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Chapter 1

Introduction

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

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

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

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

1.1 What is the Vulkan Graphics System?

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

1.1.1 The Programmer's View of Vulkan

To the programmer, Vulkan is a set of commands that allow the specification of *shader programs* or *shaders*, *kernels*, data used by kernels or shaders, and state controlling aspects of Vulkan outside 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, must not, required, shall, shall not, should, should not, recommend, may, and optional in this document are to be interpreted as described in RFC 2119:

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

must

This word, or the terms **required** or **shall**, mean that the definition is an absolute requirement of the specification.

must not

This phrase, or the phrase shall not, means that the definition is an absolute prohibition of the specification.

should

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.

should not

This phrase, or the phrase **not recommended**, 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, March 9, 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.

Chapter 2

Fundamentals

This chapter introduces fundamental concepts including the Vulkan 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 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 queues supported by a device are divided into *families*, each of which 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

It is possible that 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.

2.1.1 Queue Operation

Vulkan queues provide an interface to the execution engines of a device. Commands are recorded into command buffers ahead of execution time. These command buffers are then submitted to queues for execution. Command buffers submitted to a single queue are played back in the order they were submitted, and commands within each buffer are played back in the order they were recorded. Work performed by those commands respects the ordering guarantees provided by explicit and implicit dependencies, as described below. Work submitted to separate queues may execute in any relative order unless otherwise specified. Therefore, the application must explicitly synchronize work between queues when needed.

In order to control relative order of execution of work both within a queue and across multiple queues, Vulkan provides several synchronization primitives, which include *semaphores*, *events*, *pipeline barriers*, and *fences*. These are covered in depth in Synchronization and Cache Control. In broad terms, semaphores are used to synchronize work across queues or across coarse-grained submissions to a single queue, events and barriers are used to synchronize work within a command buffer or sequence of command buffers submitted to a single queue, and fences are used to synchronize work between the device and the host.



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.

Work is submitted to queues using queue submission commands that typically take the form **vkQueue*** (e.g. vkQueueSubmit, vkQueueBindSparse), and usually take a list of semaphores upon which to wait before work begins and a list of semaphores to signal once work has completed. Unless otherwise ordered by semaphores, command buffer execution from multiple queue submissions done using the vkQueueSubmit command may overlap (but not be reordered), sparse binding operations done using the vkQueueBindSparse command from multiple batches may overlap or be reordered, and command buffer submissions and sparse binding operations may overlap or be reordered against operations of the other type.

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 plays back 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.

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.

Submitting command buffers and sparse memory operations, signaling fences, and signaling and waiting on semaphores each provide Implicit Ordering Guarantees. Signaling a fence or semaphore each guarantees that the previous commands have completed execution and that memory writes from those commands are available to future commands. Waiting on a semaphore or submitting command buffers after a fence has been signaled each guarantees that previous writes that were available are also visible to subsequent commands.

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 *API 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

where the 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 command buffers from queues asynchronously from 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.

As part of each submission to a queue, a list of semaphores upon which to wait, and a list of semaphores to signal is provided along with the list of command buffers to execute. This is covered in more detail in Section 5.4.

2.2 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.

2.2.1 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 can be destroyed at any time they are not in use by an API command:

- VkShaderModule
- VkPipelineCache
- VkPipelineLayout

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 any uses of that object by the device (such as via command buffer execution) have completed.

The following Vulkan objects can be destroyed when no command buffers using the object are executing:

- VkEvent
- VkQueryPool

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

The following Vulkan objects can be destroyed when work on the queue that uses the object has been completed:

- 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.

2.3 Command Syntax

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.

With few exceptions, Vulkan uses the standard C types for parameters (int types from stdint.h, etc). Exceptions to this are using VkResult for return values, using VkBool32 for boolean values, VkDeviceSize for sizes and offsets pertaining to device address space, and VkFlags for passing bits or sets of bits of predefined values.

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.

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

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.

2.4 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
- $\bullet \ \ The \ \textit{imageView} \ parameter \ in \ \texttt{vkDestroyImageView}$
- The shaderModule parameter in vkDestroyShaderModule
- The pipelineCache parameter in vkDestroyPipelineCache
- The dstCache parameter in vkMergePipelineCaches
- The pipeline parameter in vkDestroyPipeline
- $\bullet \ \ The \ \textit{pipelineLayout parameter in} \ \texttt{vkDestroyPipelineLayout}$
- 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
- $\bullet \ \ The \ \textit{commandBuffer} \ parameter \ in \ \texttt{vkCmdBindDescriptorSets}$
- The commandBuffer parameter in vkCmdBindIndexBuffer
- The commandBuffer parameter in vkCmdBindVertexBuffers
- The commandBuffer parameter in vkCmdDraw
- The commandBuffer parameter in vkCmdDrawIndexed
- $\bullet \ \ The \ \textit{commandBuffer} \ parameter \ in \ \texttt{vkCmdDrawIndirect}$
- 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
- $\bullet \ \ The \ \textit{commandBuffer} \ parameter \ in \ \texttt{vkCmdNextSubpass}$
- 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
- ullet Each element of the pCommandBuffers parameter in vkFreeCommandBuffers

In addition, there are some implicit parameters that need to be externally synchronized. For example, all <code>commandBuffer</code> parameters that need to be externally synchronized imply that the <code>commandPool</code> 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

2.5 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 <code>robustBufferAccess</code> 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.

2.5.1 Valid Usage

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

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.

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.

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.

Any parameter that is a flag value 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 flag is defined as part of the bits 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 values selected from the bit flags in VkColorComponentFlagBits.
- The flag is allowed in the context in which it is being used. For example, in some cases, certain bit flags or combinations of bit flags are mutually exclusive.

Any parameter that is a structure containing a VkStructureType sType member must have a value of sType matching the type of the structure. The correct value is described for each structure type, but 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 don't have corresponding Vulkan structures in this specification.

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 that is defined by an enabled extension. Extension structures are not described in the base Vulkan specification, but either in layered specifications incorporating those extensions, or in separate vendor-provided documents.

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.

2.5.2 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,
} 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.

If a command returns a run time error, it will leave any result pointers unmodified.

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

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

2.6 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.

2.6.1 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.

2.6.2 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.

2.6.3 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.

2.6.4 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.

2.6.5 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.

2.7 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.

2.7.1 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, including for all signed normalized fixed-point parameters in Vulkan commands, such as vertex attribute values, as well as for specifying texture or framebuffer values using signed normalized fixed-point.

2.7.2 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

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

where convertFloatToUint(r,b) returns one of the two unsigned binary integer values with exactly b bits which are closest to the floating-point value r (where rounding to nearest is preferred). 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 f' 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

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

where convertFloatToInt(r,b) returns one of the two signed two's-complement binary integer values with exactly b bits which are closest to the floating-point value r (where rounding to nearest is preferred). If r is equal to an integer, then that integer value is returned. In particular, if f is equal to -1.0, 0.0, or 1.0, then f' 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, including when querying floating-point state and returning integers, as well as for specifying signed normalized texture or framebuffer values using floating-point.

2.8 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 aspect 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.

2.9 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*.

2.9.1 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. Two- and three-dimensional offsets are respectively defined by the structures

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

typedef struct VkOffset3D {
```

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

2.9.2 Extents

Extents are used to describe the size of a block of pixels within an image or framebuffer, as (width,height) for two-dimensional images, or as (width,height,depth) for three-dimensional images. Two- and three-dimensional extents are respectively defined by the structures

```
typedef struct VkExtent2D {
    uint32_t width;
    uint32_t height;
} VkExtent2D;

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

2.9.3 Rectangles

Rectangles are used to describe a specified rectangular block 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

```
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:

- instance is the instance that the function pointer will be compatible with.
- pName is the name of the command to obtain.

- If instance is not NULL, instance must be a valid VkInstance handle
- pName must be a null-terminated string
- If instance is NULL, pName must be one of: vkEnumerateInstanceExtensionProperties, vkEnumerateInstanceLayerProperties or vkCreateInstance
- If instance is not NULL, pName must be the name of a core command or a command from an enabled extension, other than: vkEnumerateInstanceExtensionProperties, vkEnumerateInstanceLayerProperties or vkCreateInstance

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**.

Function pointers to commands that don't operate on a specific instance can be obtained by using this command with <code>instance</code> equal to <code>NULL</code>. The following commands can be accessed this way:

- vkEnumerateInstanceExtensionProperties
- vkEnumerateInstanceLayerProperties
- vkCreateInstance

If *instance* is a valid VkInstance, function pointers to any commands that operate on *instance* or a child of *instance* can be obtained. The returned function pointer must only be called with a dispatchable object (the first parameter) that is a child of *instance*.

If *pName* is not the name of a core Vulkan command, or is an extension command for any extension not supported by any available layer or implementation, then **vkGetInstanceProcAddr** will return NULL.

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:

- device is the logical device that provides the function pointer.
- pName is the name of any Vulkan command whose first parameter is one of
 - VkDevice
 - VkQueue
 - VkCommandBuffer

If pName is not the name of one of these Vulkan commands, and is not the name of an extension command belonging to an extension enabled for device, then **vkGetDeviceProcAddr** will return NULL.

- device must be a valid VkDevice handle
- pName must be a null-terminated string
- pName must be the name of a supported command that has a first parameter of type VkDevice, VkQueue or VkCommandBuffer, either in the core API or an enabled extension

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.

To create an instance object, call:

- 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.

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 definition of VkInstanceCreateInfo is:

- *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.

- 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
- Any given element of ppEnabledLayerNames must be the name of a layer present on the system, exactly matching a string returned in the VkLayerProperties structure by **vkEnumerateInstanceLayerProperties**

- Any given element of ppEnabledExtensionNames must be the name of an extension present on the system, exactly matching a string returned in the VkExtensionProperties structure by vkEnumerateInstanceExtensionProperties
- If an extension listed in ppEnabledExtensionNames is provided as part of a layer, then both the layer and extension must be enabled to enable that extension

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.

The papplicationInfo member of VkInstanceCreateInfo can point to an instance of VkApplicationInfo. This structure is defined as:

- 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.

- 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:

- 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.

4.1 Physical Devices

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

- 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 structures.

If <code>pPhysicalDevices</code> is <code>NULL</code>, then the number of physical devices available is returned in <code>pPhysicalDeviceCount</code>. Otherwise, <code>pPhysicalDeviceCount</code> must point to a variable set by the user to the number of elements in the <code>pPhysicalDevices</code> array, and on return the variable is overwritten with the number of structures actually written to <code>pPhysicalDevices</code>. If <code>pPhysicalDeviceCount</code> is less than the number of physical devices available, at most <code>pPhysicalDeviceCount</code> structures will be written. If <code>pPhysicalDeviceCount</code> is smaller than the number of physical devices available, <code>VK_INCOMPLETE</code> will be returned instead of <code>VK_SUCCESS</code>, 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

Once enumerated, general properties of the physical devices are queried by calling:

- 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 definition of VkPhysicalDeviceProperties is:

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

The members of VkPhysicalDeviceProperties have the following meanings:

- 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 <code>vendorID</code> and <code>deviceID</code> 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 <code>vendorID</code> and <code>deviceID</code> 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 <code>vendorID</code> as described above for PCI-based implementations. Implementations that do not return a PCI vendor ID in <code>vendorID</code> must return a valid Khronos vendor ID, obtained as defined in the Registering a Vendor ID with Khronos section. 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 <code>deviceID</code>. 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.

Properties of queues available on a physical device are queried by calling:

- physical Device 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 <code>pQueueFamilyPropertyCount</code> is not 0, and <code>pQueueFamilyProperties</code> is not <code>NULL</code>, <code>pQueueFamilyProperties</code> must be a pointer to an array of <code>pQueueFamilyPropertyCount</code> <code>VkQueueFamilyProperties</code> structures

The definition of VkQueueFamilyProperties is:

The members of VkQueueFamilyProperties have the following meanings:

- 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 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 VkOffset 3D 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 VkOffset 3D 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 block size.

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

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

- 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.

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_LAYER_NOT_PRESENT
VK_ERROR_EXTENSION_NOT_PRESENT
VK_ERROR_FEATURE_NOT_PRESENT
VK_ERROR_TOO_MANY_OBJECTS
VK_ERROR_DEVICE_LOST
```

The definition of VkDeviceCreateInfo is:

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

The members of VkDeviceCreateInfo have the following meanings:

- 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 the number of device 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 device. See the Layers section for further details.
- $\bullet \ \ {\tt enabledExtensionCount} \ \ {\tt is} \ \ {\tt the} \ \ {\tt number} \ \ {\tt of} \ \ {\tt device} \ \ {\tt extensions} \ \ {\tt to} \ \ {\tt enable}.$
- 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 Querying Layers and Extensions chapter 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, and ppEnabledLayerNames is not NULL, ppEnabledLayerNames must be a pointer to an array of enabledLayerCount null-terminated strings
- If enabledExtensionCount is not 0, and ppEnabledExtensionNames is not NULL, 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
- Any given element of ppEnabledLayerNames must be the name of a layer present on the system, exactly matching a string returned in the VkLayerProperties structure by vkEnumerateDeviceLayerProperties
- Any given element of ppEnabledExtensionNames must be the name of an extension present on the system, exactly matching a string returned in the VkExtensionProperties structure by vkEnumerateDeviceExtensionProperties
- If an extension listed in ppEnabledExtensionNames is provided as part of a layer, then both the layer and extension must be enabled to enable that extension
- The queueFamilyIndex member of any given element of pQueueCreateInfos must be unique within pQueueCreateInfos

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.

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 Device Idle

A device is active while any of its queues have work to process. Once all device queues are idle, the device is idle. To wait for this condition, call:

• device is the logical device to idle.

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

4.2.4 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.

3

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 Lifetime). 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, 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 $VK_SUCCESS$.

4.2.5 Device Destruction

To destroy a device, call:

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

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 <code>device</code> 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

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 **vkDestroy Device**.

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 <code>queueFamilyIndex</code> that is passed to the <code>vkCreateDevice</code> command via the <code>VkDeviceQueueCreateInfo</code> 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. The definition of VkDeviceQueueCreateInfo is:

The members of VkDeviceQueueCreateInfo have the following meanings:

- *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.

- 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:

- 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.

- 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 Synchronization

To wait on the completion of all work within a single queue, call:

• queue is the queue on which to wait.

vkQueueWaitIdle will block until all command buffers and sparse binding operations in the queue have completed.

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

Synchronization between queues is done using Vulkan semaphores as described in the Synchronization and Cache Control chapter.

4.3.6 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.

4.3.7 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.

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.

To create a command pool, call:

- 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 an 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 follows:

- *sType* is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is a combination of bitfield flags indicating usage behavior for the pool and command buffers allocated from it.
 Possible values 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 created from this command pool must be submitted on queues from the same queue family.

- 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

Reset a command pool by calling:

VkResult vkResetCommandPool(
 VkDevice
 VkCommandPool
 VkCommandPoolResetFlags

device,
commandPool,
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.

Valid Usage

- device must be a valid VkDevice handle
- commandPool must be a valid VkCommandPool handle
- $\bullet \ \textit{flags} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{combination} \ \textbf{of} \ \texttt{VkCommandPoolResetFlagBits} \ \textbf{values} \\$
- commandPool must have been created, allocated or retrieved from device
- Each of device and commandPool must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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.

flags is of type VkCommandPoolResetFlags, which is defined as:

```
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.

To destroy a command pool, call:

- 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.

- device must be a valid VkDevice handle
- If commandPool is not VK_NULL_HANDLE, commandPool must be a valid VkCommandPool handle
- $\bullet \ \ If \ \textit{pAllocator} \ is \ not \ \texttt{NULL}, \ \textit{pAllocator} \ must \ be \ a \ pointer \ to \ a \ valid \ \texttt{VkAllocationCallbacks} \ structure$
- If commandPool is a valid handle, it must have been created, allocated or retrieved from device
- Each of device and commandPool that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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.

5.2 Command Buffer Allocation and Management

Command buffers are allocated by calling:

- 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:

- *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.

- 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

Command buffers are reset by calling:

- commandBuffer is the command buffer to reset. The command buffer can be in any state, and is put in the initial state.
- flags is of type VkCommandBufferResetFlags:

```
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
- $\bullet \ \textit{flags} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{combination} \ \textbf{of} \ \texttt{VkCommandBufferResetFlagBits} \ \textbf{values}$
- 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

Command buffers are freed by calling:

- 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.

- 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
- Each of device, commandPool and the elements of pCommandBuffers that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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:

- 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
- 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:

- *sType* is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is a combination of bitfield flags indicating usage behavior for the command buffer. Possible values 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 = 0x000000004,
} 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.

- 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;
                                    framebuffer;
   VkFramebuffer
   VkBool32
                                     occlusionQueryEnable;
   VkQueryControlFlags
                                     queryFlags;
   VkQueryPipelineStatisticFlags
                                     pipelineStatistics;
} VkCommandBufferInheritanceInfo;
```

- renderPass is a VkRenderPass object that must be compatible with the one that is bound when the VkCommandBuffer is executed if the command buffer was allocated with the VK_COMMAND_BUFFER_USAGE_RENDER PASS CONTINUE BIT set.
- subpass is the index of the subpass within renderPass that the VkCommandBuffer will be rendering against if it was allocated with the VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT set.
- framebuffer refers to the VkFramebuffer object that the VkCommandBuffer will be rendering to if it was allocated with the VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT set. It can be VK_NULL_HANDLE if the framebuffer is not known.



Note

Specifying the exact framebuffer that the secondary command buffer will be executed with may result in better performance at command buffer execution time.

• occlusionQueryEnable 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.

- stype must be VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO
- pNext must be NULL
- Each of renderPass and framebuffer 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.

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:

• 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.

Valid Usage

- commandBuffer must be a valid VkCommandBuffer handle
- commandBuffer must be in the recording state
- vkEndCommandBuffer must not be called inside a 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

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.

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

5.4 Command Buffer Submission

Command buffers are submitted to a queue by calling:

- queue is the handle of 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 which describe the work to submit. All work described by pSubmits must be submitted to the queue before the command returns.
- fence is an optional handle to a fence. If fence is not VK_NULL_HANDLE, the fence is signaled when execution of all VkSubmitInfo::pCommandBuffers members of pSubmits is completed. If submitCount is zero but fence is not VK_NULL_HANDLE, the fence will still be submitted to the queue and will become signaled when all work previously submitted to the queue has completed.

- 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
- Each of *queue* and *fence* that are valid handles must have been created, allocated or retrieved from the same VkDevice
- fence must be unsignalled
- 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

Each submission of work is represented by a sequence of command buffers, each preceded by a list of semaphores upon which to wait before beginning execution of specific stages of commands in the command buffers, and followed by a second list of semaphores to signal upon completion of the work contained in the command buffers.



Note

The exact definition of a submission is platform-specific, but is considered a relatively expensive operation. In general, applications should attempt to batch work together into as few calls to **vkQueueSubmit** as possible.

Each call to **vkQueueSubmit** submits zero or more *batches* of work to the queue for execution. *submitCount* is used to specify the number of batches to submit. Each batch includes zero or more semaphores to wait upon, and a

corresponding set of stages that will wait for the semaphore to be signalled before executing any work, followed by a number of command buffers that will be executed, and finally, zero or more semaphores that will be signaled after command buffer execution completes. Each batch is represented as an instance of the VkSubmitInfo structure stored in an array, the address of which is passed in *pSubmitInfo*. The definition of VkSubmitInfo is:

```
typedef struct VkSubmitInfo {
   VkStructureType
                                   sType;
   const void*
                                   pNext;
   uint32_t
                                  waitSemaphoreCount;
   const VkSemaphore*
                                  pWaitSemaphores;
   const VkPipelineStageFlags*     pWaitDstStageMask;
                                  commandBufferCount;
   uint32 t
   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 executing the command buffers in the batch.
- pWaitDstStageMask is a pointer to an array of pipeline stages at which each corresponding semaphore wait will occur.
- commandBufferCount contains 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.

- 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 pWaitSemaphores, the elements of pCommandBuffers and the elements of pSignalSemaphores that are valid handles must have been created, allocated or retrieved from the same VkDevice
- Any given element of pSignalSemaphores must currently be unsignalled
- 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 created 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 created 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 created on 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 created with VK_COMMAND_BUFFER_LEVEL_ SECONDARY
- Any given element of VkSemaphore in pWaitSemaphores must refer to a prior signal of that VkSemaphore that won't 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 <code>pWaitDstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</code>

If fence is provided, it must be in the unsignaled state (see Fences) and a fence must only be associated with a single submission until that submission completes, and the fence is subsequently reset. When all command buffers in pCommandBuffers have completed execution, the status of fence is set to signaled, providing certain implicit ordering guarantees.

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 won't be consumed by a different wait on the semaphore.

Command buffers in the submission can include vkCmdWaitEvents commands that wait on events that won't 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 isn't 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:

- commandBuffer is a handle to a primary command buffer that the secondary command buffers are submitted to, and must be in the recording state.
- 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.

- 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
- Each of commandBuffer and the elements of pCommandBuffers must have been created, allocated or retrieved from the same VkDevice
- commandBuffer must have been created with a level of VK COMMAND BUFFER LEVEL PRIMARY

- Any given element of pCommandBuffers must have been created 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 created 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 created with the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT flag
- Any given element of pCommandBuffers must be in the executable state
- 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 the *subpass* member of the *inheritanceInfo* structure 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 the framebuffer member of the VkCommandBufferInheritanceInfo structure not equal to VK_NULL_HANDLE, that VkFramebuffer must be compatible with the VkFramebuffer used in the current render pass instance
- 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 VkCommandBufferBeginInfo::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 VkCommandBufferBeginInfo::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 VkCommandBufferBeginInfo::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

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

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 block 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 submissions to queues performed with vkQueueSubmit and vkQueueBindSparse.

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.

To create a new fence object, use the command

- 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.

- 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 definition of VkFenceCreateInfo is:

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

The flags member of the VkFenceCreateInfo structure pointed to by pCreateInfo contains flags defining the initial state and behavior of the fence. The flags are:

```
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

A fence can be passed as a parameter to the queue submission commands, and when the associated queue submissions all complete execution the fence will transition from the unsignaled to the signaled state. See Command Buffer Submission and Binding Resource Memory.

To destroy a fence, call:

- 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.

- device must be a valid VkDevice handle
- If fence is not VK NULL HANDLE, fence must be a valid VkFence handle
- $\bullet \ \ If \ \textit{pAllocator} \ \textbf{is not} \ \texttt{NULL}, \ \textit{pAllocator} \ \textbf{must} \ \textbf{be} \ \textbf{a pointer to} \ \textbf{a valid} \ \texttt{VkAllocationCallbacks} \ \textbf{structure}$
- If fence is a valid handle, it must have been created, allocated or retrieved from device
- Each of device and fence that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

- device is the logical device that owns the fence.
- fence is the handle of the fence to query.

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
- Each of device and fence must have been created, allocated or retrieved from the same VkPhysicalDevice

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

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.

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

- 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.

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
- Each of device and the elements of pFences must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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

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

- 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.

- device must be a valid VkDevice handle
- \bullet $\,$ pFences must be a pointer to an array of ${\it fenceCount}$ valid ${\tt VkFence}$ handles
- fenceCount must be greater than 0
- Each element of pFences must have been created, allocated or retrieved from device
- ullet Each of device and the elements of pFences must have been created, allocated or retrieved from the same VkPhysicalDevice

Return Codes

Success

- VK SUCCESS
- VK_TIMEOUT

Failure

- VK ERROR OUT OF HOST MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

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.

Fences become signaled when the device completes executing the work that was submitted to a queue accompanied by the fence. But this alone is not sufficient for the host to be guaranteed to see the results of device writes to memory. 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 <code>dstAccessMask</code> having the VK_ACCESS_HOST_READ_BIT bit set, with <code>dstStageMask</code> having the VK_PIPELINE_STAGE_HOST_BIT bit set, and with the appropriate <code>srcStageMask</code> and <code>srcAccessMask</code> members set to guarantee completion of the writes. If the memory was allocated without the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT set, then <code>vkInvalidateMappedMemoryRanges</code> 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.

6.2 Semaphores

Semaphores are used to coordinate operations between queues and between queue submissions within a single queue. An application might associate semaphores with resources or groups of resources to marshal ownership of shared data. A semaphore's status is always either *signaled* or *unsignaled*. Semaphores are signaled by queues and can also be waited on in the same or different queues until they are signaled.

To create a new semaphore object, use the command

• 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.

- 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 definition of VkSemaphoreCreateInfo is:

The members of VkSemaphoreCreateInfo have the following meanings:

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

- sType must be VK STRUCTURE TYPE SEMAPHORE CREATE INFO
- pNext must be NULL
- flags must be 0

To destroy a semaphore, call:

- 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.

- 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
- Each of device and semaphore that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

To signal a semaphore from a queue, include it in an element of the array of VkSubmitInfo structures passed through the pSubmitInfo parameter to a call to vkQueueSubmit, or in an element of the array of VkBindSparseInfo structures passed through the pBindInfo parameter to a call to vkQueueBindSparse.

Semaphores included in the pSignalSemaphores array of one of the elements of a queue submission are signaled once queue execution reaches the signal operation, and all previous work in the queue completes. Any operations waiting on that semaphore in other queues will be released once it is signaled.

Similarly, to wait on a semaphore from a queue, include it in the <code>pWaitSemaphores</code> array of one of the elements of a batch in a queue submission. When queue execution reaches the wait operation, will stall execution of subsequently submitted operations until the semaphore reaches the signaled state due to a signaling operation. Once the semaphore is signaled, the subsequent operations will be permitted to execute and the status of the semaphore will be reset to the unsignaled state.

In the case of VkSubmitInfo, command buffers wait at specific pipeline stages, rather than delaying the entire command buffer's execution, with the pipeline stages determined by the corresponding element of the <code>pWaitDstStageMask</code> member of VkSubmitInfo. Execution of work by those stages in subsequent commands is stalled until the corresponding semaphore reaches the signaled state. Subsequent sparse binding operations wait for the semaphore to become signaled, regardless of the values of <code>pWaitDstStageMask</code>.

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, an image that was being presented 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_ATTACH MENT WRITE BIT.
- oldLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR
- newLayout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL

Alternately, 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 <code>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</code> stage, then there is a dependency from that same stage to itself with the layout transition performed in between.

When a queue signals or waits upon a semaphore, certain implicit ordering guarantees are provided.

Semaphore operations may not make the side effects of commands visible to the host.

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.

To create an event, call:

- 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.

- 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 definition of $\mbox{VkEventCreateInfo}\ is:$

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

The flags member of the VkEventCreateInfo structure pointed to by pCreateInfo contains flags defining the behavior of the event. Currently, no flags are defined. When created, the event object is in the unsignaled state.

- sType must be VK STRUCTURE TYPE EVENT CREATE INFO
- pNext must be NULL
- flags must be 0

To destroy an event, call:

- 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
- Each of device and event that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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:

- device is the logical device that owns the event.
- event is the handle of the event to query.

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
- Each of device and event must have been created, allocated or retrieved from the same VkPhysicalDevice

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

Upon success, **vkGetEventStatus** returns the state of the event object with the following return codes:

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

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.

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

- 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
- Each of device and event must have been created, allocated or retrieved from the same VkPhysicalDevice

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:

- device is the logical device that owns the event.
- event is the event to reset.

- device must be a valid VkDevice handle
- event must be a valid VkEvent handle
- event must have been created, allocated or retrieved from device
- Each of device and event must have been created, allocated or retrieved from the same VkPhysicalDevice

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:

- 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.

- 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
- Each 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, <code>stageMask</code> must not contain <code>VK_PIPELINE_STAGE_</code>
 <code>TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_</code>
 <code>SHADER_BIT</code>

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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

- 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.

- 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
- Each of commandBuffer and event must have been created, allocated or retrieved from the same VkDevice
- If the geometry shaders feature is not enabled, <code>stageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY SHADER BIT</code>
- If the tessellation shaders feature is not enabled, <code>stageMask</code> must not contain <code>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</code>

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary	Outside	GRAPHICS
Secondary		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,
                                                bufferMemoryBarrierCount,
   uint32_t
    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.

- 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
- Each 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, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the geometry shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_</code> <code>TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_</code> <code>SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_</code>
 <code>TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_</code>
 <code>SHADER_BIT</code>
- 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	Both	GRAPHICS
Secondary		COMPUTE

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 <code>dstStageMask</code> (see Section 6.5.2) until the <code>eventCount</code> event objects specified by <code>pEvents</code> become signaled. Implementations may wait for each event object to become signaled in sequence (starting with the first event object in <code>pEvents</code>, 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.

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 <code>srcStageMask</code> (see Pipeline Stage Flags) of the first set of commands completes before any work performed by the set of pipeline stages included in <code>dstStageMask</code> 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.

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.

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 <code>dependencyFlags</code> does not include <code>VK_DEPENDENCY_BY_REGION_BIT</code>, 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 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 execute first vs the commands that execute second, 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 subresource of an image to be synchronized between two sets of commands, the byte or 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 <code>srcStageMask</code> and <code>srcAccessMask</code> available, then performs the layout transition, then makes the contents of the image subresource(s) in the new layout visible to memory accesses in <code>dstStageMask</code> and <code>dstAccessMask</code>, 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. A pipeline barrier is recorded by calling:

```
const VkMemoryBarrier*
uint32_t
const VkBufferMemoryBarrier*
uint32_t
uint32_t
const VkBufferMemoryBarrier*
uint32_t
const VkImageMemoryBarrier*
plmageMemoryBarriers);
```

- 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 <code>srcStageMask</code> of the first set of commands completes before any work performed by the set of pipeline stages included in <code>dstStageMask</code> 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.

- 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, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the geometry shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_</code>
 <code>TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_</code>
 <code>SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</code>
- If **vkCmdPipelineBarrier** is called within a render pass instance, the render pass must declare at least one self-dependency from the current subpass to itself see Subpass Self-dependency

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope	Supported Queue Types
Primary	Both	TRANSFER
Secondary		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 is used, the image and 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 with the bitfield:

```
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 doesn't 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 6.1: 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_	VK_QUEUE_GRAPHICS_BIT
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 definition of VkMemoryBarrier is:

The members of VkMemoryBarrier have the following meanings:

- *sType* is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- srcAccessMask is a mask of the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- dstAccessMask is a mask of the classes of memory accesses performed by the second set of commands that will participate in the dependency.

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

<code>srcAccessMask</code> and <code>dstAccessMask</code>, along with <code>srcStageMask</code> and <code>dstStageMask</code> from <code>vkCmdPipelineBarrier</code>, define the two halves of a memory dependency and an execution dependency. Memory accesses using the set of access types in <code>srcAccessMask</code> performed in pipeline stages in <code>srcStageMask</code> 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 <code>dstAccessMask</code> performed in pipeline stages in <code>dstStageMask</code> 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.

srcAccessMask and dstAccessMask are each masks of the following bitfield:

```
typedef enum VkAccessFlagBits {
   VK_ACCESS_INDIRECT_COMMAND_READ_BIT = 0x0000001,
   VK_ACCESS_INDEX_READ_BIT = 0 \times 000000002,
   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;
```

VkAccessFlagBits has the following meanings:

- 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 <code>srcAccessMask</code>, all access types in <code>dstAccessMask</code> from pipeline stages in <code>dstStageMask</code> will observe the side effects of commands that executed before the barrier. When included in <code>dstAccessMask</code> all writes using access types in <code>srcAccessMask</code> performed by pipeline stages in <code>srcStageMask</code> 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 API 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.

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

Table 6.2: Supported access flags

Table 6.2: (continued)

Access flag	Required queue capability flag
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

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.

VkBufferMemoryBarrier has the following definition:

The members of VkBufferMemoryBarrier have the following meanings:

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- srcAccessMask is a mask of the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- dstAccessMask is a mask 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 subresource range of the specified image object. That is, a memory dependency formed from a image memory barrier is scoped to the specified 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.

VkImageMemoryBarrier has the following definition:

```
VkImageLayout oldLayout;
VkImageLayout newLayout;
uint32_t srcQueueFamilyIndex;
uint32_t dstQueueFamilyIndex;
VkImage image;
VkImageSubresourceRange subresourceRange;

VkImageMemoryBarrier;
```

The members of VkImageMemoryBarrier have the following meanings:

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- srcAccessMask is a mask of the classes of memory accesses performed by the first set of commands that will participate in the dependency.
- dstAccessMask is a mask 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 subresources whose image layouts are modified.

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 Vk Image handle
- subresourceRange must be a valid VkImageSubresourceRange structure

- oldLayout must be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED or the current layout of the image region 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 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

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.

6.6 Implicit Ordering Guarantees

Submitting command buffers and sparse memory operations, signaling fences, and signaling and waiting on semaphores each perform implicit memory barriers. The following guarantees are made:

After a fence or semaphore is signaled, it is guaranteed that:

- All commands in any command buffer submitted to the queue before and including the submission that signals the fence, or the batch that signals the semaphore, have completed execution.
- The side effects of these commands are available to any commands or sparse binding operations (on any queue) that follow a semaphore wait, if the semaphore they wait upon was signaled at a later time than this fence or semaphore, or that are submitted to any queue after the fence is signaled. Those side effects are also visible to the same sparse binding operations that follow the semaphore wait. If the semaphore wait is part of a VkSubmitInfo structure passed to vkQueueSubmit, they are also visible to the pipeline stages specified in the pWaitDstStageMask element corresponding to the semaphore wait, for the same commands that follow the semaphore wait. If the semaphore wait is part of a VkSubmitInfo structure passed to vkQueueBindSparse, they are visible to all stages for the same commands.
- All sparse binding operations submitted to the queue before and including the submission that signals the fence, or the batch that signals the semaphore, have completed.
- The bindings performed by these operations are available to any commands or sparse binding operations (on any queue) that follow a semaphore wait, if the semaphore they wait upon was signaled at a later time than this fence or semaphore, or that are submitted to any queue after the fence is signaled. Those bindings are also visible to the same sparse binding operations that follow the semaphore wait. If the semaphore wait is part of a VkSubmitInfo structure passed to vkQueueSubmit, they are also visible to the pipeline stages specified in the pWaitDstStageMask element corresponding to the semaphore wait, for the same commands that follows the semaphore wait. If the semaphore wait is part of a VkSubmitInfo structure passed to vkQueueBindSparse, they are visible to all stages for the same commands.
- Objects that were used in previous command buffers in this queue before the fence was signaled, or in another queue
 that has signaled a semaphore after using the objects and before this fence or semaphore was signaled, and which are
 not used in any subsequent command buffers, can be freed or destroyed, including the command buffers themselves.
- The fence can be reset or destroyed.
- The semaphore can be destroyed.

These rules define how a signal and wait operation combine to form the two halves of an implicit dependency. Signaling a fence or semaphore guarantees that previous work is complete and the effects are available to later operations. Waiting on a semaphore, waiting on a fence before submitting further work, or some combination of the two (e.g. waiting on a fence in a different queue, after using semaphores to synchronize between two queues) guarantees that the effects of the work that came before the synchronization primitive is visible to subsequent work that executes in the specified <code>pWaitDstStageMask</code> stages (in the case of commands following a semaphore wait as part of a <code>vkQueueSubmit</code> submission), or any stage (for all the other cases).

The rules are phrased in terms of wall clock time (*before*, at a later time, etc.). However, for these rules to apply, the order in wall clock time of two operations must be enforced either by:

- signaling a semaphore after the first operation and waiting on the semaphore before the second operation
- signaling a fence after the first operation, waiting on the host for the fence to be signaled, and then submitting command buffers or sparse binding operations to perform the second operation
- a combination of two or more uses of these ordering rules applied transitively.

vkQueueWaitIdle provides implicit ordering equivalent to having used a fence in the most recent submission on the queue and then waiting on that fence. vkDeviceWaitIdle provides implicit ordering equivalent to using vkQueueWaitIdle on all queues owned by the device.

Signaling a semaphore or fence does not guarantee that device writes are visible to the host.

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 command buffers in 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*.

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 a priori, 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 guite 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 API order.

7.1 Render Pass Creation

A render pass is created by calling:

- 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;
                                    subpassCount;
   uint32 t
   const VkSubpassDescription*
                                    pSubpasses;
                                     dependencyCount;
   uint32_t
   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 $VK_ATTACHMENT_UNUSED$

VkAttachmentDescription 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;
```

- 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 VkSampleCountFlaqBits.
- 10adOp 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.
- flags is a bitfield of VkAttachmentDescriptionFlagBits describing additional properties of the attachment:

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

Valid Usage

- $\bullet \ \textit{flags} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{combination} \ \textbf{of} \ \textbf{VkAttachmentDescriptionFlagBits} \ \textbf{values}$
- 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

If the attachment uses a color format, then <code>loadOp</code> and <code>storeOp</code> are used, and <code>stencilLoadOp</code> and <code>stencilStoreOp</code> are ignored. If the format has depth and/or stencil components, <code>loadOp</code> and <code>storeOp</code> apply only to the depth data, while <code>stencilLoadOp</code> and <code>stencilStoreOp</code> 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 <code>loadOp</code>, 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 <code>storeOp</code>. 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.

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 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.

VkSubpassDescription 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 the attachment images 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 the attachment images will be in during the subpass. Each element of the array correponds 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 a pointer to an array of VkAttachmentReference structures. 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 <code>loadOp</code> must not be <code>VK_ATTACHMENT_LOAD_OP_CLEAR</code>
- 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 <code>layout</code>

The VkAttachmentReference structure is defined as:

- 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

The VkSubpassDependency structure is defined as:

- 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 <code>srcSubpass</code> does not equal <code>dstSubpass</code> 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 <code>srcSubpass</code> equals <code>dstSubpass</code> then the first set consists of commands in the subpass before a call to <code>vkCmdPipelineBarrier</code> 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, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the geometry shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>srcStageMask</code> must not contain <code>VK_PIPELINE_STAGE_</code> <code>TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</code>
- If the tessellation shaders feature is not enabled, <code>dstStageMask</code> must not contain <code>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</code> or <code>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</code>
- 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

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 <code>srcAccessMask</code> have completed in all pipeline stages included in <code>srcStageMask</code> in the source subpass, and before any memory accesses via <code>dstAccessMask</code> occur in any pipeline stages included in <code>dstStageMask</code> in the destination subpass.

The automatic image layout transitions from <code>initialLayout</code> 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 <code>dstSubpass</code> 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 <code>loadOp</code> 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 <code>storeOp</code> is <code>VK_ATTACHMENT_STORE_OP_STORE</code>, 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 <code>loadOp</code> and the <code>storeOp</code> 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 <code>srcStageMask</code> and <code>srcAccessMask</code> are taken based on usage in the source subpass and <code>dstStageMask</code> and <code>dstAccessMask</code> 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 <code>colorWriteMask</code>, and to disable writes to depth/stencil components that are read as inputs via <code>depthWriteEnable</code> or <code>stencilTestEnable</code>.

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:

- 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
- Each of device and renderPass that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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, which represent a collection of specific memory attachments that a render pass instance uses.

An application creates a framebuffer by calling:

- 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.

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

- Each 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

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

 $\label{lem:policy} \mbox{VkPipelineMultisampleStateCreateInfo::} \emph{rasterizationSamples}.$

To destroy a framebuffer, call:

void vkDestroyFramebuffer(
 VkDevice

device,

- 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
- Each of device and framebuffer that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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
- ullet 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:

- 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.

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 <code>initialLayout</code> or <code>finalLayout</code> member of the <code>VkAttachmentDescription</code> structures or the <code>layout</code> member of the <code>VkAttachmentReference</code> structures specified when creating the render pass specified in the <code>renderPass</code> member of <code>pRenderPassBegin</code> is <code>VK_IMAGE_LAYOUT_COLOR_</code> ATTACHMENT_OPTIMAL then the corresponding attachment image of the framebuffer specified in the <code>framebuffer</code> member of <code>pRenderPassBegin</code> must have been created with <code>VK_IMAGE_USAGE_COLOR_</code> ATTACHMENT_BIT set
- If any of the <code>initialLayout</code> or <code>finalLayout</code> member of the <code>VkAttachmentDescription</code> structures or the <code>layout</code> member of the <code>VkAttachmentReference</code> structures specified when creating the render pass specified in the <code>renderPass</code> member of <code>pRenderPassBegin</code> is <code>VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL</code> or <code>VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL</code> then the corresponding attachment image of the framebuffer specified in the <code>framebuffer</code> member of <code>pRenderPassBegin</code> must have been created with <code>VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT</code> set

- If any of the <code>initialLayout</code> or <code>finalLayout</code> member of the <code>VkAttachmentDescription</code> structures or the <code>layout</code> member of the <code>VkAttachmentReference</code> structures specified when creating the render pass specified in the <code>renderPass</code> member of <code>pRenderPassBegin</code> is <code>VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL</code> then the corresponding attachment image of the framebuffer specified in the <code>framebuffer</code> member of <code>pRenderPassBegin</code> must have been created with <code>VK_IMAGE_USAGE_SAMPLED_BIT</code> or <code>VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT</code> set
- If any of the <code>initialLayout</code> or <code>finalLayout</code> member of the <code>VkAttachmentDescription</code> structures or the <code>layout</code> member of the <code>VkAttachmentReference</code> structures specified when creating the render pass specified in the <code>renderPass</code> member of <code>pRenderPassBegin</code> is <code>VK_IMAGE_LAYOUT_TRANSFER_SRC_BIT</code> then the corresponding attachment image of the framebuffer specified in the <code>framebuffer</code> member of <code>pRenderPassBegin</code> must have been created with <code>VK_IMAGE_USAGE_TRANSFER_SRC_BIT</code> set
- If any of the <code>initialLayout</code> or <code>finalLayout</code> member of the <code>VkAttachmentDescription</code> structures or the <code>layout</code> member of the <code>VkAttachmentReference</code> structures specified when creating the render pass specified in the <code>renderPass</code> member of <code>pRenderPassBegin</code> is <code>VK_IMAGE_LAYOUT_TRANSFER_DST_BIT</code> then the corresponding attachment image of the framebuffer specified in the <code>framebuffer</code> member of <code>pRenderPassBegin</code> must have been created with <code>VK_IMAGE_USAGE_TRANSFER_DST_BIT</code> set

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

After beginning a render pass instance, the command buffer is ready to record the commands for the first subpass of that render pass.

The VkRenderPassBeginInfo structure is defined as:

- 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. The array is indexed by attachment number, with elements corresponding to uncleared attachments being unused.

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
- Each of renderPass and framebuffer must have been created, allocated or retrieved from the same VkDevice
- clearValueCount must be greater than or equal to the number of attachments in renderPass that specify a loadOp of VK ATTACHMENT LOAD OP CLEAR

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.

The render area granularity is queried by calling:

- 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.

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
- Each of device and renderPass must have been created, allocated or retrieved from the same VkPhysicalDevice

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.

After recording the commands for a subpass, an application transitions to the next subpass in the render pass instance by calling:

• 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 vkCmdBeqinRenderPass.

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

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.

After recording the commands for the last subpass, an application records a command to end a render pass instance by calling:

```
void vkCmdEndRenderPass(
     VkCommandBuffer commandBuffer);
```

• commandBuffer is the command buffer in which to end the current render pass instance.

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

Ending a render pass instance performs any multisample resolve operations on the final subpass.

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.

A shader module is created by calling:

- 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 render pass object is returned.

- 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:

- 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.

- 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
- pCode must point to valid SPIR-V code, formatted and packed as described by the SPIR-V Specification v1.0
- pCode must adhere to the validation rules described by the Validation Rules within a Module section of the SPIR-V Environment appendix
- pCode must declare the **Shader** capability
- 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

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.

To destroy a shader module, call:

- 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
- Each of device and shaderModule that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- If VkAllocationCallbacks were provided when <code>shaderModule</code> 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 API 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 <code>OpMemoryBarrier</code> instruction can be used to provide stronger ordering of reads and writes performed by a single invocation. <code>OpMemoryBarrier</code> 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 <code>OpMemoryBarrier</code> 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 a vertex is a part of more than one input primitive, for example by including the same index value multiple times in an index buffer, the vertex shader may be invoked only once and the results shared amongst the resulting primitives. This is known as *vertex reuse*.

Implementor's Note

If a vertex is repeated in a draw command (i.e. the same index is repeated in an indexed draw), the shader may be executed anywhere from one to the number of repetitions times for that vertex, depending on the implementation's ability to reuse shader results.

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 <code>patchControlPoints</code> member of <code>VkPipelineTessellationStateCreateInfo</code>, as part of input assembly. The size of the output patch is controlled by the <code>OpExecutionMode OutputVertices</code> 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 <code>VkPhysicalDeviceLimits::maxTessellationPatchSize</code>.

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 <code>OpControlBarrier</code> 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 either in the shader code or via Specialization Constants. 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 <code>drawCount</code> 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.

9.1 Compute Pipelines

Compute pipelines consist of a single static compute shader stage and the pipeline layout.

The compute pipeline encapsulates a compute shader and is created by calling **vkCreateComputePipelines** with <code>module</code> and <code>pName</code> selecting an entry point from a shader module, where that entry point defines a valid compute shader, in the <code>VkPipelineShaderStageCreateInfo</code> structure contained within the <code>VkComputePipelineCreateInfo</code> structure.

Compute pipelines are created by calling:

- 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 Pipelines 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
- Each of device and pipelineCache that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 definition of VkComputePipelineCreateInfo is:

- *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

- 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
- Each of layout and basePipelineHandle 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 parameters basePipelineHandle and basePipelineIndex are described in more detail in Pipeline Derivatives.

The parameter $stage\ member\ of\ type\ VkPipelineShaderStageCreateInfo\ is:$

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

The members of the VkPipelineShaderStageCreateInfo structure are as follows:

- *sType* is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- stage is a VkShaderStageFlagBits naming the pipeline stage.
- module is a VkShaderModule object that contains the shader for this stage.
- pName is a pointer to a null-terminated UTF-8 string specifying the entry point name of the shader for this stage.
- pSpecializationInfo is a pointer to VkSpecializationInfo, as described in Specialization Constants, and can be NULL.

- 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, <code>stage</code> must not be <code>VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT</code> or <code>VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT</code>
- 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

The VkShaderStageFlagBits flags are defined as:

```
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 = 0x000000008,
    VK_SHADER_STAGE_FRAGMENT_BIT = 0x00000010,
    VK_SHADER_STAGE_COMPUTE_BIT = 0x00000020,
    VK_SHADER_STAGE_ALL_GRAPHICS = 0x0000001F,
    VK_SHADER_STAGE_ALL = 0x7FFFFFFF,
} VkShaderStageFlagBits;
```

9.2 Graphics Pipelines

Graphics pipelines consist of multiple shader stages, multiple fixed-function pipeline stages, and a pipeline layout, and are created by calling **vkCreateGraphicsPipelines**:

```
VkResult vkCreateGraphicsPipelines(
VkDevice device,
```

- 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 Pipelines 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.

- 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
- Each of device and pipelineCache that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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Success

```
    VK_SUCCESS
    Failure
    VK_ERROR_OUT_OF_HOST_MEMORY
    VK_ERROR_OUT_OF_DEVICE_MEMORY
```

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. The definition of VkGraphicsPipelineCreateInfo is:

```
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 bitfield 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.
- pRasterState 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.

- 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 layout, renderPass and basePipelineHandle 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 both a tessellation control shader stage and a tessellation evaluation shader stage, the shader code of at least one must contain an **OpExecutionMode** instruction that specifies the type of subdivision in the pipeline
- If pStages includes both a tessellation control shader stage and a tessellation evaluation shader stage, and the shader code of both contain an **OpExecutionMode** instruction that specifies the type of subdivision in the pipeline, they must both specify the same subdivision mode
- If pStages includes both a tessellation control shader stage and a tessellation evaluation shader stage, the shader code of at least one must contain an **OpExecutionMode** instruction that specifies the output patch size in the pipeline
- If pStages includes both a tessellation control shader stage and a tessellation evaluation shader stage, 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 pStages includes a geometry shader stage, and doesn't 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 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.

The definition of the pDynamicState member of type VkPipelineDynamicStateCreateInfo is:

The members of the VkPipelineDynamicStateCreateInfo structure are as follows:

- *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 definition of the VkDynamicState enumeration is as follows:

```
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 <code>lineWidth</code> 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 <code>blendConstants</code> 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 <code>blendEnable</code> 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 <code>compareMask</code> state in VkPipelineDepthStencilStateCreateInfo for both <code>front</code> and <code>back</code> will be ignored and must be set dynamically with vkCmdSetStencilCompareMask before any draws are performed with a pipeline state with VkPipelineDepthStencilStateCreateInfo member <code>stencilTestEnable</code> 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

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:

- 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
- Each of device and pipeline that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- All submitted commands that refer to pipeline must have completed execution
- If VkAllocationCallbacks were provided when <code>pipeline</code> 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 <code>pPipelines</code> output array will be filled with <code>VK_NULL_HANDLE</code> values. If any pipeline fails creation (for example, due to out of memory errors), the <code>vkCreate*Pipelines</code> commands will return an error code. The implementation will attempt to create all pipelines, and only return <code>VK_NULL_HANDLE</code> 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 and size of the pipeline cache objects are managed by the implementation. Applications can control the amount of data retrieved from a pipeline cache object.

Pipeline cache objects are created by calling:

- 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.

- 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 definition of VkPipelineCacheCreateInfo is:

- *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.

- 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

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.

Pipeline cache objects can be merged using the command:

- 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.

- 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
- Each of device, dstCache and the elements of pSrcCaches must have been created, allocated or retrieved from the same VkPhysicalDevice
- dstCache must not appear in the list of source caches

Host Synchronization

 $\bullet \ \ Host\ access\ to\ \textit{dstCache}\ must\ be\ externally\ synchronized$

Return Codes

Success

• VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY



Note

The details of the merge operation are implementation dependent, but implementations should merge the contents of the specified pipelines and prune duplicate entries.

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

- 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 dataSize 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.

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
- Each of device and pipelineCache must have been created, allocated or retrieved from the same VkPhysicalDevice

Return Codes

Success

• VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

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 dataSize is less than what is necessary to store this header, nothing will be written to pData and zero will be written to dataSize.

To destroy a pipeline cache, call:

- 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.

- 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
- Each of device and pipelineCache that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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. The definition of the VkSpecializationInfo structure is:

The members of VkSpecializationInfo are as follows:

- 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.

Valid Usage

- If mapEntryCount is not 0, pMapEntries must be a pointer to an array of mapEntryCount 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 definition of the pMapEntries member of type VkSpecializationMapEntry is:

```
typedef struct VkSpecializationMapEntry {
   uint32_t constantID;
   uint32_t offset;
   size_t size;
} VkSpecializationMapEntry;
```

The members of VkSpecializationMapEntry are as follows:

- constant ID ID of the specialization constant in SPIR-V.
- offset byte offset of the specialization constant value within the supplied data buffer.
- size byte size of the specialization constant value within the supplied data buffer.

If a constant ID value is not a specialization constant ID used in the shader, that map entry does not affect the behavior of the pipeline.

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
                                     // size
       sizeof(uint32_t)
   },
                                    // constantID
       3,
       2 * sizeof(uint32_t),
                                    // offset
       sizeof(uint32_t)
                                     // size
   }
};
const uint32_t data[] = { 16, 8, 4 }; // our workgroup size is 16x8x4
const VkSpecializationInfo info =
                                     // mapEntryCount
   3,
   entries,
                                     // pMapEntries
   3 * sizeof(uint32_t),
                                     // dataSize
                                     // pData
   data.
} ;
```

Then when calling **vkCreateComputePipelines**, and passing the VkSpecializationInfo we defined as the *pSpecializationInfo* parameter of VkPipelineShaderStageCreateInfo, we will create a compute pipeline with the runtime specified local workgroup size.

Another example would be that an application has a SPIR-V module that has some platform-dependent constants they wish to use.

In human readable SPIR-V:

```
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:

```
const VkSpecializationMapEntry entries[] =
{
                                       // constantID
       0 * sizeof(int32 t),
                                      // offset
                                       // size
       sizeof(int32_t)
   },
                                       // constantID
       12,
       1 * sizeof(int32_t),
                                       // offset
       sizeof(float)
                                       // size
   }
};
int32_t data[2];
data[0] = -42; // set the data for the 32-bit integer
((float*)data)[1] = 42.0f; // set the data for the 32-bit floating-point
const VkSpecializationInfo info =
                                       // mapEntryCount
   2,
   entries,
                                       // pMapEntries
   2 * sizeof(int32_t),
                                       // 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:

- 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 <code>pipeline</code> 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.

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
- Each 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 graphic pipeline, the current subpass has no attachments, and this is not the first call to this function with a graphic 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	Both	GRAPHICS
Secondary		COMPUTE

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.

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:

- 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.

- 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 pfnInternalAllocatione or pfnInternalFree is not NULL, both must be valid callbacks

An allocator indicates an error condition by returning NULL from pfnAllocation or pfnReallocation. If this occurs, the implementation should treat it as a run time error and should report VK_ERROR_OUT_OF_HOST_MEMORY at the appropriate time for the command in which the condition was detected, as described in Section 2.5.2.

The type of pfnAllocation is:

- 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.

pfnAllocation must either return NULL (in case of allocation failure or if size is zero) or a valid pointer to a memory allocation containing at least size bytes, and with the pointer value being a multiple of alignment.

The type of pfnReallocation is:

- 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 alter the size of the allocation poriginal, either by shrinking or growing it, to accommodate the new size.

If pOriginal is NULL, then pfnReallocation must behave similarly to PFN_vkAllocationFunction. If size is zero, then pfnReallocation must behave similarly to PFN_vkFreeFunction. The contents of the original allocation from bytes zero to min(original size, new size) -1 must be preserved in the new allocation. If the new allocation is larger than the old allocation, then the contents of the additional space are undefined. If pOriginal is non-NULL, alignment must be equal to the originally requested alignment. If satisfying these requirements involves creating a new allocation, then the old allocation must be freed. If this function fails, it must return NULL and not free the old allocation.

The type of pfnFree is:

- 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 and must be freed by the function.

The type of pfnInternalAllocation is:

- 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:

- 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 and takes a value of type 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 lifetime 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, <code>pfnInternalAllocation</code> will be called. Upon freeing executable memory, <code>pfnInternalFree</code> 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 created 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 <code>pfnAllocation</code>, <code>pfnReallocation</code> and <code>pfnFree</code> 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 <code>pfnInternalAllocation</code> and <code>pfnInternalFree</code> to <code>NULL</code>. <code>pfnInternalAllocation</code> and <code>pfnInternalFree</code> must either both be <code>NULL</code> 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 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 created 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 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 created 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.

The memory properties of the physical device describe the memory heaps and memory types available to a physical device. These can be queried by calling:

- 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 definition of VkPhysicalDeviceMemoryProperties is:

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 <code>memoryHeapCount</code> and is less than or equal to <code>VK_MAX_MEMORY_HEAPS</code>. Each heap is described by an element of the <code>memoryHeaps</code> array, as a <code>VkMemoryHeap</code> structure. The number of memory types available across all memory heaps is given by <code>memoryTypeCount</code> and is less than or equal to <code>VK_MAX_MEMORY_TYPES</code>. Each memory type is described by an element of the <code>memoryTypes</code> array, as a <code>VkMemoryType</code> structure.

The definition of VkMemoryHeap is:

- 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.

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. If there is only one heap, that heap must be marked as VK_MEMORY_ HEAP_DEVICE_LOCAL_BIT. If there are multiple heaps that all have similar performance characteristics, they may all be marked as VK_MEMORY_HEAP_DEVICE_LOCAL_BIT, but at least one will be device local.

The definition of VkMemoryType is:

- 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.

Each memory type returned by vkGetPhysicalDeviceMemoryProperties must have its propertyFlags set to one of the following values:

- ()
- 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 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_LAZILY_ALLOCATED_BIT

It is guaranteed that there is at least one memory type that has its <code>propertyFlags</code> with the <code>VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT</code> bit set and the <code>VK_MEMORY_PROPERTY_HOST_COHERENT_BIT</code> bit set.

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

- the memory property bits set for X are a 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 $X \le Y$ according to the partial order. Note that the list of all allowed memory property flag combinations above satisfies this partial order, 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:

```
// Searching for the best match for "properties"
for (i = 0; i < memoryTypeCount; ++i)
   if ((memoryTypes[i].propertyFlags & properties) == properties)
     return i;</pre>
```

This loop will find the first entry 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**. If there are multiple heaps with the same properties, it will choose the most performant 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 allocated by calling **vkAllocateMemory**:

- 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.

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 <code>device</code>, must be less than <code>VkPhysicalDeviceLimits::maxMemoryAllocationCount</code>

Return Codes

Success

• VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_TOO_MANY_OBJECTS

VkMemoryAllocateInfo 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

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.

A memory object is freed by calling:

- 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.

- 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
- Each of device and memory that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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.

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. An application retrieves a host virtual address pointer to a region of a mappable memory object by calling:

- 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, and must be zero.
- 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.

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
- Each of device and memory must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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

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.

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 (vkFlushMappedMemoryRanges or vkInvalidateMappedMemoryRanges) 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.

In order to enable applications to work with non-coherent memory allocations, two entry points are provided. To flush host write caches, an application must use **vkFlushMappedMemoryRanges**, while

vkInvalidateMappedMemoryRanges allows invalidating host input caches so that device writes become visible to the host. **vkFlushMappedMemoryRanges** 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. Similarly, **vkInvalidateMappedMemoryRanges** 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.

- 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.

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

- 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.

- 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

- *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.

- 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



Note

If the memory object was created with the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT set, **vkFlus hMappedMemoryRanges** and **vkInvalidateMappedMemoryRanges** are unnecessary and may have performance cost.

Once host access to a memory object is no longer needed by the application, it can be unmapped by calling:

- device is the logical device that owns the memory.
- memory is the memory object to be unmapped.

- device must be a valid VkDevice handle
- memory must be a valid VkDeviceMemory handle
- memory must have been created, allocated or retrieved from device
- Each of device and memory must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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.

Determining the amount of lazily-allocated memory that is currently committed for a memory object is achieved by calling:

- 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.

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
- Each of device and memory must have been created, allocated or retrieved from the same VkPhysicalDevice
- memory must have been created with a memory type that reports VK_MEMORY_PROPERTY_LAZILY_ ALLOCATED_BIT

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.

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 created by calling:

- 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 or VK_BUFFER_CREATE_SPARSE_RESIDENCY_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 definition of VkBufferCreateInfo is:

The members of VkBufferCreateInfo have the following meanings:

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

- 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, <code>flags</code> must not contain <code>VK_BUFFER_CREATE_SPARSE_ALIASED_BIT</code>
- If flags contains VK_BUFFER_CREATE_SPARSE_ALIASED_BIT, it must also contain at least one of VK_BUFFER_CREATE_SPARSE_BINDING_BIT or VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT

Bits which may 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 = 0x000000004,
    VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT = 0x000000008,
    VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT = 0x00000010,
    VK_BUFFER_USAGE_STORAGE_BUFFER_BIT = 0x000000020,
    VK_BUFFER_USAGE_INDEX_BUFFER_BIT = 0x000000040,
    VK_BUFFER_USAGE_VERTEX_BUFFER_BIT = 0x000000080,
    VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT = 0x000000100,
} 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_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_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 may 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 bitfields 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.
- 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).

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

To destroy a buffer, call:

- 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.

- 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
- Each of device and buffer that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- All submitted commands that refer to <code>buffer</code>, either directly or via a <code>VkBufferView</code>, 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

A buffer view is created by calling:

- 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 definition of $\mbox{VkBufferViewCreateInfo}\ is:$

The members of VkBufferViewCreateInfo have the following meanings:

- *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:

- 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
- Each of device and bufferView that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 created by calling:

- 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 or VK_ IMAGE_CREATE_SPARSE_RESIDENCY_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 definition of VkImageCreateInfo is:

The members of VkImageCreateInfo have the following meanings:

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is a bitfield describing additional parameters of the image. See VkImageCreateFlagBits below for a description of the supported bits.
- imageType is the basic dimensionality of the image, and 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;
```

specifying one-, two-, or three-dimensionality, respectively. 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 VkExtent 3D 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 the tiling arrangement of the data elements in memory, and must have 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).

- *usage* is a bitfield 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 subresources of the image. See Image Layouts. initialLayout must be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

- 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

equal to those in this structure)

- arrayLayers must be greater than 0
- 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
- 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
- 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
- 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

- samples must be a bit value that is set in VkPhysicalDeviceLimits::sampleCounts returned by vkGetPhysicalDeviceProperties, or VkImageFormatProperties::maxExtent.sampleCounts returned by vkGetPhysicalDeviceImageFormatProperties with format, type, tiling, usage and flags equal to those in this structure
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_
 STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT or VK_IMAGE_
 USAGE_INPUT_ATTACHMENT_BIT, extent.width must be less than or equal to
 VkPhysicalDeviceLimits::maxFramebufferWidth
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_
 STENCIL_ATTACHMENT_BIT, VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT or VK_IMAGE_
 USAGE_INPUT_ATTACHMENT_BIT, extent.height must be less than or equal to
 VkPhysicalDeviceLimits::maxFramebufferHeight
- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxFramebufferColorSamples
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a depth aspect, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxFramebufferDepthSamples
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a stencil aspect, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxFramebufferStencilSamples
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a color aspect, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxSampledImageColorSamples
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a depth aspect, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxSampledImageDepthSamples
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format is an integer format, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxSampledImageIntegerSamples
- If usage includes VK_IMAGE_USAGE_STORAGE_BIT, samples must be a bit value that is set in VkPhysicalDeviceLimits::maxStorageImageSamples
- If the ETC2 texture compression feature is not enabled, <code>format</code> 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

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, <code>format</code> 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_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 <code>imageType</code> is VK_IMAGE_TYPE_2D, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for 3D images feature is not enabled, and <code>imageType</code> is VK_IMAGE_TYPE_3D, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for images with 2 samples feature is not enabled, <code>imageType</code> is VK_IMAGE_TYPE_2D, and <code>samples</code> is VK_SAMPLE_COUNT_2_BIT, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for images with 4 samples feature is not enabled, <code>imageType</code> is VK_IMAGE_TYPE_2D, and <code>samples</code> is VK_SAMPLE_COUNT_4_BIT, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for images with 8 samples feature is not enabled, <code>imageType</code> is VK_IMAGE_TYPE_2D, and <code>samples</code> is VK_SAMPLE_COUNT_8_BIT, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT
- If the sparse residency for images with 16 samples feature is not enabled, <code>imageType</code> is VK_IMAGE_TYPE_2D, and <code>samples</code> is VK_SAMPLE_COUNT_16_BIT, <code>flags</code> must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_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_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, 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_ALIASED_BIT, it must also contain at least one of VK_IMAGE_CREATE_SPARSE_BINDING_BIT or VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT

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.

Bits which may be set in usage are:

```
typedef enum VkImageUsageFlagBits {
    VK_IMAGE_USAGE_TRANSFER_SRC_BIT = 0x00000001,
    VK_IMAGE_USAGE_TRANSFER_DST_BIT = 0x00000002,
    VK_IMAGE_USAGE_SAMPLED_BIT = 0x00000004,
    VK_IMAGE_USAGE_STORAGE_BIT = 0x00000008,
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT = 0x00000010,
    VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000020,
    VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT = 0x00000040,
    VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT = 0x00000080,
} VkImageUsageFlagBits;
```

These bitfields 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). If this is set, then bits other than VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT must not be set.
- 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.

Bits which may be set in flags are:

```
typedef enum VkImageCreateFlagBits {
   VK_IMAGE_CREATE_SPARSE_BINDING_BIT = 0x00000001,
   VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
   VK_IMAGE_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
   VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT = 0x00000008,
   VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT = 0x00000010,
} VkImageCreateFlagBits;
```

These bitfields 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.
- 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). Sparse images created with this flag must also be created with the VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.

If any of these three bits 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.

- 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.

The layout of a subresource (mipLevel/arrayLayer) of an image created with linear tiling is queried by calling:

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

- 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
- Each of device and image must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 definition of the VkImageSubresource structure is:

- 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 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 subresource begins.
- size is the size in bytes of the 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, <code>rowPitch</code>, <code>arrayPitch</code> and <code>depthPitch</code> describe the layout of the subresource in linear memory. For uncompressed formats, <code>rowPitch</code> is the number of bytes between texels with the same x coordinate in adjacent rows (y coordinates differ by one). <code>arrayPitch</code> 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). <code>depthPitch</code> 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 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 blocks in adjacent rows. arrayPitch is the number of bytes between blocks in adjacent array layers. depthPitch is the number of bytes between blocks in adjacent slices of a 3D image.

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

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

For color formats, the <code>aspectMask</code> member of <code>VkImageSubresource</code> must be <code>VK_IMAGE_ASPECT_COLOR_BIT</code>. For depth/stencil formats, <code>aspect</code> must be either <code>VK_IMAGE_ASPECT_DEPTH_BIT</code> or <code>VK_IMAGE_ASPECT_STENCIL_BIT</code>. On implementations that store depth and stencil aspects separately, querying each of these subresource layouts will return a different <code>offset</code> and <code>size</code> representing the region of memory used for that aspect. On implementations that store depth and stencil aspects interleaved, the same <code>offset</code> and <code>size</code> are returned and represent the interleaved memory allocation.

To destroy an image, call:

- 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.

- 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
- Each of device and image that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 subresource. Each layout has limitations on what kinds of operations are supported for 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-subresource, and separate subresources of the same image can be in different layouts at the same time with one exception - depth and stencil aspects of a given 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 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 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 pre-initialized 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 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 subresources of those images which are currently in either the VK_IMAGE_LAYOUT_PREINITIALIZED or VK_IMAGE_LAYOUT_GENERAL layout.

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 an initialLayout 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 an initialLayout 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 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 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 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 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 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 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 subresource's lifetime. This means that when performing a layout transition on the subresource, the old layout value must either equal the current layout of the subresource (at the time the transition executes), or else be VK_IMAGE_LAYOUT_UNDEFINED (implying that the contents of the 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.

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_LD_ARRAY = 4,
    VK_IMAGE_VIEW_TYPE_1D_ARRAY = 5,
    VK_IMAGE_VIEW_TYPE_2D_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:

- 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.

- 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:

- *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 selects the set of mipmap levels and array layers to be accessible to the view.

- sType must be VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO
- pNext must be NULL

- flags must be 0
- image must be a valid Vk Image 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, <code>format</code> must not be <code>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK</code>, <code>VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</code>, <code>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK</code>, <code>VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</code>, <code>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK</code>, <code>VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</code>, <code>VK_FORMAT_EAC_R11_UNORM_BLOCK</code>, <code>VK_FORMAT_EAC_R11_SNORM_BLOCK</code>, <code>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</code>, or <code>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</code>
- 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_SRGB_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_8x6_UNORM_BLOCK, VK_FORMAT_ASTC_8x6_UNORM_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_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, VK_FORMAT_ASTC_12x12_UNORM_BLOCK, OR VK_FORMAT_ASTC_12x12_SRGB_BLOCK
- If the BC texture compression feature is not enabled, <code>format</code> 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_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 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
- 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

• 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

• 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

- 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
- 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
- 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

• 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

- subresourceRange must be a valid 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 table below

If <code>image</code> was created with the <code>VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT</code> flag, <code>format</code> can be different from the image's format, but if they are not equal they must be <code>compatible</code>. 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 = IMAGE_TYPE_1D	viewType = VIEW_TYPE_1D
	width >= 1	baseArrayLayer >= 0
	height = 1	arrayLayers = 1
	depth = 1	
	arrayLayers >= 1	
	samples = 1	
1D, 1, 0	imageType = IMAGE_TYPE_1D	viewType = VIEW_TYPE_1D_ARRAY
	width >= 1	baseArrayLayer >= 0
	height = 1	arrayLayers >= 1
	depth = 1	
	arrayLayers >= 1	
	samples = 1	
2D, 0, 0	imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_2D
	width >= 1	baseArrayLayer >= 0
	height >= 1	arrayLayers = 1
	depth = 1	
	arrayLayers >= 1	
	samples = 1	
2D, 1, 0	imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_2D_ARRAY
	width >= 1	baseArrayLayer >= 0
	height >= 1	arrayLayers >= 1
	depth = 1	
	arrayLayers >= 1	
<u> </u>	samples = 1	
2D, 0, 1	imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_2D
	width >= 1	baseArrayLayer >= 0
	height >= 1	arrayLayers = 1
	depth = 1	
	arrayLayers >= 1	
2D, 1, 1	samples > 1 imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_2D_ARRAY
2D, 1, 1	width >= 1	baseArrayLayer >= 0
	height >= 1	arrayLayers >= 1
	depth = 1	arrayLayers >= 1
	arrayLayers >= 1	
	samples > 1	
CUBE, 0, 0	imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_CUBE
CODE, 0, 0	width >= 1	baseArrayLayer >= 0
	height = width	arrayLayers = 6
	depth = 1	
	arrayLayers >= 6	
	samples = 1	
	flags include VK_IMAGE_CREATE_	
	CUBE_COMPATIBLE_BIT	
	0000_00111111000_011	

Table 11.1: (continued)

Dim, Arrayed, MS	Image parameters	View parameters
CUBE, 1, 0	imageType = IMAGE_TYPE_2D	viewType = VIEW_TYPE_CUBE_ARRAY
	width >= 1	baseArrayLayer >= 0
	height = width	$arrayLayers = 6 \times N$
	depth = 1	
	$arrayLayers >= 6 \times N$	
	samples = 1	
	flags include VK_IMAGE_CREATE_	
	CUBE_COMPATIBLE_BIT	
3D, 0, 0	imageType = IMAGE_TYPE_3D	viewType = VIEW_TYPE_3D
	width >= 1	baseArrayLayer = 0
	height >= 1	arrayLayers = 1
	depth >= 1	
	arrayLayers = 1	
	samples = 1	

The subresourceRange member is of type VkImageSubresourceRange and is defined as:

- 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.

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

The number of mip-map levels and array layers must be a subset of the subresources in the image. If an application wants to use all mip-levels or layers in an image after the <code>baseMipLevel</code> or <code>baseArrayLayer</code>, it can set <code>levelCount</code> and <code>layerCount</code> to the special values <code>VK_REMAINING_MIP_LEVELS</code> and <code>VK_REMAINING_ARRAY_LAYERS</code> 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 <code>aspectMask</code> 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 <code>aspectMask</code> is ignored and both depth and stencil subresources are used.

The components member is defined as follows:

```
typedef struct VkComponentMapping {
    VkComponentSwizzle         r;
    VkComponentSwizzle         g;
    VkComponentSwizzle         b;
    VkComponentSwizzle         a;
} 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. The x, g, b, and a members of components are the values placed in the corresponding components of the output vector:

```
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_B = 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.

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

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_SW IZZLE_IDENTITY

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

To destroy an image view, call:

- 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
- Each of device and imageView that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- All submitted commands that refer to imageView must have completed execution
- If VkAllocationCallbacks were provided when <code>imageView</code> 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 non-sparse buffer resource, call:

- 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
- $\textit{pMemoryRequirements} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{pointer} \ \textbf{to} \ \textbf{a} \ \textbf{VkMemoryRequirements} \ \textbf{structure}$
- buffer must have been created, allocated or retrieved from device
- Each of device and buffer must have been created, allocated or retrieved from the same VkPhysicalDevice

To determine the memory requirements for a non-sparse image resource, call:

- 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.

- 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
- Each of device and image must have been created, allocated or retrieved from the same VkPhysicalDevice

The VkMemoryRequirements structure returned by vkGetBufferMemoryRequirements and vkGetImageMemoryRequirements is defined as follows:

```
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 bitfield 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_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 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 usage2 comprises 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.

• 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 VkImage does not have VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT bit set in the usage member of the VkImageCreateInfo structure passed to vkCreateImage.

To attach memory to a buffer object, call:

- 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.

- 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
- Each of device, buffer and memory must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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
- The size of buffer must be less than or equal to the size of memory minus memoryOffset
- memoryOffset must be an integer multiple of the alignment member of the VkMemoryRequirements structure returned from a call to vkGetBufferMemoryRequirements with buffer

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 a image object, call:

- 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 Vk Image 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
- Each of device, image and memory must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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, <code>bufferImageGranularity</code>, which specifies a page-like granularity at which buffer, linear image and optimal image resources must be placed in adjacent memory locations for simultaneous usage. Two resources which do not satisfy this granularity requirement are said to alias. Linear image resource are images created with <code>VK_IMAGE_TILING_LINEAR</code> and optimal image resources are those created with <code>VK_IMAGE_TILING_LINEAR</code> and optimal image resources are those created with <code>VK_IMAGE_TILING_OPTIMAL</code>. <code>bufferImageGranularity</code> 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.

Given resourceA at the lower memory offset and resourceB at the higher memory offset, 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 memory block sizes 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 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 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 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 subresource, the application must transfer exclusive ownership of the range or 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 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 <code>srcQueueFamilyIndex</code> parameter of the barrier must be set to the source queue family index, and the <code>dstQueueFamilyIndex</code> 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 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 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 an image and a buffer is defined to be the intersection of the memory ranges bound to the two resources, where each range is first bloated 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 subresources of the image *overlap* the range. When a linear image is bound to an aliased range, the 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 blocks bound to an aliased range, only subresources including those blocks overlap the range, and when the memory bound to the image's miptail overlaps an aliased range all subresources in the miptail 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 blocks (for sparse residency images) or all subresources (for non-sparse residency images) that overlap the affected bytes become undefined.

If any subresources are made undefined due to writes to an alias, then each of those 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 blocks of a sparse image have been made undefined, then only the 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 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 signalling a fence involves enough implicit ordering that the above requirements are all satisfied.

Chapter 12

Samplers

VkSampler objects encapsulate 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.

To create a sampler object, call:

- 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.

- 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 follows:

The members of VkSamplerCreateInfo are described as follows:

- *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_NEA REST** 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.

- 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_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

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 <code>maxSamplerAllocationCount limit</code>.

To destroy a sampler, call:

- 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
- Each of device and sampler that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 <code>maxBoundDescriptorSets</code> (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[L];
```

SPIR-V example

```
// 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 = OpTvpeVoid
          %3 = OpTypeFunction %2
          %6 = OpTypeFloat 32
          %7 = OpTypeImage %6 2D 0 0 1 Unknown
         %8 = OpTypeSampledImage %7
         %9 = OpTypeInt 32 0
         %10 = OpConstant %9 L
         %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

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 = 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 <code>pDynamicOffsets</code> 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 \leftrightarrow myInputAttachment;
```

SPIR-V example

```
%1 = OpExtInstImport "GLSL.std.450"
...
OpName %9 "myInputAttachment"
OpDecorate %9 DescriptorSet m
OpDecorate %9 Binding n

%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 layouts are represented by VkDescriptorSetLayout objects which are created by calling:

- 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:

- *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.

- 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 definition of the VkDescriptorSetLayoutBinding structure is:

- binding is the binding number of this entry and corresponds to a resource of the same binding number in the shader stages.
- descriptorType is an 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 bitfield 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 <code>pBindings</code> 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
- ullet 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 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
    {
                                               // binding
        VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,
                                              // descriptorType
                                               // descriptorCount
        VK_SHADER_STAGE_FRAGMENT_BIT,
                                               // stageFlags
       NULL
                                               // pImmutableSamplers
    },
    // binding to an array of image descriptors
                                               // binding
       1,
       VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE,
                                              // descriptorType
                                               // descriptorCount
       VK_SHADER_STAGE_FRAGMENT_BIT,
                                              // stageFlags
       NULL
                                               // pImmutableSamplers
    },
    // binding to a single uniform buffer descriptor
        Ο,
                                                // binding
        VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER,
                                              // descriptorType
                                               // 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
        Ο,
                                                                // flags
                                                                // 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
        Ο,
                                                                // flags
                                                                // bindingCount
        1,
        &myDescriptorSetLayoutBinding[2]
                                                                // pBindings
};
VkDescriptorSetLayout myDescriptorSetLayout[2];
11
// 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:

- 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.

- 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
- Each of device and descriptorSetLayout that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- If VkAllocationCallbacks were provided when <code>descriptorSetLayout</code> 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.

A pipeline layout is created by calling:

- 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.

- 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 definition of the VkPipelineLayoutCreateInfo structure is:

- *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 definition of VkPushConstantRange is:

- 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.

- 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 <code>stageFlags</code> 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:

- 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
- Each of device and pipelineLayout that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- If VkAllocationCallbacks were provided when <code>pipelineLayout</code> 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 VkPipelineLayoutCreateInfo createInfo =
    VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO,
                                                     // sType
   NULL,
                                                      // pNext
                                                      // flags
    Ο,
    2,
                                                      // setLayoutCount
                                                      // pSetLayouts
    layouts,
    2,
                                                      // pushConstantRangeCount
                                                      // pPushConstantRanges
    ranges
};
VkPipelineLayout myPipelineLayout;
myResult = vkCreatePipelineLayout(
    myDevice,
    &createInfo,
    NULL,
    &myPipelineLayout);
```

13.2.3 Allocation of Descriptor Sets

Descriptor sets are allocated from *descriptor pool* objects. A descriptor pool maintains a pool of descriptors, from which 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.

To create a descriptor pool object, call:

- 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:

- 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, with possible values defined below.
- 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.

- 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

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.

The flags member of VkDescriptorPoolCreateInfo can include the following values:

```
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.

The definition of the VkDescriptorPoolSize structure is:

- type is the type of descriptor.
- descriptorCount is the number of descriptors of that type to allocate.

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

To destroy a descriptor pool, call:

- 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.

- 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
- Each of device and descriptorPool that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice
- All submitted commands that refer to <code>descriptorPool</code> (via any allocated descriptor sets) must have completed execution
- If VkAllocationCallbacks were provided when <code>descriptorPool</code> was created, a compatible set of callbacks must be provided here
- $\bullet \ \ If \ no \ \ VkAllocation Callbacks \ were \ provided \ when \ \textit{descriptorPool} \ was \ created, \ \textit{pAllocator} \ must \ be \ \ \text{NULL}$

Host Synchronization

• Host access to descriptorPool must be externally synchronized

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.

Descriptor sets are allocated from a descriptor pool by calling:

- 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.

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

The VkDescriptorSetAllocateInfo structure is defined as:

- *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.

The allocated descriptor sets are returned in pDescriptorSets.

- 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
- Each 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

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.

Allocated descriptor sets are freed by calling:

- 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. All elements of pDescriptorSets must have been allocated from descriptorPool.

In order to free individual descriptor sets, <code>descriptorPool</code> must have been created with the <code>VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT</code> flag.

- 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
- Each of device, descriptorPool and the elements of pDescriptorSets that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice

- 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
- 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

After a successful call to **vkFreeDescriptorSets**, all descriptor sets in *pDescriptorSets* are invalid.

Rather than freeing individual descriptor sets, all descriptor sets allocated from a given pool can be returned to the pool by calling:

- device is the logical device that owns the descriptor pool.
- descriptorPool is the descriptor pool to be reset.
- flags is currently unused and must be zero.

- 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
- Each of device and descriptorPool must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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 <code>descriptorPool</code> must be externally synchronized

Return Codes

Success

• VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

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.

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:

- 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.

- 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

Each element in the pDescriptorWrites array describes an operation updating the descriptor set using descriptors for resources specified in the structure.

The definition of VkWriteDescriptorSet is:

```
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 the type of each descriptor in pImageInfo, pBufferInfo, or pTexelBufferView, and must be the same type as what was specified in VkDescriptorSetLayoutBinding for dstSet at dstBinding. The type of the descriptor also controls which array the descriptors are taken from. descriptorType can take on values including:

```
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_STORAGE_BUFFER_DYNAMIC = 8,
    VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC = 9,
    VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT = 10,
} VkDescriptorType;
```

- 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 or is ignored, as described below.

- 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
- Each 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 created 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 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 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

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 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 pBufferInfo array will be used to update the descriptors, and other arrays will be ignored. Each entry is of type VkDescriptorBufferInfo and is defined as:

- 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.

- 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

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.

If descriptorType is VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER or VK_DESCRIPTOR_TYPE_ STORAGE_TEXEL_BUFFER, the 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_STORAGE_IMAGE, or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, the members in pImageInfo array will be used to update the descriptors, and other arrays will be ignored. imageInfo is of type VkDescriptorImageInfo and is defined as:

- 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.

Valid Usage

• Each of sampler and imageView that are valid handles must have been created, allocated or retrieved from the same VkDevice

Members of VkDescriptorImageInfo that are not used in an update (as described above) are ignored.

If the <code>dstBinding</code> has fewer than <code>descriptorCount</code> array elements remaining starting from <code>dstArrayElement</code>, then the remainder will be used to update the subsequent binding - <code>dstBinding+1</code> starting at array element zero. This behavior applies recursively, with the update affecting consecutive bindings as needed to update all <code>descriptorCount</code> descriptors. All consecutive bindings updated via a single <code>VkWriteDescriptorSet</code> structure must have identical <code>descriptorType</code> and <code>stageFlags</code>, and must all either use immutable samplers or must all not use immutable samplers.

Each element in the pDescriptorCopies array is a VkCopyDescriptorSet structure describing an operation copying descriptors between sets. The definition of VkCopyDescriptorSet is:

- *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.
- \bullet 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.

- 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
- Each of srcSet and dstSet 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

Once descriptor sets have been allocated, one or more descriptor sets can be bound to the command buffer by calling:

```
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 a pointer to an array of VkDescriptorSet structures 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 uint 32_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.

- $\bullet \ \textit{commandBuffer} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{VkCommandBuffer} \ \textbf{handle}$
- pipelineBindPoint must be a valid VkPipelineBindPoint value
- layout must be a valid VkPipelineLayout handle
- $\bullet \ \textit{pDescriptorSets} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{pointer} \ \textbf{to} \ \textbf{an array} \ \textbf{of} \ \textit{descriptorSetCount} \ \textbf{valid} \ \texttt{VkDescriptorSet} \ \textbf{handles}$
- 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 created with a VkDescriptorSetLayout that matches the VkDescriptorSetLayout at set n in layout, where n is the sum of the index into pDescriptorSets and firstSet
- dynamicOffsetCount must be equal to the total number of dynamic descriptors in pDescriptorSets
- 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	Both	GRAPHICS
Secondary		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 contents of the push constants are undefined at the start of a command buffer. Push constants are updated by calling:

- 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
- Each 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	Both	GRAPHICS
Secondary		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.

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.

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 first member is assigned to the location specified for the **Block**, any member with its own **Location** decoration is assigned that location, and 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.

Shader Interface	Locations Available
vertex input	maxVertexInputAttributes
vertex output	maxVertexOutputComponents/4
tessellation control input	maxTessellationControlPerVertexInputComponents/4
tessellation control output	maxTessellationControlPerVertexOutputComponents/4
tessellation evaluation input	maxTessellationEvaluationInputComponents/4
tessellation evaluation output	maxTessellationEvaluationOutputComponents/4
geometry input	maxGeometryInputComponents/4
geometry output	maxGeometryOutputComponents/4
fragment input	maxFragmentInputComponents/4
fragment output	maxFragmentOutputAttachments

Table 14.1: Shader Input and Output Locations

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 <code>pVertexInputState</code> member of the <code>VkGraphicsPipelineCreateInfo</code> 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 <code>maxVertexInputAttributes</code> 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 <code>pColorAttachments</code> 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).

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 2.7.1; 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 input variables listed by **OpEntryPoint** with the **Input** storage class and a decoration of **InputAttachmentIndex** form the *fragment input attachment interface*. These variables must be declared with a type of **OpTypeImage** and a **Dim** operand of **SubpassData**.

A fragment shader input variable identified with an InputAttachmentIndex decoration of i reads from the input attachment indicated by pInputAttachments[i]. If the 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 classes of **Uniform**, **UniformConstant**, and **PushConstant**. For the fragment shader, the variables identified by operands to **OpEntryPoint** with a storage class of **Input** and a decoration of **InputAttachmentIndex** are also included in this interface.

The shader resource interface can be further broken down into 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 <code>stageFlags</code> 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 classes of **Uniform**, **UniformConstant**, and 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 <code>shaderSampledImageArrayDynamicIndexing</code> 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 **Input** and a decoration of **InputAttachmentIndex** must be declared as described above.

Each shader variable declaration must refer to the same type of resource as is indicated by the <code>descriptorType</code>. See Shader Resource and Descriptor Type Correspondence for the relationship between shader declarations and descriptor types.

Resource type	Descriptor Type
sampler	VK_DESCRIPTOR_TYPE_SAMPLER
sampled image	VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE
storage image	VK_DESCRIPTOR_TYPE_STORAGE_IMAGE
combined image sampler	VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
uniform texel buffer	VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER
storage texel buffer	VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER
uniform buffer	VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER
	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 14.2: Shader Resource and Descriptor Type Correspondence

Table 14.3: Shader Resource and Storage Class Correspondence

Resource type	Storage Class	Туре	Decoration(s) ¹
sampler	UniformConstant	OpTypeSampler	
sampled image	UniformConstant	OpTypeImage	
		(Sampled=1)	
storage image	UniformConstant	OpTypeImage	
		(Sampled=2)	
combined image	UniformConstant	OpTypeSampledImage	
sampler			
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	Input	OpTypeImage	InputAttachmentIndex
		(Dim=SubpassData)	

in addition to DescriptorSet and Binding

1

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 <code>maxBoundDescriptorSets</code> minus one. If a descriptor set value is statically used by an entry point there must be an associated <code>pSetLayout</code> 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 <code>descriptorCount</code> of that <code>VkDescriptorSetLayoutBinding</code>. The index of each element of the array is referred to as the <code>arrayElement</code>. 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.

Resources per Stage	Resource Types
maxPerStageDescriptorSamplers	sampler
maxi erstageDescriptorSamplers	combined image sampler
	sampled image
maxPerStageDescriptorSampledImages	combined image sampler
	uniform texel buffer
maxPerStageDescriptorStorageImages	storage image
maxi erstageDescriptorstoragemages	storage texel buffer
maxPerStageDescriptorUniformBuffers	uniform buffer
maxr erstage Descriptor Officerin Buriers	uniform buffer dynamic
may ParStaga DasarintarStoraga Buffars	storage buffer
maxPerStageDescriptorStorageBuffers	storage buffer dynamic
maxPerStageDescriptorInputAttachments	input attachment ¹

Table 14.4: Shader Resource Limits

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 2N
 - a three- or four-component vector, with components of size N, has a base alignment of 4N
 - 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.



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 using 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

Variables decorated with the **ClipDistance** decoration provide the mechanism for controlling user clipping. Declared as an array, the ith element of the variable decorated as **ClipDistance** specifies a 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** array is explicitly sized by the shader.

The ClipDistance decoration can be applied to array inputs in tessellation control, tessellation evaluation and geometry shader stages which will contain the values written by the previous stage. It can be applied to outputs in vertex, tessellation evaluation and geometry shaders. 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.

In the fragment shader, the **ClipDistance** decoration can be applied to an array of floating-point input variables and contains the linearly interpolated values described above.

ClipDistance must not be used in compute shaders.

ClipDistance must be declared as an array of 32-bit floating-point values.

CullDistance

A variable decorated as **CullDistance** provides a mechanism for a vertex processing stage to reject an entire primitive. **CullDistance** can be applied to an array variable. 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.

CullDistance can be applied to an output variable in the last vertex processing stage (vertex, tessellation evaluation or geometry shader).

If applied to an input variable, that variable will contain the corresponding output in the previous shader stage. **CullDistance** must not be applied to an input in the vertex shader or to an output in the fragment shader, and must not be used in compute shaders.

In fragment shaders, the values of the CullDistance array are linearly interpolated across each primitive.

CullDistance must be declared as an array of 32-bit floating-point values.

FragCoord

This variable contains 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. The x and y components of **FragCoord** reflect the location of the center of the pixel ((0.5,0.5)) when sample shading is not enabled, and the location of the sample corresponding to the shader invocation when using sample shading.

The z component of **FragCoord** is the interpolated depth value of the primitive, and the w component is the interpolated $\frac{1}{m}$.

The **FragCoord** decoration is only supported in fragment shaders. The **Centroid** interpolation decoration is ignored on **FragCoord**.

FragCoord must be declared as a four-component vector of 32-bit floating-point values.

FragDepth

Writing to an output variable decorated with **FragDepth** from the fragment shader establishes a 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

DepthReplacing execution mode. If a snader 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 is only supported in fragment shaders.

FragDepth must be declared as a scalar 32-bit floating-point value.

FrontFacing

The **FrontFacing** decoration can be applied to an input variable in the fragment shader. 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 is not available to shader stages other than fragment.

FrontFacing must be declared as a scalar 32-bit integer.



Note

In GLSL, **g1_FrontFacing** is declared as a **bool**. To achieve similar semantics in SPIR-V, a variable of **OpTypeBool** can be declared and initialized as the result of the **OpINotEqual** operation with the operands of the **FrontFacing** variable and an appropriately typed constant zero.

GlobalInvocationID

An input variable decorated with **GlobalInvocationID** will contain the location of the current compute shader invocation within the global workgroup. The value in this variable is equal to the index of the local workgroup multiplied by the size of the local workgroup plus **LocalInvocationID**.

The **GlobalInvocationID** decoration is only supported in compute shaders.

GlobalInvocationID must be declared as a three-component vector of 32-bit integers.

HelperInvocation

This variable is non-zero if the 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 is only supported in fragment shaders.

HelperInvocation must be declared as a scalar 32-bit integer.



Note

It is very likely that a helper invocation will have a value of **SampleMask** fragment shader input value that is zero.



Note

In GLSL, **HelperInvocation** is declared as a **bool**. To achieve similar semantics in SPIR-V, a variable of **OpTypeBool** can be declared and initialized as the result of the **OpINotEqual** operation with the operands of the **HelperInvocation** variable and an appropriately typed constant zero.

InvocationID

In a geometry shader, an input variable decorated with the **InvocationID** decoration contains the index of the current shader invocation, which 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.

In tessellation control shaders, and input variable decorated with the **InvocationID** decoration contains the index of the output patch vertex assigned to the tessellation control shader invocation.

The **InvocationID** decoration must not be used in vertex, tessellation evaluation, fragment, or compute shaders.

InvocationID must be declared as a scalar 32-bit integer.

InstanceIndex

The InstanceIndex decoration can be applied to a vertex shader input which will be filled with the index of the instance that is being processed by the current vertex shader invocation. InstanceIndex begins at the firstInstance parameter to vkCmdDrawIndexed or at the firstInstance member of a structure consumed by vkCmdDrawIndirect or vkCmdDrawIndexedIndirect.

The **InstanceIndex** decoration must not be used in any shader stage other than vertex.

InstanceIndex must be declared as a scalar 32-bit integer.

Layer

The **Layer** decoration can be applied to an output variable in the geometry shader that is 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 an output variable decorated with **Layer**, then the first layer is used. If a geometry shader entry point's interface includes an output variable decorated with **Layer**, it must write the same value to **Layer** for all output vertices of a given primitive. When used in a fragment shader, an input variable decorated with **Layer** contains the layer index of the primitive that the fragment invocation belongs to.

The **Layer** decoration is only supported in geometry and fragment shaders.

Layer must be declared as a scalar 32-bit integer.

LocalInvocationID

This variable contains the location of the current compute shader invocation within the local workgroup. The range of possible values for each component of LocalInvocationID range from zero through the size of the workgroup (as

defined by **LocalSize**) in that dimension minus one. If the size of the workgroup in a particular dimension is one, then LocalInvocationID in that dimension will be zero. That is, if the workgroup is effectively two-dimensional, then <code>LocalInvocationID.z</code> will be zero, and if the workgroup is one-dimensional, then both <code>LocalInvocationID.y</code> and <code>LocalInvocationID.z</code> will be zero.

The **LocalInvocationID** decoration is only supported in compute shaders.

LocalInvocationID must be declared as a three-component vector of 32-bit integers.

NumWorkGroups

The NumWorkGroups decoration can be applied to a uvec3 input variable in a compute shader, in which case it will contain the number of local workgroups that are part of the dispatch that the invocation belongs to. It reflects the values passed to a call to vkCmdDispatch or through the structure consumed by the execution of vkCmdDispatchIndirect.

The **NumWorkGroups** decoration is only supported in compute shaders.

NumWorkGroups must be declared as a three-component vector of 32-bit integers.

PatchVertices

An input variable decorated with **PatchVertices** in the tessellation control or evaluation shader is an integer specifying the number of vertices in the input patch being processed by the shader. A single tessellation control or evaluation shader can read patches of differing sizes, so the **PatchVertices** variable may differ between patches.

The **PatchVertices** decoration is only supported in tessellation control and evaluation shaders.

PatchVertices must be declared as scalar 32-bit integer.

PointCoord

During point rasterization, a variable decorated with **PointCoord** contains 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 **PointCoord** is undefined.

The **PointCoord** decoration is only supported in fragment shaders.

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

The **PointSize** built-in decoration is used to pass the size of point primitives between shader stages. It can be applied to inputs to tessellation control and geometry shaders. It can be applied to output variables in vertex, tessellation evaluation and geometry shaders. The value written to the variable decorated as **PointSize** by the last vertex processing stage in the pipeline is used as the framebuffer space size of points produced by rasterization. As an input, it reflects the value written to the output decorated with **PointSize** in the previous shader stage.

The **PointSize** decoration must not be applied to inputs in the vertex shader and must not be used in fragment or compute shaders.

PointSize must be declared as a scalar 32-bit floating-point value.

Position

The **Position** built-in decoration can be used on variables declared as input to tessellation control, tessellation evaluation and geometry shaders. It can be used on variables declared as outputs in the vertex, tessellation control,

tessellation evaluation and geometry shaders. As an input, it contains the data written to the output variable decorated as **Position** in the previous shader stage. As an output, the data written to a variable decorated as **Position** is passed to the next shader stage. In the last vertex processing stage, the output position is used in subsequent primitive assembly, clipping and rasterization operations.

Variables decorated as **Position** must not be used as inputs in vertex shaders and must not be used in fragment or compute shaders.

Position must be declared as a four-component vector of 32-bit floating-point values.

PrimitiveID

When the **PrimitiveID** decoration is applied to an input variable in the tessellation control or tessellation evaluation shader, it will be filled with the index of the patch within the current set of rendering primitives that corresponds to the shader invocation.

When the **PrimitiveID** decoration is applied to an input variable in the geometry shader, it will be filled with the number of primitives presented as input to the geometry shader since the current set of rendering primitives was started. When **PrimitiveID** is applied to an output in the geometry shader, the resulting value is seen as an input to the fragment shader.

When **PrimitiveID** is applied to an input in the fragment shader, it will be filled with 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; otherwise the **PrimitiveID** input in the fragment shader is undefined.

The **PrimitiveID** decoration must not be used in vertex or compute shaders. **PrimitiveID** must not be used on output variables in tessellation control, tessellation evaluation, or fragment shaders.

PrimitiveID must be declared as scalar 32-bit integer.

SampleID

The **SampleID** decoration can be applied to an integer input variable in the fragment shader. This variable will 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.

SampleID is not available in shader stages other than fragment.

SampleID must be declared as a scalar 32-bit integer.

SampleMask

A fragment input variable 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 fragment output variable decorated with <code>SampleMask</code> is an array of integers forming a bit array in a manner similar an input variable decorated with <code>SampleMask</code>, but where each bit represents coverage as computed by the shader. Modifying the sample mask by writing zero to a bit of <code>SampleMask</code> 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 is only supported in fragment shaders.

SampleMask must be declared as an array of 32-bit integers.

SamplePosition

This variable contains 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 is only supported in fragment shaders.

SamplePosition must be declared as a two-component vector of floating-point values.

TessellationCoord

The **TessellationCoord** is applied to an input variable in tessellation evaluation shaders and specifies 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 **TessellationCoord** decoration is only available to tessellation evaluation shaders.

TessellationCoord must be declared as three-component vector of 32-bit floating-point values.

TessellationLevelOuter

The **TessellationLevelOuter** decoration is used in tessellation control shaders to decorate an output variable to contain the outer tessellation factor for the resulting patch. This value is used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders. When applied to an input variable in a tessellation evaluation shader, the shader can read the value written by the tessellation control shader.

The **TessellationLevelOuter** decoration is not available outside tessellation control and evaluation shaders.

TessellationLevelOuter must be declared as an array of size two, containing 32-bit floating-point values.

TessellationLevelInner

The **TessellationLevelInner** decoration is used in tessellation control shaders to decorate an output variable to contain the inner tessellation factor for the resulting patch. This value is used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders. When applied to an input variable in a tessellation evaluation shader, the shader can read the value written by the tessellation control shader.

The **TessellationLevelInner** decoration is not available outside tessellation control and evaluation shaders.

TessellationLevelInner must be declared as an array of size four, containing 32-bit floating-point values.

VertexIndex

The **VertexIndex** decoration can be applied to a vertex shader input which will be filled with the index of the vertex that is being processed by the current vertex shader invocation. For non-indexed draws, this variable begins at the <code>firstVertex</code> parameter to <code>vkCmdDraw</code> or the <code>firstVertex</code> member of a structure consumed by <code>vkCmdDrawIndirect</code> 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 <code>vertexOffset</code> parameter to <code>vkCmdDrawIndexed</code> or the <code>vertexOffset</code> member of the structure consumed by <code>vkCmdDrawIndexedIndirect</code>.

VertexIndex starts at the same starting value for each instance.

The **VertexIndex** decoration must not be used in any shader stage other than vertex.

VertexIndex must be declared as a 32-bit integer.

ViewportIndex

The **ViewportIndex** decoration can be applied to an output variable in the geometry shader that is written 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 an output variable decorated with **ViewportIndex**, then the first viewport is used. If a geometry shader entry point's interface includes an output variable decorated with **ViewportIndex**, it must write the same value to **ViewportIndex** for all output vertices of a given primitive. When used in a fragment shader, an input variable decorated with **ViewportIndex** contains the viewport index of the primitive that the fragment invocation belongs to.

The **ViewportIndex** decoration is only supported in geometry and fragment shaders.

ViewportIndex must be declared as a 32-bit integer.

WorkgroupID

The **WorkgroupID** built-in decoration can be applied to an input variable in the compute shader. It will contain a three dimensional integer index of 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 is only supported in compute shaders.

WorkGroupID 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 (coordinates ranging from 0 to 1 span the image),
- unnormalized texel coordinates (floating point coordinates ranging from 0 to width/height/depth span the image), and
- integer texel coordinates (integer coordinates ranging from 0 to width-1/height-1/depth-1 address the texels within the image).

SPIR-V OpImageFetch, OpImageSparseFetch, 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.

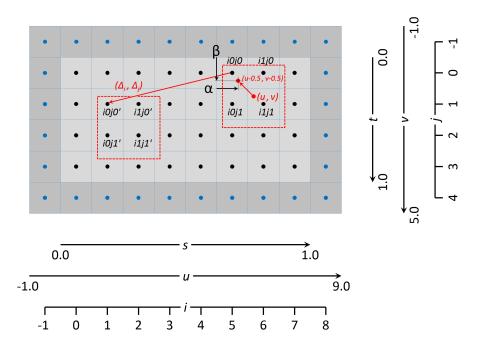
Unnormalized texel coordinates are referred to as (u, v, w, a), with the coordinates having the following meanings:

- 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:

$$exp' = \begin{cases} \left\lfloor \log_2(max_{clamped}) \right\rfloor + (B+1) & \text{for } max_{clamped} > 2^{-(B+1)} \\ 0 & \text{for } max_{clamped} \leq 2^{-(B+1)} \end{cases}$$

The shared exponent exp_{shared} is computed:

$$max_{shared} = \left\lfloor \frac{max_{clamped}}{2^{(exp'-B-N)}} + \frac{1}{2} \right\rfloor$$

$$exp_{shared} = \begin{cases} exp' & \text{for } 0 \le max_{shared} < 2^N \\ exp' + 1 & \text{for } max_{shared} = 2^N \end{cases}$$

Finally, three integer values in the range 0 to 2^N are computed:

$$red_{shared} = \left\lfloor rac{red_{clamped}}{2^{(exp_{shared} - B - N)}} + rac{1}{2}
ight
floor$$
 $green_{shared} = \left\lfloor rac{green_{clamped}}{2^{(exp_{shared} - B - N)}} + rac{1}{2}
ight
floor$ $blue_{shared} = \left\lfloor rac{blue_{clamped}}{2^{(exp_{shared} - B - N)}} + rac{1}{2}
ight
floor$

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 aspect 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 aspect 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's samples is 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

$i \geq w_s$	i < 0
$j \geq h_s$	j < 0
$k \geq d_s$	k < 0
$l \ge layers$	l < 0
$n \ge samples$	n < 0

where:

```
w_s= width of the image levelh_s= height of the image leveld_s= depth of the image levellayers= number of layers in the imagesamples= number of samples per texel in the image
```

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 miplevel, 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.

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*

This is substituted for the texel value by replacing the number of components in the image format

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 zero values in the same fashion as described for reads from buffer resources above.

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's format is depth and the operation is a **Dref** instruction, a depth comparison is performed. The initial value of the result r is 0.0, which is replaced with 1.0 if the result of the compare operation is true. The compare operation is selected by the compareOp member of the sampler.

$$r = 0.0 \qquad \qquad \text{initial value} \\ r = 0.0 \\ \begin{cases} D_{ref} \leq D_t & \text{for LEQUAL} \\ D_{ref} \geq D_t & \text{for GEQUAL} \\ D_{ref} < D_t & \text{for LESS} \\ D_{ref} > D_t & \text{for GREATER} \\ D_{ref} = D_t & \text{for EQUAL} \\ D_{ref} \neq D_t & \text{for NOTEQUAL} \\ true & \text{for ALWAYS} \\ false & \text{for NEVER} \end{cases}$$

where:

$$D_{ref} = shaderOp.D_{ref}$$
 (from optional SPIR-V operand)
 D_t 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:

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	$C_{rgba} = C_{rgba}$

Table 15.3: Texel Color After Conversion To 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.

$$C'_{rgba}[R] = egin{cases} C_{rgba}[R] & ext{for RED swizzle} \ C_{rgba}[G] & ext{for GREEN swizzle} \ C_{rgba}[B] & ext{for BLUE swizzle} \ C_{rgba}[A] & ext{for ALPHA swizzle} \ 0 & ext{for ZERO swizzle} \ one & ext{for ONE swizzle} \ C_{rgba}[R] & ext{for IDENTITY swizzle} \end{cases}$$

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=1.0f for floating point components one=1

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 struct 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 <code>OpTypeImage</code> is not compatible with the <code>VkImageView</code>'s <code>format</code>, 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.

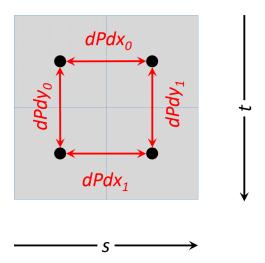
15.4.4 Texel Output Format Conversion

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:

$$s=rac{s}{q},$$
 for 1D, 2D, or 3D image $t=rac{t}{q},$ for 2D or 3D image $r=rac{r}{q},$ for 3D image $D_{ref}=rac{D_{ref}}{q},$ 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:

$\partial s/\partial x = dPdx(s),$	$\partial s/\partial y = dPdy(s),$	for 1D, 2D, Cube, or 3D image
$\partial t/\partial x = dPdx(t),$	$\partial t/\partial y = dPdy(t),$	for 2D, Cube, or 3D image
$\partial u/\partial x = dPdx(u),$	$\partial u/\partial y = dPdy(u),$	for Cube or 3D image

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.

Major Axis Direction	Layer Number	Cube Map Face	S_C	t_c	r_c
$+r_{x}$	0	PositiveX	$-r_z$	$-r_{\rm y}$	r_{χ}
$-r_{x}$	1	NegativeX	$+r_z$	$-r_{y}$	r_x
$+r_y$	2	PositiveY	$+r_{\chi}$	$+r_z$	r_{y}
$-r_y$	3	NegativeY	$+r_{x}$	$-r_z$	r_{y}
$+r_z$	4	PositiveZ	$+r_{x}$	$-r_y$	r_z
$-r_{7}$	5	NegativeZ	$-r_r$	$-r_{\rm v}$	r_{7}

Table 15.4: Cube map face and coordinate selection

Table 15.5: Cube map derivative selection

Major Axis Di- rection	$\partial s_c/\partial x$	$\partial s_c/\partial y$	$\partial t_c/\partial x$	$\partial t_c/\partial y$	$\partial r_c/\partial x$	$\partial r_c/\partial y$
$+r_{\chi}$	$-\partial r_z/\partial x$	$-\partial r_z/\partial y$	$-\partial r_{y}/\partial x$	$-\partial r_{y}/\partial y$	$+\partial r_x/\partial x$	$+\partial r_x/\partial y$
$-r_{x}$	$+\partial r_z/\partial x$	$+\partial r_z/\partial y$	$-\partial r_y/\partial x$	$-\partial r_y/\partial y$	$-\partial r_x/\partial x$	$-\partial r_x/\partial y$
$+r_y$	$+\partial r_x/\partial x$	$+\partial r_x/\partial y$	$+\partial r_z/\partial x$	$+\partial r_z/\partial y$	$+\partial r_y/\partial x$	$+\partial r_y/\partial y$
$-r_y$	$+\partial r_x/\partial x$	$+\partial r_x/\partial y$	$-\partial r_z/\partial x$	$-\partial r_z/\partial y$	$-\partial r_{y}/\partial x$	$-\partial r_{y}/\partial y$
$+r_z$	$+\partial r_x/\partial x$	$+\partial r_x/\partial y$	$-\partial r_y/\partial x$	$-\partial r_y/\partial y$	$+\partial r_z/\partial x$	$+\partial r_z/\partial y$
$-r_z$	$-\partial r_x/\partial x$	$-\partial r_x/\partial y$	$-\partial r_{y}/\partial x$	$-\partial r_{y}/\partial y$	$-\partial r_z/\partial x$	$-\partial r_z/\partial y$

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:

$$\partial t/\partial x = \partial t/\partial y = 0$$
 (for 1D image) $\partial r/\partial x = \partial r/\partial y = 0$ (for 1D, 2D or Cube image) $w_{base} = image.w$ $h_{base} = image.h$ $d_{base} = image.d$ (from image descriptor)

The *scale factors* (ρ_x, ρ_y) should be calculated by:

$$\rho_x = \sqrt{m_{ux}^2 + m_{vx}^2 + m_{wx}^2}$$

$$\rho_y = \sqrt{m_{uy}^2 + m_{vy}^2 + m_{wy}^2}$$

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

 f_x is continuous and monotonically increasing in each of m_{ux}, m_{vx} , and m_{wx} f_y is continuous and monotonically increasing in each of m_{uy}, m_{vy} , and m_{wy}

$$\max(|m_{ux}|, |m_{vx}|, |m_{wx}|) \le f_x \le |m_{ux}| + |m_{vx}| + |m_{wx}|$$

$$\max(|m_{uy}|, |m_{vy}|, |m_{wy}|) \le f_y \le |m_{uy}| + |m_{vy}| + |m_{wy}|$$

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

$$\rho_{max} = \max(\rho_x, \rho_y)$$
$$\rho_{min} = \min(\rho_x, \rho_y)$$

The sampling rate is determined by:

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

where:

$$sampler.max_{Aniso} = maxAnisotropy$$
 (from sampler descriptor)
 $limits.max_{Aniso} = maxSamplerAnisotropy$ (from physical device limits)
 $max_{Aniso} = min (sampler.max_{Aniso}, limits.max_{Aniso})$

If $\rho_{max} = \rho_{min} = 0$, then all the partial derivatives are zero, the fragment's footprint in texel space is a point, and N should be treated as 1. If $\rho_{max} \neq 0$ and $\rho_{min} = 0$ then all partial derivatives along one axis are zero, the fragment's footprint in texel space is a line segment, and N should be treated as max_{Aniso} . However, anytime the footprint is small in texel space the implementation may use a smaller value of N, even when ρ_{min} is zero or close to zero.

An implementation may round N up to the nearest supported sampling rate.

If N = 1, sampling is isotropic. If N > 1, sampling is anistropic.

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:

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

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

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

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

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

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

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:

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

and where q is the levelCount from the subresourceRange of the image view.

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

$$d_{hi} = egin{cases} q, & level_{base} + \lambda \geq q \ \lfloor level_{base} + \lambda
floor, & ext{otherwise} \ d_{lo} = egin{cases} q, & level_{base} + \lambda \geq q \ d_{hi} + 1, & ext{otherwise} \end{cases}$$

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

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

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.

$$u(x,y) = s(x,y) \times width_{level}$$

$$v(x,y) = \begin{cases} 0 & \text{for 1D images} \\ t(x,y) \times height_{level} & \text{otherwise} \end{cases}$$

$$w(x,y) = \begin{cases} 0 & \text{for 2D or Cube images} \\ r(x,y) \times depth_{level} & \text{otherwise} \end{cases}$$

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

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 1 is computed as:

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

where <code>layerCount</code> is the number of layers in the subresource range of the image view, <code>baseArrayLayer</code> is the first layer from the subresource range, and where:

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

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:

$$i = \lfloor u \rfloor$$
$$j = \lfloor v \rfloor$$
$$k = \lfloor w \rfloor$$

Linear filtering (VK_FILTER_LINEAR) computes a set of neighboring coordinates which bound the unnormalized

coordinates. The integer texel coordinates are combinations of i_0 or i_1, j_0 or j_1, k_0 or k_1 , as well as weights $\alpha, \beta, and \gamma$.

$$i_{0} = \left\lfloor u - \frac{1}{2} \right\rfloor$$

$$j_{0} = \left\lfloor v - \frac{1}{2} \right\rfloor$$

$$j_{1} = j_{0} + 1$$

$$k_{0} = \left\lfloor w - \frac{1}{2} \right\rfloor$$

$$\alpha = \operatorname{frac}\left(u - \frac{1}{2}\right)$$

$$\beta = \operatorname{frac}\left(v - \frac{1}{2}\right)$$

$$\gamma = \operatorname{frac}\left(w - \frac{1}{2}\right)$$

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 miplevel then VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE is used, and if VK_FILTER_LINEAR is used within a miplevel 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.

$$i = \begin{cases} i \operatorname{mod} size & \text{for repeat} \\ (size-1) - \operatorname{mirror}((i \operatorname{mod}(2 \times size)) - size) & \text{for mirrored repeat} \\ \operatorname{clamp}(i, 0, size-1) & \text{for clamp to edge} \\ \operatorname{clamp}(i, -1, size) & \text{for clamp to border} \\ \operatorname{clamp}(\operatorname{mirror}(i), 0, size-1) & \text{for mirror clamp to edge} \end{cases}$$

where:

$$mirror(n) = \begin{cases} n & \text{for } n \ge 0\\ -(1+n) & \text{otherwise} \end{cases}$$

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 block of texels in the base level of the image view. The rules for the 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:

$$au[R] = au_{i0j1}[level_{base}][comp] \ au[G] = au_{i1j1}[level_{base}][comp] \ au[B] = au_{i1j0}[level_{base}][comp] \ au[A] = au_{i0j0}[level_{base}][comp]$$

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 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 miplevel, 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 miplevel, 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:

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

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

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

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

Finally, mipmap filtering either selects a value from one miplevel or computes a weighted average between neighboring miplevels:

$$au = egin{cases} au[d], & ext{for mipmode BASE or NEAREST} \ (1-oldsymbol{\delta}) au[d_{hi}] + oldsymbol{\delta} au[d_{lo}], & ext{for mipmode LINEAR} \end{cases}$$

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 LINEAR and a mipmapMode of 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 $\tau_{2D}(u,v)$ at level d.

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

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

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.

To create a query pool, call:

- 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 definition of VkQueryPoolCreateInfo is:

The members of VkQueryPoolCreateInfo have the following meanings:

- *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:

- 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.

- device must be a valid VkDevice handle
- If queryPool is not VK NULL HANDLE, queryPool must be a valid VkQueryPool handle
- $\bullet \ \ If \ \textit{pAllocator} \ is \ not \ \texttt{NULL}, \ \textit{pAllocator} \ must \ be \ a \ pointer \ to \ a \ valid \ \texttt{VkAllocationCallbacks} \ structure$
- If queryPool is a valid handle, it must have been created, allocated or retrieved from device
- Each of device and queryPool that are valid handles must have been created, allocated or retrieved from the same VkPhysicalDevice

- 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:

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
- Each 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	Outside	GRAPHICS
Secondary		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 <code>occlusionQueryEnable</code>, <code>queryFlags</code>, and/or <code>pipelineStatistics</code> members of <code>VkCommandBufferBeginInfo</code> 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).

Begin a query by calling:

- 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. Valid bits in flags include:

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

If the <code>queryType</code> of the pool is <code>VK_QUERY_TYPE_OCCLUSION</code> and <code>flags</code> contains <code>VK_QUERY_CONTROL_PRECISE_BIT</code>, an implementation must return a result that matches the actual number of samples passed. This is described in more detail in Occlusion Queries.

- 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
- Each 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 created from must support graphics operations
- If the <code>queryType</code> used to create <code>queryPool</code> was <code>VK_QUERY_TYPE_PIPELINE_STATISTICS</code> and any of the <code>pipelineStatistics</code> indicate graphics operations, the <code>VkCommandPool</code> that <code>commandBuffer</code> was created from must support graphics operations
- If the <code>queryType</code> used to create <code>queryPool</code> was <code>VK_QUERY_TYPE_PIPELINE_STATISTICS</code> and any of the <code>pipelineStatistics</code> indicate compute operations, the <code>VkCommandPool</code> that <code>commandBuffer</code> was created 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	Both	GRAPHICS
Secondary		COMPUTE

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.

After the set of desired draw or dispatch commands, end a query by calling:

- 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.

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
- Each 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	Both	GRAPHICS	
Secondary		COMPUTE	

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.

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 <code>pipelineStatistics</code> 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,
                                                   dataSize,
    size_t
    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.

Valid bits in flags 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;
```

These bits have the following meanings:

- 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 **vkCmdRes etQueryPool**, **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 an 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
- Each of device and queryPool must have been created, allocated or retrieved from the same VkPhysicalDevice
- 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.

- 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, queryPool and dstBuffer 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
- $\bullet \ \ If \ \ VK_QUERY_RESULT_64_BIT \ is \ set \ in \ \textit{flags} \ then \ \textit{dstOffset} \ and \ \textit{stride} \ must \ be \ multiples \ of \ 8$
- dstBuffer must have enough storage, from dstOffset, 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

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

Command Buffer Levels	Render Pass Scope Supported Queue Types	
Primary	Outside	GRAPHICS
Secondary		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 perfragment 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 <code>pipelineStatisticsQuery</code> 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.

pipelineStatisticsQuery is a bitmask indicating different possible pipeline statistics.

Valid bits in flags 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 = 0x000000008,
    VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT = 0x000000010,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT = 0x000000020,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT = 0x000000040,
    VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT = 0x000000000,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT = 0x000000100,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT = 0 \leftarrow
    x00000200,
    VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x000000400,
} VkQUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x000000400,
} VkQUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x000000400,
} VkQUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x000000400,
} VkQUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATIONS_BIT = 0x000000400,
```

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.

A timestamp is requested by calling:

- 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
- Each 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
- ullet The command pool's queue family must support a non-zero ${\it timestampValidBits}$

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

- 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).
- \bullet rangeCount is the number of 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 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
- Each 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 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 a subresource range that is contained within image

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

To clear one or more subranges of a depth/stencil image, call:

- 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 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 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).

- 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
- Each 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 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 a subresource range that is contained within image

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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:

- 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 attachment Count 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	Inside	GRAPHICS	
Secondary			

The VkClearRect struct is defined as follows:

```
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 struct is defined as follows:

- 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.
- 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.
- 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** commands is not affected by the bound pipeline state.

Attachments can also be cleared at the beginning of a render pass instance by setting <code>loadOp</code> (or <code>stencilLoadOp</code>) of <code>VkAttachmentDescription</code> to <code>VK_ATTACHMENT_LOAD_OP_CLEAR</code>, as described for <code>vkCreateRenderPass</code>.

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 definition of VkClearColorValue is as follows:

```
typedef union VkClearColorValue {
  float    float32[4];
  int32_t    int32[4];
  uint32_t    uint32[4];
} VkClearColorValue;
```

Color clear values are taken from the VkClearColorValue union based on the format of the image or attachment. Floating point, unorm, snorm, uscaled, packed float, and sRGB images use the float32 member, unsigned integer formats use the uint32 member, and signed integer formats use the int32 member. 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.

Unsigned integer values are converted to the format of the image by casting to the integer type with fewer bits. 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.

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 **vkClear*Image** commands do not support compressed image formats.

The definition of VkClearDepthStencilValue is as follows:

```
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.

Some parts of the API require either color or depth/stencil clear values, depending on the attachment. For this the VkClearValue union is defined as follows:

- 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 to define the initial clear values in the VkRenderPassBeginInfo structure.

17.4 Filling Buffers

To clear buffer data, call:

- 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.
- 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**.

- 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
- Each 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	Outside	GRAPHICS
Secondary		COMPUTE

17.5 Updating Buffers

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

```
void vkCmdUpdateBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer dstBuffer,
    VkDeviceSize dstOffset,
    VkDeviceSize dataSize,
    const uint32_t* 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**.

- commandBuffer must be a valid VkCommandBuffer handle
- dstBuffer must be a valid VkBuffer handle
- pData must be a pointer to an array of $\frac{dataSize}{4}$ uint32_t values
- 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
- Each of commandBuffer and dstBuffer must have been created, allocated or retrieved from the same VkDevice
- dataSize must be greater than 0
- 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 <code>commandBuffer</code> must be externally synchronized

Command Properties

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

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 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:

- 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.

- 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, srcBuffer and dstBuffer must have been created, allocated or retrieved from the same VkDevice
- The copySize 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 copySize member of a given element of pRegions must be less than or equal to the size of srcBuffer minus srcOffset
- The copySize 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 access to commandBuffer must be externally synchronized

Command Properties

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

Each element of pRegions is a structure defined as:

- *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:

- 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.

- 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, srcImage and dstImage 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 dst Image
- 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 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 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 access to commandBuffer must be externally synchronized

Command Properties

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

Each element of pRegions is a structure defined as:

- srcSubresource and dstSubresource are VkImageSubresourceLayers structures specifying the 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.

- ullet 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 <code>srcImage</code> or <code>dstImage</code> parameters are of <code>VkImageTypeVK_IMAGE_Type_3D</code>, the <code>baseArrayLayer</code> and <code>layerCount</code> members of both <code>srcSubresource</code> and <code>dstSubresource</code> 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 block size in the relevant dimensions
- extent.width must be a multiple of the block width or (extent.width + srcOffset.x) must equal the source image subresource width
- extent.height must be a multiple of the block height or (extent.height + srcOffset.y) must equal the source image subresource height
- extent.depth must be a multiple of the 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 block size in the relevant dimensions
- extent.width must be a multiple of the block width or (extent.width + dstOffset.x) must equal the destination image subresource width
- extent.height must be a multiple of the block height or (extent.height + dstOffset.y) must equal the destination image subresource height
- extent.depth must be a multiple of the 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:

- 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

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 <code>srcImage</code> and <code>dstImage</code> must be compatible. Formats are considered compatible if their texel size in bytes is the same between both formats. For example, <code>VK_FORMAT_R8G8B8A8_UNORM</code> is compatible with <code>VK_FORMAT_R32_UINT</code> 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 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 becomes a single block of compressed data. When copying from a compressed format to an uncompressed format, a block of compressed data becomes a single texel of uncompressed data. Thus, for example, it is legal to copy between a 128-bit uncompressed format and a compressed format which uses 8-bit/texel 4x4 blocks, or between a 64-bit uncompressed format and a compressed format which uses 4-bit/texel 4x4 blocks.

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 block size. 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 block size. 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 block. For this reason the <code>extent</code> must be a multiple of the 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 block dimensions. If the <code>srcImage</code> is compressed and if <code>extent.width</code> is not a multiple of the block width then (<code>extent.width + srcOffset.x</code>) must equal the subresource width, if <code>extent.height</code> is not a multiple of the block height then (<code>extent.height + srcOffset.y</code>) must equal the subresource height and if <code>extent.depth</code> is not a multiple of the block depth then (<code>extent.width + srcOffset.z</code>) must equal the subresource depth. Similarly if the <code>dstImage</code> is compressed and if <code>extent.width</code> is not a multiple of the block width then (<code>extent.width + dstOffset.x</code>) must equal the subresource width, if <code>extent.height</code> is not a multiple of the block height then (<code>extent.height + dstOffset.y</code>) must equal the subresource height and if <code>extent.depth + dstOffset.z</code>) must equal the subresource depth. This allows the last block of the image in each non-multiple dimension to be included as a source or target of the copy.

vkCmdCopyImage can be used to copy image data between multisample images, but both images must have the same number of samples.

18.4 Copying Data Between Buffers and Images

To copy data from a buffer object to an image object, call:

- 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.

- 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, srcBuffer and dstImage 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
- dst Image 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 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 access to commandBuffer must be externally synchronized

Command Properties

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

To copy data from an image object to a buffer object, call:

- 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.

- 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, srcImage and dstBuffer 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 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 access to commandBuffer must be externally synchronized

Command Properties

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

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

- 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 an VkImageSubresourceLayers used to specify the specific 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.

- 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, bufferImageHeight and all members of imageOffset must be a multiple of the block size in the relevant dimensions
- bufferOffset must be a multiple of the block size in bytes
- imageExtent.width must be a multiple of the block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- imageExtent.height must be a multiple of the block height or (imageExtent.height + imageOffset.y) must equal the image subresource height
- imageExtent.depth must be a multiple of the 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 blocks, but the addressing math operates on whole 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;

blockSizeInBytes = <block size taken from the src/dstImage>;
rowLength /= blockWidth;
imageHeight /= blockHeight;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x) \(\to \)
    * blockSizeInBytes;
```

```
where x,y,z range from (0,0,0) to region->imageExtent.{width/blockWidth,height/ \hookleftarrow blockHeight,depth/blockDepth}.
```

Copying to or from block-compressed images is typically done in multiples of the block. For this reason the <code>imageExtent</code> must be a multiple of the 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 block dimensions. If <code>imageExtent.width</code> is not a multiple of the block width then (<code>imageExtent.width + imageOffset.x</code>) must equal the subresource width, if <code>imageExtent.height</code> is not a multiple of the block height then (<code>imageExtent.height + imageOffset.y</code>) must equal the subresource height and if <code>imageExtent.depth</code> is not a multiple of the block depth then (<code>imageExtent.depth</code> depth

imageOffset.z) must equal the subresource depth. This allows the last block of the image in each non-multiple dimension to be included as a source or target 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,
                                                  filter);
    VkFilter
```

- 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.
- \bullet 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.

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, srcImage and dstImage 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 dst Image
- 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 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 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 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
- $\bullet \ \ If \ \textit{srcImage} \ was \ created \ with \ a \ depth/stencil \ format, \ \textit{filter} \ must \ be \ \ VK_FILTER_NEAREST$

• Host access to commandBuffer must be externally synchronized

Command Properties

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

vkCmdBlitImage must not be used for multisampled source or destination images. Use vkCmdResolveImage for this purpose.

Each element of pRegions is a structure defined as:

For each element of the pRegions array, a blit operation is performed between the region of srcSubresource of srcImage (bounded by srcOffsets[0] and srcOffsets[1]) and a region of dstSubresource of dstImage (bounded by dstOffsets[0] and dstOffsets[1]).

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 <code>srcImage</code> or <code>dstImage</code> parameters are of <code>VkImageTypeVK_IMAGE_Type_3D</code>, the <code>baseArrayLayer</code> and <code>layerCount</code> members of both <code>srcSubresource</code> and <code>dstSubresource</code> must be 0 and 1, respectively
- The aspectMask member of srcSubresource must specify aspects present in the calling command's srcImage
- The aspectMask member of dstSubresource must specify aspects present in the calling command's dstImage
- srcOffset[0].x and srcOffset[1].x must both be greater than or equal to 0 and less than or equal to the source image subresource width
- srcOffset[0].y and srcOffset[1].y must both be greater than or equal to 0 and less than or equal to the source image subresource height
- 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

If sizes of source and destination extents do not match, scaling is performed by applying the filtering mode specified by filter parameter. VK_FILTER_LINEAR uses bilinear interpolation, and VK_FILTER_NEAREST uses point sampling. When using VK_FILTER_LINEAR, magnifying blits may generate texel coordinates outside of the source region. If those coordinates are outside the bounds of the image level, the coordinates are clamped as in VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE address mode. However, if the coordinates are outside the source region but inside the image level, the implementation may clamp coordinates to the source region.

If source and destination extents are identical, no filtering is performed. Pixels in the axis-aligned region bounded by srcOffsets[0] and srcOffsets[1] will be copied to the destination region bound by dstOffsets[0] and dstOffsets[1]. In the case where dstOffsets[0].x > dstOffsets[1].x the copied pixels are reversed in that direction. Likewise for y and z.

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).

If **vkCmdBlitImage** is used on images of different formats, the following 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.

18.6 Resolving Multisample Images

To resolve a multisample image to a non-multisample image, call:

- 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.

- 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, srcImage and dstImage 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_
- dstImage must have a sample count equal to VK_SAMPLE_COUNT_1_BIT
- srcImageLayout must specify the layout of the 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 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 access to commandBuffer must be externally synchronized

Command Properties

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

Each element of pRegions is a structure defined as:

- srcSubresource and dstSubresource are VkImageSubresourceLayers structures specifying the 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.

- $\bullet \ \mathit{srcSubresource} \ \mathbf{must} \ \mathbf{be} \ \mathbf{a} \ \mathbf{valid} \ \mathsf{VkImageSubresourceLayers} \ \mathbf{structure}$
- dstSubresource must be a valid VkImageSubresourceLayers structure
- The aspectMask member of srcSubresource and dstSubresource must only contain VK_IMAGE_ ASPECT_COLOR_BIT

- $\bullet \ \ The \ \textit{layerCount member of } \textit{srcSubresource and } \textit{dstSubresource } \textit{must match}$
- If either of the calling command's <code>srcImage</code> or <code>dstImage</code> parameters are of <code>VkImageTypeVK_IMAGE_TYPE_3D</code>, the <code>baseArrayLayer</code> and <code>layerCount</code> members of both <code>srcSubresource</code> and <code>dstSubresource</code> must be 0 and 1, respectively

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.

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:

- *sType* is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- 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.
- topology is a VkPrimitiveTopology defining the primitive topology, as described below.

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_LINE_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, <code>topology</code> must not be any of <code>VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY</code>, <code>VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY</code>, <code>VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY</code> or <code>VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY</code> or <code>VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY</code>
- If the tessellation shaders feature is not enabled, topology must not be VK_PRIMITIVE_TOPOLOGY_PATCH_LIST

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 <code>vertexOffset</code> value to the index value.

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_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.

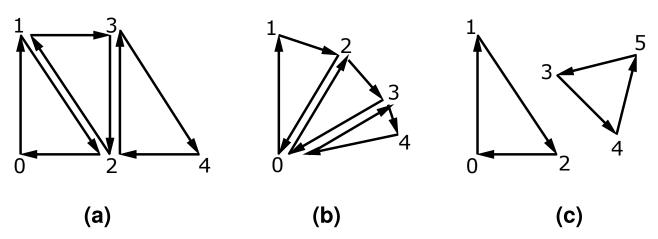
19.1.3 Line Strips

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 *i*th vertex (for i > 0) specifies the beginning of the *i*th segment and the end of the i-1st. 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 <code>topology_VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP</code>. In this case, the first three vertices define the first triangle, and their order is significant. Each subsequent vertex defines a new triangle using that point along with the last two vertices from the previous triangle, as shown in figure Triangle strips, fans, and lists. If fewer than three vertices are specified, no primitive is produced. The order of vertices in successive triangles changes as shown in the figure, so that all triangle faces have the same orientation.

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 Triangle strips, fans, and lists, so that all triangles in the fan share a common vertex.

19.1.6 Separate Triangles

Separate triangles are specified with topology VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, as shown in figure Triangle strips, fans, and lists. In this case, vertices 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 $0,1,\ldots,n-1$, 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 <code>topology VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_</code> 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 + 1st vertex to the 4i + 2nd vertex for each i = 0, 1, ..., 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 4ith and 4i + 3rd vertices are considered adjacent to the 4i + 1st and 4i + 2nd vertices, respectively, as shown in figure Lines with adjacency.

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.

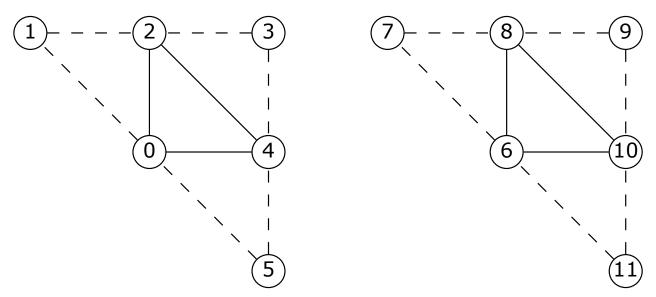
A line segment is drawn from the i+1st vertex to the i+2nd vertex for each $i=0,1,\ldots,n-1$, where there are n+3 vertices. If there are fewer than four vertices, all vertices are ignored. For line segment i, the ith and i+3rd vertex are considered adjacent to the i+1st and i+2nd vertices, respectively,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

19.1.9 Triangle List With Adjacency

Triangles with adjacency are specified with topology VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ ADJACENCY, and are similar to separate triangles except that each triangle edge has an adjacent vertex that is accessible in a geometry shader. If a geometry shader is not active, the adjacent vertices are ignored.

The 6*i*th, 6i + 2nd, and 6i + 4th vertices (in that order) determine a triangle for each i = 0, 1, ..., 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 + 1st, 6i + 3rd, and 6i + 5th vertices are considered adjacent to edges from the 6ith to the 6i + 2nd, from the 6i + 2nd to the 6i + 4th, and from the 6i + 4th to the 6ith vertices, respectively, as shown in figure Triangles with adjacency.

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 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 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 $(i = n - 1, i \text{ odd})$	2i + 2	2i	2i + 4	2i-2	2i + 3	2i + 5
last $(i = n - 1, i \text{ even})$	2i	2i+2	2i + 4	2i-2	2i+5	2i + 3

Table 19.1: Triangles generated by triangle strips with adjacency.

Triangle strips with adjacency



19.1.11 Separate Patches

Separate patches are specified with <code>topology</code> 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 <code>patchControlPoints</code> member of the <code>VkPipelineTessellationStateCreateInfo</code> structure passed to <code>vkCreateGraphicsPipelines</code>. 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 - 1st vertices (in that order) determine a patch for each $i = 0, 1, \dots, n-1$, 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_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.

19.1.13 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 (vkCmdDraw and vkCmdDrawIndirect) commands present a sequential vertexIndex
 to the vertex shader. The sequential index is generated automatically by the device.
- Indexed drawing commands (vkCmdDrawIndexed and vkCmdDrawIndexedIndirect) read index values from an *index buffer* and use this to compute the vertexIndex value for the vertex shader.

An index buffer is bound to a command buffer by calling:

- 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;
```

- 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
- Each of commandBuffer and buffer 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's 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 access to commandBuffer must be externally synchronized

Command Properties

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

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:

- 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.
- first Instance is the instance ID of the first instance to draw.

When the command is executed, primitives are assembled using the current primitive topology and <code>vertexCount</code> consecutive vertex indices with the first <code>vertexIndex</code> value equal to <code>firstVertex</code>. The primitives are drawn <code>instanceCount</code> times with <code>instanceIndex</code> starting with <code>firstInstance</code> and increasing sequentially for each instance. The assembled primitives execute the currently bound graphics pipeline.

- 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 VkImage 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 returned by
 vkGetPhysicalDeviceFormatProperties

• Host access to commandBuffer must be externally synchronized

Command Properties

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

To record an indexed draw, call:

- 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 <code>indexCount</code> 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 <code>vkCmdBindIndexBuffer::indexType</code> 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.

- 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 VkImage 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 returned by
 vkGetPhysicalDeviceFormatProperties

• Host access to commandBuffer must be externally synchronized

Command Properties

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

A non-indexed indirect draw is recorded by calling:

- 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.

- 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
- Each of commandBuffer and buffer 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
- $\bullet \ \textit{drawCount must be less than or equal to } \ \textit{VkPhysicalDeviceLimits::} \\ \textit{maxDrawIndirectCount}$
- 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 VkImage 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 returned by
 vkGetPhysicalDeviceFormatProperties

• Host access to commandBuffer must be externally synchronized

Command Properties

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

The definition of VkDrawIndirectCommand is:

```
typedef struct VkDrawIndirectCommand {
   uint32_t    vertexCount;
   uint32_t    instanceCount;
   uint32_t    firstVertex;
   uint32_t    firstInstance;
} VkDrawIndirectCommand;
```

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

An indexed indirect draw is recorded by calling:

- 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 vkCmdDrawIndirect 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.

- 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
- Each of commandBuffer and buffer 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, <code>drawCount</code> must be 0 or 1
- If the drawIndirectFirstInstance feature is not enabled, all the <code>firstInstance</code> members of the <code>VkDrawIndexedIndirectCommand</code> 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 VkImage 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 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	Inside	GRAPHICS
Secondary		

The definition of $\mbox{VkDrawIndexedIndirectCommand}\ is$

```
typedef struct VkDrawIndexedIndirectCommand {
    uint32_t     indexCount;
    uint32_t     instanceCount;
    uint32_t     firstIndex;
    int32_t     vertexOffset;
    uint32_t     firstInstance;
} VkDrawIndexedIndirectCommand;
```

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"
      OpName %18 "gl_VertexID"
      OpName %19 "gl_InstanceID"
      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.

32-bit data type	Component decoration	Components consumed
scalar	0 or unspecified	(x, 0, 0, 0)
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: Input attribute components accessed by 32-bit input variables

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)

Table 20.1: (continued)

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.

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)

Table 20.2: Input attributes accessed by 32-bit input matrix variables

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, -, -)
		scalar	i	0 or unspecified	(x, y, o, o)
R64G64	i	scalar	i	2	(o, o, z, w)
		two-component vector	i	0 or unspecified	(x, y, z, w)
		scalar	i	0 or unspecified	(x, y, o, o), (o, o, -, -)
R64G64B64	i, i+1	scalar	i	2	(0, 0, z, w), (0, 0, -, -)
		scalar	i+1	0 or unspecified	(0, 0, 0, 0), (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, -, -)
		scalar	i	0 or unspecified	(x, y, o, o), (o, o, o, o)
DC1GC1DC11C1		scalar	i	2	(o, o, z, w), (o, o, o, o)
R64G64B64A64	i, i+1	scalar	i+1	0 or unspecified	(o, o, o, o), (x, y, o, o)
		scalar	i+1	2	(0, 0, 0, 0), (0, 0, z, w)
		two-component vector	i	0 or unspecified	(x, y, z, w), (0, 0, 0, 0)
		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 compenent aliasing. Further, when location aliasing, the aliases sharing the location must have the same underlying numerical type (floating-point or integer). Failure to meet these requirements will result in an invalid pipeline.

20.2 Vertex Input Description

Applications specify vertex input attribute and vertex input binding descriptions as part of graphics pipeline creation, via the <code>pVertexInputState</code> member of <code>VkGraphicsPipelineCreateInfo</code>, which is of type <code>VkPipelineVertexInputStateCreateInfo</code>:

The members of VkPipelineVertexInputStateCreateInfo have the following meanings:

- *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 members of $\mbox{VkVertexInputBindingDescription}$ have the following meanings:

- binding is the binding number that this structure describes.
- stride is the distance in bytes between two consecutive elements within the buffer.
- inputRate is a VkVertexInputRate value that specifies whether vertex attribute addressing is a function of the vertex index or 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

The definition of VkVertexInputRate is:

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

The values of VkVertexInputRate have the following meanings:

- 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.

Each vertex input attribute is specified by an instance of the VkVertexInputAttributeDescription structure:

```
typedef struct VkVertexInputAttributeDescription {
   uint32_t location;
   uint32_t binding;
   VkFormat format;
   uint32_t offset;
} VkVertexInputAttributeDescription;
```

The members of VkVertexInputAttributeDescription have the following meanings:

- *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
- $\bullet \ \textit{offset must be less than or equal to } \ \texttt{VkPhysicalDeviceLimits::} \textit{maxVertexInputAttributeOffset } \\$
- 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

Vertex buffers are bound to a command buffer for use in subsequent draw commands by calling:

- commandBuffer is the command buffer into which the command is recorded.
- firstBinding is the index of the first vertex input binding whose state is updated by the command.
- bindingCount is the number of vertex input bindings whose state is updated by the command.
- pBuffers is a pointer to an array of buffer handles.
- poffsets is a pointer to an array of buffer offsets.

The values taken from elements i of pBuffers and pOffsets replace the current state for the vertex input binding firstBinding + i, for i in [0, bindingCount). The vertex input binding is updated to start at the offset indicated by pOffsets[i] from the start of the buffer pBuffers[i]. All vertex input attributes that use each of these bindings will use these updated addresses in their address calculations for subsequent draw commands.

Valid Usage

- 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
- Each 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
- ullet 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	Both	GRAPHICS
Secondary		

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*).

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 =
                                              // binding
   sizeof(Vertex),
                                              // stride
   VK_VERTEX_INPUT_RATE_VERTEX
                                              // inputRate
};
const VkVertexInputAttributeDescription attributes[] =
                                             // location
       binding.binding,
                                             // binding
       VK_FORMAT_R32G32B32A32_SFLOAT,
                                             // format
                                              // offset
                                             // location
                                             // binding
       binding.binding,
                                             // format
       VK_FORMAT_R8G8_UNORM,
       4 * sizeof(float)
                                             // offset
   }
};
const VkPipelineVertexInputStateCreateInfo viInfo =
   VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_CREATE_INFO, // sType
   NULL,
                                // pNext
                                // flags
   0,
   1,
                                // vertexBindingDescriptionCount
                                // pVertexBindingDescriptions
   &binding,
                                // vertexAttributeDescriptionCount
   2,
   &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 tessellation levels written by the tessellation control shader. This subdivision is performed in an implementation-dependent manner. If no tessellation shaders are present in the pipeline, the tessellator is disabled and incoming primitives are passed through without modification.

The type of subdivision performed by the tessellator is specified by an **OpExecutionMode** instruction in the tessellation evaluation or tessellation control shader using one of execution modes **Triangles**, **Quads**, and **IsoLines**. Other tessellation-related execution modes can also be specified in either the tessellation control or tessellation evaluation shaders, and if they are specified in both then the modes must be the same.

Tessellation execution modes include:

- **Triangles**, **Quads**, and **IsoLines**. These control the type of subdivision and topology of the output primitives. One mode must be set in at least one of the tessellation shader stages.
- **VertexOrderCw** and **VertexOrderCcw**. These control the orientation of triangles generated by the tessellator. One mode must be set in at least one of the tessellation shader stages.
- **PointMode**. Controls generation of points rather than triangles or lines. This functionality defaults to disabled, and is enabled if either shader stage includes the execution mode.
- SpacingEqual, SpacingFractionalEven, and SpacingFractionalOdd. Controls the spacing of segments on the edges of tessellated primitives. One mode must be set in at least one of the tessellation shader stages.
- OutputVertices. Controls the size of the output patch of the tessellation control shader. One value must be set in at least one of the tessellation shader stages.

For triangles, the tessellator subdivides a triangle primitive into smaller triangles. For quads, the tessellator subdivides a rectangle primitive into smaller triangles. For isolines, the tessellator subdivides a rectangle primitive into a collection of line segments arranged in strips stretching across the rectangle in the u dimension (i.e. the coordinates in **TessCoord** are of the form (0,x) through (1,x) for all tessellation evaluation shader invocations that share a line).

Each vertex produced by the tessellator has an associated (u,v,w) or (u,v) position in a normalized parameter space, with parameter values in the range [0,1], as illustrated in figure Domain parameterization for tessellation primitive modes.

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 should 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

$$a = u_0v_1 - u_1v_0 + u_1v_2 - u_2v_1 + u_2v_0 - u_0v_2$$

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.

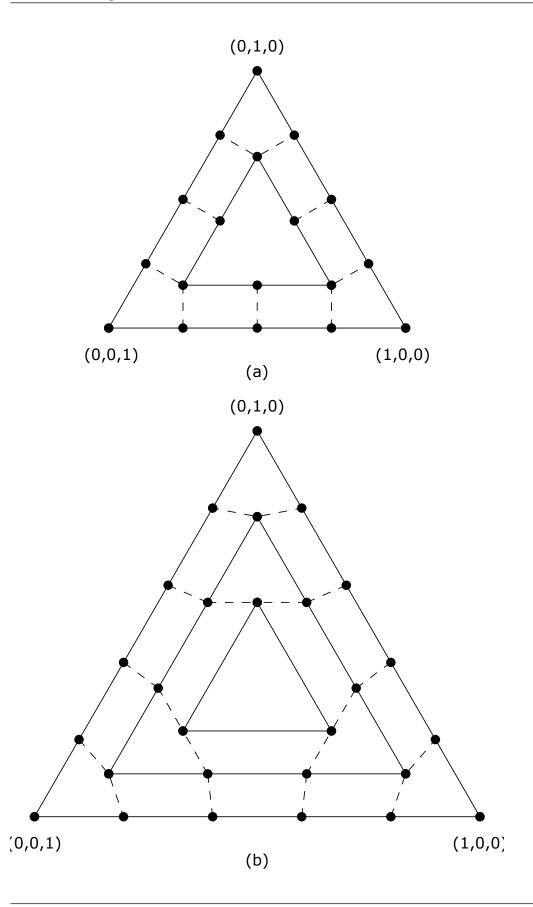
21.4 Triangle Tessellation

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.

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.

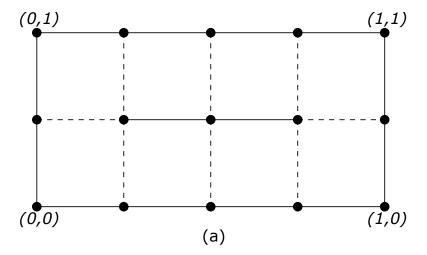
21.5 Quad Tessellation

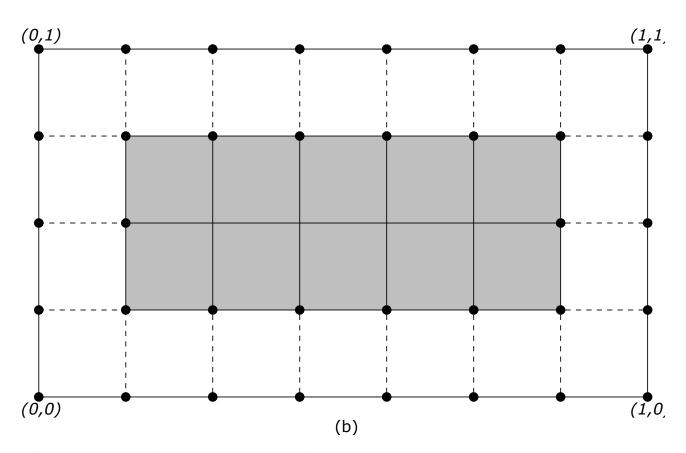
If the tessellation primitive mode is **Quads**, a rectangle is subdivided into a collection of triangles covering the area of the original rectangle. First, the original rectangle is subdivided into a regular mesh of rectangles, where the number of rectangles along the u=0 and u=1 (vertical) and v=0 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.

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.

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 is of type VkPipelineTessellationStateCreateInfo:

The members of the VkPipelineTessellationStateCreateInfo structure are as follows:

- *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 specifing 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 <code>OpExecutionMode</code> instruction with the <code>InputLines</code> mode. Such a shader is valid only for the <code>VK_PRIMITIVE_TOPOLOGY_LINE_LIST</code>, and <code>VK_PRIMITIVE_TOPOLOGY_LINE_STRIP</code> primitive topologies (if tessellation is not in use) or if tessellation is in use and the tessellation mode is <code>Isolines</code>. 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 Triangle Rasterization).

Next, rasterization is performed on primitives as described in chapter Rasterization.

23.1 Flatshading

Flatshading 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>i</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	6 <i>i</i>
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY	2i

Flatshading is applied to those vertex attributes that match fragment input attributes which are decorated as Flat.

If a geometry shader is active, the output primitive topology is either points, line strips, or triangle strips, and the selection of the provoking vertex behaves according to the corresponding row of the table. If a tessellation evaluation shader is active and a geometry shader is not active, the provoking vertex is undefined but must be one of the vertices of the primitive.

23.2 Primitive Clipping

Primitives are culled against the *cull volume* and then clipped to the *clip volume*. In clip coordinates, the *view volume* is defined by:

$$-w_c \le x_c \le w_c$$

$$-w_c \le y_c \le w_c$$

$$0 \le z_c \le w_c$$

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

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

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

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

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

$$c_i(P) \geq 0$$

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

$$0 \le z_c \le w_c$$

(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, $0 \le t \le 1$, for each clipped vertex. If the coordinates of a clipped vertex are **P** and the original vertices' coordinates are **P**₁ and **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 P_1 and P_2 of an unclipped edge be c_1 and c_2 . The value of t (see Primitive Clipping) for a clipped point P is used to obtain the output value associated with P as

$$\mathbf{c} = t\mathbf{c}_1 + (1-t)\mathbf{c}_2.$$

(Multiplying an output value by a scalar means multiplying each of x, y, z, and w by the scalar.)

Since this computation is performed in clip space before division by w_c , clipped output values are perspective-correct.

Polygon clipping creates a clipped vertex along an edge of the clip volume's boundary. This situation is handled by noting that polygon clipping proceeds by clipping against one half-space at a time. Output value clipping is done in the

same way, so that clipped points always occur at the intersection of polygon edges (possibly already clipped) with the clip volume's boundary.

For vertex output attributes whose matching fragment input attributes are decorated with **NoPerspective**, the value of *t* used to obtain the output value associated with **P** will be adjusted to produce results that vary linearly in framebuffer space.

Output attributes of integer or unsigned integer type must always be flatshaded. Flatshaded 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 flatshading 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

$$\left(\begin{array}{c} x_c \\ y_c \\ z_c \\ w_c \end{array}\right)$$

then the vertex's normalized device coordinates are

$$\begin{pmatrix} x_d \\ y_d \\ z_d \end{pmatrix} = \begin{pmatrix} \frac{\underline{x_c}}{w_c} \\ \frac{\underline{y_c}}{w_c} \\ \frac{\underline{z_c}}{w_c} \\ \end{pmatrix}$$

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:

```
const VkRect2D* pScissors;
} VkPipelineViewportStateCreateInfo;
```

The members of the VkPipelineViewportStateCreateInfo structure are as follows:

- 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 structs, 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 structs which define the rectangular bounds of the scissor for the corresponding viewport. If the scissor state is dynamic, this member is ignored.

Valid Usage

- \bullet 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 <code>viewportCount</code> 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:

- 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
- 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	Both	GRAPHICS
Secondary		

Either of these methods of setting the viewport transformation parameters use the VkViewport struct:

```
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.

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

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 $k \in \{0, 1, \dots, 2^m-1\}$, 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.

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;
                                               flags;
   VkPipelineRasterizationStateCreateFlags
   VkBool32
                                               depthClampEnable;
   VkBool32
                                               rasterizerDiscardEnable;
   VkPolygonMode
                                               polygonMode;
   VkCullModeFlags
                                               cullMode;
   VkFrontFace
                                               frontFace;
   VkBool32
                                               depthBiasEnable;
   float
                                               depthBiasConstantFactor;
   float.
                                               depthBiasClamp;
   float
                                               depthBiasSlopeFactor;
                                                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.

- 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:

```
const VkSampleMask* pSampleMask;
  VkBool32 alphaToCoverageEnable;
  VkBool32 alphaToOneEnable;
} VkPipelineMultisampleStateCreateInfo;
```

The members of the VkPipelineMultisampleStateCreateInfo structure are as follows:

- *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, <code>sampleShadingEnable</code> must be <code>VK_FALSE</code>
- 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 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 <code>rasterizationSamples</code> bits (see Sample Mask). Each fragment includes <code>rasterizationSamples</code> 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 <code>rasterizationSamples</code> is <code>VK_SAMPLE_COUNT_1_BIT</code>, 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, <code>rasterizationSamples</code> depth values and sets of associated data, and a coverage value with <code>rasterizationSamples</code> bits.

It is understood that each pixel has <code>rasterizationSamples</code> 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 <code>Sample</code> and <code>Input</code>, 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 <code>Sample</code> and <code>Input</code> need not be evaluated independently for each sample.

If the <code>standardSampleLocations</code> member of <code>VkPhysicalDeviceFeatures</code> is <code>VK_TRUE</code>, then the sample counts <code>VK_SAMPLE_COUNT_1_BIT</code>, <code>VK_SAMPLE_COUNT_2_BIT</code>, <code>VK_SAMPLE_COUNT_4_BIT</code>, <code>VK_SAMPLE_COUNT_4_BIT</code>, <code>VK_SAMPLE_COUNT_16_BIT</code> have sample locations as listed in the following table, with the <code>ith</code> entry in the table corresponding to bit <code>i</code> in the sample masks. <code>VK_SAMPLE_COUNT_32_BIT</code> and <code>VK_SAMPLE_COUNT_64_BIT</code> do not have standard sample locations. Locations are defined relative to an origin in the upper left corner of the pixel.

VK_SAMPLE_	VK_SAMPLE_	VK_SAMPLE_	VK_SAMPLE_	VK_SAMPLE_
COUNT_1_BIT	COUNT_2_BIT	COUNT_4_BIT	COUNT_8_BIT	COUNT_16_BIT
(0.5, 0.5)	(0.25, 0.25)	(0.375, 0.125)	(0.5625, 0.3125)	(0.5625, 0.5625)
	(0.75, 0.75)	(0.875, 0.375)	(0.4375, 0.6875)	(0.4375, 0.3125)
		(0.125, 0.625)	(0.8125, 0.5625)	(0.3125, 0.625)
		(0.625, 0.875)	(0.3125, 0.1875)	(0.75, 0.4375)
			(0.1875, 0.8125)	(0.1875, 0.375)
			(0.0625, 0.4375)	(0.625, 0.8125)
			(0.6875, 0.9375)	(0.8125, 0.6875)
			(0.9375, 0.0625)	(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)

Table 24.1: Standard sample locations

24.3 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 <code>sampleShadingEnable</code> member of <code>VkPipelineMultisampleStateCreateInfo</code>. If <code>sampleShadingEnable</code> is <code>VK_FALSE</code>, sample shading is considered disabled and has no effect. Otherwise, an implementation must provide a minimum of max([minSampleShading × rasterizationSamples], 1) unique associated data for each fragment, where <code>minSampleShading</code> is the minimum fraction of sample shading and <code>rasterizationSamples</code> is the number of samples requested in <code>VkPipelineMultisampleStateCreateInfo</code>. 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.

24.4 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.

24.4.1 Basic Point Rasterization

Point rasterization produces a fragment for each framebuffer pixel with one or more sample points that intersect a region centered at the point's (x_f, y_f) . This region is a square with side equal to the current point size. Coverage bits that correspond to sample points that intersect the region are 1, other coverage bits are 0.

All fragments produced in rasterizing a point are assigned the same associated data, which are those of the vertex corresponding to the point. However, the fragment shader built-in **PointCoord** contains point sprite texture coordinates. The *s* and *t* point sprite texture coordinates vary from zero to one across the point horizontally left-to-right and top-to-bottom, respectively. The following formulas are used to evaluate *s* and *t*:

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

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

where size is the point's size, (x_p, y_p) is the location at which the point sprite coordinates are evaluated - this may be the framebuffer coordinates of the pixel center (i.e. at the half-integer) or the location of a sample, and (x_f, y_f) is the exact, unrounded framebuffer coordinate of the vertex for the point. When rasterizationSamples is $VK_SAMPLE_COUNT_1_BIT$, the pixel center must be used.

24.5 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 <code>lineWidth</code> property of <code>VkPipelineRasterizationStateCreateInfo</code> in the currently active pipeline if the pipeline was not created with <code>VK_DYNAMIC_STATE_LINE_WIDTH</code> enabled. Otherwise, the line width is set by calling <code>vkCmdSetLineWidth</code>:

- 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
- 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	Both	GRAPHICS
Secondary		

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 <code>lineWidthRange</code> and <code>lineWidthGranularity</code> members of <code>VkPhysicalDeviceLimits</code>. 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.

24.5.1 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.

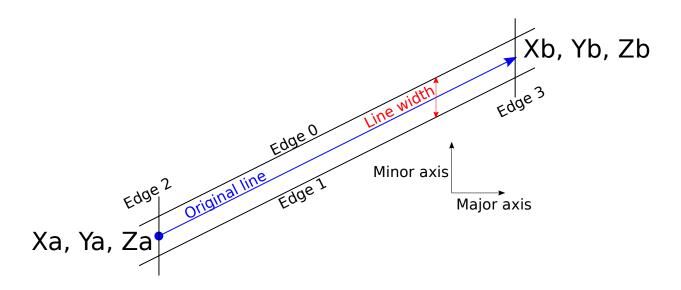
The above description documents the preferred method of line rasterization, and must be used when the implementation advertises the <code>strictLines</code> limit in <code>VkPhysicalDeviceLimits</code> as <code>VK_TRUE</code>.

When <code>strictLines</code> is VK_FALSE, the edges of the lines are generated as a parallelogram surrounding the original line. The major axis is chosen by noting the axis in which there is the greatest distance between the line start and end points. If the difference is equal in both directions then the X axis is chosen as the major axis. Edges 2 and 3 are aligned to the minor axis and are centered on the endpoints of the line as in Non strict lines, and each is <code>lineWidth</code> 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.

Non strict lines



24.6 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.

24.6.1 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 $(i+1) \mod n$. The interpretation of the sign of this value is determined by the frontFace property of the VkPipelineRasterizationStateCreateInfo in the currently active pipeline, which takes the following values:

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

When this is set to VK_FRONT_FACE_COUNTER_CLOCKWISE, a triangle with positive area is considered front-facing. When 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 <code>cullMode</code> property in the <code>VkPipelineRasterizationStateCreateInfo</code> 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 <code>cullMode</code> is set to <code>VK_CULL_MODE_NONE</code> no triangles are discarded, if it is set to <code>VK_CULL_MODE_FRONT_BIT</code> front-facing triangles are discarded, if it is set to <code>VK_CULL_MODE_BACK_BIT</code> then back-facing triangles are discarded and if it is set to <code>VK_CULL_MODE_FRONT_AND_BACK</code> 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:

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

where A(lmn) denotes the area in framebuffer coordinates of the triangle with vertices l, n, 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, $0 \le a_i \le 1$ and $\sum_{i=1}^{n} a_i = 1$. The values of a_i may differ from fragment to fragment, but at vertex i, $a_i = 1$ and $a_j = 0$ for $j \ne i$.

Note



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

24.6.2 Polygon Mode

The interpretation of polygons for rasterization is controlled using the polygonMode member of VkPipelineRasterizationStateCreateInfo, 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.

24.6.3 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 <code>depthBiasEnable</code>, <code>depthBiasConstantFactor</code>, <code>depthBiasClamp</code>, and <code>depthBiasSlopeFactor</code> members of VkPipelineRasterizationStateCreateInfo, or by the corresponding parameters to the

vkCmdSetDepthBias command if depth bias state is dynamic.

- 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.

- 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
- 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	Both	GRAPHICS
Secondary		

 $If \ \textit{depthBiasEnable} \ is \ \texttt{VK_FALSE}, \ no \ depth \ bias \ is \ applied \ and \ the \ fragment's \ depth \ values \ are \ unchanged.$

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

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

m is computed as described above. If the depth buffer uses a fixed-point representation, m is a function of depth values in the range [0, 1], and o is applied to depth values in the same range.

For fixed-point depth buffers, fragment depth values are always limited to the range [0, 1] by clamping after depth bias addition is performed. Fragment depth values are clamped even when the depth buffer uses a floating-point representation.

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:

- 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
- 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	Both	GRAPHICS
Secondary		

If offset. $x \le x_f < offset.x + extent.width$ and offset. $y \le y_f < offset.y + extent.height$ 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 a bitmask 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.

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. These operations are diagrammed in figure Fragment Operations, in the order in which they are performed. 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 <code>alphaToCoverageEnable</code> and <code>alphaToOneEnable</code> members of the <code>VkPipelineMultisampleStateCreateInfo</code> 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 Fragment Output Interface). 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 VkPipelineDepthStencilStateCreateInfo:

```
typedef struct VkPipelineDepthStencilStateCreateInfo {
   VkStructureType
                                               sType;
   const void*
                                               pNext;
   VkPipelineDepthStencilStateCreateFlags
                                               flags;
   VkBool32
                                               depthTestEnable;
   VkBool32
                                               depthWriteEnable;
   VkCompareOp
                                               depthCompareOp;
   VkBool32
                                               depthBoundsTestEnable;
   VkBool32
                                               stencilTestEnable;
   VkStencilOpState
                                               front;
   VkStencilOpState
                                               back;
                                               minDepthBounds;
   float
   float
                                               maxDepthBounds;
} VkPipelineDepthStencilStateCreateInfo;
```

The members of VkPipelineDepthStencilStateCreateInfo structure are as follows:

- *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.
- \bullet 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

- ullet 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:

- 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
- 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	Both	GRAPHICS
Secondary		

If $minDepthBounds \le z_a \le maxDepthBounds$, 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 definition of VkStencilOpState is:

```
typedef struct VkStencilOpState {
    VkStencilOp     failOp;
    VkStencilOp     passOp;
    VkStencilOp     depthFailOp;
    VkCompareOp     compareOp;
    uint32_t     compareMask;
    uint32_t     writeMask;
    uint32_t     reference;
} VkStencilOpState;
```

The members of VkStencilOpState structure are as follows:

- 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 Triangle Rasterization).

The operation of the stencil test is also affected by the <code>compareMask</code>, <code>writeMask</code>, and <code>reference</code> members of <code>VkStencilOpState</code> set in the pipeline state object if the pipeline state object is created without the <code>VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK</code>, <code>VK_DYNAMIC_STATE_STENCIL_WRITE_MASK</code>, and <code>VK_DYNAMIC_STATE</code> 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:

- 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, and may include the bits:

```
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.

- commandBuffer must be a valid VkCommandBuffer handle
- faceMask must be a valid combination of VkStencilFaceFlagBits values
- faceMask must not be 0
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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:

- 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.

- commandBuffer must be a valid VkCommandBuffer handle
- faceMask must be a valid combination of VkStencilFaceFlagBits values
- faceMask must not be 0
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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:

- 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.

- commandBuffer must be a valid VkCommandBuffer handle
- faceMask must be a valid combination of VkStencilFaceFlagBits values
- faceMask must not be 0
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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_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 <code>writeMask</code> member of the <code>VkStencilOpState</code> 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 $z_f \le z_a$.
- 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 $\min Depth$ and $\max Depth$ 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 struct during graphics pipeline creation:

```
typedef struct VkPipelineColorBlendStateCreateInfo {
   VkStructureType
                                                  sType;
   const void*
                                                  pNext;
   VkPipelineColorBlendStateCreateFlags
                                                  flags;
   VkBool32
                                                  logicOpEnable;
   VkLogicOp
                                                  logicOp;
   uint32_t
                                                  attachmentCount;
   const VkPipelineColorBlendAttachmentState* pAttachments;
                                                  blendConstants[4];
} VkPipelineColorBlendStateCreateInfo;
```

The members of the $\mbox{VkPipelineColorBlendStateCreateInfo}$ structure are as follows:

• 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: 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.

- 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, <code>logicOpEnable</code> must be <code>VK_FALSE</code>
- If logicOpEnable is VK_TRUE, logicOp must be a valid VkLogicOp value

The elements of the pAttachments array specify per-target blending state, and are of type:

Blending of each individual color attachment is controlled by the corresponding element of the pAttachments array. If the independent blending feature is not enabled on the device, all VkPipelineColorBlendAttachmentState elements in the pAttachments array must be identical. The members of the

VkPipelineColorBlendAttachmentState struct have the following meanings:

- 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_h .
- 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.

- 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_SRC1_COLOR, VK_BLEND_SRC1_ALPHA, or VK_BLEND_ONE_MINUS_SRC1_ALPHA
- If the dual source blending feature is not enabled, <code>dstColorBlendFactor</code> must not be VK_BLEND_SRC1_COLOR, VK_BLEND_ONE_MINUS_SRC1_COLOR, VK_BLEND_SRC1_ALPHA, or VK_BLEND_ONE_MINUS_SRC1_ALPHA
- If the dual source blending feature is not enabled, <code>srcAlphaBlendFactor</code> must not be <code>VK_BLEND_SRC1_COLOR</code>, <code>VK_BLEND_ONE_MINUS_SRC1_COLOR</code>, <code>VK_BLEND_SRC1_ALPHA</code>, or <code>VK_BLEND_ONE_MINUS_SRC1_ALPHA</code>
- If the dual source blending feature is not enabled, <code>dstAlphaBlendFactor</code> must not be <code>VK_BLEND_SRC1_COLOR</code>, <code>VK_BLEND_ONE_MINUS_SRC1_COLOR</code>, <code>VK_BLEND_SRC1_ALPHA</code>, or <code>VK_BLEND_ONE_MINUS_SRC1_ALPHA</code>

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	Alpha Blend
	(S_r, S_g, S_b) or (D_r, D_g, D_b)	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 the blend constant is dynamically set and changed by calling the command:

- 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

Host Synchronization

• Host access to commandBuffer must be externally synchronized

Command Properties

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

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_SRC1_ALPHA, and 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 <code>maxFragmentDualSrcAttachments</code> member of <code>VkPhysicalDeviceLimits</code>.

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:

VkBlendOp	RGB Components	Alpha Component
VK_BLEND_OP_ADD	$R = R_{s0} \times S_r + R_d \times D_r$	$A = A_{s0} \times S_a + A_d \times D_a$
	$G = G_{s0} \times S_g + G_d \times D_g$	
	$B = B_{s0} \times S_b + B_d \times D_b$	
VK_BLEND_OP_SUBTRACT	$R = R_{s0} \times S_r - R_d \times D_r$	$A = A_{s0} \times S_a - A_d \times D_a$
	$G = G_{s0} \times S_g - G_d \times D_g$	
	$B = B_{s0} \times S_b - B_d \times D_b$	
VK_BLEND_OP_REVERSE_SUBTRACT	$R = R_d \times D_r - R_{s0} \times S_r$	$A = A_d \times D_a - A_{s0} \times S_a$
	$G = G_d \times D_g - G_{s0} \times S_g$	
	$B = B_d \times D_b - B_{s0} \times S_b$	
VK_BLEND_OP_MIN	$R = \min(R_{s0}, R_d)$	$A = \min(A_{s0}, A_d)$
	$G = \min(G_{s0}, G_d)$	
	$B = \min(B_{s0}, B_d)$	
VK_BLEND_OP_MAX	$R = \max(R_{s0}, R_d)$	$A = \max(A_{s0}, A_d)$
	$G = \max(G_{s0}, G_d)$	
	$B = \max(B_{s0}, B_d)$	

Table 26.2: Blend Operations

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 $VK_COLOR_COMPONENT_B$

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.

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 <code>logicOpEnable</code> and <code>logicOp</code> members of <code>VkPipelineColorBlendStateCreateInfo</code>. If <code>logicOpEnable</code> is <code>VK_TRUE</code>, then a logical operation selected by <code>logicOp</code> is applied between each color attachment and the fragment's corresponding output value, and blending of all attachments is treated as if it were disabled. Any attachments using color formats for which logical operations are not supported simply pass through the color values unmodified. The logical operation is applied independently for each of

the red, green, blue, and alpha components. The logicop is selected from the following operations:

```
typedef enum VkLogicOp {
    VK\_LOGIC\_OP\_CLEAR = 0,
    VK\_LOGIC\_OP\_AND = 1,
    VK_LOGIC_OP_AND_REVERSE = 2,
    VK\_LOGIC\_OP\_COPY = 3,
    VK_LOGIC_OP_AND_INVERTED = 4,
    VK_LOGIC_OP_NO_OP = 5,
    VK\_LOGIC\_OP\_XOR = 6,
    VK\_LOGIC\_OP\_OR = 7,
    VK\_LOGIC\_OP\_NOR = 8,
    VK_LOGIC_OP_EQUIVALENT = 9,
    VK_LOGIC_OP_INVERT = 10,
    VK_LOGIC_OP_OR_REVERSE = 11,
    VK_LOGIC_OP_COPY_INVERTED = 12,
    VK_LOGIC_OP_OR_INVERTED = 13,
    VK_LOGIC_OP_NAND = 14,
    VK_LOGIC_OP_SET = 15,
 VkLogicOp;
```

The logical operations supported by Vulkan are summarized in the following table in which

- ¬ is bitwise invert,
- \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	$s \lor d$
VK_LOGIC_OP_NOR	$\neg(s \lor d)$
VK_LOGIC_OP_EQUIVALENT	$\neg(s \oplus d)$
VK_LOGIC_OP_INVERT	$\neg d$
VK_LOGIC_OP_OR_REVERSE	$s \lor \neg d$
VK_LOGIC_OP_COPY_INVERTED	$\neg s$
VK_LOGIC_OP_OR_INVERTED	$\neg s \lor d$
VK_LOGIC_OP_NAND	$\neg(s \land d)$
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:

- 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.

- 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 VkImage 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 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	Outside	COMPUTE
Secondary		

An indirect dispatch is recorded by calling:

- 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.

- 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
- Each of commandBuffer and buffer 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 VkImage 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 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	Outside	COMPUTE
Secondary		

The definition of VkDispatchIndirectCommand is:

```
typedef struct VkDispatchIndirectCommand {
   uint32_t     x;
   uint32_t    y;
   uint32_t    z;
} VkDispatchIndirectCommand;
```

The members of VkDispatchIndirectCommand structure have the same meaning as the similarly named parameters of vkCmdDispatch.

- 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 (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 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 block layout, allowing specific image blocks 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.
- Support is advertised on a finer grain via the following features:
 - * sparseResidencyBuffer: Support for creating VkBuffer objects with the VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT.
 - * sparseResidencyImage2D: Support for creating 2D single-sampled VkImage objects with VK_IMAGE_ CREATE SPARSE RESIDENCY BIT.
 - * sparseResidencyImage3D: Support for creating 3D VkImage objects with VK_IMAGE_CREATE_SPARSE_ RESIDENCY_BIT.
 - * sparseResidency2Samples: Support for creating 2D VkImage objects with 2 samples and VK_IMAGE_ CREATE_SPARSE_RESIDENCY_BIT.
 - * sparseResidency4Samples: Support for creating 2D VkImage objects with 4 samples and VK_IMAGE_ CREATE SPARSE RESIDENCY BIT.
 - * sparseResidency8Samples: Support for creating 2D VkImage objects with 8 samples and VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.
 - * sparseResidency16Samples: Support for creating 2D VkImage objects with 16 samples and VK_IMAGE_ CREATE_SPARSE_RESIDENCY_BIT.

Implementations supporting <code>sparseResidencyImage2D</code> are only required to support sparse 2D, single-sampled images. Support is not required for sparse 3D and MSAA images and is enabled via <code>sparseResidencyImage3D</code>, <code>sparseResidency2Samples</code>, <code>sparseResidency4Samples</code>, <code>sparseResidency8Samples</code>, and <code>sparseResidency16Samples</code>.

- 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 blocks 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 block size 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 blocks of the image to be bound to specific ranges of memory. This allows the application to manage residency at either the subresource or pixel block granularity. Each subresource (outside of the mip tail) starts on a block boundary and has a size that is an integer number of blocks of memory.

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 have no specific mapping of image region or 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 block layout, and hence each subresource must start on a block boundary. Within each array layer, the set of mip-levels that are too small to fill a block 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 is not a multiple of the block size, 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 block (i.e. must be bound using a VkSparseImageOpaqueMemoryBindInfo structure) and may be of a size greater than or equal to the normal block size. It is guaranteed to be an integer multiple of the normal image 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.

Mip Level 1 Mip Level 2 Mip Tail Mip Bayer 1 Array Layer 2 Array Layer 3 Array L

Arrayed Sparse Image

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 block size in any dimension.

Mip levels that are as large or larger than a block in all dimensions can be bound individually. Right-edges and bottom-edges of each level are allowed to have partially used blocks. Any bound partially-used-blocks must still have their full block size allocated in memory.

Arrayed Sparse Image

VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT



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.

Arrayed Sparse Image

VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT



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 blocks with an implementation-dependent mapping of pixels to blocks.

When VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT is present the first mip level that would contain partially used blocks begins the mip tail region. This level and all subsequent levels are placed in the mip tail. Only the first *N* mip levels that are an exact multiple of the sparse block size can be bound and unbound on a block basis.

Arrayed Sparse Image

VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT

VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT



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 blocks with an implementation-dependent mapping of pixels to 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 Image Block Sizes

Standard sparse image block sizes are defined by Vulkan and depend on the format of the image. Layout of pixels within a block is implementation dependent. All currently defined standard block shapes are 64 KB in size.

For compressed pixel formats (e.g. $VK_FORMAT_BC5_UNORM_BLOCK$), the pixel size is the size of the compression block (128-bit for BC5).

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 × 64 × 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 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 a custom block size.

28.4.4 Custom Image Block Sizes

An implementation that does not support the standard image block sizes may choose to support a custom block size instead. This custom block size will have the pixel region size reported in

Custom block sizes are reported through **vkGetPhysicalDeviceSparseImageFormatProperties** and **vkGetImageSparseMemoryRequirements**.

An implementation must not support both the standard block size and a custom block size for the same image. The standard size 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:

Multiple Aspect Sparse Image

Mip Level 0 Mip Level 1 Mip Level 2 Mip Level 3 Mip Tail Mip Tail Stencil Aspect Metadata Aspect Mip Tail Mip Tail Mip Tail Image Pixel Data Sparse Memory Block

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 blocks with an implementation-dependent mapping of pixels to 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 4x the number of pixels. The block byte-size 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 blocks 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 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 <code>sparseResidency</code> feature allows the sparse resource 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 <code>sparseResidencyNonResidentStrict</code>.

Not faulting on access to unbound pages is not enough to support <code>sparseResidencyNonResidentStrict</code>. 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 <code>sparseResidencyNonResidentStrict</code>.

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 <code>VkSparseImageMemoryBindInfo</code> to bind memory for the non-mip-tail 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 <code>imageMipTailOffset</code> in the sparse resource properties returned for the metadata aspect. By manipulating the value returned for <code>imageMipTailOffset</code>, the <code>resourceOffset</code> 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 capabilites are reported in the <code>sparseProperties</code> member of <code>VkPhysicalDeviceProperties</code>. The definition of <code>sparseProperties</code> is

```
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 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 image block sizes listed in the table.
- residencyStandard2DMultisampleBlockShape is VK_TRUE if the physical device will access all multisample 2D sparse resources using the standard 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 image block sizes listed in the table.
- residencyStandard3DBlockShape is VK_TRUE if the physical device will access all 3D sparse resources using the standard 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 image block sizes listed in the table.
- residencyAlignedMipSize is VK_TRUE if images with mip level dimensions that are not a multiple of a block size 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 a multiple of a block size 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 size, 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 block shape will be.

28.7.3.1 Sparse Image Format Properties API

- aspectMask is a VkImageAspectFlags specifying which aspects of the image the properties apply to.
- imageGranularity is the width, height, and depth of the block in pixels / compressed 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 that is not an exact multiple of the sparse image block size begins the mip tail region.
- If VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT is set, the image uses a non-standard sparse block size, and the <code>imageGranularity</code> values do not match the standard block size 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 bitfield 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.

- 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
- If format is an integer format, samples must be one of the bit flags specified in VkPhysicalDeviceLimits::sampledImageIntegerSampleCounts
- If format is a non-integer color format, samples must be one of the bit flags specified in VkPhysicalDeviceLimits::sampledImageColorSampleCounts
- If format is a depth format, samples must be one of the bit flags specified in VkPhysicalDeviceLimits::sampledImageDepthSampleCounts
- If format is a stencil format, samples must be one of the bit flags specified in VkPhysicalDeviceLimits::sampledImageStencilSampleCounts
- If usage includes VK_IMAGE_USAGE_STORAGE_BIT, samples must be one of the bit flags specified in VkPhysicalDeviceLimits::storageImageSampleCounts

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.

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 implies specifying VK_BUFFER_CREATE_SPARSE_BINDING_BIT or VK_IMAGE_CREATE_SPARSE_BINDING_BIT, respectively, as well. This means that resources created with either (or both) flag(s) can 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 block byte-size 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 block byte-size 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

```
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 into the same memory blocks, in which case both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT would be present.
- formatProperties.imageGranularity describes the size of a single bindable block in pixel units. For aspect VK_IMAGE_ASPECT_METADATA_BIT, this region size will be zero pixels. All metadata is located in the mip tail region.
- formatProperties.flags contains members of VkSparseImageFormatFlags:
 - 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 image mip levels must be an exact multiple of the sparse image block size for levels not located in the mip tail.
 - If VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT is set the image uses a non-standard sparse block size. The <code>formatProperties.imageGranularity</code> values do not match the standard block size for image's given pixel format.
- imageMipTailFirstLod is the first mip level at which subresources are included in the mip tail block.
- *imageMipTailSize* is the memory size (in bytes) of the mip tail block. 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 block byte-size.
- 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).

Query sparse memory requirements for an image by calling:

- device is the logical device that owns the image.
- *image* is the Vk Image 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.

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
- Each of device and image must have been created, allocated or retrieved from the same VkPhysicalDevice
- image must have been created with the VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT flag



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.

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 blocks while another queue accesses those same 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

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

```
typedef VkFlags VkSparseMemoryBindFlags;
```

• VK_SPARSE_MEMORY_BIND_METADATA_BIT is used to indicate that the memory being bound is only for the metadata aspect.

- 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 are sparse memory binding flags.

- 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

The binding range [resourceOffset, resourceOffset + size) has different constraints based on flags. If flags contains VK_SPARSE_MEMORY_BIND_METADATA_BIT, the binding range must be within the mip tail region of the metadata aspect. This metadata region is defined by:

```
metadataRegion = [imageMipTailOffset + imageMipTailStride \times n, \\ imageMipTailOffset + imageMipTailStride \times n + imageMipTailSize)
```

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).

Memory is bound to VkBuffer objects created with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT or VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT flags using the following structure:

- 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
- $\bullet \ \textit{pBinds} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{pointer} \ \textbf{to} \ \textbf{an array} \ \textbf{of} \ \textit{bindCount} \ \textbf{valid} \ \texttt{VkSparseMemoryBind} \ \textbf{structures}$
- bindCount must be greater than 0

Memory is bound to opaque regions of VkImage objects created with the VK_IMAGE_CREATE_SPARSE_BINDING_BIT or VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT flags using the following structure:

- 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 <code>flags</code> contains <code>VK_SPARSE_MEMORY_BIND_METADATA_BIT</code>, the binding range specified must be within the mip tail region of the metadata aspect. In this case the <code>resourceOffset</code> is not required to be a simple device address offset within the resource. However, it <code>is</code> defined to be within [imageMipTailOffset, imageMipTailOffset + imageMipTailSize) for the metadata aspect. See <code>VkSparseMemoryBind</code> 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:

- image is the Vk Image 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

Where VkSparseImageMemoryBind is defined as follows:

- subresource is the aspectMask and region of interest in the image.
- offset are the coordinates of the first texel within the subresource to bind.
- extent is the size in texels of the region within the subresource to bind. The extent must be a multiple of the block size, except when binding blocks along the edge of a subresource it can instead be such that any coordinate of offset + extent equals the subresource size in that dimension.
- memory is the VkDeviceMemory object that the blocks of the image are bound to. If memory is VK_NULL_HANDLE, the 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.

- subresource must be a valid VkImageSubresource structure
- If memory is not VK_NULL_HANDLE, memory must be a valid VkDeviceMemory handle
- ullet 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 subresource for image (see Section 11.5)
- offset.x must be a multiple of the block width
 (VkSparseImageFormatProperties::imageGranularity.width) of the image
- extent.width must either be a multiple of the 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 block height
 (VkSparseImageFormatProperties::imageGranularity.height) of the image
- extent.height must either be a multiple of the 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 block depth
 (VkSparseImageFormatProperties::imageGranularity.depth) of the image
- extent.depth must either be a multiple of the block depth of the image, or else extent.depth + offset.z must equal the depth of the image subresource

Sparse binding operations are submitted to a queue for execution via the command:

- queue is the queue to submit the sparse binding operation to.
- bindInfoCount is the size of the array pointed to by pBindInfo.
- pBindInfo is an array of VkBindSparseInfo structures each specifying the parameters of a sparse binding operation batch as described below.
- fence, if not VK_NULL_HANDLE, is a fence to be signaled once the sparse binding operation completes.

Each batch of sparse binding operations is represented by a list of VkSparseBufferMemoryBindInfo, VkSparseImageOpaqueMemoryBindInfo, and VkSparseImageMemoryBindInfo structures (encapsulated in a VkBindSparseInfo structure), each preceded by a list of semaphores upon which to wait before beginning execution of the operations, and followed by a second list of semaphores to signal upon completion of the operations.

When all sparse binding operations in pBindInfo have completed execution, the status of fence is set to signaled, providing certain implicit ordering guarantees.

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.

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
- Each of *queue* and *fence* that are valid handles must have been created, allocated or retrieved from the same VkDevice
- fence must be unsignalled
- 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
- $\bullet \ \ Host\ access\ to\ \textit{pBindInfo}[].pSignalSemaphores[]\ must\ be\ externally\ synchronized$
- 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

```
typedef struct VkBindSparseInfo {
   VkStructureType
                                                sType;
   const void*
                                                pNext;
   uint32_t
                                                waitSemaphoreCount;
   const VkSemaphore*
                                                pWaitSemaphores;
                                                bufferBindCount;
   uint32_t
   const VkSparseBufferMemoryBindInfo*
                                               pBufferBinds;
                                                imageOpaqueBindCount;
   const VkSparseImageOpaqueMemoryBindInfo* pImageOpaqueBinds;
                                                imageBindCount;
   uint32 t
   const VkSparseImageMemoryBindInfo*
                                                pImageBinds;
                                                signalSemaphoreCount;
   uint32_t
   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 before executing the sparse binding operations in the batch.
- bufferBindCount is the number of sparse buffer bindings to perform.
- pBufferBinds is an array of VkSparseBufferMemoryBindInfo structures, indicating sparse buffer bindings to perform as described above.
- imageOpaqueBindCount is the number of opaque sparse image bindings to perform.
- pImageOpaqueBinds is an array of VkSparseImageOpaqueMemoryBindInfo structures, indicating opaque sparse image bindings to perform as described above.
- imageBindCount is the number of sparse image bindings to perform.
- pImageBinds is an array of VkSparseImageMemoryBindInfo structures, indicating sparse image bindings to perform as described above.
- 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.

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
- Each of the elements of pWaitSemaphores and the elements of pSignalSemaphores 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 blocks.

```
VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO,
                                                 // sType
                                                 // 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 blocks
// from potentially multiple VkDeviceMemory pools.
// (Illustration purposes only, can be optimized for perf)
while (memoryRequirements.size && bindCount < MAX_CHUNKS)</pre>
    VkSparseMemoryBind* pBind = &binds[bindCount];
    pBind->resourceOffset = offset;
    AllocateOrGetMemoryBlock(
        device,
        &memoryRequirements,
        &pBind->memory,
        &pBind->memoryOffset,
        &pBind->size);
    // memory blocks 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
    . . .
                                                 // imageOpaqueBindCount
    1,
```

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
                                                // 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);
pSparseRegs = (VkSparseImageMemoryReguirements*)
    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)</pre>
    if (pSparseRegs[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 (pSparseRegs[i].formatProperties.flags &
            VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT)
        {
            VkSparseMemoryBind* pBind = &binds[bindCount];
            pBind->memorySize = pSparseReqs[i].imageMipTailSize;
            bindCount++;
            // ... Allocate memory block
            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 block per array layer.
            for (uint32_t a = 0; a < sparseImageInfo.arrayLayers; ++a)</pre>
                VkSparseMemoryBind* pBind = &binds[bindCount];
                pBind->memorySize = pSparseReqs[i].imageMipTailSize;
                bindCount++;
                // ... Allocate memory block
                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)</pre>
        {
            // ... Allocate memory block
            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
                                                // imageOpaqueBindCount
    1,
   &opaqueBindInfo,
                                                // pImageOpaqueBinds
                                                // 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.

There are two kinds of layers and extensions, instance and device. Instance layers and extensions are general purpose and do not depend on a specific device. Device layers and extensions operate on specific devices, and require a valid VkDevice to be used. Instance extensions usually affect the operation of the API as a whole, whereas device layers and extensions tend to be hardware-specific. Examples of these might be:

- Whole API validation is an example of a good instance layer.
- Debug capabilities might make a good instance extension.
- A layer that provides hardware-specific performance telemetry and analysis could be a device layer.
- 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.

To query the available instance layers, call:

- 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.

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

To enable a instance layer, the name of the layer should be added to the <code>ppEnabledLayerNames</code> member of <code>VkInstanceCreateInfo</code> when creating a <code>VkInstance</code>.

To query the layers available to a given physical device, call:

- physicalDevice is the physical device that will be queried.
- pPropertyCount is a pointer to an integer related to the number of layer properties available or queried, as described below.
- pProperties is either NULL or a pointer to an array of VkLayerProperties structures.

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

To enable a device layer, the name of the layer should be added to the ppEnabledLayerNames member of VkDeviceCreateInfo when creating a VkDevice.

For both vkEnumerateInstanceLayerProperties and vkEnumerateDeviceLayerProperties, 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 definition of VkLayerProperties is:

- 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 and VkDeviceCreateInfo structures passed to vkCreateInstance and vkCreateDevice, respectively, to enable this layer for an instance or device.
- apiVersion 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.

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 <code>ppEnabledLayerNames</code> member of <code>VkDeviceCreateInfo</code> 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.

29.2 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:

- pLayerName is either NULL or a pointer to a null-terminated UTF-8 string naming the instance 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.

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 an instance layer returned by vkEnumerateInstanceLayerProperties

Return Codes

Success

- VK SUCCESS
- VK_INCOMPLETE

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

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.

To enable a instance extension, the name of the extension should be added to the ppEnabledExtensionNames member of VkInstanceCreateInfo when creating a VkInstance.

To query the extensions available to a given physical device, call:

- 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 device 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.

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 device layer returned by vkEnumerateDeviceLayerProperties

Return Codes

Success

- VK SUCCESS
- VK INCOMPLETE

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

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.

To enable a device layer, the name of the layer should be added to the ppEnabledExtensionNames member of VkDeviceCreateInfo when creating a VkDevice.

For both vkEnumerateInstanceExtensionProperties and

vkEnumerateDeviceExtensionProperties, 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.

The definition of VkExtensionProperties is:

- 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.

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.

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:

- 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

- $\bullet \ \textit{physicalDevice} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{VkPhysicalDevice} \ \textbf{handle}$
- 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 behaviour 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 <code>pEnabledFeatures</code> 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 definition of VkPhysicalDeviceFeatures is:

```
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;
            shaderInt64;
   VkBool32
   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 inheritedOueries;
} VkPhysicalDeviceFeatures;
```

The members of the VkPhysicalDeviceFeatures structure describe the following features:

- robustBufferAccess indicates that out of bounds accesses to buffers via shader operations are well-defined.
 - When enabled, out-of-bounds buffer reads will return any of the following values:
 - * Values from anywhere within the buffer object.
 - * 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
 - When enabled, out-of-bounds writes may modify values within the buffer object or be ignored.
 - If not enabled, out of bounds accesses may cause undefined behaviour up-to and including process 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 2³²-1 when the VkIndexType is VK_INDEX_TYPE_UINT32). If this feature is supported, maxDrawIndexedIndexValue must be 2³²-1; otherwise it must be no smaller than 2²⁴-1. 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_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.
- 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. 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 behaviour.
- 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
- ${\tt vkGetPhysicalDeviceFormatProperties} \ is \ used \ to \ check \ for \ the \ supported \ properties \ of \ individual \ formats.$
- 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, the **PointSize** built-in decoration is not available in these shader stages 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, the ClipDistance built-in decoration must not be used 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, the CullDistance built-in decoration must not be used 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.
- shaderInt 64 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 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 <code>imageType</code> of VK_IMAGE_TYPE_2D and <code>samples</code> set to VK_SAMPLE_COUNT_2_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the <code>flags</code> 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 <code>imageType</code> of VK_IMAGE_TYPE_2D and <code>samples</code> set to VK_SAMPLE_COUNT_8_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the <code>flags</code> 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 <code>imageType</code> of VK_IMAGE_TYPE_2D and <code>samples</code> set to VK_SAMPLE_COUNT_16_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the <code>flags</code> 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 <code>limits</code> member of the VkPhysicalDeviceProperties structure which is returned from <code>vkGetPhysicalDeviceProperties</code>.

The definition of VkPhysicalDeviceLimits is:

```
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;
                     maxPushConstantsSize;
   uint32_t
                      maxMemoryAllocationCount;
   uint32_t
                        maxSamplerAllocationCount;
   uint32_t
   VkDeviceSize
                      bufferImageGranularity;
   VkDeviceSize
                        sparseAddressSpaceSize;
   uint32_t
                        maxBoundDescriptorSets;
   uint32_t
                        maxPerStageDescriptorSamplers;
   uint32_t
                        maxPerStageDescriptorUniformBuffers;
   uint32_t
                        maxPerStageDescriptorStorageBuffers;
   uint32_t
                        maxPerStageDescriptorSampledImages;
   uint32_t
                        maxPerStageDescriptorStorageImages;
                        maxPerStageDescriptorInputAttachments;
   uint32_t
   uint32_t
                        maxPerStageResources;
   uint32_t
                        maxDescriptorSetSamplers;
```

```
uint32_t
                      maxDescriptorSetUniformBuffers;
uint32 t
                      maxDescriptorSetUniformBuffersDynamic;
                      maxDescriptorSetStorageBuffers;
uint32_t
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;
                      maxTessellationControlPerVertexOutputComponents;
uint32_t
uint32 t
                      maxTessellationControlPerPatchOutputComponents;
uint32 t
                      maxTessellationControlTotalOutputComponents;
uint32_t
                      maxTessellationEvaluationInputComponents;
                      maxTessellationEvaluationOutputComponents;
uint32_t
uint32_t
                      maxGeometryShaderInvocations;
uint32_t
                      maxGeometryInputComponents;
uint32 t
                      maxGeometryOutputComponents;
uint32 t
                      maxGeometryOutputVertices;
uint32 t
                      maxGeometryTotalOutputComponents;
                      maxFragmentInputComponents;
uint32_t
uint32_t
                      maxFragmentOutputAttachments;
uint32 t
                      maxFragmentDualSrcAttachments;
                     maxFragmentCombinedOutputResources;
uint32_t
uint32 t
                     maxComputeSharedMemorvSize;
                     maxComputeWorkGroupCount[3];
uint32 t
                     maxComputeWorkGroupInvocations;
uint32_t
                     maxComputeWorkGroupSize[3];
uint32_t
uint32_t
                     subPixelPrecisionBits;
uint32_t
                     subTexelPrecisionBits;
                     mipmapPrecisionBits;
uint32 t
uint32_t
                     maxDrawIndexedIndexValue;
                     maxDrawIndirectCount;
uint32 t
float
                     maxSamplerLodBias;
float
                     maxSamplerAnisotropy;
uint32_t
                    maxViewports;
uint32_t
                    maxViewportDimensions[2];
float
                     viewportBoundsRange[2];
                     viewportSubPixelBits;
uint32_t
size_t
                     minMemoryMapAlignment;
VkDeviceSize
                      minTexelBufferOffsetAlignment;
VkDeviceSize
                      minUniformBufferOffsetAlignment;
VkDeviceSize
                      minStorageBufferOffsetAlignment;
int32_t
                      minTexelOffset;
uint32_t
                      maxTexelOffset;
                      minTexelGatherOffset;
int32_t
uint32_t
                      maxTexelGatherOffset;
float
                      minInterpolationOffset;
float
                      maxInterpolationOffset;
                      subPixelInterpolationOffsetBits;
uint32 t
uint32_t
                      maxFramebufferWidth;
                     maxFramebufferHeight;
uint32_t
```

```
maxFramebufferLayers;
   uint32_t
   VkSampleCountFlags framebufferColorSampleCounts;
   VkSampleCountFlags framebufferDepthSampleCounts;
   VkSampleCountFlags framebufferStencilSampleCounts;
   VkSampleCountFlags framebufferNoAttachmentsSampleCounts;
                         maxColorAttachments;
   uint32_t
   VkSampleCountFlags sampledImageColorSampleCounts; VkSampleCountFlags sampledImageIntegerSampleCounts;
   VkSampleCountFlags sampledImageDepthSampleCounts;
   VkSampleCountFlags sampledImageStencilSampleCounts;
   VkSampleCountFlags storageImageSampleCounts;
                         maxSampleMaskWords;
   uint32 t
   VkBool32
                         timestampComputeAndGraphics;
   float
                         timestampPeriod;
                       maxClipDistances;
   uint32 t
                        maxCullDistances;
   uint32_t
                       maxCombinedClipAndCullDistances;
discreteQueuePriorities;
   uint32_t
   uint32_t
                       pointSizeRange[2];
lineWidthRange[2];
   float
   float
                      pointSizeGranularity;
lineWidthGranularity;
strictLines;
   float
   float
   VkBool32
VkBool32
                      standardSampleLocations;
optimalBufferCopyOffsetAlignment;
   VkDeviceSize
   } VkPhysicalDeviceLimits;
```

The members of the VkPhysicalDeviceLimits describe the following properties of the physical device:

- 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 memory for simultaneous usage. 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_STORAGE_IMAGE, VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER, VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, VK_DESCRIPTOR_TYPE_STORAGE_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 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 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 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 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 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 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 <code>pVertexBindingDescriptions</code> member of the <code>VkPipelineVertexInputStateCreateInfo</code> structure. The <code>binding</code> member of <code>VkVertexInputBindingDescription</code> 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 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 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 miplevel 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 0xFFFFFFF. 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 viewport bounds range [minimum, maximum]. See Controlling the Viewport.
- *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_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_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 bitmask¹ of VkSampleCountFlagBits bits indicating the supported color sample counts for a framebuffer color attachment.
- framebufferDepthSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the supported depth sample counts for a framebuffer depth/stencil attachment, when the format includes a depth component.
- framebufferStencilSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the supported stencil sample counts for a framebuffer depth/stencil attachment, when the format includes a stencil component.
- \bullet 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 bitmask¹ of VkSampleCountFlagBits bits indicating the sample counts supported for all images with a non-integer color format.
- sampledImageIntegerSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the sample counts supported for all images with a integer color format.
- sampledImageDepthSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the sample counts supported for all images with a depth format.
- sampledImageStencilSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the sample supported for all images with a stencil format.
- storageImageSampleCounts is a bitmask¹ of VkSampleCountFlagBits bits indicating the sample counts supported for all images used for storage operations.
- 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.

1

- 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.

For all bitmasks of type VkSampleCountFlags above, the bits which can be set 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 = 0x000000040,
} 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 <code>vkGetPhysicalDeviceImageFormatProperties</code>. The sample count limits for images only apply to images created with the <code>tiling</code> set to <code>VK_IMAGE_TILING_OPTIMAL</code>. For <code>VK_IMAGE_TILING_LINEAR</code> images the only supported sample count is <code>VK_SAMPLE_COUNT_1_BIT</code>.

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	-
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

Table 30.1: (continued)

uint32_t uint32_t uint32_t uint32_t uint32_t uint32_t uint32_t	maxTessellationPatchSize maxTessellationControlPerVertexInputComponents maxTessellationControlPerVertexOutputComponents maxTessellationControlPerPatchOutputComponents	tessellationShader tessellationShader tessellationShader
uint32_t uint32_t uint32_t uint32_t uint32_t uint32_t	maxTessellationControlPerVertexOutputComponents	
uint32_t uint32_t uint32_t uint32_t uint32_t uint32_t	maxTessellationControlPerVertexOutputComponents	tessellationShader
uint32_t uint32_t uint32_t uint32_t		i Coscilationomatei
uint32_t uint32_t uint32_t		tessellationShader
uint32_t uint32_t	maxTessellationControlTotalOutputComponents	tessellationShader
uint32_t	maxTessellationEvaluationInputComponents	tessellationShader
	maxTessellationEvaluationOutputComponents	tessellationShader
	maxGeometryShaderInvocations	geometryShader
	maxGeometryInputComponents	geometryShader
	maxGeometryOutputComponents	geometryShader
	maxGeometryOutputVertices	geometryShader
	maxGeometryTotalOutputComponents	geometryShader
	maxFragmentInputComponents	-
	maxFragmentOutputAttachments	+_
	maxFragmentDualSrcAttachments	dualSrcBlend
	maxFragmentCombinedOutputResources	-
	maxComputeSharedMemorySize	-
	maxComputeWorkGroupCount	-
	maxComputeWorkGroupInvocations	
	maxComputeWorkGroupSize	-
	subPixelPrecisionBits	-
_ · · · · · - ·	subTexelPrecisionBits	
_		-
	mipmapPrecisionBits	- C 11D L. L. LY: 422
_	maxDrawIndexedIndexValue	fullDrawIndexUint32
	maxDrawIndirectCount	multiDrawIndirect
	maxSamplerLodBias	-
	maxSamplerAnisotropy X	samplerAnisotropy
	maxViewports	multiViewport
	maxViewportDimensions	-
	viewportBoundsRange	-
	viewportSubPixelBits	-
	minMemoryMapAlignment	-
	minTexelBufferOffsetAlignment	-
	minUniformBufferOffsetAlignment	-
	minStorageBufferOffsetAlignment	-
	minTexelOffset	-
	maxTexelOffset	-
_	minTexelGatherOffset	shaderImageGatherExtended
_	maxTexelGatherOffset	shaderImageGatherExtended
	minInterpolationOffset	sampleRateShading
	maxInterpolationOffset	sampleRateShading
	subPixelInterpolationOffsetBits	sampleRateShading
	maxFramebufferWidth	-
	maxFramebufferHeight	-
	maxFramebufferLayers	-
	framebufferColorSampleCounts	-
VkSampleCountFlags	framebufferDepthSampleCounts	-
VkSampleCountFlags	framebufferStencilSampleCounts	-
VkSampleCountFlags	framebufferNoAttachmentsSampleCounts	-

Table 30.1: (continued)

Type	Limit	Feature
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	-
$2 \times \text{float}$	pointSizeRange	largePoints
$2 \times \text{float}$	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	Supported Limit	Limit Type ¹
	Limit		
maxImageDimension1D	-	4096	min
maxImageDimension2D	-	4096	min
maxImageDimension3D	-	256	min
maxImageDimensionCube	=	4096	min
maxImageArrayLayers	-	256	min
maxTexelBufferElements	-	65536	min
maxUniformBufferRange	-	16384	min
maxStorageBufferRange	-	2^{27}	min
maxPushConstantsSize	-	128	min
maxMemoryAllocationCount	-	4096	min
maxSamplerAllocationCount	-	4000	min
bufferImageGranularity	-	131072	max
sparseAddressSpaceSize	0	2^{31}	min
maxBoundDescriptorSets	-	4	min
maxPerStageDescriptorSamplers	-	16	min
maxPerStageDescriptorUniformBuffers	-	12	min
maxPerStageDescriptorStorageBuffers	-	4	min
maxPerStageDescriptorSampledImages	-	16	min
maxPerStageDescriptorStorageImages	-	4	min

Table 30.2: (continued)

Limit	Unsupported Limit	Supported Limit	Limit Type ¹
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
max Tessellation Control Per Vertex Output Components	0	64	min
max Tessellation Control Per Patch Output Components	0	120	min
maxTessellationControlTotalOutputComponents	0	2048	min
maxTessellationEvaluationInputComponents	0	64	min
max Tessellation Evaluation Output Components	0	64	min
maxGeometryShaderInvocations	0	32	min
maxGeometryInputComponents	0	64	min
maxGeometryOutputComponents	0	64	min
maxGeometryOutputVertices	0	256	min
maxGeometryTotalOutputComponents	0	1024	min
maxFragmentInputComponents	-	64	min
maxFragmentOutputAttachments	-	4	min
maxFragmentDualSrcAttachments	0	1	min
maxFragmentCombinedOutputResources	-	4	min
maxComputeSharedMemorySize	-	16384	min
maxComputeWorkGroupCount	-	(65535,65535,65535)	min
maxComputeWorkGroupInvocations	-	128	min
maxComputeWorkGroupSize	-	(128,128,64)	min
subPixelPrecisionBits	-	4	min
subTexelPrecisionBits	-	4	min
mipmapPrecisionBits	-	4	min
maxDrawIndexedIndexValue	2 ²⁴ -1	2 ³² -1	min
maxDrawIndirectCount	1	2 ¹⁶ -1	min
maxSamplerLodBias	-	2	min
maxSamplerAnisotropy	1	16	min

Table 30.2: (continued)

Limit	Unsupported Limit	Supported Limit	Limit Type ¹
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_	min
-		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
framebufferDepthSampleCounts	-	(VK_SAMPLE_	min
•		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
framebufferStencilSampleCounts	-	(VK_SAMPLE_	min
•		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
framebufferNoAttachmentsSampleCounts	-	(VK_SAMPLE_	min
•		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
maxColorAttachments	-	4	min
sampledImageColorSampleCounts	-	(VK_SAMPLE_	min
		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
sampledImageIntegerSampleCounts	-	VK_SAMPLE_	min
		COUNT_1_BIT	
sampledImageDepthSampleCounts	-	(VK_SAMPLE_	min
		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	

Table 30.2: (continued)

Limit	Unsupported	Supported Limit	Limit Type ¹
	Limit		
sampledImageStencilSampleCounts	-	(VK_SAMPLE_	min
		COUNT_1_BIT	
		VK_SAMPLE_	
		COUNT_4_BIT)	
storageImageSampleCounts	VK_	(VK_SAMPLE_	min
	SAMPLE_	COUNT_1_BIT	
	COUNT_1_	VK_SAMPLE_	
	BIT	COUNT_4_BIT)	
maxSampleMaskWords	-	1	min
timestampComputeAndGraphics	-	-	implementation
			dependent
timestampPeriod	-	-	duration
maxClipDistances	0	8	min
maxCullDistances	0	8	min
max Combined Clip And Cull Distances	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	
·	0.0	1.0	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 bitfields 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

Maximum image attachment size or maximum display size

4

Double the maxViewportDimensions

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 <code>lineWidthGranularity</code>. If the <code>lineWidthGranularity</code> 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 available 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,
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   VK_FORMAT_ASTC_10x6_UNORM_BLOCK = 175,
   VK_FORMAT_ASTC_10x6_SRGB_BLOCK = 176,
   VK_FORMAT_ASTC_10x8_UNORM_BLOCK = 177,
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   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 2.6.4 and Section 2.6.3.

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 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data. This format has no alpha and is considered opaque.

VK FORMAT BC1 RGB SRGB BLOCK

A three-component, block compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image 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 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data, and provides 1 bit of alpha.

VK_FORMAT_BC1_RGBA_SRGB_BLOCK

A four-component, block compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data with sRGB nonlinear encoding, and provides 1 bit of alpha.

VK_FORMAT_BC2_UNORM_BLOCK

A four-component, block compressed format where each 4x4 block consists of 64-bits of unsigned normalized alpha image data followed by 64-bits of encoded unsigned normalized RGB image data.

VK FORMAT BC2 SRGB BLOCK

A four-component, block compressed format where each 4x4 block consists of 64-bits of unsigned normalized alpha image data followed by 64-bits of encoded unsigned normalized RGB image data with sRGB nonlinear encoding.

VK FORMAT BC3 UNORM BLOCK

A four-component, block compressed format where each 4x4 block consists of 64-bits of encoded alpha image data followed by 64-bits of encoded RGB image data. Both blocks are decoded as unsigned normalized values.

VK FORMAT BC3 SRGB BLOCK

A four-component, block compressed format where each 4x4 block consists of 64-bits of encoded alpha image data followed by 64-bits of encoded RGB image data with sRGB nonlinear encoding. Both blocks are decoded as unsigned normalized values.

VK_FORMAT_BC4_UNORM_BLOCK

A one-component, block compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized red image data.

VK_FORMAT_BC4_SNORM_BLOCK

A one-component, block compressed format where each 4x4 block consists of 64-bits of encoded signed normalized red image data.

VK_FORMAT_BC5_UNORM_BLOCK

A two-component, block compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized red image data followed by 64-bits of encoded unsigned normalized green image data.

VK_FORMAT_BC5_SNORM_BLOCK

A two-component, block compressed format where each 4x4 block consists of 64-bits of encoded signed normalized red image data followed by 64-bits of encoded signed normalized green image data.

VK FORMAT BC6H UFLOAT BLOCK

A three-component, block compressed format where each 4x4 block consists of 128-bits of encoded unsigned floating-point RGB image data.

VK FORMAT BC6H SFLOAT BLOCK

A three-component, block compressed format where each 4x4 block consists of 128-bits of encoded signed floating-point RGB image data.

VK_FORMAT_BC7_UNORM_BLOCK

A four-component, block compressed format where each 4x4 block consists of 128-bits of encoded unsigned normalized RGBA image data.

VK_FORMAT_BC7_SRGB_BLOCK

A four-component, block compressed format where each 4x4 block consists of 128-bits of encoded unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK

A three-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data.

VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK

A three-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data with sRGB nonlinear encoding.

VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK

A four-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data, and provides 1 bit of alpha.

VK FORMAT ETC2 R8G8B8A1 SRGB BLOCK

A four-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image 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 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data, and 64-bits of encoded unsigned normalized alpha image data.

VK FORMAT ETC2 R8G8B8A8 SRGB BLOCK

A four-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized RGB image data with sRGB nonlinear encoding, and 64-bits of encoded unsigned normalized alpha image data.

VK FORMAT EAC R11 UNORM BLOCK

A one-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized red image data.

VK_FORMAT_EAC_R11_SNORM_BLOCK

A one-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded signed normalized red image data.

VK FORMAT EAC R11G11 UNORM BLOCK

A two-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded unsigned normalized red image data followed by 64-bits of encoded unsigned normalized green image data.

VK_FORMAT_EAC_R11G11_SNORM_BLOCK

A two-component, ETC2 compressed format where each 4x4 block consists of 64-bits of encoded signed normalized red image data followed by 64-bits of encoded signed normalized green image data.

VK_FORMAT_ASTC_4x4_UNORM_BLOCK

A four-component, ASTC compressed format where each 4x4 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_4x4_SRGB_BLOCK

A four-component, ASTC compressed format where each 4x4 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK FORMAT ASTC 5x4 UNORM BLOCK

A four-component, ASTC compressed format where each 5x4 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

$\tt VK_FORMAT_ASTC_5x4_SRGB_BLOCK$

A four-component, ASTC compressed format where each 5x4 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_5x5_UNORM_BLOCK

A four-component, ASTC compressed format where each 5x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

${\tt VK_FORMAT_ASTC_5x5_SRGB_BLOCK}$

A four-component, ASTC compressed format where each 5x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK FORMAT ASTC 6x5 UNORM BLOCK

A four-component, ASTC compressed format where each 6x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_6x5_SRGB_BLOCK

A four-component, ASTC compressed format where each 6x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_6x6_UNORM_BLOCK

A four-component, ASTC compressed format where each 6x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK FORMAT ASTC 6x6 SRGB BLOCK

A four-component, ASTC compressed format where each 6x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_8x5_UNORM_BLOCK

A four-component, ASTC compressed format where each 8x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_8x5_SRGB_BLOCK

A four-component, ASTC compressed format where each 8x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK FORMAT ASTC 8x6 UNORM BLOCK

A four-component, ASTC compressed format where each 8x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK FORMAT ASTC 8x6 SRGB BLOCK

A four-component, ASTC compressed format where each 8x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_8x8_UNORM_BLOCK

A four-component, ASTC compressed format where each 8x8 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK FORMAT ASTC 8x8 SRGB BLOCK

A four-component, ASTC compressed format where each 8x8 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x5_UNORM_BLOCK

A four-component, ASTC compressed format where each 10x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_10x5_SRGB_BLOCK

A four-component, ASTC compressed format where each 10x5 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x6_UNORM_BLOCK

A four-component, ASTC compressed format where each 10x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_10x6_SRGB_BLOCK

A four-component, ASTC compressed format where each 10x6 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x8_UNORM_BLOCK

A four-component, ASTC compressed format where each 10x8 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK FORMAT ASTC 10x8 SRGB BLOCK

A four-component, ASTC compressed format where each 10x8 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_10x10_UNORM_BLOCK

A four-component, ASTC compressed format where each 10x10 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_10x10_SRGB_BLOCK

A four-component, ASTC compressed format where each 10x10 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_12x10_UNORM_BLOCK

A four-component, ASTC compressed format where each 12x10 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_12x10_SRGB_BLOCK

A four-component, ASTC compressed format where each 12x10 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data with sRGB nonlinear encoding applied to the RGB components.

VK_FORMAT_ASTC_12x12_UNORM_BLOCK

A four-component, ASTC compressed format where each 12x12 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image data.

VK_FORMAT_ASTC_12x12_SRGB_BLOCK

A four-component, ASTC compressed format where each 12x12 block consists of 128-bits of encoded image data which is decoded as unsigned normalized RGBA image 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:

```
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	Description
scheme	
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.

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	В							VK_FORMAT_R8G8B8_*																																			
В	G	R							VK_FORMAT_B8G8R8_*																																			
R	G	В	A													VK_FORMAT_R8G8B8A8_*																												
В	G	R	Α	VK_FORMAT_B8G8R8A8_*																																								
F	3	VK_FORMAT_R16_*																																										
F	₹	G		G		G								VK_FORMAT_R16G16_*																														
F	3	G		В		В			В			В						VK_FORMAT_R16G16B16_*																										
F	3	(Ĵ	F	3	P	4									VK_FORMAT_R16G16B16A16_*																												
	F	3						•								VK_FORMAT_R32_*																												
	F	3			(j										VK_FORMAT_R32G32_*																												
	F	R G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		G		I	В			VK_FORMAT_R32G32B32_*
	F	R G		G			G				G B A VK_FORMA						VK_FORMAT_R32G32B32A32_*																											
			I	3												VK_FORMAT_R64_*																												
	R G VK_FORMAT_R64G64_*																																											
		1	VK_	FOR	MAT	C_R	64G6	4B64	1_ * a	s VK	C_FC	RM	AT_l	R640	364 _	* but with B in bytes 16-23																												
	VK_FORMAT_R64G64B64A64_* as VK_FORMAT_R64G64B64_* but with A in bytes 24-31																																											

Table 30.5: Byte mappings for non-packed/compressed color formats

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

$\textbf{Bit} \rightarrow$	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 VK_FORMAT_* formats

$\textbf{Bit} \rightarrow$	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
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
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
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
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
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
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
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

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

 A7
 A6
 A5
 A4
 A3
 A2
 A1
 A0
 B7
 B6
 B5
 B4
 B3
 B2
 B1
 B0
 G7
 G6
 G5
 G4
 G3
 G2
 G1
 G0
 R7
 R6
 R5
 R4
 R3
 R2
 R1
 R0

 VK_FORMAT_A2R10G10B10_*_PACK32

 A1
 A0
 R9
 R8
 R7
 R6
 R5
 R4
 R3
 R2
 R1
 R0
 G9
 G8
 G7
 G6
 G5
 G4
 G3
 G2
 G1
 G0
 B9
 B8
 B7
 B6
 B5
 B4
 B3
 B2
 B1
 B0

 VK_FORMAT_A2B10G10R10_*_PACK32

 A1
 A0
 B9
 B8
 B7
 B6
 B5
 B4
 B3
 B2
 B1
 B0
 G9
 G8
 G7
 G6
 G5
 G4
 G3
 G2
 G1
 G0
 R9
 R8
 R7
 R6
 R5
 R4
 R3
 R2
 R1
 R0

 VK_FORMAT_B10G11R11_UFLOAT_PACK32

B₉ B₈ B₇ B₆ B₅ B₄ B₃ B₂ B₁ B₀ G₁₀G₉ G₈ G₇ G₆ G₅ G₄ G₃ G₂ G₁ G₀ R₁₀R₉ R₈ R₇ R₆ R₅ R₄ R₃ R₂ R₁ R₀ VK_FORMAT_E5B9G9R9_UFLOAT_PACK32

E₄ E₃ E₂ E₁ E₀ B₈ B₇ B₆ B₅ B₄ B₃ B₂ B₁ B₀ G₈ G₇ G₆ G₅ G₄ G₃ G₂ G₁ G₀ R₈ R₇ R₆ R₅ R₄ R₃ R₂ R₁ R₀ 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

Table 30.9: (continued)

Class	Formats
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_R10G10_UTNT, VK FORMAT R16G16 SINT,
	VK_FORMAT_R16G16_SFLOAT,
	VK_FORMAT_R10GT0_SFHOAT, VK FORMAT R32 UINT,
	VK_FORMAT_R32_SINT,
	VK_FORMAT_R32_SIN1, VK FORMAT R32 SFLOAT,
	VK_FORMAT_R32_SFLOAT, VK_FORMAT_B10G11R11_UFLOAT_PACK32,
	VK_FORMAT_E5B9G9R9_UFLOAT_PACK32
	VV_LOWNAT_EOD9G9V9_UFLOWT_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
ВС6Н	VK_FORMAT_BC6H_UFLOAT_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,
LTC2_KGB/Y	VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK
ETC2 EAC RGBA	VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK,
LTCZ_L/IC_RGB/Y	VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK
EAC_R	VK_FORMAT_EAC_R11_UNORM_BLOCK,
LAC_K	VK_FORMAT_EAC_R11_SNORM_BLOCK VK_FORMAT_EAC_R11_SNORM_BLOCK
EAC RG	VK_FORMAT_EAC_R11G11_UNORM_BLOCK,
LAC_KO	VK_FORMAT_EAC_R11G11_ONORM_BLOCK, VK_FORMAT_EAC_R11G11_SNORM_BLOCK
ASTC 4x4	
ASTC_4X4	VK_FORMAT_ASTC_4x4_UNORM_BLOCK,
ASTC 5x4	VK_FORMAT_ASTC_4x4_SRGB_BLOCK
ASTC_3X4	VK_FORMAT_ASTC_5x4_UNORM_BLOCK,
ASTC 5x5	VK_FORMAT_ASTC_5x4_SRGB_BLOCK
AS1C_5x5	VK_FORMAT_ASTC_5x5_UNORM_BLOCK,
ASTC 6x5	VK_FORMAT_ASTC_5x5_SRGB_BLOCK
ASIC_6x5	VK_FORMAT_ASTC_6x5_UNORM_BLOCK,
A CITICA (VK_FORMAT_ASTC_6x5_SRGB_BLOCK
ASTC_6x6	VK_FORMAT_ASTC_6x6_UNORM_BLOCK,
1 GT G 0 7	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:

- 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

- $\bullet \ \textit{physicalDevice} \ \textbf{must} \ \textbf{be} \ \textbf{a} \ \textbf{valid} \ \textbf{VkPhysicalDevice} \ \textbf{handle}$
- format must be a valid VkFormat value
- pFormatProperties must be a pointer to a VkFormatProperties structure

vkGetPhysicalDeviceFormatProperties returns VkFormatProperties:

The features are described as a set of VkFormatFeatureFlagBits:

```
typedef enum VkFormatFeatureFlagBits {
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT = 0x00000001,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT = 0x000000002,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT = 0x000000004,
    VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT = 0x000000008,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT = 0x00000010,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT = 0x00000020,
    VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT = 0x000000040,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT = 0x000000000,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT = 0x000000100,
    VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x000000200,
    VK_FORMAT_FEATURE_BLIT_SRC_BIT = 0x000000400,
    VK_FORMAT_FEATURE_BLIT_DST_BIT = 0x000000800,
    VK_FORMAT_FEATURE_BLIT_DST_BIT = 0x000000800,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT = 0x00001000,
} VKFORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT = 0x00001000,
```

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 features may be supported by images or image views created with 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

VkImage 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. This bit must only be exposed for formats that also support the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT.

If the format being queried is a depth/stencil format, this bit only indicates that the depth aspect (not the stencil aspect) 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 bufferFeatures member of the VkFormatProperties structure describes what features are supported by buffers.

The following features may be supported by buffers or buffer views created with 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).

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
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

VK_FORMAT_FEA	TURE	S	ΓOR.	AGE	_TE	XEI	BI	JFF	ER_	ATO	OMIC	C_B	ΙΤ
VK_FORMAT	_FEA	ATU	RE_	STC	RAC	GE_	ΓEX	EL_	BUE	FE	R_B	ΙΤ	
VK_FORMAT_F	EATU:	RE_	UNI	FOF	RM_	ГЕХ	EL_	BUE	FE	R_B	ΙT		
VK_FORM	AT_F	EAI	URI	E_V	ERT	EX_	BUF	'FEI	R_B	ΙT			
VK_FORMAT_FEATURE_DEP									ΙT				
VK_FORMAT_FEATURE_COLC								ΙT					
VK_FORMAT_F							ΙT						
VK_FORMAT_FEATURE_COL(IT				١.	1	↓	*
VK_FORMAT_FEATURE_STORAGE_IM					ΙT					↓	*		
VK_FORMAT_FEATURE_STORAG				ΙΤ		١.	1	↓	•				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI			ΙΤ		↓	↓	*						
VK_FORMAT_FEATURE_BLIT_SI		IT.	1	↓	'								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_	BIT	↓	,										
Format	+												
VK_FORMAT_UNDEFINED													
VK_FORMAT_R4G4_UNORM_PACK8													
VK_FORMAT_R4G4B4A4_UNORM_PACK16	—		,										
VK_FORMAT_B4G4R4A4_UNORM_PACK16	1	V	/										
VK_FORMAT_R5G6B5_UNORM_PACK16	/	/	✓			/	/	/					
VK_FORMAT_B5G6R5_UNORM_PACK16													
VK_FORMAT_R5G5B5A1_UNORM_PACK16													
VK_FORMAT_B5G5R5A1_UNORM_PACK16			1										
VK_FORMAT_A1R5G5B5_UNORM_PACK16	/	/	✓			✓	✓	✓					

Table 30.14: Mandatory format support: 1-3 byte-sized channels

VK_FORMAT_FEAT	rurf	: S:	ror	AGE	ТЕ	EXEI	L B	UFF	ER	ATO)MT(. B	ΙΤ
VK_FORMAT													_
VK_FORMAT_FE													
VK_FORMA								_					
VK_FORMAT_FEATURE_DEP1													
VK_FORMAT_FEATURE_COLO													
VK_FORMAT_F									1				١.
VK FORMAT FEATURE COLO				_							١,	↓	↓
VK_FORMAT_FEATURE_STORAGE_IMA	GE	ATC)MI	СВ	IT		1		١.		1	'	
VK_FORMAT_FEATURE_STORAGE						1			↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI	VEAI	R_B	ΙΤ		١.		\downarrow	'					
VK_FORMAT_FEATURE_BLIT_SR	СВ	ΙΤ		↓	↓	'							
VK_FORMAT_FEATURE_SAMPLED_IMAGE_B		Ţ	+	'									
Format	T	•											
VK FORMAT R8 UNORM	1	1	1			1	1	1		1	1		
VK FORMAT R8 SNORM	1		1							1			
VK_FORMAT_R8_USCALED													
VK FORMAT R8 SSCALED													
VK_FORMAT_R8_UINT	1	1				1	1			1	1		
VK FORMAT R8 SINT	1	1				1	1			1	1		
VK_FORMAT_R8_SRGB													
VK_FORMAT_R8G8_UNORM	1	1	1			1	1	1		1	1		
VK_FORMAT_R8G8_SNORM	1	1	1							1	1		
VK_FORMAT_R8G8_USCALED													
VK_FORMAT_R8G8_SSCALED													
VK_FORMAT_R8G8_UINT	1	1				1	1			1	1		
VK_FORMAT_R8G8_SINT	1	1				1	1			1	1		
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

VK FORMAT FEAT	URE	: S:	ΓOR	AGE	TE	EXEI	L B	UFF	ER	ATC)MI(С В	IT
VK_FORMAT	FEA	TU:	RE	STC)RA(GE '	EX	EL	BUE	FEF	R B	TT	
VK_FORMAT_FE.													
VK_FORMA	T_F	EAI	URE	V	ERT	EX_	BUE	FEI	R_B	ΙT			
VK_FORMAT_FEATURE_DEPT	H_S	TEI	ICI	L_A	TTA	CHN	IEN:	Г_В	ΙT				
VK_FORMAT_FEATURE_COLOR	R_A]	TA	СНМ	ENT	_BI	LENI	D_B	ΙT					
VK_FORMAT_F	EAT	JRE	_BL	IT_	DS'	Г_В	ΙT						
VK_FORMAT_FEATURE_COLO	R_A	TTA	CHM	IEN:	Г_В	ΙT						$ \downarrow $	+
VK_FORMAT_FEATURE_STORAGE_IMA	GE_	ATC)IMC	С_В	ΙΤ				١,	↓	+		
VK_FORMAT_FEATURE_STORAGE	_IM	1AGI	E_B	ΙT					↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI	IEAI	R_B	ΙT		1	↓	+						
VK_FORMAT_FEATURE_BLIT_SR	С_В	ΙT		↓	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_B	ΙT	\downarrow	+										
Format													
VK_FORMAT_R8G8B8A8_UNORM	1	1	1	1		1	√	1		1	√	1	
VK_FORMAT_R8G8B8A8_SNORM	1	1	1	1						1	1	1	
VK_FORMAT_R8G8B8A8_USCALED													
VK_FORMAT_R8G8B8A8_SSCALED													
VK_FORMAT_R8G8B8A8_UINT	1	1		1		1	✓			1	✓	1	
VK_FORMAT_R8G8B8A8_SINT	1	1		1		1	✓			1	✓	1	
VK_FORMAT_R8G8B8A8_SRGB	1	1	1			1	✓	1					
VK_FORMAT_B8G8R8A8_UNORM	1	1	1			1	✓	1		1	√		
VK_FORMAT_B8G8R8A8_SNORM													
VK_FORMAT_B8G8R8A8_USCALED													
VK_FORMAT_B8G8R8A8_SSCALED													
VK_FORMAT_B8G8R8A8_UINT													
VK_FORMAT_B8G8R8A8_SINT													
VK_FORMAT_B8G8R8A8_SRGB	1	✓	✓			✓	✓	✓					
VK_FORMAT_A8B8G8R8_UNORM_PACK32	√	✓	1			1	✓	√		1	✓	/	
VK_FORMAT_A8B8G8R8_SNORM_PACK32	1	✓	✓							1	✓	/	
VK_FORMAT_A8B8G8R8_USCALED_PACK32													
VK_FORMAT_A8B8G8R8_SSCALED_PACK32													
VK_FORMAT_A8B8G8R8_UINT_PACK32	1	1				1	✓			1	✓	1	
VK_FORMAT_A8B8G8R8_SINT_PACK32	1	1				1	✓			1	✓	1	
VK_FORMAT_A8B8G8R8_SRGB_PACK32	1	1	1			1	✓	1					

Table 30.16: Mandatory format support: 10-bit channels

VK_FORMAT_FEA	TURF	: S:	ror:	AGF.	ТЕ	XEI	. BI	TFF	ER	ΑΤС) T MC	T B	ТТ
VK_FORMAT													
VK_FORMAT_FE													
VK FORM													
VK_FORMAT_FEATURE_DEP:	<u> </u>	TEN	ICII	L A	TTA	.CHM	EN:	ΓВ	IT				
VK_FORMAT_FEATURE_COLO										1			
VK_FORMAT_F													١, ١
VK_FORMAT_FEATURE_COLO	R_A	TTA	CHM	IEN:	Г_В	ΙΤ							+
VK_FORMAT_FEATURE_STORAGE_IM	AGE_	ATO	MIC	С_В	ΙT				١,		+		
VK_FORMAT_FEATURE_STORAG	E_IN	1AGI	E_B	ΙΤ					↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI	NEAI	R_B	ΙT		١,	↓	+						
VK_FORMAT_FEATURE_BLIT_SR	.C_B	ΙT	1	\downarrow	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_E	BIT		↓										
Format	1												
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	ļ.,												\sqcup
VK_FORMAT_A2B10G10R10_UINT_PACK32	/	1				1	✓				1		\square
VK_FORMAT_A2B10G10R10_SINT_PACK32													

Table 30.17: Mandatory format support: 16-bit channels

VK_FORMAT_FEA	TURE	S	ror.	AGE	_TE	XEI	B	UFF	ER_	ATC	MIC	B	IT
VK_FORMAT	Γ_FE	ATU	RE_	STC	RAC	GE_	ГЕХ	EL_	BUE	FEI	R_B	ΙΤ	
VK_FORMAT_F	EATU:	RE_	UNI	FOF	RM_	ГЕХ	EL_	BUE	FEI	R_B	ΙT		
VK_FORM	AT_F	EAT	URE	C_VI	ERT	EX_	BUE	FE.	R_B	ΙT			
VK_FORMAT_FEATURE_DEP	TH_S	TEI	ICI:	L_A	TTA	СНМ	IEN:	Г_В	ΙT				
VK_FORMAT_FEATURE_COLO	DR_AT	TA	СНМ	ENT	_BI	ENI	D_B	ΙT					
VK_FORMAT_I	FEAT	JRE	_BL	IT_	DS:	Г_В	ΙΤ		1				١,
VK_FORMAT_FEATURE_COL	OR_A	TTA	CHN	IEN:	Г_В	ΙΤ						\downarrow	↓
VK_FORMAT_FEATURE_STORAGE_IM	AGE_	ATO)IMC	С_В	ΙΤ				١,		↓		
VK_FORMAT_FEATURE_STORAG	SE_IN	1AGI	E_B	ΙT					↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_L	INEAI	R_B	ΙT		١,		+	,					
VK_FORMAT_FEATURE_BLIT_S	RC_B	ΙT		↓	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_	BIT	1	\										
Format	\perp	'											
VK_FORMAT_R16_UNORM										1			
VK FORMAT R16 SNORM										1			
VK FORMAT R16 USCALED													
VK_FORMAT_R16_SSCALED													
VK_FORMAT_R16_UINT	1	1				1	1			1	1		
VK_FORMAT_R16_SINT	1	1				1	1			1	1		
VK_FORMAT_R16_SFLOAT	1	1	1			1	1	1		1	1		
VK_FORMAT_R16G16_UNORM										1			
VK_FORMAT_R16G16_SNORM										1			
VK_FORMAT_R16G16_USCALED													
VK_FORMAT_R16G16_SSCALED													
VK_FORMAT_R16G16_UINT	1	1				1	1			1	1		
VK_FORMAT_R16G16_SINT	1	1				1	√			1	1		
VK_FORMAT_R16G16_SFLOAT	1	1	1			1	√	1		1	1		
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										1			
VK_FORMAT_R16G16B16A16_SNORM										√			
VK_FORMAT_R16G16B16A16_USCALED													
VK_FORMAT_R16G16B16A16_SSCALED													
VK_FORMAT_R16G16B16A16_UINT	/			1		1	✓			✓	1	✓	
VK_FORMAT_R16G16B16A16_SINT	/	1		1		1	1			1	✓	✓	_
VK_FORMAT_R16G16B16A16_SFLOAT	√	✓	✓	✓		✓	✓	/		✓	✓	√	

Table 30.18: Mandatory format support: 32-bit channels

VK_FORMAT_FEA	THE	7. S	ΓΩR	AGE.	ТЕ	'XEI	. B1	नचा	ER	ΔΤΟ) T M	¬ R	ТТ
VK_FORMA													
VK_FORMAT_F:													
VK_FORM													
VK_FORMAT_FEATURE_DEP													
VK_FORMAT_FEATURE_COLO													
VK_FORMAT_I													١.
VK_FORMAT_FEATURE_COL	OR_A	TTA	CHN	IEN:	 Г_В	ΙΤ							+
VK_FORMAT_FEATURE_STORAGE_IM	AGE_	ATC)IMC	С_В	ΙΤ				١,	↓	↓		
VK_FORMAT_FEATURE_STORAG	E_IN	1AGI	E_B	ΙT				↓	↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_L	INEA	R_B	ΙT		١,		1						
VK_FORMAT_FEATURE_BLIT_S	RC_B	ΙT	1	↓	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_	BIT		+										
Format	1												
VK_FORMAT_R32_UINT	✓	1		/	✓	1	✓			1	\	1	1
VK_FORMAT_R32_SINT	✓	1		✓	✓	✓	✓			1	\	✓	✓
VK_FORMAT_R32_SFLOAT	✓	1		1		/	✓			1	>	√	
VK_FORMAT_R32G32_UINT	✓	1		1		1	1			✓	\	1	
VK_FORMAT_R32G32_SINT	✓	1		/		/	1			1	√	√	
VK_FORMAT_R32G32_SFLOAT	1	/		1		/	/			1	√	1	
VK_FORMAT_R32G32B32_UINT										1			
VK_FORMAT_R32G32B32_SINT										/			
VK_FORMAT_R32G32B32_SFLOAT										/			
			1	/	I	/	/	1	1	./		/	1
VK_FORMAT_R32G32B32A32_UINT	/	/				_	_			٧	v	٧.	
	1	1		1		1	1			1	✓	1	

Table 30.19: Mandatory format support: 64-bit/uneven channels and depth/stencil

VK_FORMAT_FEAT	ruri	S	ror.	AGE	TE	XEI	B	UFF	ER_	ATC)IMC	B	IT
VK_FORMAT	_FE	ATU:	RE_	STO	RAC	GE_	TEX	EL_	BUE	FEI	R_B	ΙΤ	
VK_FORMAT_FE	ATU	RE_	UNI	FOI	RM_	TEX	EL_	BUE	FEI	R_B	ΙΤ		
VK_FORMA	T_F	EAT	URE	V	ERT	EX_	BUE	FEI	R_B	ΙT			
VK_FORMAT_FEATURE_DEP1	'H_S	TEN	ICI:	L_A	TTA	CHN	IEN:	Г_В	ΙT				
VK_FORMAT_FEATURE_COLO	R_A	ГТА	СНМ	ENT	_BI	LENI	D_B	ΙT					
VK_FORMAT_F	EAT	URE.	_BL	IT_	DS:	Г_В	ΙT						١,
VK_FORMAT_FEATURE_COLC	R_A	TTA	CHN	IEN'	Г_В	ΙT						↓	+
VK_FORMAT_FEATURE_STORAGE_IMA	GE_	ATC)IMC	С_В	ΙT				١,		↓		
VK_FORMAT_FEATURE_STORAGE	E_IN	1AGI	E_B	ΙΤ		1		↓	↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI	VEA:	R_B	ΙT		1 ,		+						
VK_FORMAT_FEATURE_BLIT_SR	С_В	ΙT		1	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_E	IT	 	\										
Format	1												
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	1	1	1								1		
VK_FORMAT_E5B9G9R9_UFLOAT_PACK32	1	1	1										
VK_FORMAT_D16_UNORM	1	1							1				
VK_FORMAT_X8_D24_UNORM_PACK32									†				
VK_FORMAT_D32_SFLOAT	1	1							†				
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													
VK_FORMAT_X8_D24_UNORM_PACK32 and VK_FORMAT_	D32	_SF	'LO <i>P</i>	AT, a	ınd 1	nust	be s	supp	orte	d for	at 1	east	

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 $\mbox{VkImageType VK_IMAGE_TYPE_2D} \ \mbox{and VK_IMAGE_TYPE_3D}$

VK_FORMAT_FI	EATURE	E S	TOR.	AGE	TE	XEI	B	UFF	ER	ATO		 С В	IT
VK_FORM													
VK_FORMAT_	FEATU	RE_	UNI	FOF	RM_	TEX	EL_	BUE	FE	R_B	IT		1
VK_FOR	MAT_F	EAI	URI	V	ERT	EX_	BUE	FEI	R_B				
VK_FORMAT_FEATURE_DF	VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT												
VK_FORMAT_FEATURE_CO	LOR_A	ГТА	СНМ	ENT	'_BI	LENI	D_B	IT					
VK_FORMAT	_FEAT	URE	_BI	IT_	DS:	Г_В	ΙΤ		1				
VK_FORMAT_FEATURE_CO	LOR_A	TTA	CHN	IEN:	Г_В	ΙT							\
VK_FORMAT_FEATURE_STORAGE_I	MAGE_	ATO	OMI	С_В	ΙT				١,		+		
VK_FORMAT_FEATURE_STORA	AGE_IN	1AG1	E_B	ΙΤ		İ			↓				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_	LINEA	R_B	ΙT		1 ,		+						
VK_FORMAT_FEATURE_BLIT_	SRC_B	ΙT		1	↓								
VK_FORMAT_FEATURE_SAMPLED_IMAGE	_BIT	\downarrow	1										
Format	1	i .											
VK_FORMAT_BC1_RGB_UNORM_BLOCK	†	†	†										T
VK_FORMAT_BC1_RGB_SRGB_BLOCK	†	†	†										Г
VK_FORMAT_BC1_RGBA_UNORM_BLOCK	†	†	†										Г
VK_FORMAT_BC1_RGBA_SRGB_BLOCK	†	†	†										Г
VK_FORMAT_BC2_UNORM_BLOCK	†	†	†										Г
VK_FORMAT_BC2_SRGB_BLOCK	†	†	†										Г
VK_FORMAT_BC3_UNORM_BLOCK	†	†	†										Г
VK_FORMAT_BC3_SRGB_BLOCK	†	†	†										Г
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, VI										IT a	nd V	K_	
FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINE													
optimalTilingFeatures for all the formats in at least on	e of: th	is tal	ble, '	Tabl	e 30	.21,	or T	able	30.	22.			

Table 30.21: Mandatory format support: ETC2 and EAC compressed formats with ${\tt VkImageType\ VK_IMAGE_TYPE_2D}$

VK_FORMAT_FEAT	rure	S	ror.	AGE	_TE	CXEI	L_BI	UFF	ER_	ATO)IMC	С_В	IT
VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT													
VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT													
VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT													
VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT													
VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT													
VK_FORMAT_FEATURE_BLIT_DST_BIT								,					
VK_FORMAT_FEATURE_COLO	R_A	TTA	CHM	IEN:	Г_В	ΙT					↓	↓	*
VK_FORMAT_FEATURE_STORAGE_IMA					ΙT				l ,	↓	*		
VK_FORMAT_FEATURE_STORAGE				ΙT				↓	+				
VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LI			ΙT			↓	*						
VK_FORMAT_FEATURE_BLIT_SR		ΙT		\	*								
VK_FORMAT_FEATURE_SAMPLED_IMAGE_B	IT] ↓	+										
Format	↓												
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	†	†	†								<u> </u>		
The VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_I										T a	nd ∨	K_	
FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR													
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 for $mats \ with \ \verb"VkImageType VK_IMAGE_TYPE_2D"$

- -	AIUKE	<u> </u>	I'OR.	AGE	_TE	XEI	_B	UFF	ER_	ATC)IM	C_B	ΙT
VK_FORMA	T_FE	ATU	RE_	STO)RA(GE_	TEX	EL_	BUE	FEF	R_B	ΙT	
VK_FORMAT_F	'EATU	RE_	UNI	FOI	RM_	TEX	EL_	BUF	FEI	R_B	ΙT		
VK_FORM	/AT_F	EAT	URE	V	ERT	EX_	BUE	FEI	R_B	ΙT			
VK_FORMAT_FEATURE_DE	PTH_S	TEN	ICI	L_A	TTA	CHN	IEN:	Г_В	ΙΤ				
VK_FORMAT_FEATURE_COL	OR_A	ГТА	СНМ	ENT	_BI	LENI	D_B	ΙΤ					
VK FORMAT	FEAT	URE	BL	ΙT	DS	ΓВ	IT		1				١.
VK FORMAT FEATURE COI	JOR A	TTA	CHM	IEN'	<u>-</u> ГВ	 IT		1				↓	1
VK_FORMAT_FEATURE_STORAGE_IN									١.	↓	↓	'	
VK FORMAT FEATURE STORA									↓	*			
VK FORMAT FEATURE SAMPLED IMAGE FILTER L					1		+	· ·					
VK FORMAT FEATURE BLIT S			T -	↓ ↓	↓	*							
VK FORMAT FEATURE SAMPLED IMAGE		Ιī	\	*									
Format		+											
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The VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK				ATI	JRF.	BT.	L ТТ	SRC	BI	T at	nd V	L К	

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:

- 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 bitfield 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.

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
- ${\it flags}$ must be a valid combination of ${\it VkImageCreateFlagBits}$ 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 definition of the VkImageFormatProperties structure is:

- maxExtent are the maximum image dimensions. See the Allowed extent values based on imageType table 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 greater than or equal to the log2 of the maxImageDimension1D, maxImageDimension2D, or maxImageDimension3D (depending on type) members of VkPhysicalDeviceLimits.
- 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. When tiling is VK_IMAGE_TILING_LINEAR the sampleCounts will be set to VK_SAMPLE_COUNT_ 1_BIT. Otherwise the bits set here are a superset of the corresponding limits for the image type in the VkPhysicalDeviceLimits struct. For non-integer color images this is sampledImageColorSampleCounts, for integer format color images this is sampledImageIntegerSampleCounts, for depth/stencil images with a depth component this is sampledImageDepthSampleCounts, for depth/stencil with a stencil component images this is sampledImageStencilSampleCounts, and if usage has VK_IMAGE_USAGE_STORAGE_BIT set this is storageImageSampleCounts. For depth/stencil images with both a depth and stencil component, both the depth and stencil limits must be satisfied.
- maxResourceSize is the maximum total image size in bytes, inclusive of all 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 2³¹.



Note

There is no mechanism to query the size of an image before creating it, to compare that size against <code>maxResou</code> <code>rceSize</code>. If an application attempts to create an image that exceeds this limit, the creation will fail or the image will be invalid.

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.

Table 30.23: Allowed extent values based on imageType

VkImageType	maxExtent values
	width >= 1
VK_IMAGE_TYPE_1D	height = 1
	depth = 1
	width >= 1
	height >= 1
VK_IMAGE_TYPE_2D	depth = 1
	width >= 1
	height >= 1
VK_IMAGE_TYPE_3D	depth >= 1

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 and **flags1** and **flags2** of type VkImageCreateFlags are such that **usage1** contains a subset of the bits set in **usage2** and **flags1** contains 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*.

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 <code>stageFlags</code> 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.

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 collection of command buffers that are submitted to a queue, and corresponding semaphores to wait and signal. Corresponds to an instance of the VkSubmitInfo structure.

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 <code>vkBindBufferMemory</code> command for non-sparse buffer objects, using the <code>vkBindImageMemory</code> command for non-sparse image objects, and using the <code>vkQueueBindSparse</code> 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.

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-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.

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 vkCmdCreateInstance or vkCmdCreateDevice.

Event

A synchronization primitive that is signalled 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.

Flatshading

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 **Input** 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.

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 a 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 created 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.

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 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 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 flatshaded 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 Submission

An operation that is enqueued for execution on a queue typically as a result of the issue of commands of the form **vkQueue***.

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 access in a shader.

Sampler

An object that contains state that controls how sampled image data is sampled (or filtered) when accessed in a shader. Also a descriptor type describing the object. Represented by a VkSampler object.

Secondary Command Buffer

A command buffer that can be executed by a primary command buffer, and must not be submitted directly to a queue.

Self-Dependency

A subpass dependency from a subpass to itself, i.e. with *srcSubpass* equal to *dstSubpass*. A self-dependency is not automatically performed during a render pass instance, rather a subset of it can be performed via vkCmdPipelineBarrier during the subpass.

Semaphore

A synchronization primitive that supports signal and wait operations, and can be used to synchronize operations within a queue or across queues. Represented by a VkSemaphore object.

Shader

Instructions selected (via an entry point) from a shader module, which are executed in a shader stage.

Shader Code

A stream of instructions used to describe the operation of a shader.

Shader Module

A collection of shader code, potentially including several functions and entry points, that is used to create shaders in pipelines. Represented by a VkShaderModule object.

Shader Stage

A stage of the graphics or compute pipeline that executes shader code.

Side Effect

A store to memory or atomic operation on memory from a shader invocation.

Sparse 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

Src

G

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:

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

Green color component

В

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

 $The application \ must \ not \ pass \ a \ SPIR-V \ module \ containing \ any \ of \ the \ following \ to \ \verb|vkCreateShaderModule|:$

- 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.
- 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.

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,	Correct result.
OpFUnordGreaterThanEqual	
OpFDiv	2.5 ULP for b in the range [2 ⁻¹²⁶ , 2 ¹²⁶].
conversions between types	Correctly rounded.

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.

A.5 Compatibility Between SPIR-V Image Formats And Vulkan Formats

SPIR-V Image Format	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

SPIR-V Image Format	Vulkan Format
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 punchthrough alpha	
VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK	RGB ETC2 with punchthrough 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	Block size	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.



Note

The mechanism and process of specifying extensions is subject to change, as we receive feedback from authors and further requirements of documentation tooling. This appendix will be updated as this evolves.

C.1 Introduction

The Khronos extension registries and extension naming conventions serve several purposes:

- Avoiding naming collisions between extensions developed by mutually unaware parties, both in the extension names themselves, as well as their token, command, and type names.
- Allocating enumerant values for tokens added by extensions
- Creating a defined order between extensions. Extensions with higher numbers may have dependencies upon extensions with lower numbers, and must define any relevant interactions with lower-numbered extensions.
- · Provides a central repository for documentation and header changes associated with extensions

Vulkan's design and general software development trends introduces two new paradigms that require rethinking the existing mechanisms:

- Layers, and with them a focus on a more open ecosystem where non-Khronos members are expected to extend a Khronos API using the Layer mechanism.
- Namespaced constants (enumerations) that don't necessarily draw from a single global set of token values.

C.2 General Rules/Guidelines

Some general rules to simplify the specific rules below:

- Extensions and layers must each have a globally unique name.
- All commands and tokens must have a globally unique name.
- Extensions can expose new commands, types, and/or tokens, but layers must not.
 - However, layers can expose their own extensions, which in turn are allowed to expose new commands and tokens.
- All extensions must be registered with Khronos.
- Extensions must be strictly additive and backwards-compatible. That is, extensions must not remove existing functionality, or change existing default behaviors. A Vulkan implementation may support any combination of extensions, but applications written using only the core API, or a subset of the supported extensions, must continue to work in such an implementation without changes in behavior.

C.3 Extension and Layer Naming Conventions

- Extensions are named with the syntax: VK_AUTHOR_<name>.
- Layers are named with the syntax: VK_LAYER_{AUTHOR|FQDN}_<name>.

Both extensions and layer names include a VK_ prefix. In addition, layers add a LAYER_ prefix. Extension and layer names also contain an *author prefix* identifying the author of the extension/layer. This prefix is a short, capitalized, registered string identifying an author, such as a Khronos member developing Vulkan implementations for their devices, or a non-Khronos developer creating Vulkan layers.

Some authors have platform communities they wish to distinguish between, and can register additional author prefixes for that purpose. For example, Google has separate Android and Chrome communities.

Details on how to register an author prefix are provided below. Layer authors not wishing to register an author prefix with Khronos can instead use a fully-qualified domain name (FQDN) as the prefix. The FQDN should be a domain name owned by the author. FQDNs cannot be used for extensions, only for layers.

- The following are examples of extension and layer names, demonstrating the above syntax:
 - Extension names all use the base prefix VK .
 - Khronos-ratified extensions add the special author prefix KHR, and will use the prefix VK_KHR_.
 - The following author prefixes are reserved and must not be used:
 - * VK To avoid confusion with the top-level VK_ prefix.
 - * VULKAN To avoid confusion with the name of the Vulkan API.
 - * LAYER To avoid confusion with the higher-level "LAYER" prefix.
 - * KHRONOS To avoid confusion with the Khronos organization.
 - Multi-author extensions that have not been ratified by Khronos (those developed via cooperation between, and
 intended to be supported by two or more registered authors) add the special author prefix EXT to the base prefix, and
 will use the prefix VK_EXT_.

- Traditional author-specific extensions developed by one author (or one author in cooperation with non-authors) add the author prefix to the base prefix. For example, NVIDIA will use the prefix VK_NV_, and Valve will use the prefix VK_VALVE_. Some authors can have additional registered author prefixes for special purposes. For example, an Android extension developed by Google but part of an Android open-source community project, and so not a proprietary Google extension will use the prefix VK_ANDROID_.
- Layer names follow the same conventions as extensions, but use the base prefix VK_LAYER_.
- Because layers need not be registered with Khronos, an alternative prefix mechanism is needed to allow creating unique layer names without registering an author prefix. Layer authors that prefer not to register an author prefix can instead use a fully-qualified domain name (FQDN) in reverse-order as an author prefix, replacing . (period) with _ (underscore) characters. For example, a layer written by the owner of www.3dxcl.invalid would use the prefix VK_ LAYER_invalid_3dxcl_www_. FQDNs must be encoded in UTF-8, and should be in lower case, if possible for the domain FQDN in question.



Note

To avoid linking to a nonexistent domain, the reserved TLD .invalid is used.

"Lower case" is not a straightforward concept for all possible encodings of domain names. We suggest using RFC 5895 to interpret this phrase. The recommendation is that the representation of a FQDN in a layer name should be the same way one would naturally type that name into a web browser.

C.4 Extension Command, Type, and Token Naming Conventions

Extensions may add new commands, types, and tokens, or collectively "objects", to the Vulkan API. These objects are given globally unique names by appending the author prefix defined above for the extension name according to the following templates.

A command or type name simply appends the author prefix. For example, a Khronos-blessed extension could expose the following command:

```
void vkDoSomethingKHR(void);
```

A Google extension could expose the following command:

```
void vkDoSomethingGOOGLE(void);
```

And a multi-author extension could expose the following type:

```
typedef struct VkSomeDataEXT;
```

Enumeration or constant token names are constructed by following the token name with _ and the author prefix, so a non-Khronos extension could expose this enumeration:

```
enum VkSomeValuesGRPHX {
    VK_SOME_VALUE_0_GRPHX = 0,
    VK_SOME_VALUE_1_GRPHX = 1,
    VK_SOME_VALUE_2_GRPHX = 2,
};
```

C.5 The Vulkan Registry

The canonical definition of the Vulkan APIs is kept in an XML file known as the **Vulkan registry**. The registry is kept in src/spec/vk.xml in the branch of the vulkan project containing the most recently released core API specification. The registry contains reserved author prefixes, core and extension interface definitions, definitions of individual commands and structures, and other information which must be agreed on by all implementations. The registry is used to maintain a single, consistent global namespace for the registered entities, to generate the Khronos-supplied vulkan.h, and to create a variety of related documentation used in generating the API specification and reference pages.

C.6 Registering an Author Prefix with Khronos

Previous Khronos APIs could only officially be modified by Khronos members. In an effort to build a more flexible platform, Vulkan allows non-Khronos developers to extend and modify the API via layers and extensions in the same manner as Khronos members. However, extensions must still be registered with Khronos. A mechanism for non-members to register layers and extensions is provided.

Extension authors will be able to create an account on the Khronos github project and, using this account, register an author prefix with Khronos. This string must be used as the author prefix in any extensions the author registers. The same account will be used to request registration of extensions or layers with Khronos, as described below.

To reserve an author prefix, propose a merge request against vk.xml. The merge must add a <tag> XML tag and fill in the name, author and contact attributes with the requested author prefix, the author's formal name (e.g. company or project name), and contact email address, respectively. The author prefix will be reserved only once this merge request is accepted.

Please do not try to reserve author names which clearly belong to another existing company or software project which may wish to develop Vulkan extensions or layers in the future, as a matter of courtesy and respect. Khronos may decline to register author names that are not requested in good faith.

C.7 Registering a Vendor ID with Khronos

Vulkan implementers must report a valid vendor ID for their implementation, as reported by physical device queries. If there is no valid PCI vendor ID defined for the physical device, implementations must obtain a Khronos vendor ID.

Khronos vendor IDs are reserved in a similar fashion to author prefixes. While vendor IDs are not directly related to API extensions, the reservation process is very similar and so is described in this section.

To reserve an Khronos vendor ID, you must first have a Khronos author prefix. Propose a merge request against vk.xml. The merge must add a vendorid tag and fill in the name and id attributes. The name attribute must be set to the author prefix. The id attribute must be the first sequentially available ID in the list of vendorid tags. The vendor ID will be reserved only once this merge request has been accepted.

Please do not try to reserve vendor IDs unless you are making a good faith effort to develop a Vulkan implementation and require one for that purpose.

C.8 Registering Extensions and Layers

Extensions must be registered with Khronos. Layers may be registered, and registration is strongly recommended. Registration means:

- · Receiving an extension number.
- Adding the extension or layer name to the list in vk.xml and appearing on the Khronos registry website, which will link to associated documentation hosted on Khronos.
- For extensions which add to the Vulkan API, including definitions of those additions to vk.xml.

Registration for Khronos members is handled by filing a merge request in the internal gitlab repository against the branch containing the core specification against which the extension or layer will be written. The merge must modify vk.xml to define extension names, API interfaces, and related information. Registration is not complete until the registry maintainer has validated and accepted the merge.

Since this process could in principle be completely automated, this suggests a scalable mechanism for accepting registration of non-Khronos extensions. Non-Khronos members who want to create extensions must register with Khronos by creating a github account, and registering their author prefix and/or FQDNs to that account. They can then submit new extension registration requests by proposing merges to vk.xml. On acceptance of the merge, the extension will be registered, though its specification need not be checked into the Khronos github repository at that point.

The registration process can be split into several steps to accommodate extension number assignment prior to extension publication:

- Acquire an extension number. This is done by proposing a merge request against vk.xml similarly to how author prefixes are reserved. The merge should add a new <extension> tag at the end of the file with attributes specifying the proposed extension name, the next unused sequential extension number, the author and contact information (if different than that already specified for the author prefix used in the extension name), and finally, specifying supported="disabled". The extension number will be reserved only once this merge request is accepted into the master branch.
- Develop and test the extension using the registered extension number.
- Publish the extension to Khronos using the previously registered extension number, by creating a branch of the repository with appropriate changes relative to the core Vulkan API branch.
- Mark the extension as enabled, by proposing a merge to master changing the supported attribute value of the <extension> to supported="vulkan". This should be completely automated and under the control of the publishers, to allow them to align publication on Khronos with product releases. However, complete automation might be difficult, since steps such as regenerating and validating vulkan.h are involved. Once the merge is accepted and the corresponding updated header with the new extension interface is committed to the master branch, publication is complete.

The automated process does not exist yet, and would require significant investment in infrastructure to support the process on the Khronos servers.

C.9 Documenting Extensions

Extensions are documented as modifications to the Vulkan specification. These modifications will be on Git branches that are named with the following syntax: <major.minor core spec version>-<extension_name>

For example, the VK_KHR_surface extension will be documented relative to version 1.0 of the Vulkan specification. As such, the branch name will be: $1.0-VK_KHR_surface$

If the extension modifies an existing section of the Vulkan specification, those modifications are made in-place. Since the changes are on a branch, the core-only specification can be easily produced. A specification with an extension is created by merging in the extension's branch contents.

Extensions should be merged according to their registered extension number. If two extensions both modify the same portion of the specification, the higher-numbered extension should take care to deal with any conflicts.

The WSI extensions were used to help pioneer what should be done for extensions. This includes the following:

- All extensions should add to the appendix of the Vulkan specification. This should be modeled after what was done for the VK_KHR_surface extension, which contains some high-level information about the extension (as well as code examples, and revision history) in the appendices/vk_khr_surface.txt file.
- Each extension's appendix file is included by adding an include statement to the vkspec.txt file. Since most extensions will all put their include line at the same place in this file, they should add this statement on the master branch, even though the file won't actually exist on the master branch. This will avoid merge conflicts when multiple extensions' branches are merged in order to create the "full" branch specification.
- If there are any other places where 2 or more extensions will extend the Vulkan specification, it is best to put that content in a file, and use an include statement to put that content into the spec. Again, this include line should be put on the master branch in order to avoid merge conflicts.
- If an extension is more of an addition to the Vulkan specification, the extension should add a chapter to the Vulkan specification.

C.10 Assigning Extension Token Values

Extensions can define their own enumeration types and assign any values to their enumerants that they like. Each enumeration has a private namespace, so collisions are not a problem. However, when extending existing enumeration objects with new values, care must be taken to preserve global uniqueness of values. Enumerations which define new bitfields are treated specially as described in Reserving Bitfield Values below.

Each extension is assigned a range of values that can be used to create globally-unique enum values. Most values will be negative numbers, but positive numbers are also reserved. The ability to create both positive and negative extension values is necessary to enable extending enumerations such as VkResult that assign special meaning to negative and positive values. Therefore, 1000 positive and 1000 negative values are reserved for each extension. Extensions must not define enum values outside their reserved range without explicit permission from the owner of those values (e.g. from the author of another extension whose range is infringed on, or from the Khronos Registrar if the values do not belong to any extension's range).



Note

Typically, extensions use a unique offset for each enumeration constant they add, yielding 1000 distinct token values per extension. Since each enumeration object has its own namespace, if an extension needs to add many enumeration constant values, it can reuse offsets on a per-type basis.

The information needed to add new values to the XML are as follows:

- The extension name (e.g. VK_KHR_swapchain) that is adding the new enumeration constant.
- The existing enumeration **type** being extended (e.g. VkStructureType).
- The name of the new enumeration token being added (e.g. VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR).
- The **offset**, which is an integer between 0 and 999 relative to the base being used for the extension.

• The **direction** may be specified to indicate a negative value (dir="-") when needed for negative VkResult values indicating errors, like VK_ERROR_SURFACE_LOST_KHR. The default direction is positive, if not specified.

Implicit is the registered number of an extension, which is used to create a block of unused values offset against a global extension base value. Individual enumerant values are calculated as offsets in that block. Values are calculated as follows:

- base_value = 1000000000
- block size = 1000
- enum_offset(extension_number,offset) = base_value
 (extension_number 1) × block_size + offset
- Positive values: enum_offset(extension_number,offset)
- Negative values: -enum_offset(extension_number,offset)

The exact syntax for specifying extension enumerant values is defined in the readme.pdf specifying the format of vk.xml, and extension authors can also refer to existing extensions for examples.

C.11 Required Extension Tokens

In addition to any tokens specific to the functionality of an extension, all extensions must define two additional tokens.

- VK_EXTNAME_SPEC_VERSION is an integer constant which is the revision of the extension named VK_extname (EXTNAME is all upper-case, while extname is the capitalization of the actual extension name) in vulkan.h. This value begins at 1 with the initial version of an extension specification, and is incremented when significant changes (bugfixes or added functionality) are made. Note that the revision of an extension defined in vulkan.h and the revision supported by the Vulkan implementation (the <code>specVersion</code> field of the VkExtensionProperties structure corresponding to the extension and returned by one of the Extension Queries) may differ. In such cases, only the functionality and behavior of the lowest-numbered revision can be used.
- VK_EXTNAME_EXTENSION_NAME is a string constant which is the name of the extension.

For example, for the WSI extension VK KHR surface, at the time of writing the following definitions were in effect:

```
#define VK_KHR_SURFACE_SPEC_VERSION 24
#define VK_KHR_SURFACE_EXTENSION_NAME "VK_KHR_surface"
```

C.12 Extension Objects, Enums, and Typedefs

Expanding on previous discussion, extensions can add values to existing enums; and can add their own commands, enums, typedefs, etc. This is done by adding to vk.xml. All such additions will be included in the vulkan.h header supplied by Khronos.



Note

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

C.13 Extension Function Prototypes

Function pointer declarations and function prototypes for all core Vulkan API commands are included in the vulkan.h file. These come from the official XML specification of the Vulkan API hosted by Khronos.

Function pointer declarations are also included in the <code>vulkan.h</code> file for all commands defined by registered extensions. Function prototypes for extensions may be included in <code>vulkan.h</code>. Extension commands that are part of the Vulkan ABI must be flagged in the XML. Function prototypes will be included in <code>vulkan.h</code> for all extension commands that are part of the Vulkan ABI.

An extension can be considered platform specific, in which case its interfaces in vulkan.h are protected by #ifdefs. This is orthogonal to whether an extension command is considered to be part of the Vulkan ABI.

The initial set of WSI extension commands are considered to be part of the Vulkan ABI. Function prototypes for these WSI commands are included in the vulkan.h provided by Khronos, though the platform-specific portions of vulkan.h are protected by #ifdefs.



Note

Based on feedback from implementers, Khronos expects that the Android, Linux, and Windows Vulkan SDKs will include our vulkan.h and export the supported WSI functions for those platforms from their loader libraries. Other implementations can make different choices for their headers and loader libraries, but are encouraged to be consistent with these implementations.

C.14 Accessing Extension Functions from Programs

vkGetInstanceProcAddr and vkGetDeviceProcAddr can be used in order to obtain function pointer addresses for core and extension commands (per the description in Command Function Pointers). Different Vulkan API loaders can choose to statically export functions for some or all of the core Vulkan API commands, and can statically export functions for some or all extension commands. If a loader statically exports a function, an application can link against that function without needing to call one of the **vkGet*ProcAddr** commands.



Note

The Khronos-provided Vulkan API loader for Android, Linux, and Windows exports functions for all core Vulkan API and WSI extension commands. The WSI functions are considered special, because they are required for many applications.

C.14.1 Reserving Bitfield Values

Enumerants which define bitfield values are a special case, since there are only a small number of unused bits available for extensions. For core Vulkan API and KHR extension bitfield types, reservations must be approved by a vote of the Vulkan Working Group. For EXT and vendor extension bitfield types, reservations must be approved by the listed contact of the extension. Bits are not reserved, and must not be used in a published implementation or specification until the reservation is merged into vk.xml by the registry maintainer.



Note

In reality the approving authority for EXT and vendor extension bitfield additions will probably be the owner of the github branch containing the specification of that extension; however, until the github process is fully defined and locked down, it's safest to refer to the listed contact.

C.15 Extension Interactions

Extensions modifying the behavior of existing commands should provide additional parameters by using the *pNext* field of an existing structure, pointing to a new structure defined by the extension, as described in the Valid Usage section. Extension structures defined by multiple extensions affecting the same structure can be chained together in this fashion.

It is in principle possible for extensions to provide additional parameters through alternate means, such as passing a handle parameter to a structure with a sType defined by the extension, but this approach is discouraged and should not be used.

When chaining multiple extensions to a structure, the implementation will process the chain starting with the base parameter and proceeding through each successive chained structure in turn. Extensions should be defined to accept any order of chaining, and must define their interactions with other extensions such that the results are deterministic. If an extension needs a specific ordering of its extension structure with respect to other extensions in a chain to provide deterministic results, it must define the required ordering and expected behavior as part of its specification.

C.16 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

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VK_KHR_sampler_mirror_clamp_to_edge extends the set of sampler address modes to include an additional mode (VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE) that effectively uses a texture map twice as large as the original image in which the additional half of the new image is a mirror image of the original image.

This new mode relaxes the need to generate images whose opposite edges match by using the original image to generate a matching "mirror image". This mode allows the texture to be mirrored only once in the negative s, t, and r directions.

C.16.1 New Enum Constants

- Extending VkSamplerAddressMode:
 - VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE

C.16.2 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,
    &createInfo,
    &sampler);
```

C.16.3 Version History

- Revision 1, 2016-02-16 (Tobias Hector)
 - Initial draft

Appendix D

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.

D.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 doesn't 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 doublebuffered 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.

D.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.

D.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 bitplanes)
- 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.

D.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 v = 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 **TessellationCoord** will be in the range [0, 1]. Additionally, for any defined component x of **TessellationCoord**, 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 E

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.
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- Cemil Azizoglu, Canonical
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- 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
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- 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
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- · Mark Callow
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- Piers Daniell, NVIDIA (dynamic state, copy commands, memory types)
- Piotr Bialecki, Intel
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- Timothy Lottes, AMD
- Tobias Hector, Imagination Technologies (validity language and toolchain)
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