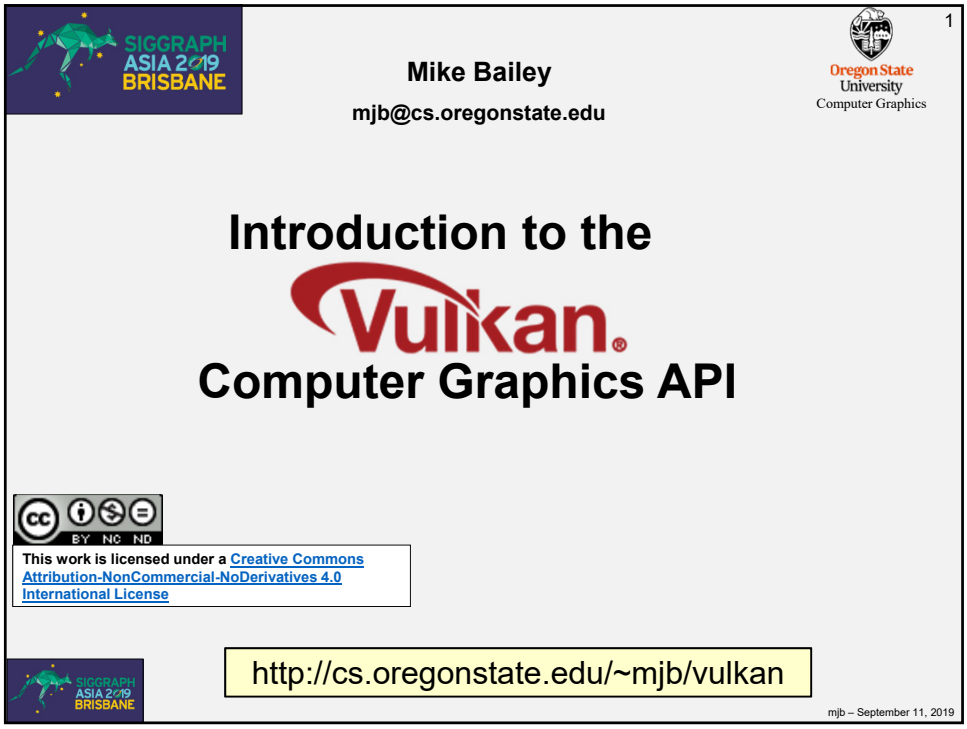


SA '19 Courses, November 17-20, 2019, Brisbane, QLD, Australia
ACM 978-1-4503-6941-1/19/11.
10.1145/3355047.3359405

Top Three Reasons that Prompted the Development of Vulkan

3

1. Performance
2. Performance
3. Performance

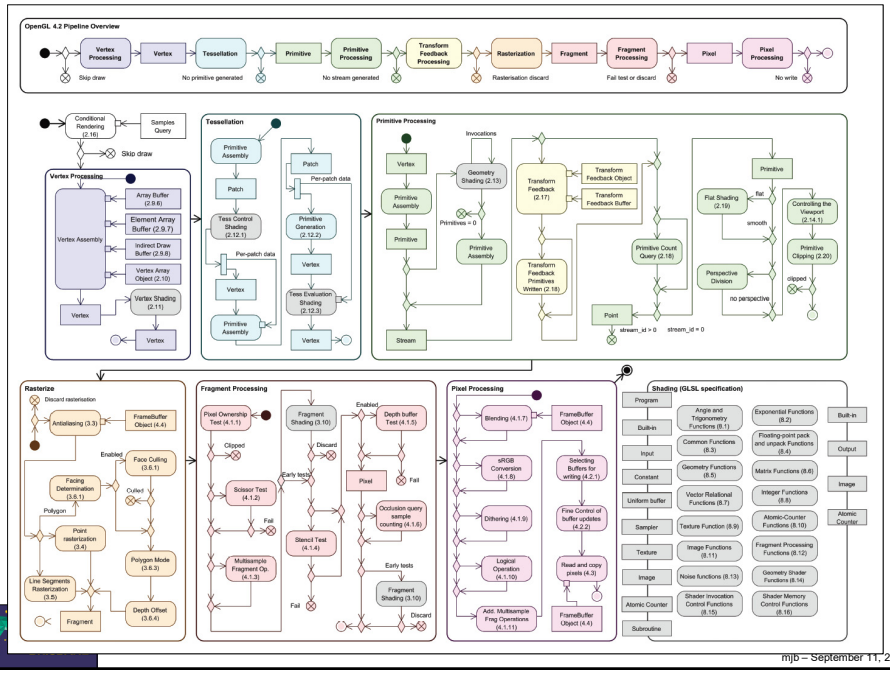
Vulkan is better at keeping the GPU busy than OpenGL is. OpenGL drivers need to do a lot of CPU work before handing work off to the GPU. Vulkan lets you get more power from the GPU card you already have.

This is especially important if you can hide the complexity of Vulkan from your customer base and just let them see the improved performance. Thus, Vulkan has had a lot of support and interest from game engine developers, 3rd party software vendors, etc.

As an aside, the Vulkan development effort was originally called “glNext”, which created the false impression that this was a replacement for OpenGL. It’s not.

OpenGL 4.2 Pipeline Flowchart

4



Who is the Khronos Group?

The Khronos Group, Inc. is a non-profit member-funded industry consortium, focused on the creation of open standard, royalty-free application programming interfaces (APIs) for authoring and accelerated playback of dynamic media on a wide variety of platforms and devices. Khronos members may contribute to the development of Khronos API specifications, vote at various stages before public deployment, and accelerate delivery of their platforms and applications through early access to specification drafts and conformance tests.

COLLADA DataFormat EGL glTF NNEF

OpenCL OpenGL ES OpenGL OpenGL SC OpenVG

OpenXR OpenVX SPIR SYCL Vulkan

WebGL

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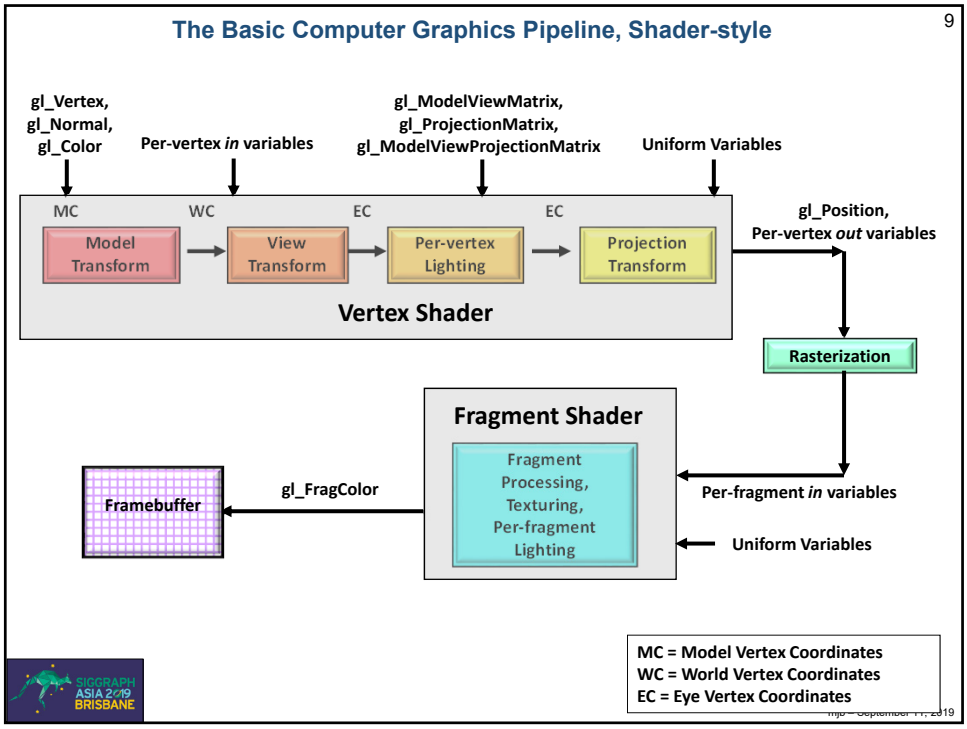
Who's Been Specifically Working on Vulkan?

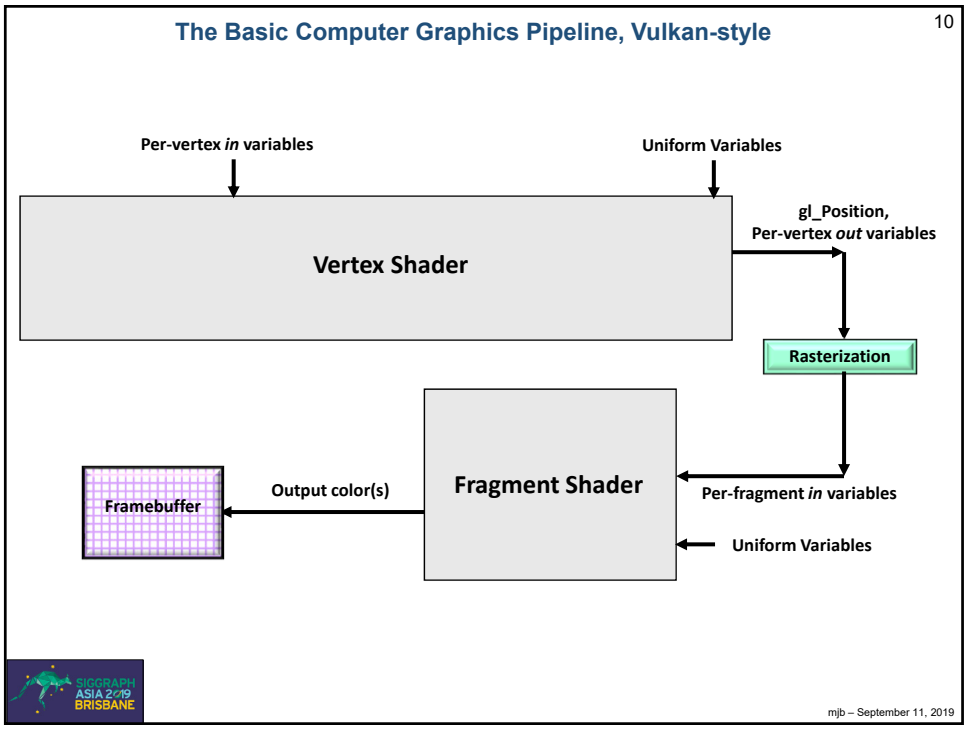
7

Vulkan Differences from OpenGL

8

- More low-level information must be provided (by you!) in the application, rather than the driver
- Screen coordinate system is Y-down
- No "current state", at least not one maintained by the driver
- All of the things that we have talked about being ***deprecated*** in OpenGL are *really* **deprecated** in Vulkan: built-in pipeline transformations, begin-end, fixed-function, etc.
- You must manage your own transformations.
- All transformation, color, texture functionality must be done in shaders.
- Shaders are pre-"half-compiled" outside of your application. The compilation process is then finished during the pipeline-building process.


The Basic Computer Graphics Pipeline, Shader-style
9
gl_Vertex,
gl_Normal,
gl_Color
Per-vertex in variables
gl_ModelViewMatrix,
gl_ProjectionMatrix,
gl_ModelViewProjectionMatrix
Uniform Variables
MC
WC
EC
EC
Model Transform
View Transform
Per-vertex Lighting
Projection Transform
Vertex Shader
gl_Position,
Per-vertex out variables
Rasterization
Fragment Shader
Fragment Processing, Texturing, Per-fragment Lighting
Framebuffer
gl_FragColor
Per-fragment in variables
Uniform Variables
MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates
SIGGRAPH ASIA 2019 BRISBANE


The Basic Computer Graphics Pipeline, Vulkan-style
10
Per-vertex in variables
Uniform Variables
Vertex Shader
gl_Position,
Per-vertex out variables
Rasterization
Fragment Shader
Framebuffer
Output color(s)
Per-fragment in variables
Uniform Variables
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mjb – September 11, 2019

Vulkan Shaders

11

- GLSL is the same as before … almost
- For places it's not, an implied
  #define VULKAN 100
  is automatically supplied by the compiler
- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V (Standard Portable Intermediate Representation for Vulkan)
- SPIR-V gets turned into fully-compiled code at runtime
- The SPIR-V spec has been public for months –new shader languages are surely being developed
- OpenCL and OpenGL have adopted SPIR-V as well

Moving part of the driver into the application

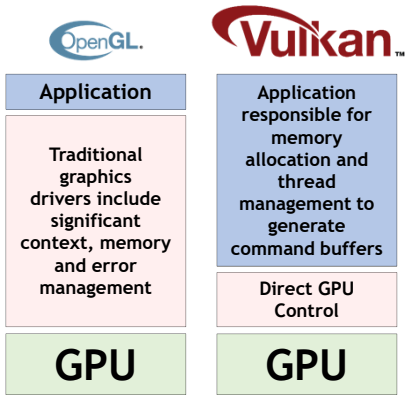
12

Complex drivers lead to driver overhead and cross vendor unpredictability

Error management is always active

Driver processes full shading language source

Separate APIs for desktop and mobile markets



Khronos Group

Simpler drivers for low-overhead efficiency and cross vendor portability

Layered architecture so validation and debug layers can be unloaded when not needed

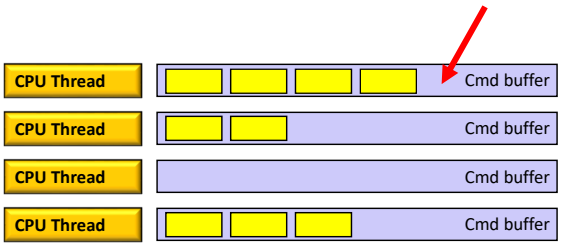
Run-time only has to ingest SPIR-V intermediate language

Unified API for mobile, desktop, console and embedded platforms

Vulkan Highlights: Command Buffers

13

- Graphics commands are sent to command buffers
- Think OpenCL…
- E.g., *vkCmdDoSomething(cmdBuffer, …);*
- You can have as many simultaneous Command Buffers as you want
- Buffers are flushed to Queues when the application wants them to be flushed
- Each command buffer can be filled from a different thread



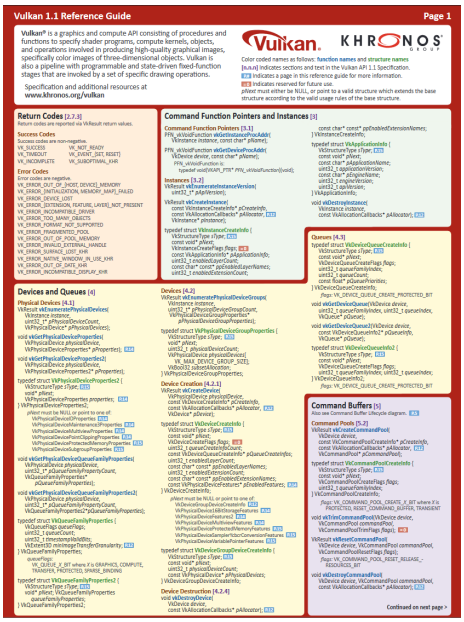
Vulkan Highlights: Pipelines

14

- In OpenGL, your “pipeline state” is whatever your current graphics attributes are: color, transformations, textures, shaders, etc.
- Changing the state on-the-fly one item at-a-time is very expensive
- Vulkan forces you to set all your state variables at once into a “pipeline state object” (PSO) and then invoke the entire PSO whenever you want to use that state combination
- Think of the pipeline state as being immutable.
- Potentially, you could have thousands of these pre-prepared state objects

Vulkan Quick Reference Card – I Recommend you Get This!

15


Vulkan 1.1 Reference Guide Page 1

Vulkan® is a graphics and compute API consisting of procedures and functions to specify shader programs, compute kernels, objects, and operations involved in producing high-quality graphical images, specifically color images of three-dimensional objects. Vulkan is also a pipeline with programmable and state-driven fixed-function stages that are invoked by a set of specific drawing operations.

Specification and additional resources at www.khronos.org/vulkan

Return Codes [2.7.3]

Command Function Pointers and Instances [3]

Devices and Queues [4]

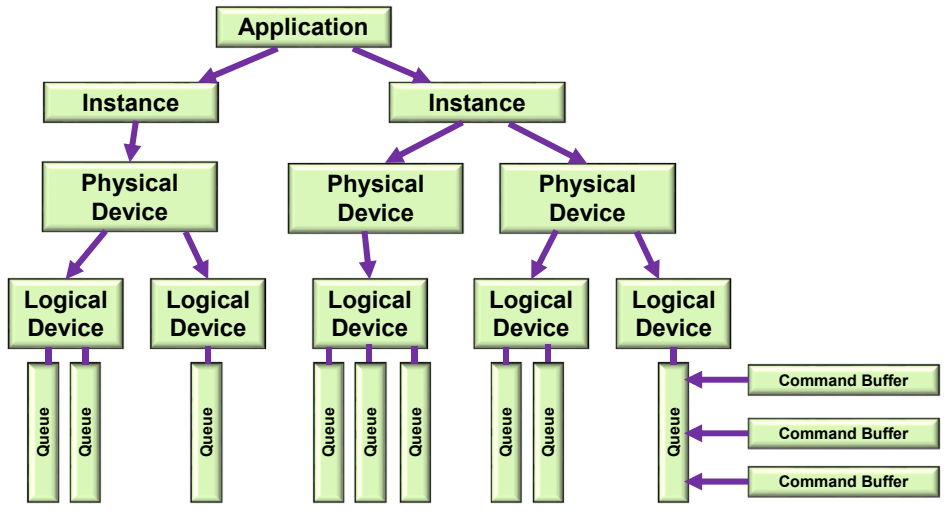
Queues [4.3]

Command Buffers [6]

https://www.khronos.org/files/vulkan11-reference-guide.pdf

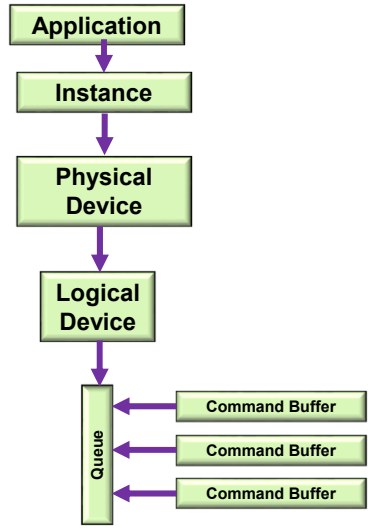
Vulkan Highlights: Overall Block Diagram

16



Vulkan Highlights: a More Typical Block Diagram

17



Steps in Creating Graphics using Vulkan

18

1. Create the Vulkan Instance
2. Setup the Debug Callbacks
3. Create the Surface
4. List the Physical Devices
5. Pick the right Physical Device
6. Create the Logical Device
7. Create the Uniform Variable Buffers
8. Create the Vertex Data Buffers
9. Create the texture sampler
10. Create the texture images
11. Create the Swap Chain
12. Create the Depth and Stencil Images
13. Create the RenderPass
14. Create the Framebuffer(s)
15. Create the Descriptor Set Pool
16. Create the Command Buffer Pool
17. Create the Command Buffer(s)
18. Read the shaders
19. Create the Descriptor Set Layouts
20. Create and populate the Descriptor Sets
21. Create the Graphics Pipeline(s)
22. Update-Render-Update-Render- …

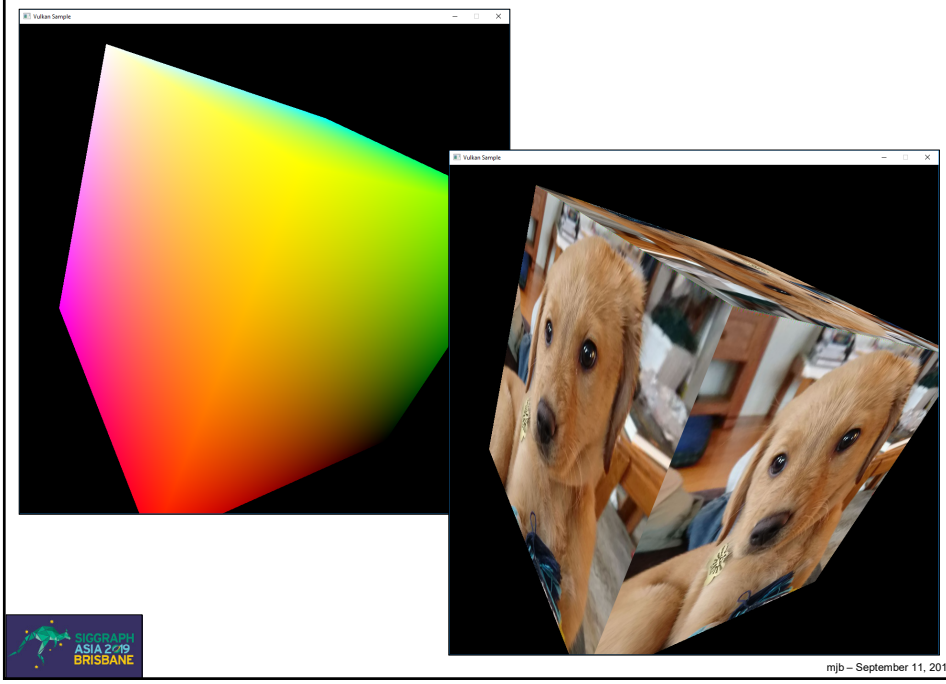
The Vulkan Sample Code Included with These Notes

Mike Bailey

mjb@cs.oregonstate.edu

http://cs.oregonstate.edu/~mjb/vulkan

Sample Program Output



Sample Program Keyboard Inputs

'i', 'I':	Toggle using a vertex buffer only vs. an **i**ndex buffer
'l', 'L':	Toggle **l**ighting off and on
'm', 'M':	Toggle display **m**ode (textures vs. colors, for now)
'p', 'P':	**P**ause the animation
'q', 'Q':	**q**uit the program
Esc:	quit the program
'r', 'R':	**T**oggle rotation-animation and using the mouse

Caveats on the Sample Code, I

1. I've written everything out in appalling longhand.
2. Everything is in one .cpp file (except the geometry data). It really should be broken up, but this way you can find everything easily.
3. At times, I could have hidden complexity, but I didn't. At all stages, I have tried to err on the side of showing you *everything*, so that nothing happens in a way that's kept a secret from you.
4. I've setup Vulkan structs every time they are used, even though, in many cases, they could have been setup once and then re-used each time.
5. At times, I've setup things that didn't need to be setup just to show you what could go there.

Caveats on the Sample Code, II

6. There are good uses for C++ classes and methods here to hide some complexity, but I've not done that.
7. I've typedef'ed a couple things to make the Vulkan phraseology more consistent.
8. Even though it is not good software style, I have put persistent information in global variables, rather than a separate data structure
9. At times, I have copied lines from vulkan.h into the code as comments to show you what certain options could be.
10. I've divided functionality up into the pieces that make sense to me. Many other divisions are possible. Feel free to invent your own.

Main Program


```
int
main( int argc, char * argv[ ] )
{
	Width  = 800;
	Height = 600;

	errno_t err = fopen_s( &FpDebug, DEBUGFILE, "w" );
	if( err != 0 )
	{
		fprintf( stderr, "Cannot open debug print file '%s'\n", DEBUGFILE );
		FpDebug = stderr;
	}
	fprintf(FpDebug, "FpDebug: Width = %d ; Height = %d\n", Width, Height);

	Reset( );
	InitGraphics( );

	// loop until the user closes the window:

	while( glfwWindowShouldClose( MainWindow ) == 0 )
	{
		glfwPollEvents( );
		Time = glfwGetTime( );		// elapsed time, in double-precision seconds
		UpdateScene( );
		RenderScene( );
	}

	fprintf(FpDebug, "Closing the GLFW window\n");

	vkQueueWaitIdle( Queue );
	vkDeviceWaitIdle( LogicalDevice );
	DestroyAllVulkan( );
	glfwDestroyWindow( MainWindow );
	glfwTerminate( );
	return 0;
}
```

InitGraphics( ), I

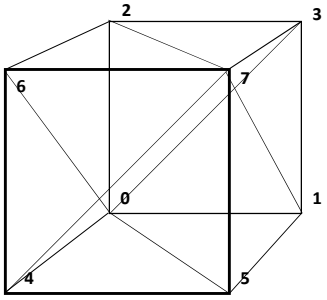

```
void
InitGraphics( )
{
	HERE_I_AM( "InitGraphics" );

	VkResult result = VK_SUCCESS;

	Init01Instance( );

	InitGLFW( );

	Init02CreateDebugCallbacks( );

	Init03PhysicalDeviceAndGetQueueFamilyProperties( );

	Init04LogicalDeviceAndQueue( );

	Init05UniformBuffer( sizeof(Matrices),		&MyMatrixUniformBuffer );
	Fill05DataBuffer( MyMatrixUniformBuffer,	(void *) &Matrices );

	Init05UniformBuffer( sizeof(Light),	&MyLightUniformBuffer );
	Fill05DataBuffer( MyLightUniformBuffer, (void *) &Light );

	Init05MyVertexDataBuffer(  sizeof(VertexData), &MyVertexDataBuffer );
	Fill05DataBuffer( MyVertexDataBuffer,		(void *) VertexData );

	Init06CommandPool( );
	Init06CommandBuffers( );
```


InitGraphics( ), II


```
	Init07TextureSampler( &MyPuppyTexture.texSampler );
	Init07TextureBufferAndFillFromBmpFile("puppy.bmp", &MyPuppyTexture);

	Init08Swapchain( );

	Init09DepthStencilImage( );

	Init10RenderPasses( );

	Init11Framebuffers( );

	Init12SpirvShader( "sample-vert.spv", &ShaderModuleVertex );
	Init12SpirvShader( "sample-frag.spv", &ShaderModuleFragment );

	Init13DescriptorSetPool( );
	Init13DescriptorSetLayouts();
	Init13DescriptorSets( );

	Init14GraphicsVertexFragmentPipeline( ShaderModuleVertex, ShaderModuleFragment,
					VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, &GraphicsPipeline  );
}
```

A Colored Cube

27



```
static GLfloat CubeColors[ ][3] =
{
        { 0., 0., 0. },
        { 1., 0., 0. },
        { 0., 1., 0. },
        { 1., 1., 0. },
        { 0., 0., 1. },
        { 1., 0., 1. },
        { 0., 1., 1. },
        { 1., 1., 1. },
};
```

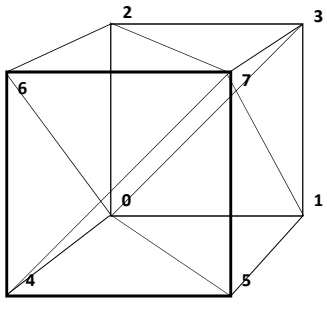
```
static GLfloat CubeVertices[ ][3] =
{
        { -1., -1., -1. },
        {  1., -1., -1. },
        { -1.,  1., -1. },
        {  1.,  1., -1. },
        { -1., -1.,  1. },
        {  1., -1.,  1. },
        { -1.,  1.,  1. },
        {  1.,  1.,  1. }
};
```

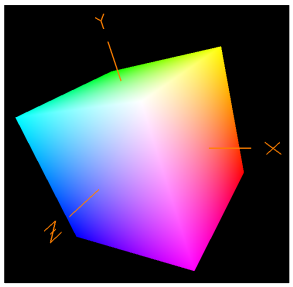
```
static GLuint CubeTriangleIndices[ ][3] =
{
        { 0, 2, 3 },
        { 0, 3, 1 },
        { 4, 5, 7 },
        { 4, 7, 6 },
        { 1, 3, 7 },
        { 1, 7, 5 },
        { 0, 4, 6 },
        { 0, 6, 2 },
        { 2, 6, 7 },
        { 2, 7, 3 },
        { 0, 1, 5 }
        { 0, 5, 4 }
};
```

A Colored Cube

28

```
struct vertex
{
        glm::vec3       position;
        glm::vec3       normal;
        glm::vec3       color;
        glm::vec2       texCoord;
};

struct vertex VertexData[ ] =
{
        // triangle 0-2-3:
        // vertex #0:
        {
                { -1., -1., -1. },
                {  0.,  0., -1. },
                {  0.,  0.,  0. },
                {  1., 0. }
        },

        // vertex #2:
        {
                { -1.,  1., -1. },
                {  0.,  0., -1. },
                {  0.,  1.,  0. },
                {  1., 1. }
        },

        // vertex #3:
        {
                {  1.,  1., -1. },
                {  0.,  0., -1. },
                {  1.,  1.,  0. },
                {  0., 1. }
        },
```





The Vertex Data is in a Separate File

#include "SampleVertexData.cpp"

```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

struct vertex VertexData[ ] =
{
	// triangle 0-2-3:
	// vertex #0:
	{
		{ -1., -1., -1. },
		{  0.,  0., -1. },
		{  0.,  0.,  0. },
		{  1., 0. }
	},

	// vertex #2:
	{
		{ -1.,  1., -1. },
		{  0.,  0., -1. },
		{  0.,  1.,  0. },
		{  1., 1. }
	},
. . .
```

What if you don't need all of this information?


```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};
```

For example, what if you are not doing texturing in this application? Should you re-do this struct and leave the texCoord element out?

As best as I can tell, the only penalties for leaving in vertex attributes that you aren't going to use is memory space and possibly some inefficient uses of the cache, but not gross performance. So, I recommend keeping this struct intact, and, if you don't need texturing, simply don't use the texCoord values in your vertex shader.

Vulkan Software Philosophy

31

1. There are lots of typedefs that define C/C++ structs and enums
2. Vulkan takes a non-C++ object-oriented approach in that those typedef'ed structs pass all the necessary information into a function. For example, where we might normally say in C++:

   result = **LogicalDevice->**vkGetDeviceQueue (queueFamilyIndex, queueIndex, OUT &Queue);

   we would actually say in C:

   result = vkGetDeviceQueue (**LogicalDevice**, queueFamilyIndex, queueIndex, OUT &Queue);

Vulkan Code has a Distinct "Style" of Setting Information in *structs* and then Passing that Information as a pointer-to-the-struct

32

```
VkBufferCreateInfo          vbci;
        vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
        vbci.pNext = nullptr;
        vbci.flags = 0;
        vbci.size = << buffer size in bytes >>
        vbci.usage = VK_USAGE_UNIFORM_BUFFER_BIT;
        vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
        vbci.queueFamilyIndexCount = 0;
        vbci.pQueueFamilyIndices = nullptr;

VK_RESULT result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &Buffer );

VkMemoryRequirements        vmr;

result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );      // fills vmr

VkMemoryAllocateInfo        vmai;
        vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
        vmai.pNext = nullptr;
        vmai.flags = 0;
        vmai.allocationSize = vmr.size;
        vmai.memoryTypeIndex = 0;

result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, &MatrixBufferMemoryHandle );

result = vkBindBufferMemory( LogicalDevice, Buffer, MatrixBufferMemoryHandle, 0 );
```

Vulkan Conventions

33

VkXxx is a typedef, probably a struct

vkXxx( ) is a function call

VK_XXX is a constant

My Conventions

"Init" in a function call name means that something is being setup that only needs to be setup once

The number after "Init" gives you the ordering

In the source code, after main( ) comes InitGraphics( ), then all of the InitxxYYY( ) functions in numerical order. After that comes the helper functions

"Find" in a function call name means that something is being looked for

"Fill" in a function call name means that some data is being supplied to Vulkan

"IN" and "OUT" ahead of function call arguments are just there to let you know how an argument is going to be used by the function. Otherwise, IN and OUT have no significance. They are each actually #define'd to nothing.

Querying the Number of Something and Allocating Enough Structures to Hold Them All

34

```
uint32_t  count;
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT (VkPhysicalDevice *)nullptr );

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ count ];
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT &physicalDevices[0] );
```

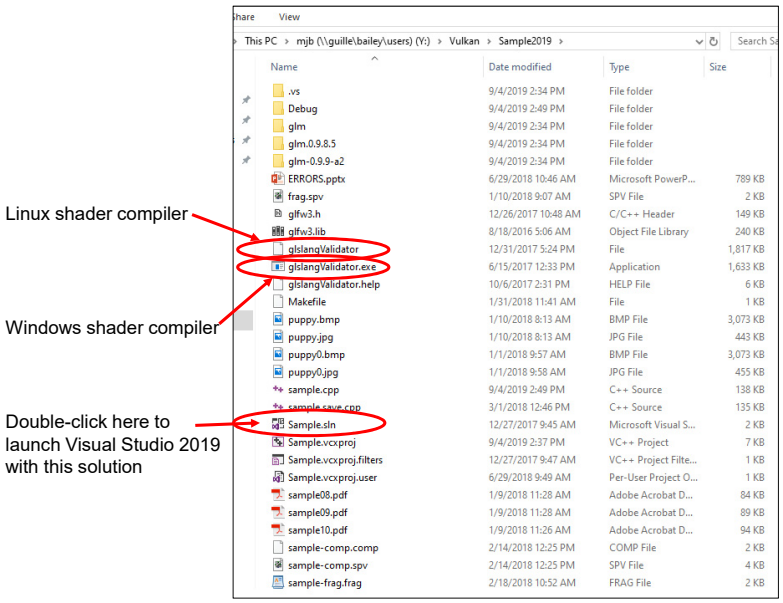
This way of querying information is a recurring OpenCL and Vulkan pattern (get used to it):

How many total there are — **Where to put them**

```
result = vkEnumeratePhysicalDevices( Instance,   &count,        nullptr   );

result = vkEnumeratePhysicalDevices( Instance,   &count,   &physicalDevices[0] );
```

Your Sample2019.zip File Contains This

35



The "19" refers to the version of Visual Studio, not the year of development.

Extras in the Code

36

```
#define REPORT(s)           { PrintVkError( result, s );  fflush(FpDebug); }

#define HERE_I_AM(s)        if( Verbose )  { fprintf( FpDebug, "***** %s *****\n", s );  fflush(FpDebug); }

bool                Paused;

bool                Verbose;



#define DEBUGFILE           "VulkanDebug.txt"

errno_t err = fopen_s( &FpDebug, DEBUGFILE, "w" );
```

37

Drawing

Mike Bailey

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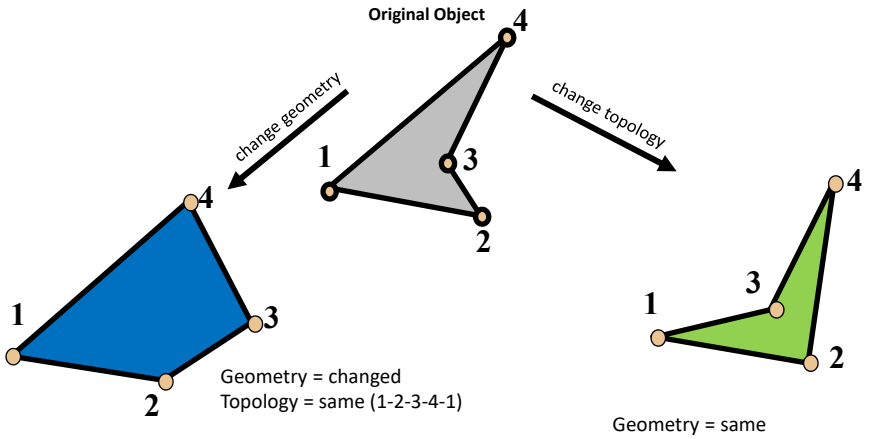
http://cs.oregonstate.edu/~mjb/vulkan

38

Geometry vs. Topology



Geometry = changed
Topology = same (1-2-3-4-1)

Geometry = same
Topology = changed (1-2-4-3-1)

Geometry:

Where things are (e.g., coordinates)

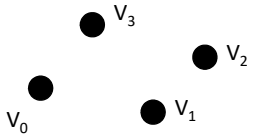
Topology:

How things are connected

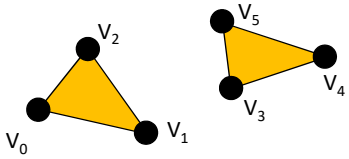
39

Vulkan Topologies

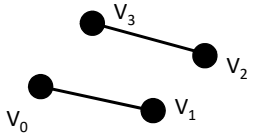
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



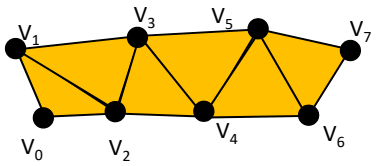
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



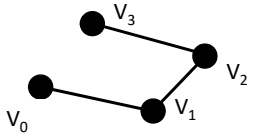
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



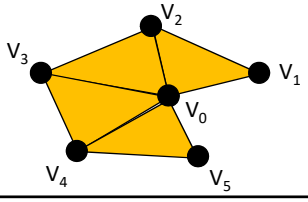
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



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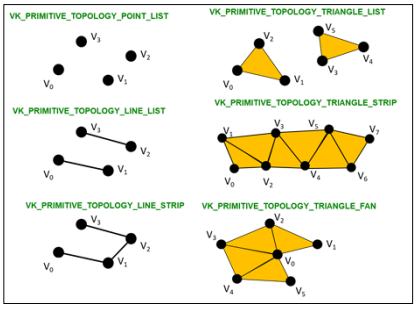
Vulkan Topologies




```
typedef enum VkPrimitiveTopology
{
    VK_PRIMITIVE_TOPOLOGY_POINT_LIST
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY
    VK_PRIMITIVE_TOPOLOGY_PATCH_LIST
} VkPrimitiveTopology;
```

Vertex Orientation Issues

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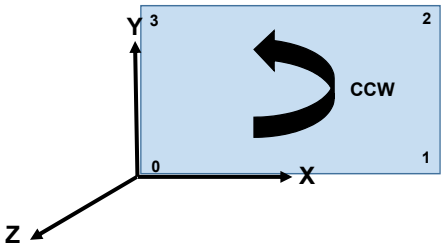
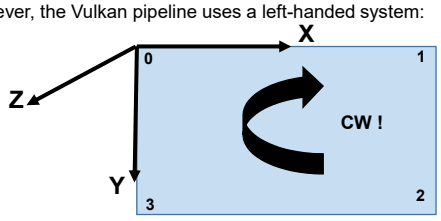
Thanks to OpenGL, we are all used to drawing in a right-handed coordinate system.



Internally, however, the Vulkan pipeline uses a left-handed system:



The best way to handle this is to continue to draw in a RH coordinate system and then fix it up in the projection matrix, like this:

ProjectionMatrix[1][1] *= -1.;

This is like saying "Y' = -Y".

Vertex Orientation Issues

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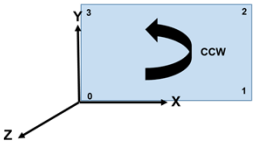
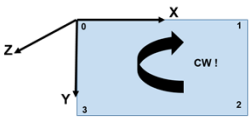




This object was modeled such that triangles that face the viewer will look like their vertices are oriented CCW (this is detected by looking at vertex orientation at the start of the rasterization).

Because this 3D object is closed, Vulkan can save rendering time by not even bothering with triangles whose vertices look like they are oriented CW. This is called **backface culling**.

Vulkan's change in coordinate systems can mess up the backface culling.

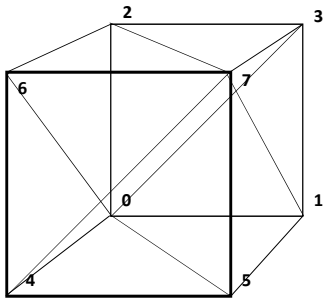
So I recommend, at least at first, that you do no culling.

```
VkPipelineRasterizationStateCreateInfo        vprsci;

. . .

vprsci.cullMode = VK_CULL_MODE_NONE
vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
```

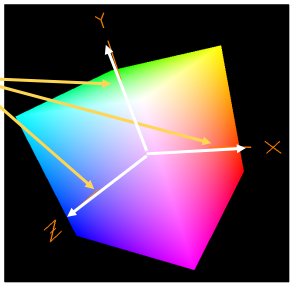
Triangles Represented as an Array of Structures

From the file **SampleVertexData.cpp**:

```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

struct vertex VertexData[ ] =
{
	// triangle 0-2-3:
	// vertex #0:
	{
		{ -1., -1., -1. },
		{  0.,  0., -1. },
		{  0.,  0.,  0. },
		{  1., 0. }
	},

	// vertex #2:
	{
		{ -1.,  1., -1. },
		{  0.,  0., -1. },
		{  0.,  1.,  0. },
		{  1., 1. }
	},

	// vertex #3:
	{
		{  1.,  1., -1. },
		{  0.,  0., -1. },
		{  1.,  1.,  0. },
		{  0., 1. }
	},
```



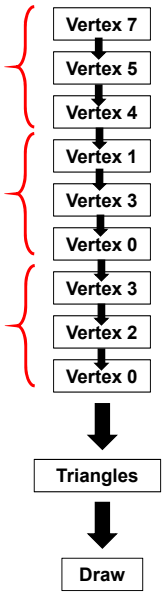
Modeled in right-handed coordinates



Non-indexed Buffer Drawing

From the file **SampleVertexData.cpp**:

```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

struct vertex VertexData[ ] =
{
	// triangle 0-2-3:
	// vertex #0:
	{
		{ -1., -1., -1. },
		{  0.,  0., -1. },
		{  0.,  0.,  0. },
		{  1., 0. }
	},

	// vertex #2:
	{
		{ -1.,  1., -1. },
		{  0.,  0., -1. },
		{  0.,  1.,  0. },
		{  1., 1. }
	},

	// vertex #3:
	{
		{  1.,  1., -1. },
		{  0.,  0., -1. },
		{  1.,  1.,  0. },
		{  0., 1. }
	},
```



Filling the Vertex Buffer


```
MyBuffer        MyVertexDataBuffer;


Init05MyVertexDataBuffer(  sizeof(VertexData), &MyVertexDataBuffer );
Fill05DataBuffer( MyVertexDataBuffer,              (void *) VertexData );


VkResult
Init05MyVertexDataBuffer( IN VkDeviceSize size, OUT MyBuffer * pMyBuffer )
{
        VkResult result;
        result = Init05DataBuffer( size, VK_BUFFER_USAGE_VERTEX_BUFFER_BIT, pMyBuffer );
        return result;
}
```

A Preview of What *Init05DataBuffer* Does


```
VkResult
Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
        VkResult result = VK_SUCCESS;
        VkBufferCreateInfo  vbci;
                vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
                vbci.pNext = nullptr;
                vbci.flags = 0;
                vbci.size = pMyBuffer->size = size;
                vbci.usage = usage;
                vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
                vbci.queueFamilyIndexCount = 0;
                vbci.pQueueFamilyIndices = (const uint32_t *)nullptr;
        result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &pMyBuffer->buffer );

        VkMemoryRequirements                vmr;
        vkGetBufferMemoryRequirements( LogicalDevice, IN pMyBuffer->buffer, OUT &vmr );        // fills vmr

        VkMemoryAllocateInfo                vmai;
                vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
                vmai.pNext = nullptr;
                vmai.allocationSize = vmr.size;
                vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

        VkDeviceMemory                      vdm;
        result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm );
        pMyBuffer->vdm = vdm;

        result = vkBindBufferMemory( LogicalDevice, pMyBuffer->buffer, IN vdm, 0 );            // 0 is the offset
        return result;
}
```

Telling the Pipeline about its Input

We will come to the Pipeline later, but for now, know that a Vulkan pipeline is essentially a very large data structure that holds (what OpenGL would call) the **state**, including how to parse its input.

C/C++:

```
struct vertex
{
    glm::vec3    position;
    glm::vec3    normal;
    glm::vec3    color;
    glm::vec2    texCoord;
};
```

GLSL Shader:

```
layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;
```

```
VkVertexInputBindingDescription     vvibd[1];     // one of these per buffer data buffer
        vvibd[0].binding = 0;                     // which binding # this is
        vvibd[0].stride = sizeof( struct vertex );    // bytes between successive structs
        vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
```

Telling the Pipeline about its Input


```
struct vertex
{
    glm::vec3    position;
    glm::vec3    normal;
    glm::vec3    color;
    glm::vec2    texCoord;
};
```

```
layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;
```

```
VkVertexInputAttributeDescription     vviad[4];     // array per vertex input attribute
        // 4 = vertex, normal, color, texture coord
        vviad[0].location = 0;              // location in the layout decoration
        vviad[0].binding = 0;               // which binding description this is part of
        vviad[0].format = VK_FORMAT_VEC3;   // x, y, z
        vviad[0].offset = offsetof( struct vertex, position );          // 0

        vviad[1].location = 1;
        vviad[1].binding = 0;
        vviad[1].format = VK_FORMAT_VEC3;   // nx, ny, nz
        vviad[1].offset = offsetof( struct vertex, normal );            // 12

        vviad[2].location = 2;
        vviad[2].binding = 0;
        vviad[2].format = VK_FORMAT_VEC3;   // r, g, b
        vviad[2].offset = offsetof( struct vertex, color );             // 24

        vviad[3].location = 3;
        vviad[3].binding = 0;
        vviad[3].format = VK_FORMAT_VEC2;   // s, t
        vviad[3].offset = offsetof( struct vertex, texCoord );          // 36
```

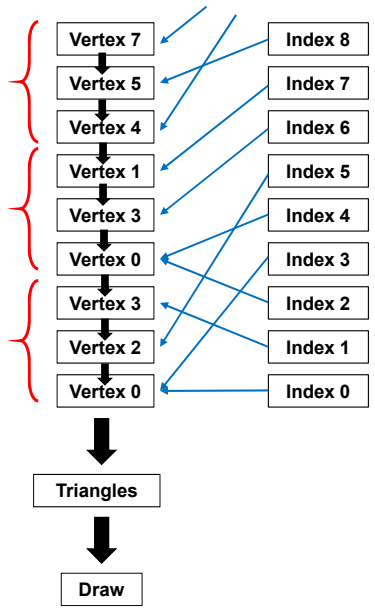
Telling the Command Buffer what Vertices to Draw

We will come to Command Buffers later, but for now, know that you will specify the vertex buffer that you want drawn.

```
VkBuffer buffers[1] = MyVertexDataBuffer.buffer;

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, vertexDataBuffers, offsets );

const uint32_t  vertexCount = sizeof( VertexData ) / sizeof( VertexData[0] );
const uint32_t  instanceCount = 1;
const uint32_t  firstVertex = 0;
const uint32_t  firstInstance = 0;

vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );
```

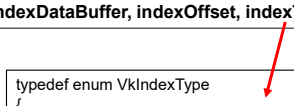

Drawing with an Indexed Buffer


```
struct vertex JustVertexData[ ] =
{
        // vertex #0:
        {
                { -1., -1., -1. },
                {  0.,  0., -1. },
                {  0.,  0.,  0. },
                {  1., 0. }
        },

        // vertex #1:
        {
                {  1., -1., -1. },
                {  0.,  0., -1. },
                {  1.,  0.,  0. },
                {  0., 0. }
        },
          . . .


int JustIndexData[ ] =
{
        0, 2, 3,
        0, 3, 1,
        4, 5, 7,
        4, 7, 6,
        1, 3, 7,
        1, 7, 5,
        0, 4, 6,
        0, 6, 2,
        2, 6, 7,
        2, 7, 3,
        0, 1, 5,
        0, 5, 4,
};
```



Drawing with an Indexed Buffer


```
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, vertexDataBuffers, vertexOffsets );

vkCmdBindIndexBuffer( commandBuffer, indexDataBuffer, indexOffset, indexType );
```



```
typedef enum VkIndexType
{
    VK_INDEX_TYPE_UINT16 = 0,       // 0 –           65,535
    VK_INDEX_TYPE_UINT32 = 1,       // 0 – 4,294,967,295
} VkIndexType;
```

```
vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex,  vertexOffset, firstInstance);
```

Drawing with an Indexed Buffer

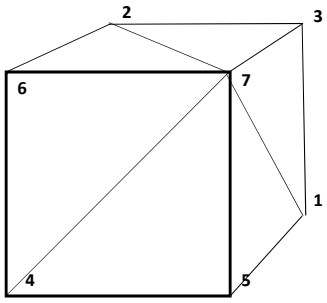

```
VkResult
Init05MyIndexDataBuffer(IN VkDeviceSize size, OUT MyBuffer * pMyBuffer)
{
        VkResult result = Init05DataBuffer(size, VK_BUFFER_USAGE_INDEX_BUFFER_BIT, pMyBuffer);
                                                        // fills pMyBuffer
         return result;
}
```

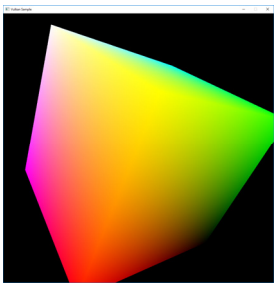
```
Init05MyVertexDataBuffer(  sizeof(JustVertexData), IN &MyJustVertexDataBuffer );
Fill05DataBuffer( MyJustVertexDataBuffer,              (void *) JustVertexData );

Init05MyIndexDataBuffer(  sizeof(JustIndexData),   IN &MyJustIndexDataBuffer );
Fill05DataBuffer( MyJustIndexDataBuffer,              (void *) JustIndexData );
```

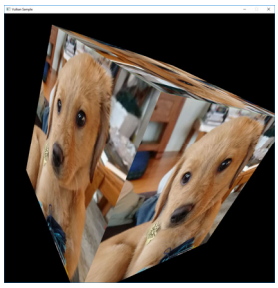
Drawing with an Indexed Buffer


```
VkBuffer vBuffers[1] = { MyJustVertexDataBuffer.buffer };
VkBuffer iBuffer     = { MyJustIndexDataBuffer.buffer  };

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, vBuffers, offsets );
                                                  // 0, 1 = firstBinding, bindingCount
vkCmdBindIndexBuffer( CommandBuffers[nextImageIndex], iBuffer, 0, VK_INDEX_TYPE_UINT32 );

const uint32_t vertexCount = sizeof( JustVertexData ) / sizeof( JustVertexData[0] );
const uint32_t indexCount  = sizeof( JustIndexData )  / sizeof( JustIndexData[0] );
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstIndex = 0;
const uint32_t firstInstance = 0;
const uint32_t vertexOffset  = 0;

vkCmdDrawIndexed( CommandBuffers[nextImageIndex], indexCount, instanceCount, firstIndex,
                                vertexOffset, firstInstance );
```


Sometimes the Same Point Needs Multiple Attributes





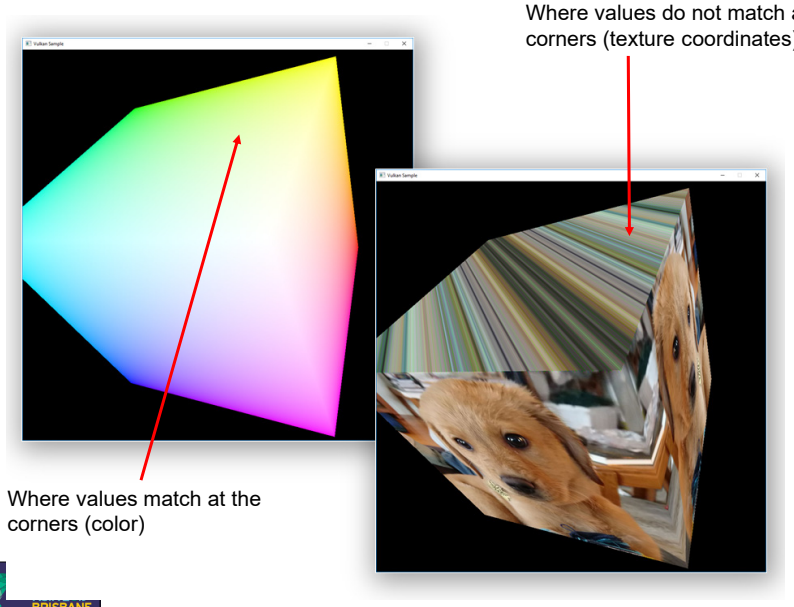


Sometimes a point that is common to multiple faces has the same attributes, no matter what face it is in. Sometimes it doesn't.

A color-interpolated cube like this actually has both. Point #7 above has the same color, regardless of what face it is in. However, Point #7 has 3 different normal vectors, depending on which face you are defining. Same with its texture coordinates.

Thus, when using index-ed buffer drawing, you need to create a new vertex struct if *any* of {position, normal, color, texCoords} changes from what was previously-stored at those coordinates.

Sometimes the Same Point Needs Multiple Attributes



Shaders and SPIR-V

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http://cs.oregonstate.edu/~mjb/vulkan

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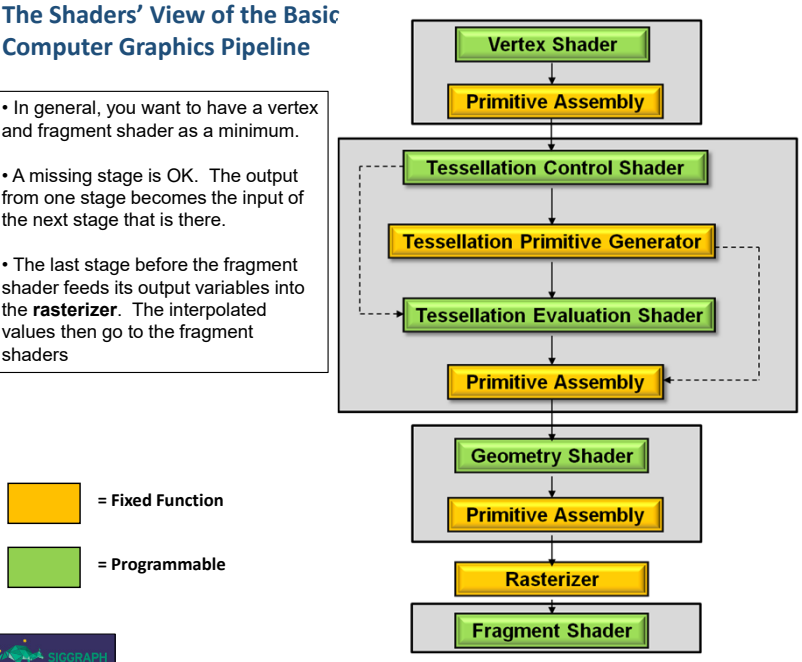
The Shaders' View of the Basic Computer Graphics Pipeline

• In general, you want to have a vertex and fragment shader as a minimum.

• A missing stage is OK. The output from one stage becomes the input of the next stage that is there.

• The last stage before the fragment shader feeds its output variables into the **rasterizer**. The interpolated values then go to the fragment shaders



= Fixed Function

= Programmable

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Vulkan: GLSL Differences from OpenGL, I

Detecting that a GLSL Shader is being used with Vulkan/SPIR-V:

- In the compiler, there is an automatic
  #define VULKAN 100

Vulkan Vertex and Instance indices:

gl_VertexIndex
gl_InstanceIndex

OpenGL uses:

gl_VertexID
gl_InstanceID

- Both are 0-based

gl_FragColor:

- In OpenGL, gl_FragColor broadcasts to all color attachments
- In Vulkan, it just broadcasts to color attachment location #0
- Best idea: don't use it at all – explicitly declare out variables to have specific location numbers

Vulkan: GLSL Differences from OpenGL, II

Shader combinations of separate texture data and samplers:

```
uniform sampler s;
uniform texture2D t;
vec4 rgba = texture(  sampler2D( t, s ),  vST  );
```

Descriptor Sets:

```
layout( set=0, binding=0 ) . . .  ;
```

Push Constants:

```
layout( push_constant ) . . .  ;
```

Specialization Constants:

```
layout( constant_id = 3 )  const int N = 5;
```

- Only for scalars, but a vector's components can be constructed from specialization constants

Specialization Constants for Compute Shaders:

```
layout( local_size_x_id = 8, local_size_y_id = 16 );
```

- This sets gl_WorkGroupSize.x and gl_WorkGroupSize.y
- gl_WorkGroupSize.z is set as a constant

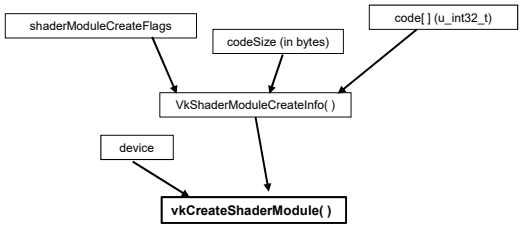
Vulkan: Shaders' use of Layouts for Uniform Variables


```
// non-sampler variables must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

// non-sampler variables must be in a uniform block:
layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
	vec4 uLightPos;
} Light;

layout( set = 2, binding = 0 ) uniform sampler2D uTexUnit;
```

All non-sampler uniform variables must be in block buffers



Vulkan Shader Compiling

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- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V, which stands for **Standard Portable Intermediate Representation.**
- SPIR-V gets turned into fully-compiled code at runtime
- SPIR-V spec has been public for a couple of years –new shader languages are surely being developed
- OpenGL and OpenCL have adopted SPIR-V as well

Advantages:

1. Software vendors don't need to ship their shader source
2. Syntax errors appear during the SPIR-V step, not during runtime
3. Software can launch faster because half of the compilation has already taken place
4. This guarantees a common front-end syntax
5. This allows for other language front-ends

SPIR-V:
Standard Portable Intermediate Representation for Vulkan

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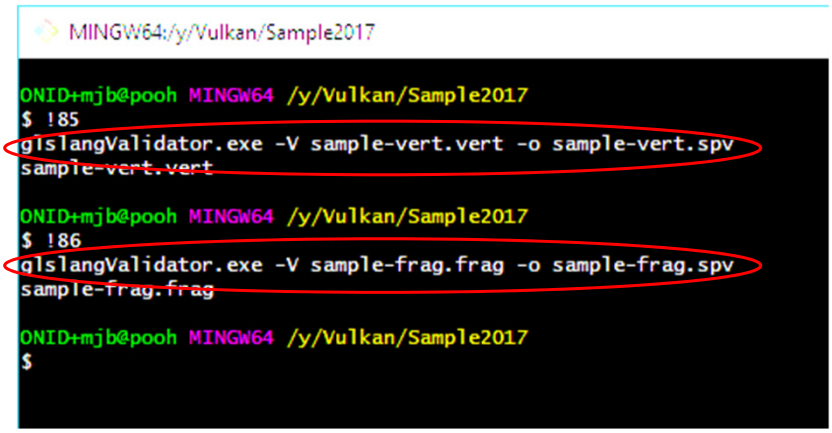
glslangValidator shaderFile -V [-H] [-I<dir>] [-S <stage>] -o shaderBinaryFile.spv

Shaderfile extensions:
.vert Vertex
.tesc Tessellation Control
.tese Tessellation Evaluation
.geom Geometry
.frag Fragment
.comp Compute
(Can be overridden by the –S option)

-V Compile for Vulkan
-G Compile for OpenGL
-I Directory(ies) to look in for #includes
-S Specify stage rather than get it from shaderfile extension
-c Print out the maximum sizes of various properties

Windows: glslangValidator.exe
Linux: setenv LD_LIBRARY_PATH /usr/local/common/gcc-6.3.0/lib64/

Running glslangValidator.exe



How do you know if SPIR-V compiled successfully?

Same as C/C++ -- the compiler gives you no nasty messages.

Also, if you care, legal .spv files have a magic number of **0x07230203**

So, if you do an **od –x** on the .spv file, the magic number looks like this:

0203 0723 . . .

Reading a SPIR-V File into a Vulkan Shader Module

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```
#define SPIRV_MAGIC		0x07230203
. . .
VkResult
Init12SpirvShader( std::string filename, VkShaderModule * pShaderModule )
{
	FILE *fp;
	(void) fopen_s( &fp, filename.c_str(), "rb");
	if( fp == NULL )
	{
		fprintf( FpDebug, "Cannot open shader file '%s'\n", filename.c_str( ) );
		return VK_SHOULD_EXIT;
	}
	uint32_t magic;
	fread( &magic, 4, 1, fp );
	if( magic != SPIRV_MAGIC )
	{
		fprintf( FpDebug, "Magic number for spir-v file '%s is 0x%08x -- should be 0x%08x\n",
					filename.c_str( ), magic, SPIRV_MAGIC );
		return VK_SHOULD_EXIT;
	}

	fseek( fp, 0L, SEEK_END );
	int size = ftell( fp );
	rewind( fp );
	unsigned char *code = new unsigned char [size];
	fread( code, size, 1, fp );
	fclose( fp );
```

Reading a SPIR-V File into a Shader Module

66

```
VkShaderModule		ShaderModuleVertex;
. . .

	VkShaderModuleCreateInfo		vsmci;
		vsmci.sType = VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO;
		vsmci.pNext = nullptr;
		vsmci.flags = 0;
		vsmci.codeSize = size;
		vsmci.pCode = (uint32_t *)code;

	VkResult result = vkCreateShaderModule( LogicalDevice, &vsmci, PALLOCATOR, OUT & ShaderModuleVertex );
	fprintf( FpDebug, "Shader Module '%s' successfully loaded\n", filename.c_str() );
	delete [ ] code;
	return result;
}
```

Vulkan: Creating a Graphics Pipeline

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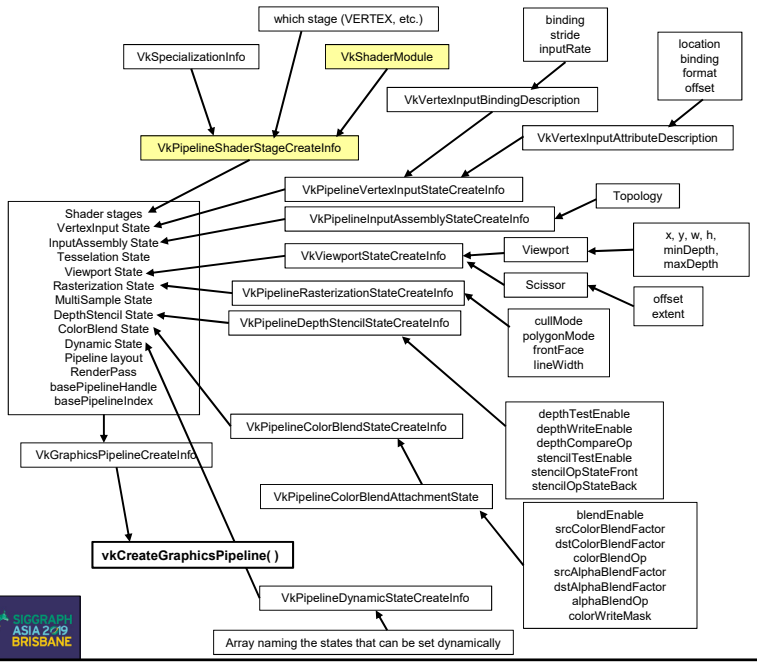

SPIR-V: More Information

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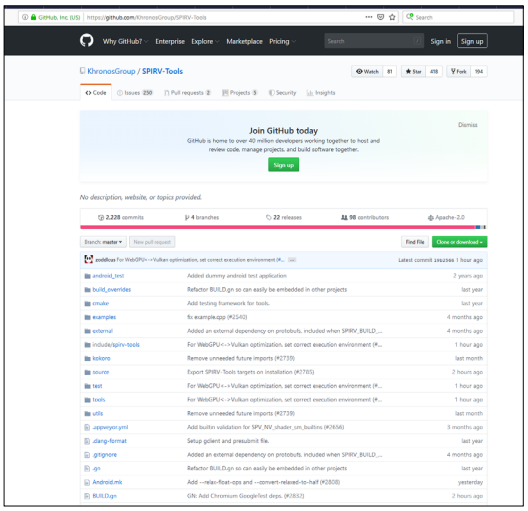
SPIR-V Tools:
http://github.com/KhronosGroup/SPIRV-Tools



Vertex Buffers

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What is a Vertex Buffer?

Vertex Buffers are how you draw things in Vulkan. They are very much like Vertex Buffer Objects in OpenGL, but more detail is exposed to you (a lot more…).

But, the good news is that Vertex Buffers are really just ordinary Data Buffers, so some of the functions will look familiar to you.

First, a quick review of computer graphics geometry . . .

Filling the Vertex Buffer


```
MyBuffer          MyVertexDataBuffer;


Init05MyVertexDataBuffer(  sizeof(VertexData), &MyVertexDataBuffer );
Fill05DataBuffer( MyVertexDataBuffer,              (void *) VertexData );


VkResult
Init05MyVertexDataBuffer( IN VkDeviceSize size, OUT MyBuffer * pMyBuffer )
{
        VkResult result = Init05DataBuffer( size, VK_BUFFER_USAGE_VERTEX_BUFFER_BIT, pMyBuffer );
        return result;
}
```

Data Buffers

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From the Quick Reference Card

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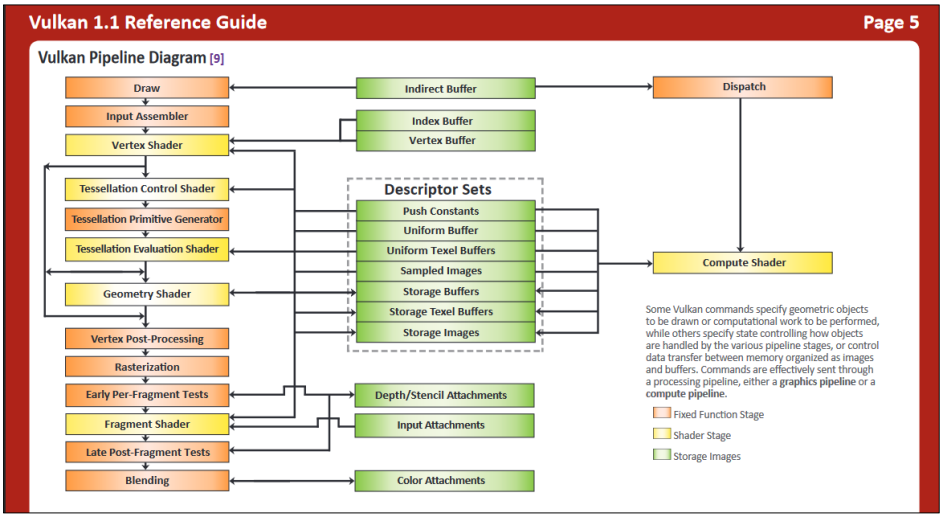

Vulkan: Creating a Data Buffer

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```
VkBufferCreateInfo  vbci;
        vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
        vbci.pNext = nullptr;
        vbci.flags = 0;
        vbci.size = << buffer size in bytes >>
        vbci.usage = <<or'ed bits of: >>
                VK_USAGE_TRANSFER_SRC_BIT
                VK_USAGE_TRANSFER_DST_BIT
                VK_USAGE_UNIFORM_TEXEL_BUFFER_BIT
                VK_USAGE_STORAGE_TEXEL_BUFFER_BIT
                VK_USAGE_UNIFORM_BUFFER_BIT
                VK_USAGE_STORAGE_BUFFER_BIT
                VK_USAGE_INDEX_BUFFER_BIT
                VK_USAGE_VERTEX_BUFFER_BIT
                VK_USAGE_INDIRECT_BUFFER_BIT
        vbci.sharingMode = << one of: >>
                VK_SHARING_MODE_EXCLUSIVE
                VK_SHARING_MODE_CONCURRENT
        vbci.queueFamilyIndexCount = 0;
        vbci.pQueueFamilyIndices = (const uint32_t) nullptr;

VkBuffer  Buffer;

result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &Buffer );
```

Vulkan: Allocating Memory for a Buffer, Binding a Buffer to Memory, and Writing to the Buffer


```
VkMemoryRequirements            vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );


VkMemoryAllocateInfo            vmai;
        vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
        vmai.pNext = nullptr;
        vmai.flags = 0;
        vmai.allocationSize = vmr.size;
        vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

. . .

VkDeviceMemory                  vdm;
result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR,  OUT &vdm );

result = vkBindBufferMemory( LogicalDevice, Buffer, IN vdm, 0 );            // 0 is the offset

. . .

result = vkMapMemory( LogicalDevice, IN vdm, 0, VK_WHOLE_SIZE, 0, &ptr );

        << do the memory copy >>

result = vkUnmapMemory( LogicalDevice, IN vdm );
```


Finding the Right Type of Memory


```
int
FindMemoryThatIsHostVisible( )
{
        VkPhysicalDeviceMemoryProperties        vpdmp;
        vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );
        for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
        {
                VkMemoryType vmt = vpdmp.memoryTypes[ i ];
                if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT ) != 0 )
                {
                        return i;
                }
        }
        return  -1;
}
```

Finding the Right Type of Memory


```
int
FindMemoryThatIsDeviceLocal( )
{
	VkPhysicalDeviceMemoryProperties	vpdmp;
	vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );
	for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
	{
		VkMemoryType vmt = vpdmp.memoryTypes[ i ];
		if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT ) != 0 )
		{
			return i;
		}
	}
	return  -1;
}
```

Finding the Right Type of Memory


```
VkPhysicalDeviceMemoryProperties	vpdmp;
vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );
```

```
11 Memory Types:
Memory  0:
Memory  1:
Memory  2:
Memory  3:
Memory  4:
Memory  5:
Memory  6:
Memory  7:  DeviceLocal
Memory  8:  DeviceLocal
Memory  9:  HostVisible HostCoherent
Memory 10:  HostVisible HostCoherent HostCached

2 Memory Heaps:
Heap 0:  size = 0xb7c00000 DeviceLocal
Heap 1:  size = 0xfac00000
```

Something I've Found Useful

I find it handy to encapsulate buffer information in a struct:

```
typedef struct MyBuffer
{
	VkDataBuffer		buffer;
	VkDeviceMemory		vdm;
	VkDeviceSize		size;
} MyBuffer;

. . .

MyBuffer			MyMatrixUniformBuffer;
```

It's the usual object-oriented benefit – you can pass around just one data-item and everyone can access whatever information they need.

Initializing a Data Buffer

It's the usual object-oriented benefit – you can pass around just one data-item and everyone can access whatever information they need.

```
VkResult
Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
. . .
	vbci.size = pMyBuffer->size = size;
. . .
	result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &pMyBuffer->buffer );
. . .
	pMyBuffer->vdm = vdm;
. . .
}
```

Here's a C struct to hold some uniform variables


```
struct matBuf
{
	glm::mat4 uModelMatrix;
	glm::mat4 uViewMatrix;
	glm::mat4 uProjectionMatrix;
	glm::mat3 uNormalMatrix;
} Matrices;
```

Here's the shader code to access those uniform variables

```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat4 uNormalMatrix;
} Matrices;
```

Filling those Uniform Variables


```
uint32_t                Height, Width;
const double FOV =      glm::radians(60.);     // field-of-view angle

glm::vec3  eye(0.,0.,EYEDIST);
glm::vec3  look(0.,0.,0.);
glm::vec3  up(0.,1.,0.);

Matrices.uModelMatrix      = glm::mat4( );          // identity

Matrices.uViewMatrix       = glm::lookAt( eye, look, up );

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.;            // account for Vulkan's LH screen coordinate system

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix )  );
```

The Parade of Data

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MyBuffer MyMatrixUniformBuffer;

The MyBuffer does not hold any actual data itself. It just represents the collection of data buffer information that will be used by Vulkan

```
VkResult
Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
...
	vbci.size = pMyBuffer->size = size;
...
	result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &pMyBuffer->buffer );
...
	pMyBuffer->vdm = vdm;
...
}
```

This C struct is holding the actual data. It is writeable by the application.

Memory-mapped copy

The Data Buffer in GPU memory is holding the actual data. It is readable by the shaders

struct matBuf Matrices;

```
glm::vec3  eye(0.,0.,EYEDIST);
glm::vec3  look(0.,0.,0.);
glm::vec3  up(0.,1.,0.);

Matrices.uModelMatrix      = glm::mat4( );          // identity

Matrices.uViewMatrix       = glm::lookAt( eye, look, up );

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.;

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix ) );
```

uniform matBuf Matrices;

```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4  uModelMatrix;
	mat4  uViewMatrix;
	mat4  uProjectionMatrix;
	mat4  uNormalMatrix;
} Matrices;
```

There is one more step in here– **Descriptor Sets**. Here's a quick preview…

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The Descriptor Set for the Buffer

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We will come to **Descriptor Sets** later, but for now think of them as the link between the BLOB of uniform variables in GPU memory and the block of variable names in your shader programs.

```
VkDescriptorBufferInfo		vdbi0;
	vdbi0.buffer = MyMatrixUniformBuffer.buffer;
	vdbi0.offset = 0;	// bytes
	vdbi0.range = sizeof(Matrices);
```

```
VkWriteDescriptorSet		vwds0;
	// ds 0:
	vwds0.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
	vwds0.pNext = nullptr;
	vwds0.dstSet = DescriptorSets[0];
	vwds0.dstBinding = 0;
	vwds0.dstArrayElement = 0;
	vwds0.descriptorCount = 1;
	vwds0.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
	vwds0.pBufferInfo = &vdbi0;
	vwds0.pImageInfo = (VkDescriptorImageInfo *)nullptr;
```

```
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds0, IN 0, (VkCopyDescriptorSet *)nullptr );
```

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Filling the Data Buffer


```
typedef struct MyBuffer
{
	VkDataBuffer		buffer;
	VkDeviceMemory		vdm;
	VkDeviceSize		size;
} MyBuffer;

. . .

MyBuffer			MyMatrixUniformBuffer;
```

```
Init05UniformBuffer( sizeof(Matrices),		&MyMatrixUniformBuffer );

Fill05DataBuffer( MyMatrixUniformBuffer,	(void *) &Matrices );
```

```
glm::vec3  eye(0.,0.,EYEDIST);
glm::vec3  look(0.,0.,0.);
glm::vec3  up(0.,1.,0.);

Matrices.uModelMatrix	= glm::mat4( );		// identity

Matrices.uViewMatrix	= glm::lookAt( eye, look, up );

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.;

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix ) );
```

Creating and Filling the Data Buffer – the Details


```
VkResult
Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
	VkResult result = VK_SUCCESS;
	VkBufferCreateInfo  vbci;
		vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
		vbci.pNext = nullptr;
		vbci.flags = 0;
		vbci.size = pMyBuffer->size = size;
		vbci.usage = usage;
	    vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
	    vbci.queueFamilyIndexCount = 0;
		vbci.pQueueFamilyIndices = (const uint32_t *)nullptr;
	result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &pMyBuffer->buffer );

	VkMemoryRequirements		vmr;
	vkGetBufferMemoryRequirements( LogicalDevice, IN pMyBuffer->buffer, OUT &vmr );	// fills vmr

	VkMemoryAllocateInfo		vmai;
		vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
		vmai.pNext = nullptr;
		vmai.allocationSize = vmr.size;
		vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

	VkDeviceMemory			vdm;
	result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm );
	pMyBuffer->vdm = vdm;

	result = vkBindBufferMemory( LogicalDevice, pMyBuffer->buffer, IN vdm, 0 );		// 0 is the offset
	return result;
}
```

Creating and Filling the Data Buffer – the Details


```
VkResult
Fill05DataBuffer( IN MyBuffer myBuffer, IN void * data )
{
	// the size of the data had better match the size that was used to Init the buffer!

	void * pGpuMemory;
	vkMapMemory( LogicalDevice, IN myBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT &pGpuMemory );
	                                                    // 0 and 0 are offset and flags
	memcpy( pGpuMemory, data, (size_t)myBuffer.size );
	vkUnmapMemory( LogicalDevice, IN myBuffer.vdm );
	return VK_SUCCESS;
}
```

Remember – to Vulkan and GPU memory, these are just *bits*. It is up to *you* to handle their meaning correctly.

GLFW

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Setting Up GLFW


```
void
InitGLFW( )
{
	glfwInit( );
	glfwWindowHint( GLFW_CLIENT_API, GLFW_NO_API );
	glfwWindowHint( GLFW_RESIZABLE, GLFW_FALSE );
	MainWindow    =  glfwCreateWindow( Width, Height, "Vulkan Sample", NULL, NULL );
	VkResult result = glfwCreateWindowSurface( Instance, MainWindow, NULL, &Surface );

	glfwSetErrorCallback( GLFWErrorCallback );
	glfwSetKeyCallback( MainWindow,		GLFWKeyboard );
	glfwSetCursorPosCallback( MainWindow,	GLFWMouseMotion );
	glfwSetMouseButtonCallback( MainWindow,	GLFWMouseButton );
}
```

GLFW Keyboard Callback


```
void
GLFWKeyboard( GLFWwindow * window, int key, int scancode, int action, int mods )
{
	if( action == GLFW_PRESS )
	{
		switch( key )
		{
			//case GLFW_KEY_M:
			case 'm':
			case 'M':
				Mode++;
				if( Mode >= 2 )
					Mode = 0;
				break;

			default:
				fprintf( FpDebug, "Unknow key hit: 0x%04x = '%c'\n", key, key );
				fflush(FpDebug);
		}
	}
}
```

GLFW Mouse Button Callback

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```
void
GLFWMouseButton( GLFWwindow *window, int button, int action, int mods )
{
	int b = 0;			// LEFT, MIDDLE, or RIGHT

	// get the proper button bit mask:
	switch( button )
	{
		case GLFW_MOUSE_BUTTON_LEFT:
			b = LEFT;		break;

		case GLFW_MOUSE_BUTTON_MIDDLE:
			b = MIDDLE;		break;

		case GLFW_MOUSE_BUTTON_RIGHT:
			b = RIGHT;		break;

		default:
			b = 0;
			fprintf( FpDebug, "Unknown mouse button: %d\n", button );
	}

	// button down sets the bit, up clears the bit:
	if( action == GLFW_PRESS )
	{
		double xpos, ypos;
		glfwGetCursorPos( window, &xpos, &ypos);
		Xmouse = (int)xpos;
		Ymouse = (int)ypos;
		ActiveButton |= b;		// set the proper bit
	}
	else
	{
		ActiveButton &= ~b;		// clear the proper bit
	}
}
```

GLFW Mouse Motion Callback

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```
void
GLFWMouseMotion( GLFWwindow *window, double xpos, double ypos )
{
	int dx = (int)xpos - Xmouse;		// change in mouse coords
	int dy = (int)ypos - Ymouse;

	if( ( ActiveButton & LEFT ) != 0 )
	{
		Xrot += ( ANGFACT*dy );
		Yrot += ( ANGFACT*dx );
	}

	if( ( ActiveButton & MIDDLE ) != 0 )
	{
		Scale += SCLFACT * (float) ( dx - dy );

		// keep object from turning inside-out or disappearing:

		if( Scale < MINSCALE )
			Scale = MINSCALE;
	}

	Xmouse = (int)xpos;			// new current position
	Ymouse = (int)ypos;
}
```

Looping and Closing GLFW


```
while( glfwWindowShouldClose( MainWindow ) == 0 )
{
	glfwPollEvents( );
	Time = glfwGetTime( );		// elapsed time, in double-precision seconds
	UpdateScene( );
	RenderScene( );
}

vkQueueWaitIdle( Queue );
vkDeviceWaitIdle( LogicalDevice );
DestroyAllVulkan( );
glfwDestroyWindow( MainWindow );
glfwTerminate( );
```

GLM

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What is GLM?

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GLM is a set of C++ classes and functions to fill in the programming gaps in writing the basic vector and matrix mathematics for OpenGL applications. However, even though it was written for OpenGL, it works fine with Vulkan (with one small exception which can be worked around.

Even though GLM looks like a library, it actually isn't – it is all specified in ***.hpp** header files so that it gets compiled in with your source code.

You can find it at:

http://glm.g-truc.net/0.9.8.5/

You invoke GLM like this:

```
#define    GLM_FORCE_RADIANS
#include <glm/glm.hpp>
#include  <glm/gtc/matrix_transform.hpp>
#include  <glm/gtc/matrix_inverse.hpp>
```

If GLM is not installed in a system place, put it somewhere you can get access to. Later on, these notes will show you how to use it from there.

Why are we even talking about this?

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All of the things that we have talked about being ***deprecated*** in OpenGL are *really* **deprecated** in Vulkan -- built-in pipeline transformations, begin-end, fixed-function, etc. So, where you might have said in OpenGL:

```
gluLookAt( 0., 0., 3.,     0., 0., 0.,     0., 1., 0. );
glRotatef( (GLfloat)Yrot, 0., 1., 0. );
glRotatef( (GLfloat)Xrot, 1., 0., 0. );
glScalef( (GLfloat)Scale, (GLfloat)Scale, (GLfloat)Scale );
```

you would now have to say:

```
glm::mat4 modelview;
glm::vec3 eye(0.,0.,3.);
glm::vec3 look(0.,0.,0.);
glm::vec3   up(0.,1.,0.);
modelview = glm::lookAt( eye, look, up );
modelview = glm::rotate( modelview, D2R*Yrot, glm::vec3(0.,1.,0.) );
modelview = glm::rotate( modelview, D2R*Xrot, glm::vec3(1.,0.,0.) );
modelview = glm::scale( modelview, glm::vec3(Scale,Scale,Scale) );
```

Exactly the same concept, but a different expression of it. Read on for details …

The Most Useful GLM Variables, Operations, and Functions

// constructor:

```
glm::mat4( );                  // identity matrix
glm::vec4( );
glm::vec3( );
```

GLM recommends that you use the **"glm::"** syntax and avoid **"using namespace"** syntax because they have not made any effort to create unique function names

// multiplications:

```
glm::mat4  *  glm::mat4
glm::mat4  *  glm::vec4
glm::mat4  *  glm::vec4(  glm::vec3,  1.  )       // promote a vec3 to a vec4 via a constructor
```

// emulating OpenGL transformations *with concatenation*:

```
glm::mat4 glm::rotate(  glm::mat4 const & m,  float angle,  glm::vec3 const & axis );

glm::mat4 glm::scale(  glm::mat4 const & m,  glm::vec3 const & factors );

glm::mat4 glm::translate(  glm::mat4 const & m,  glm::vec3 const & translation );
```


The Most Useful GLM Variables, Operations, and Functions

// viewing volume (assign, not concatenate):

```
glm::mat4  glm::ortho(  float left,  float right,  float bottom,  float top,  float near,  float far );
glm::mat4  glm::ortho(  float left,  float right,  float bottom,  float top );

glm::mat4  glm::frustum(  float left,  float right,  float bottom,  float top,  float near,  float far );
glm::mat4  glm::perspective(  float fovy,  float aspect,  float near,  float far);
```

// viewing (assign, not concatenate):

```
glm::mat4  glm::lookAt(  glm::vec3 const & eye,  glm::vec3 const & look,  glm::vec3 const & up );
```

Installing GLM into your own space

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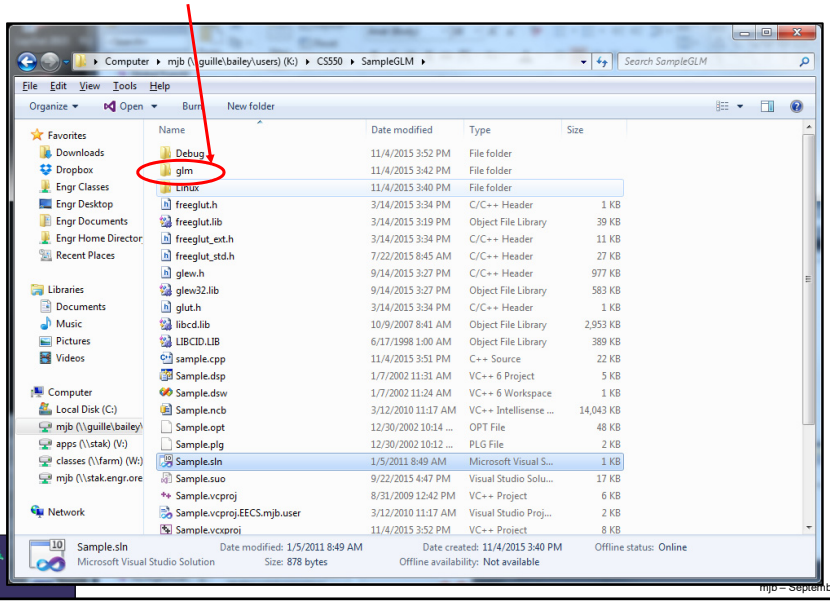
I like to just put the whole thing under my Visual Studio project folder so I can zip up a complete project and give it to someone else.



Here's what that GLM folder looks like

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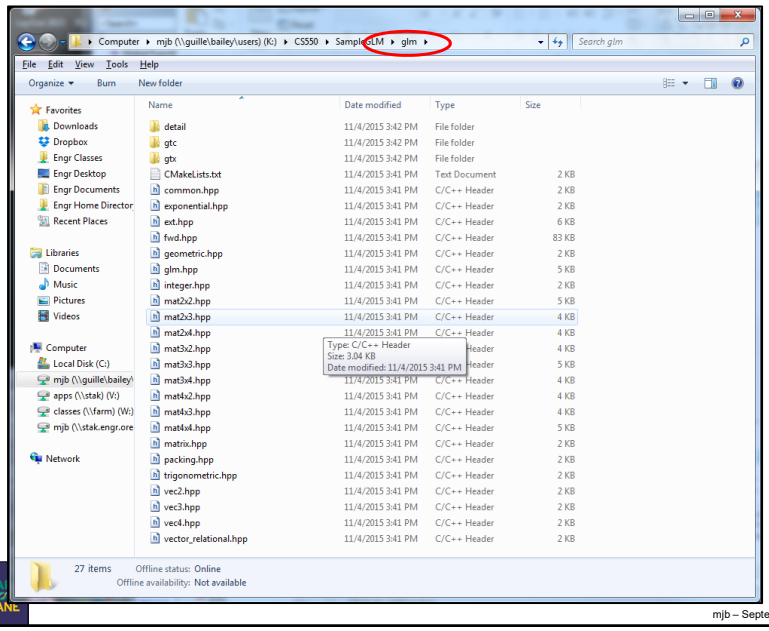

Telling Visual Studio about where the GLM folder is

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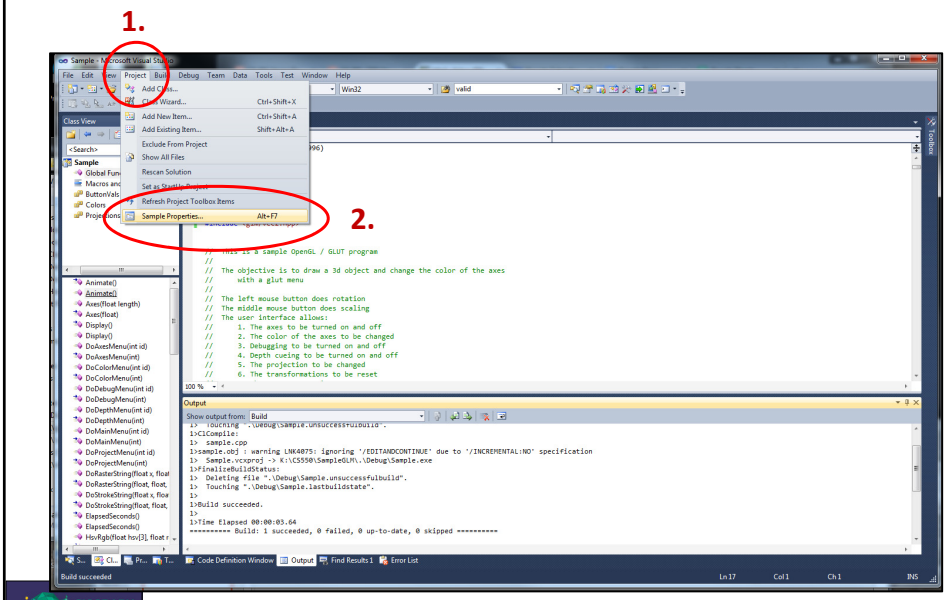

Telling Visual Studio about where the GLM folder is

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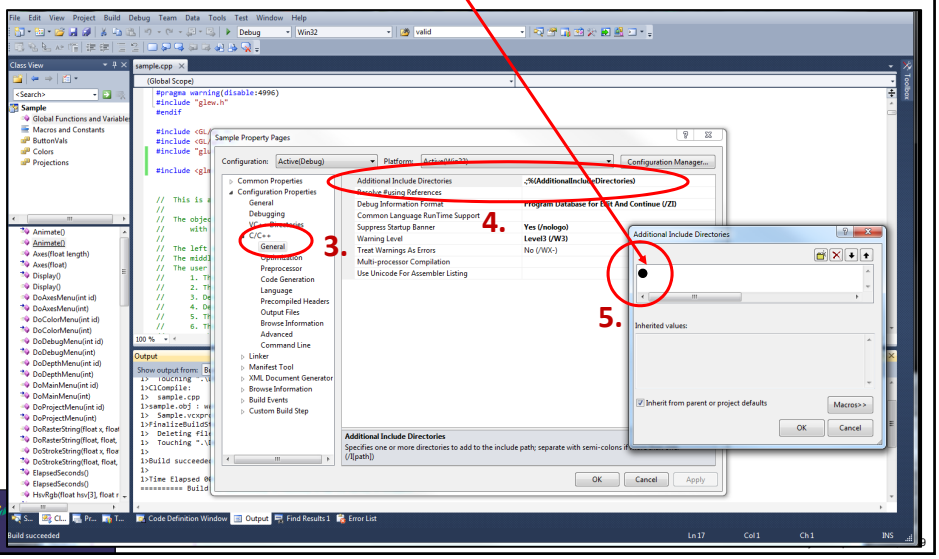
A ***period***, indicating that the **project folder** should also be searched when a

#include <xxx>

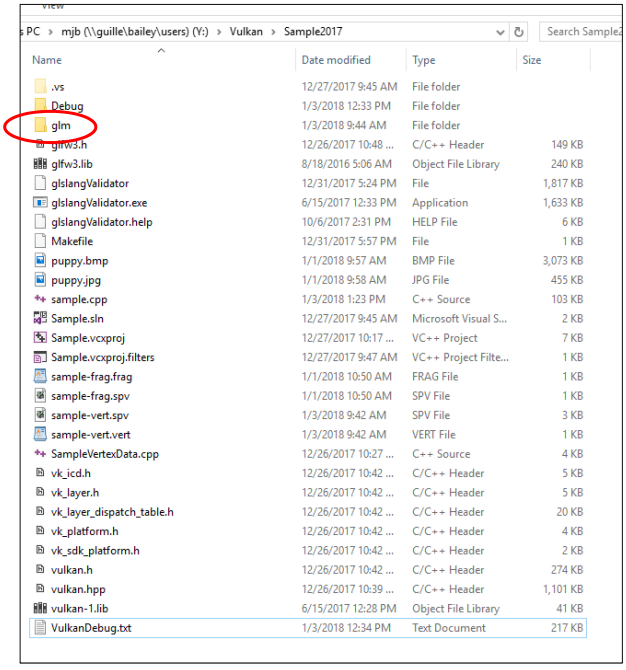
is encountered. If you put it somewhere else, enter that full or relative path instead.



GLM in the Vulkan sample.cpp Program

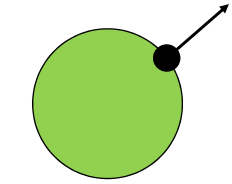

```
if( UseMouse )
{
	if( Scale < MINSCALE )
		Scale = MINSCALE;
	Matrices.uModelMatrix = glm::mat4( );		// identity
	Matrices.uModelMatrix = glm::scale(  Matrices.uModelMatrix, glm::vec3(Scale,Scale,Scale) );
	Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Yrot, glm::vec3( 0.,1.,0.) );
	Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Xrot, glm::vec3( 1.,0.,0.) );
				// done this way, the Xrot is applied first, then the Yrot, then the Scale

}
else
{
	if( ! Paused )
	{
		const glm::vec3 axis = glm::vec3( 0., 1., 0. );
		Matrices.uModelMatrix	= glm::rotate( glm::mat4( ),  (float)glm::radians( 360.f*Time/SECONDS_PER_CYCLE ),   axis );
	}
}

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.			// Vulkan's projected Y is inverted from OpenGL

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix ) );
Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix ) );

Fill05DataBuffer( MyMatrixUniformBuffer, (void *) &Matrices );

Misc.uTime = (float)Time;
Misc.uMode = Mode;
Fill05DataBuffer( MyMiscUniformBuffer, (void *) &Misc );
```

Your Sample2019.zip File Contains GLM Already



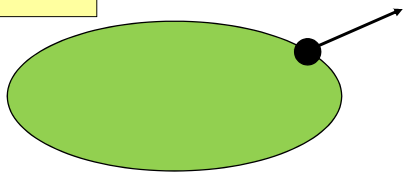
Why Isn't The Normal Matrix just the Same as the Model Matrix?

It is, if the Model Matrix is all rotations and uniform scalings, but if it has non-uniform scalings, then it is not. These diagrams show you why.



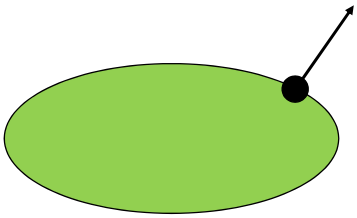
Original object and normal

Wrong!



glm::mat3 NormalMatrix = glm::mat3(Model);

Right!



glm::mat3 NormalMatrix = glm::**inverseTranspose**(glm::mat3(Model));

Instancing

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Instancing – What and why?

- Instancing is the ability to draw the same object multiple times
- It uses all the same vertices and graphics pipeline each time
- It avoids the overhead of the program asking to have the object drawn again, letting the GPU/driver handle all of that

vkCmdDraw(CommandBuffers[nextImageIndex], vertexCount, **instanceCount**, firstVertex, **firstInstance**);

But, this will only get us multiple instances of identical objects drawn on top of each other. How can we make each instance look differently?

Making each Instance look differently -- Approach #1

Use the built-in vertex shader variable **gl_InstanceIndex** to define a unique display property, such as position or color.

gl_InstanceIndex starts at 0

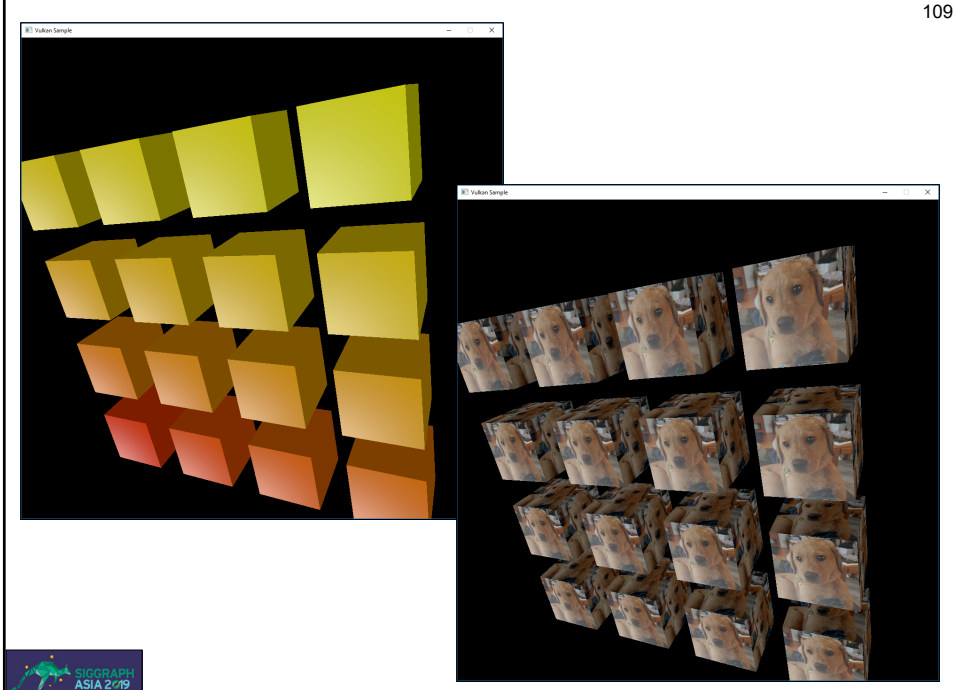
In the vertex shader:

```
int    NUMINSTANCES = 16;
float DELTA                =   3.0;

float xdelta = DELTA * float( gl_InstanceIndex % 4 );
float ydelta = DELTA * float( gl_InstanceIndex / 4 );
vColor = vec3( 1., float( (1.+gl_InstanceIndex) ) / float( NUMINSTANCES ), 0. );

xdelta -= DELTA * sqrt( float(NUMINSTANCES) ) / 2.;
ydelta -= DELTA * sqrt( float(NUMINSTANCES) ) / 2.;
vec4 vertex = vec4( aVertex.xyz + vec3( xdelta, ydelta, 0. ), 1. );

gl_Position = PVM * vertex;
```



Making each Instance look differently -- Approach #2

Put the unique characteristics in a uniform buffer and reference them

Still uses **gl_InstanceIndex**

In the vertex shader:

```
layout( std140, set = 3, binding = 0 ) uniform colorBuf
{
	vec3 uColors[1024];
} Colors;

out vec3 vColor;

	. . .

int index = gl_InstanceIndex % 1024;	// 0 - 1023

vColor = Colors.uColors[ index ];

gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
```

How We Constructed the Graphics Pipeline Structure Before

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```
VkVertexInputBindingDescription		vvibd[1];
                    // an array containing one of these per buffer being used
        vvibd[0].binding = 0;                       // which binding # this is
        vvibd[0].stride = sizeof( struct vertex );  // bytes between successive
        vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
```

This definition says that we should advance through the input buffer by this much every time we hit a new **vertex**

How We Write the Vertex Shader Now

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```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable

        . . .

layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;

layout( location = 4 ) in vec3 aInstanceColor;

layout ( location = 0 ) out vec3 vNormal;
layout ( location = 1 ) out vec3 vColor;
layout ( location = 2 ) out vec2 vTexCoord;

void
main( )
{
        mat4 PVM = Matrices.uProjectionMatrix * Matrices.uViewMatrix * Matrices.uModelMatrix;

        vNormal    = normalize( vec3( Matrices.uNormalMatrix * vec4(aNormal, 1.) ) );
        //vColor    = aColor;
        vColor = aInstanceColor;
        vTexCoord = aTexCoord;

        gl_Position = PVM * vec4( aVertex, 1. );
}
```

Descriptor Sets

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In OpenGL

OpenGL puts all uniform data in the same "set", but with different binding numbers, so you can get at each one.

Each uniform variable gets updated one-at-a-time.

Wouldn't it be nice if we could update a collection of related uniform variables all at once, without having to update the uniform variables that are not related to this collection?

```
layout( std140, binding = 0 )  uniform mat4        uModelMatrix;
layout( std140, binding = 1 ) uniform mat4         uViewMatrix;
layout( std140, binding = 2 ) uniform mat4         uProjectionMatrix;
layout( std140, binding = 3 ) uniform mat3         uNormalMatrix;
layout( std140, binding = 4 ) uniform vec4         uLightPos;
layout( std140, binding = 5 ) uniform float        uTime;
layout( std140, binding = 6 ) uniform  int         uMode;
layout(             binding = 7 ) uniform sampler2D uSampler;
```

What are Descriptor Sets?

Descriptor Sets are an intermediate data structure that tells shaders how to connect information held in GPU memory to groups of related uniform variables and texture sampler declarations in shaders. There are three advantages in doing things this way:

- Related uniform variables can be updated as a group, gaining efficiency.
- Descriptor Sets are activated when the Command Buffer is filled. Different values for the uniform buffer variables can be toggled by just swapping out the Descriptor Set that points to GPU memory, rather than re-writing the GPU memory.
- Values for the shaders' uniform buffer variables can be compartmentalized into what quantities change often and what change seldom (scene-level, model-level, draw-level), so that uniform variables need to be re-written no more often than is necessary.

```
for( each scene )
{
        Bind Descriptor Set #0
        for( each object )
        {
                Bind Descriptor Set #1
                for( each draw )
                {
                        Bind Descriptor Set #2
                        Do the drawing
                }
        }
}
```

Descriptor Sets

Our example will assume the following shader uniform variables:

```
// non-opaque must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
        vec4 uLightPos;
} Light;


layout( std140, set = 2, binding = 0 ) uniform miscBuf
{
        float uTime;
        int   uMode;
} Misc;

layout( set = 3, binding = 0 ) uniform sampler2D uSampler;
```

Descriptor Sets

CPU:

Uniform data created in a C++ data structure

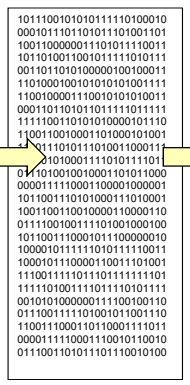
- Knows the CPU data structure
- Knows where the data starts
- Knows the data's size

```
struct matBuf
{
	glm::mat4 uModelMatrix;
	glm::mat4 uViewMatrix;
	glm::mat4 uProjectionMatrix;
	glm::mat3 uNormalMatrix;
};

struct lightBuf
{
	glm::vec4 uLightPos;
};

struct miscBuf
{
	float uTime;
	int   uMode;
};
```

GPU:

Uniform data in a "blob"*

- Knows where the data starts
- Knows the data's size
- Doesn't know the CPU or GPU data structure



* "binary large object"

GPU:

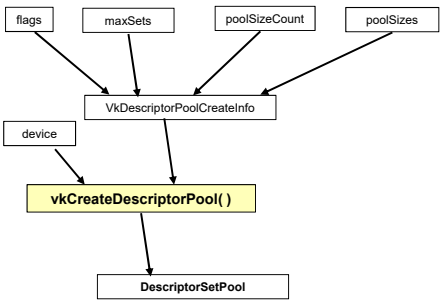
Uniform data used in the shader

- Knows the shader data structure
- Doesn't know where each piece of data starts

```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
	vec4 uLightPos;
} Light;

layout( std140, set = 2, binding = 0 ) uniform miscBuf
{
	float uTime;
	int   uMode;
} Misc;

layout( set = 3, binding = 0 ) uniform sampler2D uSampler;
```


Step 1: Descriptor Set Pools

You don't allocate Descriptor Sets on the fly – that is too slow.
Instead, you allocate a "pool" of Descriptor Sets and then pull from that pool later.



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```
VkResult
Init13DescriptorSetPool( )
{
	VkResult result;

	VkDescriptorPoolSize		vdps[4];
		vdps[0].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		vdps[0].descriptorCount = 1;
		vdps[1].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		vdps[1].descriptorCount = 1;
		vdps[2].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		vdps[2].descriptorCount = 1;
		vdps[3].type = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
		vdps[3].descriptorCount = 1;

#ifdef CHOICES
VK_DESCRIPTOR_TYPE_SAMPLER
VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE
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_UNIFORM_BUFFER
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER
VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC
VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT
#endif

	VkDescriptorPoolCreateInfo		vdpci;
		vdpci.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO;
		vdpci.pNext = nullptr;
		vdpci.flags = 0;
		vdpci.maxSets = 4;
		vdpci.poolSizeCount = 4;
		vdpci.pPoolSizes = &vdps[0];

	result = vkCreateDescriptorPool( LogicalDevice, IN &vdpci, PALLOCATOR, OUT &DescriptorPool);
	return result;
}
```


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Step 2: Define the Descriptor Set Layouts

I think of Descriptor Set Layouts as a kind of "Rosetta Stone" that allows the Graphics Pipeline data structure to allocate room for the uniform variables and to access them.

https://www.britishmuseum.org

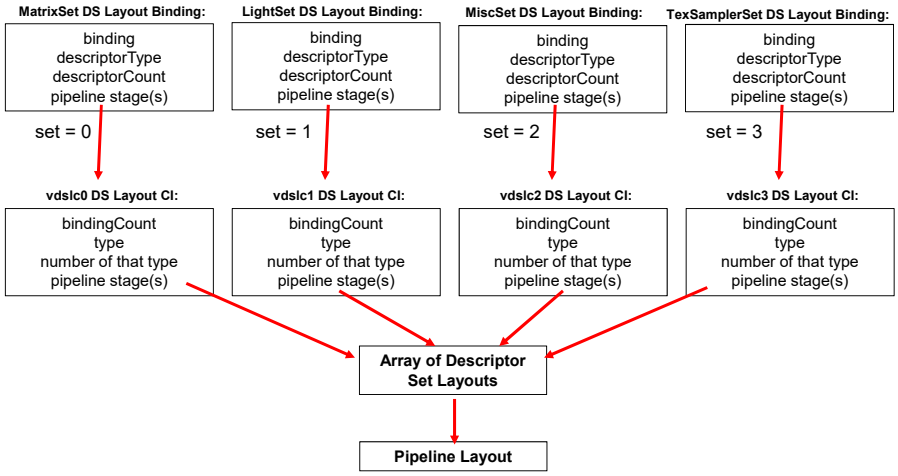
```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
	vec4 uLightPos;
} Light;

layout( std140, set = 2, binding = 0 ) uniform miscBuf
{
	float uTime;
	int   uMode;
} Misc;

layout( set = 3, binding = 0 ) uniform sampler2D uSampler;
```

MatrixSet DS Layout Binding:	LightSet DS Layout Binding:	MiscSet DS Layout Binding:	TexSamplerSet DS Layout Binding:
binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)
set = 0	set = 1	set = 2	set = 3

```
VkResult
Init13DescriptorSetLayouts( )
{
	VkResult result;

	//DS #0:
	VkDescriptorSetLayoutBinding		MatrixSet[1];
		MatrixSet[0].binding		= 0;
		MatrixSet[0].descriptorType	= VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		MatrixSet[0].descriptorCount	= 1;
		MatrixSet[0].stageFlags		= VK_SHADER_STAGE_VERTEX_BIT;
		MatrixSet[0].pImmutableSamplers = (VkSampler *)nullptr;

	// DS #1:
	VkDescriptorSetLayoutBinding		LightSet[1];
		LightSet[0].binding		= 0;
		LightSet[0].descriptorType	= VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		LightSet[0].descriptorCount	= 1;
		LightSet[0].stageFlags		= VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
		LightSet[0].pImmutableSamplers = (VkSampler *)nullptr;

	//DS #2:
	VkDescriptorSetLayoutBinding		MiscSet[1];
		MiscSet[0].binding		= 0;
		MiscSet[0].descriptorType	= VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		MiscSet[0].descriptorCount	= 1;
		MiscSet[0].stageFlags		= VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
		MiscSet[0].pImmutableSamplers = (VkSampler *)nullptr;

	// DS #3:
	VkDescriptorSetLayoutBinding		TexSamplerSet[1];
		TexSamplerSet[0].binding		= 0;
		TexSamplerSet[0].descriptorType	= VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
		TexSamplerSet[0].descriptorCount	= 1;
		TexSamplerSet[0].stageFlags		= VK_SHADER_STAGE_FRAGMENT_BIT;
		TexSamplerSet[0].pImmutableSamplers = (VkSampler *)nullptr;
```

```
uniform sampler2D   uSampler;
vec4 rgba = texture( uSampler, vST );
```

Step 2: Define the Descriptor Set Layouts



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```
VkDescriptorSetLayoutCreateInfo  vdslc0;
    vdslc0.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc0.pNext = nullptr;
    vdslc0.flags = 0;
    vdslc0.bindingCount = 1;
    vdslc0.pBindings = &MatrixSet[0];

VkDescriptorSetLayoutCreateInfo  vdslc1;
    vdslc1.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc1.pNext = nullptr;
    vdslc1.flags = 0;
    vdslc1.bindingCount = 1;
    vdslc1.pBindings = &LightSet[0];

VkDescriptorSetLayoutCreateInfo  vdslc2;
    vdslc2.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc2.pNext = nullptr;
    vdslc2.flags = 0;
    vdslc2.bindingCount = 1;
    vdslc2.pBindings = &MiscSet[0];

VkDescriptorSetLayoutCreateInfo  vdslc3;
    vdslc3.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc3.pNext = nullptr;
    vdslc3.flags = 0;
    vdslc3.bindingCount = 1;
    vdslc3.pBindings = &TexSamplerSet[0];

result = vkCreateDescriptorSetLayout( LogicalDevice, IN &vdslc0, PALLOCATOR, OUT &DescriptorSetLayouts[0] );
result = vkCreateDescriptorSetLayout( LogicalDevice, IN &vdslc1, PALLOCATOR, OUT &DescriptorSetLayouts[1] );
result = vkCreateDescriptorSetLayout( LogicalDevice, IN &vdslc2, PALLOCATOR, OUT &DescriptorSetLayouts[2] );
result = vkCreateDescriptorSetLayout( LogicalDevice, IN &vdslc3, PALLOCATOR, OUT &DescriptorSetLayouts[3] );

return result;
}
```


Step 3: Include the Descriptor Set Layouts in a Graphics Pipeline Layout

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```
VkResult
Init14GraphicsPipelineLayout( )
{
    VkResult result;

    VkPipelineLayoutCreateInfo  vplci;
        vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
        vplci.pNext = nullptr;
        vplci.flags = 0;
        vplci.setLayoutCount = 4;
        vplci.pSetLayouts = &DescriptorSetLayouts[0];
        vplci.pushConstantRangeCount = 0;
        vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

    result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR, OUT &GraphicsPipelineLayout );

    return result;
}
```

Step 4: Allocating the Memory for Descriptor Sets


```
VkResult
Init13DescriptorSets( )
{
	VkResult result;

	VkDescriptorSetAllocateInfo		vdsai;
		vdsai.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO;
		vdsai.pNext = nullptr;
		vdsai.descriptorPool = DescriptorPool;
		vdsai.descriptorSetCount = 4;
		vdsai.pSetLayouts = DescriptorSetLayouts;

	result = vkAllocateDescriptorSets( LogicalDevice, IN &vdsai, OUT &DescriptorSets[0] );
```

Step 5: Tell the Descriptor Sets where their CPU Data is


```
VkDescriptorBufferInfo		vdbi0;
	vdbi0.buffer = MyMatrixUniformBuffer.buffer;
	vdbi0.offset = 0;
	vdbi0.range = sizeof(Matrices);

VkDescriptorBufferInfo		vdbi1;
	vdbi1.buffer = MyLightUniformBuffer.buffer;
	vdbi1.offset = 0;
	vdbi1.range = sizeof(Light);

VkDescriptorBufferInfo		vdbi2;
	vdbi2.buffer = MyMiscUniformBuffer.buffer;
	vdbi2.offset = 0;
	vdbi2.range = sizeof(Misc);

VkDescriptorImageInfo		vdii0;
	vdii.sampler     = MyPuppyTexture.texSampler;
	vdii.imageView = MyPuppyTexture.texImageView;
	vdii.imageLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
```

This struct identifies what buffer it owns and how big it is

This struct identifies what buffer it owns and how big it is

This struct identifies what buffer it owns and how big it is

This struct identifies what texture sampler and image view it owns

Step 5: Tell the Descriptor Sets where their CPU Data is

This struct links a Descriptor Set to the buffer it is pointing tto

```
VkWriteDescriptorSet            vwds0;
        // ds 0:
        vwds0.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds0.pNext = nullptr;
        vwds0.dstSet = DescriptorSets[0];
        vwds0.dstBinding = 0;
        vwds0.dstArrayElement = 0;
        vwds0.descriptorCount = 1;
        vwds0.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        vwds0.pBufferInfo = IN &vdbi0;
        vwds0.pImageInfo = (VkDescriptorImageInfo *)nullptr;
        vwds0.pTexelBufferView = (VkBufferView *)nullptr;
```

This struct links a Descriptor Set to the buffer it is pointing tto

```
        // ds 1:
    VkWriteDescriptorSet            vwds1;
        vwds1.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds1.pNext = nullptr;
        vwds1.dstSet = DescriptorSets[1];
        vwds1.dstBinding = 0;
        vwds1.dstArrayElement = 0;
        vwds1.descriptorCount = 1;
        vwds1.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        vwds1.pBufferInfo = IN &vdbi1;
        vwds1.pImageInfo = (VkDescriptorImageInfo *)nullptr;
        vwds1.pTexelBufferView = (VkBufferView *)nullptr;
```

Step 5: Tell the Descriptor Sets where their data is

This struct links a Descriptor Set to the buffer it is pointing tto

```
    VkWriteDescriptorSet            vwds2;
        // ds 2:
        vwds2.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds2.pNext = nullptr;
        vwds2.dstSet = DescriptorSets[2];
        vwds2.dstBinding = 0;
        vwds2.dstArrayElement = 0;
        vwds2.descriptorCount = 1;
        vwds2.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        vwds2.pBufferInfo = IN &vdbi2;
        vwds2.pImageInfo = (VkDescriptorImageInfo *)nullptr;
        vwds2.pTexelBufferView = (VkBufferView *)nullptr;
```

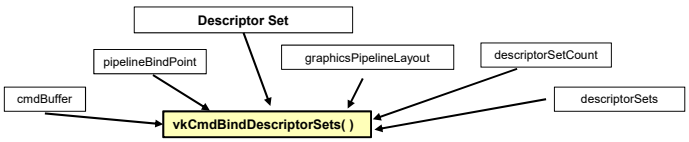
This struct links a Descriptor Set to the image it is pointing to

```
        // ds 3:
    VkWriteDescriptorSet            vwds3;
        vwds3.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds3.pNext = nullptr;
        vwds3.dstSet = DescriptorSets[3];
        vwds3.dstBinding = 0;
        vwds3.dstArrayElement = 0;
        vwds3.descriptorCount = 1;
        vwds3.descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
        vwds3.pBufferInfo = (VkDescriptorBufferInfo *)nullptr;
        vwds3.pImageInfo = IN &vdii0;
        vwds3.pTexelBufferView = (VkBufferView *)nullptr;

    uint32_t copyCount = 0;

    // this could have been done with one call and an array of VkWriteDescriptorSets:

    vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds0, IN copyCount, (VkCopyDescriptorSet *)nullptr );
    vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds1, IN copyCount, (VkCopyDescriptorSet *)nullptr );
    vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds2, IN copyCount, (VkCopyDescriptorSet *)nullptr );
    vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds3, IN copyCount, (VkCopyDescriptorSet *)nullptr );
```

Step 6: Include the Descriptor Set Layout when Creating a Graphics Pipeline


```
VkGraphicsPipelineCreateInfo                vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
        vgpci.flags = 0;
#ifdef CHOICES
VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT
VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT
VK_PIPELINE_CREATE_DERIVATIVE_BIT
#endif
        vgpci.stageCount = 2;                   // number of stages in this pipeline
        vgpci.pStages = vpssci;
        vgpci.pVertexInputState = &vpvisci;
        vgpci.pInputAssemblyState = &vpiasci;
        vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;
        vgpci.pViewportState = &vpvsci;
        vgpci.pRasterizationState = &vprsci;
        vgpci.pMultisampleState = &vpmsci;
        vgpci.pDepthStencilState = &vpdssci;
        vgpci.pColorBlendState = &vpcbsci;
        vgpci.pDynamicState = &vpdsci;
        vgpci.layout = IN GraphicsPipelineLayout;
        vgpci.renderPass = IN RenderPass;
        vgpci.subpass = 0;                      // subpass number
        vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
        vgpci.basePipelineIndex = 0;

    result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,
                                        PALLOCATOR, OUT &GraphicsPipeline );
```


Step 7: Bind Descriptor Sets into the Command Buffer when Drawing




```
vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex],
                VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipelineLayout,
                0, 4, DescriptorSets, 0, (uint32_t *)nullptr );
```

So, the Pipeline Layout contains the ***structure*** of the Descriptor Sets.
Any collection of Descriptor Sets that match that structure can be bound into that pipeline.

Textures

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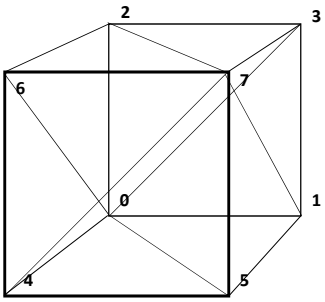
Triangles in an Array of Structures

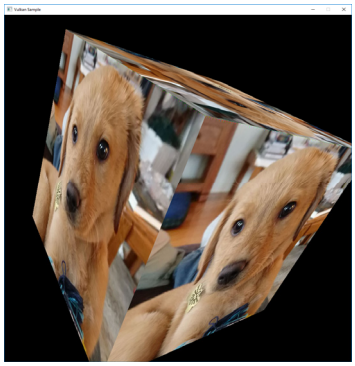
```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

struct vertex VertexData[ ] =
{
	// triangle 0-2-3:
	// vertex #0:
	{
		{ -1., -1., -1. },
		{  0.,  0., -1. },
		{  0.,  0.,  0. },
		{  1., 0. }
	},

	// vertex #2:
	{
		{ -1.,  1., -1. },
		{  0.,  0., -1. },
		{  0.,  1.,  0. },
		{  1., 1. }
	},

	// vertex #3:
	{
		{  1.,  1., -1. },
		{  0.,  0., -1. },
		{  1.,  1.,  0. },
		{  0., 1. }
	},
```





Memory Types

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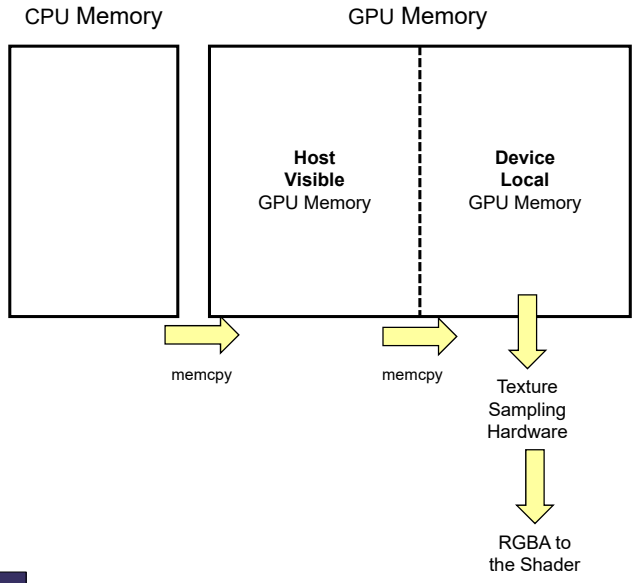

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Memory Types

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NVIDIA Discrete Graphics:

11 Memory Types:
Memory 0:
Memory 1:
Memory 2:
Memory 3:
Memory 4:
Memory 5:
Memory 6:
Memory 7: DeviceLocal
Memory 8: DeviceLocal
Memory 9: HostVisible HostCoherent
Memory 10: HostVisible HostCoherent HostCached

Intel Integrated Graphics:

3 Memory Types:
Memory 0: DeviceLocal
Memory 1: DeviceLocal HostVisible HostCoherent
Memory 2: DeviceLocal HostVisible HostCoherent HostCached

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Texture Sampling Parameters

OpenGL

```
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
```

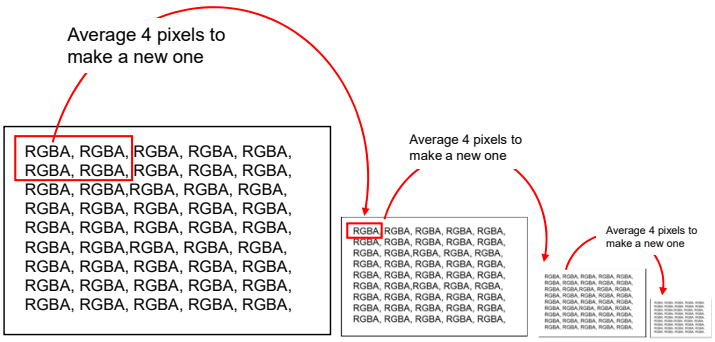
Vulkan

```
VkSamplerCreateInfo                 vsci;
        vsci.magFilter = VK_FILTER_LINEAR;
        vsci.minFilter  = VK_FILTER_LINEAR;
        vsci.mipmapMode    = VK_SAMPLER_MIPMAP_MODE_LINEAR;
        vsci.addressModeU  = VK_SAMPLER_ADDRESS_MODE_REPEAT;
        vsci.addressModeV  = VK_SAMPLER_ADDRESS_MODE_REPEAT;
        vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;

        . . .

result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, pTextureSampler );
```


Texture Mip*-mapping



- Total texture storage is ~ 2x what it was without mip-mapping
- Graphics hardware determines which level to use based on the texels : pixels ratio.
- In addition to just picking one mip-map level, the rendering system can sample from two of them, one less that the T:P ratio and one more, and then blend the two RGBAs returned. This is known as **VK_SAMPLER_MIPMAP_MODE_LINEAR**.

* Latin: *multim in parvo*, “many things in a small place”

```
VkResult
Init07TextureSampler( MyTexture * pMyTexture )
{
	VkResult result;

	VkSamplerCreateInfo			vsci;
		vsci.sType = VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO;
		vsci.pNext = nullptr;
		vsci.flags = 0;
		vsci.magFilter = VK_FILTER_LINEAR;
		vsci.minFilter = VK_FILTER_LINEAR;
		vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
		vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
		vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
		vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;
#ifdef CHOICES
VK_SAMPLER_ADDRESS_MODE_REPEAT
VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT
VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE
VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER
VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE
#endif
		vsci.mipLodBias = 0.;
		vsci.anisotropyEnable = VK_FALSE;
		vsci.maxAnisotropy = 1.;
		vsci.compareEnable = VK_FALSE;
		vsci.compareOp = VK_COMPARE_OP_NEVER;
#ifdef CHOICES
VK_COMPARE_OP_NEVER
VK_COMPARE_OP_LESS
VK_COMPARE_OP_EQUAL
VK_COMPARE_OP_LESS_OR_EQUAL
VK_COMPARE_OP_GREATER
VK_COMPARE_OP_NOT_EQUAL
VK_COMPARE_OP_GREATER_OR_EQUAL
VK_COMPARE_OP_ALWAYS
#endif
		vsci.minLod = 0.;
		vsci.maxLod = 0.;
		vsci.borderColor = VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK;
#ifdef CHOICES
VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK
VK_BORDER_COLOR_INT_TRANSPARENT_BLACK
VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK
VK_BORDER_COLOR_INT_OPAQUE_BLACK
VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE
VK_BORDER_COLOR_INT_OPAQUE_WHITE
#endif
		vsci.unnormalizedCoordinates = VK_FALSE;	// VK_TRUE means we are use raw texels as the index
								// VK_FALSE means we are using the usual 0. - 1.

	result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, OUT &pMyTexture->texSampler );
```


```
VkResult
Init07TextureBuffer( INOUT MyTexture * pMyTexture)
{
	VkResult result;

	uint32_t texWidth = pMyTexture->width;;
	uint32_t texHeight = pMyTexture->height;
	unsigned char *texture = pMyTexture->pixels;
	VkDeviceSize textureSize = texWidth * texHeight * 4;		// rgba, 1 byte each

	VkImage  stagingImage;
	VkImage  textureImage;

	// *****************************************************************************
	// this first {...} is to create the staging image:
	// *****************************************************************************
	{
		VkImageCreateInfo		vici;
			vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
			vici.pNext = nullptr;
			vici.flags = 0;
			vici.imageType = VK_IMAGE_TYPE_2D;
			vici.format = VK_FORMAT_R8G8B8A8_UNORM;
			vici.extent.width = texWidth;
			vici.extent.height = texHeight;
			vici.extent.depth = 1;
			vici.mipLevels = 1;
			vici.arrayLayers = 1;
			vici.samples = VK_SAMPLE_COUNT_1_BIT;
			vici.tiling = VK_IMAGE_TILING_LINEAR;
#ifdef CHOICES
VK_IMAGE_TILING_OPTIMAL
VK_IMAGE_TILING_LINEAR
#endif
			vici.usage = VK_IMAGE_USAGE_TRANSFER_SRC_BIT;
#ifdef CHOICES
VK_IMAGE_USAGE_TRANSFER_SRC_BIT
VK_IMAGE_USAGE_TRANSFER_DST_BIT
VK_IMAGE_USAGE_SAMPLED_BIT
VK_IMAGE_USAGE_STORAGE_BIT
VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT
VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
#endif
			vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
```

```
#ifdef CHOICES
VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_PREINITIALIZED
#endif
        vici.queueFamilyIndexCount = 0;
        vici.pQueueFamilyIndices = (const uint32_t *)nullptr;

    result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &stagingImage); // allocated, but not filled

    VkMemoryRequirements        vmr;
    vkGetImageMemoryRequirements( LogicalDevice, IN stagingImage, OUT &vmr);

    if (Verbose)
    {
        fprintf(FpDebug, "Image vmr.size = %lld\n", vmr.size);
        fprintf(FpDebug, "Image vmr.alignment = %lld\n", vmr.alignment);
        fprintf(FpDebug, "Image vmr.memoryTypeBits = 0x%08x\n", vmr.memoryTypeBits);
        fflush(FpDebug);
    }

    VkMemoryAllocateInfo        vmai;
        vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
        vmai.pNext = nullptr;
        vmai.allocationSize = vmr.size;
        vmai.memoryTypeIndex = FindMemoryThatIsHostVisible();   // because we want to mmap it

    VkDeviceMemory              vdm;
    result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);
    pMyTexture->vdm = vdm;

    result = vkBindImageMemory( LogicalDevice, IN stagingImage, IN vdm, 0);  // 0 = offset

    // we have now created the staging image -- fill it with the pixel data:

    VkImageSubresource          vis;
        vis.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        vis.mipLevel = 0;
        vis.arrayLayer = 0;

    VkSubresourceLayout         vsl;
    vkGetImageSubresourceLayout( LogicalDevice, stagingImage, IN &vis, OUT &vsl);

    if (Verbose)
    {
        fprintf(FpDebug, "Subresource Layout:\n");
        fprintf(FpDebug, "\toffset = %lld\n", vsl.offset);
        fprintf(FpDebug, "\tsize = %lld\n", vsl.size);
        fprintf(FpDebug, "\trowPitch = %lld\n", vsl.rowPitch);
        fprintf(FpDebug, "\tarrayPitch = %lld\n", vsl.arrayPitch);
        fprintf(FpDebug, "\tdepthPitch = %lld\n", vsl.depthPitch);
        fflush(FpDebug);
    }
```



```
    void * gpuMemory;
    vkMapMemory( LogicalDevice, vdm, 0, VK_WHOLE_SIZE, 0, OUT &gpuMemory);
                        // 0 and 0 = offset and memory map flags

    if (vsl.rowPitch == 4 * texWidth)
    {
        memcpy(gpuMemory, (void *)texture, (size_t)textureSize);
    }
    else
    {
        unsigned char *gpuBytes = (unsigned char *)gpuMemory;
        for (unsigned int y = 0; y < texHeight; y++)
        {
            memcpy(&gpuBytes[y * vsl.rowPitch], &texture[4 * y * texWidth], (size_t)(4*texWidth) );
        }
    }

    vkUnmapMemory( LogicalDevice, vdm);

}
// *************************************************************************
```

```
// ********************************************************************************
// this second {...} is to create the actual texture image:
// ********************************************************************************
{
	VkImageCreateInfo		vici;
		vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
		vici.pNext = nullptr;
		vici.flags = 0;
		vici.imageType = VK_IMAGE_TYPE_2D;
		vici.format = VK_FORMAT_R8G8B8A8_UNORM;
		vici.extent.width  = texWidth;
		vici.extent.height = texHeight;
		vici.extent.depth = 1;
		vici.mipLevels = 1;
		vici.arrayLayers = 1;
		vici.samples = VK_SAMPLE_COUNT_1_BIT;
		vici.tiling = VK_IMAGE_TILING_OPTIMAL;
		vici.usage = VK_IMAGE_USAGE_TRANSFER_DST_BIT | VK_IMAGE_USAGE_SAMPLED_BIT;
			// because we are transferring into it and will eventual sample from it
		vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
		vici.initialLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
		vici.queueFamilyIndexCount = 0;
		vici.pQueueFamilyIndices = (const uint32_t *)nullptr;

	result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &textureImage); // allocated, but not filled

	VkMemoryRequirements		vmr;
	vkGetImageMemoryRequirements( LogicalDevice, IN textureImage, OUT &vmr);

	if( Verbose )
	{
		fprintf( FpDebug, "Texture vmr.size = %lld\n", vmr.size );
		fprintf( FpDebug, "Texture vmr.alignment = %lld\n", vmr.alignment );
		fprintf( FpDebug, "Texture vmr.memoryTypeBits = 0x%08x\n", vmr.memoryTypeBits );
		fflush( FpDebug );
	}
	VkMemoryAllocateInfo		vmai;
		vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
		vmai.pNext = nullptr;
		vmai.allocationSize = vmr.size;
		vmai.memoryTypeIndex = FindMemoryThatIsDeviceLocal( );  // because we want to sample from it

	VkDeviceMemory			vdm;
	result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);

	result = vkBindImageMemory( LogicalDevice, IN textureImage, IN vdm, 0 );	// 0 = offset
}
// ********************************************************************************
```



```
	// copy pixels from the staging image to the texture:

	VkCommandBufferBeginInfo		vcbbi;
		vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
		vcbbi.pNext = nullptr;
		vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
		vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

	result = vkBeginCommandBuffer( TextureCommandBuffer, IN &vcbbi);

	// ********************************************************************************
	// transition the staging buffer layout:
	// ********************************************************************************
	{
		VkImageSubresourceRange		visr;
			visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
			visr.baseMipLevel = 0;
			visr.levelCount = 1;
			visr.baseArrayLayer = 0;
			visr.layerCount = 1;

		VkImageMemoryBarrier		vimb;
			vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
			vimb.pNext = nullptr;
			vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
			vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL;
			vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
			vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
			vimb.image = stagingImage;
			vimb.srcAccessMask = VK_ACCESS_HOST_WRITE_BIT;
			vimb.dstAccessMask = 0;
			vimb.subresourceRange = visr;

		vkCmdPipelineBarrier( TextureCommandBuffer,
				VK_PIPELINE_STAGE_HOST_BIT, VK_PIPELINE_STAGE_HOST_BIT, 0,
				0, (VkMemoryBarrier *)nullptr,
				0, (VkBufferMemoryBarrier *)nullptr,
				1, IN &vimb );
	}
	// ********************************************************************************
```

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```
// ********************************************************************************
// transition the texture buffer layout:
// ********************************************************************************
{
	VkImageSubresourceRange		visr;
		visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
		visr.baseMipLevel = 0;
		visr.levelCount = 1;
		visr.baseArrayLayer = 0;
		visr.layerCount = 1;

	VkImageMemoryBarrier		vimb;
		vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
		vimb.pNext = nullptr;
		vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
		vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
		vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
		vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
		vimb.image = textureImage;
		vimb.srcAccessMask = 0;
		vimb.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;
		vimb.subresourceRange = visr;

	vkCmdPipelineBarrier( TextureCommandBuffer,
		VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_TRANSFER_BIT, 0,
		0, (VkMemoryBarrier *)nullptr,
		0, (VkBufferMemoryBarrier *)nullptr,
		1, IN &vimb);

	// now do the final image transfer:

	VkImageSubresourceLayers	visl;
		visl.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
		visl.baseArrayLayer = 0;
		visl.mipLevel = 0;
		visl.layerCount = 1;

	VkOffset3D			vo3;
		vo3.x = 0;
		vo3.y = 0;
		vo3.z = 0;

	VkExtent3D			ve3;
		ve3.width = texWidth;
		ve3.height = texHeight;
		ve3.depth = 1;
```


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```
	VkImageCopy			vic;
		vic.srcSubresource = visl;
		vic.srcOffset = vo3;
		vic.dstSubresource = visl;
		vic.dstOffset = vo3;
		vic.extent = ve3;

	vkCmdCopyImage(TextureCommandBuffer,
		stagingImage, VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL,
		textureImage, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, IN &vic);
}
// ********************************************************************************
```

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```
// ********************************************************************************
// transition the texture buffer layout a second time:
// ********************************************************************************
	{
		VkImageSubresourceRange		visr;
			visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
			visr.baseMipLevel = 0;
			visr.levelCount = 1;
			visr.baseArrayLayer = 0;
			visr.layerCount = 1;

		VkImageMemoryBarrier		vimb;
			vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
			vimb.pNext = nullptr;
			vimb.oldLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
			vimb.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
			vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
			vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
			vimb.image = textureImage;
			vimb.srcAccessMask = 0;
			vimb.dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
			vimb.subresourceRange = visr;

		vkCmdPipelineBarrier(TextureCommandBuffer,
			VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0,
			0, (VkMemoryBarrier *)nullptr,
			0, (VkBufferMemoryBarrier *)nullptr,
			1, IN &vimb);
	}
	// ********************************************************************************

	result = vkEndCommandBuffer( TextureCommandBuffer );

	VkSubmitInfo		vsi;
		vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
		vsi.pNext = nullptr;
		vsi.commandBufferCount = 1;
		vsi.pCommandBuffers = &TextureCommandBuffer;
		vsi.waitSemaphoreCount = 0;
		vsi.pWaitSemaphores = (VkSemaphore *)nullptr;
		vsi.signalSemaphoreCount = 0;
		vsi.pSignalSemaphores = (VkSemaphore *)nullptr;
		vsi.pWaitDstStageMask = (VkPipelineStageFlags *)nullptr;

	result = vkQueueSubmit( Queue, 1, IN &vsi, VK_NULL_HANDLE );
	result = vkQueueWaitIdle( Queue );
```

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```
	// create an image view for the texture image:

	VkImageSubresourceRange		visr;
		visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
		visr.baseMipLevel = 0;
		visr.levelCount = 1;
		visr.baseArrayLayer = 0;
		visr.layerCount = 1;

	VkImageViewCreateInfo		vivci;
		vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
		vivci.pNext = nullptr;
		vivci.flags = 0;
		vivci.image = textureImage;
		vivci.viewType = VK_IMAGE_VIEW_TYPE_2D;
		vivci.format = VK_FORMAT_R8G8B8A8_UNORM;
		vivci.components.r = VK_COMPONENT_SWIZZLE_R;
		vivci.components.g = VK_COMPONENT_SWIZZLE_G;
		vivci.components.b = VK_COMPONENT_SWIZZLE_B;
		vivci.components.a = VK_COMPONENT_SWIZZLE_A;
		vivci.subresourceRange = visr;

	result = vkCreateImageView( LogicalDevice, IN &vivci, PALLOCATOR, OUT &pMyTexture->texImageView);

	return result;
}
```

Note that, at this point, the Staging Buffer is no longer needed, and can be destroyed.

Reading in a Texture from a BMP File


```
typedef struct MyTexture
{
        uint32_t                width;
        uint32_t                height;
        VkImage                 texImage;
        VkImageView             texImageView;
        VkSampler               texSampler;
        VkDeviceMemory          vdm;
} MyTexture;

...

MyTexture       MyPuppyTexture;
```

```
result = Init06TextureBufferAndFillFromBmpFile ( "puppy.bmp", &MyTexturePuppy);
Init06TextureSampler( &MyPuppyTexture.texSampler );
```

This function can be found in the **sample.cpp** file. The BMP file needs to be created by something that writes uncompressed 24-bit color BMP files, or was converted to the uncompressed BMP format by a tool such as ImageMagick's *convert*, Adobe *Photoshop*, or GNU's *GIMP*.

The Graphics Pipeline Data Structure

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What is the Vulkan Graphics Pipeline?

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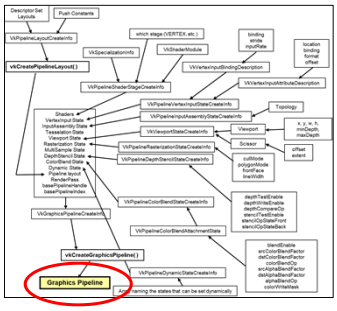
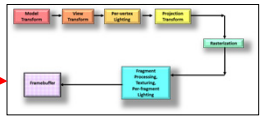


Don't worry if this is too small to read – a larger version is coming up.

There is also a Vulkan Compute Pipeline – we will get to that later.

Here's what you need to know:

1. The Vulkan Graphics Pipeline is like what OpenGL would call "The State", or "The Context". It is a ***data structure***.
2. The Vulkan Graphics Pipeline is *not* the processes that OpenGL would call "the graphics pipeline".



3. For the most part, the Vulkan Graphics Pipeline is meant to be immutable – that is, once this combination of state variables is combined into a Pipeline, that Pipeline never gets changed. To make new combinations of state variables, create a new Graphics Pipelines.
4. The shaders get compiled the rest of the way when their Graphics Pipeline gets created.

The First Step: Create the Graphics Pipeline Layout

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The Graphics Pipeline Layout is fairly static. Only the layout of the Descriptor Sets and information on the Push Constants need to be supplied.

```
VkResult
Init14GraphicsPipelineLayout( )
{
	VkResult result;

	VkPipelineLayoutCreateInfo		vplci;
		vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
		vplci.pNext = nullptr;
		vplci.flags = 0;
		vplci.setLayoutCount = 4;
		vplci.pSetLayouts = &DescriptorSetLayouts[0];
		vplci.pushConstantRangeCount = 0;
		vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

	result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR, OUT &GraphicsPipelineLayout );

	return result;
}
```

Let the Pipeline Layout know about the Descriptor Set and Push Constant layouts.

Vulkan: A Pipeline Records the Following Items:

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- Pipeline Layout: DescriptorSets, PushConstants
- Which Shaders are going to be used
- Per-vertex input attributes: location, binding, format, offset
- Per-vertex input bindings: binding, stride, inputRate
- Assembly: topology
- ***Viewport***: x, y, w, h, minDepth, maxDepth
- ***Scissoring***: x, y, w, h
- Rasterization: cullMode, polygonMode, frontFace, ***lineWidth***
- Depth: depthTestEnable, depthWriteEnable, depthCompareOp
- Stencil: stencilTestEnable, stencilOpStateFront, stencilOpStateBack
- Blending: blendEnable, ***srcColorBlendFactor, dstColorBlendFactor,*** colorBlendOp***, srcAlphaBlendFactor, dstAlphaBlendFactor,*** alphaBlendOp, colorWriteMask
- DynamicState: which states can be set dynamically (bound to the command buffer, outside the Pipeline)

Bold/Italics indicates that this state item can also be set with Dynamic Variables

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Creating a Graphics Pipeline from a lot of Pieces

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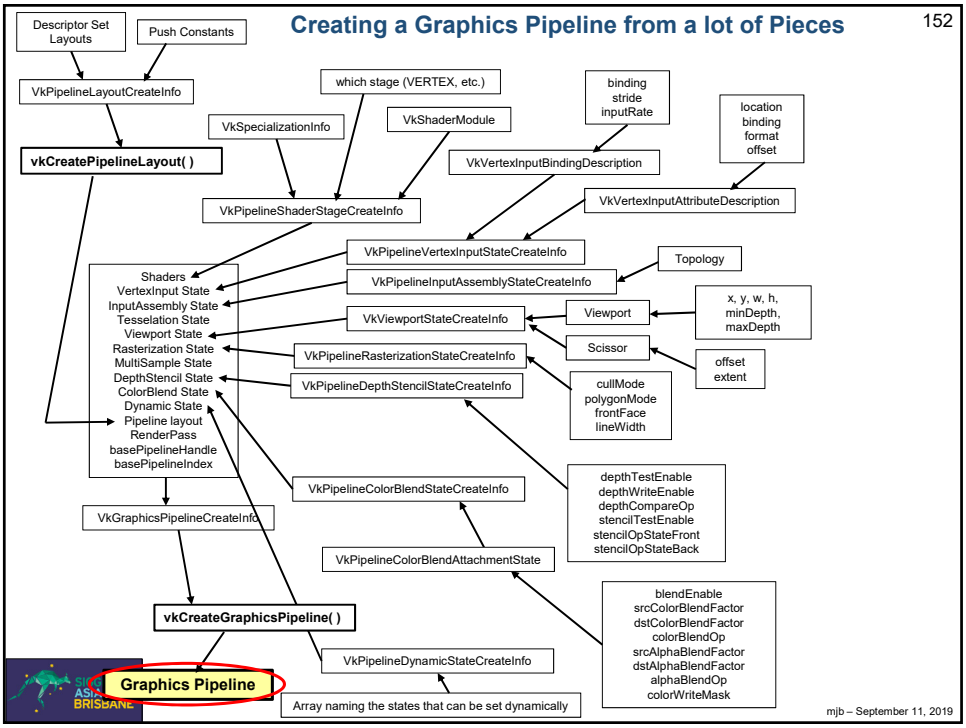

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Creating a Typical Graphics Pipeline

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```
VkResult
Init14GraphicsVertexFragmentPipeline( VkShaderModule vertexShader, VkShaderModule fragmentShader,
                                      VkPrimitiveTopology topology, OUT VkPipeline *pGraphicsPipeline  )
{
#ifdef ASSUMPTIONS
        vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
        vprsci.depthClampEnable = VK_FALSE;
        vprsci.rasterizerDiscardEnable = VK_FALSE;
        vprsci.polygonMode = VK_POLYGON_MODE_FILL;
        vprsci.cullMode = VK_CULL_MODE_NONE;    // best to do this because of the projectionMatrix[1][1] *= -1.;
        vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
        vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_ONE_BIT;
        vpcbas.blendEnable = VK_FALSE;
        vpcbsci.logicOpEnable = VK_FALSE;
        vpdssci.depthTestEnable = VK_TRUE;
        vpdssci.depthWriteEnable = VK_TRUE;
        vpdssci.depthCompareOp = VK_COMPARE_OP_LESS;
#endif

    . . .
```

These settings seem pretty typical to me. Let's write a simplified Pipeline-creator that accepts Vertex and Fragment shader modules and the topology, and always uses the settings in red above.

Link in the Shaders

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```
VkPipelineShaderStageCreateInfo                 vpssci[2];
        vpssci[0].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci[0].pNext = nullptr;
        vpssci[0].flags = 0;
        vpssci[0].stage = VK_SHADER_STAGE_VERTEX_BIT;
        vpssci[0].module = vertexShader;
        vpssci[0].pName = "main";
        vpssci[0].pSpecializationInfo = (VkSpecializationInfo *)nullptr;
#ifdef BITS
VK_SHADER_STAGE_VERTEX_BIT
VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT
VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT
VK_SHADER_STAGE_GEOMETRY_BIT
VK_SHADER_STAGE_FRAGMENT_BIT
VK_SHADER_STAGE_COMPUTE_BIT
VK_SHADER_STAGE_ALL_GRAPHICS
VK_SHADER_STAGE_ALL
#endif
        vpssci[1].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci[1].pNext = nullptr;
        vpssci[1].flags = 0;
        vpssci[1].stage = VK_SHADER_STAGE_FRAGMENT_BIT;
        vpssci[1].module = fragmentShader;
        vpssci[1].pName = "main";
        vpssci[1].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

    VkVertexInputBindingDescription             vvibd[1];   // an array containing one of these per buffer being used
        vvibd[0].binding = 0;           // which binding # this is
        vvibd[0].stride = sizeof( struct vertex );          // bytes between successive
        vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
#ifdef CHOICES
VK_VERTEX_INPUT_RATE_VERTEX
VK_VERTEX_INPUT_RATE_INSTANCE
#endif
```

Use one **vpssci** array member per shader module you are using

Use one **vvibd** array member per vertex input array-of-structures you are using

Link in the Per-Vertex Attributes


```
VkVertexInputAttributeDescription		vviad[4];		// an array containing one of these per vertex attribute in all bindings
	// 4 = vertex, normal, color, texture coord
	vviad[0].location = 0;			// location in the layout
	vviad[0].binding = 0;			// which binding description this is part of
	vviad[0].format = VK_FORMAT_VEC3;	// x, y, z
	vviad[0].offset = offsetof( struct vertex, position );		// 0
#ifdef EXTRAS_DEFINED_AT_THE_TOP
// these are here for convenience and readability:
#define VK_FORMAT_VEC4		VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_XYZW		VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_VEC3		VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_STP		VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_XYZ		VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_VEC2		VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_ST		VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_XY		VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_FLOAT		VK_FORMAT_R32_SFLOAT
#define VK_FORMAT_S		VK_FORMAT_R32_SFLOAT
#define VK_FORMAT_X		VK_FORMAT_R32_SFLOAT
#endif
	vviad[1].location = 1;
	vviad[1].binding = 0;
	vviad[1].format = VK_FORMAT_VEC3;	// nx, ny, nz
	vviad[1].offset = offsetof( struct vertex, normal );		// 12

	vviad[2].location = 2;
	vviad[2].binding = 0;
	vviad[2].format = VK_FORMAT_VEC3;	// r, g, b
	vviad[2].offset = offsetof( struct vertex, color );		// 24

	vviad[3].location = 3;
	vviad[3].binding = 0;
	vviad[3].format = VK_FORMAT_VEC2;	// s, t
	vviad[3].offset = offsetof( struct vertex, texCoord );		// 36
```

Use one **vviad** array member per element in the struct for the array-of-structures element you are using as vertex input

These are defined at the top of the sample code so that you don't need to use confusing image-looking formats for positions, normals, and tex coords


```
VkPipelineVertexInputStateCreateInfo		vpvisci;		// used to describe the input vertex attributes
	vpvisci.sType = VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO;
	vpvisci.pNext = nullptr;
	vpvisci.flags = 0;
	vpvisci.vertexBindingDescriptionCount = 1;
	vpvisci.pVertexBindingDescriptions = vvibd;
	vpvisci.vertexAttributeDescriptionCount = 4;
	vpvisci.pVertexAttributeDescriptions = vviad;

VkPipelineInputAssemblyStateCreateInfo		vpiasci;
	vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
	vpiasci.pNext = nullptr;
	vpiasci.flags = 0;
	vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;;
#ifdef CHOICES
VK_PRIMITIVE_TOPOLOGY_POINT_LIST
VK_PRIMITIVE_TOPOLOGY_LINE_LIST
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN
VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY
#endif
	vpiasci.primitiveRestartEnable = VK_FALSE;

VkPipelineTessellationStateCreateInfo		vptsci;
	vptsci.sType = VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO;
	vptsci.pNext = nullptr;
	vptsci.flags = 0;
	vptsci.patchControlPoints = 0;		// number of patch control points

// VkPipelineGeometryStateCreateInfo		vpgsci;
	// vptsci.sType = VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO;
	// vptsci.pNext = nullptr;
	// vptsci.flags = 0;
```

Declare the binding descriptions and attribute descriptions

Declare the vertex topology

Tessellation Shader info

Geometry Shader info

What is "Primitive Restart Enable"?

vpiasci.primitiveRestartEnable = VK_FALSE;

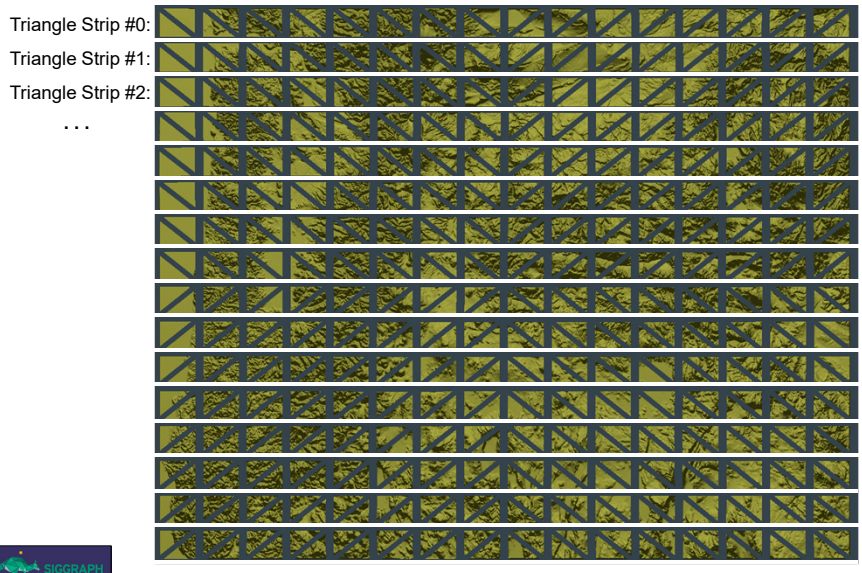
"Restart Enable" is used with:
- Indexed drawing.
- Triangle Fan and *Strip topologies

If vpiasci.primitiveRestartEnable is VK_TRUE, then a special "index" indicates that the primitive should start over. This is more efficient than explicitly ending the current primitive and explicitly starting a new primitive of the same type.

```
typedef enum VkIndexType
{
    VK_INDEX_TYPE_UINT16 = 0,       // 0 –           65,535
    VK_INDEX_TYPE_UINT32 = 1,       // 0 – 4,294,967,295
} VkIndexType;
```

If your VkIndexType is VK_INDEX_TYPE_UINT16, then the special index is 0xffff.
If your VkIndexType is VK_INDEX_TYPE_UINT32, it is 0xffffffff.

One Really Good use of Restart Enable is in Drawing Terrain Surfaces with Triangle Strips



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```
VkViewport                          vv;
        vv.x = 0;
        vv.y = 0;
        vv.width = (float)Width;
        vv.height = (float)Height;
        vv.minDepth = 0.0f;
        vv.maxDepth = 1.0f;

VkRect2D                            vr;
        vr.offset.x = 0;
        vr.offset.y = 0;
        vr.extent.width = Width;
        vr.extent.height = Height;

VkPipelineViewportStateCreateInfo   vpvsci;
        vpvsci.sType = VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO;
        vpvsci.pNext = nullptr;
        vpvsci.flags = 0;
        vpvsci.viewportCount = 1;
        vpvsci.pViewports = &vv;
        vpvsci.scissorCount = 1;
        vpvsci.pScissors = &vr;
```

Declare the viewport information

Declare the scissoring information

Group the viewport and scissor information together

What is the Difference Between Changing the Viewport and Changing the Scissoring?

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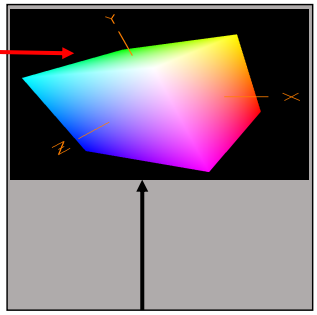
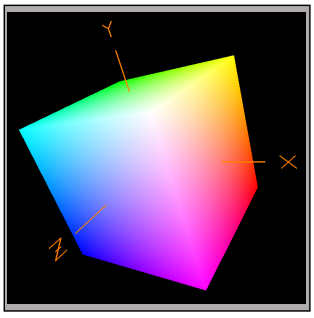
Viewport:

Viewporting operates on ***vertices*** and takes place right before the rasterizer. Changing the vertical part of the **viewport** causes the entire scene to get scaled (scrunched) into the viewport area.

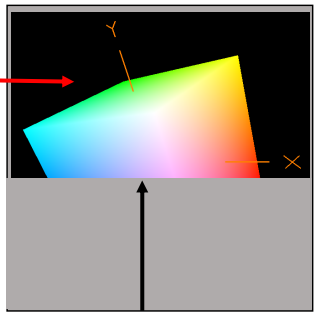


Original Image



Scissoring:

Scissoring operates on ***fragments*** and takes place right after the rasterizer. Changing the vertical part of the **scissor** causes the entire scene to get clipped where it falls outside the scissor area.



Setting the Rasterizer State


```
VkPipelineRasterizationStateCreateInfo vprsci;
        vprsci.sType = VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO;
        vprsci.pNext = nullptr;
        vprsci.flags = 0;
        vprsci.depthClampEnable = VK_FALSE;
        vprsci.rasterizerDiscardEnable = VK_FALSE;
        vprsci.polygonMode = VK_POLYGON_MODE_FILL;
#ifdef CHOICES
VK_POLYGON_MODE_FILL
VK_POLYGON_MODE_LINE
VK_POLYGON_MODE_POINT
#endif
        vprsci.cullMode = VK_CULL_MODE_NONE;      // recommend this because of the projMatrix[1][1] *= -1.;
#ifdef CHOICES
VK_CULL_MODE_NONE
VK_CULL_MODE_FRONT_BIT
VK_CULL_MODE_BACK_BIT
VK_CULL_MODE_FRONT_AND_BACK_BIT
#endif
        vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
#ifdef CHOICES
VK_FRONT_FACE_COUNTER_CLOCKWISE
VK_FRONT_FACE_CLOCKWISE
#endif
        vprsci.depthBiasEnable = VK_FALSE;
        vprsci.depthBiasConstantFactor = 0.f;
        vprsci.depthBiasClamp = 0.f;
        vprsci.depthBiasSlopeFactor = 0.f;
        vprsci.lineWidth = 1.f;
```

Declare information about how the rasterization will take place

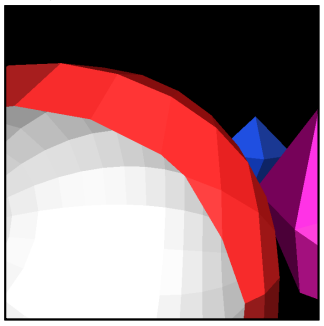
What is "Depth Clamp Enable"?

vprsci.depthClampEnable = VK_FALSE;

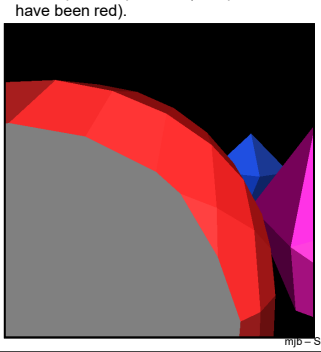
Depth Clamp Enable causes the fragments that would normally have been discarded because they are closer to the viewer than the near clipping plane to instead get projected to the near clipping plane and displayed.

A good use for this is **Polygon Capping**:

The front of the polygon is clipped, revealing to the viewer that this is really a shell, not a solid



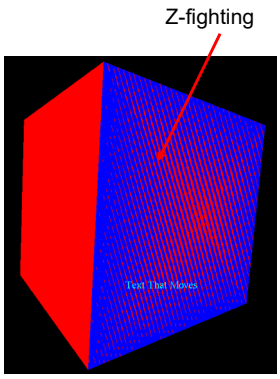
The gray area shows what would happen with depthClampEnable (except it would have been red).



What is "Depth Bias Enable"?


```
vprsci.depthBiasEnable = VK_FALSE;
vprsci.depthBiasConstantFactor = 0.f;
vprsci.depthBiasClamp = 0.f;
vprsci.depthBiasSlopeFactor = 0.f;
```

Depth Bias Enable allows scaling and translation of the Z-depth values as they come through the rasterizer to avoid Z-fighting.



Color Blending State for each Color Attachment

Create an array with one of these for each color buffer attachment.
Each color buffer attachment can use different blending operations.

```
VkPipelineColorBlendAttachmentState        vpcbas;
        vpcbas.blendEnable = VK_FALSE;
        vpcbas.srcColorBlendFactor = VK_BLEND_FACTOR_SRC_COLOR;
        vpcbas.dstColorBlendFactor = VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR;
        vpcbas.colorBlendOp = VK_BLEND_OP_ADD;
        vpcbas.srcAlphaBlendFactor = VK_BLEND_FACTOR_ONE
        vpcbas.dstAlphaBlendFactor = VK_BLEND_FACTOR_ZERO;
        vpcbas.alphaBlendOp = VK_BLEND_OP_ADD;
        vpcbas.colorWriteMask =       VK_COLOR_COMPONENT_R_BIT
                                    | VK_COLOR_COMPONENT_G_BIT
                                    | VK_COLOR_COMPONENT_B_BIT
                                    | VK_COLOR_COMPONENT_A_BIT;
```

This controls blending between the output of each color attachment and its image memory.

Color Blending State for each Color Attachment


```
VkPipelineColorBlendStateCreateInfo		vpcbsci;
		vpcbsci.sType = VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO;
		vpcbsci.pNext = nullptr;
		vpcbsci.flags = 0;
		vpcbsci.logicOpEnable = VK_FALSE;
		vpcbsci.logicOp = VK_LOGIC_OP_COPY;
#ifdef CHOICES
VK_LOGIC_OP_CLEAR
VK_LOGIC_OP_AND
VK_LOGIC_OP_AND_REVERSE
VK_LOGIC_OP_COPY
VK_LOGIC_OP_AND_INVERTED
VK_LOGIC_OP_NO_OP
VK_LOGIC_OP_XOR
VK_LOGIC_OP_OR
VK_LOGIC_OP_NOR
VK_LOGIC_OP_EQUIVALENT
VK_LOGIC_OP_INVERT
VK_LOGIC_OP_OR_REVERSE
VK_LOGIC_OP_COPY_INVERTED
VK_LOGIC_OP_OR_INVERTED
VK_LOGIC_OP_NAND
VK_LOGIC_OP_SET
#endif
		vpcbsci.attachmentCount = 1;
		vpcbsci.pAttachments = &vpcbas;
		vpcbsci.blendConstants[0] = 0;
		vpcbsci.blendConstants[1] = 0;
		vpcbsci.blendConstants[2] = 0;
		vpcbsci.blendConstants[3] = 0;
```

This controls blending between the output of the fragment shader and the input to the color attachments.

Which Pipeline Variables can be Set Dynamically

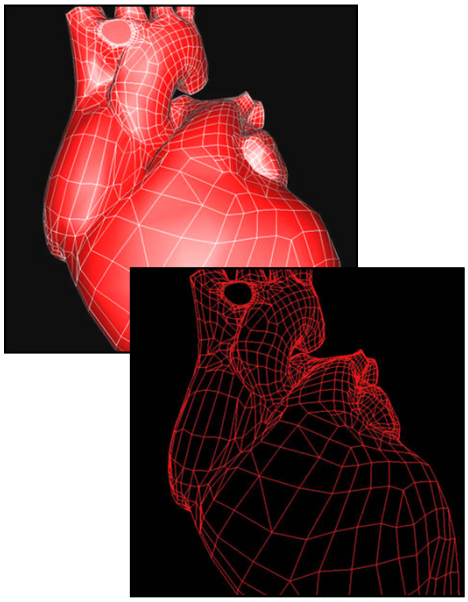

```
VkDynamicState		vds[ ] = { VK_DYNAMIC_STATE_VIEWPORT, VK_DYNAMIC_STATE_SCISSOR };
#ifdef CHOICES
VK_DYNAMIC_STATE_VIEWPORT		--  vkCmdSetViewport( )
VK_DYNAMIC_STATE_SCISSOR		--  vkCmdSetScissor( )
VK_DYNAMIC_STATE_LINE_WIDTH		--  vkCmdSetLineWidth( )
VK_DYNAMIC_STATE_DEPTH_BIAS		-- vkCmdSetDepthBias( )
VK_DYNAMIC_STATE_BLEND_CONSTANTS		-- vkCmdSetBendConstants( )
VK_DYNAMIC_STATE_DEPTH_BOUNDS		-- vkCmdSetDepthZBounds( )
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK		-- vkCmdSetStencilCompareMask( )
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK		-- vkCmdSetStencilWriteMask( )
VK_DYNAMIC_STATE_STENCIL_REFERENCE		-- vkCmdSetStencilReferences( )
#endif
	VkPipelineDynamicStateCreateInfo		vpdsci;
		vpdsci.sType = VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO;
		vpdsci.pNext = nullptr;
		vpdsci.flags = 0;
		vpdsci.dynamicStateCount = 0;		// leave turned off for now
		vpdsci.pDynamicStates = vds;
```

Stencil Operations for Front and Back Faces

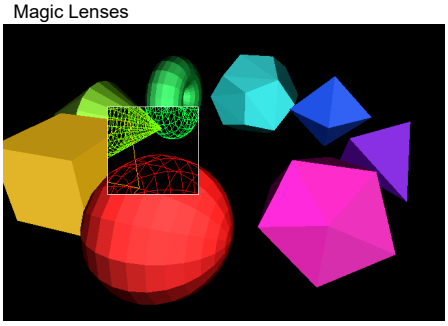

```
VkStencilOpState                                vsosf;      // front
        vsosf.depthFailOp = VK_STENCIL_OP_KEEP;   // what to do if depth operation fails
        vsosf.failOp      = VK_STENCIL_OP_KEEP;   // what to do if stencil operation fails
        vsosf.passOp      = VK_STENCIL_OP_KEEP;   // what to do if stencil operation succeeds
#ifdef CHOICES
VK_STENCIL_OP_KEEP                              -- keep the stencil value as it is
VK_STENCIL_OP_ZERO                              -- set stencil value to 0
VK_STENCIL_OP_REPLACE                           -- replace stencil value with the reference value
VK_STENCIL_OP_INCREMENT_AND_CLAMP               -- increment stencil value
VK_STENCIL_OP_DECREMENT_AND_CLAMP               -- decrement stencil value
VK_STENCIL_OP_INVERT                            -- bit-invert stencil value
VK_STENCIL_OP_INCREMENT_AND_WRAP                -- increment stencil value
VK_STENCIL_OP_DECREMENT_AND_WRAP                -- decrement stencil value
#endif
        vsosf.compareOp = VK_COMPARE_OP_NEVER;
#ifdef CHOICES
VK_COMPARE_OP_NEVER                             -- never succeeds
VK_COMPARE_OP_LESS                              -- succeeds if stencil value is <  the reference value
VK_COMPARE_OP_EQUAL                             -- succeeds if stencil value is == the reference value
VK_COMPARE_OP_LESS_OR_EQUAL                     -- succeeds if stencil value is <= the reference value
VK_COMPARE_OP_GREATER                           -- succeeds if stencil value is >  the reference value
VK_COMPARE_OP_NOT_EQUAL                         -- succeeds if stencil value is !=  the reference value
VK_COMPARE_OP_GREATER_OR_EQUAL                  -- succeeds if stencil value is >= the reference value
VK_COMPARE_OP_ALWAYS                            -- always succeeds
#endif
        vsosf.compareMask = ~0;
        vsosf.writeMask = ~0;
        vsosf.reference = 0;

    VkStencilOpState                            vsosb;      // back
        vsosb.depthFailOp = VK_STENCIL_OP_KEEP;
        vsosb.failOp      = VK_STENCIL_OP_KEEP;
        vsosb.passOp      = VK_STENCIL_OP_KEEP;
        vsosb.compareOp = VK_COMPARE_OP_NEVER;
        vsosb.compareMask = ~0;
        vsosb.writeMask = ~0;
        vsosb.reference = 0;
```


Uses for Stencil Operations

Polygon edges without Z-fighting



Magic Lenses



Operations for Depth Values

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```
VkPipelineDepthStencilStateCreateInfo vpdssci;
        vpdssci.sType = VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO;
        vpdssci.pNext = nullptr;
        vpdssci.flags = 0;
        vpdssci.depthTestEnable  = VK_TRUE;
        vpdssci.depthWriteEnable = VK_TRUE;
        vpdssci.depthCompareOp = VK_COMPARE_OP_LESS;
VK_COMPARE_OP_NEVER                 -- never succeeds
VK_COMPARE_OP_LESS                  -- succeeds if new depth value is <  the existing value
VK_COMPARE_OP_EQUAL                 -- succeeds if new depth value is == the existing value
VK_COMPARE_OP_LESS_OR_EQUAL         -- succeeds if new depth value is <= the existing value
VK_COMPARE_OP_GREATER               -- succeeds if new depth value is >  the existing value
VK_COMPARE_OP_NOT_EQUAL             -- succeeds if new depth value is !=  the existing value
VK_COMPARE_OP_GREATER_OR_EQUAL      -- succeeds if new depth value is >= the existing value
VK_COMPARE_OP_ALWAYS                -- always succeeds
#endif
        vpdssci.depthBoundsTestEnable = VK_FALSE;
        vpdssci.front  = vsosf;
        vpdssci.back  = vsosb;
        vpdssci.minDepthBounds  = 0.;
        vpdssci.maxDepthBounds = 1.;
        vpdssci.stencilTestEnable = VK_FALSE;
```


Putting it all Together! (finally…)

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```
VkGraphicsPipelineCreateInfo vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
        vgpci.flags = 0;
#ifdef CHOICES
VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT
VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT
VK_PIPELINE_CREATE_DERIVATIVE_BIT
#endif
        vgpci.stageCount = 2;                   // number of stages in this pipeline
        vgpci.pStages = vpssci;
        vgpci.pVertexInputState = &vpvisci;
        vgpci.pInputAssemblyState = &vpiasci;
        vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;
        vgpci.pViewportState = &vpvsci;
        vgpci.pRasterizationState = &vprsci;
        vgpci.pMultisampleState = &vpmsci;
        vgpci.pDepthStencilState = &vpdssci;
        vgpci.pColorBlendState = &vpcbsci;
        vgpci.pDynamicState = &vpdsci;
        vgpci.layout = IN GraphicsPipelineLayout;
        vgpci.renderPass = IN RenderPass;
        vgpci.subpass = 0;                      // subpass number
        vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
        vgpci.basePipelineIndex = 0;

    result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,
                                        PALLOCATOR, OUT pGraphicsPipeline );

    return result;
}
```

Group all of the individual state information and create the pipeline

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Later on, we will Bind the Graphics Pipeline to the Command Buffer when Drawing

```
vkCmdBindPipeline( CommandBuffers[nextImageIndex],
                   VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
```

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Queues and Command Buffers

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Simplified Block Diagram

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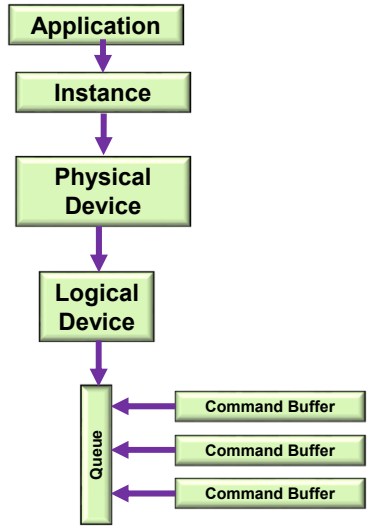

Vulkan Queues and Command Buffers

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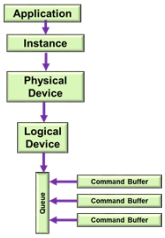
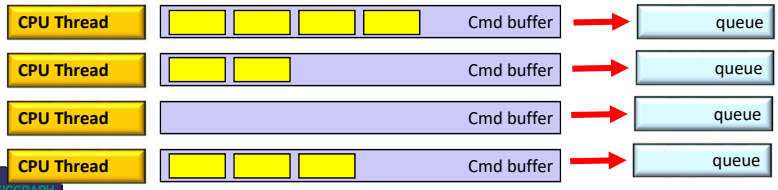
- Graphics commands are recorded in command buffers, e.g., *vkCmdDoSomething(cmdBuffer, …);*
- You can have as many simultaneous Command Buffers as you want
- Each command buffer can be filled from a different thread
- Command Buffers record commands, but no work takes place until a Command Buffer is submitted to a Queue
- We don't create Queues – the Logical Device has them already
- Each Queue belongs to a Queue Family
- We don't create Queue Families – the Physical Device already has them





Querying what Queue Families are Available


```
uint32_t  count;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *) nullptr );

VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceFamilyProperties(  PhysicalDevice, &count, OUT &vqfp, );

for( unsigned int i = 0; i < count; i++ )
{
        fprintf( FpDebug, "\t%d: Queue Family Count = %2d  ;  ", i, vqfp[i].queueCount );
        if( ( vqfp[i].queueFlags & VK_QUEUE_GRAPHICS_BIT ) != 0 )      fprintf( FpDebug, " Graphics" );
        if( ( vqfp[i].queueFlags & VK_QUEUE_COMPUTE_BIT  ) != 0 )      fprintf( FpDebug, " Compute " );
        if( ( vqfp[i].queueFlags & VK_QUEUE_TRANSFER_BIT ) != 0 )      fprintf( FpDebug, " Transfer" );
        fprintf(FpDebug, "\n");
}
```

```
Found 3 Queue Families:
        0: Queue Family Count = 16  ;   Graphics Compute Transfer
        1: Queue Family Count =  1  ;   Transfer
        2: Queue Family Count =  8  ;   Compute
```

Similarly, we Can Write a Function that Finds the Proper Queue Family


```
int
FindQueueFamilyThatDoesGraphics( )
{
        uint32_t count = -1;
        vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, OUT &count, OUT (VkQueueFamilyProperties *)nullptr );

        VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
        vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, IN &count, OUT vqfp );

        for( unsigned int i = 0; i < count; i++ )
        {
                if( ( vqfp[ i ].queueFlags & VK_QUEUE_GRAPHICS_BIT ) != 0 )
                        return i;
        }
        return -1;
}
```

Creating a Logical Device Needs to Know Queue Family Information

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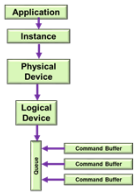


```
float queuePriorities[ ] =
{
        1.              // one entry per queueCount
};

VkDeviceQueueCreateInfo vdqci[1];
        vdqci[0].sType = VK_STRUCTURE_TYPE_QUEUE_CREATE_INFO;
        vdqci[0].pNext = nullptr;
        vdqci[0].flags = 0;
        vdqci[0].queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );
        vdqci[0].queueCount = 1;
        vdqci[0].queuePriorities = (float *) queuePriorities;

VkDeviceCreateInfo vdci;
        vdci.sType = VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO;
        vdci.pNext = nullptr;
        vdci.flags = 0;
        vdci.queueCreateInfoCount = 1;              // # of device queues wanted
        vdci.pQueueCreateInfos = IN &vdqci[0];      // array of VkDeviceQueueCreateInfo's
        vdci.enabledLayerCount = sizeof(myDeviceLayers) / sizeof(char *);
        vdci.ppEnabledLayerNames = myDeviceLayers;
        vdci.enabledExtensionCount = sizeof(myDeviceExtensions) / sizeof(char *);
        vdci.ppEnabledExtensionNames = myDeviceExtensions;
        vdci.pEnabledFeatures = IN &PhysicalDeviceFeatures;     // already created

result = vkCreateLogicalDevice( PhysicalDevice, IN &vdci, PALLOCATOR, OUT &LogicalDevice );

VkQueue Queue;
uint32_t  queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );
uint32_t  queueIndex = 0;

result = vkGetDeviceQueue ( LogicalDevice, queueFamilyIndex, queueIndex,  OUT &Queue );
```

Creating the Command Pool as part of the Logical Device

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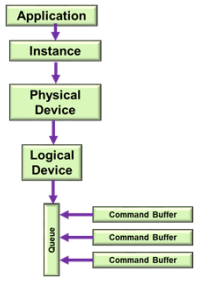
```
VkResult
Init06CommandPool( )
{
        VkResult result;

        VkCommandPoolCreateInfo                 vcpci;
                vcpci.sType = VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO;
                vcpci.pNext = nullptr;
                vcpci.flags =       VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
                                  | VK_COMMAND_POOL_CREATE_TRANSIENT_BIT;
#ifdef CHOICES
VK_COMMAND_POOL_CREATE_TRANSIENT_BIT
VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
#endif
                vcpci.queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );

        result = vkCreateCommandPool( LogicalDevice, IN &vcpci, PALLOCATOR, OUT &CommandPool );

        return result;
}
```

Creating the Command Buffers




```
VkResult
Init06CommandBuffers( )
{
	VkResult result;

	// allocate 2 command buffers for the double-buffered rendering:

	{
		VkCommandBufferAllocateInfo		vcbai;
			vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
			vcbai.pNext = nullptr;
			vcbai.commandPool = CommandPool;
			vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
			vcbai.commandBufferCount = 2;		// 2, because of double-buffering

		result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &CommandBuffers[0] );
	}


	// allocate 1 command buffer for the transferring pixels from a staging buffer to a texture buffer:

	{
		VkCommandBufferAllocateInfo		vcbai;
			vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
			vcbai.pNext = nullptr;
			vcbai.commandPool = CommandPool;
			vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
			vcbai.commandBufferCount = 1;

		result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &TextureCommandBuffer );
	}

	return result;
}
```


Beginning a Command Buffer


```
VkSemaphoreCreateInfo		vsci;
	vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
	vsci.pNext = nullptr;
	vsci.flags = 0;

VkSemaphore  imageReadySemaphore;
result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t  nextImageIndex;
vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN UINT64_MAX,
                       IN imageReadySemaphore, IN VK_NULL_HANDLE, OUT &nextImageIndex );


VkCommandBufferBeginInfo		vcbbi;
	vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
	vcbbi.pNext = nullptr;
	vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
	vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

result = vkBeginCommandBuffer( CommandBuffers[nextImageIndex], IN &vcbbi );

	. . .

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
```

These are the Commands that could be entered into the Command Buffer, I

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```
vkCmdBeginQuery( commandBuffer, flags );
vkCmdBeginRenderPass( commandBuffer, const contents );
vkCmdBindDescriptorSets( commandBuffer, pDynamicOffsets );
vkCmdBindIndexBuffer( commandBuffer, indexType );
vkCmdBindPipeline( commandBuffer, pipeline );
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, const pOffsets );
vkCmdBlitImage( commandBuffer, filter );
vkCmdClearAttachments( commandBuffer, attachmentCount, const pRects );
vkCmdClearColorImage( commandBuffer, pRanges );
vkCmdClearDepthStencilImage( commandBuffer, pRanges );
vkCmdCopyBuffer( commandBuffer, pRegions );
vkCmdCopyBufferToImage( commandBuffer, pRegions );
vkCmdCopyImage( commandBuffer, pRegions );
vkCmdCopyImageToBuffer( commandBuffer, pRegions );
vkCmdCopyQueryPoolResults( commandBuffer, flags );
vkCmdDebugMarkerBeginEXT( commandBuffer, pMarkerInfo );
vkCmdDebugMarkerEndEXT( commandBuffer );
vkCmdDebugMarkerInsertEXT( commandBuffer, pMarkerInfo );
vvkCmdDispatch( commandBuffer, groupCountX, groupCountY, groupCountZ );
vkCmdDispatchIndirect( commandBuffer, offset );
vkCmdDraw( commandBuffer, vertexCount, instanceCount, firstVertex, firstInstance );
vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex, int32_t vertexOffset, firstInstance );
vkCmdDrawIndexedIndirect( commandBuffer, stride );
vkCmdDrawIndexedIndirectCountAMD( commandBuffer, stride );
vkCmdDrawIndirect( commandBuffer, stride );
vkCmdDrawIndirectCountAMD( commandBuffer, stride );
vkCmdEndQuery( commandBuffer, query );
vkCmdEndRenderPass( commandBuffer );
vkCmdExecuteCommands( commandBuffer, commandBufferCount, const pCommandBuffers );
```

These are the Commands that could be entered into the Command Buffer, II

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```
vkCmdFillBuffer( commandBuffer, dstBuffer, dstOffset, size, data );
vkCmdNextSubpass( commandBuffer, contents );
vkCmdPipelineBarrier( commandBuffer, srcStageMask, dstStageMask, dependencyFlags, memoryBarrierCount, VkMemoryBarrier* pMemoryBarriers,
bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdProcessCommandsNVX( commandBuffer, pProcessCommandsInfo );
vkCmdPushConstants( commandBuffer, layout, stageFlags, offset, size, pValues );
vkCmdPushDescriptorSetKHR( commandBuffer, pipelineBindPoint, layout, set, descriptorWriteCount, pDescriptorWrites );
vkCmdPushDescriptorSetWithTemplateKHR( commandBuffer, descriptorUpdateTemplate, layout, set, pData );
vkCmdReserveSpaceForCommandsNVX( commandBuffer, pReserveSpaceInfo );
vkCmdResetEvent( commandBuffer, event, stageMask );
vkCmdResetQueryPool( commandBuffer, queryPool, firstQuery, queryCount );
vkCmdResolveImage( commandBuffer, srcImage, srcImageLayout, dstImage, dstImageLayout, regionCount, pRegions );
vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );
vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );
vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );
vkCmdSetDeviceMaskKHX( commandBuffer, deviceMask );
vkCmdSetDiscardRectangleEXT( commandBuffer, firstDiscardRectangle, discardRectangleCount, pDiscardRectangles );
vkCmdSetEvent( commandBuffer, event, stageMask );
vkCmdSetLineWidth( commandBuffer, lineWidth );
vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetViewportWScalingNV( commandBuffer, firstViewport, viewportCount, pViewportWScalings );
vkCmdUpdateBuffer( commandBuffer, dstBuffer, dstOffset, dataSize, pData );
vkCmdWaitEvents( commandBuffer, eventCount, pEvents, srcStageMask, dstStageMask, memoryBarrierCount, pMemoryBarriers,
                 bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdWriteTimestamp( commandBuffer, pipelineStage, queryPool, query );
```

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```
VkResult
RenderScene( )
{
	VkResult result;
	VkSemaphoreCreateInfo		vsci;
	  vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
	  vsci.pNext = nullptr;
	  vsci.flags = 0;

	VkSemaphore  imageReadySemaphore;
	result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

	uint32_t nextImageIndex;
	vkAcquireNextImageKHR( LogicalDevice,    IN SwapChain, IN UINT64_MAX, IN VK_NULL_HANDLE,
	                                         IN VK_NULL_HANDLE, OUT &nextImageIndex );

	VkCommandBufferBeginInfo		vcbbi;
	      vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
	      vcbbi.pNext = nullptr;
	      vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
	      vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

	result = vkBeginCommandBuffer( CommandBuffers[nextImageIndex], IN &vcbbi );
```

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```
VkClearColorValue		vccv;
	vccv.float32[0] = 0.0;
	vccv.float32[1] = 0.0;
	vccv.float32[2] = 0.0;
	vccv.float32[3] = 1.0;

VkClearDepthStencilValue		vcdsv;
	vcdsv.depth = 1.f;
	vcdsv.stencil = 0;

VkClearValue		vcv[2];
	vcv[0].color = vccv;
	vcv[1].depthStencil = vcdsv;

VkOffset2D o2d = { 0, 0 };
VkExtent2D e2d = { Width, Height };
VkRect2D r2d = { o2d, e2d };

VkRenderPassBeginInfo		vrpbi;
	vrpbi.sType = VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO;
	vrpbi.pNext = nullptr;
	vrpbi.renderPass = RenderPass;
	vrpbi.framebuffer = Framebuffers[ nextImageIndex ];
	vrpbi.renderArea = r2d;
	vrpbi.clearValueCount = 2;
	vrpbi.pClearValues = vcv;		// used for VK_ATTACHMENT_LOAD_OP_CLEAR

vkCmdBeginRenderPass( CommandBuffers[nextImageIndex], IN &vrpbi, IN VK_SUBPASS_CONTENTS_INLINE );
```

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```
VkViewport viewport =
{
        0.,             // x
        0.,             // y
        (float)Width,
        (float)Height,
        0.,             // minDepth
        1.              // maxDepth
};

vkCmdSetViewport( CommandBuffers[nextImageIndex], 0, 1, IN &viewport );        // 0=firstViewport, 1=viewportCount

VkRect2D scissor =
{
        0,
        0,
        Width,
        Height
};

vkCmdSetScissor( CommandBuffers[nextImageIndex], 0, 1, IN &scissor );

vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS,
                         GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *)nullptr );
                                                                    // dynamic offset count, dynamic offsets
vkCmdBindPushConstants( CommandBuffers[nextImageIndex], PipelineLayout, VK_SHADER_STAGE_ALL, offset, size, void *values );

VkBuffer buffers[1] = { MyVertexDataBuffer.buffer };

VkDeviceSize offsets[1] = { 0 };

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets );              // 0, 1 = firstBinding, bindingCount

const uint32_t vertexCount = sizeof(VertexData) / sizeof(VertexData[0]);
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstInstance = 0;
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
```

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The Entire Submission / Wait / Display Process

```
VkFenceCreateInfo                vfci;
        vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
        vfci.pNext = nullptr;
        vfci.flags = 0;

VkFence  renderFence;
vkCreateFence( LogicalDevice, IN &vfci, PALLOCATOR, OUT &renderFence );
result = VK_SUCCESS;

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;
VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue );\
                                        // 0 =, queueIndex

VkSubmitInfo                     vsi;
        vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
        vsi.pNext = nullptr;
        vsi.waitSemaphoreCount = 1;
        vsi.pWaitSemaphores = &imageReadySemaphore;
        vsi.pWaitDstStageMask = &waitAtBottom;
        vsi.commandBufferCount = 1;
        vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
        vsi.signalSemaphoreCount = 0;
        vsi.pSignalSemaphores = &SemaphoreRenderFinished;

result = vkQueueSubmit( presentQueue,   1, IN &vsi, IN renderFence );    // 1 = submitCount
result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );    // waitAll, timeout

vkDestroyFence( LogicalDevice, renderFence, PALLOCATOR );

VkPresentInfoKHR                 vpi;
        vpi.sType = VK_STRUCTURE_TYPE_PRESENT_INFO_KHR;
        vpi.pNext = nullptr;
        vpi.waitSemaphoreCount = 0;
        vpi.pWaitSemaphores = (VkSemaphore *)nullptr;
        vpi.swapchainCount = 1;
        vpi.pSwapchains = &SwapChain;
        vpi.pImageIndices = &nextImageIndex;
        vpi.pResults = (VkResult *)nullptr;

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```

er 11, 2019

What Happens After a Queue has Been Submitted?

As the Vulkan 1.1 Specification says:

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

In other words, the Vulkan driver on your system will execute the commands in a single buffer in the order in which they were put there.

But, between different command buffers submitted to different queues, the driver is allowed to execute commands between buffers in-order or out-of-order or overlapped-order, depending on what it thinks it can get away with.

The message here is, I think, always consider using some sort of Vulkan synchronization when one command depends on a previous command reaching a certain state first.

The Swap Chain

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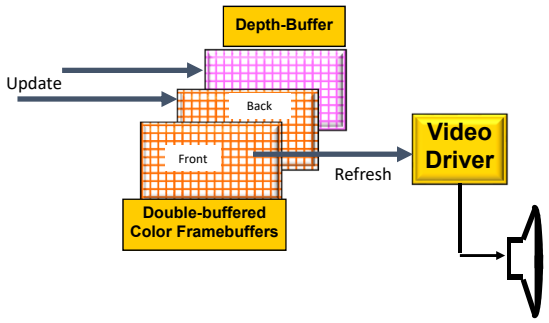
How We Think of OpenGL Framebuffers



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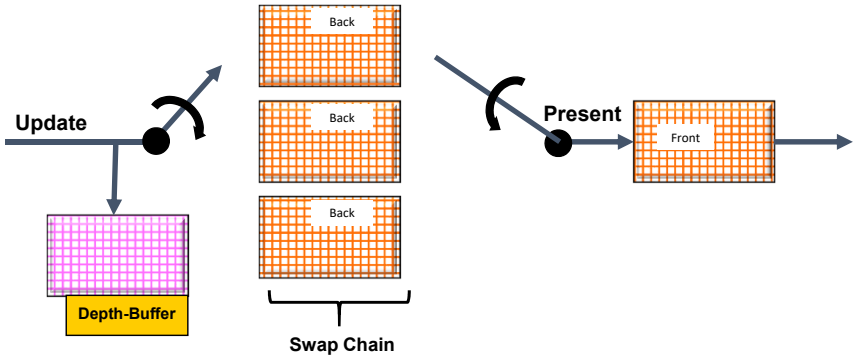
Vulkan Thinks of it This Way



What is a Swap Chain?

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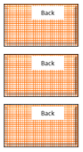
Vulkan does not use the idea of a "back buffer". So, we need a place to render into before moving an image into place for viewing. The is called the **Swap Chain**.

In essence, the Swap Chain manages one or more image objects that form a sequence of images that can be drawn into and then given to the Surface to be presented to the user for viewing.

Swap Chains are arranged as a ring buffer



Swap Chains are tightly coupled to the window system.

After creating the Swap Chain in the first place, the process for using the Swap Chain is:

1. Ask the Swap Chain for an image
2. Render into it via the Command Buffer and a Queue
3. Return the image to the Swap Chain for presentation
4. Present the image to the viewer (copy to "front buffer")

What is a Swap Chain?

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Because it has the word "chain" in it, let's try to visualize the Swap Chain as a physical chain.

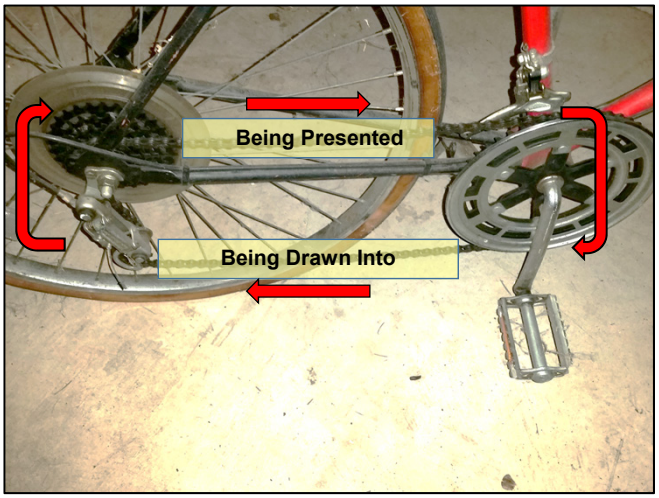
A bicycle chain isn't far off. A bicycle chain goes around and around, each section of the chain taking its turn on the gear teeth, off the gear teeth, on, off, on, off, etc.

Because the Swap Chain is actually a ring buffer, the images in a Swap Chain go around and around too, each image taking its turn being drawn into, being presented, drawn into, being presented etc.

In the same way that bicycle chain links are "re-used", Swap Chain images get re-used too.

What is a Swap Chain?

193



We Need to Find Out What our Display Capabilities Are

194

```
VkSurfaceCapabilitiesKHR        vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;
fprintf( FpDebug, "\nvkGetPhysicalDeviceSurfaceCapabilitiesKHR:\n" );

        . . .

VkBool32  supported;
result = vkGetPhysicalDeviceSurfaceSupportKHR( PhysicalDevice, FindQueueFamilyThatDoesGraphics( ), Surface, &supported );
if( supported == VK_TRUE )
        fprintf( FpDebug, "** This Surface is supported by the Graphics Queue **\n" );


uint32_t formatCount;
vkGetPhysicalDeviceSurfaceFormatsKHR( PhysicalDevice, Surface, &formatCount, (VkSurfaceFormatKHR *) nullptr );
VkSurfaceFormatKHR * surfaceFormats = new VkSurfaceFormatKHR[ formatCount ];
vkGetPhysicalDeviceSurfaceFormatsKHR( PhysicalDevice, Surface, &formatCount, surfaceFormats );
fprintf( FpDebug, "\nFound %d Surface Formats:\n", formatCount )

        . . .

uint32_t presentModeCount;
vkGetPhysicalDeviceSurfacePresentModesKHR( PhysicalDevice, Surface, &presentModeCount, (VkPresentModeKHR *) nullptr );
VkPresentModeKHR * presentModes = new VkPresentModeKHR[ presentModeCount ];
vkGetPhysicalDeviceSurfacePresentModesKHR( PhysicalDevice, Surface, &presentModeCount, presentModes );
fprintf( FpDebug, "\nFound %d Present Modes:\n", presentModeCount );

        . . .
```

We Need to Find Out What our Display Capabilities Are

VulkanDebug.txt output:

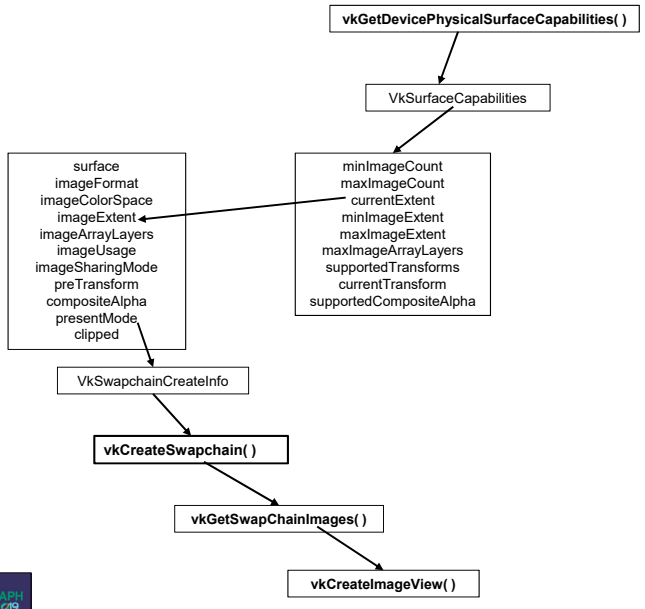
```
vkGetPhysicalDeviceSurfaceCapabilitiesKHR:
        minImageCount = 2 ; maxImageCount = 8
        currentExtent = 1024 x 1024
        minImageExtent = 1024 x 1024
        maxImageExtent = 1024 x 1024
        maxImageArrayLayers = 1
        supportedTransforms = 0x0001
        currentTransform = 0x0001
        supportedCompositeAlpha = 0x0001
        supportedUsageFlags = 0x009f

** This Surface is supported by the Graphics Queue **


Found 2 Surface Formats:
 0:     44          0           ( VK_FORMAT_B8G8R8A8_UNORM,  VK_COLOR_SPACE_SRGB_NONLINEAR_KHR )
 1:     50          0           ( VK_FORMAT_B8G8R8A8_SRGB,   VK_COLOR_SPACE_SRGB_NONLINEAR_KHR )


Found 3 Present Modes:
 0:     2                       ( VK_PRESENT_MODE_FIFO_KHR )
 1:     3                       ( VK_PRESENT_MODE_FIFO_RELAXED_KHR )
 2:     1                       ( VK_PRESENT_MODE_MAILBOX_KHR )
```

Creating a Swap Chain



Creating a Swap Chain


```
VkSurfaceCapabilitiesKHR        vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;

VkSwapchainCreateInfoKHR        vscci;
        vscci.sType = VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR;
        vscci.pNext = nullptr;
        vscci.flags = 0;
        vscci.surface = Surface;
        vscci.minImageCount = 2;                    // double buffering
        vscci.imageFormat = VK_FORMAT_B8G8R8A8_UNORM;
        vscci.imageColorSpace = VK_COLORSPACE_SRGB_NONLINEAR_KHR;
        vscci.imageExtent.width = surfaceRes.width;
        vscci.imageExtent.height = surfaceRes.height;
        vscci.imageUsage = VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT;
        vscci.preTransform = VK_SURFACE_TRANSFORM_IDENTITY_BIT_KHR;
        vscci.compositeAlpha = VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR;
        vscci.imageArrayLayers = 1;
        vscci.imageSharingMode = VK_SHARING_MODE_EXCLUSIVE;
        vscci.queueFamilyIndexCount = 0;
        vscci.pQueueFamilyIndices = (const uint32_t *)nullptr;
        vscci.presentMode = VK_PRESENT_MODE_MAILBOX_KHR;
        vscci.oldSwapchain = VK_NULL_HANDLE;
        vscci.clipped = VK_TRUE;

result = vkCreateSwapchainKHR( LogicalDevice, IN &vscci, PALLOCATOR, OUT &SwapChain );
```


Creating the Swap Chain Images and Image Views


```
uint32_t  imageCount;           // # of display buffers – 2?  3?
result = vkGetSwapchainImagesKHR( LogicalDevice, IN SwapChain, OUT &imageCount, (VkImage *)nullptr );

PresentImages = new VkImage[ imageCount ];
result = vkGetSwapchainImagesKHR( LogicalDevice, SwapChain, OUT &imageCount, PresentImages );

// present views for the double-buffering:

PresentImageViews = new VkImageView[ imageCount ];

for( unsigned int i = 0; i < imageCount; i++ )
{
    VkImageViewCreateInfo       vivci;
        vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
        vivci.pNext = nullptr;
        vivci.flags = 0;
        vivci.viewType = VK_IMAGE_VIEW_TYPE_2D;
        vivci.format = VK_FORMAT_B8G8R8A8_UNORM;
        vivci.components.r = VK_COMPONENT_SWIZZLE_R;
        vivci.components.g = VK_COMPONENT_SWIZZLE_G;
        vivci.components.b = VK_COMPONENT_SWIZZLE_B;
        vivci.components.a = VK_COMPONENT_SWIZZLE_A;
        vivci.subresourceRange.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        vivci.subresourceRange.baseMipLevel = 0;
        vivci.subresourceRange.levelCount = 1;
        vivci.subresourceRange.baseArrayLayer = 0;
        vivci.subresourceRange.layerCount = 1;
        vivci.image = PresentImages[ i ];

    result = vkCreateImageView( LogicalDevice, IN &vivci, PALLOCATOR, OUT &PresentImageViews[ i ] );
}
```

Rendering into the Swap Chain, I


```
VkSemaphoreCreateInfo                vsci;
        vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
        vsci.pNext = nullptr;
        vsci.flags = 0;

VkSemaphore  imageReadySemaphore;
result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t  nextImageIndex;
uint64_t  tmeout = UINT64_MAX;
vkAcquireNextImageKHR( LogicalDevice,    IN SwapChain, IN timeout, IN imageReadySemaphore,
                       IN VK_NULL_HANDLE,  OUT &nextImageIndex );
        . . .

result = vkBeginCommandBuffer( CommandBuffers[ nextImageIndex ], IN &vcbbi );

        . . .

vkCmdBeginRenderPass( CommandBuffers[nextImageIndex], IN &vrpbi,
                                  IN  VK_SUBPASS_CONTENTS_INLINE );

vkCmdBindPipeline( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );

        . . .

vkCmdEndRenderPass( CommandBuffers[ nextImageIndex ] );
vkEndCommandBuffer(  CommandBuffers[ nextImageIndex ] );
```


Rendering into the Swap Chain, II


```
VkFenceCreateInfo                vfci;
        vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
        vfci.pNext = nullptr;
        vfci.flags = 0;

VkFence  renderFence;
vkCreateFence( LogicalDevice, &vfci, PALLOCATOR, OUT &renderFence );

VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0,
                  OUT &presentQueue );

    . . .

VkSubmitInfo                vsi;
        vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
        vsi.pNext = nullptr;
        vsi.waitSemaphoreCount = 1;
        vsi.pWaitSemaphores = &imageReadySemaphore;
        vsi.pWaitDstStageMask = &waitAtBottom;
        vsi.commandBufferCount = 1;
        vsi.pCommandBuffers = &CommandBuffers[ nextImageIndex ];
        vsi.signalSemaphoreCount = 0;
        vsi.pSignalSemaphores = &SemaphoreRenderFinished;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );    // 1 = submitCount
```

Rendering into the Swap Chain, III


```
result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );

VkPresentInfoKHR                vpi;
        vpi.sType = VK_STRUCTURE_TYPE_PRESENT_INFO_KHR;
        vpi.pNext = nullptr;
        vpi.waitSemaphoreCount = 0;
        vpi.pWaitSemaphores = (VkSemaphore *)nullptr;
        vpi.swapchainCount = 1;
        vpi.pSwapchains = &SwapChain;
        vpi.pImageIndices = &nextImageIndex;
        vpi.pResults = (VkResult *) nullptr;

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```

Physical Devices

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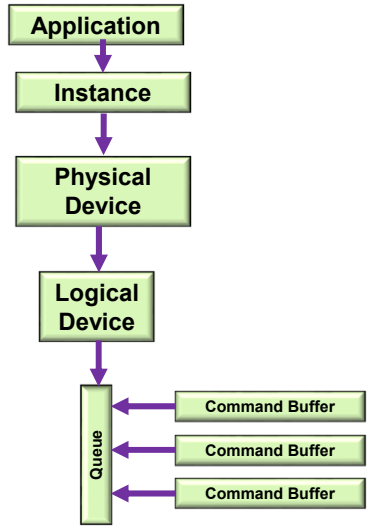
Vulkan: a More Typical (and Simplified) Block Diagram

203



Querying the Number of Physical Devices

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```
uint32_t  count;
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT (VkPhysicalDevice *)nullptr );

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ count ];
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT physicalDevices  );
```

This way of querying information is a recurring OpenCL and Vulkan pattern (get used to it):

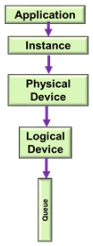
How many total there are

Where to put them

```
result = vkEnumeratePhysicalDevices( Instance,    &count,          nullptr    );

result = vkEnumeratePhysicalDevices( Instance,    &count,    physicalDevices );
```

Vulkan: Identifying the Physical Devices




```
VkResult result = VK_SUCCESS;

result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, (VkPhysicalDevice *)nullptr );
if( result != VK_SUCCESS || PhysicalDeviceCount <= 0 )
{
	fprintf( FpDebug, "Could not count the physical devices\n" );
	return VK_SHOULD_EXIT;
}

fprintf(FpDebug, "\n%d physical devices found.\n", PhysicalDeviceCount);

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ PhysicalDeviceCount ];
result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, OUT physicalDevices  );
if( result != VK_SUCCESS )
{
	fprintf( FpDebug, "Could not enumerate the %d physical devices\n", PhysicalDeviceCount );
	return VK_SHOULD_EXIT;
}
```


Which Physical Device to Use, I


```
int discreteSelect   = -1;
int integratedSelect = -1;
for( unsigned int i = 0; i < PhysicalDeviceCount; i++ )
{
	VkPhysicalDeviceProperties vpdp;
	vkGetPhysicalDeviceProperties( IN physicalDevices[i], OUT &vpdp );
	if( result != VK_SUCCESS )
	{
		fprintf( FpDebug, "Could not get the physical device properties of device %d\n", i );
		return VK_SHOULD_EXIT;
	}

	fprintf( FpDebug, " \n\nDevice %2d:\n", i );
	fprintf( FpDebug, "\tAPI version: %d\n", vpdp.apiVersion );
	fprintf( FpDebug, "\tDriver version: %d\n", vpdp.apiVersion );
	fprintf( FpDebug, "\tVendor ID: 0x%04x\n", vpdp.vendorID );
	fprintf( FpDebug, "\tDevice ID: 0x%04x\n", vpdp.deviceID );
	fprintf( FpDebug, "\tPhysical Device Type: %d =", vpdp.deviceType );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )   fprintf( FpDebug, " (Discrete GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU ) fprintf( FpDebug, " (Integrated GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU )    fprintf( FpDebug, " (Virtual GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_CPU )            fprintf( FpDebug, " (CPU)\n" );
	fprintf( FpDebug, "\tDevice Name: %s\n", vpdp.deviceName );
	fprintf( FpDebug, "\tPipeline Cache Size: %d\n", vpdp.pipelineCacheUUID[0] );
```

Which Physical Device to Use, II


```
        // need some logical here to decide which physical device to select:

        if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )
            discreteSelect = i;

        if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU )
            integratedSelect = i;
    }

    int which = -1;
    if( discreteSelect >= 0 )
    {
        which = discreteSelect;
        PhysicalDevice = physicalDevices[which];
    }
    else if( integratedSelect >= 0 )
    {
        which = integratedSelect;
        PhysicalDevice = physicalDevices[which];
    }
    else
    {
        fprintf( FpDebug, "Could not select a Physical Device\n" );
        return VK_SHOULD_EXIT;
    }
```

Asking About the Physical Device's Features


```
    VkPhysicalDeviceProperties  PhysicalDeviceFeatures;
    vkGetPhysicalDeviceFeatures( IN PhysicalDevice, OUT &PhysicalDeviceFeatures );

    fprintf( FpDebug, "\nPhysical Device Features:\n");
    fprintf( FpDebug, "geometryShader = %2d\n", PhysicalDeviceFeatures.geometryShader);
    fprintf( FpDebug, "tessellationShader = %2d\n", PhysicalDeviceFeatures.tessellationShader );
    fprintf( FpDebug, "multiDrawIndirect = %2d\n", PhysicalDeviceFeatures.multiDrawIndirect );
    fprintf( FpDebug, "wideLines = %2d\n", PhysicalDeviceFeatures.wideLines );
    fprintf( FpDebug, "largePoints = %2d\n", PhysicalDeviceFeatures.largePoints );
    fprintf( FpDebug, "multiViewport = %2d\n", PhysicalDeviceFeatures.multiViewport );
    fprintf( FpDebug, "occlusionQueryPrecise = %2d\n", PhysicalDeviceFeatures.occlusionQueryPrecise );
    fprintf( FpDebug, "pipelineStatisticsQuery = %2d\n", PhysicalDeviceFeatures.pipelineStatisticsQuery );
    fprintf( FpDebug, "shaderFloat64 = %2d\n", PhysicalDeviceFeatures.shaderFloat64 );
    fprintf( FpDebug, "shaderInt64 = %2d\n", PhysicalDeviceFeatures.shaderInt64 );
    fprintf( FpDebug, "shaderInt16 = %2d\n", PhysicalDeviceFeatures.shaderInt16 );
```

Here's What the NVIDIA RTX 2080 Ti Produced


```
vkEnumeratePhysicalDevices:

Device  0:
        API version: 4198499
        Driver version: 4198499
        Vendor ID: 0x10de
        Device ID: 0x1e04
        Physical Device Type: 2 = (Discrete GPU)
        Device Name: RTX 2080 Ti
        Pipeline Cache Size: 206
Device #0 selected ('RTX 2080 Ti')

Physical Device Features:
geometryShader =  1
tessellationShader =  1
multiDrawIndirect =  1
wideLines =  1
largePoints =  1
multiViewport =  1
occlusionQueryPrecise =  1
pipelineStatisticsQuery =  1
shaderFloat64 =  1
shaderInt64 =  1
shaderInt16 =  1
```

Here's What the Intel HD Graphics 520 Produced


```
vkEnumeratePhysicalDevices:

Device  0:
        API version: 4194360
        Driver version: 4194360
        Vendor ID: 0x8086
        Device ID: 0x1916
        Physical Device Type: 1 = (Integrated GPU)
        Device Name: Intel(R) HD Graphics 520
        Pipeline Cache Size: 213
Device #0 selected ('Intel(R) HD Graphics 520')

Physical Device Features:
geometryShader =  1
tessellationShader =  1
multiDrawIndirect =  1
wideLines =  1
largePoints =  1
multiViewport =  1
occlusionQueryPrecise =  1
pipelineStatisticsQuery =  1
shaderFloat64 =  1
shaderInt64 =  1
shaderInt16 =  1
```

Asking About the Physical Device's Different Memories


```
VkPhysicalDeviceMemoryProperties                vpdmp;
vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );

fprintf( FpDebug, "\n%d Memory Types:\n", vpdmp.memoryTypeCount );
for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
{
	VkMemoryType vmt = vpdmp.memoryTypes[i];
	fprintf( FpDebug, "Memory %2d: ", i );
	if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT      ) != 0 )    fprintf( FpDebug, " DeviceLocal" );
	if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT      ) != 0 )    fprintf( FpDebug, " HostVisible" );
	if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_COHERENT_BIT     ) != 0 )    fprintf( FpDebug, " HostCoherent" );
	if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_CACHED_BIT       ) != 0 )    fprintf( FpDebug, " HostCached" );
	if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT  ) != 0 )    fprintf( FpDebug, " LazilyAllocated" );
	fprintf(FpDebug, "\n");
}

fprintf( FpDebug, "\n%d Memory Heaps:\n", vpdmp.memoryHeapCount );
for( unsigned int  i = 0; i < vpdmp.memoryHeapCount; i++ )
{
	fprintf(FpDebug, "Heap %d: ", i);
	VkMemoryHeap vmh = vpdmp.memoryHeaps[i];
	fprintf( FpDebug, " size = 0x%08lx", (unsigned long int)vmh.size );
	if( ( vmh.flags & VK_MEMORY_HEAP_DEVICE_LOCAL_BIT  ) != 0 )    fprintf( FpDebug, " DeviceLocal" );    // only one in use
	fprintf(FpDebug, "\n");
}
```

Here's What I Got


```
11 Memory Types:
Memory  0:
Memory  1:
Memory  2:
Memory  3:
Memory  4:
Memory  5:
Memory  6:
Memory  7:  DeviceLocal
Memory  8:  DeviceLocal
Memory  9:  HostVisible HostCoherent
Memory 10:  HostVisible HostCoherent HostCached

2 Memory Heaps:
Heap 0:  size = 0xb7c00000 DeviceLocal
Heap 1:  size = 0xfac00000
```

Asking About the Physical Device's Queue Families


```
uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr );
fprintf( FpDebug, "\nFound %d Queue Families:\n", count );

VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT vqfp );
for( unsigned int i = 0; i < count; i++ )
{
	fprintf( FpDebug, "\t%d: queueCount = %2d  ;  ", i, vqfp[i].queueCount );
	if( ( vqfp[i].queueFlags & VK_QUEUE_GRAPHICS_BIT ) != 0 )	fprintf( FpDebug, " Graphics" );
	if( ( vqfp[i].queueFlags & VK_QUEUE_COMPUTE_BIT  ) != 0 )	fprintf( FpDebug, " Compute " );
	if( ( vqfp[i].queueFlags & VK_QUEUE_TRANSFER_BIT ) != 0 )	fprintf( FpDebug, " Transfer" );
	fprintf(FpDebug, "\n");
}
```

Here's What I Got


```
Found 3 Queue Families:
	0: queueCount = 16  ;  Graphics Compute  Transfer
	1: queueCount =  2  ;  Transfer
	2: queueCount =  8  ;  Compute
```

Logical Devices

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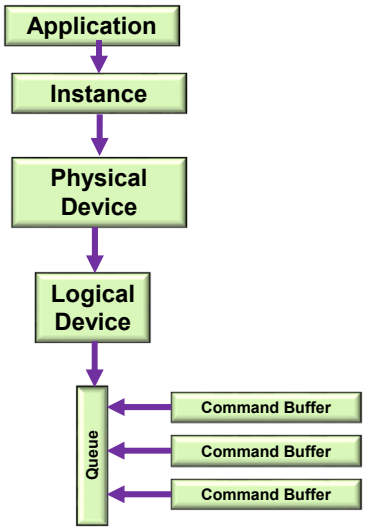
Vulkan: a More Typical (and Simplified) Block Diagram



Looking to See What Device Layers are Available


```
const char * myDeviceLayers[ ] =
{
	// "VK_LAYER_LUNARG_api_dump",
	// "VK_LAYER_LUNARG_core_validation",
	// "VK_LAYER_LUNARG_image",
	"VK_LAYER_LUNARG_object_tracker",
	"VK_LAYER_LUNARG_parameter_validation",
	// "VK_LAYER_NV_optimus"
};

const char * myDeviceExtensions[ ] =
{
	"VK_KHR_surface",
	"VK_KHR_win32_surface",
	"VK_EXT_debug_report"
	// "VK_KHR_swapchains"
};

// see what device layers are available:

uint32_t  layerCount;
vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, (VkLayerProperties *)nullptr);

VkLayerProperties * deviceLayers = new VkLayerProperties[layerCount];

result = vkEnumerateDeviceLayerProperties( PhysicalDevice, &layerCount, deviceLayers);
```

Looking to See What Device Extensions are Available


```
// see what device extensions are available:

uint32_t  extensionCount;
vkEnumerateDeviceExtensionProperties(PhysicalDevice, deviceLayers[i].layerName,
                                     &extensionCount, (VkExtensionProperties *)nullptr);

VkExtensionProperties * deviceExtensions = new VkExtensionProperties[extensionCount];

result = vkEnumerateDeviceExtensionProperties(PhysicalDevice, deviceLayers[i].layerName,
                                     &extensionCount, deviceExtensions);
```

What Device Layers and Extensions are Available

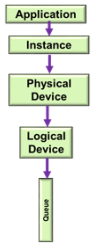
219

```
4 physical device layers enumerated:


0x00401063   1  'VK_LAYER_NV_optimus'  'NVIDIA Optimus layer'
      0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00401072   1  'VK_LAYER_LUNARG_core_validation'  'LunarG Validation Layer'
      2 device extensions enumerated for 'VK_LAYER_LUNARG_core_validation':
      0x00000001  'VK_EXT_validation_cache'
      0x00000004  'VK_EXT_debug_marker'

0x00401072   1  'VK_LAYER_LUNARG_object_tracker'  'LunarG Validation Layer'
      2 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':
      0x00000001  'VK_EXT_validation_cache'
      0x00000004  'VK_EXT_debug_marker'

0x00401072   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
      2 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
      0x00000001  'VK_EXT_validation_cache'
      0x00000004  'VK_EXT_debug_marker'
```


Vulkan: Creating a Logical Device

220

```
float   queuePriorities[1] =
{
            1.
};
VkDeviceQueueCreateInfo  vdqci;
      vdqci.sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
      vdqci.pNext = nullptr;
      vdqci.flags = 0;
      vdqci.queueFamiltyIndex = 0;
      vdqci.queueCount = 1;
      vdqci.pQueueProperties = queuePriorities;
```




```
VkDeviceCreateInfo  vdci;
            vdci.sType = VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO;
            vdci.pNext = nullptr;
            vdci.flags = 0;
            vdci.queueCreateInfoCount = 1;                  // # of device queues
            vdci.pQueueCreateInfos = IN vdqci;              // array of VkDeviceQueueCreateInfo's
            vdci.enabledLayerCount = sizeof(myDeviceLayers) / sizeof(char *);
            vdci.enabledLayerCount = 0;
            vdci.ppEnabledLayerNames = myDeviceLayers;
            vdci.enabledExtensionCount = 0;
            vdci.ppEnabledExtensionNames = (const char **)nullptr;          // no extensons
            vdci.enabledExtensionCount = sizeof(myDeviceExtensions) / sizeof(char *);
            vdci.ppEnabledExtensionNames = myDeviceExtensions;
            vdci.pEnabledFeatures = IN &PhysicalDeviceFeatures;

      result = vkCreateLogicalDevice( PhysicalDevice, IN &vdci, PALLOCATOR, OUT &LogicalDevice );
```

Vulkan: Creating the Logical Device's Queue


```
// get the queue for this logical device:

vkGetDeviceQueue( LogicalDevice, 0, 0,  OUT &Queue );          // 0, 0 = queueFamilyIndex, queueIndex
```

Dynamic State Variables

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Creating a Pipeline with Dynamically Changeable State Variables

The graphics pipeline is full of state information, and, as previously-discussed, is immutable, that is, the information contained inside it is fixed, and can only be changed by creating a new graphics pipeline with new information.

That isn't quite true. To a certain extent, you can declare parts of the pipeline state changeable. This allows you to change pipeline information on the fly.

This is useful for managing state information that needs to change frequently. This also creates possible optimization opportunities for the Vulkan driver.

Which Pipeline State Variables can be Changed Dynamically

The possible uses for dynamic variables are shown in the **VkDynamicState** enum:

VK_DYNAMIC_STATE_VIEWPORT
VK_DYNAMIC_STATE_SCISSOR
VK_DYNAMIC_STATE_LINE_WIDTH
VK_DYNAMIC_STATE_DEPTH_BIAS
VK_DYNAMIC_STATE_BLEND_CONSTANTS
VK_DYNAMIC_STATE_DEPTH_BOUNDS
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK
VK_DYNAMIC_STATE_STENCIL_REFERENCE

Creating a Pipeline


```
VkDynamicState                          vds[ ] =
{
        VK_DYNAMIC_STATE_VIEWPORT,
        VK_DYNAMIC_STATE_LINE_WIDTH
};


VkPipelineDynamicStateCreateInfo        vpdsci;
        vpdsci.sType =  VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO;
        vpdsci.pNext = nullptr;
        vpdsci.flags = 0;
        vpdsci.dynamicStateCount = sizeof(vds) / sizeof(VkDynamicState);
        vpdsci.pDynamicStates = &vds;


VkGraphicsPipelineCreateInfo            vgpci;
        . . .
        vgpci.pDynamicState = &vpdsci;
        . . .


vkCreateGraphicsPipelines( LogicalDevice, pipelineCache, 1, &vgpci, PALLOCATOR, &GraphicsPipeline );
```

If you declare certain state variables to be dynamic like this, then you *must* fill them in the command buffer! Otherwise, they are ***undefined***.

Filling the Dynamic State Variables in the Command Buffer

The command buffer-bound function calls to set these dynamic states are:

```
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );
vkCmdSetLineWidth( commandBuffer, linewidth );
vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );
vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );
vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
```

Push Constants

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Push Constants

In an effort to expand flexibility and retain efficiency, Vulkan provides something called **Push Constants**. Like the name implies, these let you "push" constant values out to the shaders. These are typically used for small, frequently-updated data values. This is good, since Vulkan, at times, makes it cumbersome to send changes to the graphics.

By "small", Vulkan specifies that these must be at least 128 bytes in size, although they can be larger. For example, the maximum size is 256 bytes on the NVIDIA 1080ti. (You can query this limit by looking at the **maxPushConstantSize** parameter in the **VkPhysicalDeviceLimits** structure.) Unlike uniform buffers and vertex buffers, these are not backed by memory. They are actually part of the Vulkan pipeline.

Push Constants

On the shader side, if, for example, you are sending a 4x4 matrix, the use of push constants in the shader looks like this:

```
layout( push_constant ) uniform matrix
{
        mat4 modelMatrix;
} Matrix;
```

On the application side, push constants are pushed at the shaders by binding them to the Vulkan Command Buffer:

```
vkCmdPushConstants( CommandBuffer, PipelineLayout, stageFlags,
                    offset, size, pValues );
```

where:
stageFlags are or'ed bits of VK_PIPELINE_STAGE_VERTEX_SHADER_BIT,
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, etc.

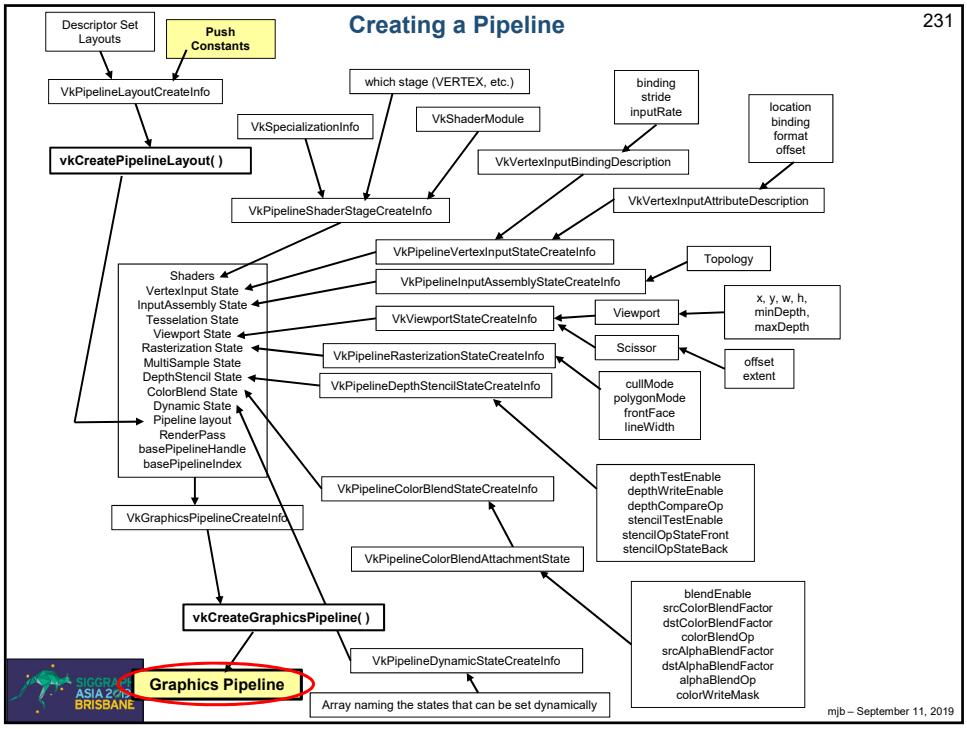
size is in bytes

pValues is a void * pointer to the data, which in this 4x4 matrix example, would be of type **glm::mat4**.

Setting up the Push Constants for the Pipeline Structure

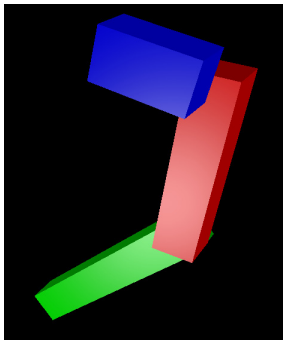
Prior to that, however, the pipeline layout needs to be told about the Push Constants:

```
VkPushConstantRange                     vpcr[1];
    vpcr[0].stageFlags =
            VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
          | VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
    vpcr[0].offset = 0;
    vpcr[0].size = sizeof( glm::mat4 );

VkPipelineLayoutCreateInfo                  vplci;
    vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
    vplci.pNext = nullptr;
    vplci.flags = 0;
    vplci.setLayoutCount = 4;
    vplci.pSetLayouts = DescriptorSetLayouts;
    vplci.pushConstantRangeCount = 1;
    vplci.pPushConstantRanges = &vpcr[0];

result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR,
                OUT &GraphicsPipelineLayout );
```



An Robotic Example using Push Constants

A robotic animation (i.e., a hierarchical transformation system)



Where each arm is represented by:

```
struct arm
{
        glm::mat4   armMatrix;
        glm::vec3   armColor;
        float       armScale;     // scale factor in x
};

struct armArm1;
struct armArm2;
struct armArm3;
```

In the *Reset* Function


```
struct arm                  Arm1;
struct arm                  Arm2;
struct arm                  Arm3;

. . .

        Arm1.armMatrix = glm::mat4(1.);
        Arm1.armColor  = glm::vec3( 0.f, 1.f, 0.f );
        Arm1.armScale  = 6.f;

        Arm2.armMatrix = glm::mat4(1.);
        Arm2.armColor  = glm::vec3( 1.f, 0.f, 0.f );
        Arm2.armScale  = 4.f;

        Arm3.armMatrix = glm::mat4(1.);
        Arm3.armColor  = glm::vec3( 0.f, 0.f, 1.f );
        Arm3.armScale  = 2.f;
```

The constructor **glm::mat4( )** produces an identity matrix. The actual transformation matrices will be set in *UpdateScene( )*.

Setup the Push Constant for the Pipeline Structure

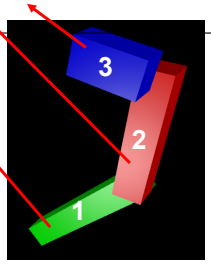

```
VkPushConstantRange                 vpcr[1];
        vpcr[0].stageFlags =
                VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
              | VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
        vpcr[0].offset = 0;
        vpcr[0].size = sizeof( struct arm );

VkPipelineLayoutCreateInfo                  vplci;
        vplci.sType =
                VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
        vplci.pNext = nullptr;
        vplci.flags = 0;
        vplci.setLayoutCount = 4;
        vplci.pSetLayouts = DescriptorSetLayouts;
        vplci.pushConstantRangeCount = 1;
        vplci.pPushConstantRanges = &vpcr[0];

result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR,
                OUT &GraphicsPipelineLayout );
```

In the *UpdateScene* Functiom


```
float rot1 = (float)Time;
float rot2 = 2.f * rot1;
float rot3 = 2.f * rot2;

glm::vec3 zaxis  =  glm::vec3(0., 0., 1.);

glm::mat4 m1g = glm::mat4();
m1g = glm::translate(m1g, glm::vec3(0., 0., 0.));
m1g = glm::rotate(m1g, rot1, zaxis);

glm::mat4 m21 = glm::mat4();
m21 = glm::translate(m21, glm::vec3(2.*Arm1.armScale, 0., 0.));
m21 = glm::rotate(m21, rot2, zaxis);
m21 = glm::translate(m21, glm::vec3(0., 0., 2.));

glm::mat4 m32 = glm::mat4();
m32 = glm::translate(m32, glm::vec3(2.*Arm2.armScale, 0., 0.));
m32 = glm::rotate(m32, rot3, zaxis);
m32 = glm::translate(m32, glm::vec3(0., 0., 2.));

Arm1.armMatrix = m1g;                 // m1g
Arm2.armMatrix = m1g * m21;           // m2g
Arm3.armMatrix = m1g * m21 * m32;     // m3g
```


In the *RenderScene* Function


```
VkBuffer buffers[1]  =  { MyVertexDataBuffer.buffer };

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets );

vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
        VK_SHADER_STAGE_ALL, 0, sizeof(struct arm),  (void *)&Arm1 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );


vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
        VK_SHADER_STAGE_ALL, 0, sizeof(struct arm),  (void *)&Arm2 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );


vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
        VK_SHADER_STAGE_ALL, 0, sizeof(struct arm),  (void *)&Arm3 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );
```



In the Vertex Shader


```
layout( push_constant ) uniform arm
{
	mat4  armMatrix;
	vec3  armColor;
	float   armScale;	// scale factor in x
} RobotArm;

layout( location = 0 ) in vec3 aVertex;

	. . .

vec3 bVertex = aVertex;				// arm coordinate system is [-1., 1.] in X
bVertex.x +=  1.;				// now is [0., 2.]
bVertex.x  /=  2.;				// now is [0., 1.]
bVertex.x *=  (RobotArm.armScale );		// now is [0., RobotArm.armScale]
bVertex = vec3(  RobotArm.armMatrix * vec4( bVertex, 1. )  );

	. . .

gl_Position = PVM * vec4( bVertex, 1. );	// Projection * Viewing * Modeling matrices
```

Getting Information Back from the Graphics System

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Setting up Query Pools

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- There are 3 types of Queries: Occlusion, Pipeline Statistics, and Timestamp
- Vulkan requires you to first setup “Query Pools”, one for each specific type
- This indicates that Vulkan thinks that Queries are time-consuming (relatively) to setup, and thus better to set them up in program-setup than in program-runtime

Setting up Query Pools

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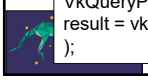
```
VkQueryPoolCreateInfo                vqpci;
        vqpci.sType = VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO;
        vqpci.pNext = nullptr;
        vqpci.flags = 0;
        vqpci.queryType = << one of: >>
                VK_QUERY_TYPE_OCCLUSION
                VK_QUERY_TYPE_PIPELINE_STATISTICS
                VK_QUERY_TYPE_TIMESTAMP
        vqpci.queryCount = 1;
        vqpci.pipelineStatistics = 0;        // bitmask of what stats you are querying for if you
                                             // are doing a pipeline statistics query
VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT
VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT

VkQueryPool          occlusionQueryPool;
result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &occlusionQueryPool );

VkQueryPool          statisticsQueryPool;
result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &statisticsQueryPool );

VkQueryPool          timestampQueryPool;
result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &timestampQueryPool
);
```



Resetting, Filling, and Examining a Query Pool


```
vkCmdResetQueryPool( CommandBuffer, occlusionQueryPool, 0, 1 );

vkCmdBeginQuery( CommandBuffer, occlusionQueryPool, 0, VK_QUERY_CONTROL_PRECISE_BIT );

        . . .

vkCmdEndQuery( CommandBuffer, occlusionQueryPool, 0 );

#define DATASIZE       128
uint32_t     data[DATASIZE];

result = vkGetQueryPoolResults( LogicalDevice, occlusionQueryPool, 0, 1, DATASIZE*sizeof(uint32_t), data, stride, flags );
                // or'ed combinations of:
                // VK_QUERY_RESULT_64_BIT
                // VK_QUERY_RESULT_WAIT_BIT
                // VK_QUERY_RESULT_WITH_AVAILABILTY_BIT
                // VK_QUERY_RESULT_PARTIAL_BIT
                // stride is # of bytes in between each result
```

query index number

Occlusion Query

Occlusion Queries count the number of fragments drawn between the **vkCmdBeginQuery** and the **vkCmdEndQuery** that pass both the Depth and Stencil tests

This is commonly used to see what level-of-detail should be used when drawing a complicated object

Some hints:

- Don't draw the whole scene – just draw the object you are interested in
- Don't draw the whole object – just draw a simple bounding volume at least as big as the object
- Don't draw the whole bounding volume – cull away the back faces (two reasons: time and correctness)
- Don't draw the colors – just draw the depths (especially if the fragment shader is time-consuming)

```
uint32_t   fragmentCount;
result = vkGetQueryPoolResults( LogicalDevice, occlusionQueryPool, 0, 1,
                                sizeof(uint32_t), &fragmentCount, 0, VK_QUERY_RESULT_WAIT_BIT );
```

Pipeline Statistics Query

Pipeline Statistics Queries count how many of various things get done between the **vkCmdBeginQuery** and the **vkCmdEndQuery**

```
uint32_t   counts[NUM_STATS];
result = vkGetQueryPoolResults( LogicalDevice, statisticsQueryPool, 0, 1,
                                NUM_STATS*sizeof(uint32_t), counts, 0, VK_QUERY_RESULT_WAIT_BIT );


// vqpci.pipelineStatistics = or'ed bits of:;
// VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT
// VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT
// VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT
```

Timestamp Query

Timestamp Queries count how many nanoseconds of time elapsed between the **vkCmdBeginQuery** and the **vkCmdEndQuery**.

```
uint64_t   nanosecondsCount;
result = vkGetQueryPoolResults( LogicalDevice, timestampQueryPool, 0, 1,
                                sizeof(uint64_t), &nanosecondsCount, 0,
                                 VK_QUERY_RESULT_64_BIT | VK_QUERY_RESULT_WAIT_BIT);
```

Timestamp Query

The vkCmdWriteTimeStamp( ) function produces the time between when this function is called and when the first thing reaches the specified pipeline stage.

Even though the stages are “bits”, you are supposed to only specify one of them, not “or” multiple ones together

```
vkCmdWriteTimeStamp( CommandBuffer, pipelineStages, timestampQueryPool, 0 );

// VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
// VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
// VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
// VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
// VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT,
// VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
// VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT,
// VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
// VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
// VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
// VK_PIPELINE_STAGE_TRANSFER_BIT
// VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT
// VK_PIPELINE_STAGE_HOST_BIT
```

Compute Shaders

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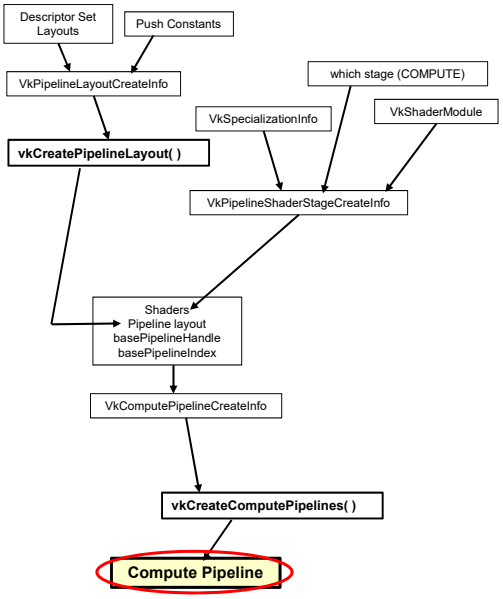
Here is how you create a Compute Pipeline



Start by Creating the Data Buffers

This is a Particle System application, so we need Positions, Velocities, and (possibly) Colors

```
layout( std140, set = 0, binding = 0 )  buffer  Pos
{
        vec4  Positions[   ];          // array of structures
};

layout( std140, set = 0, binding = 1 )  buffer  Vel
{
        vec4  Velocities[   ];         // array of structures
};

layout( std140, set = 0, binding = 2 )  buffer  Col
 {
        vec4  Colors[   ];             // array of structures
};
```

1

2

3

You can use the empty brackets, but only on the *last* element of the buffer. The actual dimension will be determined for you when Vulkan examines the size of this buffer's data store.

Creating a Shader Storage Buffer


```
VkBuffer  Buffer;
. . .

VkBufferCreateInfo  vbci;
        vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
        vbci.pNext = nullptr;
        vbci.flags = 0;
        vbci.size = << buffer size in bytes >>
        vbci.usage = VK_USAGE_STORAGE_BUFFER_BIT;
        vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
        vbci.queueFamilyIndexCount = 0;
        vbci.pQueueFamilyIndices = (const iont32_t) nullptr;

result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR,  OUT &Buffer );
```

Vulkan: Allocating Memory for a Buffer, Binding a Buffer to Memory, and Writing to the Buffer


```
VkMemoryRequirements            vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );


VkMemoryAllocateInfo            vmai;
        vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
        vmai.pNext = nullptr;
        vmai.flags = 0;
        vmai.allocationSize = vmr.size;
        vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

. . .

VkDeviceMemory                  vdm;
result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR,  OUT &vdm );

result = vkBindBufferMemory( LogicalDevice, Buffer, IN vdm, 0 );            // 0 is the offset

. . .

result = vkMapMemory( LogicalDevice, IN vdm, 0, VK_WHOLE_SIZE, 0, &ptr );

        << do the memory copy >>

result = vkUnmapMemory( LogicalDevice, IN vdm );
```

Fill the Data Buffer


```
VkResult
Fill05DataBuffer( IN MyBuffer myBuffer, IN void * data )
{
	// the size of the data had better match the size that was used to init the buffer!

	void * pGpuMemory;
	vkMapMemory( LogicalDevice, IN myBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT &pGpuMemory );
	                                                        // 0 and 0 are offset and flags
	memcpy( pGpuMemory, data, (size_t)myBuffer.size );
	vkUnmapMemory( LogicalDevice, IN myBuffer.vdm );
	return VK_SUCCESS;
}
```


Create the Compute Pipeline Layout


```
VkPipelineLayout		ComputePipelineLayout;
VkDescriptorSetLayout	ComputeSetLayout;

. . .

VkDescriptorSetLayoutBinding		ComputeSet[1];
		ComputeSet[0].binding		= 0;
		ComputeSet[0].descriptorType	= VK_DESCRIPTOR_TYPE_STORAGE_BUFFER;
		ComputeSet[0].descriptorCount	= 3;
		ComputeSet[0].stageFlags		= VK_SHADER_STAGE_COMPUTE_BIT;
		ComputeSet[0].pImmutableSamplers = (VkSampler *)nullptr;

VkDescriptorSetLayoutCreateInfo		vdslc;
		vdslc0.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
		vdslc0.pNext = nullptr;
		vdslc0.flags = 0;
		vdslc0.bindingCount = 1;
		vdslc0.pBindings = &ComputeSet[0];

result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc, PALLOCATOR, OUT &ComputeSetLayout );

VkPipelineLayoutCreateInfo		vplci;
		vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
		vplci.pNext = nullptr;
		vplci.flags = 0;
		vplci.setLayoutCount = 1;
		vplci.pSetLayouts = ComputeSetLayout;
		vplci.pushConstantRangeCount = 0;
		vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR, OUT &ComputePipelineLayout );
```

Create the Compute Pipeline

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```
VkPipeline                  ComputePipeline;
. . .

VkPipelineShaderStageCreateInfo             vpssci;
        vpssci.sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci.pNext = nullptr;
        vpssci.flags = 0;
        vpssci.stage = VK_SHADER_STAGE_COMPUTE_BIT;
        vpssci.module = computeShader;
        vpssci.pName = "main";
        vpssci.pSpecializationInfo = (VkSpecializationInfo *)nullptr;


VkComputePipelineCreateInfo                 vcpci[1];
        vcpci[0].sType = VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO;
        vcpci[0].pNext = nullptr;
        vcpci[0].flags = 0;
        vcpci[0].stage = vpssci;
        vcpci[0].layout = ComputePipelineLayout;
        vcpci[0].basePipelineHandle = VK_NULL_HANDLE;
        vcpci[0].basePipelineIndex = 0;

result = vkCreateComputePipelines( LogicalDevice, VK_NULL_HANDLE, 1, &vcpci[0], PALLOCATOR, &ComputePipeline );
```

The Particle System Compute Shader -- Setup

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```
#version 430
#extension GL_ARB_compute_shader :  enable

layout( std140, set = 0, binding = 0 )  buffer  Pos
{
        vec4  Positions[   ];               // array of structures
};

layout( std140, set = 0, binding = 1 )  buffer  Vel
{
        vec4  Velocities[   ];              // array of structures
};

layout( std140, set = 0, binding = 2 )  buffer  Col
 {
        vec4  Colors[   ];          // array of structures
};

layout( local_size_x = 64,  local_size_y = 1, local_size_z = 1 )   in;
```

This is the number of work-items per work-group, set in the compute shader.
The number of work-groups is set in the vkCmdDispatch( ) function call in the C/C++ program.

The Particle System Compute Shader – The Physics


```
#define POINT           vec3
#define VELOCITY        vec3
#define VECTOR          vec3
#define SPHERE          vec4

const  VECTOR  G      =  VECTOR( 0., -9.8, 0. );
const  float   DT     =  0.1;

const SPHERE Sphere = vec4( -100., -800., 0.,  600. );          // x, y, z, r

      . . .

uint  gid = gl_GlobalInvocationID.x;              // the .y and .z are both 1 in this case

POIINT      p  = Positions[  gid  ].xyz;
VELOCITY  v  = Velocities[  gid  ].xyz;

POINT       pp = p + v*DT + .5*DT*DT*G;
VELOCITY  vp = v + G*DT;

Positions[  gid  ].xyz  = pp;
Velocities[  gid  ].xyz = vp;
```

$$p' = p + v \cdot t + \frac{1}{2} G \cdot t^2$$

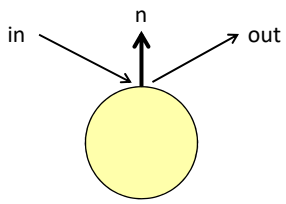
$$v' = v + G \cdot t$$

The Particle System Compute Shader – How About Introducing a Bounce?


```
VELOCITY
Bounce( VELOCITY vin, VECTOR n )
{
      VELOCITY vout = reflect( vin, n );
      return vout;
}

VELOCITY
BounceSphere( POINT p, VELOCITY v, SPHERE s )
{
      VECTOR  n = normalize( p - s.xyz );
      return Bounce( v, n );
}

bool
IsInsideSphere( POINT p, SPHERE s )
{
      float r = length( p - s.xyz );
      return  ( r < s.w  );
}
```



The Particle System Compute Shader – How About Introducing a Bounce?

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```
uint  gid = gl_GlobalInvocationID.x;              // the .y and .z are both 1 in this case

POINT       p  = Positions[  gid  ].xyz;
VELOCITY v  = Velocities[  gid  ].xyz;

POINT       pp = p + v*DT + .5*DT*DT*G;
VELOCITY  vp = v + G*DT;

if(  IsInsideSphere( pp, Sphere )  )
{
      vp = BounceSphere( p, v, S );
      pp = p + vp*DT + .5*DT*DT*G;
}

Positions[   gid  ].xyz = pp;
Velocities[  gid  ].xyz = vp;
```

$$p' = p + v \cdot t + \frac{1}{2} G \cdot t^2$$

$$v' = v + G \cdot t$$

Graphics Trick Alert: Making the bounce happen from the surface of the sphere is time-consuming. Instead, bounce from the previous position in space. If DT is small enough (and it is), nobody will ever know…

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Dispatching the Compute Shader from the Command Buffer

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```
const int NUM_PARTICLES       = 1024*1024;
const int NUM_WORK_ITEMS    =          64;
const int NUM_X_WORK_GROUPS = NUM_PARTICLES / NUM_WORK_ITEMS;

      . . .

vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );

vkCmdDispatch( CommandBuffer, NUM_X_WORK_GROUPS, 1,  1 );
```

This is the number of work-groups, set in the C/C++ program.
The number of work-items per work-group is set in a layout in the compute shader.

Or,

```
vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );

vkCmdDispatchIndirect( CommandBuffer, Buffer, 0 );          // Buffer holds the 3 sizes, offset=0
```

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The Bouncing Particle System Compute Shader – What Does It Look Like?

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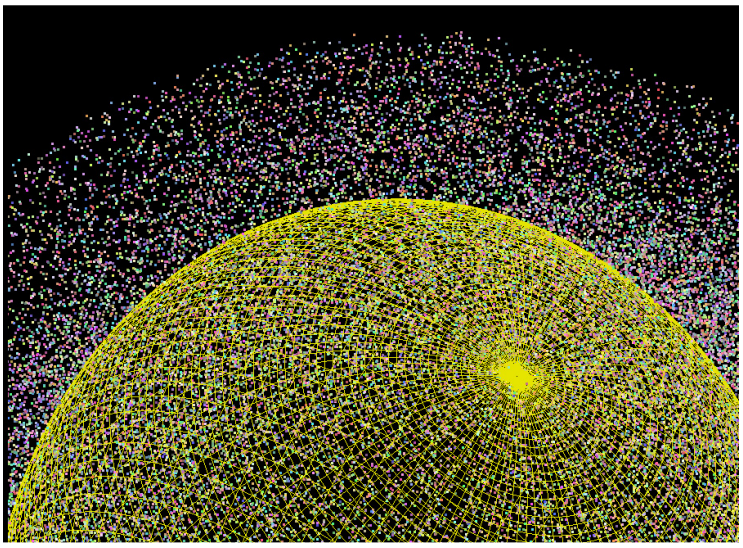

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Specialization Constants

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What Are Specialization Constants?

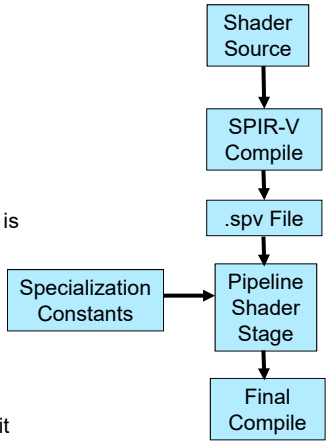
In Vulkan, all shaders get halfway-compiled by SPIR-V and then the rest-of-the-way compiled by the Vulkan driver.

Normally, the half-way compile fixes all constant values and compiles the code that uses them.

But, it would be nice every so often to have your Vulkan program sneak into the halfway-compiled binary and manipulate some constants at runtime. This is what Specialization Constants are for. A Specialization Constant is a way of injecting an integer, Boolean, uint, float, or double constant into an *halfway-compiled* version of a shader right before the *rest-of-the-way* compilation.

That final compilation happens when you call **vkCreateComputePipelines( )**

Without Specialization Constants, you would have to commit to a final value before the SPIR-V compile was done, which could have been a long time ago



Why Do We Need Specialization Constants?

Specialization Constants could be used for:

- Setting the work-items per work-group in a compute shader
- Setting a Boolean flag and then eliminating the if-test that used it
- Setting an integer constant and then eliminating the switch-statement that looked for it
- Making a decision to unroll a for-loop because the number of passes through it are small enough
- Collapsing arithmetic expressions into a single value
- Collapsing trivial simplifications, such as adding by zero or multiplying by 1

Specialization Constant Example -- Setting an Array Size

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In the compute shader

```
layout( constant_id = 7 )  const int ASIZE = 32;

int array[ASIZE];
```

In the Vulkan C/C++ program:

```
int asize = 64;

VkSpecializationMapEntry    vsme[1];      // one array element for each
                                          //      Specialization Constant
        vsme[0].constantID = 7;
        vsme[0].offset = 0;               // # bytes into the Specialization Constant
                                          //      array this one item is
        vsme[0].size = sizeof(asize);     // size of just this Specialization Constant

VkSpecializationInfo        vsi;
        vsi.mapEntryCount = 1;
        vsi.pMapEntries = &vsme[0];
        vsi.dataSize = sizeof(asize);     // size of all the Specialization Constants together
        vsi.pData = &asize;               // array of all the Specialization Constants
```


Linking the Specialization Constants into the Compute Pipeline

264

```
int asize = 64;

VkSpecializationMapEntry                vsme[1];
        vsme[0].constantID = 7;
        vsme[0].offset = 0;
        vsme[0].size = sizeof(asize);

VkSpecializationInfo        vsi;
        vsi.mapEntryCount = 1;
        vsi.pMapEntries = &vsme[0];
        vsi.dataSize = sizeof(asize);
        vsi.pData = &asize;

VkPipelineShaderStageCreateInfo         vpssci;
        vpssci.sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci.pNext = nullptr;
        vpssci.flags = 0;
        vpssci.stage = VK_SHADER_STAGE_COMPUTE_BIT;
        vpssci.module = computeShader;
        vpssci.pName = "main";
        vpssci.pSpecializationInfo = &vsi;

VkComputePipelineCreateInfo             vcpci[1];
        vcpci[0].sType = VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO;
        vcpci[0].pNext = nullptr;
        vcpci[0].flags = 0;
        vcpci[0].stage = vpssci;
        vcpci[0].layout = ComputePipelineLayout;
        vcpci[0].basePipelineHandle = VK_NULL_HANDLE;
        vcpci[0].basePipelineIndex = 0;

result = vkCreateComputePipelines( LogicalDevice, VK_NULL_HANDLE, 1, &vcpci[0], PALLOCATOR, OUT &ComputePipeline );
```

Specialization Constant Example – Setting Multiple Constants

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In the compute shader

```
layout( constant_id =  9 )  const int    a = 1;
layout( constant_id = 10 )  const int    b = 2;
layout( constant_id = 11 )  const float  c = 3.14;
```

In the C/C++ program:

```
struct abc { int a, int b, float c; } abc;

VkSpecializationMapEntry    vsme[3];
        vsme[0].constantID = 9;
        vsme[0].offset = offsetof( abc, a );
        vsme[0].size = sizeof(abc.a);
        vsme[1].constantID = 10;
        vsme[1].offset = offsetof( abc, b );
        vsme[1].size = sizeof(abc.b);
        vsme[2].constantID = 11;
        vsme[2].offset = offsetof( abc, c );
        vsme[2].size = sizeof(abc.c);

VkSpecializationInfo            vsi;
        vsi.mapEntryCount = 3;
        vsi.pMapEntries = &vsme[0];
        vsi.dataSize = sizeof(abc);          // size of all the Specialization Constants together
        vsi.pData = &abc;                    // array of all the Specialization Constants
```

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Specialization Constants – Setting the Number of Work-items Per Work-Group in the Compute Shader

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In the compute shader

```
layout( local_size_x_id=12 )  in;

layout( local_size_x = 32,  local_size_y = 1, local_size_z = 1 )   in;
```

In the C/C++ program:

```
int numXworkItems = 64;

VkSpecializationMapEntry      vsme[1];
        vsme[0].constantID = 12;
        vsme[0].offset = 0;
        vsme.size = sizeof(int);

VkSpecializationInfo          vsi;
        vsi.mapEntryCount = 1;
        vsi.pMapEntries = &vsme[0];
        vsi.dataSize = sizeof(int);
        vsi.pData = &numXworkItems;
```

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Synchronization

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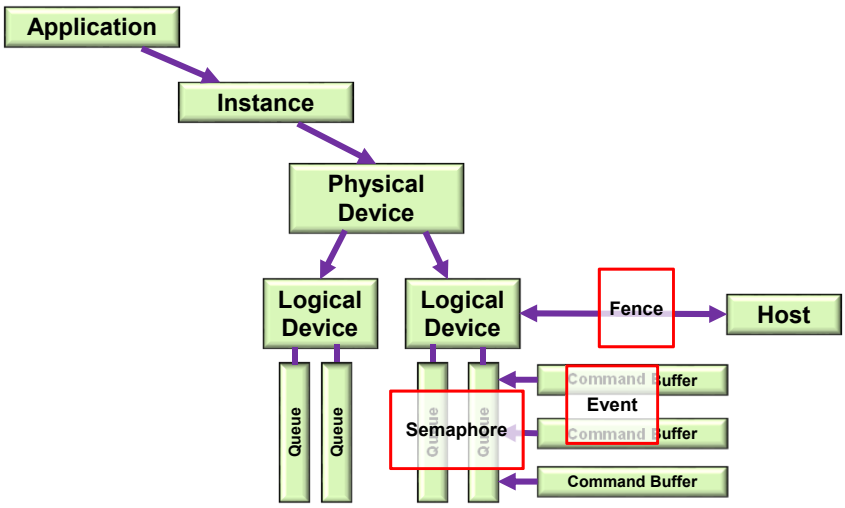
Where Synchronization Fits in the Overall Block Diagram



Semaphores

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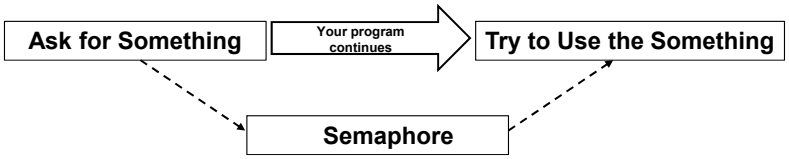
- Used to control readiness of resources within one queue or across different queues belonging to the same logical device
- You create them, and give them to a Vulkan function which sets them. Later on, you tell a Vulkan function to wait on this particular semaphore
- You don't end up setting, resetting, or checking the semaphore yourself
- Semaphores must be initialized ("created") before they can be used



Creating a Semaphore

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```
VkSemaphoreCreateInfo                   vsci;
        vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
        vsci.pNext = nullptr;
        vsci.flags = 0;;

VkSemaphore             semaphore;
result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &semaphore );
```

Semaphores Example during the Render Loop


```
VkSemaphore imageReadySemaphore;

VkSemaphoreCreateInfo                vsci;
        vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
        vsci.pNext = nullptr;
        vsci.flags = 0;

result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t nextImageIndex;
vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN UINT64_MAX,
                       IN imageReadySemaphore, IN VK_NULL_HANDLE, OUT &nextImageIndex );

    . . .

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;
VkSubmitInfo                vsi;
        vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
        vsi.pNext = nullptr;
        vsi.waitSemaphoreCount = 1;
        vsi.pWaitSemaphores = &imageReadySemaphore;
        vsi.pWaitDstStageMask = &waitAtBottom;
        vsi.commandBufferCount = 1;
        vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
        vsi.signalSemaphoreCount = 0;
        vsi.pSignalSemaphores = (VkSemaphore) nullptr;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );
```

Could be an array of semaphores

Fences

- Used to synchronize the application with commands submitted to a queue
- Announces that queue-submitted work is finished
- Much finer control than semaphores
- You can un-signal, signal, test or block-while-waiting

Fences


```
#define VK_FENCE_CREATE_UNSIGNALED_BIT        0

VkFenceCreateInfo                   vfci;
        vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
        vfci.pNext = nullptr;
        vfci.flags = VK_FENCE_CREATE_UNSIGNALED_BIT;          // = 0
                // VK_FENCE_CREATE_SIGNALED_BIT is only other option

VkFence             fence;
result = vkCreateFence( LogicalDevice, IN &vfci, PALLOCATOR, OUT &fence );

        , , ,

// returns right away:
result = vkGetFenceStatus( LogicalDevice, IN fence );
                // result = VK_SUCCESS means it has signaled
                // result = VK_NOT_READY means it has not signaled


// blocks:
result = vkWaitForFences( LogicalDevice, 1, IN &fence, waitForAll, timeout );
                // waitForAll = VK_TRUE:   wait for all fences in the list
                // waitForAll = VK_FALSE: wait for any one fence in the list
                // timeout is a uint64_t timeout in nanoseconds  (could be 0, which means to return immediately)
                // timeout can be up to UINT64_MAX  = 0xffffffffffffffff (= 580+ years)
                // result = VK_SUCCESS means it returned because a fence  (or all fences) signaled
                // result = VK_TIMEOUT means it returned because the timeout was exceeded
```

Could be an array of fences

Fence Example


```
VkFence renderFence;
vkCreateFence( LogicalDevice, &vfci, PALLOCATOR, OUT &renderFence );

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;

VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue );

VkSubmitInfo                    vsi;
        vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
        vsi.pNext = nullptr;
        vsi.waitSemaphoreCount = 1;
        vsi.pWaitSemaphores = &imageReadySemaphore;
        vsi.pWaitDstStageMask = &waitAtBottom;
        vsi.commandBufferCount = 1;
        vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
        vsi.signalSemaphoreCount = 0;
        vsi.pSignalSemaphores = (VkSemaphore) nullptr;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );

        . . .

result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );

        . . .

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```

Events

- Events provide even finer-grained synchronization
- Events are a primitive that can be signaled by the host or the device
- Can even signal at one place in the pipeline and wait for it at another place in the pipeline
- Signaling in the pipeline means “signal me as the last piece of this draw command passes that point in the pipeline”.
- You can signal, un-signal, or test from a vk function or from a vkCmd function
- Can wait from a vkCmd function

Controlling Events from the Host


```
VkEventCreateInfo                       veci;
        veci.sType = VK_STRUCTURE_TYPE_EVENT_CREATE_INFO;
        veci.pNext = nullptr;
        veci.flags = 0;

VkEvent             event;
result = vkCreateEvent( LogicalDevice, IN &veci, PALLOCATOR, OUT &event );

result = vkSetEvent( LogicalDevice, IN event );

result = vkResetEvent( LogicalDevice, IN event );

result = vkGetEventStatus( LogicalDevice, IN event );
                // result = VK_EVENT_SET: signaled
                 // result = VK_EVENT_RESET: not signaled
```

Note: the host cannot *block* waiting for an event, but it can test for it

Controlling Events from the Device

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```
result = vkCmdSetEvent(     CommandBuffer, IN event, pipelineStageBits );

result = vkCmdResetEvent( CommandBuffer, IN event, pipelineStageBits );

result = vkCmdWaitEvents( CommandBuffer, 1, &event,
        srcPipelineStageBits, dstPipelineStageBits,
        memoryBarrierCount, pMemoryBarriers,
        bufferMemoryBarrierCount, pBufferMemoryBarriers,
        imageMemoryBarrierCount, pImageMemoryBarriers );
```

Could be an array of events

Where signaled, where wait for the signal

Memory barriers get executed after events have been signaled

Note: the device cannot *test* for an event, but it can block

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Pipeline Barriers

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From the Command Buffer Notes:
These are the Commands that can be entered into the Command Buffer, I

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```
vkCmdBeginQuery( commandBuffer, flags );
vkCmdBeginRenderPass( commandBuffer, const contents );
vkCmdBindDescriptorSets( commandBuffer, pDynamicOffsets );
vkCmdBindIndexBuffer( commandBuffer, indexType );
vkCmdBindPipeline( commandBuffer, pipeline );
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, const pOffsets );
vkCmdBlitImage( commandBuffer, filter );
vkCmdClearAttachments( commandBuffer, attachmentCount, const pRects );
vkCmdClearColorImage( commandBuffer, pRanges );
vkCmdClearDepthStencilImage( commandBuffer, pRanges );
vkCmdCopyBuffer( commandBuffer, pRegions );
vkCmdCopyBufferToImage( commandBuffer, pRegions );
vkCmdCopyImage( commandBuffer, pRegions );
vkCmdCopyImageToBuffer( commandBuffer, pRegions );
vkCmdCopyQueryPoolResults( commandBuffer, flags );
vkCmdDebugMarkerBeginEXT( commandBuffer, pMarkerInfo );
vkCmdDebugMarkerEndEXT( commandBuffer );
vkCmdDebugMarkerInsertEXT( commandBuffer, pMarkerInfo );
vvkCmdDispatch( commandBuffer, groupCountX, groupCountY, groupCountZ );
vkCmdDispatchIndirect( commandBuffer, offset );
vkCmdDraw( commandBuffer, vertexCount, instanceCount, firstVertex, firstInstance );
vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex, int32_t vertexOffset, firstInstance );
vkCmdDrawIndexedIndirect( commandBuffer, stride );
vkCmdDrawIndexedIndirectCountAMD( commandBuffer, stride );
vkCmdDrawIndirect( commandBuffer, stride );
vkCmdDrawIndirectCountAMD( commandBuffer, stride );
vkCmdEndQuery( commandBuffer, query );
vkCmdEndRenderPass( commandBuffer );
vkCmdExecuteCommands( commandBuffer, commandBufferCount, const pCommandBuffers );
```

From the Command Buffer Notes:
These are the Commands that can be entered into the Command Buffer, II

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```
vkCmdFillBuffer( commandBuffer, dstBuffer, dstOffset, size, data );
vkCmdNextSubpass( commandBuffer, contents );
vkCmdPipelineBarrier( commandBuffer, srcStageMask, dstStageMask, dependencyFlags, memoryBarrierCount, VkMemoryBarrier* pMemoryBarriers,
        bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdProcessCommandsNVX( commandBuffer, pProcessCommandsInfo );
vkCmdPushConstants( commandBuffer, layout, stageFlags, offset, size, pValues );
vkCmdPushDescriptorSetKHR( commandBuffer, pipelineBindPoint, layout, set, descriptorWriteCount, pDescriptorWrites );
vkCmdPushDescriptorSetWithTemplateKHR( commandBuffer, descriptorUpdateTemplate, layout, set, pData );
vkCmdReserveSpaceForCommandsNVX( commandBuffer, pReserveSpaceInfo );
vkCmdResetEvent( commandBuffer, event, stageMask );
vkCmdResetQueryPool( commandBuffer, queryPool, firstQuery, queryCount );
vkCmdResolveImage( commandBuffer, srcImage, srcImageLayout, dstImage, dstImageLayout, regionCount, pRegions );
vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );
vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );
vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );
vkCmdSetDeviceMaskKHX( commandBuffer, deviceMask );
vkCmdSetDiscardRectangleEXT( commandBuffer, firstDiscardRectangle, discardRectangleCount, pDiscardRectangles );
vkCmdSetEvent( commandBuffer, event, stageMask );
vkCmdSetLineWidth( commandBuffer, lineWidth );
vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetViewportWScalingNV( commandBuffer, firstViewport, viewportCount, pViewportWScalings );
vkCmdUpdateBuffer( commandBuffer, dstBuffer, dstOffset, dataSize, pData );
vkCmdWaitEvents( commandBuffer, eventCount, pEvents, srcStageMask, dstStageMask, memoryBarrierCount, pMemoryBarriers,
            bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdWriteTimestamp( commandBuffer, pipelineStage, queryPool, query );
```

Potential Memory Race Conditions that Pipeline Barriers can Prevent

1. Write-then-Read (WtR) – the memory write in one operation starts overwriting the memory that another operation's read needs to use
2. Read-then-Write (RtW) – the memory read in one operation hasn't yet finished before another operation starts overwriting that memory
3. Write-then-Write (WtW) – two operations start overwriting the same memory and the end result is non-deterministic

Note: there is no problem with Read-then-Read (RtR) as no data has been changed

vkCmdPipelineBarrier( ) Function Call

A **Pipeline Barrier** is a way to establish a memory dependency between commands that were submitted before the barrier and commands that are submitted after the barrier

```
vkCmdPipelineBarrier( commandBuffer,
        srcStageMask,
        dstStageMask,
        VK_DEPENDENCY_BY_REGION_BIT,
        memoryBarrierCount,          pMemoryBarriers,
        bufferMemoryBarrierCount,    pBufferMemoryBarriers,
        imageMemoryBarrierCount,     pImageMemoryBarriers
);
```

Guarantee that this pipeline stage has completely generated one set of data before …

… allowing this pipeline stage to consume it

Defines what data we will be blocking/un-blocking on

The Scenario

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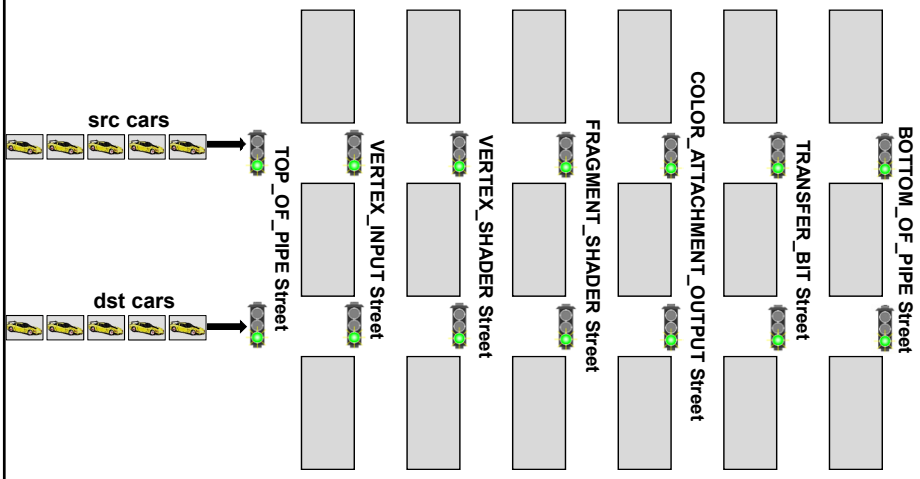

The Scenario

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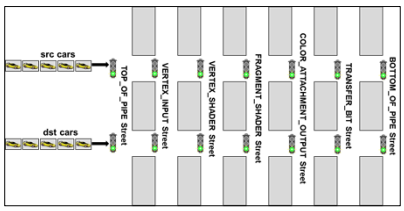
1. The cross-streets are named after pipeline stages
2. All traffic lights start out green
3. There are special sensors at all intersections that will know when the ***first car in the src group*** enters that intersection
4. There are connections from those sensors to the traffic lights so that when the ***first car in the src group*** enters its intersection, the proper ***dst*** traffic light will be turned red
5. When the ***last car in the src group*** completely makes it through its intersection, the proper ***dst*** traffic light can be turned back to green
6. The Vulkan command pipeline ordering is this: (1) the **src** cars get released, (2) the pipeline barrier is invoked (which turns some lights red), (3) the **dst** cars get released (which end up being stopped by a red light somewhere)



Pipeline Stage Masks – Where in the Pipeline is this Memory Data being Generated or Consumed?

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VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Pipeline Stages

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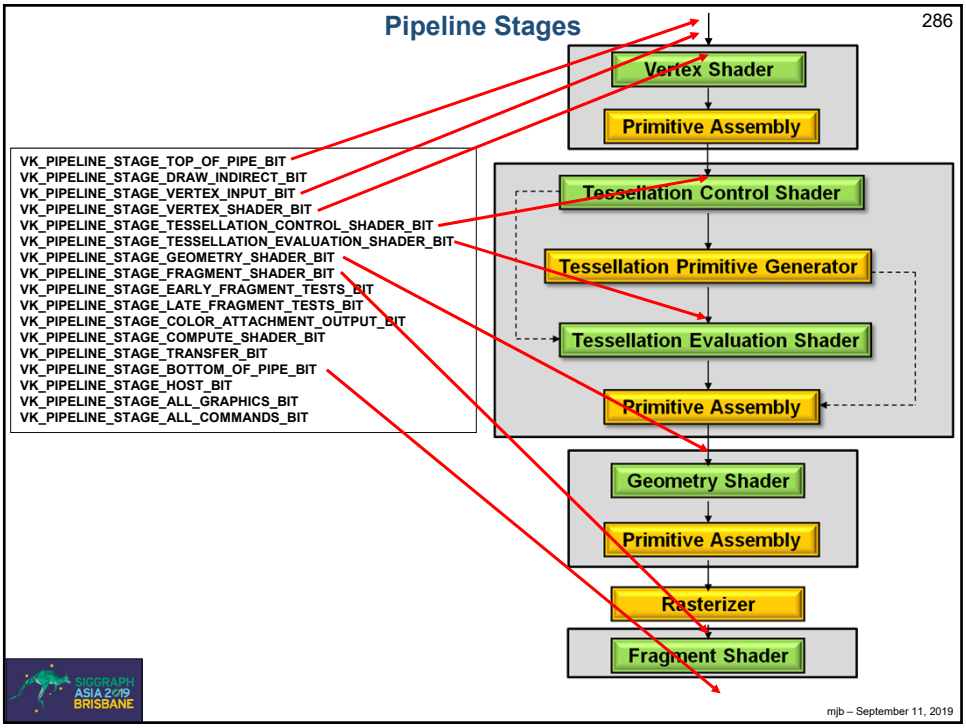

Access Masks – What are you Interested in Generating or Consuming this Memory for?

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- VK_ACCESS_INDIRECT_COMMAND_READ_BIT
- VK_ACCESS_INDEX_READ_BIT
- VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT
- VK_ACCESS_UNIFORM_READ_BIT
- VK_ACCESS_INPUT_ATTACHMENT_READ_BIT
- VK_ACCESS_SHADER_READ_BIT
- VK_ACCESS_SHADER_WRITE_BIT
- VK_ACCESS_COLOR_ATTACHMENT_READ_BIT
- VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT
- VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT
- VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT
- VK_ACCESS_TRANSFER_READ_BIT
- VK_ACCESS_TRANSFER_WRITE_BIT
- VK_ACCESS_HOST_READ_BIT
- VK_ACCESS_HOST_WRITE_BIT
- VK_ACCESS_MEMORY_READ_BIT
- VK_ACCESS_MEMORY_WRITE_BIT

Pipeline Stages and what Access Operations can Happen There

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		VK_ACCESS_INDIRECT_COMMAND_READ_BIT	VK_ACCESS_INDEX_READ_BIT	VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT	VK_ACCESS_UNIFORM_READ_BIT	VK_ACCESS_INPUT_ATTACHMENT_READ_BIT	VK_ACCESS_SHADER_READ_BIT	VK_ACCESS_SHADER_WRITE_BIT	VK_ACCESS_COLOR_ATTACHMENT_READ_BIT	VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT	VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT	VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT	VK_ACCESS_TRANSFER_READ_BIT	VK_ACCESS_TRANSFER_WRITE_BIT	VK_ACCESS_HOST_READ_BIT	VK_ACCESS_HOST_WRITE_BIT	VK_ACCESS_MEMORY_READ_BIT	VK_ACCESS_MEMORY_WRITE_BIT
1	VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT																	
2	VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT	●																
3	VK_PIPELINE_STAGE_VERTEX_INPUT_BIT		●	●														
4	VK_PIPELINE_STAGE_VERTEX_SHADER_BIT				●		●	●										
5	VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT				●		●	●										
6	VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT				●		●	●										
7	VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT				●		●	●										
8	VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT										●	●						
9	VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT				●	●	●	●										
10	VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT										●	●						
11	VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT								●	●								
12	VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT																	
	VK_PIPELINE_STAGE_COMPUTE_SHADER				●		●	●										
	VK_PIPELINE_STAGE_TRANSFER_BIT												●	●				
	VK_PIPELINE_STAGE_HOST_BIT														●	●		

Access Operations and what Pipeline Stages they can be used In

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	1 VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT	2 VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT	3 VK_PIPELINE_STAGE_VERTEX_INPUT_BIT	4 VK_PIPELINE_STAGE_VERTEX_SHADER_BIT	5 VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT	6 VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT	7 VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT	8 VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT	9 VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT	10 VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT	11 VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT	12 VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT	VK_PIPELINE_STAGE_COMPUTE_SHADER	VK_PIPELINE_STAGE_TRANSFER_BIT	VK_PIPELINE_STAGE_HOST_BIT
VK_ACCESS_INDIRECT_COMMAND_READ_BIT		•													
VK_ACCESS_INDEX_READ_BIT			•												
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT			•												
VK_ACCESS_UNIFORM_READ_BIT				•	•	•	•		•				•		
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT									•						
VK_ACCESS_SHADER_READ_BIT				•	•	•	•		•				•		
VK_ACCESS_SHADER_WRITE_BIT				•	•	•	•		•				•		
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT											•				
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT											•				
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT								•		•					
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT								•		•					
VK_ACCESS_TRANSFER_READ_BIT														•	
VK_ACCESS_TRANSFER_WRITE_BIT														•	
VK_ACCESS_HOST_READ_BIT															•
VK_ACCESS_HOST_WRITE_BIT															•
VK_ACCESS_MEMORY_READ_BIT															
VK_ACCESS_MEMORY_WRITE_BIT															

Example: Be sure we are done writing an output image before using it for something else

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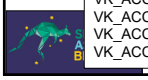
VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT ← **src**
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT ← **dst**
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Stages

VK_ACCESS_INDIRECT_COMMAND_READ_BIT
VK_ACCESS_INDEX_READ_BIT
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT
VK_ACCESS_UNIFORM_READ_BIT
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT
VK_ACCESS_SHADER_READ_BIT ← **src**
VK_ACCESS_SHADER_WRITE_BIT
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT
VK_ACCESS_TRANSFER_READ_BIT
VK_ACCESS_TRANSFER_WRITE_BIT
VK_ACCESS_HOST_READ_BIT
VK_ACCESS_HOST_WRITE_BIT
VK_ACCESS_MEMORY_READ_BIT
VK_ACCESS_MEMORY_WRITE_BIT

Access types

dst (no access setting needed)



The Scenario

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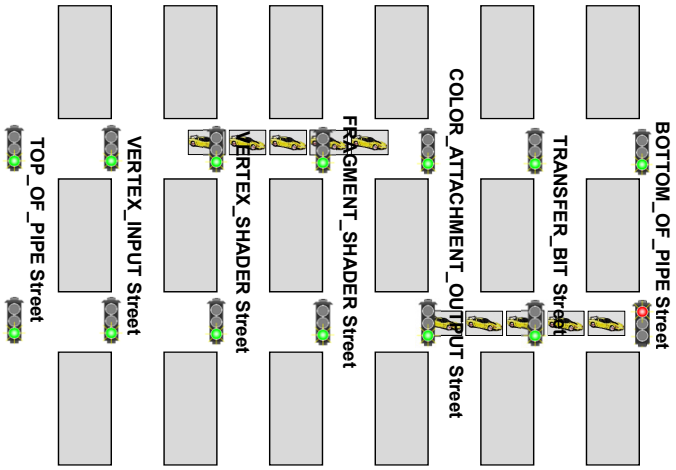
src cars are generating the image

dst cars are doing something with that image



Example: Don't read a buffer back to the host until a shader is done writing it

Stages

VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT ← **src**
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT ← **dst**
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Access types

VK_ACCESS_INDIRECT_COMMAND_READ_BIT
VK_ACCESS_INDEX_READ_BIT
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT
VK_ACCESS_UNIFORM_READ_BIT
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT
VK_ACCESS_SHADER_READ_BIT
VK_ACCESS_SHADER_WRITE_BIT ← **src**
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT
VK_ACCESS_TRANSFER_READ_BIT
VK_ACCESS_TRANSFER_WRITE_BIT
VK_ACCESS_HOST_READ_BIT
VK_ACCESS_HOST_WRITE_BIT
VK_ACCESS_MEMORY_READ_BIT
VK_ACCESS_MEMORY_WRITE_BIT

dst (no access setting needed)

The Scenario

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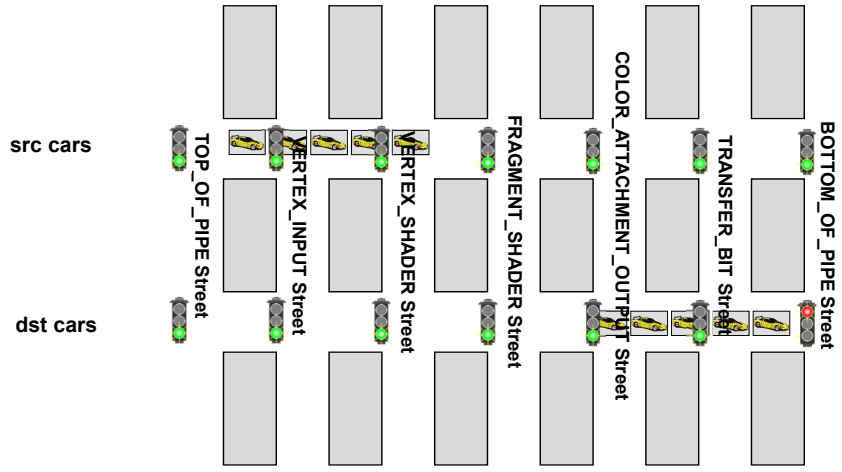

VkImageLayout – How an Image gets Laid Out in Memory depends on how it will be Used

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```
VkImageMemoryBarrier vimb’
        vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
        vimb.pNext = nullptr;
        vimb.srcAccessMask = ??;
        vimb.dstAccessMask = ??;
        vimb.oldLayout   = ??;
        vimb.newLayout = ??;
        vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
        vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
        vimb.image = ??;
        vimb.subresourceRange = visr;
```

VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_GENERAL
VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL ← Used as a color attachment
VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL
VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL ← Read into a shader as a texture
VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL ← Copy from
VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL ← Copy to
VK_IMAGE_LAYOUT_PREINITIALIZED
VK_IMAGE_LAYOUT_PRESENT_SRC_KHR ← Show image to viewer
VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR

Here, the use of vkCmdPipelineBarrier( ) is to simply change the layout of an image

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Antialiasing and Multisampling

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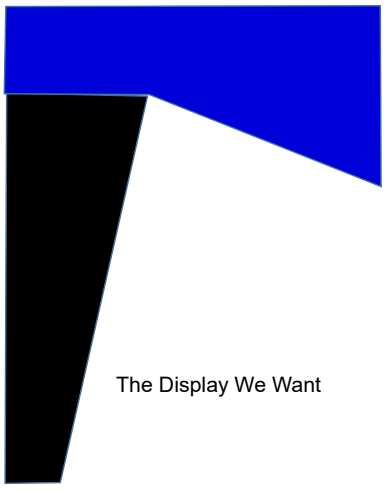
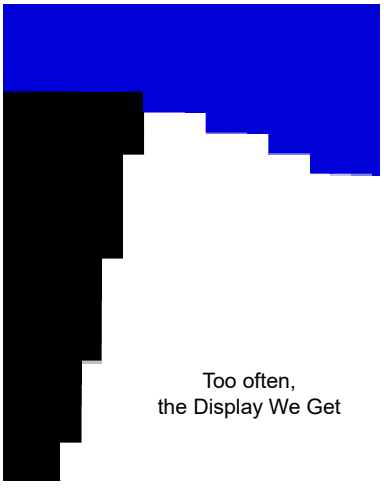
Aliasing



The Display We Want



Too often,
the Display We Get

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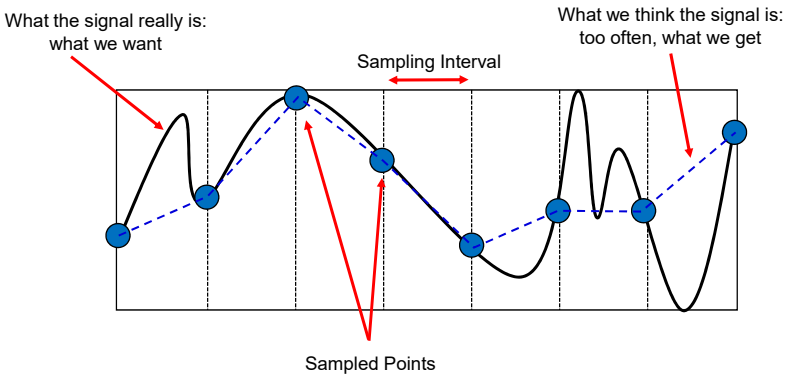
Aliasing

"Aliasing" is a signal-processing term for "under-sampled compared with the frequencies in the signal".



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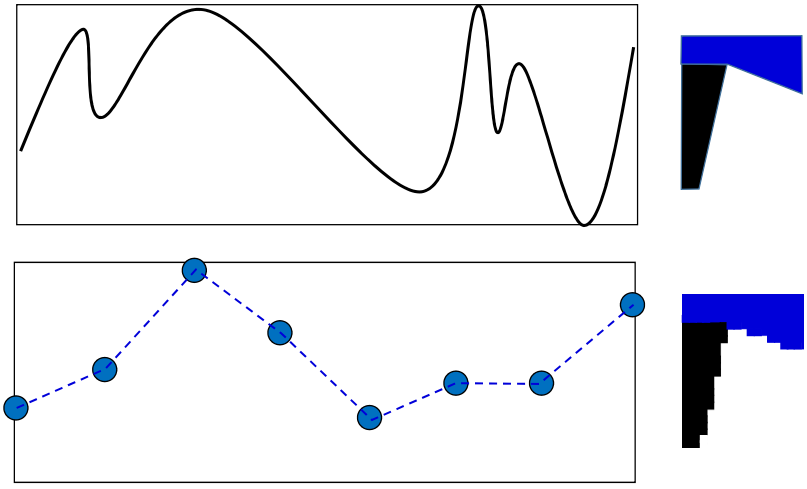
Aliasing



MultiSampling

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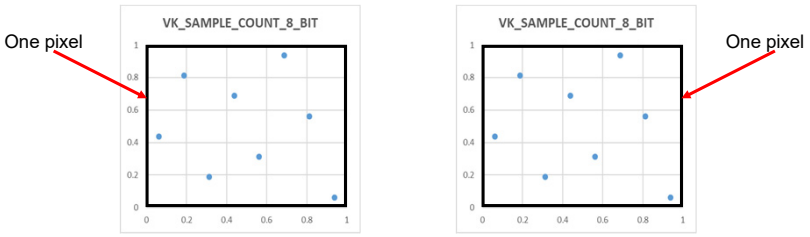
Multisampling is a computer graphics technique to improve the quality of your output image by looking inside every pixel to see what the rendering is doing there.

There are two approaches to this:

1. **Supersampling**: Pick some number of unique sub-pixels within a pixel, render the image at each of these sub-pixels (including depth and stencil tests), then average them together.



2. **Multisampling**: Perform a single color render for the one pixel. Then, pick some number of unique sub-pixels within that pixel and perform depth and stencil tests there. Assign the single color to all the sub-pixels that made it through the depth and stencil tests

Vulkan Distribution of Sampling Points within a Pixel

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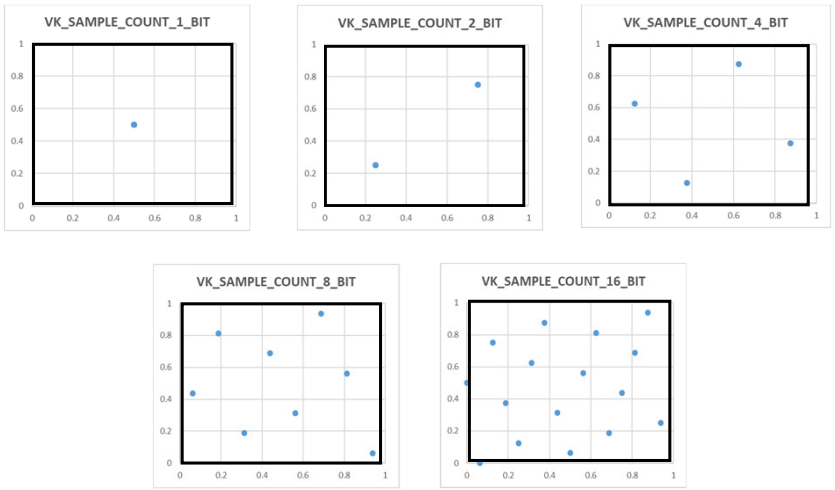

Vulkan Distribution of Sampling Points within a Pixel

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VK_SAMPLE_COUNT_2_BIT	VK_SAMPLE_COUNT_4_BIT	VK_SAMPLE_COUNT_8_BIT	VK_SAMPLE_COUNT_16_BIT
		(0.5625, 0.3125)	(0.5625, 0.5625)
	(0.375, 0.125)		(0.4375, 0.3125)
		(0.4375, 0.6875)	(0.3125, 0.625)
			(0.75, 0.4375)
(0.25,0.25)		(0.8125, 0.5625)	(0.1875, 0.375)
	(0.875, 0.375)		(0.625, 0.8125)
		(0.3125, 0.1875)	(0.8125, 0.6875)
			(0.6875, 0.1875)
		(0.1875, 0.8125)	(0.375, 0.875)
	(0.125, 0.625)		(0.5, 0.0625)
		(0.0625, 0.4375)	(0.25, 0.125)
(0.75,0.75)			(0.125, 0.75)
		(0.6875, 0.9375)	(0.0, 0.5)
	(0.625, 0.875)		(0.9375, 0.25)
		(0.9375, 0.0625)	(0.875, 0.9375)
			(0.0625, 0.0)

Consider Two Triangles Whose Edges Pass Through the Same Pixel

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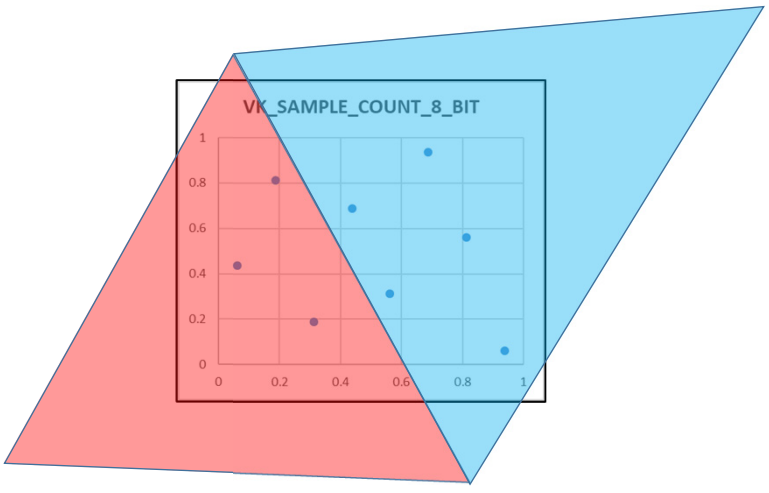

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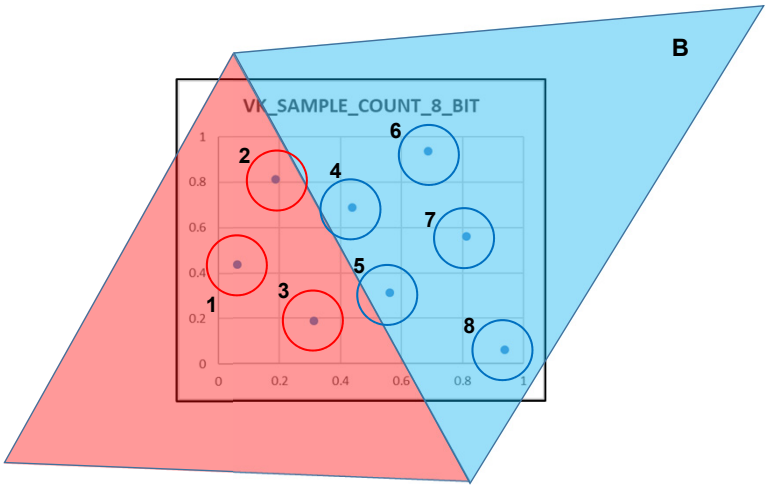
Supersampling



$$Final\ Pixel\ Color = \frac{\sum_{i=1}^{8} Color\ sample\ from\ subpixel_i}{8}$$

 # Fragment Shader calls = 8

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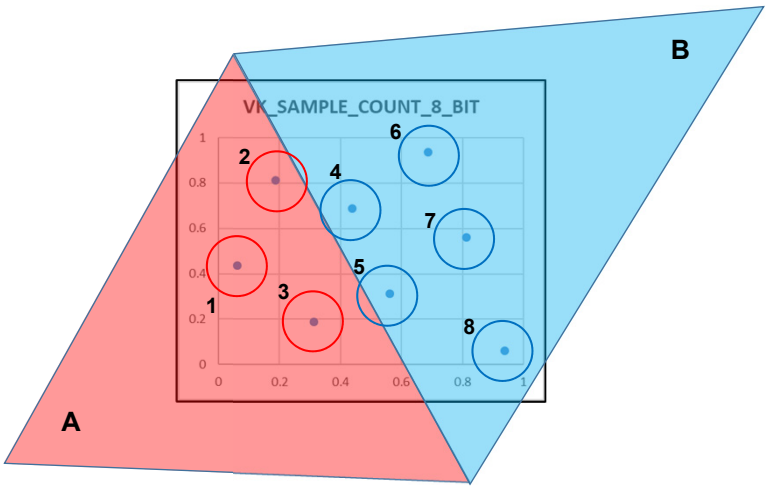
Multisampling



$$Final\ Pixel\ Color = \frac{3 * One\ color\ sample\ from\ A\ +\ 5 * One\ color\ sample\ from\ B}{8}$$

 # Fragment Shader calls = 2

Setting up the Image

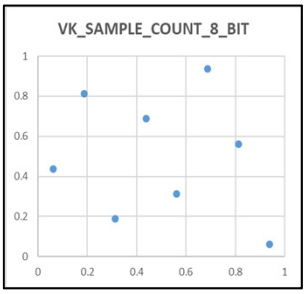

```
VkPipelineMultisampleStateCreateInfo            vpmsci;
        vpmsci.sType = VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO;
        vpmsci.pNext = nullptr;
        vpmsci.flags = 0;
        vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_8_BIT;
        vpmsci.sampleShadingEnable = VK_TRUE;
        vpmsci.minSampleShading = 0.5f;
        vpmsci.pSampleMask = (VkSampleMask *)nullptr;
        vpmsci.alphaToCoverageEnable = VK_FALSE;
        vpmsci.alphaToOneEnable = VK_FALSE;

VkGraphicsPipelineCreateInfo                    vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
    . . .
        vgpci.pMultisampleState = &vpmsci;

result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,\
                                    PALLOCATOR, OUT pGraphicsPipeline );
```

How dense is the sampling

VK_TRUE means to allow some sort of multisampling to take place

Setting up the Image


```
VkPipelineMultisampleStateCreateInfo            vpmsci;
        . . .
        vpmsci.minSampleShading = 0.5;
        . . .
```



At least this fraction of samples will get their own fragment shader calls (as long as they pass the depth and stencil tests).

0. produces simple multisampling

(0.,1.) produces partial supersampling

1. Produces complete supersampling

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Setting up the Image

```
VkAttachmentDescription                 vad[2];
        vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
        vad[0].samples = VK_SAMPLE_COUNT_8_BIT;
        vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
        vad[0].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
        vad[0].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[0].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[0].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[0].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
        vad[0].flags = 0;

        vad[1].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
        vad[1].samples = VK_SAMPLE_COUNT_8_BIT;
        vad[1].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
        vad[1].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[1].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[1].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[1].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[1].finalLayout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
        vad[1].flags = 0;

VkAttachmentReference                   colorReference;
        colorReference.attachment = 0;
        colorReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   depthReference;
        depthReference.attachment = 1;
        depthReference.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
```


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Setting up the Image

```
VkSubpassDescription                    vsd;
        vsd.flags = 0;
        vsd.pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd.inputAttachmentCount = 0;
        vsd.pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd.colorAttachmentCount = 1;
        vsd.pColorAttachments = &colorReference;
        vsd.pResolveAttachments = (VkAttachmentReference *)nullptr;
        vsd.pDepthStencilAttachment = &depthReference;
        vsd.preserveAttachmentCount = 0;
        vsd.pPreserveAttachments = (uint32_t *)nullptr;

VkRenderPassCreateInfo                  vrpci;
        vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
        vrpci.pNext = nullptr;
        vrpci.flags = 0;
        vrpci.attachmentCount = 2;              // color and depth/stencil
        vrpci.pAttachments = vad;
        vrpci.subpassCount = 1;
        vrpci.pSubpasses = IN &vsd;
        vrpci.dependencyCount = 0;
        vrpci.pDependencies = (VkSubpassDependency *)nullptr;


result = vkCreateRenderPass( LogicalDevice, IN &vrpci, PALLOCATOR, OUT &RenderPass );
```

Resolving the Image: Converting the Multisampled Image to a VK_SAMPLE_COUNT_1_BIT image

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```
VIOffset3D                          vo3;
        vo3.x = 0;
        vo3.y = 0;
        vo3.z = 0;

VkExtent3D                          ve3;
        ve3.width = Width;
        ve3.height = Height;
        ve3.depth = 1;

VkImageSubresourceLayers            visl;
        visl.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
        visl.mipLevel = 0;
        visl.baseArrayLayer = 0;
        visl.layerCount = 1;

VkImageResolve                      vir;
        vir.srcSubresource = visl;
        vir.srcOffset = vo3;
        vir.dstSubresource = visl;
        vir.dstOffset = vo3;
        vir.extent = ve3;

vkCmdResolveImage( cmdBuffer, srcImage, srcImageLayout,  dstImage, dstImageLayout, 1, &vir  );
```

mjb – September 11, 2019

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Oregon State University
Computer Graphics

Introduction to the

Vulkan®

Computer Graphics API

Thanks for coming today!

http://cs.oregonstate.edu/~mjb/vulkan

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