdResetQueryPool** followed by **vkCmdBeginQuery**, must make the effects of the first command visible to the second command.

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

- *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`
- *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*

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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:

```c
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 indicating constraints on the types of queries that can be performed. Bits which can be set include:

```c
typedef enum VkQueryControlFlagBits {
    VK_QUERY_CONTROL_PRECISE_BIT = 0x00000001,
} VkQueryControlFlagBits;
```

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

- *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`
- 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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS COMPUTE

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

- *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`
- The query identified by *queryPool* and *query* must currently be active
- *query* must be less than the number of queries in *queryPool*

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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.
- *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. Bits which can be set include:

```
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 indicates 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 indicates that Vulkan will wait for each query's status to become available before retrieving its results.
  - VK_QUERY_RESULT_WITH_AVAILABILITY_BIT indicates that the availability status accompanies the results.
  - VK_QUERY_RESULT_PARTIAL_BIT indicates that returning partial results is acceptable.

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

- *device* must be a valid `VkDevice` handle
- *queryPool* must be a valid `VkQueryPool` handle
- *pData* must be a 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*
- *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`

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 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

- *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`
- *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 the *queryType* used to create *queryPool* was `VK_QUERY_TYPE_TIMESTAMP`, *flags* must not contain `VK_QUERY_RESULT_PARTIAL_BIT`

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS COMPUTE

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.

The pipeline statistic counters are individually enabled for query pools with `VkQueryPoolCreateInfo`::*pipelineStatistics*, and for secondary command buffers with `VkCommandBufferInheritanceInfo`::*pipelineStatistics*.

Bits which can be set in *pipelineStatistics* include:

```
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 = 0 ↩
        x00000200,
    VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x00000400,
} VkQueryPipelineStatisticFlagBits;
```

These bits have the following meanings:

- If `VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT` is set, 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.
- If `VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT` is set, 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.

- If VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT is set, 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.
- If VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT is set, 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.
- If VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT is set, 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.
- If VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT is set, 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**).

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.

Valid Usage

- *`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 graphics, or compute operations
- Both of *`commandBuffer`*, and *`queryPool`* must have been created, allocated, or retrieved from the same `VkDevice`
- The query identified by *`queryPool`* and *`query`* must be *unavailable*
- The command pool's queue family must support a non-zero *`timestampValidBits`*

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS COMPUTE

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 Section 17.3 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

- *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 pointer to a valid VkClearColorValue union
- *pRanges* must be a 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
- *image* must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- *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 image range of any given element of *pRanges* must be an image subresource range that is contained within *image*
- *image* must not have a compressed or depth/stencil format

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS COMPUTE

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 Section 17.3 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 Section 17.3 below).

Valid Usage

- *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 pointer to a valid VkClearDepthStencilValue structure
- *pRanges* must be a 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
- *image* must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- *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 image range of any given element of *pRanges* must be an image subresource range that is contained within *image*
- *image* must have a depth/stencil format

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS

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

- *commandBuffer* must be a valid VkCommandBuffer handle
- *pAttachments* must be a pointer to an array of *attachmentCount* valid VkClearAttachment structures
- *pRects* must be a 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
- If the *aspectMask* member of any given element of *pAttachments* contains VK_IMAGE_ASPECT_COLOR_BIT, the *colorAttachment* member of those elements must refer to a valid color attachment in the current subpass
- The rectangular region specified by a given element of *pRects* must be contained within the render area of the current render pass instance
- The layers specified by a given element of *pRects* must be contained within every attachment that *pAttachments* refers to

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Inside	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` or is greater than or equal to `VkSubpassDescription`::*`colorAttachmentCount`*, 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

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

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 floating point, unorm, snorm, uscaled, packed float, or sRGB. 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. 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. 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:

```
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.

The `VkClearValue` union is defined as:

```
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.

17.4 Filling Buffers

To clear buffer data, call:

```
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

- `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`
- `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

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS COMPUTE

17.5 Updating Buffers

To update buffer data inline in a command buffer, call:

```c
void vkCmdUpdateBuffer(
    VkCommandBuffer                             commandBuffer,
    VkBuffer                                    dstBuffer,
    VkDeviceSize                                dstOffset,
    VkDeviceSize                                dataSize,
    const void*                                 pData);
```

- *commandBuffer* is the command buffer into which the command will be recorded.
- *dstBuffer* is a handle to the buffer to be updated.
- *dstOffset* is the byte offset into the buffer to start updating, and must be a multiple of 4.
- *dataSize* is the number of bytes to update, and must be a multiple of 4.
- *pData* is a pointer to the source data for the buffer update, and must be at least *dataSize* bytes in size.

dataSize must be less than or equal to 65536 bytes. For larger updates, applications can use buffer to buffer copies.

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

- *commandBuffer* must be a valid `VkCommandBuffer` handle
- *dstBuffer* must be a valid `VkBuffer` handle
- *pData* must be a 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`
- *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
- *dstOffset* must be a multiple of `4`
- *dataSize* must be less than or equal to `65536`
- *dataSize* must be a multiple of `4`

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	TRANSFER GRAPHICS COMPUTE

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

Some rules for valid operation are common to all copy commands:

- Copy commands must be recorded outside of a render pass instance.
- For non-sparse resources, the union of the source regions in a given buffer or image must not overlap the union of the destination regions in the same buffer or image.
- For sparse resources, the set of bytes used by all the source regions must not intersect the set of bytes used by all the destination regions.
- 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 either 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

- *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 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`
- The *size* member of a given element of *pRegions* must be greater than `0`
- The *srcOffset* member of a given element of *pRegions* must be less than the size of *srcBuffer*
- The *dstOffset* member of a given element of *pRegions* must be less than the size of *dstBuffer*

- The *size* member of a given element of *pRegions* must be less than or equal to the size of *srcBuffer* minus *srcOffset*
- The *size* member of a given 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
- *dstBuffer* must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	TRANSFER GRAPHICS COMPUTE

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.

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.

The formats of *srcImage* and *dstImage* must be compatible. Formats are considered compatible if their texel size in bytes 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 texel size of the uncompressed format is equal to the compressed texel block size in bytes 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 4x4 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 4x4 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. 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 and 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 and 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 and 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 and 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

- *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 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`
- The source region specified by a given element of *pRegions* must be a region that is contained within *srcImage*
- The destination region specified by a given 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
- *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 either of `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
- *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 either of `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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	TRANSFER GRAPHICS COMPUTE

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 source image to copy in *width*, *height* and *depth*. 1D images use only *x* and *width*. 2D images use *x*, *y*, *width* and *height*. 3D images use *x*, *y*, *z*, *width*, *height* and *depth*.

Valid Usage

- *srcSubresource* must be a valid `VkImageSubresourceLayers` structure
- *dstSubresource* must be a valid `VkImageSubresourceLayers` structure
- 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
- *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
- *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
- *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 format image:
  - all members of *srcOffset* must be a multiple of the corresponding dimensions of the compressed texel block
  - *extent.width* must be a multiple of the compressed texel block width or (*extent.width* + *srcOffset.x*) must equal the source image subresource width

- `extent.height` must be a multiple of the compressed texel block height or (`extent.height` + `srcOffset.y`) must equal the source image subresource height
- `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
  - `extent.width` must be a multiple of the compressed texel block width or (`extent.width` + `dstOffset.x`) must equal the destination image subresource width
  - `extent.height` must be a multiple of the compressed texel block height or (`extent.height` + `dstOffset.y`) must equal the destination image subresource height
  - `extent.depth` must be a multiple of the compressed texel block depth or (`extent.depth` + `dstOffset.z`) must equal the destination image subresource depth

- `srcOffset`, `dstOffset`, and `extent` must respect the image transfer granularity requirements of the queue family that it will be submitted against, as described in Physical Device Enumeration

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

- `aspectMask` must be a valid combination of `VkImageAspectFlagBits` values
- `aspectMask` must not be `0`
- 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`
- `mipLevel` must be less than the `mipLevels` specified in `VkImageCreateInfo` when the image was created

- $(baseArrayLayer + layerCount)$ must be less than or equal to the *arrayLayers* specified in `VkImageCreateInfo` when the image was created

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

- *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 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`
- The buffer region specified by a given element of *pRegions* must be a region that is contained within *srcBuffer*
- The image region specified by a given 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
- *dstImage* must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag
- *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 either of `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	TRANSFER GRAPHICS COMPUTE

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

- *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 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`
- The image region specified by a given element of *pRegions* must be a region that is contained within *srcImage*
- The buffer region specified by a given 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
- *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 either of `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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	TRANSFER GRAPHICS COMPUTE

For both `vkCmdCopyBufferToImage` and `vkCmdCopyImageToBuffer`, each element of *pRegions* is a structure defined as:

```
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*. 1D images use only *x* and *width*. 2D images use *x*, *y*, *width* and *height*. 3D images use *x*, *y*, *z*, *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.

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

- *imageSubresource* must be a valid `VkImageSubresourceLayers` structure
- *bufferOffset* must be a multiple of the calling command's `VkImage` parameter's texel 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

- *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 `VkImage` parameter is a compressed format image:
  - *bufferRowLength* must be a multiple of the compressed texel block width
  - *bufferImageHeight* must be a multiple of the compressed texel block height
  - all members of *imageOffset* must be a multiple of the corresponding dimensions of the compressed texel block
  - *bufferOffset* must be a multiple of the compressed texel block size in bytes
  - *imageExtent.width* must be a multiple of the compressed texel block width or (*imageExtent.width* + *imageOffset.x*) must equal the image subresource width
  - *imageExtent.height* must be a multiple of the compressed texel block height or (*imageExtent.height* + *imageOffset.y*) must equal the image subresource height
  - *imageExtent.depth* must be a multiple of the compressed texel block depth or (*imageExtent.depth* + *imageOffset.z*) must equal the image subresource depth
- *bufferOffset*, *bufferRowLength*, *bufferImageHeight* and all members of *imageOffset* and *imageExtent* must respect the image transfer granularity requirements of the queue family that it will be submitted against, as described in Physical Device Enumeration
- 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

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;

texelSize = <texel size taken from the src/dstImage>;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x)  ↩
    * texelSize;

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/compressedTexelBlockDepth}.
```

Copying to or from block-compressed images is typically done in multiples of the compressed texel block. 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 and 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:

$$u_{base} = i + \frac{1}{2}$$
$$v_{base} = j + \frac{1}{2}$$
$$w_{base} = k + \frac{1}{2}$$

- These base coordinates are then offset by the first destination offset:

$$u_{offset} = u_{base} - x_{dst_0}$$
$$v_{offset} = v_{base} - y_{dst_0}$$
$$w_{offset} = w_{base} - z_{dst_0}$$
$$a_{offset} = a - baseArrayCount_{dst}$$

- The scale is determined from the source and destination regions, and applied to the offset coordinates:

$$scale_u = \frac{x_{src_1} - x_{src_0}}{x_{dst_1} - x_{dst_0}}$$
$$scale_v = \frac{y_{src_1} - y_{src_0}}{y_{dst_1} - y_{dst_0}}$$
$$scale_w = \frac{z_{src_1} - z_{src_0}}{z_{dst_1} - z_{dst_0}}$$

$$u_{scaled} = u_{offset} * scale_u$$
$$v_{scaled} = v_{offset} * scale_v$$
$$w_{scaled} = w_{offset} * scale_w$$

- Finally the source offset is added to the scaled coordinates, to determine the final unnormalized coordinates used to sample from *srcImage*:

$$
\begin{aligned}
u &= u_{scaled} + x_{src_0} \\
v &= v_{scaled} + y_{src_0} \\
w &= w_{scaled} + z_{src_0} \\
q &= mipLevel \\
a &= a_{offset} + baseArrayCount_{src}
\end{aligned}
$$

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.
- In case of sRGB source format, 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

- *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 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`
- The source region specified by a given element of *pRegions* must be a region that is contained within *srcImage*
- The destination region specified by a given 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 linear 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
- *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 either of `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 linear 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
- *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 either of `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**

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS

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

- `srcSubresource` must be a valid `VkImageSubresourceLayers` structure
- `dstSubresource` must be a valid `VkImageSubresourceLayers` structure
- 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`
- The `layerCount` member of `dstSubresource` must be equal to the `layerCount` member of `srcSubresource`
- `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
- `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
- `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
- `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

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*. 1D images use only *x* and *width*. 2D images use *x*, *y*, *width* and *height*. 3D images use *x*, *y*, *z*, *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

- *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 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
- The source region specified by a given element of *pRegions* must be a region that is contained within *srcImage*
- The destination region specified by a given 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 a sample count equal to any valid sample count value other than VK_SAMPLE_COUNT_1_BIT
- *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 either of 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 either of 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**

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	GRAPHICS

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*. 1D images use only *x* and *width*. 2D images use *x*, *y*, *width* and *height*. 3D images use *x*, *y*, *z*, *width*, *height* and *depth*.

Valid Usage

- *srcSubresource* must be a valid `VkImageSubresourceLayers` structure
- *dstSubresource* must be a valid `VkImageSubresourceLayers` structure
- 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

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

- *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
- 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

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:

```
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.

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, the ith vertex (for $i > 0$) specifies the beginning of the ith segment and the end of the $i-1$st. 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 Figure 19.1. 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.

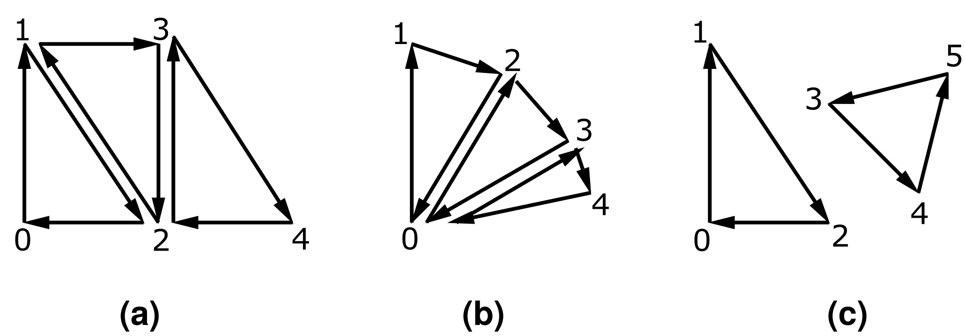


Figure 19.1: Triangle strips, fans, and lists

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 Figure 19.1, 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 Figure 19.1. In this case, vertices $3i$, $3i+1$, and $3i+2$ vertices (in that order) determine a triangle for each $i = 0, 1, \ldots, n-1$, where there are $3n+k$ 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 the $4i+1$st vertex to the $4i+2$nd vertex for each $i = 0, 1, \ldots, n-1$, where there are $4n+k$ vertices. k is either 0, 1, 2, or 3; if k is not zero, the final k vertices are ignored. For line segment i, the $4i$th and $4i+3$rd vertices are considered adjacent to the $4i+1$st and $4i+2$nd vertices, respectively, as shown in figure Figure 19.2.

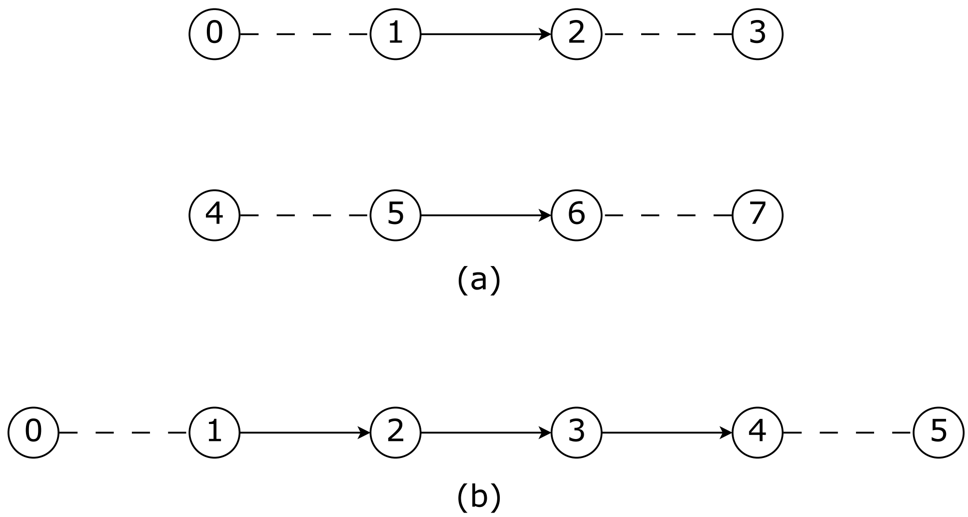


Figure 19.2: Lines with adjacency

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 the $i+1$st vertex to the $i+2$nd vertex for each $i = 0, 1, \ldots, n-1$, where there are $n+3$ vertices. If there are fewer than four vertices, all vertices are ignored. For line segment i, the ith and $i+3$rd vertex are considered adjacent to the $i+1$st and $i+2$nd vertices, respectively, as shown in figure Figure 19.2.

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.

The $6i$th, $6i+2$nd, and $6i+4$th vertices (in that order) determine a triangle for each $i = 0, 1, \ldots, n-1$, where there are $6n+k$ 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, the $6i+1$st, $6i+3$rd, and $6i+5$th vertices are considered adjacent to edges from the $6i$th to the $6i+2$nd, from the $6i+2$nd to the $6i+4$th, and from the $6i+4$th to the $6i$th vertices, respectively, as shown in figure Figure 19.3.

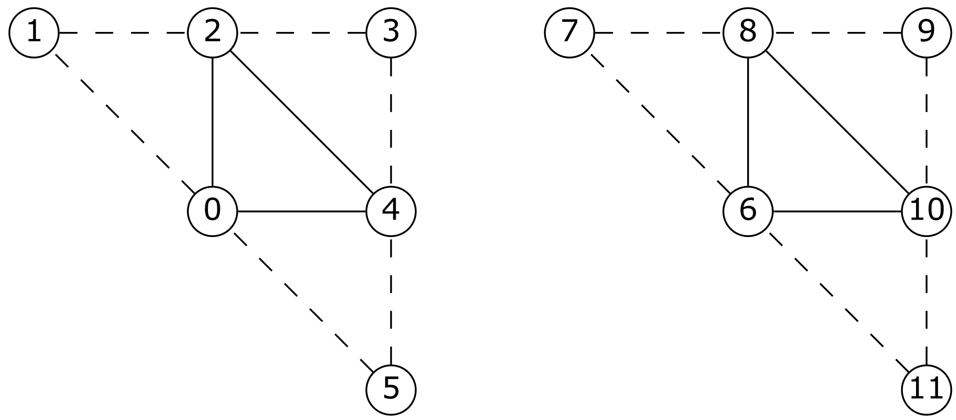


Figure 19.3: Triangles with adjacency

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.

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 Table 19.1 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 Figure 19.4.

Table 19.1: 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)	$2i+2$	$2i$	$2i+4$	$2i-2$	$2i+3$	$2i+6$
middle (i even)	$2i$	$2i+2$	$2i+4$	$2i-2$	$2i+6$	$2i+3$
last ($i=n-1$, i odd)	$2i+2$	$2i$	$2i+4$	$2i-2$	$2i+3$	$2i+5$
last ($i=n-1$, i even)	$2i$	$2i+2$	$2i+4$	$2i-2$	$2i+5$	$2i+3$

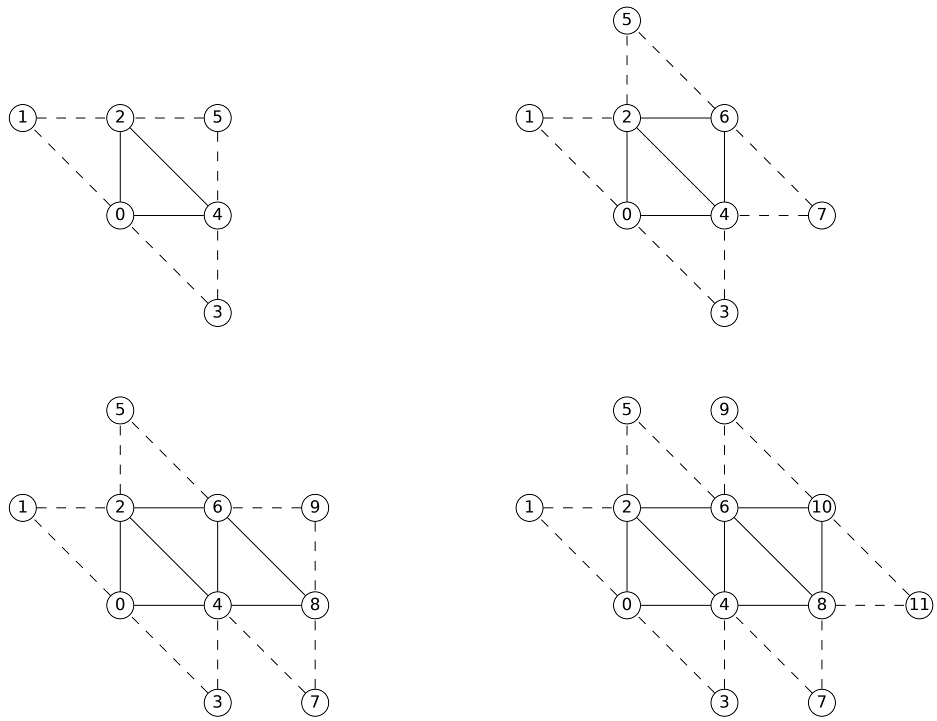


Figure 19.4: Triangle strips with adjacency

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, the vith through $vi+v-1$st vertices (in that order) determine a patch for each $i = 0, 1, \ldots n-1$, where there are $vn+k$ 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 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`* selects whether indices are treated as 16 bits or 32 bits. Possible values include:

```
typedef enum VkIndexType {
    VK_INDEX_TYPE_UINT16 = 0,
    VK_INDEX_TYPE_UINT32 = 1,
} VkIndexType;
```

Valid Usage

- `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`
- `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

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS

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.

Primitives assembled by draw commands are considered to have an API order, which defines the order their fragments affect the framebuffer. When a draw command includes multiple instances, the lower numbered instances are earlier in API order. For non-indexed draws, primitives with lower numbered **`vertexIndex`** values are earlier in API order. For indexed draws, primitives assembled from lower index buffer addresses are earlier in API order.

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

- *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
- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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 Section 20.2

- 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`**

Host Synchronization

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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Inside	GRAPHICS

To record an indexed draw, call:

```
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

- *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
- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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 Section 20.2
- 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`**

Host Synchronization

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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Inside	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

- *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
- *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**
- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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* x (*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`**

Host Synchronization

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

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Inside	GRAPHICS

The `VkDrawIndirectCommand` structure is defined as:

```c
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 Section 20.2
- If the drawIndirectFirstInstance feature is not enabled, `firstInstance` must be **0**

To record an indexed indirect draw, call:

```c
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

- *`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`
- *`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`**
- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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`* x (*`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**

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Inside	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 Section 20.2
- (*`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 Table 20.1. 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 20.1: 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)

Table 20.1: (continued)

32-bit data type	`Component` decoration	Components consumed
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 Table 20.2. 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 20.2: 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 Table 20.3. 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 20.3: 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, -, -)
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 Table 20.3. 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

- *`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 pointer to an array of *vertexBindingDescriptionCount* valid VkVertexInputBindingDescription structures
- If *vertexAttributeDescriptionCount* is not 0, *pVertexAttributeDescriptions* must be a pointer to an array of *vertexAttributeDescriptionCount* valid VkVertexInputAttributeDescription structures
- *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 any given 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

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* specifies whether vertex attribute addressing is a function of the vertex index or of the instance index. Possible values include:

  ```
  typedef enum VkVertexInputRate {
      VK_VERTEX_INPUT_RATE_VERTEX = 0,
      VK_VERTEX_INPUT_RATE_INSTANCE = 1,
  } VkVertexInputRate;
  ```

  – VK_VERTEX_INPUT_RATE_VERTEX indicates that vertex attribute addressing is a function of the vertex index.
  – VK_VERTEX_INPUT_RATE_INSTANCE indicates that vertex attribute addressing is a function of the instance index.

Valid Usage

- *inputRate* must be a valid `VkVertexInputRate` value
- *binding* must be less than `VkPhysicalDeviceLimits`::*maxVertexInputBindings*
- *stride* must be less than or equal to `VkPhysicalDeviceLimits`::*maxVertexInputBindingStride*

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

- *format* must be a valid `VkFormat` value
- *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`**

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 $\mathit{firstBinding} + i$, for i in $[0, \mathit{bindingCount})$. 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

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pBuffers` must be a pointer to an array of `bindingCount` valid `VkBuffer` handles
- `pOffsets` must be a 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`
- `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

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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 Figure 21.1.

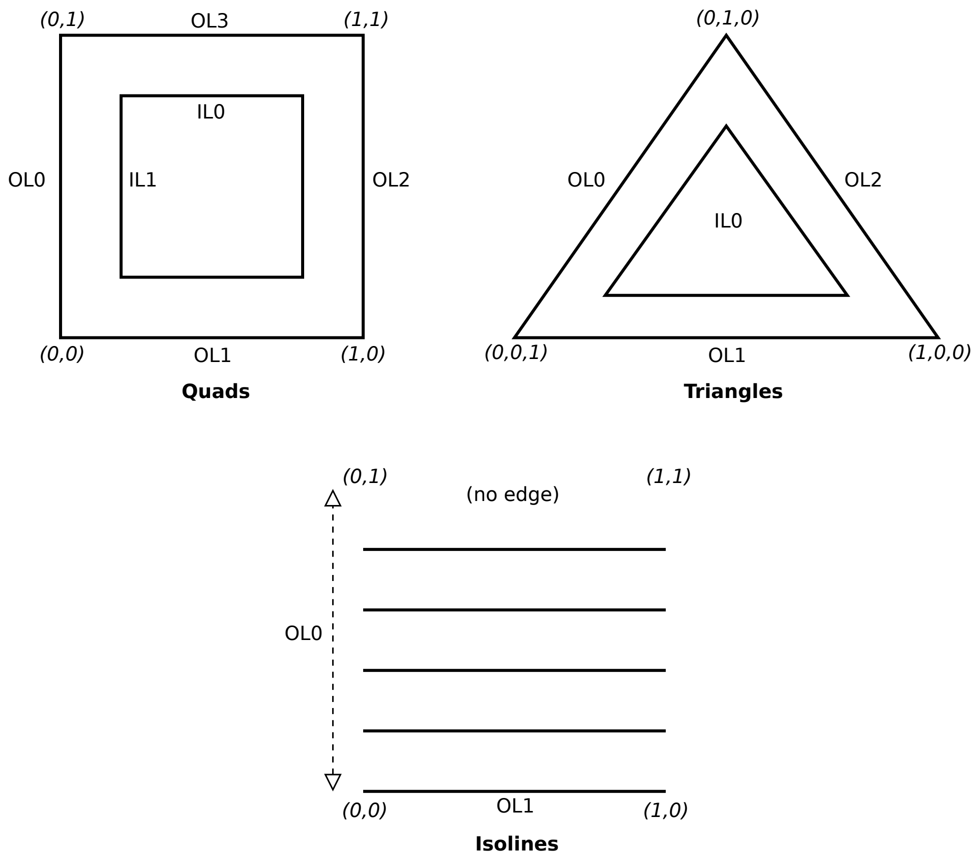


Figure 21.1: Domain parameterization for tessellation primitive modes

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.

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 positive, and clockwise ordering if a is negative. 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.

The points, lines, or triangles produced by the tessellator are passed to subsequent pipeline stages in an implementation-dependent order.

21.4 Triangle Tessellation

If the tessellation primitive mode is **`Triangles`**, an equilateral triangle is subdivided into a collection of triangles covering the area of the original triangle. First, the original triangle is subdivided into a collection of concentric equilateral triangles. The edges of each of these triangles are subdivided, and the area between each triangle pair is filled by triangles produced by joining the vertices on the subdivided edges. The number of concentric triangles and the number of subdivisions along each triangle except the outermost is derived from the first inner tessellation level. The edges of the outermost triangle are subdivided independently, using the first, second, and third outer tessellation levels to control the number of subdivisions of the $u = 0$ (left), $v = 0$ (bottom), and $w = 0$ (right) edges, respectively. The second inner tessellation level and the fourth outer tessellation level have no effect in this mode.

If the first inner tessellation level and all three outer tessellation levels are exactly one after clamping and rounding, only a single triangle with (u,v,w) coordinates of (0,0,1), (1,0,0), and (0,1,0) is generated. If the inner tessellation level is one and any of the outer tessellation levels is greater than one, the inner tessellation level is treated as though it were originally specified as $1 + \varepsilon$ and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce *inner vertices* positioned on the edge of the triangle.

If any tessellation level is greater than one, tessellation begins by producing a set of concentric inner triangles and subdividing their edges. First, the three outer edges are temporarily subdivided using the clamped and rounded first inner tessellation level and the specified tessellation spacing, generating n segments. For the outermost inner triangle, the inner triangle is degenerate — a single point at the center of the triangle — if n is two. Otherwise, for each corner of the outer triangle, an inner triangle corner is produced at the intersection of two lines extended perpendicular to the corner's two adjacent edges running through the vertex of the subdivided outer edge nearest that corner. If n is three, the edges of the inner triangle are not subdivided and 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.

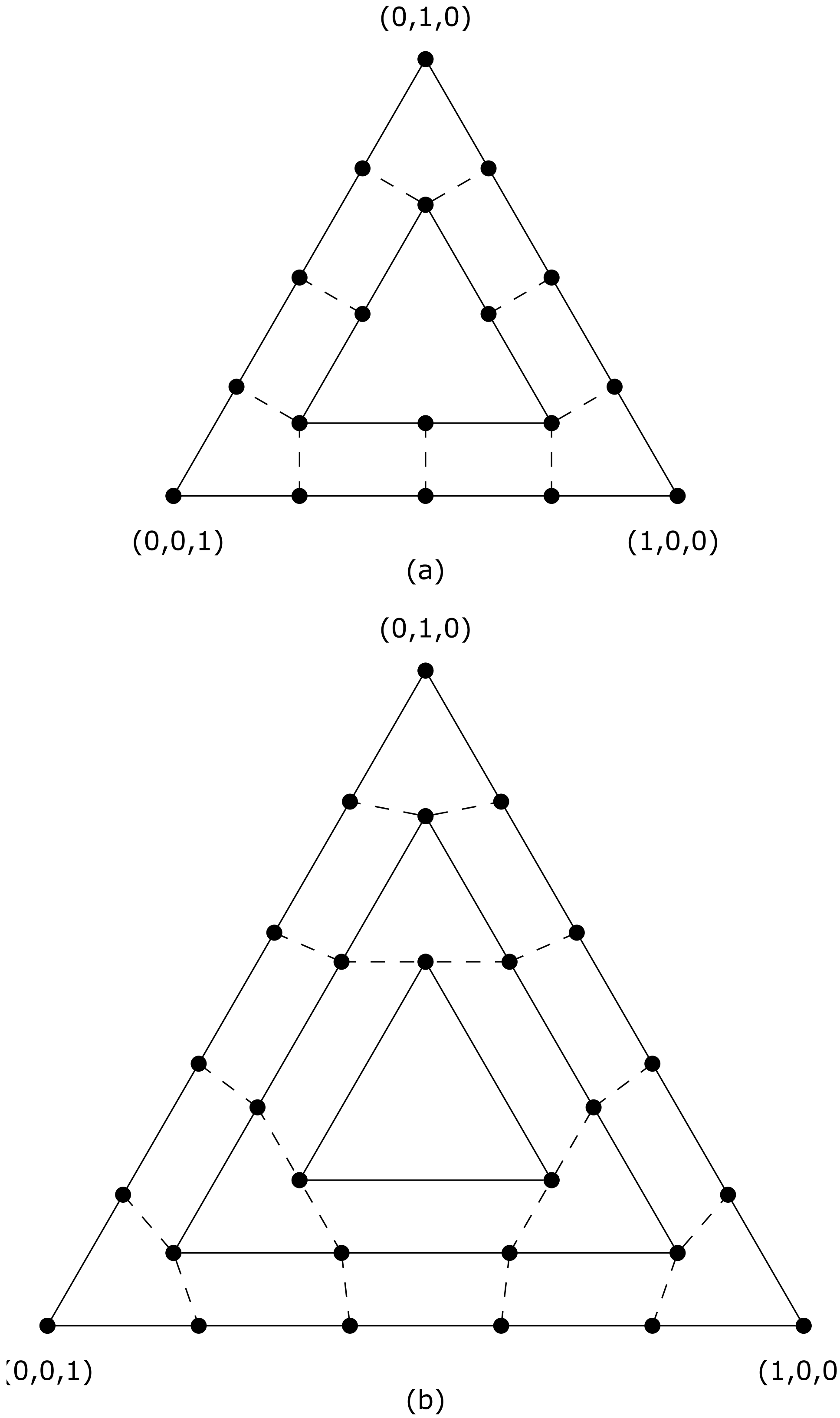


Figure 21.2: Inner Triangle Tessellation

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 generated triangles passed to subsequent pipeline stages and the order of the vertices in those triangles are both implementation-dependent. However, when depicted in a manner similar to Inner Triangle Tessellation, the order of the vertices in the generated triangles will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

21.5 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 $1 + \varepsilon$ and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce *inner vertices* positioned on the edge of the rectangle.

If any tessellation level is greater than one, tessellation begins by subdividing the $u = 0$ and $u = 1$ edges of the outer rectangle into m segments using the clamped and rounded first inner tessellation level and the tessellation spacing. The $v = 0$ and $v = 1$ edges are subdivided into n segments using the second inner tessellation level. Each vertex on the $u = 0$ and $v = 0$ edges are joined with the corresponding vertex on the $u = 1$ and $v = 1$ edges to produce a set of vertical and horizontal lines that divide the rectangle into a grid of smaller rectangles. The primitive generator emits a pair of non-overlapping triangles covering each such rectangle not adjacent to an edge of the outer rectangle. The boundary of the region covered by these triangles forms an inner rectangle, the edges of which are subdivided by the grid vertices that lie on the edge. If either m or n is two, the inner rectangle is degenerate, and one or both of the rectangle's *edges* consist of a single point. This subdivision is illustrated in Figure Inner Quad Tessellation.

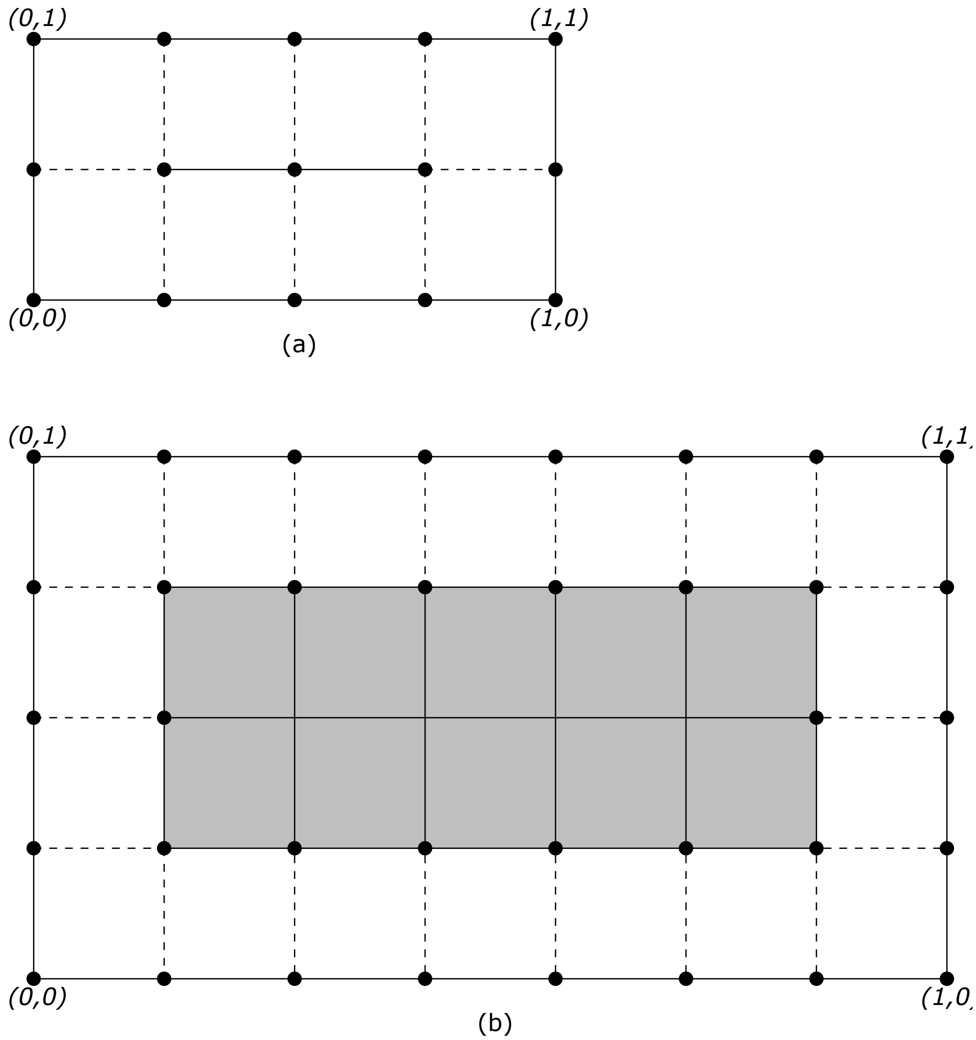


Figure 21.3: Inner Quad Tessellation

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 generated triangles passed to subsequent pipeline stages and the order of the vertices in those triangles are both implementation-dependent. However, when depicted in a manner similar to Inner Quad Tessellation, the order of the vertices in the generated triangles will be either all clockwise or all counter-clockwise, according to the vertex order layout declaration.

21.6 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 generated line segments are passed to subsequent pipeline stages and the order of the vertices in each generated line segment are both implementation-dependent.

21.7 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

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

- `flags` must be `0`
- `patchControlPoints` must be greater than zero and less than or equal to `VkPhysicalDeviceLimits`::`maxTessellationPatchSize`

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 Chapter 24. 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.

- 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:

- Flatshading (see Flatshading).
- 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 23.1: Provoking vertex selection

Primitive type of primitive i	Provoking vertex number
VK_PRIMITIVE_TOPOLOGY_POINT_LIST	i
VK_PRIMITIVE_TOPOLOGY_LINE_LIST	$2i$
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP	i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST	$3i$
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP	i
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN	$i+1$
VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY	$4i+1$
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY	$i+1$
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY	$6i$
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY	$2i$

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:

$$
\begin{aligned}
-w_c \leq x_c \leq w_c \\
-w_c \leq y_c \leq w_c \\
0 \leq z_c \leq w_c
\end{aligned}
$$

This view volume can be further restricted by as many as `VkPhysicalDeviceLimits`::*`maxClipDistances`* client-defined half-spaces.

The cull volume is the intersection of up to `VkPhysicalDeviceLimits`::*`maxCullDistances`* client-defined half-spaces (if no client-defined cull half-spaces are enabled, culling against the cull volume is skipped).

A shader must write a single cull distance for each enabled cull half-space to elements of the **`CullDistance`** array. If the cull distance for any enabled cull half-space is negative for all of the vertices of the primitive under consideration, the primitive is discarded. Otherwise the primitive is clipped against the clip volume as defined below.

The clip volume is the intersection of up to `VkPhysicalDeviceLimits`::*`maxClipDistances`* client-defined half-spaces with the view volume (if no client-defined clip half-spaces are enabled, the clip volume is the view volume).

A shader must write a single clip distance for each enabled clip half-space to elements of the **`ClipDistance`** array. Clip half-space i is then given by the set of points satisfying the inequality

$$c_i(P) \geq 0$$

where $c_i(P)$ is the clip distance i at point P. For point primitives, $c_i(P)$ is simply the clip distance for the vertex in question. For line and triangle primitives, per-vertex clip distances are interpolated using a weighted mean, with weights derived according to the algorithms described in sections Basic Line Segment Rasterization and Basic Polygon Rasterization, using the perspective interpolation equations.

The number of client-defined clip and cull half-spaces that are enabled is determined by the explicit size of the built-in arrays **`ClipDistance`** and **`CullDistance`**, respectively, declared as an output in the interface of the entry point of the final shader stage before clipping.

Depth clamping is enabled or disabled via the *`depthClampEnable`* enable of the `VkPipelineRasterizationStateCreateInfo` structure. 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, then clipping passes it unchanged if it lies within the clip volume; otherwise, it is discarded.

If the primitive is a line segment, then clipping does nothing to it if it lies entirely within the clip volume, and discards it if it lies entirely outside the volume.

If part of the line segment lies in the volume and part lies outside, then the line segment is clipped and new vertex coordinates are computed for one or both vertices. 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 $\mathbf{P}$ 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 $\mathbf{P}$ is used to obtain the output value associated with $\mathbf{P}$ 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 $\mathbf{P}$ 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 $\mathbf{c}$ 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, $\begin{pmatrix} x_f \\ y_f \\ z_f \end{pmatrix}$, are given by

$$\begin{pmatrix} x_f \\ y_f \\ z_f \end{pmatrix} = \begin{pmatrix} \frac{p_x}{2} x_d + o_x \\ \frac{p_y}{2} y_d + o_y \\ p_z \times z_d + o_z \end{pmatrix}.$$

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

- *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`
- 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

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

- *commandBuffer* must be a valid `VkCommandBuffer` handle
- *pViewports* must be a pointer to an array of *viewportCount* valid `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`
- 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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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 $k \in \{0, 1, \ldots, 2^m - 1\}$, as k (e.g. 1.0 is represented in binary as a string of all ones).

The viewport parameters shown in the above equations are found from these values as

$$o_x = x + \frac{width}{2}$$
$$o_y = y + \frac{height}{2}$$
$$o_z = minDepth$$
$$p_x = width$$
$$p_y = height$$
$$p_z = maxDepth - minDepth.$$

The 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` and less than or equal to `VkPhysicalDeviceLimits`::*`maxViewportDimensions`*[0]
- *`height`* must be greater than `0.0` and less than or equal to `VkPhysicalDeviceLimits`::*`maxViewportDimensions`*[1]
- *`x`* and *`y`* must each be between *`viewportBoundsRange`*[0] and *`viewportBoundsRange`*[1], inclusive
- *`x`* + *`width`* must be less than or equal to *`viewportBoundsRange`*[1]
- *`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 the front-facing triangle orientation to be used for culling. See VkFrontFace.
* *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

* *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
* 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

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* specifies that fragment shading executes per-sample if `VK_TRUE`, or per-fragment if `VK_FALSE`, as described in Sample Shading.
- *minSampleShading* is the minimum fraction of sample shading, as described in Sample Shading.
- *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

- *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 pointer to an array of $\lceil \frac{rasterizationSamples}{32} \rceil$ `VkSampleMask` values
- 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 $[0,1]$

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. Otherwise, `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 stages are guaranteed to execute in *rasterization order* for each separate primitive that includes that sample location:

- depth bounds test
- stencil test, stencil op and stencil write
- depth test and depth write
- occlusion queries
- blending, logic op and color write

Rasterization order must follow API 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 VkPhysicalDeviceFeatures is VK_TRUE, then the sample counts VK_SAMPLE_COUNT_1_BIT, VK_SAMPLE_COUNT_2_BIT, VK_SAMPLE_COUNT_4_BIT, VK_SAMPLE_COUNT_8_BIT, and VK_SAMPLE_COUNT_16_BIT have sample locations as listed in the following table, with the *i*th entry in the table corresponding to 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 24.1: 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. Sample shading is controlled by the *sampleShadingEnable* member of `VkPipelineMultisampleStateCreateInfo`. If *sampleShadingEnable* is `VK_FALSE`, sample shading is considered disabled and has no effect. Otherwise, an implementation must provide a minimum of $\max(\lceil minSampleShading \times rasterizationSamples \rceil, 1)$ unique associated data for each fragment, where *minSampleShading* is the minimum fraction of sample shading and *rasterizationSamples* is the number of samples requested in `VkPipelineMultisampleStateCreateInfo`. These are associated with the samples in an implementation-dependent manner. When the sample shading fraction 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.

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:

$$s = \frac{1}{2} + \frac{(x_p - x_f)}{size}$$

$$t = \frac{1}{2} + \frac{(y_p - y_f)}{size}.$$

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 set by the *lineWidth* property of `VkPipelineRasterizationStateCreateInfo` in 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

- *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
- 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`

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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 $\mathbf{p}_a$ and $t = 1$ at $\mathbf{p}_b$. Also note that this calculation projects the vector from $\mathbf{p}_a$ to $\mathbf{p}_r$ onto the line, and thus computes the normalized distance of the fragment along the line.)

The value of an associated datum f for the fragment, whether it be a shader output or the clip w coordinate, is found as

$$f = \frac{(1-t)f_a/w_a + tf_b/w_b}{(1-t)/w_a + t/w_b}$$

EQUATION 24.1: line_perspective_interpolation

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. However, depth values for lines must be interpolated by

$$z = (1-t)z_a + tz_b$$

EQUATION 24.2: line_noperspective_interpolation

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, interpolation is performed as described in Equation line_perspective_interpolation. When the **`NoPerspective`** decoration is used, interpolation is performed in the same fashion as for depth values, as described in Equation line_noperspective_interpolation. 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 Figure 24.1, 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.

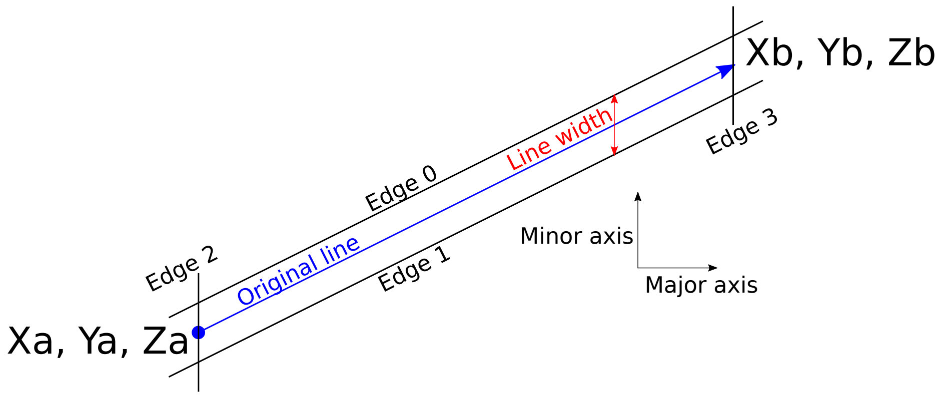


Figure 24.1: Non strict lines

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 $i \oplus 1$ is $(i+1) \bmod n$.

The interpretation of the sign of a is determined by the `VkPipelineRasterizationStateCreateInfo`::*`frontFace`* property of the currently active pipeline, which takes the following values:

```
typedef enum VkFrontFace {
    VK_FRONT_FACE_COUNTER_CLOCKWISE = 0,
    VK_FRONT_FACE_CLOCKWISE = 1,
} VkFrontFace;
```

If *`frontFace`* is set to `VK_FRONT_FACE_COUNTER_CLOCKWISE`, a triangle with positive area is considered front-facing. If it is set to `VK_FRONT_FACE_CLOCKWISE`, 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 setting of the VkPipelineRasterizationStateCreateInfo::*cullMode* property of the currently active pipeline, which takes the following values:

```
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;
```

If the *cullMode* is set to VK_CULL_MODE_NONE no triangles are discarded, if it is set to VK_CULL_MODE_FRONT_BIT front-facing triangles are discarded, if it is set to VK_CULL_MODE_BACK_BIT then back-facing triangles are discarded and if it is set to VK_CULL_MODE_FRONT_AND_BACK then all triangles are discarded. Following culling, fragments are produced for any triangles which have not been discarded.

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

$$p = ap_a + bp_b + cp_c$$

where p_a, p_b, and p_c are the vertices of the triangle. a, b, and c are determined by:

$$a = \frac{\mathrm{A}(pp_bp_c)}{\mathrm{A}(p_ap_bp_c)}, \quad b = \frac{\mathrm{A}(pp_ap_c)}{\mathrm{A}(p_ap_bp_c)}, \quad c = \frac{\mathrm{A}(pp_ap_b)}{\mathrm{A}(p_ap_bp_c)},$$

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. Then the value f of a datum at a fragment produced by rasterizing a triangle is given by:

$$f = \frac{af_a/w_a + bf_b/w_b + cf_c/w_c}{a/w_a + b/w_b + c/w_c}$$

EQUATION 24.3: triangle_perspective_interpolation

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 interpolated by

$$z = az_a + bz_b + cz_c$$

EQUATION 24.4: triangle_noperspective_interpolation 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, interpolation is performed as described in Equation triangle_perspective_interpolation. When the **NoPerspective** decoration is used, interpolation is performed in the same fashion as for depth values, as described in Equation triangle_noperspective_interpolation. 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, $0 \leq a_i \leq 1$ and $\sum_{i=1}^{n} a_i = 1$. The values of a_i may differ from fragment to fragment, but at vertex i, $a_i = 1$ and $a_j = 0$ for $j \neq i$.

Note

One algorithm that achieves the required behavior is to triangulate a polygon (without adding any vertices) and then treat each triangle individually as already discussed. A scan-line rasterizer that linearly interpolates data along each edge and then linearly interpolates data across each horizontal span from edge to edge also satisfies the restrictions (in this case, the numerator and denominator of equation Equation triangle_perspective_interpolation are iterated independently and a division performed for each fragment).

24.7.2 Polygon Mode

The method of rasterization for polygons is determined by the `VkPipelineRasterizationStateCreateInfo`::*`polygonMode`* property of the currently active pipeline, which takes the following values:

```
typedef enum VkPolygonMode {
    VK_POLYGON_MODE_FILL = 0,
    VK_POLYGON_MODE_LINE = 1,
    VK_POLYGON_MODE_POINT = 2,
} VkPolygonMode;
```

The *`polygonMode`* selects which method of rasterization is used for polygons. If *`polygonMode`* is `VK_POLYGON_MODE_POINT`, then the vertices of polygons are treated, for rasterization purposes, as if they had been drawn as points. `VK_POLYGON_MODE_LINE` causes polygon edges to be drawn as line segments. `VK_POLYGON_MODE_FILL` causes polygons to render using the polygon rasterization rules in this section.

Note that 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

$$m = \sqrt{\left(\frac{\partial z_f}{\partial x_f}\right)^2 + \left(\frac{\partial z_f}{\partial y_f}\right)^2} \tag{24.1}$$

where (x_f, y_f, z_f) is a point on the triangle. m may be approximated as

$$m = \max\left(\left|\frac{\partial z_f}{\partial x_f}\right|, \left|\frac{\partial z_f}{\partial y_f}\right|\right). \tag{24.2}$$

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

$$r = 2^{e-n} \tag{24.3}$$

If no depth buffer is present, r is undefined.

The bias value o for a polygon is

$$o = \begin{cases} m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor & depthBiasClamp = 0 \text{ or } NaN \\ \min(m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor, depthBiasClamp) & depthBiasClamp > 0 \\ \max(m \times depthBiasSlopeFactor + r \times depthBiasConstantFactor, depthBiasClamp) & depthBiasClamp < 0 \end{cases} \tag{24.4}$$

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

- *`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
- 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

Host Synchronization

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

Command Properties

Command Buffer Levels	**Render Pass Scope**	**Supported Queue Types**
Primary Secondary	Both	GRAPHICS

Chapter 25

Fragment Operations

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.

Two 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 tests are also performed in the following order:

- the depth bounds tests (see Depth Bounds Tests)
- the stencil test (see Stencil Test)
- the depth test (see Depth Test)
- sample counting (see Sample Counting)

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

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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS

If $offset.x \leq x_f < offset.x + extent.width$ and $offset.y \leq y_f < offset.y + extent.height$ 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 only apply 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 Section 9.2.

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 $32 \times M + B$. The array is sized to a length of $\lceil rasterizationSamples/32 \rceil$ 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 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.
- *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

- *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
- If the depth bounds testing feature is not enabled, *depthBoundsTestEnable* must be `VK_FALSE`

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

- *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
- 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

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS

If $minDepthBounds \leq z_a \leq maxDepthBounds$, 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 the action performed on samples that fail the stencil test.
- *passOp* is the action performed on samples that pass both the depth and stencil tests.
- *depthFailOp* is the action performed on samples that pass the stencil test and fail the depth test.

- *compareOp* is 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

- *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 fragments rasterized from non-polygon primitives (points and lines) and front-facing polygon primitives while the back set of stencil state is used when processing fragments rasterized from back-facing polygon primitives. For the purposes of stencil testing, a primitive is still considered a polygon even if the polygon is to be 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 specifying the set of stencil state for which to update the compare mask. Bits which can be set include:

```
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` indicates that only the front set of stencil state is updated.
  - `VK_STENCIL_FACE_BACK_BIT` indicates 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 indicates that both sets of stencil state are updated.

- *compareMask* is the new value to use as the stencil compare mask.

Valid Usage

- *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
- The currently bound graphics pipeline must have been created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS

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

- *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
- The currently bound graphics pipeline must have been created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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

- *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
- The currently bound graphics pipeline must have been created with the `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic state enabled

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Both	GRAPHICS

reference is an integer reference value that is used in the unsigned stencil comparison. Stencil comparison clamps the reference value to $[0, 2^s - 1]$, where s is the number of bits in the stencil framebuffer attachment. 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.

compareOp is a symbolic constant that determines the stencil comparison function:

```
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`: the test never passes.
- `VK_COMPARE_OP_LESS`: the test passes when $R < S$.
- `VK_COMPARE_OP_EQUAL`: the test passes when $R = S$.
- `VK_COMPARE_OP_LESS_OR_EQUAL`: the test passes when $R \leq S$.
- `VK_COMPARE_OP_GREATER`: the test passes when $R > S$.
- `VK_COMPARE_OP_NOT_EQUAL`: the test passes when $R \neq S$.
- `VK_COMPARE_OP_GREATER_OR_EQUAL`: the test passes when $R \geq S$.
- `VK_COMPARE_OP_ALWAYS`: the test always passes.

As described earlier, the *`failOp`*, *`passOp`*, and *`depthFailOp`* members of `VkStencilOpState` indicate what happens to the stored stencil value if this or certain subsequent tests fail or pass. Each enum is of type `VkStencilOp`, which is defined as:

```
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;
```

The possible values are:

- `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 facing-ness 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.

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 will be 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

* *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 pointer to an array of *attachmentCount* valid VkPipelineColorBlendAttachmentState structures
* 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

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 selecting which of the R, G, B, and/or A components are enabled for writing, as described later in this chapter.

Valid Usage

- *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
- 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`

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 26.1: 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	$(1-R_c,1-G_c,1-B_c)$	$1-A_c$
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

- *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
- The currently bound graphics pipeline must have been created with the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
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 operation. The blending operations are selected from the following enum, with RGB and alpha components potentially using different blend operations:

```
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 enum value is described in the table below:

Table 26.2: 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.

The *colorWriteMask* member of `VkPipelineColorBlendAttachmentState` determines whether the final color values R, G, B and A are written to the framebuffer attachment. *colorWriteMask* is any combination of the following bits:

```
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;
```

If `VK_COLOR_COMPONENT_R_BIT` is set, then the R value is written to color attachment for the appropriate sample, otherwise the value in memory is unmodified. The `VK_COLOR_COMPONENT_G_BIT`, `VK_COLOR_COMPONENT_B_`

BIT, and VK_COLOR_COMPONENT_A_BIT bits similarly control writing of the G, B, and A values. The *colorWriteMask* is applied regardless of whether blending is enabled.

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 "KHR_DF_TRANSFER_SRGB" 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 "KHR_DF_TRANSFER_SRGB" 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

- $\neg$ is bitwise invert,
- $\wedge$ is bitwise and,
- $\vee$ is bitwise or,
- $\oplus$ is bitwise exclusive or,
- s is the fragment's R_{s0}, G_{s0}, B_{s0} or A_{s0} component value for the fragment output corresponding to the color attachment being updated, and
- d is the color attachment's R, G, B or A component value:

Table 26.3: Logical Operations

Mode	Operation
VK_LOGIC_OP_CLEAR	0
VK_LOGIC_OP_AND	$s \wedge d$
VK_LOGIC_OP_AND_REVERSE	$s \wedge \neg d$
VK_LOGIC_OP_COPY	s
VK_LOGIC_OP_AND_INVERTED	$\neg s \wedge d$
VK_LOGIC_OP_NO_OP	d
VK_LOGIC_OP_XOR	$s \oplus d$
VK_LOGIC_OP_OR	$s \vee d$
VK_LOGIC_OP_NOR	$\neg(s \vee d)$
VK_LOGIC_OP_EQUIVALENT	$\neg(s \oplus d)$
VK_LOGIC_OP_INVERT	$\neg d$
VK_LOGIC_OP_OR_REVERSE	$s \vee \neg d$
VK_LOGIC_OP_COPY_INVERTED	$\neg s$
VK_LOGIC_OP_OR_INVERTED	$\neg s \vee d$
VK_LOGIC_OP_NAND	$\neg(s \wedge d)$
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.

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                                    x,
    uint32_t                                    y,
    uint32_t                                    z);
```

- *commandBuffer* is the command buffer into which the command will be recorded.
- *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.

When the command is executed, a global workgroup consisting of $x \times y \times z$ local workgroups is assembled.

Valid Usage

- *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
- *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]
- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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**

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	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

- *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

- 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 Section 13.2.2.1
- 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 Section 13.2.2.1
- 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`**

Host Synchronization

- Host access to *commandBuffer* must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary Secondary	Outside	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` structure have the same meaning as the similarly named 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.
- 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 texel 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 pixel 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 level-of-detail 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 pixel 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.

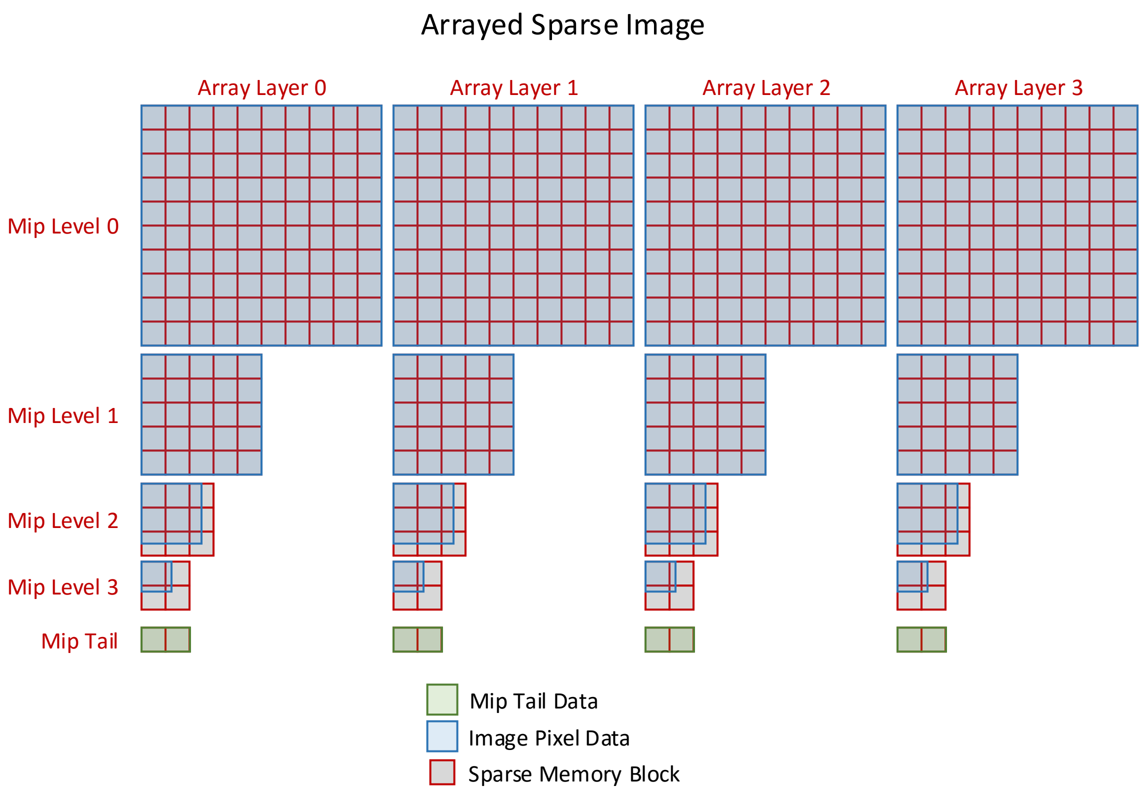


Figure 28.1: Sparse Image

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 pixel 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.

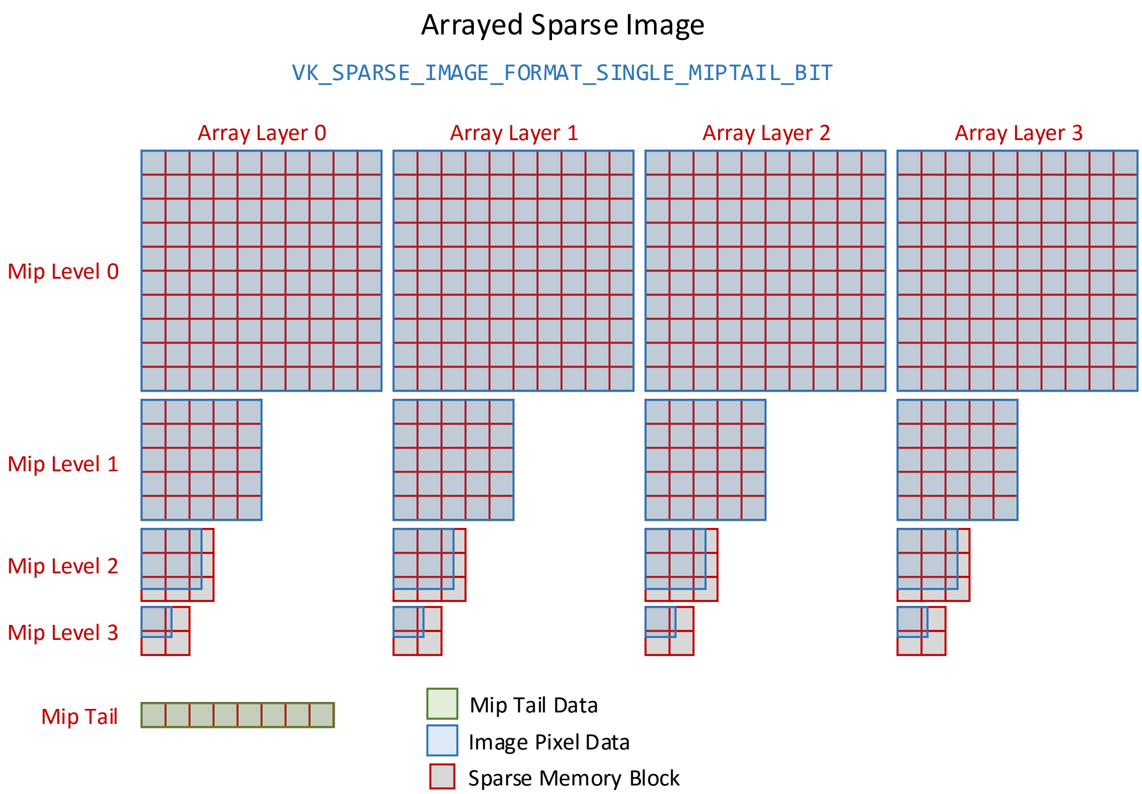


Figure 28.2: Sparse Image with Single Mip Tail

When `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` is present all array layers will share a single mip tail region.

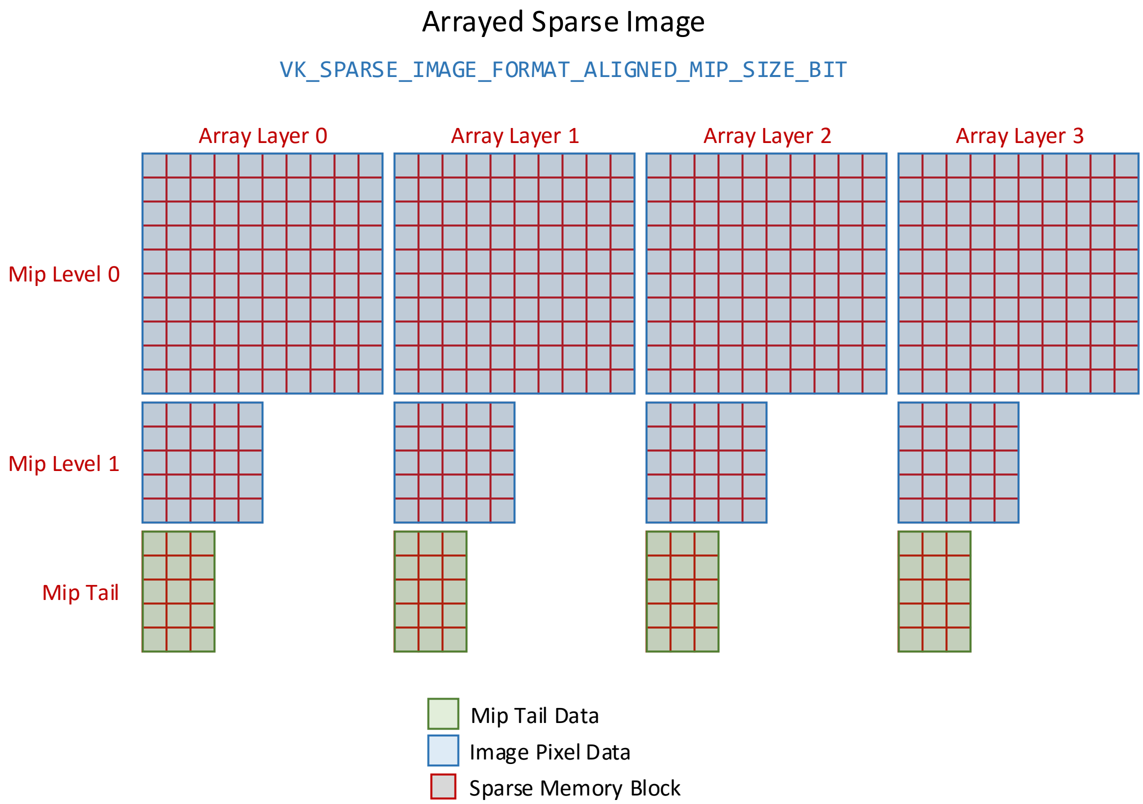


Figure 28.3: Sparse Image with Aligned Mip Size

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 pixels 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.

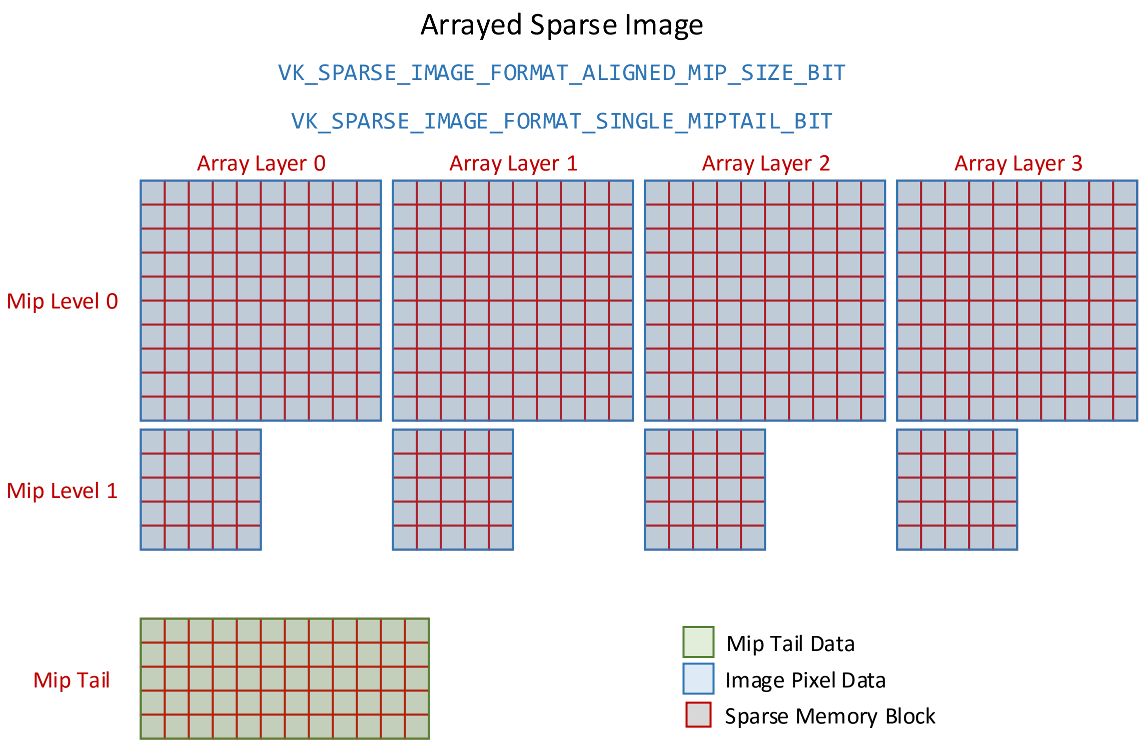


Figure 28.4: Sparse Image with Aligned Mip Size and Single Mip Tail

---

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 pixels 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 pixels 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 pixel size is the size of the compressed texel block (128-bit for `BC5`) thus the dimensions of the standard sparse image block shapes apply in terms of compressed texel blocks.

Note
For block-compressed formats, the dimensions of a sparse image block in terms of texels can be calculated by multiplying the sparse image block dimensions by the compressed texel block dimensions.

Table 28.1: Standard Sparse Image Block Shapes (Single Sample)

PIXEL SIZE (bits)	Block Shape (2D)	Block Shape (3D)
8-Bit	$256 \times 256 \times 1$	$64 \times 32 \times 32$
16-Bit	$256 \times 128 \times 1$	$32 \times 32 \times 32$
32-Bit	$128 \times 128 \times 1$	$32 \times 32 \times 16$
64-Bit	$128 \times 64 \times 1$	$32 \times 16 \times 16$
128-Bit	$64 \times 64 \times 1$	$16 \times 16 \times 16$

Table 28.2: Standard Sparse Image Block Shapes (MSAA)

PIXEL SIZE (bits)	Block Shape (2X)	Block Shape (4X)	Block Shape (8X)	Block Shape (16X)
8-Bit	$128 \times 256 \times 1$	$128 \times 128 \times 1$	$64 \times 128 \times 1$	$64 \times 64 \times 1$
16-Bit	$128 \times 128 \times 1$	$128 \times 64 \times 1$	$64 \times 64 \times 1$	$64 \times 32 \times 1$
32-Bit	$64 \times 128 \times 1$	$64 \times 64 \times 1$	$32 \times 64 \times 1$	$32 \times 32 \times 1$
64-Bit	$64 \times 64 \times 1$	$64 \times 32 \times 1$	$32 \times 32 \times 1$	$32 \times 16 \times 1$
128-Bit	$32 \times 64 \times 1$	$32 \times 32 \times 1$	$16 \times 32 \times 1$	$16 \times 16 \times 1$

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:

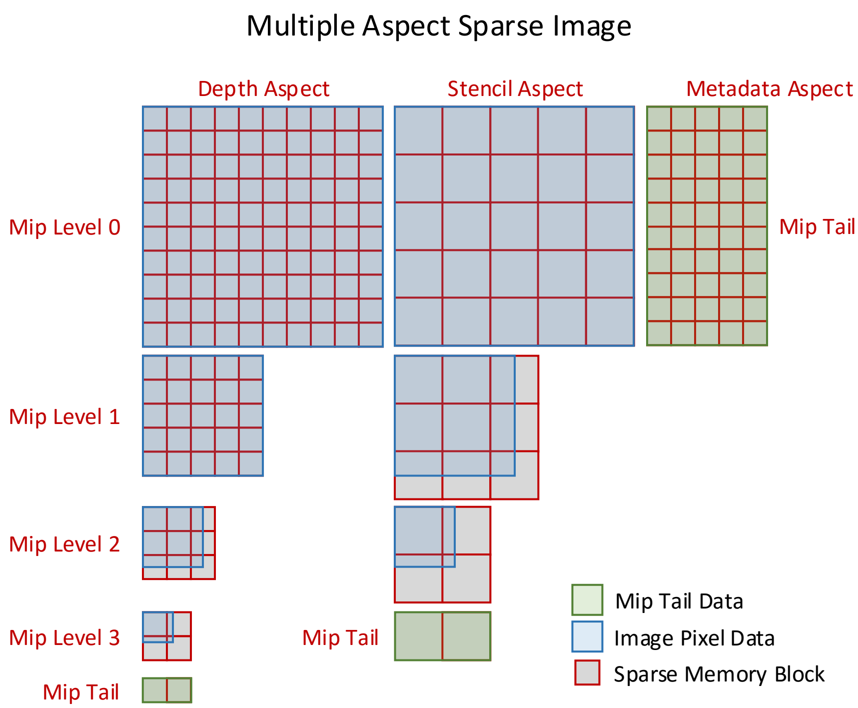


Figure 28.5: Multiple Aspect Sparse Image

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 pixels to sparse blocks.

In the figure above the depth, stencil, and metadata aspects all have unique sparse properties. The per-pixel stencil data is $^1/_4$ the size of the depth data, hence the stencil sparse blocks include 4*x* the number of pixels. The sparse block size in bytes for all of the aspects is identical and defined by `VkMemoryRequirements`::*`alignment`*.

28.4.5.1 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 *sparseResidencyNonResidentStrict*. 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 *sparseResidencyNonResidentStrict*.

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 pixel 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 $\rightarrow$ 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.

28.7.1.1 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.

28.7.3.1 Sparse Image Format Properties API

The `VkSparseImageFormatProperties` structure is defined as:

```
typedef struct VkSparseImageFormatProperties {
    VkImageAspectFlags          aspectMask;
    VkExtent3D                  imageGranularity;
    VkSparseImageFormatFlags    flags;
} VkSparseImageFormatProperties;
```

- *`aspectMask`* is a bitmask of `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 specifying additional information about the sparse resource. Bits which can be set include:

  ```
  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;
  ```

  - 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 first mip level whose dimensions are not integer multiples of the corresponding dimensions of the sparse image block begins the mip tail region.
  - If `VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT` is set, 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 pixel format.

`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 pixel 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

- `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 pointer to a `uint32_t` value
- If the value referenced by `pPropertyCount` is not `0`, and `pProperties` is not `NULL`, `pProperties` must be a pointer to an array of `pPropertyCount` `VkSparseImageFormatProperties` structures
- `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 sname::VkImageCreateInfo::pname::flags when the image is created

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.

28.7.5.1 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`.

28.7.5.2 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.

28.7.5.3 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 pixel units. For aspect `VK_IMAGE_ASPECT_METADATA_BIT`, all dimensions will be zero pixels. 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 pixel 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

- *device* must be a valid `VkDevice` handle
- *image* must be a valid `VkImage` handle
- *pSparseMemoryRequirementCount* must be a pointer to a `uint32_t` value
- If the value referenced by *pSparseMemoryRequirementCount* is not `0`, and *pSparseMemoryRequirements* is not `NULL`, *pSparseMemoryRequirements* must be a 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.

28.7.6.1 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 specifying usage of the binding operation. Bits which can be set include:

```
typedef enum VkSparseMemoryBindFlagBits {
    VK_SPARSE_MEMORY_BIND_METADATA_BIT = 0x00000001,
} VkSparseMemoryBindFlagBits;
```

- VK_SPARSE_MEMORY_BIND_METADATA_BIT indicates that the memory being bound is only for the metadata aspect.

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:

$$\begin{aligned} metadataRegion = [&imageMipTailOffset + imageMipTailStride \times n, \\ &imageMipTailOffset + imageMipTailStride \times n + imageMipTailSize) \end{aligned}$$

Where *imageMipTailOffset*, *imageMipTailSize*, and *imageMipTailStride* values are from the VkSparseImageMemoryRequirements that correspond to the metadata aspect of the image. The term 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* must be a valid VkDeviceMemory handle
- *flags* must be a valid combination of VkSparseMemoryBindFlagBits values
- If *memory* is not VK_NULL_HANDLE, *memory* and *memoryOffset* must match the memory requirements of the resource, as described in section Section 11.6
- 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*

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

- *buffer* must be a valid `VkBuffer` handle
- *pBinds* must be a 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

- *image* must be a valid `VkImage` handle
- *pBinds* must be a pointer to an array of *bindCount* valid `VkSparseMemoryBind` structures
- *bindCount* must be greater than `0`
- For any given element of *pBinds*, if the *flags* member of that element contains `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range defined must be within the mip tail region of the metadata aspect of *image*

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

- *image* must be a valid VkImage handle
- *pBinds* must be a 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

- *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
- 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 Section 11.6
- *subresource* must be a valid image subresource for *image* (see Section 11.5)
- *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

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.

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

- *queue* must be a valid `VkQueue` handle
- If *bindInfoCount* is not `0`, *pBindInfo* must be a 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`
- *fence* must be unsignaled
- *fence* must not be associated with any other queue command that has not yet completed execution on that queue

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
-	-	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

- *sType* must be VK_STRUCTURE_TYPE_BIND_SPARSE_INFO
- *pNext* must be NULL
- If *waitSemaphoreCount* is not 0, *pWaitSemaphores* must be a pointer to an array of *waitSemaphoreCount* valid VkSemaphore handles
- If *bufferBindCount* is not 0, *pBufferBinds* must be a pointer to an array of *bufferBindCount* valid VkSparseBufferMemoryBindInfo structures

- If *imageOpaqueBindCount* is not 0, *pImageOpaqueBinds* must be a pointer to an array of *imageOpaqueBindCount* valid VkSparseImageOpaqueMemoryBindInfo structures
- If *imageBindCount* is not 0, *pImageBinds* must be a pointer to an array of *imageBindCount* valid VkSparseImageMemoryBindInfo structures
- If *signalSemaphoreCount* is not 0, *pSignalSemaphores* must be a 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;
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, &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 application 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;
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, &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;
```

```
        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 application 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 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 "https://github.com/KhronosGroup/Vulkan-LoaderAndValidationLayers/blob/master/loader/LoaderAndLayerInterface.md" file 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

- *pPropertyCount* must be a pointer to a uint32_t value
- If the value referenced by *pPropertyCount* is not 0, and *pProperties* is not NULL, *pProperties* must be a 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

- *physicalDevice* must be a valid `VkPhysicalDevice` handle
- *pPropertyCount* must be a pointer to a `uint32_t` value
- If the value referenced by *pPropertyCount* is not `0`, and *pProperties* is not `NULL`, *pProperties* must be a 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 Section 3.1. Extensions may be provided by layers as well as by a Vulkan implementation.

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

- If *pLayerName* is not `NULL`, *pLayerName* must be a null-terminated string
- *pPropertyCount* must be a pointer to a `uint32_t` value
- If the value referenced by *pPropertyCount* is not `0`, and *pProperties* is not `NULL`, *pProperties* must be a pointer to an array of *pPropertyCount* `VkExtensionProperties` structures
- If *pLayerName* is not `NULL`, it must be the name of a layer returned by `vkEnumerateInstanceLayerProperties`

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

- *physicalDevice* must be a valid VkPhysicalDevice handle

- If *pLayerName* is not `NULL`, *pLayerName* must be a null-terminated string
- *pPropertyCount* must be a pointer to a `uint32_t` value
- If the value referenced by *pPropertyCount* is not `0`, and *pProperties* is not `NULL`, *pProperties* must be a pointer to an array of *pPropertyCount* `VkExtensionProperties` structures
- If *pLayerName* is not `NULL`, it must be the name of a layer returned by `vkEnumerateDeviceLayerProperties`

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

Because an instance extension can affect the operation of an instance and any of its child objects, the decision to expose functionality as an instance extension or as a device extension is not always clear. This section provides some guidelines and rules for when to expose new functionality as an instance extension, device extension, or both.

The decision is influenced by whether extension functionality affects instance-level objects (e.g. instances and physical devices) and commands, or device-level objects (e.g. logical devices, queues, and command buffers) and commands, or both.

In some cases, the decision is clear:

- Functionality that is restricted to the instance-level must be implemented as an instance extension.
- Functionality that is restricted to the device-level must be implemented as a device extension.

In other cases, the decision is not so clear:

- Global functionality that affects the entire Vulkan API, including instance and device-level objects and commands, should be an instance extension.
- Device-level functionality that contains physical-device queries, can be implemented as an instance extension. If some part of an instance extension's functionality might not be available on all physical devices, the extension should provide a query to determine which physical devices provide the functionality.
- For a set of global functionality that provides new instance-level and device-level commands, and can be enabled for a subset of devices, it is recommended that the functionality be partitioned across two extensions—one for the instance-level functionality, and one for the device-specific functionality. In this latter case, it is generally recommended that the two extensions have unique names.

Examples of instance extensions include:

- Logging of debug messages by any enabled layers for all Vulkan commands.
- Functionality creating new objects which are direct children of an instance.
- Functionality creating new objects which are direct children of a physical device and intended to work with any logical device created from the physical device.
- Functionality adding new instance-level Vulkan commands that do not affect any device-level commands.

Note
Instance extensions generally require support in the Vulkan loader. This is especially true for commands that are dispatched from instances and physical devices. Additional information about supporting instance-level commands may be found in the "Vulkan Loader Specification and Architecture Overview" document, located at URL
https://github.com/KhronosGroup/Vulkan-LoaderAndValidationLayers/blob/sdk-1.0.13/loader/-LoaderAndLayerInterface.md
Please see the "Architectural overview of layers and loader" section for information about how both instance-level and device-level commands are supported and dispatched.

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 on extensibility**
> The features and limits are reported via basic structures (that is `VkPhysicalDeviceFeatures` and `VkPhysicalDeviceLimits`). It is expected that when new features or limits are added in a future Vulkan version, new structure(s) and entry point(s) will be added as necessary to query these. New functionality added by extensions is not expected to modify the core feature and limit structures.

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

- *physicalDevice* must be a valid `VkPhysicalDevice` handle
- *pFeatures* must be a 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. To disable all features which are not required, set *pEnabledFeatures* to `NULL`.

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 address of the attribute plus the size of the attribute is greater than the size of the bound buffer. 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 per-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 Section 26.1.2.
- *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 *maxAnisotropy* member of the VkSamplerCreateInfo structure must be 1.0.

- *textureCompressionETC2* indicates whether the ETC2 and EAC compressed texture formats are supported. If this feature is not enabled, the following formats must not be used to create images:

  - 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 is used to check for the supported properties of individual formats.

- *textureCompressionASTC_LDR* indicates whether the ASTC LDR compressed texture formats are supported. If this feature is not enabled, the following formats must not be used to create images:

  - 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` is used to check for the supported properties of individual formats.

- *`textureCompressionBC`* indicates whether the BC compressed texture formats are supported. If this feature is not enabled, the following formats must not be used to create images:

  - 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` is used to check for the 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 level-of-detail (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.

Valid Usage

- If any member of this structure is VK_FALSE, as returned by vkGetPhysicalDeviceFeatures, then it must be VK_FALSE when passed as part of the VkDeviceCreateInfo struct when creating a device

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*) of an image created with an *imageType* of VK_IMAGE_TYPE_1D.
- *maxImageDimension2D* is the maximum dimension (*width* or *height*) of an image 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*) of an image created with an *imageType* of VK_IMAGE_TYPE_3D.
- *maxImageDimensionCube* is the maximum dimension (*width* or *height*) of an image 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 Section 13.2.
- *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 Section 13.1.2 and Section 13.1.4.
- *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 Section 13.1.7 and Section 13.1.9.
- *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 Section 13.1.8 and Section 13.1.10.
- *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 Section 13.1.4, Section 13.1.3, and Section 13.1.5.
- *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 Section 13.1.1, and Section 13.1.6.
- *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 Section 13.1.11.
- *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 Section 13.1.2 and Section 13.1.4.
- *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 Section 13.1.7 and Section 13.1.9.
- *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 Section 13.1.9.
- *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 Section 13.1.8 and Section 13.1.10.
- *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 Section 13.1.10.
- *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 Section 13.1.4, Section 13.1.3, and Section 13.1.5.
- *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 Section 13.1.1, and Section 13.1.6.
- *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 Section 13.1.11.
- *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 Section 20.1 and Section 20.2.
- *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 Section 20.2.

- *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 Section 20.2.
- *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 Section 20.2.
- *maxVertexOutputComponents* is the maximum number of components of output variables which can be output by a vertex shader. See Section 8.5.
- *maxTessellationGenerationLevel* is the maximum tessellation generation level supported by the fixed-function tessellation primitive generator. See Chapter 21.
- *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 Chapter 21.
- *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 Chapter 22.
- *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 Section 26.1.2 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 *x*, *y*, and *z* parameters to the `vkCmdDispatch` command, or members of the `VkDispatchIndirectCommand` structure must be less than or equal to the corresponding limit. See Chapter 27.
- *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 Chapter 24.
- *subTexelPrecisionBits* is the number of bits of precision in the division along an axis of an image used for minification and magnification filters. $2^{subTexelPrecisionBits}$ 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. $2^{mipmapPrecisionBits}$ 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 level of detail 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 $[-2 \times maxViewportDimensions, 2 \times maxViewportDimensions - 1]$. 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 $[-maxViewportDimensions + 1, 2 \times maxViewportDimensions - 1]$ 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 Section 10.2.1.

- *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 bits indicating the color sample counts that are supported for all framebuffer color attachments.
- *framebufferDepthSampleCounts* is a bitmask[1] of VkSampleCountFlagBits bits 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 bits 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 bits 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 bits 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 bits 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 bits 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 bits 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 bits 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 Section 4.3.4.

- *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 still enforced, this is just an additional alignment recommendation for optimal performance and power.

- *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 still enforced, this is just an additional alignment recommendation for optimal performance and power.

- `nonCoherentAtomSize` is the size and alignment in bytes that bounds concurrent access to host-mapped device memory.

1

For all bitmasks of type `VkSampleCountFlags` above, possible values include:

```
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;
```

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.

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 30.1: 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	-

Table 30.1: (continued)

Type	Limit	Feature
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	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	-

Table 30.1: (continued)

Type	Limit	Feature
int32_t	minTexelOffset	-
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	-
$2 \times$ float	pointSizeRange	largePoints
$2 \times$ float	lineWidthRange	wideLines
float	pointSizeGranularity	largePoints
float	lineWidthGranularity	wideLines
VkBool32	strictLines	-
VkBool32	standardSampleLocations	-
VkDeviceSize	optimalBufferCopyOffsetAlignment	-
VkDeviceSize	optimalBufferCopyRowPitchAlignment	-
VkDeviceSize	nonCoherentAtomSize	-

Table 30.2: 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

Table 30.2: (continued)

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
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	min, 6×PerStage
maxDescriptorSetUniformBuffers	-	72	min, 6×PerStage
maxDescriptorSetUniformBuffersDynamic	-	8	min
maxDescriptorSetStorageBuffers	-	24	min, 6×PerStage
maxDescriptorSetStorageBuffersDynamic	-	4	min
maxDescriptorSetSampledImages	-	96	min, 6×PerStage
maxDescriptorSetStorageImages	-	24	min, 6×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

Table 30.2: (continued)

Limit	**Unsupported Limit**	**Supported Limit**	**Limit Type**[1]
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
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

Table 30.2: (continued)

Limit	Unsupported Limit	Supported Limit	Limit Type[1]
maxColorAttachments	-	4	min
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	-	128	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].

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

The available formats are defined by the `VkFormat` enumeration:

```
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
The format is not specified.

VK_FORMAT_R4G4_UNORM_PACK8
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
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
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
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
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
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
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
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
A one-component, 8-bit unsigned normalized format that has a single 8-bit R component.

VK_FORMAT_R8_SNORM
A one-component, 8-bit signed normalized format that has a single 8-bit R component.

VK_FORMAT_R8_USCALED
A one-component, 8-bit unsigned scaled integer format that has a single 8-bit R component.

VK_FORMAT_R8_SSCALED
A one-component, 8-bit signed scaled integer format that has a single 8-bit R component.

VK_FORMAT_R8_UINT
A one-component, 8-bit unsigned integer format that has a single 8-bit R component.

VK_FORMAT_R8_SINT
A one-component, 8-bit signed integer format that has a single 8-bit R component.

VK_FORMAT_R8_SRGB
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
A one-component, 16-bit unsigned normalized format that has a single 16-bit R component.

VK_FORMAT_R16_SNORM
A one-component, 16-bit signed normalized format that has a single 16-bit R component.

VK_FORMAT_R16_USCALED
A one-component, 16-bit unsigned scaled integer format that has a single 16-bit R component.

VK_FORMAT_R16_SSCALED
A one-component, 16-bit signed scaled integer format that has a single 16-bit R component.

VK_FORMAT_R16_UINT
A one-component, 16-bit unsigned integer format that has a single 16-bit R component.

VK_FORMAT_R16_SINT
A one-component, 16-bit signed integer format that has a single 16-bit R component.

VK_FORMAT_R16_SFLOAT
A one-component, 16-bit signed floating-point format that has a single 16-bit R component.

VK_FORMAT_R16G16_UNORM
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
A one-component, 32-bit unsigned integer format that has a single 32-bit R component.

VK_FORMAT_R32_SINT
A one-component, 32-bit signed integer format that has a single 32-bit R component.

VK_FORMAT_R32_SFLOAT
A one-component, 32-bit signed floating-point format that has a single 32-bit R component.

VK_FORMAT_R32G32_UINT
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
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
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
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
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
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
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
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
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
A one-component, 64-bit unsigned integer format that has a single 64-bit R component.

VK_FORMAT_R64_SINT
A one-component, 64-bit signed integer format that has a single 64-bit R component.

VK_FORMAT_R64_SFLOAT
A one-component, 64-bit signed floating-point format that has a single 64-bit R component.

VK_FORMAT_R64G64_UINT
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
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
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
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
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
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
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
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
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
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 Section 2.7.4 and Section 2.7.3.

VK_FORMAT_E5B9G9R9_UFLOAT_PACK32
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
A one-component, 16-bit unsigned normalized format that has a single 16-bit depth component.

VK_FORMAT_X8_D24_UNORM_PACK32
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
A one-component, 32-bit signed floating-point format that has 32-bits in the depth component.

VK_FORMAT_S8_UINT
A one-component, 8-bit unsigned integer format that has 8-bits in the stencil component.

VK_FORMAT_D16_UNORM_S8_UINT
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
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
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
A three-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

VK_FORMAT_BC1_RGB_SRGB_BLOCK
A three-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 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
: A four-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

VK_FORMAT_BC1_RGBA_SRGB_BLOCK
: A four-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.

VK_FORMAT_BC2_UNORM_BLOCK
: A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A one-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized red texel data.

VK_FORMAT_BC4_SNORM_BLOCK
: A one-component, block-compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of signed normalized red texel data.

VK_FORMAT_BC5_UNORM_BLOCK
: A two-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A two-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 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
: A three-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of unsigned floating-point RGB texel data.

VK_FORMAT_BC6H_SFLOAT_BLOCK
: A three-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of signed floating-point RGB texel data.

VK_FORMAT_BC7_UNORM_BLOCK
: A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_BC7_SRGB_BLOCK
A four-component, block-compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK
A three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK
A three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 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
A four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK
A four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.

VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK
A four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4x4 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
A four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 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
A one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized red texel data.

VK_FORMAT_EAC_R11_SNORM_BLOCK
A one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4x4 rectangle of signed normalized red texel data.

VK_FORMAT_EAC_R11G11_UNORM_BLOCK
A two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4x4 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
A two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4x4 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
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_4x4_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4x4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_5x4_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5x4 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_5x4_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5x4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_5x5_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5x5 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_5x5_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5x5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_6x5_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6x5 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_6x5_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6x5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_6x6_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6x6 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_6x6_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6x6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_8x5_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x5 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_8x5_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_8x6_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x6 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_8x6_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_8x8_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x8 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_8x8_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8x8 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x5_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x5 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_10x5_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x6_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x6 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_10x6_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x8_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x8 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_10x8_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x8 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x10_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x10 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_10x10_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10x10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_12x10_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12x10 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_12x10_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12x10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_12x12_UNORM_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12x12 rectangle of unsigned normalized RGBA texel data.

VK_FORMAT_ASTC_12x12_SRGB_BLOCK
A four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12x12 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

30.3.1.1 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

30.3.1.2 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:

`etext: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 30.3: 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 30.4: Interpretation of Compression Scheme

Compression scheme	Description
BC	Block Compression. See Section B.1.
ETC2	Ericsson Texture Compression. See Section B.2.
EAC	ETC2 Alpha Compression. See Section B.2.
ASTC	Adaptive Scalable Texture Compression (LDR Profile). See Section B.3.

30.3.1.3 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.

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 30.5: 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 30.6: Bit mappings for packed 8-bit formats

Bit →	7	6	5	4	3	2	1	0
VK_FORMAT_R4G4_UNORM_PACK8	R_3	R_2	R_1	R_0	G_3	G_2	G_1	G_0

Table 30.7: 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_3	R_2	R_1	R_0	G_3	G_2	G_1	G_0	B_3	B_2	B_1	B_0	A_3	A_2	A_1	A_0
VK_FORMAT_B4G4R4A4_ UNORM_PACK16	B_3	B_2	B_1	B_0	G_3	G_2	G_1	G_0	R_3	R_2	R_1	R_0	A_3	A_2	A_1	A_0
VK_FORMAT_R5G6B5_UNORM_ PACK16	R_4	R_3	R_2	R_1	R_0	G_5	G_4	G_3	G_2	G_1	G_0	B_4	B_3	B_2	B_1	B_0
VK_FORMAT_B5G6R5_UNORM_ PACK16	B_4	B_3	B_2	B_1	B_0	G_5	G_4	G_3	G_2	G_1	G_0	R_4	R_3	R_2	R_1	R_0
VK_FORMAT_R5G5B5A1_ UNORM_PACK16	R_4	R_3	R_2	R_1	R_0	G_4	G_3	G_2	G_1	G_0	B_4	B_3	B_2	B_1	B_0	A_0

Table 30.7: (continued)

Bit →	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
`VK_FORMAT_B5G5R5A1_UNORM_PACK16`	B_4	B_3	B_2	B_1	B_0	G_4	G_3	G_2	G_1	G_0	R_4	R_3	R_2	R_1	R_0	A_0
`VK_FORMAT_A1R5G5B5_UNORM_PACK16`	A_0	R_4	R_3	R_2	R_1	R_0	G_4	G_3	G_2	G_1	G_0	B_4	B_3	B_2	B_1	B_0

Table 30.8: Bit mappings for packed 32-bit formats

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_7	A_6	A_5	A_4	A_3	A_2	A_1	A_0	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0	G_7	G_6	G_5	G_4	G_3	G_2	G_1	G_0	R_7	R_6	R_5	R_4	R_3	R_2	R_1	R_0
`VK_FORMAT_A2R10G10B10_*_PACK32`																															
A_1	A_0	R_9	R_8	R_7	R_6	R_5	R_4	R_3	R_2	R_1	R_0	G_9	G_8	G_7	G_6	G_5	G_4	G_3	G_2	G_1	G_0	B_9	B_8	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0
`VK_FORMAT_A2B10G10R10_*_PACK32`																															
A_1	A_0	B_9	B_8	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0	G_9	G_8	G_7	G_6	G_5	G_4	G_3	G_2	G_1	G_0	R_9	R_8	R_7	R_6	R_5	R_4	R_3	R_2	R_1	R_0
`VK_FORMAT_B10G11R11_UFLOAT_PACK32`																															
B_9	B_8	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0	G_{10}	G_9	G_8	G_7	G_6	G_5	G_4	G_3	G_2	G_1	G_0	R_{10}	R_9	R_8	R_7	R_6	R_5	R_4	R_3	R_2	R_1	R_0
`VK_FORMAT_E5B9G9R9_UFLOAT_PACK32`																															
E_4	E_3	E_2	E_1	E_0	B_8	B_7	B_6	B_5	B_4	B_3	B_2	B_1	B_0	G_8	G_7	G_6	G_5	G_4	G_3	G_2	G_1	G_0	R_8	R_7	R_6	R_5	R_4	R_3	R_2	R_1	R_0
`VK_FORMAT_X8_D24_UNORM_PACK32`																															
X_7	X_6	X_5	X_4	X_3	X_2	X_1	X_0	D_{23}	D_{22}	D_{21}	D_{20}	D_{19}	D_{18}	D_{17}	D_{16}	D_{15}	D_{14}	D_{13}	D_{12}	D_{11}	D_{10}	D_9	D_8	D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0

30.3.1.4 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).

30.3.1.5 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 30.9: 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
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

Table 30.9: (continued)

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

Table 30.9: (continued)

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
BC5	VK_FORMAT_BC5_UNORM_BLOCK, VK_FORMAT_BC5_SNORM_BLOCK
BC6H	VK_FORMAT_BC6H_UFLOAT_BLOCK, VK_FORMAT_BC6H_SFLOAT_BLOCK

Table 30.9: (continued)

Class	Formats
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
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**
>
> - *physicalDevice* must be a valid `VkPhysicalDevice` handle
> - *format* must be a valid `VkFormat` value
> - *pFormatProperties* must be a pointer to a `VkFormatProperties` structure

The `VkPhysicalDeviceLimits` structure is defined as:

```
typedef struct VkFormatProperties {
    VkFormatFeatureFlags    linearTilingFeatures;
    VkFormatFeatureFlags    optimalTilingFeatures;
    VkFormatFeatureFlags    bufferFeatures;
} VkFormatProperties;
```

- *linearTilingFeatures* describes the features supported by `VK_IMAGE_TILING_LINEAR`.
- *optimalTilingFeatures* describes the features supported by `VK_IMAGE_TILING_OPTIMAL`.
- *bufferFeatures* describes the features supported by buffers.

Supported features are described as a set of `VkFormatFeatureFlagBits`:

```
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 *linearTilingFeatures* and *optimalTilingFeatures* members of the VkFormatProperties structure describe what features are supported by VK_IMAGE_TILING_LINEAR and VK_IMAGE_TILING_OPTIMAL images, respectively.

The following bits may be set in *linearTilingFeatures* and *optimalTilingFeatures*, indicating they are supported by images or image views created with the queried vkGetPhysicalDeviceFormatProperties::*format*:

VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT
VkImageView can be sampled from. See sampled images section.

VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT
VkImageView can be used as storage image. See storage images section.

VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT
VkImageView can be used as storage image that supports atomic operations.

VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT
VkImageView can be used as a framebuffer color attachment and as an input attachment.

VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT
VkImageView can be used as a framebuffer color attachment that supports blending and as an input attachment.

VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT
VkImageView can be used as a framebuffer depth/stencil attachment and as an input attachment.

VK_FORMAT_FEATURE_BLIT_SRC_BIT
VkImage can be used as *srcImage* for the **vkCmdBlitImage** command.

VK_FORMAT_FEATURE_BLIT_DST_BIT
VkImage can be used as *dstImage* for the **vkCmdBlitImage** command.

VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT
If VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT is also set, VkImageView 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, VkImage 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 features may appear in *bufferFeatures*, indicating they are supported by buffers or buffer views created with the queried vkGetPhysicalDeviceFormatProperties::*format*:

VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT
Format can be used to create a `VkBufferView` that can be bound to a `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` descriptor.

VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT
Format can be used to create a `VkBufferView` that can be bound to a `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` descriptor.

VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT
Atomic operations are supported on `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` with this format.

VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT
Format can be used as a vertex attribute format (`VkVertexInputAttributeDescription`::*`format`*).

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.

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 30.10: 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 30.11: 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

Table 30.11: (continued)

VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT

Table 30.12: 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 30.13: 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 30.14: 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 30.15: 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 30.16: 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 30.17: 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 30.18: 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 30.19: Mandatory format support: 64-bit/uneven channels and depth/stencil

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	✓	✓	✓										
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 30.20: 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, Table 30.21, or Table 30.22.

Table 30.21: 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, Table 30.20, or Table 30.22.

Table 30.22: 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, Table 30.20, or Table 30.21.

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 the image format, corresponding to VkImageCreateInfo::*format*.
- *type* is the image type, corresponding to VkImageCreateInfo::*imageType*.
- *tiling* is the image tiling, corresponding to VkImageCreateInfo::*tiling*.
- *usage* is the intended usage of the image, corresponding to VkImageCreateInfo::*usage*.
- *flags* is a bitmask describing 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.

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

- *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 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 $\lceil \log_2(\max(width, height, depth)) \rceil + 1$ where *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.

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
- The VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag in VkFormatProperties::*optimalTilingFeatures* returned by vkGetPhysicalDeviceFormatProperties is not 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, 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.

30.4.2 Allowed Extent Values Based On Image Type

For `VK_IMAGE_TYPE_1D`:

- $maxExtent.width \leq VkPhysicalDeviceLimits.maxImageDimension1D$
- $maxExtent.height = 1$
- $maxExtent.depth = 1$

For `VK_IMAGE_TYPE_2D`:

- $maxExtent.width \leq VkPhysicalDeviceLimits.maxImageDimension2D$
- $maxExtent.height \leq VkPhysicalDeviceLimits.maxImageDimension2D$
- $maxExtent.depth = 1$

For `VK_IMAGE_TYPE_3D`:

- $maxExtent.width \leq VkPhysicalDeviceLimits.maxImageDimension3D$
- $maxExtent.height \leq VkPhysicalDeviceLimits.maxImageDimension3D$
- $maxExtent.depth \leq VkPhysicalDeviceLimits.maxImageDimension3D$

Chapter 31

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.

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.

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.

Available
See Memory Dependency.

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.

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.

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.

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.

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 an execution dependency.

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.

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.

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 command happens-after a dependency if they are separated by an execution dependency chain, with the command included in the destination of the last dependency of the chain. A memory barrier makes visible memory writes to commands that happen-after it.

Happen-before
A command happens-before a dependency if they are separated by an execution dependency chain, with the command included in the source of the first dependency of the chain. A memory barrier makes available memory writes of commands that happen-before it.

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.

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.

Indirect Commands
Drawing or dispatching commands that source some of their parameters from structures in buffer memory. Includes `vkCmdDrawIndirect`, `vkCmdDrawIndexedIndirect`, and `vkCmdDispatchIndirect`.

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.

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 sequence of operations that makes writes available, performs an execution dependency between the writes and subsequent accesses, and makes available writes visible to later accesses. In order for the effects of a write to be coherent with later accesses, it must be made available from the old access type and then made visible to the new access type.

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.

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.

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.

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.

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.

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.

Sampled Image
A descriptor type that represents an image view, and supports filtered (sampled) and unfiltered read-only acccess 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.

Visible
See Memory Dependency.

Chapter 32

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

Chapter 33

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 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.

A.1 Required 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.

A.2 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 A.1: SPIR-V Capabilities which are not required, and corresponding feature names

SPIR-V OpCapability	Vulkan feature name
`Geometry`	geometryShader
`Tessellation`	tessellationShader
`Float64`	shaderFloat64
`Int64`	shaderInt64
`Int16`	shaderInt16
`TessellationPointSize`	shaderTessellationAndGeometryPointSize
`GeometryPointSize`	shaderTessellationAndGeometryPointSize
`ImageGatherExtended`	shaderImageGatherExtended
`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 which has not been enabled.

A.3 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**

- 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`** in the **`Uniform`** storage class.
- 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.

A.4 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 A.2: Precision of core SPIR-V Instructions

Instruction	Precision
`OpFAdd`	Correctly rounded.
`OpFSub`	Correctly rounded.
`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 A.3: Precision of GLSL.std.450 Instructions

Instruction	Precision
`fma`()	Inherited from **`OpFMul`** followed by **`OpFAdd`**.
`exp`(x), **`exp2`**(x)	$(3+2\times\|x\|)$ 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 A.4: 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
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.

B.1 Block-Compressed Image Formats

Table B.1: Mapping of Vulkan BC formats to descriptions

VkFormat	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

B.2 ETC Compressed Image Formats

The following formats are described in the “ETC2 Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

Table B.2: Mapping of Vulkan ETC formats to descriptions

VkFormat	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

B.3 ASTC Compressed Image Formats

ASTC formats are described in the “ASTC Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

Table B.3: 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 each registered and published extension at a high level. Extensions are grouped as Khronos, multivendor, and then by vendor alphabetically.

C.1 VK_KHR_sampler_mirror_clamp_to_edge

Name String
: VK_KHR_sampler_mirror_clamp_to_edge

Extension Type
: Device extension

Registered Extension Number
: 15

Status
: Final

Last Modified Date
: 16/02/2016

Revision
: 1

Dependencies

- This extension is written against version 1.0. of the Vulkan API.

Contributors

- Tobias Hector, Imagination Technologies

Contacts

- Tobias Hector (tobias.hector@imgtec.com)

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.

C.1.1 New Enum Constants

- Extending `VkSamplerAddressMode`:
  - `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE`

C.1.2 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);
```

C.1.3 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.

D.1 Structure Types

Vulkan structures containing *sType* members must have a value of *sType* matching the type of the structure, as described more fully in Valid Usage for Structure Types. 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;
```

D.2 Flag Types

Vulkan flag types are all bitmasks aliasing the base type `VkFlags` and with corresponding bit flag types defining the valid bits for that flag, as described in Valid Usage for Flags. Flag types supported by the Vulkan API include:

```
typedef VkFlags VkAccessFlags;
```

```
typedef VkFlags VkAttachmentDescriptionFlags;
```

```
typedef VkFlags VkBufferCreateFlags;
```

```
typedef VkFlags VkBufferUsageFlags;
```

```
typedef VkFlags VkBufferViewCreateFlags;
```

```
typedef VkFlags VkColorComponentFlags;
```

```
typedef VkFlags VkCommandBufferResetFlags;
```

```
typedef VkFlags VkCommandBufferUsageFlags;
```

```
typedef VkFlags VkCommandPoolCreateFlags;
```

```
typedef VkFlags VkCommandPoolResetFlags;
```

```
typedef VkFlags VkCullModeFlags;
```

```
typedef VkFlags VkDependencyFlags;
```

```
typedef VkFlags VkDescriptorPoolCreateFlags;
```

```
typedef VkFlags VkDescriptorPoolResetFlags;
```

```
typedef VkFlags VkDescriptorSetLayoutCreateFlags;
```

```
typedef VkFlags VkDeviceCreateFlags;
```

```
typedef VkFlags VkDeviceQueueCreateFlags;
```

```
typedef VkFlags VkEventCreateFlags;
```

```
typedef VkFlags VkFenceCreateFlags;
```

```
typedef VkFlags VkFormatFeatureFlags;
```

```
typedef VkFlags VkFramebufferCreateFlags;
```

```
typedef VkFlags VkImageAspectFlags;
```

```
typedef VkFlags VkImageCreateFlags;
```

```
typedef VkFlags VkImageUsageFlags;
```

```
typedef VkFlags VkImageViewCreateFlags;
```

```
typedef VkFlags VkInstanceCreateFlags;
```

```
typedef VkFlags VkMemoryHeapFlags;
```

```
typedef VkFlags VkMemoryMapFlags;
```

```
typedef VkFlags VkMemoryPropertyFlags;
```

```
typedef VkFlags VkPipelineCacheCreateFlags;
```

```
typedef VkFlags VkPipelineColorBlendStateCreateFlags;
```

```
typedef VkFlags VkPipelineCreateFlags;
```

```
typedef VkFlags VkPipelineDepthStencilStateCreateFlags;
```

```
typedef VkFlags VkPipelineDynamicStateCreateFlags;
```

```
typedef VkFlags VkPipelineInputAssemblyStateCreateFlags;
```

```c
typedef VkFlags VkPipelineLayoutCreateFlags;
```

```c
typedef VkFlags VkPipelineMultisampleStateCreateFlags;
```

```c
typedef VkFlags VkPipelineRasterizationStateCreateFlags;
```

```c
typedef VkFlags VkPipelineShaderStageCreateFlags;
```

```c
typedef VkFlags VkPipelineStageFlags;
```

```c
typedef VkFlags VkPipelineTessellationStateCreateFlags;
```

```c
typedef VkFlags VkPipelineVertexInputStateCreateFlags;
```

```c
typedef VkFlags VkPipelineViewportStateCreateFlags;
```

```c
typedef VkFlags VkQueryControlFlags;
```

```c
typedef VkFlags VkQueryPipelineStatisticFlags;
```

```c
typedef VkFlags VkQueryPoolCreateFlags;
```

```c
typedef VkFlags VkQueryResultFlags;
```

```c
typedef VkFlags VkQueueFlags;
```

```c
typedef VkFlags VkRenderPassCreateFlags;
```

```c
typedef VkFlags VkSampleCountFlags;
```

```c
typedef VkFlags VkSamplerCreateFlags;
```

```c
typedef VkFlags VkSemaphoreCreateFlags;
```

```c
typedef VkFlags VkShaderModuleCreateFlags;
```

```c
typedef VkFlags VkShaderStageFlags;
```

```c
typedef VkFlags VkSparseImageFormatFlags;
```

```c
typedef VkFlags VkSparseMemoryBindFlags;
```

```c
typedef VkFlags VkStencilFaceFlags;
```

```c
typedef VkFlags VkSubpassDescriptionFlags;
```

D.3 Macro Definitions in `vulkan.h`

Vulkan is defined as a C API. The supplied `vulkan.h` header defines a small number of C preprocessor macros that are described below.

D.3.1 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)
```

`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)
```

`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`.

D.3.2 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 26
```

D.3.3 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
```

D.4 Platform-Specific Macro Definitions in `vk_platform.h`

In addition to the macros described for `vulkan.h`, platform-specific macros specified and used in the included `vk_platform.h` file are described in this section. These macros are specifically used to control platform-dependent behavior and their exact definitions are under the control of specific platforms and Vulkan implementations.

D.4.1 Platform-Specific Calling Conventions

VKAPI_ATTR is a macro placed before the return type in Vulkan API function declarations. If not empty, the interpretation of this macro depends on the platform and compiler in use, but normally 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. If not empty, the interpretation of this macro depends on the platform and compiler in use, but normally controls calling conventions for MSVC-style compilers.

VKAPI_PTR is a macro placed between the *(* and * in Vulkan API function pointer declarations. If not empty, the interpretation of this macro depends on the platform and compiler in use, and normally controls calling conventions. VKAPI_PTR typically has the same definition as VKAPI_ATTR or VKAPI_CALL, depending on the compiler.

D.4.2 Platform-Specific Header Control

If the VK_NO_STDINT_H macro is defined by the application at compile time, extended integer types required 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.

D.4.3 Window System-Specific Header Control

When using different window systems with Khronos extensions, header files for those window systems must be included at compile time in order for the corresponding extension definitions to compile. The Vulkan header files cannot determine whether or not an external header is available at compile time, so applications must include macros enabling those headers. 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, and window systems they correspond to are defined in the following table.

Table D.1: Window System Extensions and Required Compile-Time Symbol Definitions

Extension Name	Required Compile-Time Symbol	Window System Name
VK_KHR_android_surface	VK_USE_PLATFORM_ANDROID_KHR	Android Native
VK_KHR_mir_surface	VK_USE_PLATFORM_MIR_KHR	Mir
VK_KHR_wayland_surface	VK_USE_PLATFORM_WAYLAND_KHR	Wayland
VK_KHR_win32_surface	VK_USE_PLATFORM_WIN32_KHR	Microsoft Windows
VK_KHR_xcb_surface	VK_USE_PLATFORM_XCB_KHR	X Window System Xcb library
VK_KHR_xlib_surface	VK_USE_PLATFORM_XLIB_KHR	X Window System Xlib library

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.

E.1 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.

E.2 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.

E.3 Invariance Rules

For a given instantiation of an Vulkan rendering context:

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:

- *Framebuffer contents (all bit planes)*
- *The color buffers enabled for writing*
- *Scissor parameters (other than enable)*
- *Writemasks (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)*
- *Pixel storage state*

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 buffers sharing the same framebuffer, either simultaneously or separately using the same command sequence, are pixel identical.*

Rule 4 *The same vertex or fragment shader will produce the same result when run multiple times with the same input. The wording "the same shader" means a program object that is populated with the same SPIR-V binary, which is used to create pipelines, possibly multiple times, and which program object is then 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 *The same vertex or fragment shader 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.*

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.

E.4 Tessellation Invariance

When using a program 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 active program 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.*

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.

- Adam Jackson, Red Hat
- 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
- Ben Bowman, Imagination Technologies
- Benj Lipchak
- Bill Hollings, The Brenwill Workshop

- Bill Licea-Kane, Qualcomm Technologies, Inc.
- Brent E. Insko, Intel
- Brian Ellis, Qualcomm Technologies, Inc.
- Cass Everitt, Oculus VR
- Cemil Azizoglu, Canonical
- Chad Versace, Intel
- Chang-Hyo Yu, Samsung Electronics
- Chia-I Wu, LunarG
- Chris Frascati, Qualcomm Technologies, Inc.
- Christophe Riccio, Unity
- Cody Northrop, LunarG
- Courtney Goeltzenleuchter, LunarG
- Damien Leone, NVIDIA
- Dan Baker, Oxide Games
- Dan Ginsburg, Valve
- Daniel Johnston, Intel
- Daniel Koch, NVIDIA (Shader Interfaces; Features)
- Daniel Rakos, AMD
- David Airlie, Red Hat
- David Neto, Google
- David Mao, AMD
- David Yu, Pixar
- Dominik Witczak, AMD
- Frank (LingJun) Chen, Qualcomm Technologies, Inc.
- Fred Liao, Mediatek
- Gabe Dagani, Freescale
- 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
- Jeff Vigil, Qualcomm Technologies, Inc.
- Jens Owen, LunarG
- Jeremy Hayes, LunarG
- Jesse Barker, ARM
- Jesse Hall, Google
- Johannes van Waveren, Oculus VR
- John Kessenich, Independent (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)
- Kristian Kristensen, Intel
- Krzysztof Iwanicki, Samsung Electronics
- Larry Seiler, Intel
- Lutz Latta, Lucasfilm
- Maria Rovatsou, Codeplay Software Ltd.
- Mark Callow
- Mark Lobodzinski, LunarG
- Mateusz Przybylski, Intel
- Mathias Heyer, NVIDIA
- Mathias Schott, NVIDIA

- Maxim Lukyanov, Samsung Electronics
- Maurice Ribble, Qualcomm Technologies, Inc.
- Michael Lentine, Google
- Michael Worcester, Imagination Technologies
- Michal Pietrasiuk, Intel
- Mika Isojarvi, Google
- Mike Stroyan, LunarG
- Minyoung Son, Samsung Electronics
- Mitch Singer, AMD
- Mythri Venugopal, Samsung Electronics
- Naveen Leekha, Google
- Neil Henning, Codeplay Software Ltd.
- Neil Trevett, NVIDIA
- Nick Penwarden, Epic Games
- Niklas Smedberg, Epic Games
- Norbert Nopper, Freescale
- Pat Brown, NVIDIA
- Patrick Doane, Blizzard Entertainment
- Peter Lohrmann, Valve
- Pierre Boudier, NVIDIA
- Pierre-Loup A. Griffais, Valve
- Piers Daniell, NVIDIA (dynamic state, copy commands, memory types)
- Piotr Bialecki, Intel
- Prabindh Sundareson, Samsung Electronics
- Pyry Haulos, Google (Vulkan conformance test subcommittee chair)
- Ray Smith, ARM
- 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
- Wayne Lister, Imagination Technologies
- Yanjun Zhang, Vivante
- Zhenghong Wang, Mediatek

In addition to the Working Group, the Vulkan Advisory Panel members provided important real-world usage information and advice that helped guide design decisions.

Administrative support to the Working Group was provided by members of Gold Standard Group, including Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, Kathleen Mattson and Michelle Clark. Technical support was provided by James Riordon, webmaster of Khronos.org and OpenGL.org.