Vulkan

Introduction

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

Acknowledgements

First of all, thanks to the inaugural class of 19 students who braved new, unrefined, and just-in-time course materials to take the first Vulkan class at Oregon State University – Winter Quarter, 2018. Thanks for your courage and patience!

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Zach Lerew	Logan Wingard
Victor Li	

Second, thanks to NVIDIA for all of their support!

Third, thanks to the Khronos Group for the great laminated Vulkan Quick Reference Cards! (Look at those happy faces in the photo holding them.)

History of Shaders

- 2004: OpenGL 2.0 / GLSL 1.10 includes Vertex and Fragment Shaders
- 2008: OpenGL 3.0 / GLSL 1.30 adds features left out before
- 2010: OpenGL 3.3 / GLSL 3.30 adds Geometry Shaders
- 2010: OpenGL 4.0 / GLSL 4.00 adds Tessellation Shaders
- 2012: OpenGL 4.3 / GLSL 4.30 adds Compute Shaders
- 2017: OpenGL 4.6 / GLSL 4.60

There is lots more detail at:

https://www.khronos.org/opengl/wiki/History_of_OpenGL

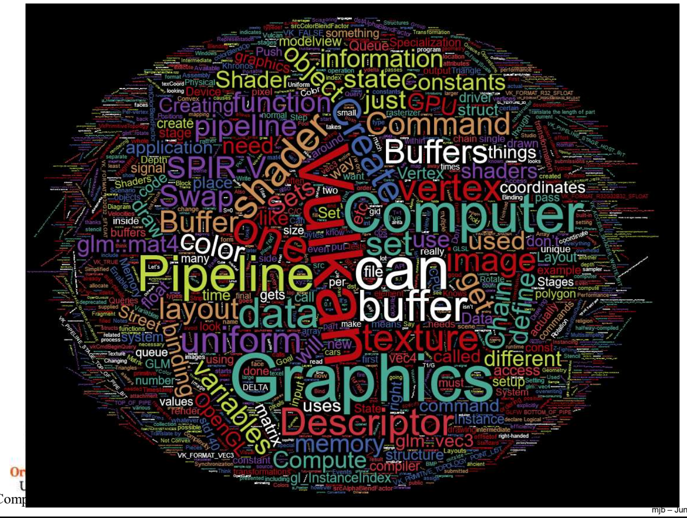
History of Shaders

- 2014: Khronos starts Vulkan effort
- 2016: Vulkan 1.0
- 2016: Vulkan 1.1
- 2020: Vulkan 1.2

There is lots more detail at:

https://en.wikipedia.org/wiki/Vulkan_(API)

Everything You Need to Know is Right Here … Somewhere



Top Three Reasons that Prompted the Development of Vulkan

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.

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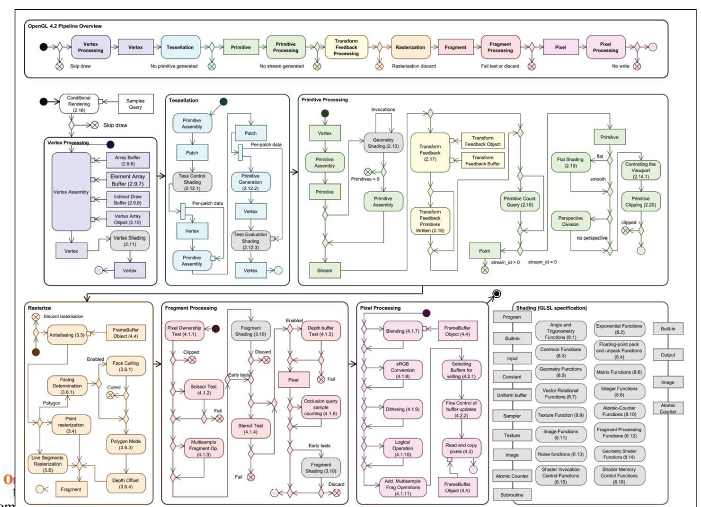
OpenGL 4.2 Pipeline Flowchart



Why is it so important to keep the GPU Busy?

NVidia Titan V Specs vs. Titan Xp, 1080 Ti

	Titan V	Tesla V100	Tesla P100	GTX 1080 Ti	GTX 1080
GPU	GV100	GV100	GP100 Cut-Down Pascal	GP102 Pascal	GP104-400 Pascal
Transistor Count	21.1B	21.1B	15.3B	12B	7.2B
Fab Process	12nm FFN	12nm FFN	16nm FinFET	16nm FinFET	16nm FinFET
CUDA Cores / Tensor Cores	5120 / 640	5120 / 640	3584 / 0	3584 / 0	2560 / 0
TMUs	320		224	224	160
ROPs	?		96 (?)	88	64
Core Clock	1200MHz		1328MHz	-	1607MHz
Boost Clock	1455MHz	1370MHz	1480MHz	1600MHz	1733MHz
FP32 TFLOPs	15TFLOPs	14TFLOPs	10.6TFLOPs	~11.4TFLOPs	9TFLOPs
Memory Type	HBM2	HBM2	HBM2	GDDR5X	GDDR5X
Memory Capacity	12GB	16GB	16GB	11GB	8GB
Memory Clock	1.7Gbps HBM2	1.75Gbps HBM2	?	11Gbps	10Gbps GDDR5X
Memory Interface	3072-bit	4096-bit	4096-bit	352-bit	256-bit
Memory Bandwidth	653GB/s	900GB/s	?	~484GBs	320.32GB/s
Total Power Budget ("TDP")	250W	250W	300W	250W	180W
Power Connectors	1x 8-pin 1x 6-pin		?	1x 8-pin 1x 6-pin	1x 8-pin
Release Date	12/07/2017		4Q16-1Q17	TBD	5/27/2016
Release Price	$3000	$10000	-	$700	Reference: $700 MSRP: $600 Now: $500

The nVidia Titan V graphics card is not targeted at gamers, but rather at scientific and machine/deep learning applications. That does not, however, mean that the card is incapable of gaming, nor does it mean that we can't extrapolate future key performance metrics for Volta. The Titan V is a derivative of the earlier-released GV100 GPU, part of the Tesla accelerator card series. The key differentiator is that the Titan V ships at $3000, whereas the Tesla V100 was available as part of a $10,000 developer kit. The Tesla V100 still offers greater memory capacity by 4GB – 16GB HBM2 versus 12GB HBM2 – and has a wider memory interface, but other core features remain matched or nearly matched. Core count, for one, is 5120 CUDA cores on each GPU, with 640 Tensor cores (used for Tensorflow deep/machine learning workloads) on each GPU.

Who was the original Vulcan?

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From WikiPedia:

"Vulcan is the god of fire including the fire of volcanoes, metalworking, and the forge in ancient Roman religion and myth. Vulcan is often depicted with a blacksmith's hammer. The **Vulcanalia** was the annual festival held August 23 in his honor. His Greek counterpart is Hephaestus, the god of fire and smithery. In Etruscan religion, he is identified with Sethlans. Vulcan belongs to the most ancient stage of Roman religion: Varro, the ancient Roman scholar and writer, citing the Annales Maximi, records that king Titus Tatius dedicated altars to a series of deities among which Vulcan is mentioned."

https://en.wikipedia.org/wiki/Vulcan_(mythology)

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Why Name it after the God of the Forge?

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Who is the Khronos Group?

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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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Playing "Where's Waldo" with Khronos Membership

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Who's Been Specifically Working on Vulkan?

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Vulkan

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- Originally derived from AMD's *Mantle* API
- Also heavily influenced by Apple's *Metal* API and Microsoft's *DirectX 12*
- Goal: much less driver complexity and overhead than OpenGL has
- Goal: much less user hand-holding
- Goal: higher single-threaded performance than OpenGL can deliver
- Goal: able to do multithreaded graphics
- Goal: able to handle tiled rendering

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Vulkan Differences from OpenGL

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- 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 and texture functionality must be done in shaders.
- Shaders are pre-"half-compiled" outside of your application. The compilation process is then finished during the runtime pipeline-building process.

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The Basic OpenGL Computer Graphics Pipeline, OpenGL-style

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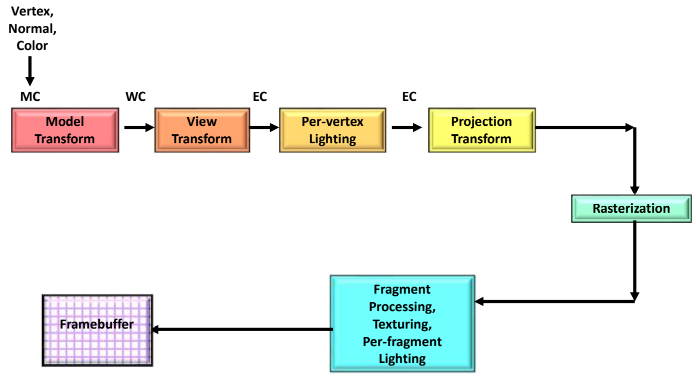

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MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates

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The Basic Computer Graphics Pipeline, Shader-style

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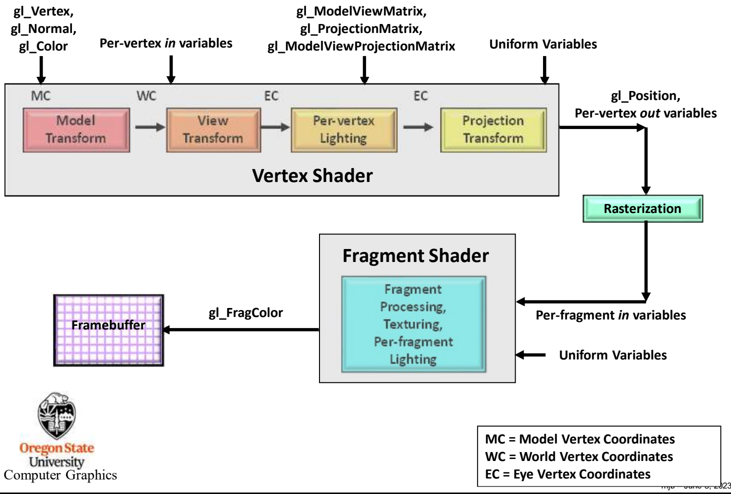

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The Basic Computer Graphics Pipeline, Vulkan-style

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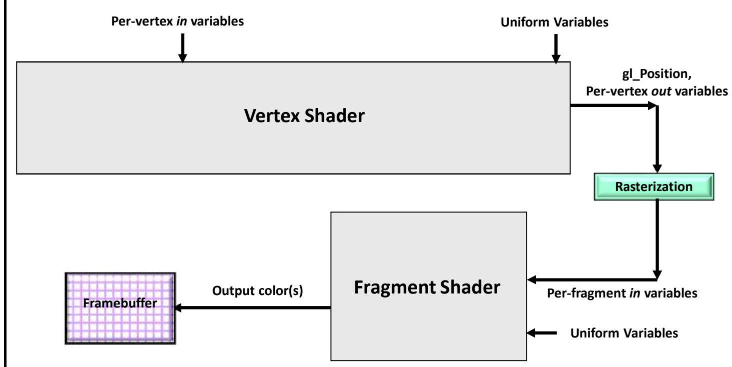

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Moving part of the driver into the application

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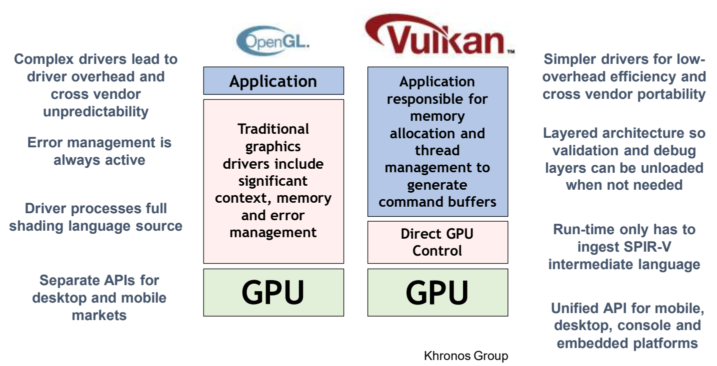

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Vulkan Highlights: Command Buffers

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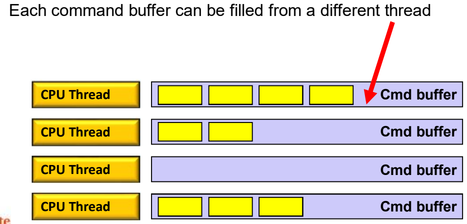
- Graphics commands are sent to command buffers
- E.g., *vkCmdDoSomething(cmdBuffer, …);*
- You can have as many simultaneous Command Buffers as you want
- Buffers are flushed to Queues when the application wants them to be flushed
- Each command buffer can be filled from a different thread



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Vulkan Highlights: Pipeline State Objects

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- In OpenGL, your "pipeline state" is the combination of 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) data structure and then invoke the entire PSO *at once* 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 pipeline state objects

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Vulkan: Creating a Pipeline

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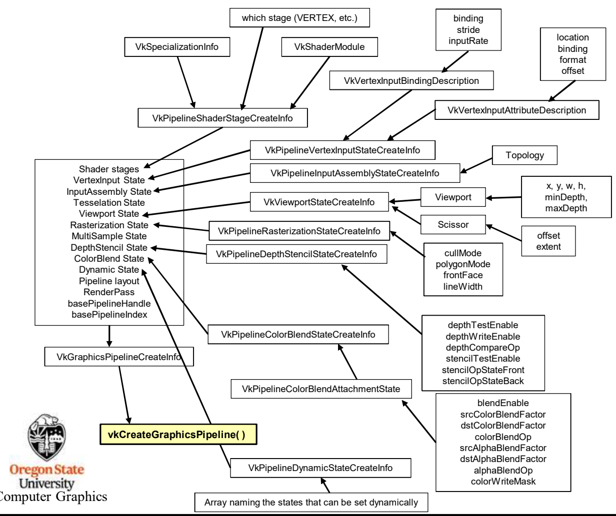

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Querying the Number of Something

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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 );
```

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

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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 = 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, OUT &MatrixBufferMemoryHandle );

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

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Vulkan Quick Reference Card – I Recommend you Print This!

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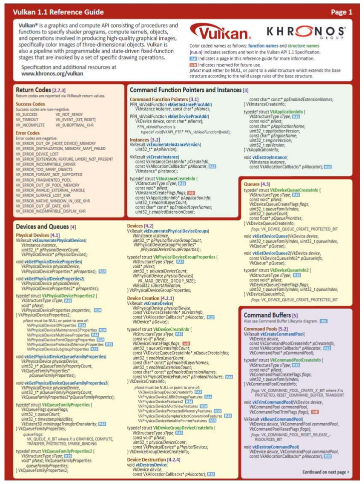

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https://www.khronos.org/files/vulkan11-reference-guide.pdf

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Vulkan Quick Reference Card

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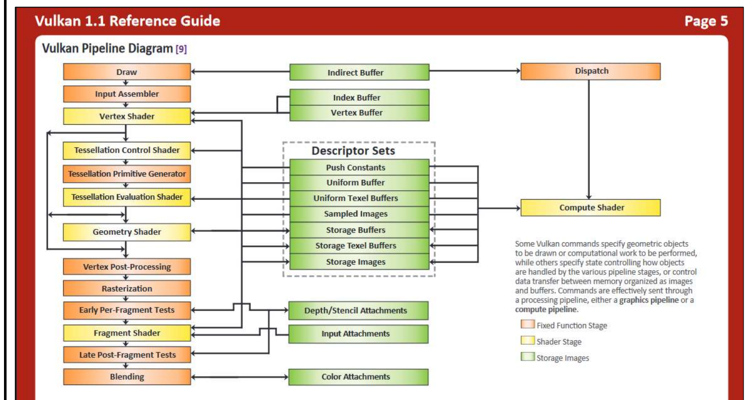

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https://www.khronos.org/files/vulkan11-reference-guide.pdf

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Vulkan Highlights: Overall Block Diagram

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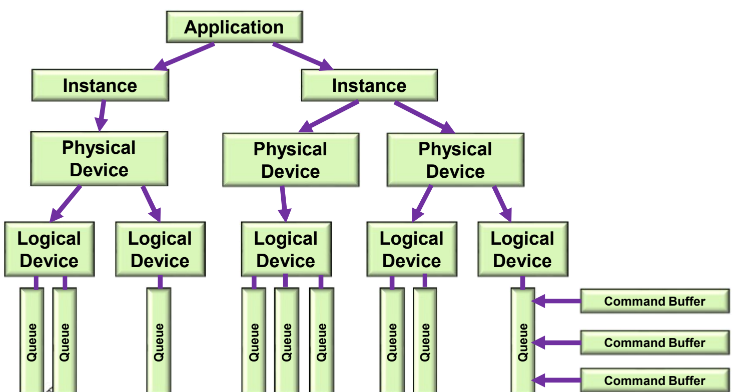

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Vulkan Highlights: a More Typical Block Diagram

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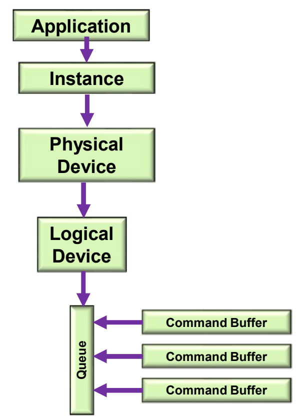

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Steps in Creating Graphics using Vulkan

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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- …

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Vulkan GPU Memory

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- Your application allocates GPU memory for the objects it needs
- To write and read that GPU memory, you map that memory to the CPU address space
- Your application is responsible for making sure that what you put into that memory is actually in the right format, is the right size, has the right alignment, etc.

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Vulkan Render Passes

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- Drawing is done inside a render pass
- Each render pass contains what framebuffer attachments to use
- Each render pass is told what to do when it begins and ends

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Vulkan Compute Shaders

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- Compute pipelines are allowed, but they are treated as something special (just like OpenGL treats them)
- Compute passes are launched through dispatches
- Compute command buffers can be run asynchronously

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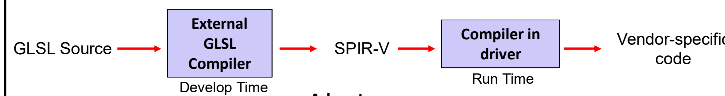
Vulkan Synchronization

- Synchronization is the responsibility of the application
- Events can be set, polled, and waited for (much like OpenCL)
- Vulkan itself does not ever lock – that's your application's job
- Threads can concurrently read from the same object
- Threads can concurrently write to different objects

Vulkan Shaders

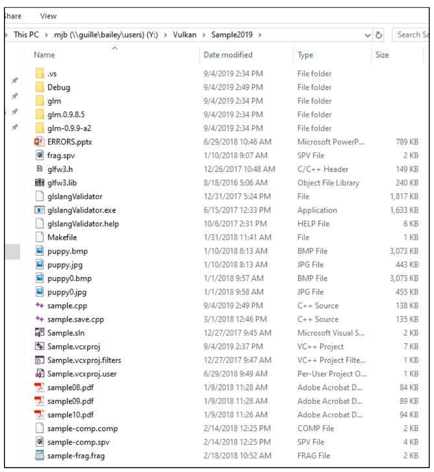
- GLSL is the same as before … almost
- For places it's not, an implied
  #define VULKAN 100
  is automatically supplied by the compiler
- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V (Standard Portable Intermediate Representation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



Advantages:

1. Software vendors don't need to ship their shader source
2. Software can launch faster because half of the compilation has already taken place
3. This guarantees a common front-end syntax
4. This allows for other language front-ends

Your Sample2019.zip File Contains This



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Name	Date modified	Type	Size
.vs	9/4/2019 2:34 PM	File folder	
Debug	9/4/2019 2:49 PM	File folder	
glm	9/4/2019 2:34 PM	File folder	
glm.0.9.8.5	9/4/2019 2:34 PM	File folder	
glm-0.9.9-a2	9/4/2019 2:34 PM	File folder	
ERRORS.pptx	6/29/2018 10:46 AM	Microsoft PowerP...	789 KB
frag.spv	1/10/2018 9:07 AM	SPV File	2 KB
glfw3.h	12/26/2017 10:48 AM	C/C++ Header	149 KB
glfw3.lib	8/18/2016 5:06 AM	Object File Library	240 KB
glslangValidator	12/31/2017 5:24 PM	File	1,817 KB
glslangValidator.exe	6/15/2017 12:33 PM	Application	1,633 KB
glslangValidator.help	10/6/2017 2:31 PM	HELP File	6 KB
Makefile	1/31/2018 11:41 AM	File	1 KB
puppy.bmp	1/10/2018 8:13 AM	BMP File	3,073 KB
puppy.jpg	1/10/2018 8:13 AM	JPG File	443 KB
puppy0.bmp	1/1/2018 9:57 AM	BMP File	3,073 KB
puppy0.jpg	1/1/2018 9:58 AM	JPG File	455 KB
sample.cpp	9/4/2019 2:49 PM	C++ Source	138 KB
sample.save.cpp	3/1/2018 12:46 PM	C++ Source	135 KB
Sample.sln	12/27/2017 9:45 AM	Microsoft Visual S...	2 KB
Sample.vcxproj	9/4/2019 2:37 PM	VC++ Project	7 KB
Sample.vcxproj.filters	12/27/2017 9:47 AM	VC++ Project Filte...	1 KB
Sample.vcxproj.user	6/29/2018 9:49 AM	Per-User Project O...	1 KB
sample08.pdf	1/9/2018 11:28 AM	Adobe Acrobat D...	84 KB
sample09.pdf	1/9/2018 11:28 AM	Adobe Acrobat D...	89 KB
sample10.pdf	1/9/2018 11:26 AM	Adobe Acrobat D...	94 KB
sample-comp.comp	2/14/2018 12:25 PM	COMP File	2 KB
sample-comp.spv	2/14/2018 12:25 PM	SPV File	4 KB
sample-frag.frag	2/18/2018 10:52 AM	FRAG File	2 KB

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

Vulkan.

The Vulkan Sample Code Included with These Notes

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Mike Bailey
mjb@cs.oregonstate.edu

Sample Program Output

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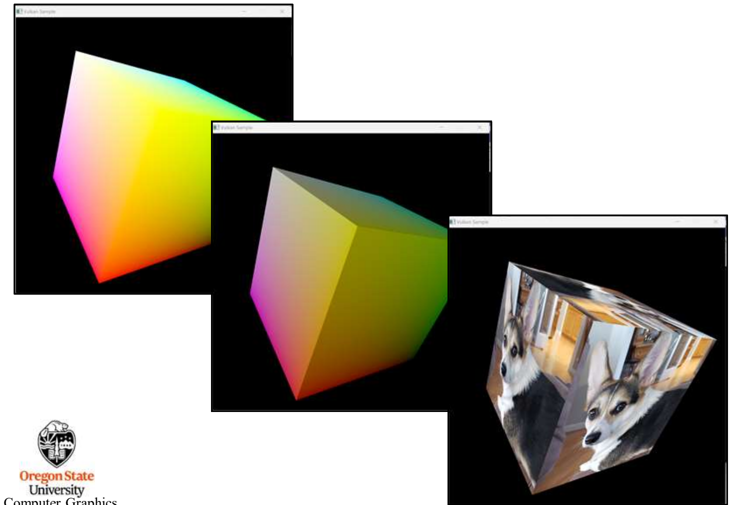

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Sample Program Keyboard Inputs

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'l' (ell), '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':	Toggle **r**otation-animation and using the mouse
'i', 'I':	Toggle using a vertex buffer only vs. an **i**ndex buffer (in the index buffer version)
'1', …,'9','a',…'g'	Set the number of instances (in the instancing version)

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Caveats on the Sample Code, I

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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 (most?), 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.

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Caveats on the Sample Code, II

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6. There are great 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_core.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.

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Main Program

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```
int
main( int argc, char * argv[ ] )
{
	Width  = 1024;
	Height = 1024;

	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;
}
```

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InitGraphics( ), I

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```
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( );
```

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InitGraphics( ), II

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```
	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  );
}
```

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A Colored Cube

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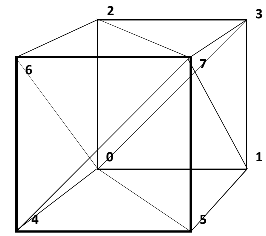

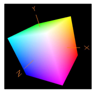

```
static GLfloat CubeColors[ ][3] =
{
		{ 0., 0., 0. },
		{ 1., 0., 0. },
		{ 0., 1., 0. },
		{ 1., 1., 0. },
		{ 0., 0., 1. },
		{ 1., 0., 1. },
		{ 0., 1., 1. },
		{ 1., 1., 1. },
};
```

```
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 }
};
```

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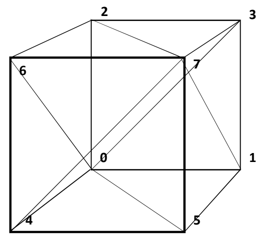
A Colored Cube

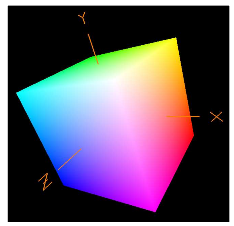

```
struct vertex
{
        glm::vec3       position;
        glm::vec3       normal;
        glm::vec3       color;
        glm::vec2       texCoord;
};

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 that is #include'd into sample.cpp

#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 costs for retaining vertex attributes that you aren't going to use are some GPU 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 or fragment shaders.

Vulkan Software Philosophy

Vulkan has lots of typedefs that define C/C++ structs and enums

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 using C++ class methods:

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

Vulkan has chosen to do it like this:

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

Vulkan Conventions

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VkXxx is a typedef, probably a struct

vkYyy( ) is a function call

VK_ZZZ 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 actually #define'd to nothing.

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

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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[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]);

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Your Sample2019.zip File Contains This

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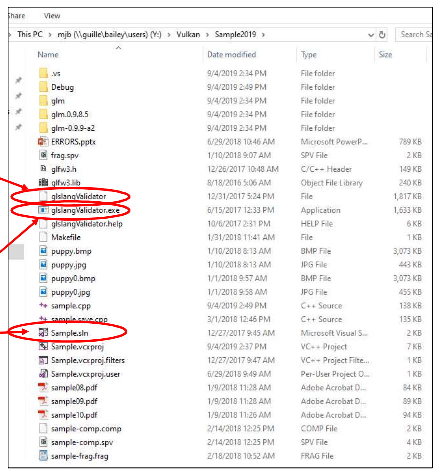
Linux shader compiler

Windows shader compiler

Double-click here to launch Visual Studio 2019 with this solution



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

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Reporting Error Results, I

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```
struct errorcode
{
        VkResult      resultCode;
        std::stringmeaning;
}
ErrorCodes[ ] =
{
        { VK_NOT_READY,                              "Not Ready"                },
        { VK_TIMEOUT,                                "Timeout"                  },
        { VK_EVENT_SET,                              "Event Set"                },
        { VK_EVENT_RESET,                            "Event Reset"              },
        { VK_INCOMPLETE,                             "Incomplete"               },
        { VK_ERROR_OUT_OF_HOST_MEMORY,               "Out of Host Memory"       },
        { VK_ERROR_OUT_OF_DEVICE_MEMORY,             "Out of Device Memory"     },
        { VK_ERROR_INITIALIZATION_FAILED,            "Initialization Failed"    },
        { VK_ERROR_DEVICE_LOST,                      "Device Lost"              },
        { VK_ERROR_MEMORY_MAP_FAILED,                "Memory Map Failed"        },
        { VK_ERROR_LAYER_NOT_PRESENT,                "Layer Not Present"        },
        { VK_ERROR_EXTENSION_NOT_PRESENT,            "Extension Not Present"    },
        { VK_ERROR_FEATURE_NOT_PRESENT,              "Feature Not Present"      },
        { VK_ERROR_INCOMPATIBLE_DRIVER,              "Incompatible Driver"      },
        { VK_ERROR_TOO_MANY_OBJECTS,                 "Too Many Objects"         },
        { VK_ERROR_FORMAT_NOT_SUPPORTED,             "Format Not Supported"     },
        { VK_ERROR_FRAGMENTED_POOL,                  "Fragmented Pool"          },
        { VK_ERROR_SURFACE_LOST_KHR,                 "Surface Lost"             },
        { VK_ERROR_NATIVE_WINDOW_IN_USE_KHR,         "Native Window in Use"     },
        { VK_SUBOPTIMAL_KHR,                         "Suboptimal"               },
        { VK_ERROR_OUT_OF_DATE_KHR,                  "Error Out of Date"        },
        { VK_ERROR_INCOMPATIBLE_DISPLAY_KHR,         "Incompatible Display"     },
        { VK_ERROR_VALIDATION_FAILED_EXT,            "Valuidation Failed"       },
        { VK_ERROR_INVALID_SHADER_NV,                "Invalid Shader"           },
        { VK_ERROR_OUT_OF_POOL_MEMORY_KHR,           "Out of Pool Memory"       },
        { VK_ERROR_INVALID_EXTERNAL_HANDLE,          "Invalid External Handle"  },
};
```

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Reporting Error Results, II

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```
void
PrintVkError( VkResult result, std::string prefix )
{
        if (Verbose  &&  result == VK_SUCCESS)
        {
                fprintf(FpDebug, "%s: %s\n", prefix.c_str(), "Successful");
                fflush(FpDebug);
                return;
        }

        const int numErrorCodes = sizeof( ErrorCodes ) / sizeof( struct errorcode );
        std::string meaning = "";
        for( int i = 0; i < numErrorCodes; i++ )
        {
                if( result == ErrorCodes[i].resultCode )
                {
                        meaning = ErrorCodes[i].meaning;
                        break;
                }
        }

        fprintf( FpDebug, "\n%s: %s\n", prefix.c_str(), meaning.c_str() );
        fflush(FpDebug);
}
```

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Extras in the Code

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```
#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" );

const int32_t   OFFSET_ZERO =   0;
```

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Vulkan Program Flow – the Setup

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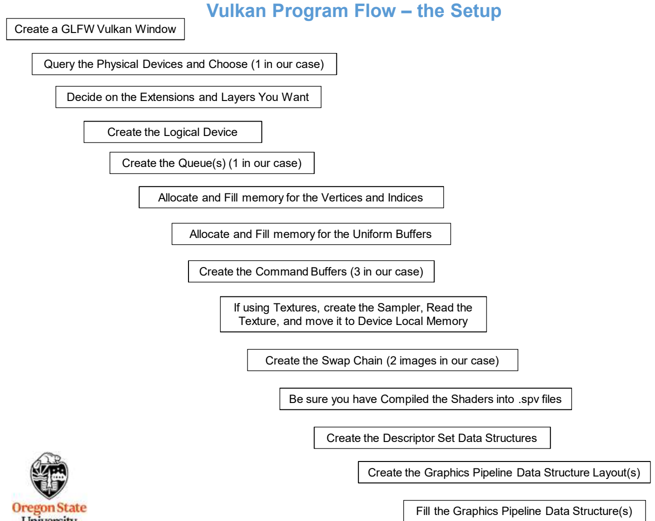

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VulkanFlowDiagram.pptx

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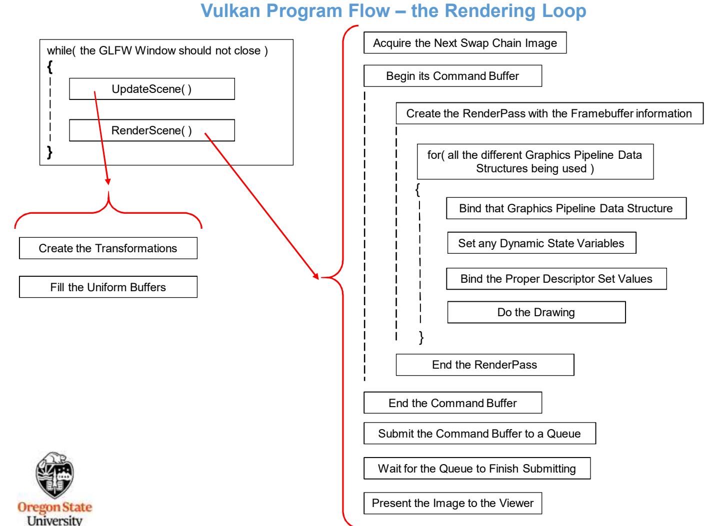
Vulkan Program Flow – the Rendering Loop

56



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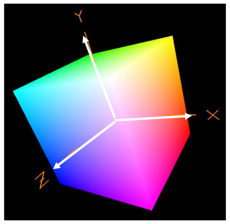
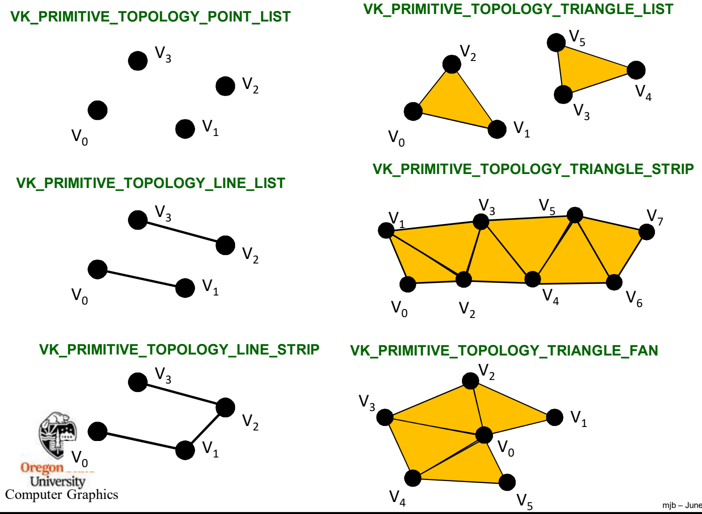
Vulkan

Drawing

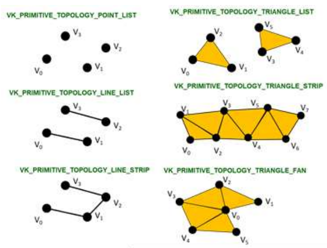
Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu



Vulkan Topologies



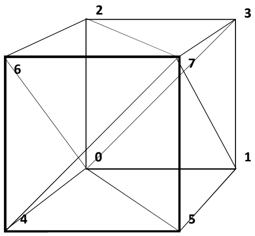
Vulkan Topologies

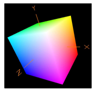


The same as OpenGL topologies, with a few left out.

```
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;
```


A Colored Cube Example





```
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. },
};
```

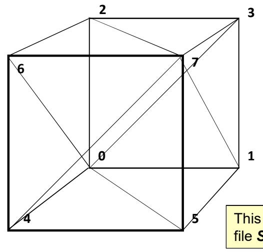
```
static GLfloat CubeVertices[ ][3] =
{
        { -1., -1., -1. },
        {  1., -1., -1. },
        { -1.,  1., -1. },
        {  1.,  1., -1. },
        { -1., -1.,  1. },
        {  1., -1.,  1. },
        { -1.,  1.,  1. },
        {  1.,  1.,  1. }
};
```

```
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 }
};
```

This data is contained in the file ***SampleVertexData.cpp***

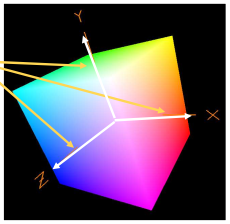
Triangles Represented as an Array of Structures


```
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. }
        },
```



This data is contained in the file ***SampleVertexData.cpp***

Modeled in right-handed coordinates

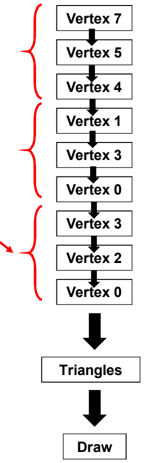


Non-indexed Buffer Drawing

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. }
        },
```

Stream of Vertices



Initializing and Filling the Vertex Buffer


```
struct vertex  VertexData[ ] =
{
        . . .
};

MyBuffer          MyVertexDataBuffer;

        . . .

Init05MyVertexDataBuffer(  sizeof(VertexData), OUT &MyVertexDataBuffer );     // create
Fill05DataBuffer( MyVertexDataBuffer,             (void *) VertexData );        // fill

        . . .

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

VkResult
Fill05DataBuffer( IN MyBuffer myBuffer, IN void * data )
{
        . . .
}
```


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;     // read one value per vertex
```

Always use the C/C++ **sizeof( )** construct rather than hardcoding the byte count!

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
```

Always use the C/C++ construct ***offsetof***, rather than hardcoding the byte offset!

Telling the Pipeline Data Structure about its Input

We will come to the Pipeline Data Structure 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 vertex input.

```
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;
```


Telling the Pipeline Data Structure about its Input

We will come to the Pipeline Data Structure 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 vertex input.

```
VkGraphicsPipelineCreateInfo                    vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
        vgpci.flags = 0;
        vgpci.stageCount = 2;           // number of shader stages in this pipeline
        vgpci.pStages = vpssci;
        vgpci.pVertexInputState = &vpvisci;
        vgpci.pInputAssemblyState = &vpiasci;
        vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;        // &vptsci
        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 );
```

Telling the Command Buffer what Vertices to Draw

69

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 };
VkDeviceSize offsets[1]     = { 0 };

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

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

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

Always use the C/C++ construct ***sizeof***, rather than hardcoding a byte count!

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Drawing with an Index Buffer

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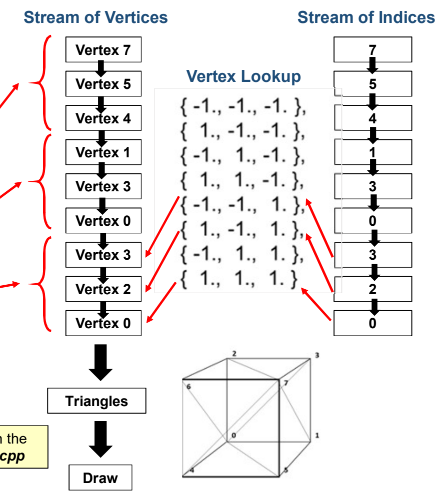
```
struct vertex JustVertexData[ ] =
{
        // vertex #0:
        {
                { -1., -1., -1. },
                {  0.,  0., -1. },
                {  0.,  0.,  0. },
                {  1., 0. }
        },

        // 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,
};
```



This data is contained in the file ***SampleVertexData.cpp***

Drawing with an Index Buffer

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```
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);
```

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Drawing with an Index Buffer

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```
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 );
```

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Drawing with an Index Buffer

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```
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 );
```

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Indirect Drawing (not to be confused with *Indexed*)

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

In Vulkan, "Indirect" means that you store the arguments in GPU memory and then give the vkCmdXxx call a pointer to those arguments

```
vkCmdDrawIndirect( CommandBuffers[nextImageIndex], buffer, offset, drawCount, stride);
```

Compare this with:

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

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Indexed Indirect Drawing (i.e., both Indexed and Indirect)

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

In Vulkan, "Indirect" means that you store the arguments in GPU memory and then give the vkCmdXxx call a pointer to those arguments

```
vkCmdDrawIndexedIndirect( commandBuffer, buffer, offset, drawCount, stride );
```

Compare this with:

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

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Sometimes the Same Vertex Needs Multiple Attributes

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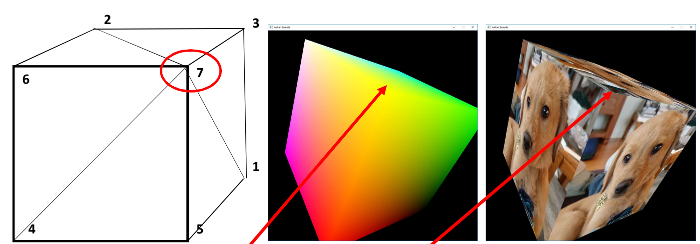

Sometimes a vertex that is common to multiple faces has the same attributes, no matter what face it is in. Sometimes it doesn't.

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

Thus, when using indexed 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.

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Sometimes the Same Vertex Needs Multiple Attributes

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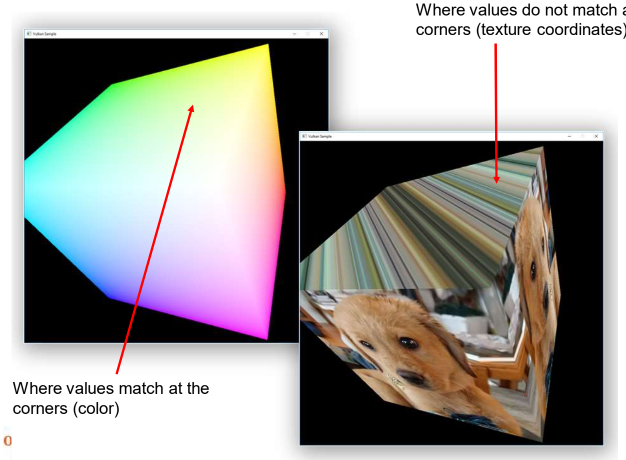
Where values do not match at the corners (texture coordinates)



Where values match at the corners (color)

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Terrain Surfaces are a Great Application of Indexed Drawing

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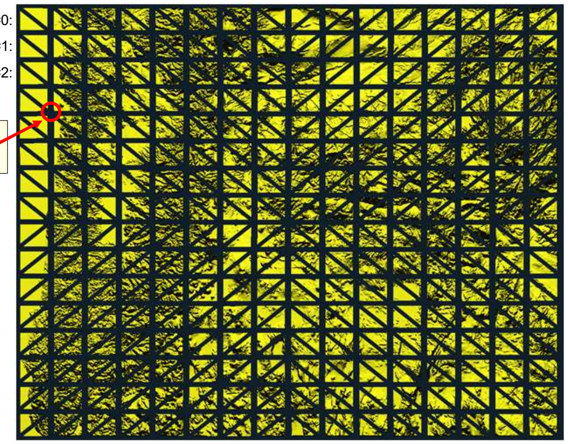
Triangle Strip #0:

Triangle Strip #1:

Triangle Strip #2:

. . .

There is no question that it is OK for the (s,t) at these vertices to all be the same



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But, to Draw that Terrain Surface, You Need "Primitive Restart"

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"Primitive Restart" is used with:

- Indexed drawing
- TRIANGLE_FAN and TRIANGLE_STRIP topologies

A special "index" is used to indicate that the triangle strip should start over. This is more efficient than explicitly ending the current triangle strip and explicitly starting a new one.

```
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 restart index is **0xffff**.
If your VkIndexType is VK_INDEX_TYPE_UINT32, then the restart index is **0xffffffff**.

That is, a one in all available bits

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The OBJ File Format – a triple-indexed way of Drawing

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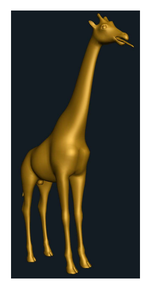

```
v 1.710541 1.283360 -0.040860
v 1.714593 1.273043 -0.041268
v 1.706114 1.279109 -0.040795
v 1.719083 1.277235 -0.041195
v 1.722786 1.267216 -0.041939
v 1.727196 1.271285 -0.041795
v 1.730680 1.261384 -0.042630
v 1.723121 1.280378 -0.037323
v 1.714513 1.286599 -0.037101

. . .

vn 0.1725 0.2557 -0.9512
vn -0.1979 -0.1899 -0.9616
vn -0.2050 -0.2127 -0.9554
vn 0.1664 0.3020 -0.9387
vn -0.2040 -0.1718 -0.9638
vn 0.1645 0.3203 -0.9329
vn -0.2055 -0.1698 -0.9638
vn 0.4419 0.6436 -0.6249
```

```
vt 0.816406 0.955536
vt 0.822754 0.959168
vt 0.815918 0.959442
vt 0.823242 0.955292
vt 0.829102 0.958862
vt 0.829590 0.955109
vt 0.835449 0.958618
vt 0.824219 0.951263

. . .

f 73/73/75 65/65/67 66/66/68
f 66/66/68 74/74/76 73/73/75
f 74/74/76 66/66/68 67/67/69
f 67/67/69 75/75/77 74/74/76
f 75/75/77 67/67/69 69/69/71
f 69/69/71 76/76/78 75/75/77
f 71/71/73 72/72/74 77/77/79
f 72/72/74 78/78/80 77/77/79
f 78/78/80 72/72/74 73/73/75
```

V / T / N

Note: The OBJ file format uses ***1-based*** indexing for faces!

We have a **vkuLoadObjFile( )** function to load an OBJ file into your Vulkan program!

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Drawing an OBJ Object

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```
MyBuffer  MyObjBuffer;               // global

  . . .

MyObjBuffer = VkOsuLoadObjFile( "filename.obj" );       // initializes and fills the buffer with
                            // triangles defined in GPU memory with an array of struct vertex
```

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

```
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;
```

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

```
VkBuffer        objBuffer[1] = { MyObjBuffer.buffer };
VkDeviceSize offsets[1]    = { 0 };
vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, objBuffer, offsets );

const uint32_t  firstInstance = 0;
const uint32_t  firstVertex = 0;
const uint32_t  instanceCount = 1;
const uint32_t  vertexCount = MyObjBuffer.size / sizeof( struct vertex );

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

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Vulkan

Data Buffers

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Mike Bailey

mjb@cs.oregonstate.edu

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DataBuffers.pptx

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From the Quick Reference Card

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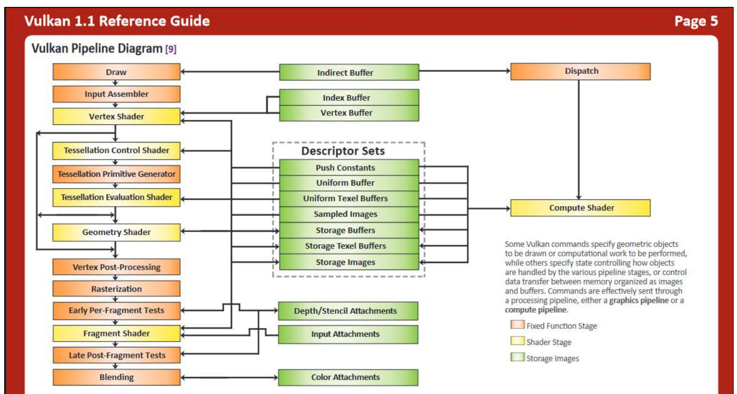
Even though Vulkan is up to 1.3, the most current Vulkan Reference card is version 1.1



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

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Terminology Issues

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A Vulkan **Data Buffer** is just a group of contiguous bytes in GPU memory. They have no inherent meaning. The data that is stored there is whatever you want it to be. (This is sometimes called a “Binary Large Object”, or “BLOB”.)

It is up to you to be sure that the writer and the reader of the Data Buffer are interpreting the bytes in the same way!

Vulkan calls these things “Buffers”. But, Vulkan calls other things “Buffers”, too, such as Texture Buffers and Command Buffers. So, I sometimes have taken to calling these things “Data Buffers” and have even gone so far as to extend some of Vulkan’s own terminology:

typedef VkBuffer   VkDataBuffer;

This is probably a bad idea in the long run.

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Creating and Filling Vulkan Data Buffers

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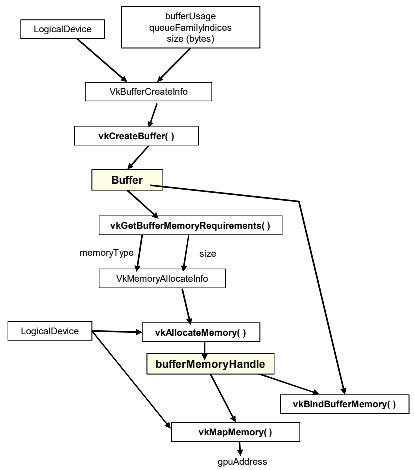

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Creating a Vulkan Data Buffer

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```
VkBuffer  Buffer;              // or "VkDataBuffer   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 = <<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 iont32_t) nullptr;

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

"or" these bits together to specify how this buffer will be used

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

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```
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 );
```

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Finding the Right Type of Memory

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```
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;
}
```

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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 );
```

```
6 Memory Types:
Memory  0:
Memory  1:  DeviceLocal
Memory  2:  HostVisible HostCoherent
Memory  3:  HostVisible HostCoherent HostCached
Memory  4:  DeviceLocal HostVisible HostCoherent
Memory  5:  DeviceLocal

4 Memory Heaps:
Heap 0:  size = 0xdbb00000 DeviceLocal
Heap 1:  size = 0xfd504000
Heap 2:  size = 0x0d600000 DeviceLocal
Heap 3:  size = 0x02000000 DeviceLocal
```

These are the numbers for the Nvidia A6000 cards

Memory-Mapped Copying to GPU Memory, Example I


```
void *mappedDataAddr;

vkMapMemory( LogicalDevice, myBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT (void *)&mappedDataAddr );

    memcpy( mappedDataAddr, &VertexData, sizeof(VertexData) );

vkUnmapMemory( LogicalDevice, myBuffer.vdm );
```


Memory-Mapped Copying to GPU Memory, Example II


```
struct vertex *vp;

vkMapMemory( LogicalDevice, IN myBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT (void *)&vp );

for( int i = 0; i < numTrianglesInObjFile; i++ )        // number of triangles
{
    for( int j = 0; j < 3; j++ )                        // 3 vertices per triangle
    {
        vp->position = glm::vec3( . . . );
        vp->normal = glm::vec3( . . . );
        vp->color = glm::vec3( . . . );
        vp->texCoord = glm::vec2( . . . );
        vp++;
    }
}

vkUnmapMemory( LogicalDevice, myBuffer.vdm );
```

Sidebar: The Vulkan Memory Allocator (VMA)

93

The **Vulkan Memory Allocator** is a set of functions to simplify your view of allocating buffer memory. I am including its github link here and a little sample code in case you want to take a peek.

https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator

This repositoryalso includes a smattering of documentation.

See our class VMA noteset for more VMA details

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Sidebar: The Vulkan Memory Allocator (VMA)

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```
#define VMA_IMPLEMENTATION
#include "vk_mem_alloc.h"
. . .
VkBufferCreateInfo                 vbci;
. . .
VmaAllocationCreateInfo            vaci;
        vaci.physicalDevice = PhysicalDevice;
        vaci.device = LogicalDevice;
        vaci.usage = VMA_MEMORY_USAGE_GPU_ONLY;

VmaAllocator                       var;
vmaCreateAllocator( IN &vaci, OUT &var );
. . .
. .
VkBuffer                           Buffer;
VmaAllocation                      van;
vmaCreateBuffer( IN var, IN &vbci, IN &vaci, OUT &Buffer. OUT &van, nullptr );
```

```
void *mappedDataAddr;
vmaMapMemory( var, van, OUT &mappedDataAddr );

        memcpy( mappedDataAddr, &VertexData, sizeof(VertexData) );

vmaUnmapMemory( var, van );
```

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See our class VMA noteset for more VMA details

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Something I've Found Useful

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

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

. . .

// example:
MyBuffer                 MyObjectUniformBuffer;
```

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

It also makes it impossible to accidentally associate the wrong VkDeviceMemory and/or VkDeviceSize with the wrong data buffer.

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Initializing a Data Buffer

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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;
. . .
}
```

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Here are C/C++ structs used by the Sample Code to hold some uniform variables


```
struct sceneBuf
{
        glm:: mat4      uProjection;
        glm:: mat4      uView;
        glm:: mat4      uSceneOrient;
        vec4            uLightPos;
        vec4            uLightColor;
        vec4            uLightKaKdKs;
        float           uTime;
} Scene;

struct objectBuf
{
        glm::mat4       uModel;
        glm:: mat4      uNormal;
        vec4            uColor;
        float           uShininess;
} Object;
```

The uNormal is set to:
glm::inverseTranspose(uView * uSceneOrient * uModel)

Here's the associated GLSL shader code to access those uniform variables:

```
layout( std140, set = 1, binding = 0 ) uniform sceneBuf
{
        mat4      uProjection;
        mat4      uView;
        mat4      uSceneOrient;
        vec4      uLightPos;
        vec4      uLightColor;
        vec4      uLightKaKdKs;
        float     uTime;
} Scene;

layout( std140, set = 2, binding = 0 ) uniform objectBuf
{
        mat4      uModel;
        mat4      uNormal;
        vec4      uColor;
        float     uShininess;
} Object;
```

In the vertex shader, each object vertex gets transformed by:
uProjection* uView * uSceneOrient * uModel

In the vertex shader, each surface normal vector gets transformed by the **uNormal**

Filling those Uniform Variables


```
const float EYEDIST =   3.0f;
const double FOV    =   glm::radians(60.);     // field-of-view angle in radians

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

Scene.uProjection        = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Scene.uProjection[1][1]  *= -1.;              // account for Vulkan's LH screen coordinate system
Scene.uView              = glm::lookAt( eye, look, up );
Scene.uSceneOrient       = glm::mat4( 1. );

Object.uModelOrient = glm::mat4( 1. );        // identity
Object.uNormal      = glm::inverseTranspose( Scene.uView * Scene.uSceneOrient * Object.uModel )
```

This code assumes that this line:

#define GLM_FORCE_RADIANS

is listed before GLM is #included!

The Parade of Buffer Data

MyBuffer MyObjectUniformBuffer;

The MyBuffer does not hold any actual data itself. It just information about what is in the data buffer

```
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 original data, written by the application.

Memory-mapped copy operation

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

struct objectBuf Object;

```
Object.uModelOrient = glm::mat4( 1. );        // identity
Object.uNormal      = glm::inverseTranspose( Scene.uView * Scene.uSceneOrient * Object.uModel )
```

uniform objectBuf Object;

```
layout( std140, set = 2, binding = 0 ) uniform objectBuf
{
        mat4      uModel;
        mat4      uNormal;
        vec4      uColor;
        float     uShininess;
} Object;
```


Filling the Data Buffer


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

. . .

// example:
MyBuffer            MyObjectUniformBuffer;
```

```
Init05UniformBuffer( sizeof(Object),       OUT &MyObjectUniformBuffer );

Fill05DataBuffer( MyObjectUniformBuffer,    IN (void *) &Object );
```

```
struct objectBuf
{
        glm::mat4       uModel;
        glm:: mat4      uNormal;
        vec4            uColor;
        float           uShininess;
} Object;
```

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, OFFSET_ZERO );
    return result;
}
```

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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.

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Vertex Buffers

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

Oregon State University
Computer Graphics

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 . . .

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Geometry vs. Topology

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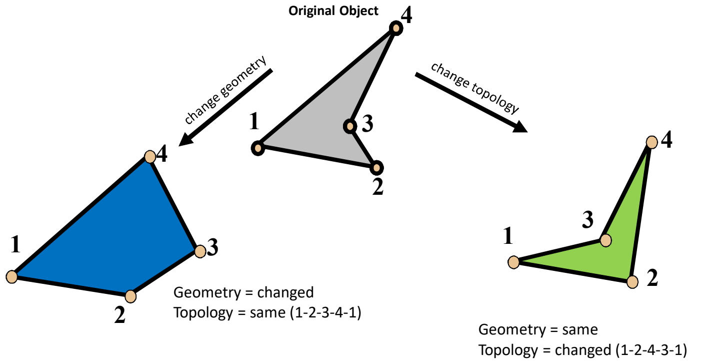

Geometry:

Where things are (e.g., coordinates)

Topology:

How things are connected

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Vulkan Topologies

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```
typedef enum VkPrimitiveTopology
{
   VK_PRIMITIVE_TOPOLOGY_POINT_LIST = 0,
   VK_PRIMITIVE_TOPOLOGY_LINE_LIST = 1,
   VK_PRIMITIVE_TOPOLOGY_LINE_STRIP = 2,
   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST = 3,
   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP = 4,
   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN = 5,
   VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY = 6,
   VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY = 7,
   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY = 8,
   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY = 9,
   VK_PRIMITIVE_TOPOLOGY_PATCH_LIST = 10,
} VkPrimitiveTopology;
```

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Vulkan Topologies

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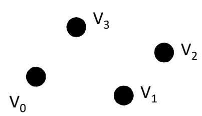
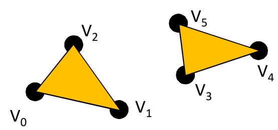
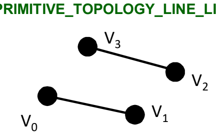
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



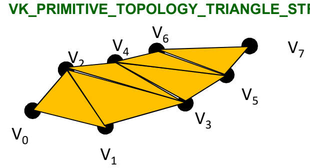
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



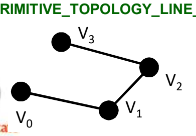
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



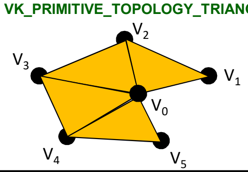
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



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Vulkan Topologies – Requirements and Orientation

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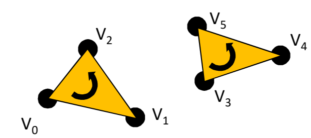
Polygons must be:

- **Convex** and
- **Planar**

Polygons are traditionally:

- **CCW when viewed from outside the solid object**

VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



It's not absolutely necessary, but there are possible optimizations if you are ***consistent***

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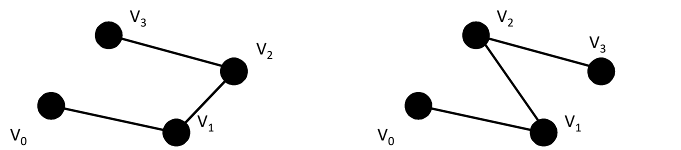
OpenGL Topologies – Vertex Order Matters

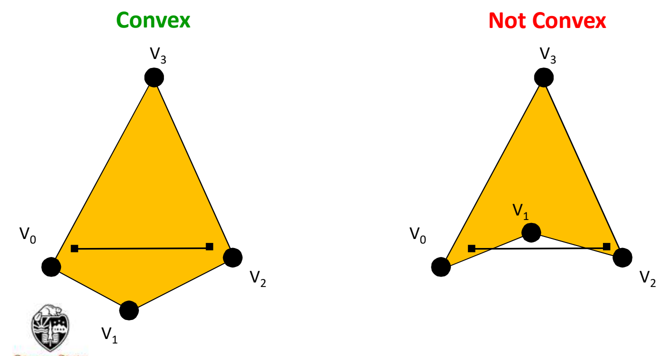
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP

VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



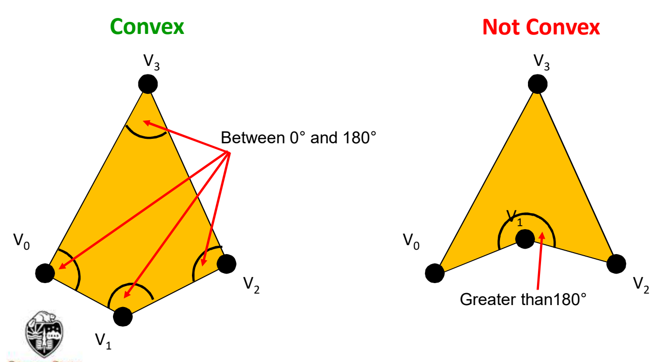
What does "Convex Polygon" Mean?

We could go all mathematical here, but let's go visual instead. In a convex polygon, a line between ***any*** two points inside the polygon never leaves the inside of the polygon.



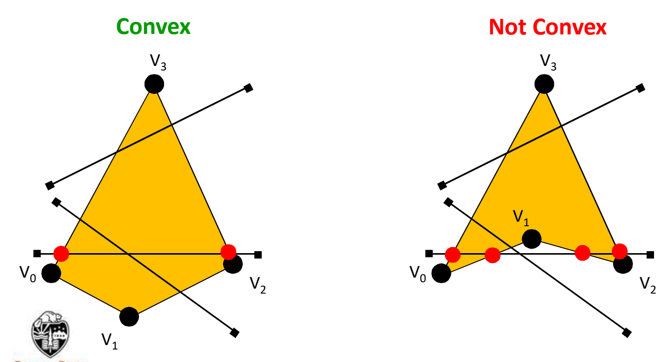
What does "Convex Polygon" Mean?

OK, now let's go all mathematical. In a convex polygon, every interior angle is between 0° and 180°.



Why is there a Requirement for Polygons to be Convex?

Graphics polygon-filling hardware can be highly optimized if you know that, no matter what direction you fill the polygon in, there will be two and only two intersections between the scanline and the polygon's edges



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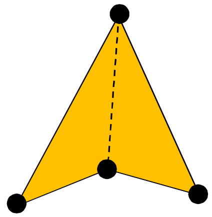
What if you need to display Polygons that are not Convex?

There is an open source library to break a non-convex polygon into convex polygons. It is called ***Polypartition***, and is found here:

https://github.com/ivanfratric/polypartition



If you ever need to do this, contact me. I have working code …

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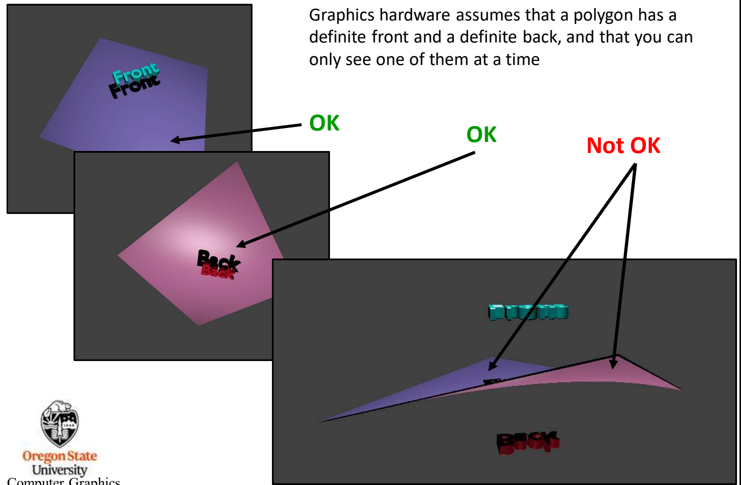
Why is there a Requirement for Polygons to be Planar?

Graphics hardware assumes that a polygon has a definite front and a definite back, and that you can only see one of them at a time



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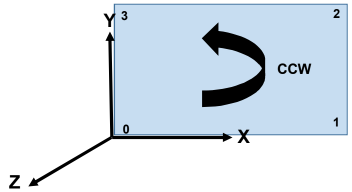
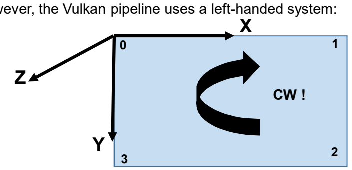
Vertex Orientation Issues

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 GLM projection matrix, like this:
ProjectionMatrix[1][1] *= -1.;
This is like saying "Y' = -Y".

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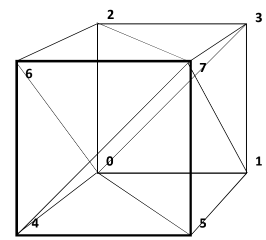
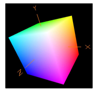
A Colored Cube Example





```
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 }
};
```

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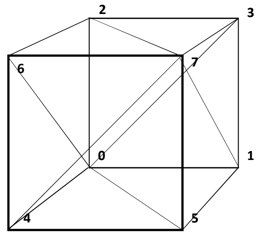
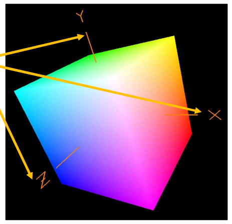
Triangles in an Array of Structures

From the file SampleVertexData.cpp:

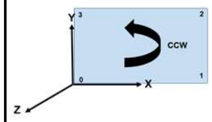
```
struct vertex
{
        glm::vec3       position;
        glm::vec3       normal;
        glm::vec3       color;
        glm::vec2       texCoord;
};

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. }
        },
```

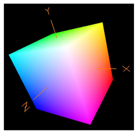


Modeled in right-handed coordinates



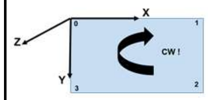
Vertex Orientation Issues





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;
```

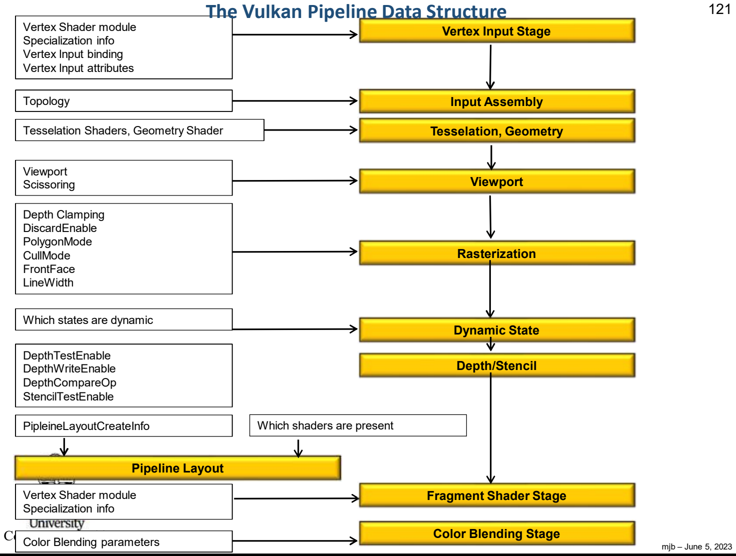

Filling the Vertex Buffer


```
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;
}
```


A Reminder 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;
}
```

The Vulkan Pipeline Data Structure



Telling the Pipeline Data Structure 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.

```
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;
```

```
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;
```

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Telling the Pipeline Data Structure 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
```

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Telling the Pipeline Data Structure 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.

```
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;
```

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Telling the Pipeline Data Structure about its Input

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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.

```
VkGraphicsPipelineCreateInfo                    vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
        vgpci.flags = 0;
        vgpci.stageCount = 2;            // number of shader stages in this pipeline
        vgpci.pStages = vpssci;
        vgpci.pVertexInputState = &vpvisci;
        vgpci.pInputAssemblyState = &vpiasci;
        vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;        // &vptsci
        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 );
```

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Telling the Command Buffer what Vertices to Draw

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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, buffers, 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 );
```

Don't *ever* hardcode the size of an array! Always get the compiler to generate it for you.

```
const uint32_t  vertexCount = 100;
```

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Vulkan.

Shaders and SPIR-V

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

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ShadersAndSpirv.pptx

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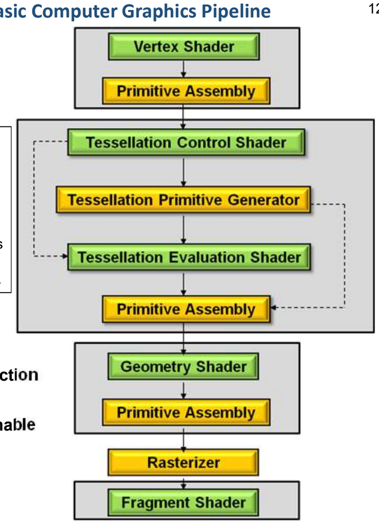
The Shaders' View of the Basic Computer Graphics Pipeline

128



- You need 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 Shader Stages

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Shader stages

```
typedef enum VkPipelineStageFlagBits {
    VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT = 0x00000001,
    VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT = 0x00000002,
    VK_PIPELINE_STAGE_VERTEX_INPUT_BIT = 0x00000004,
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT = 0x00000008,
    VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT = 0x00000010,
    VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT = 0x00000020,
    VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT = 0x00000040,
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT = 0x00000080,
    VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT = 0x00000100,
    VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT = 0x00000200,
    VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT = 0x00000400,
    VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT = 0x00000800,
    VK_PIPELINE_STAGE_TRANSFER_BIT = 0x00001000,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT = 0x00002000,
    VK_PIPELINE_STAGE_HOST_BIT = 0x00004000,
    VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT = 0x00008000,
    VK_PIPELINE_STAGE_ALL_COMMANDS_BIT = 0x00010000,
} VkPipelineStageFlagBits;
```

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How Vulkan GLSL Differs from OpenGL GLSL

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

- In the compiler, there is an automatic
  #define VULKAN 130
  or whatever the current version number is.
  Typically you use this like:
  #ifdef VULKAN
  . . .
  #endif

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:
  layout (location = 0) out vec4 fFragColor;

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How Vulkan GLSL Differs from OpenGL GLSL

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Shader combinations of separate texture data and samplers as an option:

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

Note: our sample code doesn't use this.

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

For example, Specialization Constants can be used with 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

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Vulkan: Shaders' use of Layouts for Uniform Variables

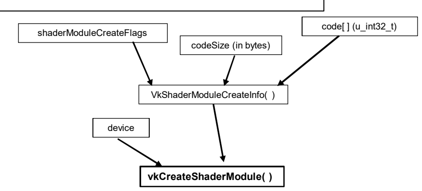
132

```
layout( std140, set = 0, binding = 0 ) uniform sceneMatBuf
{
    mat4 uProjectionMatrix;
    mat4 uViewMatrix;
    mat4 uSceneMatrix;
} SceneMatrices;

layout( std140, set = 1, binding = 0 ) uniform objectMatBuf
{
    mat4 uModelMatrix;
    mat4 uNormalMatrix;
} ObjectMatrices;

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

All non-sampler uniform variables *must* be in block buffers



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Vulkan Shader Compiling

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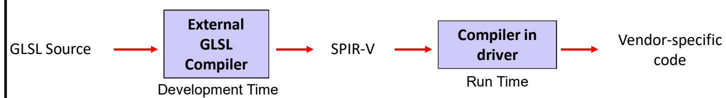
- You half-precompile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V, which stands for **Standard Portable Intermediate Representation.**
- SPIR-V gets turned into fully-compiled code at runtime, when the pipeline structure is finally created
- The SPIR-V spec has been public for a few years –new shader languages are surely being developed
- OpenGL and OpenCL have now 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

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SPIR-V: Standard Portable Intermediate Representation for Vulkan

134

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: glslangValidator

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You Can Run the SPIR-V Compiler on Windows from a Bash Shell

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You can run the glslangValidator program from the Windows Command Prompt, but I have found it easier to run the SPIR-V compiler from Windows-Bash.

To install the bash shell on your own Windows machine, go to this URL:

https://www.msn.com/en-us/news/technology/how-to-install-and-run-bash-on-windows-11/ar-AA10EoPk

Or, follow these instructions:

1. Head to the **Start menu** search bar, type in 'terminal,' and launch the Windows Terminal as administrator. (On some systems, this is called the **Command Prompt**.)
2. Type in the following command in the administrator: **wsl --install**
3. Restart your PC once the installation is complete.

As soon as your PC boots up, the installation will begin again. Your PC will start downloading and installing the Ubuntu software. You'll soon get asked to set up a username and password. This can be the same as your system's username and password, but doesn't have to be. The installation will automatically start off from where you left it.

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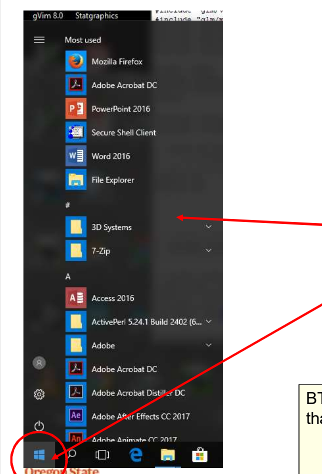
You Can Run the SPIR-V Compiler on Windows from a Bash Shell

136



2. Type the word *bash*

1. Click on the Microsoft Start icon

BTW, within bash, if you want to list your files without that sometimes-hard-to-read filename coloring, do this:

ls -l --color=none

(ell-ess minus-ell minus-minus-color=none)

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Running glslangValidator.exe in bash

As long as I am on bash, I like using the *make* utility. To do that, put these shader compile lines in a file called *Makefile*:

```
ALLSHADERS:     sample-vert.vert  sample-frag.frag
                glslangValidator.exe -V sample-vert.vert  -o sample-vert.spv
                glslangValidator.exe -V sample-frag.frag  -o sample-frag.spv
```

Then type *make ALLSHADERS*:

```
mjb@PC:/mnt/c/MJB/Vulkan/Sample2019-COLOREDCUBE$ make ALLSHADERS
glslangValidator.exe -V sample-vert.vert  -o sample-vert.spv
sample-vert.vert
glslangValidator.exe -V sample-frag.frag  -o sample-frag.spv
sample-frag.frag
mjb@PC:/mnt/c/MJB/Vulkan/Sample2019-COLOREDCUBE$
```


Running glslangValidator.exe

glslangValidator.exe -V sample-vert.vert -o sample-vert.spv

Compile for Vulkan ("-G" is compile for OpenGL)

Specify the SPIR-V output file

The input file. The compiler determines the shader type by the file extension:

.vert	**Vertex shader**
.tccs	**Tessellation Control Shader**
.tecs	**Tessellation Evaluation Shader**
.geom	**Geometry shader**
.frag	**Fragment shader**
.comp	**Compute shader**

How do you know if SPIR-V compiled successfully?

Same as C/C++ -- the compiler gives you no nasty messages, it just prints the name of the source file you just compiled.

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

So, if you use the Linux command **od -x** on the .spv file, like this:

od -x sample-vert.spv

the magic number shows up like this:

```
0000000 0203 0723 0000 0001 000a 0008 007e 0000
0000020 0000 0000 0011 0002 0001 0000 000b 0006
. . .
```

"od" stands for "octal dump", even though it can format the raw bits as most anything: octal, hexadecimal, bytes, characters, etc. "-x" means to format in hexadecimal.

Reading a SPIR-V File into a Vulkan Shader Module


```
#ifndef _WIN32
        typedef int errno_t;
        int     fopen_s( FILE**, const char *, const char * );
#endif

#define SPIRV_MAGIC         0x07230203
. . .

VkResult
Init12SpirvShader( std::string filename,  VkShaderModule * pShaderModule  )
{
     FILE *fp;
#ifdef WIN32
         errno_t err = fopen_s( &fp, filename.c_str( ), "rb" );
         if( err != 0 )
#else
        fp = fopen( filename.c_str( ), "rb" );
        if( fp == NULL )
#endif
     {
          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

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```
. . .
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;
}
```

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Vulkan: Creating a Pipeline

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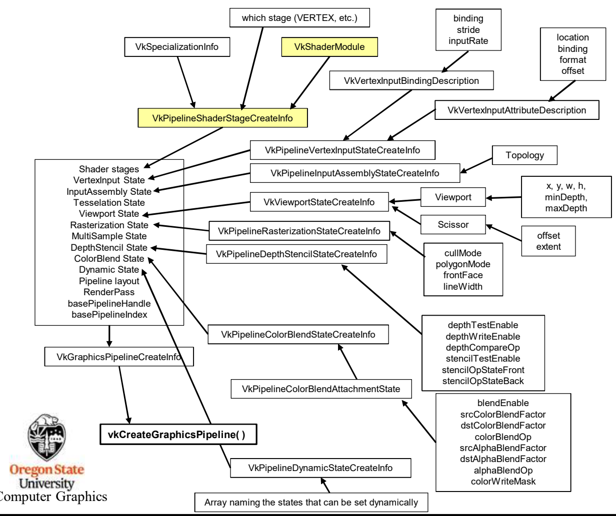

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You can also take a look at SPIR-V Assembly

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glslangValidator.exe -V -H sample-vert.vert -o sample-vert.spv

This prints out the SPIR-V "assembly" to standard output.
Other than nerd interest, there is no graphics-programming reason to look at this. ☺

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For example, if this is your Shader Source

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```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
      mat4 uModelMatrix;
      mat4 uViewMatrix;
      mat4 uProjectionMatrix;
      mat3 uNormalMatrix;
} Matrices;

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

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

      vNormal   = Matrices.uNormalMatrix * aNormal;
      vColor    = aColor;
      vTexCoord = aTexCoord;
}
```

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This is the SPIR-V Assembly, Part I

145

```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

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

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

        vNormal   = Matrices.uNormalMatrix * aNormal;
        vColor    = aColor;
        vTexCoord = aTexCoord;
}
```

```
           Capability Shader
    1:     ExtInstImport  "GLSL.std.450"
           MemoryModel Logical GLSL450
           EntryPoint Vertex 4  "main" 34 37 48 53 56 57 61 63
           Source GLSL 400
           SourceExtension  "GL_ARB_separate_shader_objects"
           SourceExtension  "GL_ARB_shading_language_420pack"
           Name 4  "main"
           Name 10  "PVM"
           Name 13  "matBuf"
           MemberName 13(matBuf) 0  "uModelMatrix"
           MemberName 13(matBuf) 1  "uViewMatrix"
           MemberName 13(matBuf) 2  "uProjectionMatrix"
           MemberName 13(matBuf) 3  "uNormalMatrix"
           Name 15  "Matrices"
           Name 32  "gl_PerVertex"
           MemberName 32(gl_PerVertex) 0  "gl_Position"
           MemberName 32(gl_PerVertex) 1  "gl_PointSize"
           MemberName 32(gl_PerVertex) 2  "gl_ClipDistance"
           Name 34  ""
           Name 37  "aVertex"
           Name 48  "vNormal"
           Name 53  "aNormal"
           Name 56  "vColor"
           Name 57  "aColor"
           Name 61  "vTexCoord"
           Name 63  "aTexCoord"
           Name 65  "lightBuf"
           MemberName 65(lightBuf) 0  "uLightPos"
           Name 67  "Light"
           MemberDecorate 13(matBuf) 0 ColMajor
           MemberDecorate 13(matBuf) 0 Offset 0
           MemberDecorate 13(matBuf) 0 MatrixStride 16
           MemberDecorate 13(matBuf) 1 ColMajor
           MemberDecorate 13(matBuf) 1 Offset 64
           MemberDecorate 13(matBuf) 1 MatrixStride 16
           MemberDecorate 13(matBuf) 2 ColMajor
           MemberDecorate 13(matBuf) 2 Offset 128
           MemberDecorate 13(matBuf) 2 MatrixStride 16
           MemberDecorate 13(matBuf) 3 ColMajor
           MemberDecorate 13(matBuf) 3 Offset 192
           MemberDecorate 13(matBuf) 3 MatrixStride 16
           Decorate 13(matBuf) Block
           Decorate 15(Matrices) DescriptorSet 0
```

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This is the SPIR-V Assembly, Part II

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```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

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

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

        vNormal   = Matrices.uNormalMatrix * aNormal;
        vColor    = aColor;
        vTexCoord = aTexCoord;
}
```


```
                    Decorate 15(Matrices) Binding 0
                    MemberDecorate 32(gl_PerVertex) 0 BuiltIn Position
                    MemberDecorate 32(gl_PerVertex) 1 BuiltIn PointSize
                    MemberDecorate 32(gl_PerVertex) 2 BuiltIn ClipDistance
                    Decorate 32(gl_PerVertex) Block
                    Decorate 37(aVertex) Location 0
                    Decorate 48(vNormal) Location 0
                    Decorate 53(aNormal) Location 1
                    Decorate 56(vColor) Location 1
                    Decorate 57(aColor) Location 2
                    Decorate 61(vTexCoord) Location 2
                    Decorate 63(aTexCoord) Location 3
                    MemberDecorate 65(lightBuf) 0 Offset 0
                    Decorate 65(lightBuf) Block
                    Decorate 67(Light) DescriptorSet 1
                    Decorate 67(Light) Binding 0
          2:        TypeVoid
          3:        TypeFunction 2
          6:        TypeFloat 32
          7:        TypeVector 6(float) 4
          8:        TypeMatrix 7(fvec4) 4
          9:        TypePointer Function 8
         11:        TypeVector 6(float) 3
         12:        TypeMatrix 11(fvec3) 3
  13(matBuf):          TypeStruct 8 8 8 12
         14:        TypePointer Uniform 13(matBuf)
15(Matrices):    14(ptr) Variable Uniform
         16:        TypeInt 32 1
         17:    16(int) Constant 2
         18:        TypePointer Uniform 8
         21:    16(int) Constant 1
         25:    16(int) Constant 0
         29:        TypeInt 32 0
         30:    29(int) Constant 1
         31:        TypeArray 6(float) 30
32(gl_PerVertex):        TypeStruct 7(fvec4) 6(float) 31
         33:        TypePointer Output 32(gl_PerVertex)
         34:    33(ptr) Variable Output
         36:        TypePointer Input 11(fvec3)
 37(aVertex):    36(ptr) Variable Input
         39:    6(float) Constant 1065353216
         45:        TypePointer Output 7(fvec4)
         47:        TypePointer Output 11(fvec3)
 48(vNormal):    47(ptr) Variable Output
         49:    16(int) Constant 3
```

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This is the SPIR-V Assembly, Part III

147


```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

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

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

        vNormal   = Matrices.uNormalMatrix * aNormal;
        vColor    = aColor;
        vTexCoord = aTexCoord;
}
```


```
  50:              TypePointer Uniform 12
  53(aNormal):     36(ptr) Variable Input
   56(vColor):    47(ptr) Variable Output
   57(aColor):    36(ptr) Variable Input
         59:        TypeVector 6(float) 2
         60:        TypePointer Output 59(fvec2)
61(vTexCoord):     60(ptr) Variable Output
         62:        TypePointer Input 59(fvec2)
63(aTexCoord):     62(ptr) Variable Input
 65(lightBuf):          TypeStruct 7(fvec4)
         66:        TypePointer Uniform 65(lightBuf)
   67(Light):    66(ptr) Variable Uniform
    4(main):         2 Function None 3
          5:         Label
     10(PVM):      9(ptr) Variable Function
         19:    18(ptr) AccessChain 15(Matrices) 17
         20:         8 Load 19
         22:    18(ptr) AccessChain 15(Matrices) 21
         23:         8 Load 22
         24:         8 MatrixTimesMatrix 20 23
         26:    18(ptr) AccessChain 15(Matrices) 25
         27:         8 Load 26
         28:         8 MatrixTimesMatrix 24 27
                     Store 10(PVM) 28
         35:         8 Load 10(PVM)
         38:   11(fvec3) Load 37(aVertex)
         40:    6(float) CompositeExtract 38 0
         41:    6(float) CompositeExtract 38 1
         42:    6(float) CompositeExtract 38 2
         43:    7(fvec4) CompositeConstruct 40 41 42 39
         44:    7(fvec4) MatrixTimesVector 35 43
         46:    45(ptr) AccessChain 34 25
                     Store 46 44
         51:    50(ptr) AccessChain 15(Matrices) 49
         52:        12 Load 51
         54:   11(fvec3) Load 53(aNormal)
         55:   11(fvec3) MatrixTimesVector 52 54
                     Store 48(vNormal) 55
         58:   11(fvec3) Load 57(aColor)
                     Store 56(vColor) 58
         64:   59(fvec2) Load 63(aTexCoord)
                     Store 61(vTexCoord) 64
                     Return
                     FunctionEnd
```

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SPIR-V: Printing the Configuration

glslangValidator –c

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```
MaxLights 32
MaxClipPlanes 6
MaxTextureUnits 32
MaxTextureCoords 32
MaxVertexAttribs 64
MaxVertexUniformComponents 4096
MaxVaryingFloats 64
MaxVertexTextureImageUnits 32
MaxCombinedTextureImageUnits 80
MaxTextureImageUnits 32
MaxFragmentUniformComponents 4096
MaxDrawBuffers 32
MaxVertexUniformVectors 128
MaxVaryingVectors 8
MaxFragmentUniformVectors 16
MaxVertexOutputVectors 16
MaxFragmentInputVectors 15
MinProgramTexelOffset -8
MaxProgramTexelOffset 7
MaxClipDistances 8
MaxComputeWorkGroupCountX 65535
MaxComputeWorkGroupCountY 65535
MaxComputeWorkGroupCountZ 65535
MaxComputeWorkGroupSizeX 1024
MaxComputeWorkGroupSizeY 1024
MaxComputeWorkGroupSizeZ 64
MaxComputeUniformComponents 1024
MaxComputeTextureImageUnits 16
MaxComputeImageUniforms 8
MaxComputeAtomicCounters 8
MaxComputeAtomicCounterBuffers 1
MaxVaryingComponents 60
MaxVertexOutputComponents 64
MaxGeometryInputComponents 64
MaxGeometryOutputComponents 128
MaxFragmentInputComponents 128
MaxImageUnits 8
MaxCombinedImageUnitsAndFragmentOutputs 8
MaxCombinedShaderOutputResources 8
MaxImageSamples 0
MaxVertexImageUniforms 0
MaxTessControlImageUniforms 0
MaxTessEvaluationImageUniforms 0
MaxGeometryImageUniforms 0
MaxFragmentImageUniforms 81
```

```
MaxCombinedImageUniforms 8
MaxGeometryTextureImageUnits 16
MaxGeometryOutputVertices 256
MaxGeometryTotalOutputComponents 1024
MaxGeometryUniformComponents 1024
MaxGeometryVaryingComponents 64
MaxTessControlInputComponents 128
MaxTessControlOutputComponents 128
MaxTessControlTextureImageUnits 16
MaxTessControlUniformComponents 1024
MaxTessControlTotalOutputComponents 4096
MaxTessEvaluationInputComponents 128
MaxTessEvaluationOutputComponents 128
MaxTessEvaluationTextureImageUnits 16
MaxTessEvaluationUniformComponents 1024
MaxTessPatchComponents 120
MaxPatchVertices 32
MaxTessGenLevel 64
MaxViewports 16
MaxVertexAtomicCounters 0
MaxTessControlAtomicCounters 0
MaxTessEvaluationAtomicCounters 0
MaxGeometryAtomicCounters 0
MaxFragmentAtomicCounters 8
MaxCombinedAtomicCounters 8
MaxAtomicCounterBindings 1
MaxVertexAtomicCounterBuffers 0
MaxTessControlAtomicCounterBuffers 0
MaxTessEvaluationAtomicCounterBuffers 0
MaxGeometryAtomicCounterBuffers 0
MaxFragmentAtomicCounterBuffers 1
MaxCombinedAtomicCounterBuffers 1
MaxAtomicCounterBufferSize 16384
MaxTransformFeedbackBuffers 4
MaxTransformFeedbackInterleavedComponents 64
MaxCullDistances 8
MaxCombinedClipAndCullDistances 8
MaxSamples 4
nonInductiveForLoops 1
whileLoops 1
doWhileLoops 1
generalUniformIndexing 1
generalAttributeMatrixVectorIndexing 1
generalVaryingIndexing 1
generalSamplerIndexing 1
generalVariableIndexing 1
generalConstantMatrixVectorIndexing 1
```

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SPIR-V: More Information

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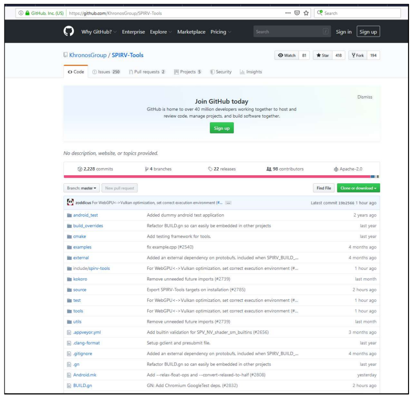
SPIR-V Tools:
http://github.com/KhronosGroup/SPIRV-Tools



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A Google-Wrapped Version of glslangValidator

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The shaderc project from Google (https://github.com/google/shaderc) provides a glslangValidator wrapper program called ***glslc*** that has a much improved command-line interface. You use, basically, the same way:

glslc.exe –target-env=vulkan sample-vert.vert -o sample-vert.spv

There are several really nice features. The two I really like are:

1. You can #include files into your shader source

2. You can "#define" definitions on the command line like this:
   glslc.exe --target-env=vulkan -DNUMPONTS=4 sample-vert.vert -o sample-vert.spv

glslc is included in your Sample .zip file

This causes a:
#define NUMPOINTS 4
to magically be inserted into the top of your source code.

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Vulkan

Instancing

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Mike Bailey
mjb@cs.oregonstate.edu

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Instancing.pptx

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Instancing – What and why?

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- Instancing is the ability to draw the same object multiple times
- It uses all the same vertices and the same graphics pipeline data structure 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**);

BTW, when not using instancing, be sure the **instanceCount** is **1**, not **0** !

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?

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Making each Instance look differently -- Approach #1

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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:

```
layout( std140, set = 0, binding = 0 ) uniform sporadicBuf
{
        int          uMode;
        int          uUseLighting;
        int          uNumInstances;
} Sporadic;
. . .
void
main( )
{
        . . .

        float DELTA        = 3.0;
        float s = sqrt(  float( Sporadic.uNumInstances )  );
        float c = ceil( float(s) );
        int cols = int( c );
        int fullRows    = gl_InstanceIndex / cols;
        int remainder = gl_InstanceIndex % cols;

        float xdelta = DELTA * float( remainder );
        float ydelta = DELTA * float( fullRows );
        vColor = vec3( 1., float( (1.+ gl_InstanceIndex) ) / float( Sporadic.uNumInstances ), 0. );

        vec4 vertex = vec4( aVertex.xyz + vec3( xdelta, ydelta, 0. ), 1. );
        gl_Position = PVM * vertex;
}
```

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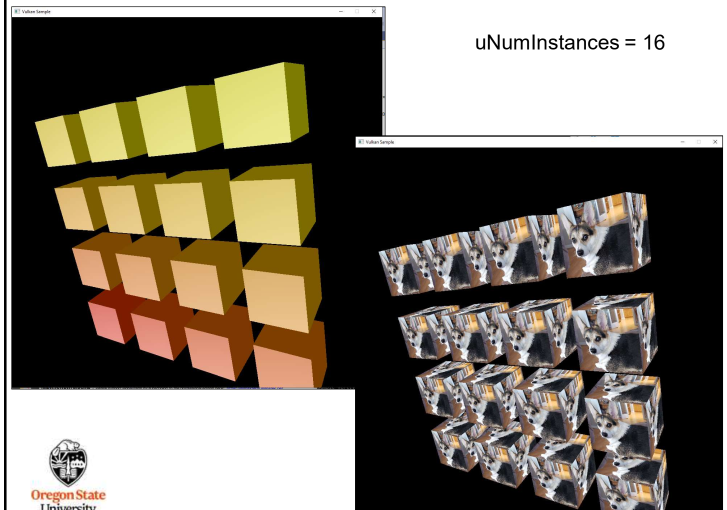

uNumInstances = 16

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Making each Instance look differently -- Approach #2

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Put the unique characteristics in a uniform buffer array and reference them

Still uses **gl_InstanceIndex**

In the vertex shader:

```
layout( std140, set = 4, binding = 0 ) uniform colorBuf
{
       vec3  uColors[1024];
} Colors;

out vec3 vColor;

        . . .

int index = gl_InstanceIndex % 1024;      // gives 0 - 1023
vColor = Colors.uColors[ index ];

. . .
 vec4 vertex = vec4( aVertex.xyz + vec3( xdelta, ydelta, 0. ), 1. );
gl_Position = PVM * vertex;
```

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Vulkan.

GLFW

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Mike Bailey

mjb@cs.oregonstate.edu

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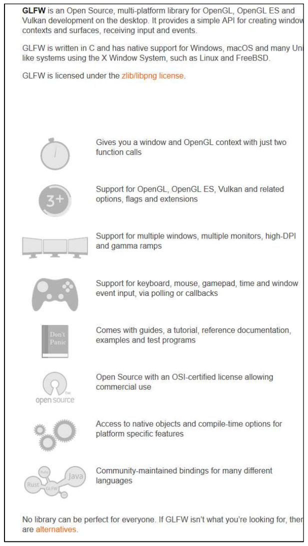
http://www.glfw.org/



GLFW is an Open Source, multi-platform library for OpenGL, OpenGL ES and Vulkan development on the desktop. It provides a simple API for creating window contexts and surfaces, receiving input and events.

GLFW is written in C and has native support for Windows, macOS and many Uni like systems using the X Window System, such as Linux and FreeBSD.

GLFW is licensed under the zlib/libpng license.

- Gives you a window and OpenGL context with just two function calls
- Support for OpenGL, OpenGL ES, Vulkan and related options, flags and extensions
- Support for multiple windows, multiple monitors, high-DPI and gamma ramps
- Support for keyboard, mouse, gamepad, time and window event input, via polling or callbacks
- Comes with guides, a tutorial, reference documentation, examples and test programs
- Open Source with an OSI-certified license allowing commercial use
- Access to native objects and compile-time options for platform specific features
- Community-maintained bindings for many different languages

No library can be perfect for everyone. If GLFW isn't what you're looking for, ther are alternatives.

Setting Up GLFW


```
#define GLFW_INCLUDE_VULKAN
#include "glfw3.h"
      . . .

uint32_t                    Width, Height;
VkSurfaceKHR            Surface;
      . . .

void
InitGLFW( )
{
      glfwInit( );
       if( ! glfwVulkanSupported( ) )
       {
              fprintf( stderr, "Vulkan is not supported on this system!\n" );
              exit( 1 );
       }
      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, OUT &Surface );

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


You Can Also Query What Vulkan Extensions GLFW Requires


```
uint32_t count;
const char ** extensions = glfwGetRequiredInstanceExtensions (&count);

fprintf( FpDebug, "\nFound %d GLFW Required Instance Extensions:\n", count );

for( uint32_t  i = 0; i < count; i++ )
{
        fprintf( FpDebug, "\t%s\n", extensions[ i ] );
}
```

```
Found 2 GLFW Required Instance Extensions:
       VK_KHR_surface
       VK_KHR_win32_surface
```


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
	}
}
```

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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;
}
```

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Looping and Closing GLFW

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

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

Does not block – processes any waiting events, then returns

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Looping and Closing GLFW

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If you would like to *block* waiting for events, use:

glfwWaitEvents( );

You can have the blocking wake up after a timeout period with:

glfwWaitEventsTimeout(double secs);

You can wake up one of these blocks from another thread with:

glfwPostEmptyEvent( );

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GLM

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

What is GLM?

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.

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>
```

OpenGL treats all angles as given in *degrees*. This line forces GLM to treat all angles as given in *radians*. I recommend this so that *all* angles you create in *all* programming will be in radians.

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?

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:

```
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );
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 say:

```
glm::mat4 modelview = glm::mat4( 1. );       // identity
glm::vec3 eye(0.,0.,3.);
glm::vec3 look(0.,0.,0.);
glm::vec3   up(0.,1.,0.);
modelview = glm::lookAt( eye, look, up );                                        // {x',y',z'} = [v]*{x,y,z}
modelview = glm::rotate( modelview, D2R*Yrot, glm::vec3(0.,1.,0.) );  // {x',y',z'} = [v]*[yr]*{x,y,z}
modelview = glm::rotate( modelview, D2R*Xrot, glm::vec3(1.,0.,0.) );  // {x',y',z'} = [v]*[yr]*[xr]*{x,y,z}
modelview = glm::scale( modelview, glm::vec3(Scale,Scale,Scale) );     // {x',y',z'} = [v]*[yr]*[xr]*[s]*{x,y,z}
```

This is exactly the same concept as OpenGL, but a different expression of it. Read on for details …

The Most Useful GLM Variables, Operations, and Functions


```
// constructor:

glm::mat4( 1. );             // 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

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// 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 );
```

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Installing GLM into your own space

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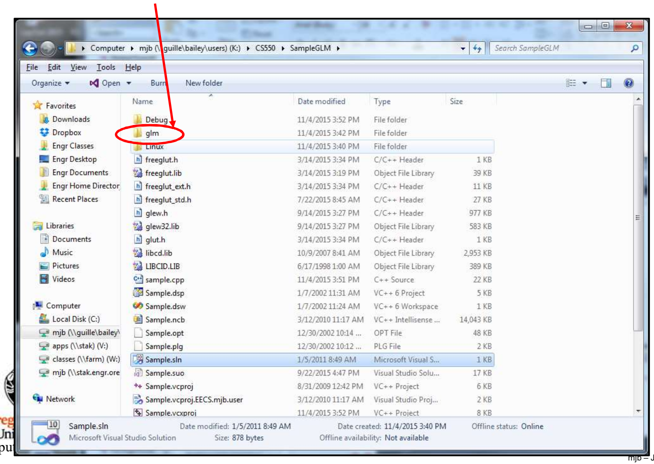
I like to just put the whole thing under my Visual Studio project folder so I can zip up a complete project and give it to someone else.



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Here's what that GLM folder looks like

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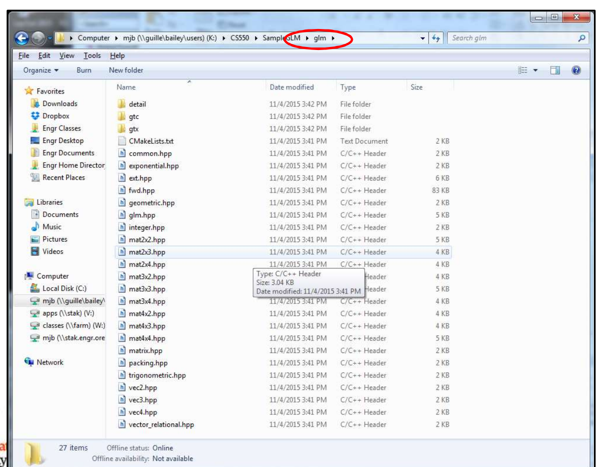

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Telling Visual Studio about where the GLM folder is

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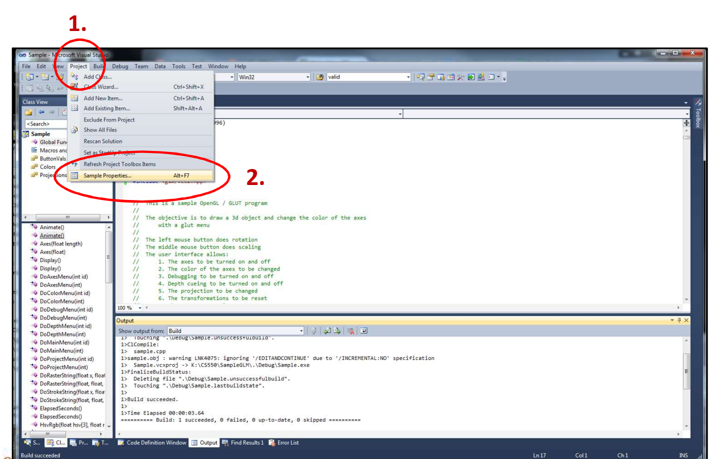

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Telling Visual Studio about where the GLM folder is

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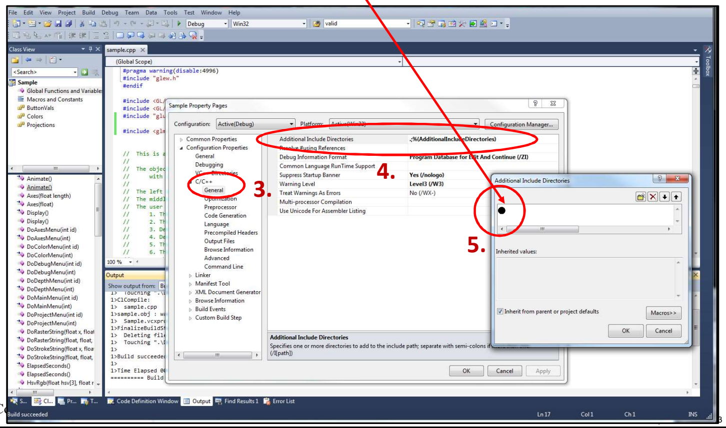
A ***period***, indicating that the **project folder** should also be searched when a

#include <xxx>

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



GLM in the Vulkan sample.cpp Program

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```
if( UseMouse )
{
        if( Scale < MINSCALE )
           Scale = MINSCALE;
        Matrices.uModelMatrix = glm::mat4( 1. );        // identity
        Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Yrot, glm::vec3( 0.,1.,0.) );
        Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Xrot, glm::vec3( 1.,0.,0.) );
        Matrices.uModelMatrix = glm::scale(  Matrices.uModelMatrix, glm::vec3(Scale,Scale,Scale) );
                        // done this way, the Scale is applied first, then the Xrot, then the Yrot
}
else
{
     if( ! Paused )
     {
           const glm::vec3 axis = glm::vec3( 0., 1., 0. );
           Matrices.uModelMatrix      = glm::rotate( glm::mat4( 1. ),  (float)glm::radians( 360.f*Time/SECONDS_PER_CYCLE ),   axis );
     }
}

glm::vec3 eye(0.,0.,EYEDIST );
glm::vec3 look(0.,0.,0.);
glm::vec3   up(0.,1.,0.);
Matrices.uVewMatrix = glm::lookAt( eye, look, up );

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

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix );  // note: inverseTransform !

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

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

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How Does this Matrix Stuff Really Work?

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$$x' = Ax + By + Cz + D$$
$$y' = Ex + Fy + Gz + H$$
$$z' = Ix + Jy + Kz + L$$

This is called a "Linear Transformation" because all of the coordinates are raised to the 1st power, that is, there are no x^2, x^3, etc. terms.

Or, in matrix form:

x consuming column

y consuming column

z consuming column

constant column

x' producing row

y' producing row

z' producing row

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} A & B & C & D \\ E & F & G & H \\ I & J & K & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

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Transformation Matrices

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Translation

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

Rotation about X

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

Scaling

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

Rotation about Y

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

Rotation about Z

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

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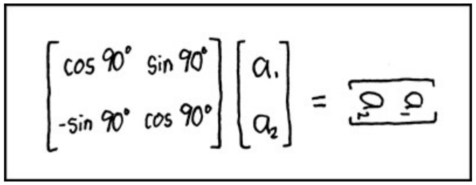
How it Really Works :-)



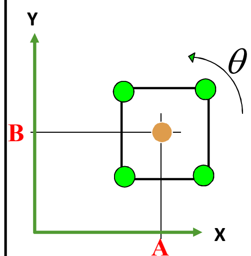
http://xkcd.com

The Rotation Matrix for an Angle (θ) about an Arbitrary Axis (Ax, Ay, Az)

$$[M] = \begin{bmatrix} A_xA_x + \cos\theta(1 - A_xA_x) & A_xA_y - \cos\theta(A_xA_y) - \sin\theta A_z & A_xA_z - \cos\theta(A_xA_z) + \sin\theta A_y \\ A_yA_x - \cos\theta(A_yA_x) + \sin\theta A_z & A_yA_y + \cos\theta(1 - A_yA_y) & A_yA_z - \cos\theta(A_yA_z) - \sin\theta A_x \\ A_zA_x - \cos\theta(A_zA_x) - \sin\theta A_y & A_zA_y - \cos\theta(A_zA_y) + \sin\theta A_x & A_zA_z + \cos\theta(1 - A_zA_z) \end{bmatrix}$$

For this to be correct, A must be a unit vector

Compound Transformations



Q: Our rotation matrices only work around the origin? What if we want to rotate about an arbitrary point (A,B)?

A: We create more than one matrix.

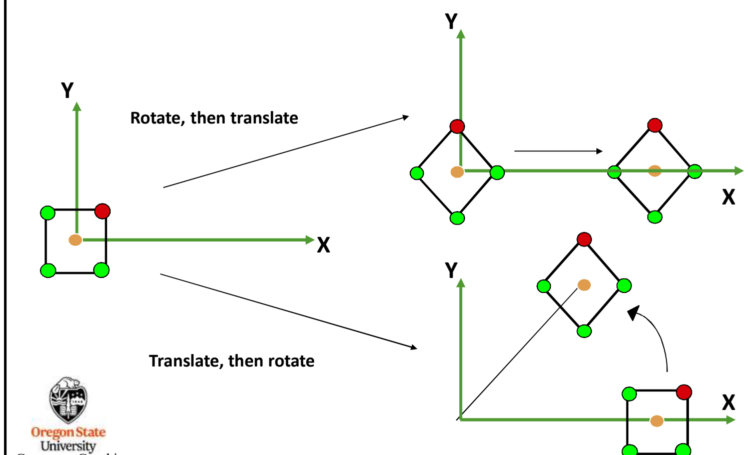
Write it →

3 2 1

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left([T_{+A,+B}] \cdot \left([R_\theta] \cdot \left([T_{-A,-B}] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \right) \right) \right)$$

← Say it

Matrix Multiplication *is not* Commutative



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Matrix Multiplication *is* Associative

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left(\left[T_{+A,+B} \right] \cdot \left(\left[R_\theta \right] \cdot \left(\left[T_{-A,-B} \right] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \right) \right) \right)$$

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left(\left[T_{+A,+B} \right] \cdot \left[R_\theta \right] \cdot \left[T_{-A,-B} \right] \right) \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

One matrix to rule them all –
the Current Transformation Matrix, or **CTM**

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From the Data Buffer Noteset

Here's the vertex shader shader code to use the matrices:

```
layout( std140, set = 0, binding = 0 ) uniform sceneMatBuf
{
        mat4 uProjectionMatrix;
        mat4 uViewMatrix;
        mat4 uSceneMatrix;
} SceneMatrices;

layout( std140, set = 1, binding = 0 ) uniform objectMatBuf
{
        mat4 uModelMatrix;
        mat4 uNormalMatrix;
} ObjectMatrices;
```

```
vNormal = uNormalMatrix * aNormal;

gl_Position = uProjectMatrix * uViewMatrix * uSceneMatrix * uModelMatrix * aVertex;
```

"CTM"

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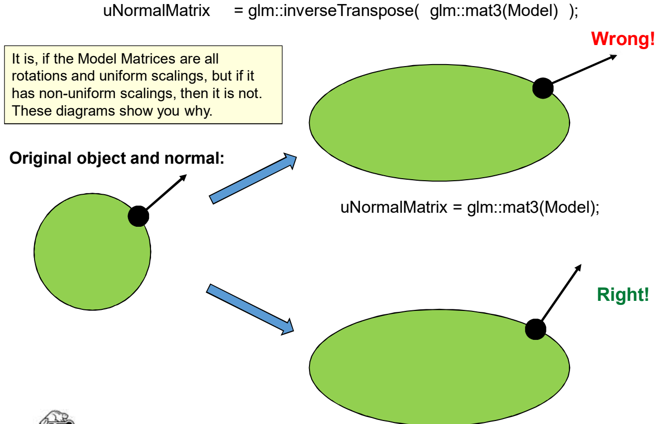
Why Isn't The Normal Matrix exactly the same as the Model Matrix?

```
glm::mat4  Model = uViewMatrix*uSceneMatrix*uModelMatrix;
uNormalMatrix     = glm::inverseTranspose(  glm::mat3(Model)  );
```

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



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

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Descriptor Sets

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Mike Bailey

mjb@cs.oregonstate.edu

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DescriptorSets.pptx

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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;
```

std140 has to do with the alignment of the different data types. It is the simplest, and so we use it in class to give everyone the highest probability that their system will be compatible with the alignment.

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


Descriptor Sets

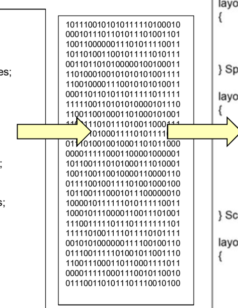
Our example will assume the following shader uniform variables:

```
// non-opaque must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform sporadicBuf
{
        int         uMode;
        int         uUseLighting;
        int         uNumInstances;
} Sporadic;

layout( std140, set = 1, binding = 0 ) uniform sceneBuf
{
        mat4        uProjection;
        mat4        uView;
        mat4        uSceneOrient;
        vec4        uLightPos;
        vec4        uLightColor;
        vec4        uLightKaKdKs;
        float       uTime;
} Scene;

layout( std140, set = 2, binding = 0 ) uniform objectBuf
{
        mat4        uModel;
        mat4        uNormal;
        vec4        uColor;
        float       uShininess;
} Object;

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


Descriptor Sets

CPU:	GPU:	GPU:
Uniform data created in a C++ data structure	Uniform data in a "blob"*	Uniform data used in the shader

```
struct sporadicBuf
{
        int           uMode;
        int           uUseLighting;
        int           uNumInstances;
} Sporadic;

struct sceneBuf
{
        glm::mat4     uProjection;
        glm::mat4     uView;
        glm::mat4     uSceneOrient;
        glm::vec4     uLightPos;
        glm::vec4     uLightColor;
        glm::vec4     uLightKaKdKs;
        float         uTime;
} Scene;

struct objectBuf
{
        glm::mat4     uModel;
        glm::mat4     uNormal;
        glm::vec4     uColor;
        float         uShininess;
} Object;
```

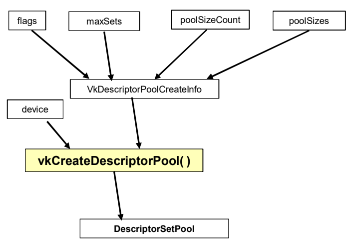


```
// non-opaque must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform sporadicBuf
{
        int         uMode;
        int         uUseLighting;
        int         uNumInstances;
} Sporadic;

layout( std140, set = 1, binding = 0 ) uniform sceneBuf
{
        mat4        uProjection;
        mat4        uView;
        mat4        uSceneOrient;
        vec4        uLightPos;
        vec4        uLightColor;
        vec4        uLightKaKdKs;
        float       uTime;
} Scene;

layout( std140, set = 2, binding = 0 ) uniform objectBuf
{
        mat4        uModel;
        mat4        uNormal;
        vec4        uColor;
        float       uShininess;
} Object;

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

* "binary large object"

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 during initialization and then pull from that pool later.




```
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;
}
```


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

```
// non-opaque must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform sporadicBuf
{
	int		uMode;
	int		uUseLighting;
	int		uNumInstances;
} Sporadic;

layout( std140, set = 1, binding = 0 ) uniform sceneBuf
{
	mat4		uProjection;
	mat4		uView;
	mat4		uSceneOrient;
	vec4		uLightPos;
	vec4		uLightColor;
	vec4		uLightKaKdKs;
	float		uTime;
} Scene;

layout( std140, set = 2, binding = 0 ) uniform objectBuf
{
	mat4		uModel;
	mat4		uNormal;
	vec4		uColor;
	float		uShininess;
} Object;

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

SporadicSet DS Layout Binding:	SceneSet DS Layout Binding:	ObjectSet 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		SporadicSet[1];
		SporadicSet[0].binding			= 0;
		SporadicSet[0].descriptorType		= VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		SporadicSet[0].descriptorCount		= 1;
		SporadicSet[0].stageFlags		= VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
		SporadicSet[0].pImmutableSamplers = (VkSampler *)nullptr;

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

	//DS #2:
	VkDescriptorSetLayoutBinding		ObjectSet[1];
		ObjectSet[0].binding			= 0;
		ObjectSet[0].descriptorType		= VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
		ObjectSet[0].descriptorCount		= 1;
		ObjectSet[0].stageFlags			= VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
		ObjectSet[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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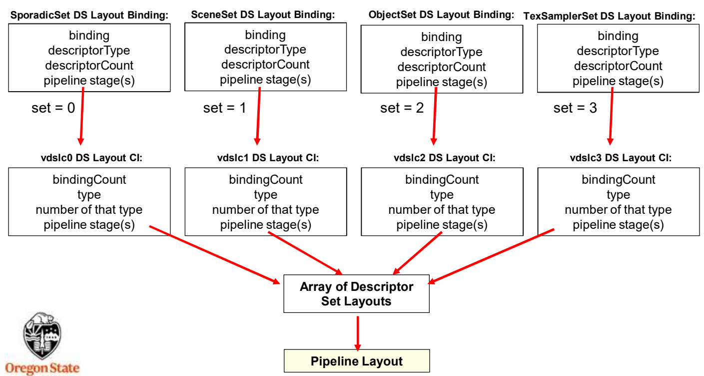
```
// globals:
VkDescriptorPool          DescriptorPool;
VkDescriptorSetLayout     DescriptorSetLayouts[4];
VkDescriptorSet           DescriptorSets[4];
```



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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 = &SporadicSet[0];

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

	VkDescriptorSetLayoutCreateInfo		vdslc2;
		vdslc2.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
		vdslc2.pNext = nullptr;
		vdslc2.flags = 0;
		vdslc2.bindingCount = 1;
		vdslc2.pBindings = &ObjectSet[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;
}
```

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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;
}
```

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Step 4: Allocating the Memory for Descriptor Sets

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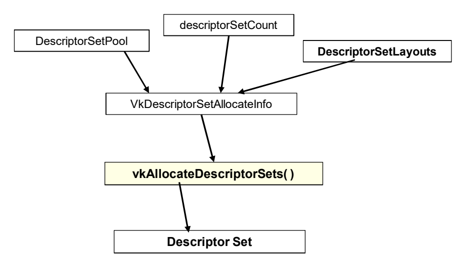

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Step 4: Allocating the Memory for Descriptor Sets

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```
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] );
```

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

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```
VkDescriptorBufferInfo			vdbi0;
	vdbi0.buffer = MySporadicUniformBuffer.buffer;
	vdbi0.offset = 0;
	vdbi0.range = sizeof(Sporadic);

VkDescriptorBufferInfo			vdbi1;
	vdbi1.buffer = MySceneUniformBuffer.buffer;
	vdbi1.offset = 0;
	vdbi1.range = sizeof(Scene);

VkDescriptorBufferInfo			vdbi2;
	vdbi2.buffer = MyObjectUniformBuffer.buffer;
	vdbi2.offset = 0;
	vdbi2.range = sizeof(Object);

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

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

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```
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;

	// 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;
```

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

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

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Step 5: Tell the Descriptor Sets where their data is

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```
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;

	// 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 );
```

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

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

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

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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 &GraphicsPipeline );
```

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

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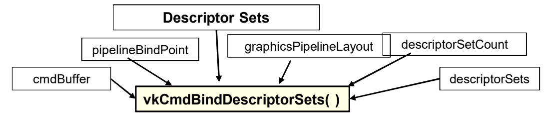


```
vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex],
                         VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipelineLayout,
                         0, 4, DescriptorSets, 0, (uint32_t *)nullptr );
```

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.

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Sidebar: The Entire Descriptor Set Journey

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VkDescriptorPoolCreateInfo
vkCreateDescriptorPool( )
— Create the pool of Descriptor Sets for future use

VkDescriptorSetLayoutBinding
VkDescriptorSetLayoutCreateInfo
vkCreateDescriptorSetLayout( )
vkCreatePipelineLayout( )
— Describe a particular Descriptor Set layout and use it in a specific Pipeline layout

VkDescriptorSetAllocateInfo
vkAllocateDescriptorSets( )
— Allocate memory for particular Descriptor Sets

VkDescriptorBufferInfo
VkDescriptorImageInfo
VkWriteDescriptorSet
— Tell a particular Descriptor Set where its CPU data is
vkUpdateDescriptorSets( )
— Re-write CPU data into a particular Descriptor Set

vkCmdBindDescriptorSets( )
— Make a particular Descriptor Set "current" for rendering

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Sidebar: Why Do Descriptor Sets Need to Provide Layout Information to the Pipeline Data Structure?

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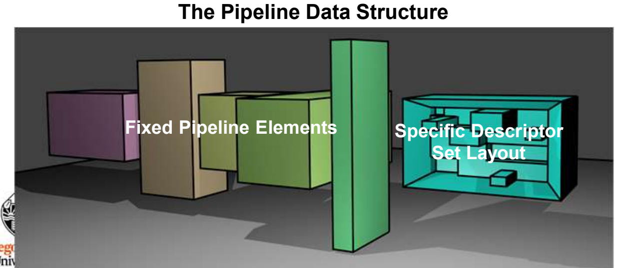
The pieces of the Pipeline Data Structure are fixed in size – with the exception of the Descriptor Sets and the Push Constants. Each of these two can be any size, depending on what you allocate for them. So, the Pipeline Data Structure needs to know how these two are configured before it can set its own total layout.

Think of the DS layout as being a particular-sized hole in the Pipeline Data Structure. Any data you have that matches this hole's shape and size can be plugged in there.

The Pipeline Data Structure



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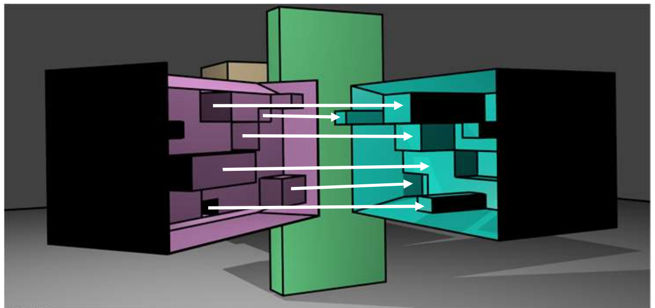
Sidebar: Why Do Descriptor Sets Need to Provide Layout Information to the Pipeline Data Structure?

Any set of data that matches the Descriptor Set Layout can be plugged in there.



Vulkan

Textures

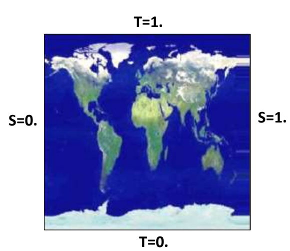
Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

The Basic Idea

Texture mapping is a computer graphics operation in which a separate image, referred to as the **texture**, is stretched onto a piece of 3D geometry and follows it however it is transformed. This image is also known as a ***texture map***.

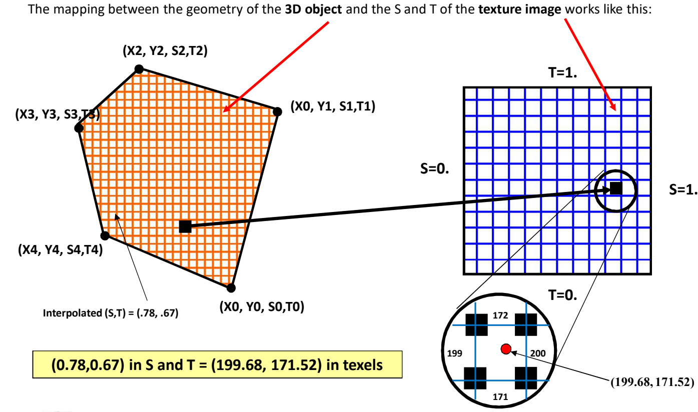
Also, to prevent confusion, the texture pixels are not called ***pixels***. A pixel is a dot in the final screen image. A dot in the texture image is called a ***texture element***, or ***texel***.

Similarly, to avoid terminology confusion, a texture's width and height dimensions are not called *X* and *Y*. They are called **S** and **T**. A texture map is not generally indexed by its actual resolution coordinates. Instead, it is indexed by a coordinate system that is resolution-independent. The left side is always **S=0.**, the right side is **S=1.**, the bottom is **T=0.**, and the top is **T=1.** Thus, you do not need to be aware of the texture's resolution when you are specifying coordinates that point into it. Think of S and T as a measure of what fraction of the way you are into the texture.



The Basic Idea

The mapping between the geometry of the **3D object** and the S and T of the **texture image** works like this:



You specify an (s,t) pair at each vertex, along with the vertex coordinate. At the same time that the rasterizer is interpolating the coordinates, colors, etc. inside the polygon, it is also interpolating the (s,t) coordinates. Then, when it goes to draw each pixel, it uses that pixel's interpolated (s,t) to lookup a color in the texture image.

In OpenGL terms: assigning an (s,t) to each vertex

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Enable texture mapping:

```
glEnable( GL_TEXTURE_2D );
```

Draw your polygons, specifying **s** and **t** at each vertex:

```
glBegin( GL_POLYGON );
	glTexCoord2f( s0, t0 );
	glNormal3f( nx0, ny0, nz0 );
	glVertex3f( x0, y0, z0 );

	glTexCoord2f( s1, t1 );
	glNormal3f( nx1, ny1, nz1 );
	glVertex3f( x1, y1, z1 );

	. . .
glEnd( );
```

Disable texture mapping:

```
glDisable( GL_TEXTURE_2D );
```

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Triangles in an Array of Structures

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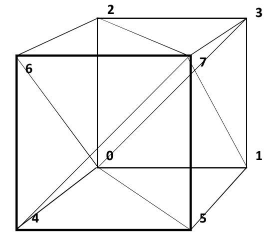
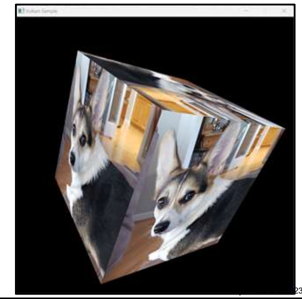
```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

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. }
	},
```





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Using a Texture: How do you know what (s,t) to assign to each vertex?

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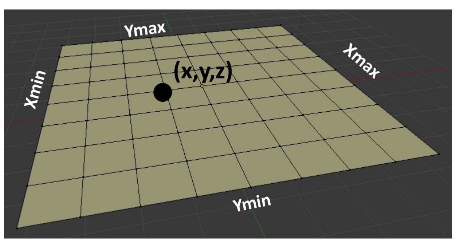
The easiest way to figure out what s and t are at a particular vertex is to figure out what *fraction* across the object the vertex is living at. For a plane,



$$s = \frac{x - Xmin}{Xmax - Xmin} \qquad t = \frac{y - Ymin}{Ymax - Ymin}$$

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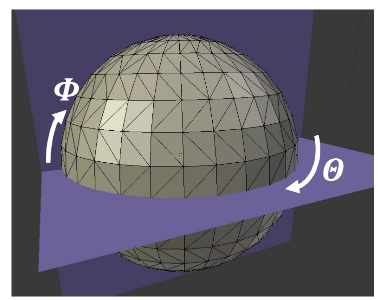
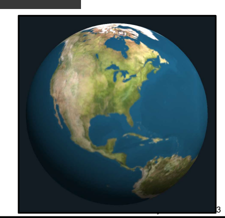
Or, for a sphere,



$$s = \frac{\Theta - (-\pi)}{2\pi} \qquad t = \frac{\Phi - (-\frac{\pi}{2})}{\pi}$$

```
s = ( lng + M_PI    ) / ( 2.*M_PI );
t  = ( lat + M_PI/2. ) / M_PI;
```



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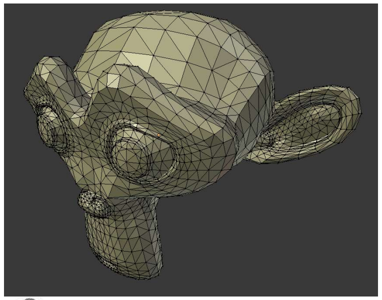
Using a Texture: How do you know what (s,t) to assign to each vertex?

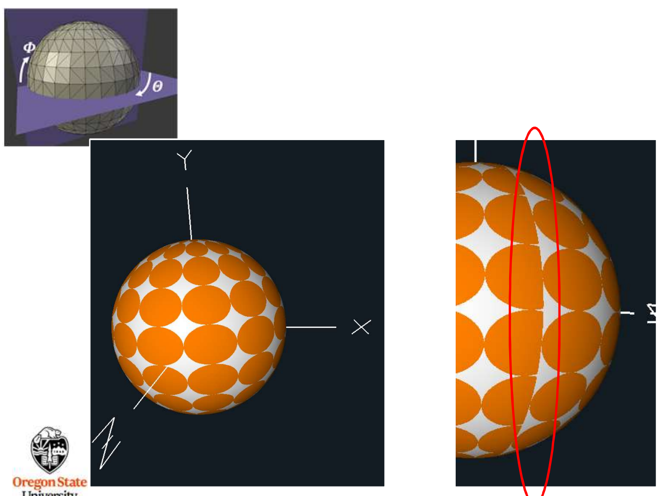
Uh-oh. Now what? Here's where it gets tougher…,



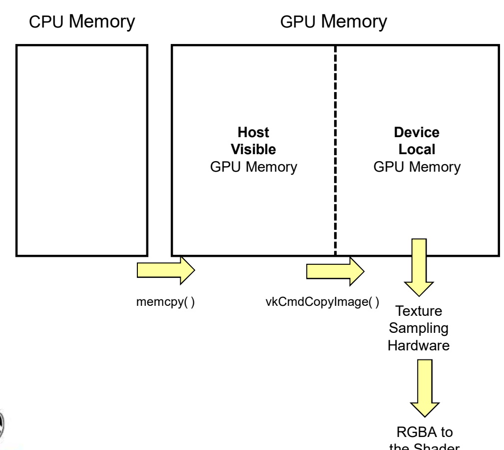
$s = ?$ $t = ?$

You really are at the mercy of whoever did the modeling…

Be careful where *s* abruptly transitions from 1. back to 0.



Memory Types



Memory Types

NVIDIA A6000 Graphics:

6 Memory Types:
Memory 0:
Memory 1: DeviceLocal
Memory 2: HostVisible HostCoherent
Memory 3: HostVisible HostCoherent HostCached
Memory 4: DeviceLocal HostVisible HostCoherent
Memory 5: DeviceLocal

Intel Integrated Graphics:

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

Something I've Found Useful

I find it handy to encapsulate texture information in a struct, just like I do with buffer information:

```
// holds all the information about a data buffer so it can be encapsulated in one variable:

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

// holds all the information about a texture so it can be encapsulated in one variable:

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


Texture Sampling Parameters

OpenGL

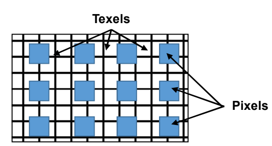
```
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
```

Vulkan

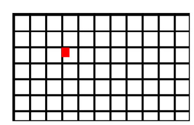
```
MyTexture  MyPuppyTexture;
. . .
VkSamplerCreateInfo                 vsci;
        vsci.magFilter = VK_FILTER_LINEAR;
        vsci.minFilter  = VK_FILTER_LINEAR;
        vsci.mipmapMode   = VK_SAMPLER_MIPMAP_MODE_LINEAR;
        vsci.addressModeU  = VK_SAMPLER_ADDRESS_MODE_REPEAT;
        vsci.addressModeV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

        . . .

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


Textures' Undersampling Artifacts

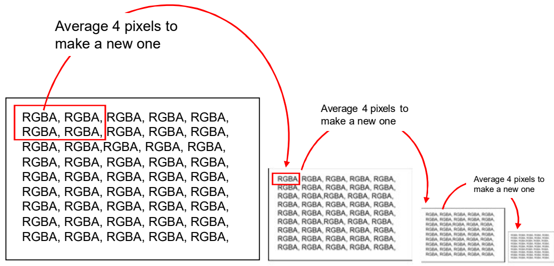
As an object gets farther away and covers a smaller and smaller part of the screen, the **texels : pixels ratio** used in the coverage becomes larger and larger. This means that there are pieces of the texture leftover in between the pixels that are being drawn into, so that some of the texture image is not being taken into account in the final image. This means that the texture is being undersampled and could end up producing artifacts in the rendered image.



Consider a texture that consists of one red texel and all the rest white. It is easy to imagine an object rendered with that texture as ending up all *white*, with the red texel having never been included in the final image. The solution is to create lower-resolutions of the same texture so that the red texel gets included somehow in all resolution-level textures.



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 Texture:Pixel 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 &MyPuppyTexture->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);
		}
```

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```
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);

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

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

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```
// 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);
}
// *****************************************************************************
```



```
// *****************************************************************************
// 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 );
```



```
        // create an image view for the texture image:
        // (an "image view" is used to indirectly access an 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;
}
```

Access to an Image ↔ Image View ↔ The Actual Image Data

8 bits Red	8 bits Green	8 bits Blue	8 bits Alpha

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 ( "puppy1.bmp", &MyPuppyTexture);
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*.

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The Graphics Pipeline Data Structure (GPDS)

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

What is the Vulkan Graphics Pipeline Data Structure (GPDS)?

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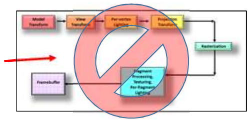
Here's what you need to know:

1. The Vulkan Graphics Pipeline is like what OpenGL would call "The State", or "The Context". It is a ***data structure***.
2. Since you know the OpenGL state, a lot of the Vulkan GPDS will seem familiar to you.
3. The current shader program is part of the state. (It was in OpenGL too, we just didn't make a big deal of it.)
4. The Vulkan Graphics Pipeline is *not* the processes that OpenGL would call "the graphics pipeline".



5. For the most part, the Vulkan Graphics Pipeline Data Structure is 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 GPDS.
6. The shaders get compiled the rest of the way when their Graphics Pipeline Data Structure gets created.

There are also a Vulkan **Compute Pipeline Data Structure** and a **Raytrace Pipeline Data Structure** – we will get to those later.

Vulkan Graphics Pipeline Stages and what goes into Them

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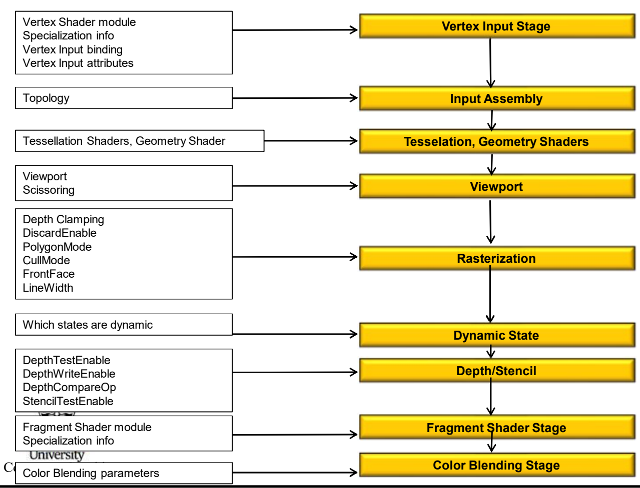
The GPU and Driver specify the Pipeline Stages – the Vulkan Graphics Pipeline declares what goes in them



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.

```
VkPipelineLayout        GraphicsPipelineLayout;      // global
. . .
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.

Why is this necessary? It is because the Descriptor Sets and Push Constants data structures have different sizes depending on how many of each you have. So, the exact structure of the Pipeline Layout depends on you telling Vulkan about the Descriptor Sets and Push Constants that you will be using.

A Graphics Pipeline Data Structure Contains the Following State Items:

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- Pipeline Layout: Descriptor Sets, Push Constants
- Which Shaders to use (half-compiled SPIR-V modules)
- Per-vertex input attributes: location, binding, format, offset
- Per-vertex input bindings: binding, stride, inputRate
- Assembly: topology (e.g., **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST)**
- ***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 be changed with Dynamic State Variables

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Creating a Graphics Pipeline from a lot of Pieces

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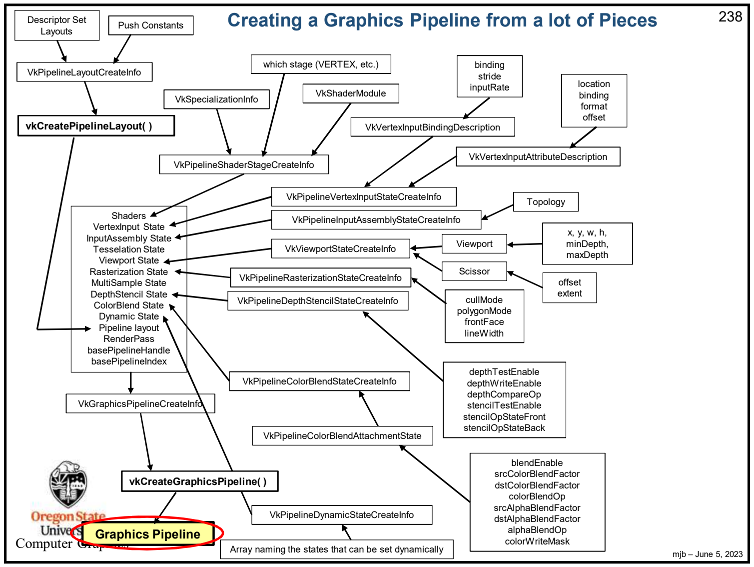

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Creating a Typical Graphics Pipeline

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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.

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The Shaders to Use

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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

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Link in the Per-Vertex Attributes

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```
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

I #defined these 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

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```
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

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Options for vpiasci.topology

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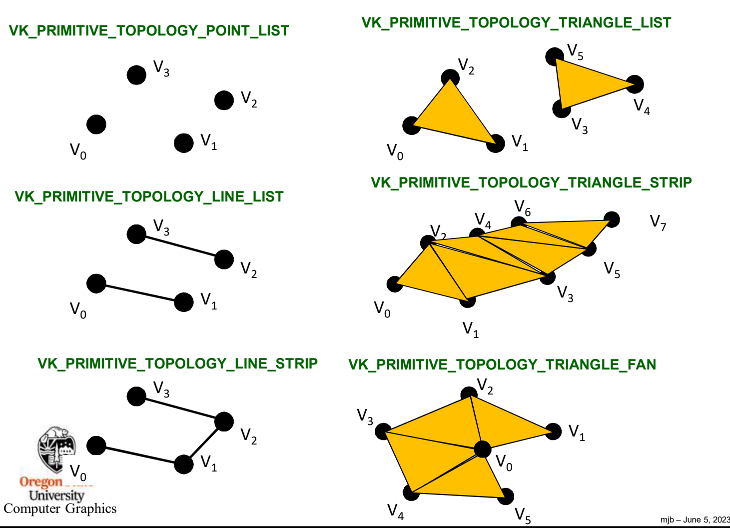

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What is "Primitive Restart Enable"?

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vpiasci.primitiveRestartEnable = VK_FALSE;

"Restart Enable" is used with:

- Indexed drawing.
- TRIANGLE_FAN and TRIANGLE_STRIP topologies

If vpiasci.primitiveRestartEnable is VK_TRUE, then a special "index" can be used to indicate that the primitive should start over. This is more efficient than explicitly ending the current triangle strip and explicitly starting a new one.

```
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, then the special index is **0xffffffff**.

That is, a one in all available bits

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

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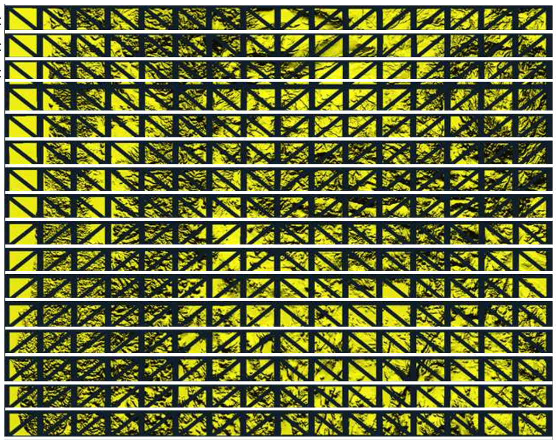
Triangle Strip #0:
Triangle Strip #1:
Triangle Strip #2:
. . .



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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

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

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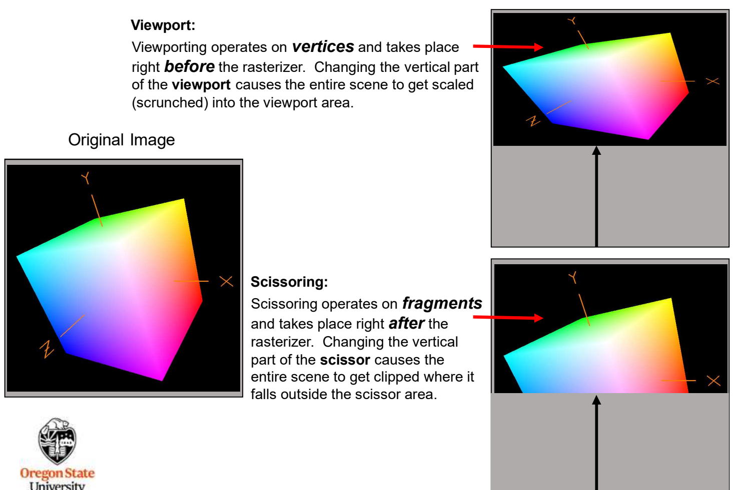
Viewport:
Viewporting operates on ***vertices*** and takes place right ***before*** the rasterizer. Changing the vertical part of the **viewport** causes the entire scene to get scaled (scrunched) into the viewport area.

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.

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Setting the Rasterizer State

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```
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

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What is "Depth Clamp Enable"?

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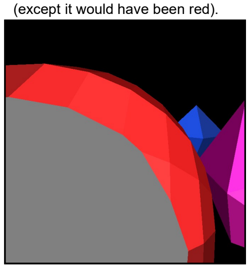
```
vprsci.depthClampEnable = VK_FALSE;
```

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).



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What is "Depth Bias Enable"?

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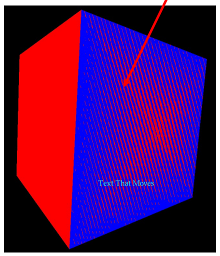
```
vprsci.depthBiasEnable = VK_FALSE;
vprsci.depthBiasConstantFactor = 0.f;
vprsci.depthBiasClamp = 0.f;
vprsci.depthBiasSlopeFactor = 0.f;
```

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

Z-fighting



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MultiSampling State

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```
VkPipelineMultisampleStateCreateInfo          vpmsci;
        vpmsci.sType = VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO;
        vpmsci.pNext = nullptr;
        vpmsci.flags = 0;
        vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_1_BIT;
        vpmsci.sampleShadingEnable = VK_FALSE;
        vpmsci.minSampleShading = 0;
        vpmsci.pSampleMask = (VkSampleMask *)nullptr;
        vpmsci.alphaToCoverageEnable = VK_FALSE;
        vpmsci.alphaToOneEnable = VK_FALSE;
```

Declare information about how the multisampling will take place

We will discuss MultiSampling in a separate noteset.

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Color Blending State for each Color Attachment *

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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.

$$Color_{new} = (1.-\alpha) * Color_{existing} + \alpha * Color_{incoming}$$

$$0. \leq \alpha \leq 1.$$

*A "Color Attachment" is a framebuffer to be rendered into. You can have as many of these as you want.

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Raster Operations for each Color Attachment

253

```
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.

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Which Pipeline Variables can be Set Dynamically

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Just used as an example in the Sample Code

```
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;
```

This allows you to give the graphics a full Graphics Pipeline Data Structure and then change some elements of it.

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The Stencil Buffer

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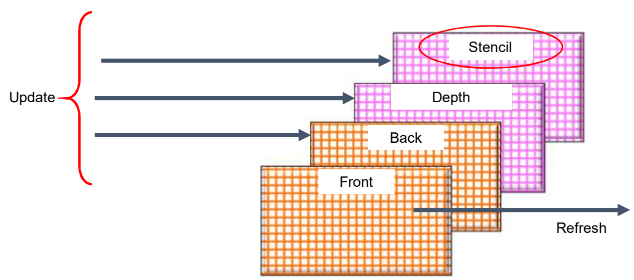

Here's what the Stencil Buffer can do for you:

1. While drawing into the Back Buffer, you can write values into the Stencil Buffer at the same time.
2. While drawing into the Back Buffer, you can do arithmetic on values in the Stencil Buffer at the same time.
3. The Stencil Buffer can be used to write-protect certain parts of the Back Buffer.

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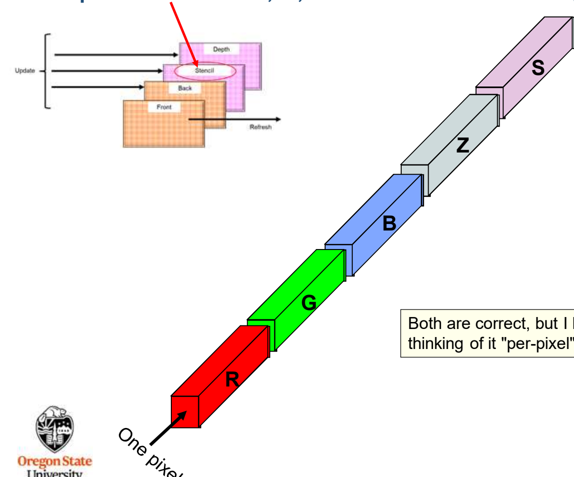
You Can Think of the Stencil Buffer as a Separate Framebuffer, or, You Can Think of it as being Per-Pixel

256



Both are correct, but I like thinking of it "per-pixel" better.

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Using the Stencil Buffer to Create a *Magic Lens*

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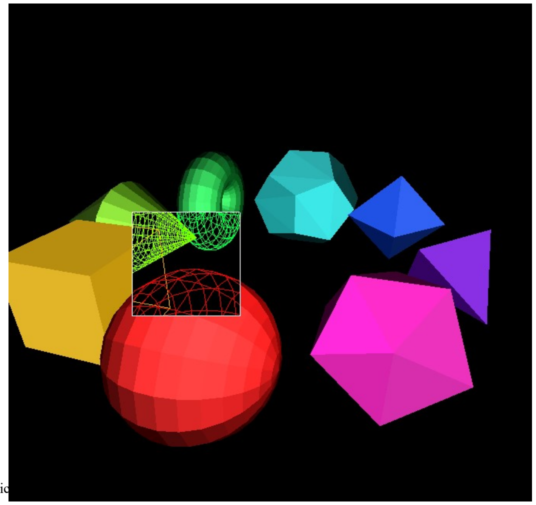

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Using the Stencil Buffer to Create a *Magic Lens*

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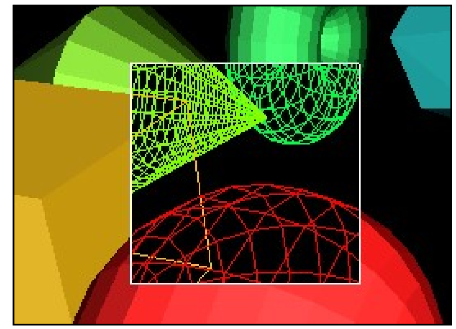
1. Clear the SB = 0
2. Write protect the color buffer
3. Fill a square, setting SB = 1
4. Write-enable the color buffer
5. Draw the solids wherever SB == 0
6. Draw the wireframes wherever SB == 1



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I Once Used the Stencil Buffer to Create a *Magic Lens* for Volume Data

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In this case, the scene inside the lens was created by drawing the same object, but drawing it with its near clipping plane being farther away from the eye position

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Using the Stencil Buffer to Perform *Polygon Capping*

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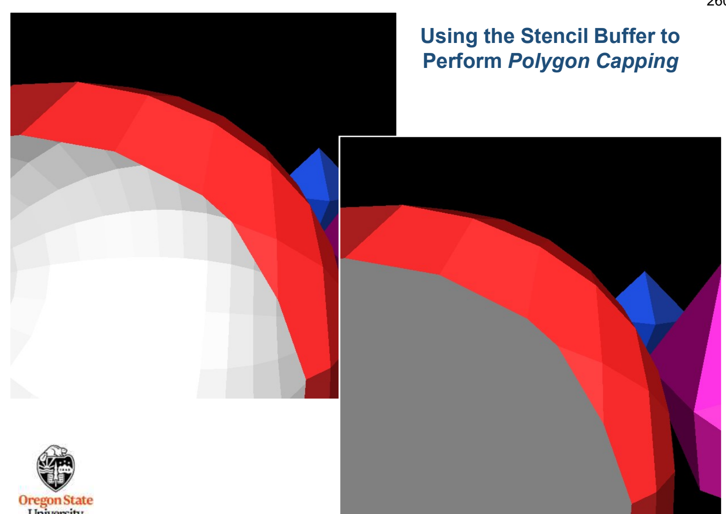

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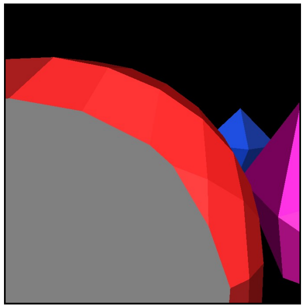
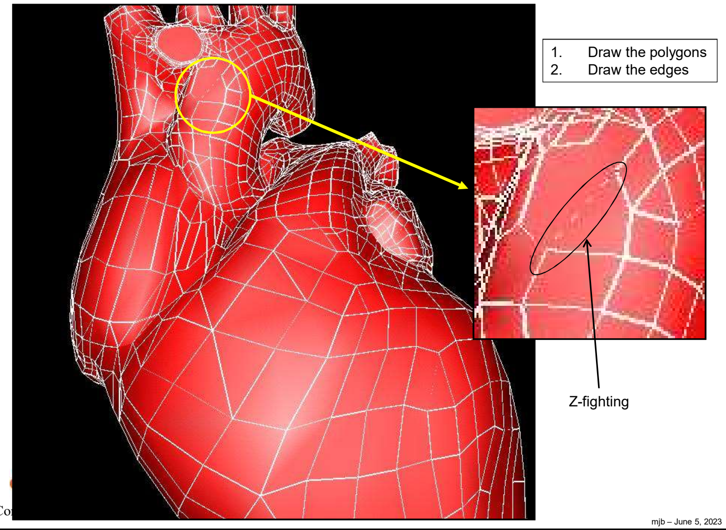
Using the Stencil Buffer to Perform *Polygon Capping*

1. Clear the SB = 0
2. Draw the polygons, setting SB = ~ SB
3. Draw a large gray polygon across the entire scene wherever SB != 0

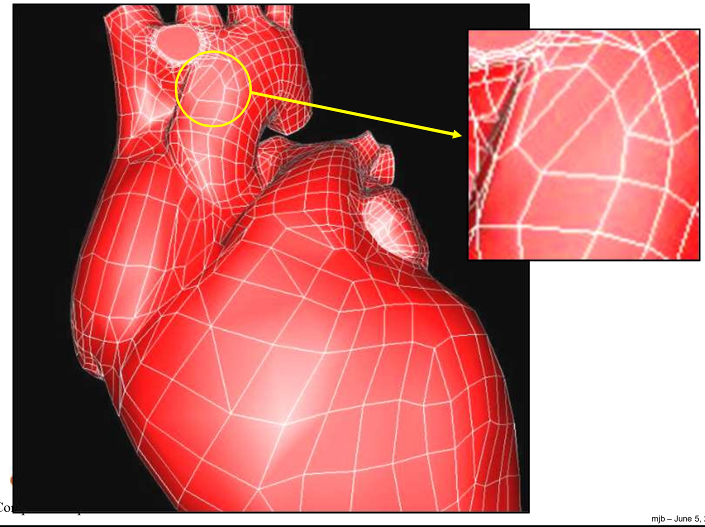


Outlining Polygons the Naïve Way

1. Draw the polygons
2. Draw the edges



Using the Stencil Buffer to Better Outline Polygons



Using the Stencil Buffer to Better Outline Polygons

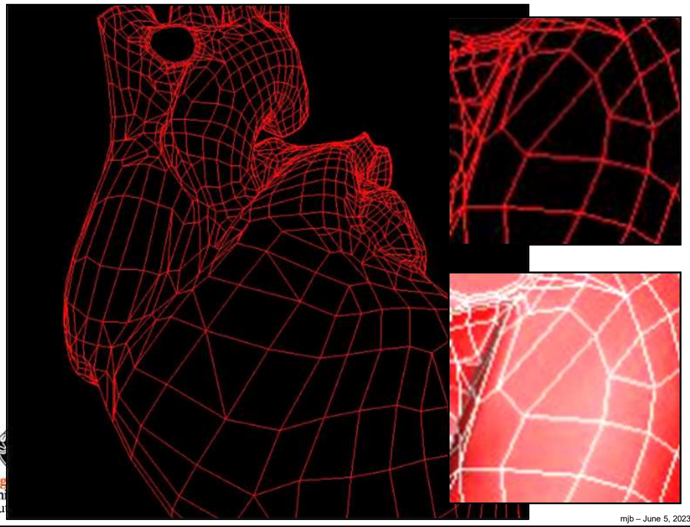

```
Clear the SB = 0

for( each polygon )
{
      Draw the edges, setting SB = 1
      Draw the polygon wherever SB  !=  1
      Draw the edges, setting SB = 0
}
```

Before **After**

Using the Stencil Buffer to Perform *Hidden Line Removal*

265



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Stencil Operations for Front and Back Faces

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```
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;
```

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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;
```

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Putting it all Together! (finally…)

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```
VkPipeline   GraphicsPipeline;        // global
. . .

    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 );

    return result;
}
```

Group all of the individual state information and create the pipeline

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When Drawing, We will Bind a Specific Graphics Pipeline Data Structure to the Command Buffer

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```
VkPipeline        GraphicsPipeline;            // global

. . .

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

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Sidebar: What is the Organization of the Pipeline Data Structure?

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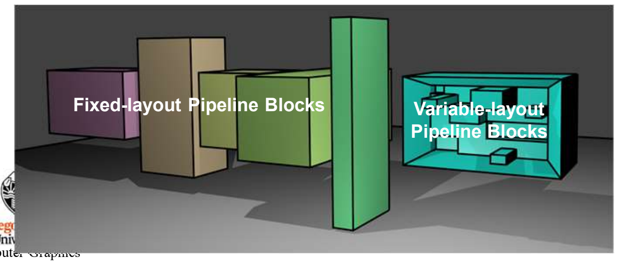
If you take a close look at the pipeline data structure creation information, you will see that almost all the pieces have a *fixed size*. For example, the viewport only needs 6 pieces of information – ever:

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

There are two exceptions to this -- the Descriptor Sets and the Push Constants. Each of these two can be almost any size, depending on what you allocate for them. So, I think of the Graphics Pipeline Data Structure as consisting of some fixed-layout blocks and 2 variable-layout blocks, like this:



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Vulkan.

Dynamic State Variables

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mjb@cs.oregonstate.edu

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DynamicStateVariables.pptx

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Creating a Pipeline with Dynamically Changeable State Variables

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

That isn't quite true. To a certain extent, Vulkan allows you to declare parts of the pipeline state changeable. This allows you to alter pipeline state 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.

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Creating a Pipeline

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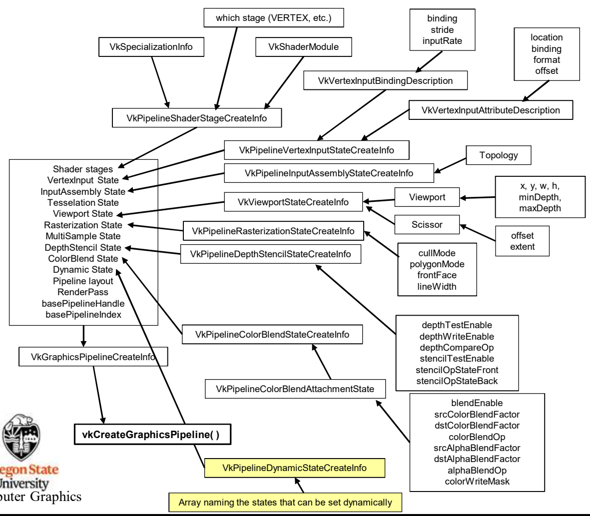

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Which Pipeline State Variables can be Changed Dynamically

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The possible 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

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Creating a Pipeline

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```
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);            // i.e., 2
        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***.

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Filling the Dynamic State Variables in the Command Buffer

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First call:

vkCmdBindPipeline(…);

Then, 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 );
```

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This is from one of the Vulkan .h Files
Does this mean more Dynamic States are in the Works?

```
VK_DYNAMIC_STATE_VIEWPORT = 0,
VK_DYNAMIC_STATE_SCISSOR = 1,
VK_DYNAMIC_STATE_LINE_WIDTH = 2,
VK_DYNAMIC_STATE_DEPTH_BIAS = 3,
VK_DYNAMIC_STATE_BLEND_CONSTANTS = 4,
VK_DYNAMIC_STATE_DEPTH_BOUNDS = 5,
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK = 6,
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK = 7,
VK_DYNAMIC_STATE_STENCIL_REFERENCE = 8,
VK_DYNAMIC_STATE_CULL_MODE = 1000267000,
VK_DYNAMIC_STATE_FRONT_FACE = 1000267001,
VK_DYNAMIC_STATE_PRIMITIVE_TOPOLOGY = 1000267002,
VK_DYNAMIC_STATE_VIEWPORT_WITH_COUNT = 1000267003,
VK_DYNAMIC_STATE_SCISSOR_WITH_COUNT = 1000267004,
VK_DYNAMIC_STATE_VERTEX_INPUT_BINDING_STRIDE = 1000267005,
VK_DYNAMIC_STATE_DEPTH_TEST_ENABLE = 1000267006,
VK_DYNAMIC_STATE_DEPTH_WRITE_ENABLE = 1000267007,
VK_DYNAMIC_STATE_DEPTH_COMPARE_OP = 1000267008,
VK_DYNAMIC_STATE_DEPTH_BOUNDS_TEST_ENABLE = 1000267009,
VK_DYNAMIC_STATE_STENCIL_TEST_ENABLE = 1000267010,
VK_DYNAMIC_STATE_STENCIL_OP = 1000267011,
```


Vulkan.
Queues and Command Buffers

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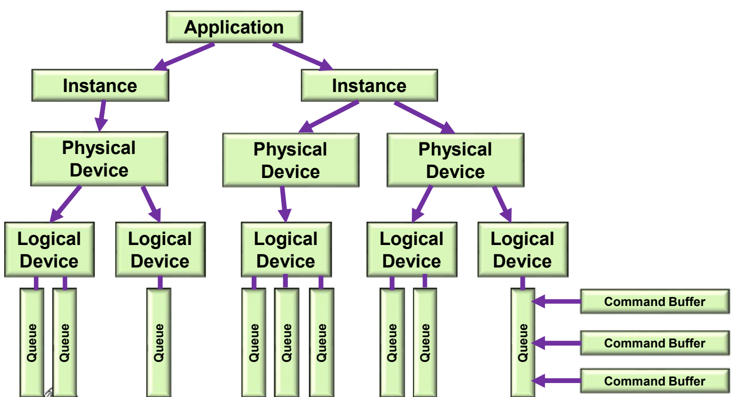
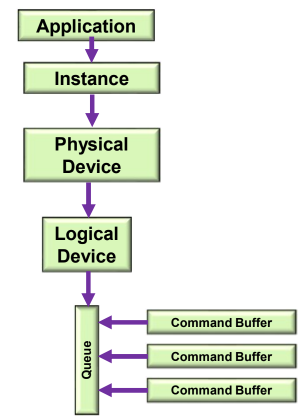
Mike Bailey
mjb@cs.oregonstate.edu

Vulkan: Overall Block Diagram



Simplified Block Diagram



Vulkan Queues and Command Buffers

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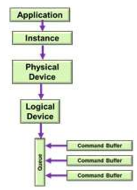
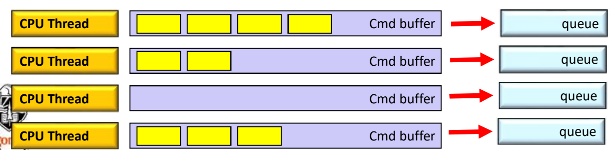
- Graphics commands are recorded in command buffers, e.g., *vkCmdDoSomething(cmdBuffer, …);*
- You can have as many simultaneous Command Buffers as you want
- Each command buffer can be filled from a different thread, but doesn't have to be
- Command Buffers record commands, but no work takes place until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





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Querying what Queue Families are Available

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```
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");
}
```

For the Nvidia A6000 cards:

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

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

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```
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;
}
```

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Creating a Logical Device Needs to Know Queue Family Information

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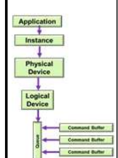


```
float  queuePriorities[ ] =
{
        1.                // one entry per queueCount
};

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 );
```

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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;
}
```

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Creating the Command Buffers

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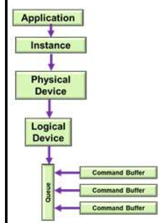


```
VkResult
Init06CommandBuffers( )
{
	VkResult result;

	// 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;
}
```

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Beginning a Command Buffer – One per Image

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```
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] );
```

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Beginning a Command Buffer

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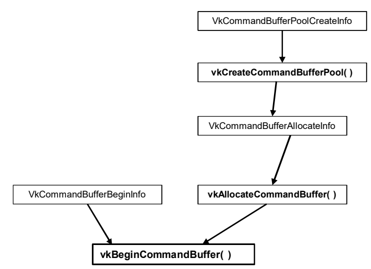

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These are the Commands that could be entered into a Command Buffer, I

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vkCmdBeginConditionalRendering
vkCmdBeginDebugUtilsLabel
vkCmdBeginQuery
vkCmdBeginQueryIndexed
vkCmdBeginRendering
vkCmdBeginRenderPass
vkCmdBeginRenderPass2
vkCmdBeginTransformFeedback
vkCmdBindDescriptorSets
vkCmdBindIndexBuffer
vkCmdBindInvocationMask
vkCmdBindPipeline
vkCmdBindPipelineShaderGroup
vkCmdBindShadingRateImage
vkCmdBindTransformFeedbackBuffers
vkCmdBindVertexBuffers
vkCmdBindVertexBuffers2
vkCmdBlitImage

vkCmdBlitImage2
vkCmdBuildAccelerationStructure
vkCmdBuildAccelerationStructuresIndirect
vkCmdBuildAccelerationStructures
vkCmdClearAttachments
vkCmdClearColorImage
vkCmdClearDepthStencilImage
vkCmdCopyAccelerationStructure
vkCmdCopyAccelerationStructureToMemory
vkCmdCopyBuffer
vkCmdCopyBuffer2
vkCmdCopyBufferToImage
vkCmdCopyBufferToImage2
vkCmdCopyImage
vkCmdCopyImage2
vkCmdCopyImageToBuffer
vkCmdCopyImageToBuffer2
vkCmdCopyMemoryToAccelerationStructure

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

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vkCmdCopyQueryPoolResults
vkCmdCuLaunchKernelX
vkCmdDebugMarkerBegin
vkCmdDebugMarkerEnd
vkCmdDebugMarkerInsert
vkCmdDispatch
vkCmdDispatchBase
vkCmdDispatchIndirect
vkCmdDraw
vkCmdDrawIndexed
vkCmdDrawIndexedIndirect
vkCmdDrawIndexedIndirectCount
vkCmdDrawIndirect
vkCmdDrawIndirectByteCount
vkCmdDrawIndirectCount
vkCmdDrawMeshTasksIndirectCount
vkCmdDrawMeshTasksIndirect
vkCmdDrawMeshTasks

vkCmdDrawMulti
vkCmdDrawMultiIndexed
vkCmdEndConditionalRendering
vkCmdEndDebugUtilsLabel
vkCmdEndQuery
vkCmdEndQueryIndexed
vkCmdEndRendering
vkCmdEndRenderPass
vkCmdEndRenderPass2
vkCmdEndTransformFeedback
vkCmdExecuteCommands
vkCmdExecuteGeneratedCommands
vkCmdFillBuffer
vkCmdInsertDebugUtilsLabel
vkCmdNextSubpass
vkCmdNextSubpass2
vkCmdPipelineBarrier
vkCmdPipelineBarrier2

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

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vkCmdPreprocessGeneratedCommands
vkCmdPushConstants
vkCmdPushDescriptorSet
vkCmdPushDescriptorSetWithTemplate
vkCmdResetEvent
vkCmdResetEvent2
vkCmdResetQueryPool
vkCmdResolveImage
vkCmdResolveImage2
vkCmdSetBlendConstants
vkCmdSetCheckpoint
vkCmdSetCoarseSampleOrder
vkCmdSetCullMode
vkCmdSetDepthBias
vkCmdSetDepthBiasEnable
vkCmdSetDepthBounds
vkCmdSetDepthBoundsTestEnable
vkCmdSetDepthCompareOp

vkCmdSetDepthTestEnable
vkCmdSetDepthWriteEnable
vkCmdSetDeviceMask
vkCmdSetDiscardRectangle
vkCmdSetEvent
vkCmdSetEvent2
vkCmdSetExclusiveScissor
vkCmdSetFragmentShadingRateEnum
vkCmdSetFragmentShadingRate
vkCmdSetFrontFace
vkCmdSetLineStipple
vkCmdSetLineWidth
vkCmdSetLogicOp
vkCmdSetPatchControlPoints
vkCmdSetPrimitiveRestartEnable
vkCmdSetPrimitiveTopology
vkCmdSetRasterizerDiscardEnable
vkCmdSetRayTracingPipelineStackSize

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

292

vkCmdSetSampleLocations
vkCmdSetScissor
vkCmdSetScissorWithCount
vkCmdSetStencilCompareMask
vkCmdSetStencilOp
vkCmdSetStencilReference
vkCmdSetStencilTestEnable
vkCmdSetStencilWriteMask
vkCmdSetVertexInput
vkCmdSetViewport
vkCmdSetViewportShadingRatePalette
vkCmdSetViewportWithCount
vkCmdSetViewportWScaling

vkCmdSubpassShading
vkCmdTraceRaysIndirect2
vkCmdTraceRaysIndirect
vkCmdTraceRays
vkCmdUpdateBuffer
vkCmdWaitEvents
vkCmdWaitEvents2
vkCmdWriteAccelerationStructuresProperties
vkCmdWriteBufferMarker2
vkCmdWriteBufferMarker
vkCmdWriteTimestamp
vkCmdWriteTimestamp2

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How the *RenderScene( )* Function Works

293

```
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] );
```

Co

Submitting a Command Buffer to a Queue for Execution

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

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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 );
```


What Happens After a Queue has Been Submitted?

As the Vulkan 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.

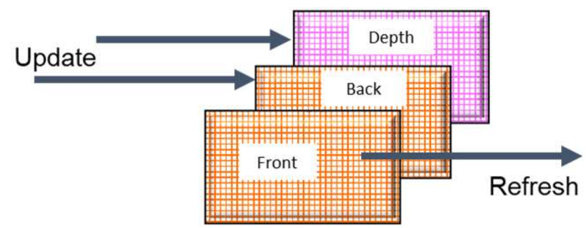
The message here is, I think, always consider using some sort of Vulkan synchronization when one command depends on a previous command reaching a certain state first.

Vulkan.

The Swap Chain

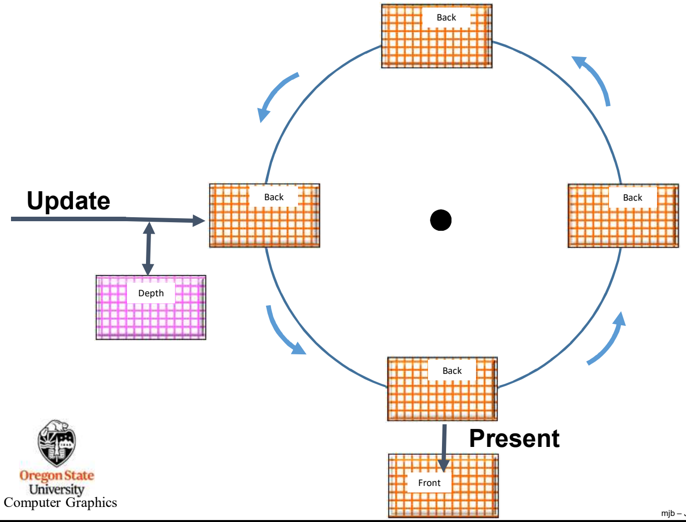
Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

How OpenGL Thinks of Framebuffers



How Vulkan Thinks of Framebuffers – the Swap Chain

301



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What is a Swap Chain?

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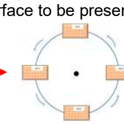
Vulkan does not use the idea of a "back buffer". So, we need a place to render into before moving an image into place for viewing. The is called the **Swap Chain**.

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")

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We Need to Find Out What our Display Capabilities Are

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```
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 );

        . . .
```

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We Need to Find Out What our Display Capabilities Are

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VulkanDebug.txt output for an Nvidia A6000:

```
***** Init08Swapchain *****

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

vkGetPhysicalDeviceSurfaceSupportKHR:

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

Found 3 Surface Formats:
 0:    44         0  VK_COLOR_SPACE_SRGB_NONLINEAR_KHR
 1:    50         0  VK_COLOR_SPACE_SRGB_NONLINEAR_KHR
 2:    64         0  VK_COLOR_SPACE_SRGB_NONLINEAR_KHR

Found 4 Present Modes:
 0:     2  VK_PRESENT_MODE_FIFO_KHR
 1:     3  VK_PRESENT_MODE_FIFO_RELAXED_KHR
 2:     1  VK_PRESENT_MODE_MAILBOX_KHR
 3:     0  VK_PRESENT_MODE_IMMEDIATE_KHR
```

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Here's What the Vulkan Spec Has to Say About Present Modes, I

305

`VK_PRESENT_MODE_IMMEDIATE_KHR` specifies that the presentation engine does not wait for a vertical blanking period to update the current image, meaning this mode **may** result in visible tearing. No internal queuing of presentation requests is needed, as the requests are applied immediately.

`VK_PRESENT_MODE_MAILBOX_KHR` specifies that the presentation engine waits for the next vertical blanking period to update the current image. Tearing **cannot** be observed. An internal single-entry queue is used to hold pending presentation requests. If the queue is full when a new presentation request is received, the new request replaces the existing entry, and any images associated with the prior entry become available for re-use by the application. One request is removed from the queue and processed during each vertical blanking period in which the queue is non-empty.

`VK_PRESENT_MODE_FIFO_KHR` specifies that the presentation engine waits for the next vertical blanking period to update the current image. Tearing **cannot** be observed. An internal queue is used to hold pending presentation requests. New requests are appended to the end of the queue, and one request is removed from the beginning of the queue and processed during each vertical blanking period in which the queue is non-empty. This is the only value of `presentMode` that is **required** to be supported.

`VK_PRESENT_MODE_FIFO_RELAXED_KHR` specifies that the presentation engine generally waits for the next vertical blanking period to update the current image. If a vertical blanking period has already passed since the last update of the current image then the presentation engine does not wait for another vertical blanking period for the update, meaning this mode **may** result in visible tearing in this case. This mode is useful for reducing visual stutter with an application that will mostly present a new image before the next vertical blanking period, but may occasionally be late, and present a new image just after the next vertical blanking period. An internal queue is used to hold pending presentation requests. New requests are appended to the end of the queue, and one request is removed from the beginning of the queue and processed during or after each vertical blanking period in which the queue is non-empty.

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Here's What the Vulkan Spec Has to Say About Present Modes, II

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`VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` specifies that the presentation engine and application have concurrent access to a single image, which is referred to as a *shared presentable image*. The presentation engine is only required to update the current image after a new presentation request is received. Therefore the application **must** make a presentation request whenever an update is required. However, the presentation engine **may** update the current image at any point, meaning this mode **may** result in visible tearing.

`VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR` specifies that the presentation engine and application have concurrent access to a single image, which is referred to as a *shared presentable image*. The presentation engine periodically updates the current image on its regular refresh cycle. The application is only required to make one initial presentation request, after which the presentation engine **must** update the current image without any need for further presentation requests. The application **can** indicate the image contents have been updated by making a presentation request, but this does not guarantee the timing of when it will be updated. This mode **may** result in visible tearing if rendering to the image is not timed correctly.

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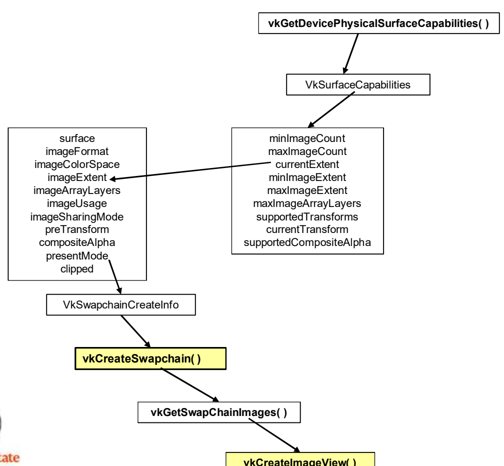
Creating a Swap Chain

307



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Creating a Swap Chain

308

```
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 );
```

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Creating the Swap Chain Images and Image Views

309

```
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

310

```
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 ] );
```

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Rendering into the Swap Chain, II

311

```
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
```

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Rendering into the Swap Chain, III

312

```
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 );
```

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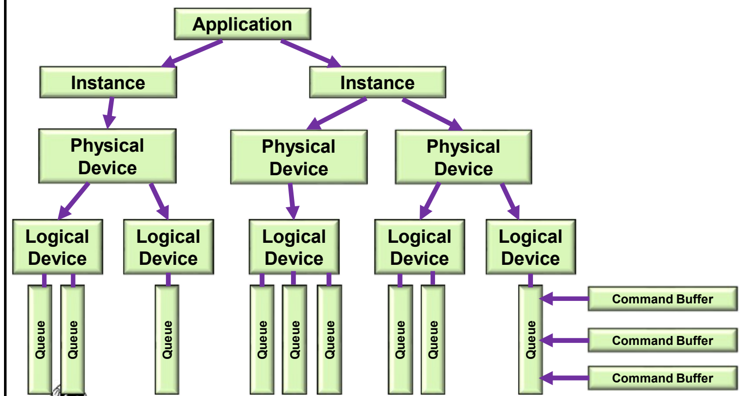
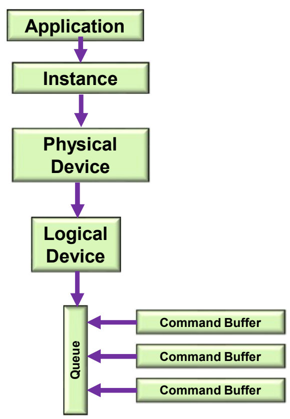
Physical Devices

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

Vulkan: Overall Block Diagram



Vulkan: a More Typical (and Simplified) Block Diagram



Querying the Number of Physical Devices

```
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):

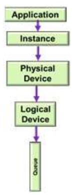
How many total there are — Where to put them

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

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

Vulkan: Identifying the Physical Devices

317




```
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;
}
```

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Which Physical Device to Use, I

318

```
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] );
```

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Which Physical Device to Use, II

319

```
        // 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;
}
```

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Asking About the Physical Device's Features

320

```
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 );
```

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Here's What the NVIDIA A6000 Produced


```
Init03PhysicalDeviceAndGetQueueFamilyProperties

Device  0:
      API version: 4206797
      Driver version: 4206797
      Vendor ID: 0x10de
      Device ID: 0x2230
      Physical Device Type: 2 = (Discrete GPU)
      Device Name: NVIDIA RTX A6000
      Pipeline Cache Size: 72
Device #0 selected ('NVIDIA RTX A6000')

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
```

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Here's What the Intel HD Graphics 520 Produced


```
Init03PhysicalDeviceAndGetQueueFamilyProperties

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
```

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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");
}
```

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Here's What I Got on the A6000's


```
6 Memory Types:
Memory  0:
Memory  1:  DeviceLocal
Memory  2:  HostVisible  HostCoherent
Memory  3:  HostVisible  HostCoherent HostCached
Memory  4:  DeviceLocal HostVisible HostCoherent
Memory  5:  DeviceLocal

4 Memory Heaps:
Heap 0:  size = 0xdbb00000 DeviceLocal
Heap 1:  size = 0xfd504000
Heap 2:  size = 0x0d600000 DeviceLocal
Heap 3:  size = 0x02000000 DeviceLocal
```

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Asking About the Physical Device's Queue Families

325

```
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");
}
```

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Here's What I Got on the A6000's

326

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

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Vulkan.

Logical Devices

Oregon State University

Mike Bailey

mjb@cs.oregonstate.edu

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LogicalDevices.pptx

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Vulkan: Overall Block Diagram

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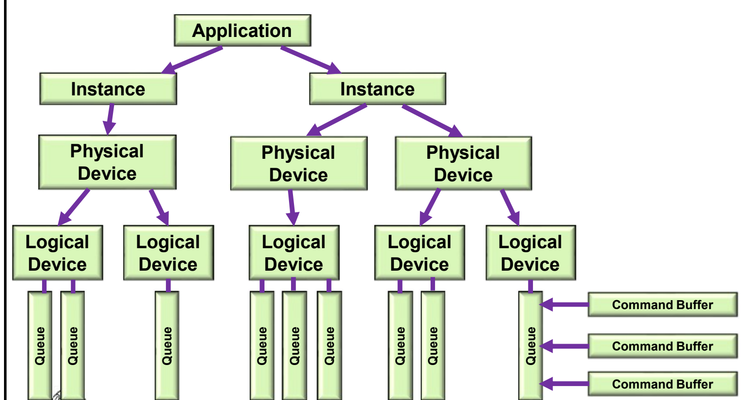

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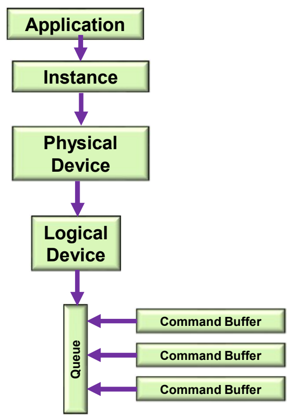
Vulkan: a More Typical (and Simplified) Block Diagram



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);
```

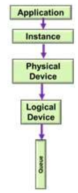

What Device Layers and Extensions are Available


```
4 physical device layers enumerated:

0x004030cd   1  'VK_LAYER_NV_optimus'  'NVIDIA Optimus layer'
      160 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00400033   1  'VK_LAYER_LUNARG_core_validation'  'LunarG Validation Layer'
      0 device extensions enumerated for 'VK_LAYER_LUNARG_core_validation':

0x00400033   1  'VK_LAYER_LUNARG_object_tracker'  'LunarG Validation Layer'
      160 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':

0x00400033   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
      160 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
```

Vulkan: Creating a Logical Device

333

```
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 = sizeof(myDeviceExtensions) / sizeof(char *);
        vdci.ppEnabledExtensionNames = myDeviceExtensions;
        vdci.pEnabledFeatures = IN &PhysicalDeviceFeatures;

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

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Vulkan: Creating the Logical Device's Queue

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

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

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Vulkan.

Layers and Extensions

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

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LayersAndExtensions.pptx

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336

```
vkEnumerateInstanceLayerProperties:

13 instance layers enumerated:
0x00400033   2  'VK_LAYER_LUNARG_api_dump'              'LunarG debug layer'
0x00400033   1  'VK_LAYER_LUNARG_core_validation'       'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_monitor'               'Execution Monitoring Layer'
0x00400033   1  'VK_LAYER_LUNARG_object_tracker'        'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_screenshot'            'LunarG image capture layer'
0x00400033   1  'VK_LAYER_LUNARG_standard_validation'   'LunarG Standard Validation'
0x00400033   1  'VK_LAYER_GOOGLE_threading'             'Google Validation Layer'
0x00400033   1  'VK_LAYER_GOOGLE_unique_objects'        'Google Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_vktrace'               'Vktrace tracing library'
0x00400038   1  'VK_LAYER_NV_optimus'                   'NVIDIA Optimus layer'
0x0040000d   1  'VK_LAYER_NV_nsight'                    'NVIDIA Nsight interception layer'
0x00400000  34  'VK_LAYER_RENDERDOC_Capture'            'Debugging capture layer for RenderDoc'
```

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```
vkEnumerateInstanceExtensionProperties:

11 extensions enumerated:
0x00000008  'VK_EXT_debug_report'
0x00000001  'VK_EXT_display_surface_counter'
0x00000001  'VK_KHR_get_physical_device_properties2'
0x00000001  'VK_KHR_get_surface_capabilities2'
0x00000019  'VK_KHR_surface'
0x00000006  'VK_KHR_win32_surface'
0x00000001  'VK_KHX_device_group_creation'
0x00000001  'VK_KHR_external_fence_capabilities'
0x00000001  'VK_KHR_external_memory_capabilities'
0x00000001  'VK_KHR_external_semaphore_capabilities'
0x00000001  'VK_NV_external_memory_capabilities'
```



```
vkEnumerateDeviceLayerProperties:

3 physical device layers enumerated:
0x00400038   1  'VK_LAYER_NV_optimus'  'NVIDIA Optimus layer'
      0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00400033   1  'VK_LAYER_LUNARG_object_tracker'  'LunarG Validation Layer'
      0 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':

0x00400033   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
      0 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
```



```
const char * instanceLayers[ ] =
{
		//"VK_LAYER_LUNARG_api_dump",   // turn this on if want to see each function call and its arguments (very slow!)
		"VK_LAYER_LUNARG_core_validation",
		"VK_LAYER_LUNARG_object_tracker",
		"VK_LAYER_LUNARG_parameter_validation",
		"VK_LAYER_NV_optimus"
;

const char * instanceExtensions[ ] =
{
		"VK_KHR_surface",
#ifdef _WIN32
		"VK_KHR_win32_surface",
#endif
		"VK_EXT_debug_report",
};
uint32_t numExtensionsWanted = sizeof(instanceExtensions) / sizeof(char *);

// see what layers are available:

vkEnumerateInstanceLayerProperties( &numLayersAvailable, (VkLayerProperties *)nullptr );
InstanceLayers = new VkLayerProperties[ numLayersAvailable ];
result = vkEnumerateInstanceLayerProperties( &numLayersAvailable, InstanceLayers );

// see what extensions are available:

uint32_t numExtensionsAvailable;
vkEnumerateInstanceExtensionProperties( (char *)nullptr, &numExtensionsAvailable, (VkExtensionProperties *)nullptr );
InstanceExtensions = new VkExtensionProperties[ numExtensionsAvailable ];
result = vkEnumerateInstanceExtensionProperties( (char *)nullptr, &numExtensionsAvailable, InstanceExtensions );
```



```
13 instance layers available:
0x00400033   2  'VK_LAYER_LUNARG_api_dump'  'LunarG debug layer'
0x00400033   1  'VK_LAYER_LUNARG_core_validation'  'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_monitor'  'Execution Monitoring Layer'
0x00400033   1  'VK_LAYER_LUNARG_object_tracker'  'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_screenshot'  'LunarG image capture layer'
0x00400033   1  'VK_LAYER_LUNARG_standard_validation'  'LunarG Standard Validation'
0x00400033   1  'VK_LAYER_GOOGLE_threading'  'Google Validation Layer'
0x00400033   1  'VK_LAYER_GOOGLE_unique_objects'  'Google Validation Layer'
0x00400033   1  'VK_LAYER_LUNARG_vktrace'  'Vktrace tracing library'
0x00400038   1  'VK_LAYER_NV_optimus'  'NVIDIA Optimus layer'
0x0040000d   1  'VK_LAYER_NV_nsight'  'NVIDIA Nsight interception layer'
0x00400000  34  'VK_LAYER_RENDERDOC_Capture'  'Debugging capture layer for RenderDoc'
```

```
11 instance extensions available:
0x00000008  'VK_EXT_debug_report'
0x00000001  'VK_EXT_display_surface_counter'
0x00000001  'VK_KHR_get_physical_device_properties2'
0x00000001  'VK_KHR_get_surface_capabilities2'
0x00000019  'VK_KHR_surface'
0x00000006  'VK_KHR_win32_surface'
0x00000001  'VK_KHX_device_group_creation'
0x00000001  'VK_KHR_external_fence_capabilities'
0x00000001  'VK_KHR_external_memory_capabilities'
0x00000001  'VK_KHR_external_semaphore_capabilities'
0x00000001  'VK_NV_external_memory_capabilities'
```



```
 // look for extensions both on the wanted list and the available list:

std::vector<char *> extensionsWantedAndAvailable;
extensionsWantedAndAvailable.clear( );
for( uint32_t wanted = 0; wanted < numExtensionsWanted; wanted++ )
{
		for( uint32_t available = 0; available < numExtensionsAvailable; available++ )
		{
			if( strcmp( instanceExtensions[wanted], InstanceExtensions[available].extensionName ) == 0 )
			{
				extensionsWantedAndAvailable.push_back( InstanceExtensions[available].extensionName );
				break;
			}
		}
}

// create the instance, asking for the layers and extensions:

VkInstanceCreateInfo vici;
		vici.sType = VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO;
		vici.pNext = nullptr;
		vici.flags = 0;
		vici.pApplicationInfo = &vai;
		vici.enabledLayerCount = sizeof(instanceLayers) / sizeof(char *);
		vici.ppEnabledLayerNames = instanceLayers;
		vici.enabledExtensionCount = extensionsWantedAndAvailable.size( );
		vici.ppEnabledExtensionNames = extensionsWantedAndAvailable.data( );;


result = vkCreateInstance( IN &vici, PALLOCATOR, OUT &Instance );
```


Will now ask for 3 instance extensions
- VK_KHR_surface
- VK_KHR_win32_surface
- VK_EXT_debug_report


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

int discreteSelect   = -1;
int integratedSelect = -1;
for( unsigned int i = 0; i < PhysicalDeviceCount; i++ )
{
		VkPhysicalDeviceProperties vpdp;
		vkGetPhysicalDeviceProperties( IN physicalDevices[i], OUT &vpdp );

		// 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;
}
delete[ ] physicalDevices;
```

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```
vkGetPhysicalDeviceProperties( PhysicalDevice, OUT &PhysicalDeviceProperties );

vkGetPhysicalDeviceFeatures( IN PhysicalDevice, OUT &PhysicalDeviceFeatures );

vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_R32G32B32A32_SFLOAT, &vfp );
vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_R8G8B8A8_UNORM, &vfp );
vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_B8G8R8A8_UNORM, &vfp );

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

uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr );
VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT vqfp );

delete[ ] vqfp;
```

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```
VkResult result;
float   queuePriorities[NUM_QUEUES_WANTED] =
{
        1.
};

VkDeviceQueueCreateInfo             vdqci[NUM_QUEUES_WANTED];
        vdqci[0].sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
        vdqci[0].pNext = nullptr;
        vdqci[0].flags = 0;
        vdqci[0].queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );
        vdqci[0].queueCount = 1;            // how many queues to create
        vdqci[0].pQueuePriorities = queuePriorities;    // array of queue priorities [0.,1.]

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_swapchain",
};
```

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```
uint32_t layerCount;
vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, (VkLayerProperties *)nullptr);
VkLayerProperties * deviceLayers = new VkLayerProperties[layerCount];
result = vkEnumerateDeviceLayerProperties( PhysicalDevice, &layerCount, deviceLayers);
for (unsigned int i = 0; i < layerCount; i++)
{
        // 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);

}

delete[ ] deviceLayers;
```

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```
4 physical device layers enumerated:
0x00400038   1  'VK_LAYER_NV_optimus'  'NVIDIA Optimus layer'
vkEnumerateDeviceExtensionProperties: Successful
      0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00400033   1  'VK_LAYER_LUNARG_core_validation'  'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
      0 device extensions enumerated for 'VK_LAYER_LUNARG_core_validation':

0x00400033   1  'VK_LAYER_LUNARG_object_tracker'  'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
      0 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':

0x00400033   1  'VK_LAYER_LUNARG_parameter_validation'  'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
      0 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
```

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Vulkan.

Push Constants

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

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, such as mat4 transformation matrices. This is a good feature, since Vulkan, at times, makes it cumbersome to send changes to the graphics.

By "small", Vulkan specifies that there will be at least 128 bytes that can be used, 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 do not live in their own GPU memory. They are actually included inside the Vulkan graphics pipeline data structure.

Creating a Graphics Pipeline Data Structure

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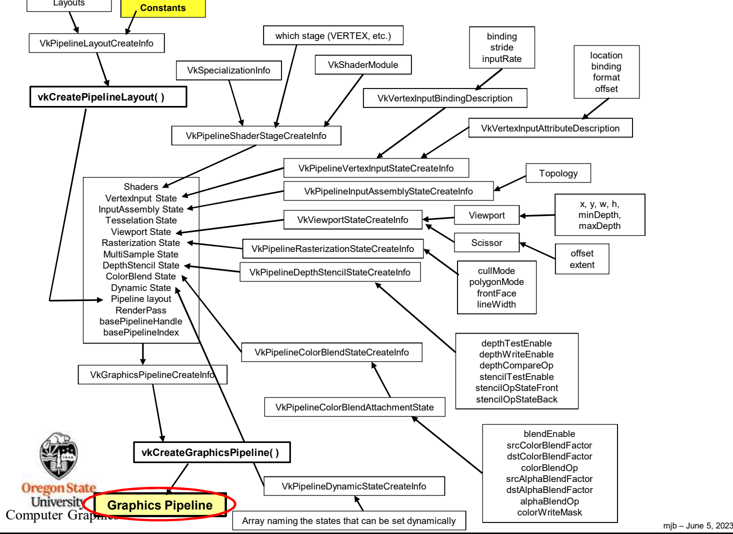

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Push Constants

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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 giving 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_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT

size is in bytes

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

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Setting up the Push Constants for the Graphics Pipeline Data Structure

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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;

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

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A Robotic Example using Push Constants

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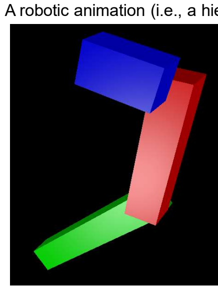
A robotic animation (i.e., a hierarchical transformation system)



Where each arm is represented by:

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

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

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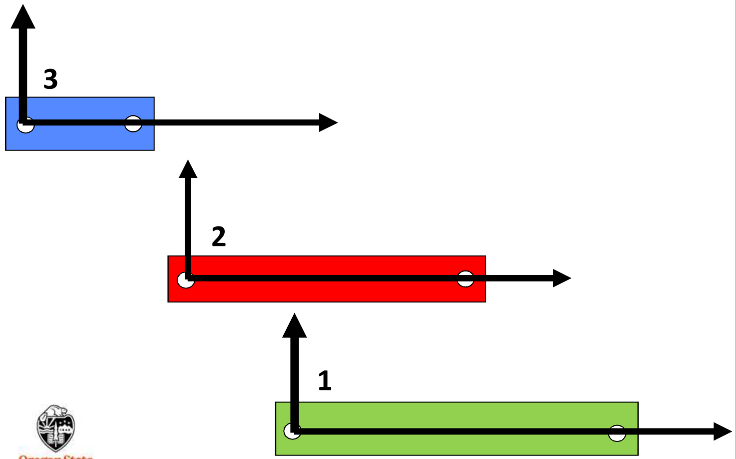
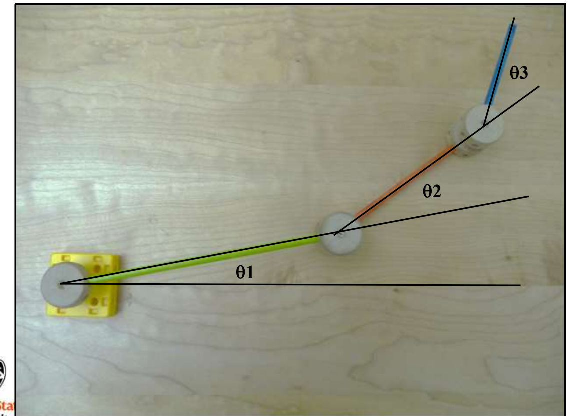
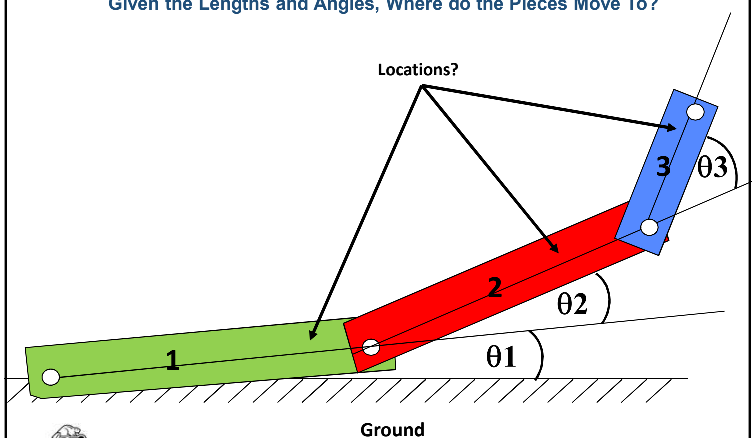
Forward Kinematics: You Start with Separate Pieces, all Defined in their Own Local Coordinate System



Forward Kinematics: Hook the Pieces Together, Change Parameters, and Things Move (All Young Children Understand This)



Forward Kinematics: Given the Lengths and Angles, Where do the Pieces Move To?



Positioning Part #1 With Respect to Ground

1. Rotate by Θ1
2. Translate by $T_{1/G}$

Code it →

$$\left[M_{1/G}\right] = \left[T_{1/G}\right] * \left[R_{\theta 1}\right]$$

← Say it

Why Do We Say it Right-to-Left?

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Write it →

$[M_{1/G}] = [T_{1/G}] * [R_{\theta 1}]$

← Say it

We adopt the convention that the coordinates are multiplied on the right side of the matrix:

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = \begin{bmatrix} A & B & C & D \\ E & F & G & H \\ I & J & K & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

$$\begin{Bmatrix} x' \\ y' \\ z' \\ 1 \end{Bmatrix} = [M_{1/G}] \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix} = [T_{1/G}] * [R_{\theta 1}] * \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

So the right-most transformation in the sequence multiplies the (x,y,z,1) *first* and the left-most transformation multiplies it *last*

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Positioning Part #2 With Respect to Ground

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1. Rotate by Θ2
2. Translate the length of part 1
3. Rotate by Θ 1
4. Translate by $T_{1/G}$

Code it →

$$[M_{2/G}] = [T_{1/G}] * [R_{\theta 1}] * [T_{2/1}] * [R_{\theta 2}]$$

$$[M_{2/G}] = [M_{1/G}] * [M_{2/1}]$$

← Say it

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Positioning Part #3 With Respect to Ground

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1. Rotate by Θ3
2. Translate the length of part 2
3. Rotate by Θ2
4. Translate the length of part 1
5. Rotate by Θ1
6. Translate by $T_{1/G}$

Code it →

$$[M_{3/G}] = [T_{1/G}] * [R_{\theta 1}] * [T_{2/1}] * [R_{\theta 2}] * [T_{3/2}] * [R_{\theta 3}]$$

$$[M_{3/G}] = [M_{1/G}] * [M_{2/1}] * [M_{3/2}]$$

← Say it

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In the *Reset* Function

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

. . .

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

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

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

The constructor **glm::mat4(1.)** produces an identity matrix. The actual transformation matrices will be set in *UpdateScene( )*.

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Set the Push Constant for the Graphics Pipeline Data Structure

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```
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 = 5;
        vplci.pSetLayouts = DescriptorSetLayouts;
        vplci.pushConstantRangeCount = 1;
        vplci.pPushConstantRanges = vpcr;

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

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In the *UpdateScene( )* Function

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```
float rot1 = (float)(2.*M_PI*Time);          // rotation for arm1, in radians
float rot2 = 2.f * rot1;                     // rotation for arm2, in radians
float rot3 = 2.f * rot2;                     // rotation for arm3, in radians

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

glm::mat4 m1g = glm::mat4( 1. );    // identity
m1g = glm::translate(m1g, glm::vec3(0., 0., 0.));
m1g = glm::rotate(m1g, rot1, zaxis);                // [T]*[R]

glm::mat4 m21 = glm::mat4( 1. );    // identity
m21 = glm::translate(m21, glm::vec3(2.*Arm1.armScale, 0., 0.));
m21 = glm::rotate(m21, rot2, zaxis);                // [T]*[R]
m21 = glm::translate(m21, glm::vec3(0., 0., 2.));   // z-offset from previous arm

glm::mat4 m32 = glm::mat4( 1. );    // identity
m32 = glm::translate(m32, glm::vec3(2.*Arm2.armScale, 0., 0.));
m32 = glm::rotate(m32, rot3, zaxis);                // [T]*[R]
m32 = glm::translate(m32, glm::vec3(0., 0., 2.));   // z-offset from previous arm

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

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In the *RenderScene( )* Function

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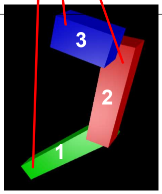
```
VkBuffer buffers[1]   = { MyVertexDataBuffer.buffer };

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 );
```

The strategy is to draw each link using the same vertex buffer, but modified with a unique color, length, and matrix transformation



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In the Vertex Shader

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

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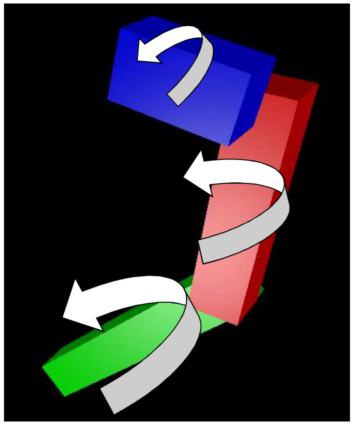
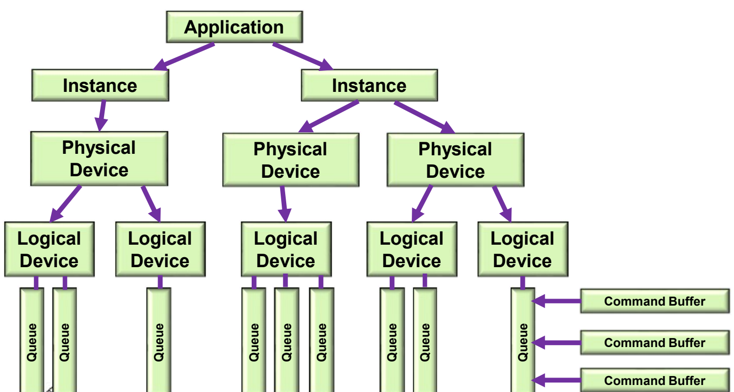


Vulkan

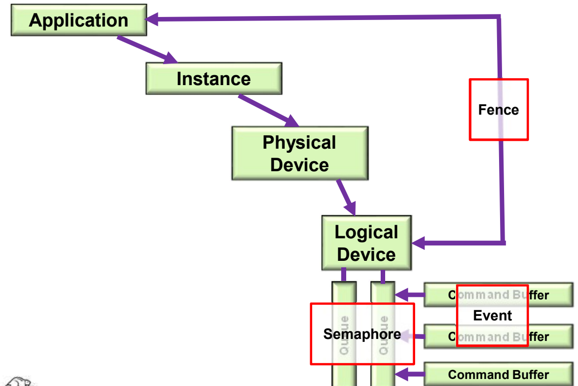
Synchronization

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

Remember the Overall Block Diagram?



Where Synchronization Fits in the Overall Block Diagram



Semaphores

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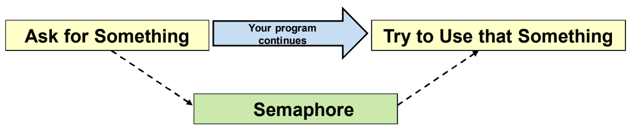
- Indicates that a batch of commends has been processed from a queue. Basically announces "I am finished!".
- You create one and give it to a Vulkan function which sets it. Later on, you tell another Vulkan function to wait for this semaphore to be signaled.
- You don't end up setting, resetting, or checking the semaphore yourself.
- Semaphores must be initialized ("created") before they can be used.



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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 );
```

This doesn't actually do anything with the semaphore – it just sets it up

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Semaphores Example during the Render Loop

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```
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 waitAtBottomOfPipe = 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 = &waitAtBottomOfPipe;
            vsi.commandBufferCount = 1;
            vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
            vsi.signalSemaphoreCount = 0;
            vsi.pSignalSemaphores = (VkSemaphore) nullptr;

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

Set the semaphore

Wait on the semaphore

You do this to wait for an image to be ready to be rendered into

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Fences

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- Used to synchronize CPU-GPU tasks.
- Used when the host needs to wait for the device to complete something big.
- Announces that queue-submitted work is finished.
- You can un-signal, signal, test or block-while-waiting.

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

// blocks the host from executing:
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
```

Set the fence

Wait on the fence(s)

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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 );          // don't present the image until done rendering
```

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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.

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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

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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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Vulkan

Pipeline Barriers

Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

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PipelineBarriers.pptx

Why Do We Need Pipeline Barriers?

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A series of vkCmdxxx( ) calls are meant to run "flat-out", that is, as fast as the Vulkan runtime can get them executing. But, many times, that is not desirable because the output of one command might be needed as the input to a subsequent command.

Pipeline Barriers solve this problem by declaring which stages of the hardware pipeline in subsequent vkCmdyyy( ) calls need to wait until which stages in previous vkCmdxxx( ) calls are completed.

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Potential Memory Race Conditions that Pipeline Barriers can Prevent

384

1. Read-after-Write (R-a-W) – the memory write in one operation starts overwriting the memory that another operation's read needs to use.
2. Write-after-Read (W-a-R) – the memory read in one operation hasn't yet finished before another operation starts overwriting that memory.
3. Write-after-Write (W-a-W) – two operations start overwriting the same memory and the end result is non-deterministic.

Note: there is no problem with Read-after-Read (R-a-R) as no data gets changed.

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

385

vkCmdBeginConditionalRendering
vkCmdBeginDebugUtilsLabel
vkCmdBeginQuery
vkCmdBeginQueryIndexed
vkCmdBeginRendering
vkCmdBeginRenderPass
vkCmdBeginRenderPass2
vkCmdBeginTransformFeedback
vkCmdBindDescriptorSets
vkCmdBindIndexBuffer
vkCmdBindInvocationMask
vkCmdBindPipeline
vkCmdBindPipelineShaderGroup
vkCmdBindShadingRateImage
vkCmdBindTransformFeedbackBuffers
vkCmdBindVertexBuffers
vkCmdBindVertexBuffers2
vkCmdBlitImage

vkCmdBlitImage2
vkCmdBuildAccelerationStructure
vkCmdBuildAccelerationStructuresIndirect
vkCmdBuildAccelerationStructures
vkCmdClearAttachments
vkCmdClearColorImage
vkCmdClearDepthStencilImage
vkCmdCopyAccelerationStructure
vkCmdCopyAccelerationStructureToMemory
vkCmdCopyBuffer
vkCmdCopyBuffer2
vkCmdCopyBufferToImage
vkCmdCopyBufferToImage2
vkCmdCopyImage
vkCmdCopyImage2
vkCmdCopyImageToBuffer
vkCmdCopyImageToBuffer2
vkCmdCopyMemoryToAccelerationStructure

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

386

vkCmdCopyQueryPoolResults
vkCmdCuLaunchKernelX
vkCmdDebugMarkerBegin
vkCmdDebugMarkerEnd
vkCmdDebugMarkerInsert
vkCmdDispatch
vkCmdDispatchBase
vkCmdDispatchIndirect
vkCmdDraw
vkCmdDrawIndexed
vkCmdDrawIndexedIndirect
vkCmdDrawIndexedIndirectCount
vkCmdDrawIndirect
vkCmdDrawIndirectByteCount
vkCmdDrawIndirectCount
vkCmdDrawMeshTasksIndirectCount
vkCmdDrawMeshTasksIndirect
vkCmdDrawMeshTasks

vkCmdDrawMulti
vkCmdDrawMultiIndexed
vkCmdEndConditionalRendering
vkCmdEndDebugUtilsLabel
vkCmdEndQuery
vkCmdEndQueryIndexed
vkCmdEndRendering
vkCmdEndRenderPass
vkCmdEndRenderPass2
vkCmdEndTransformFeedback
vkCmdExecuteCommands
vkCmdExecuteGeneratedCommands
vkCmdFillBuffer
vkCmdInsertDebugUtilsLabel
vkCmdNextSubpass
vkCmdNextSubpass2
vkCmdPipelineBarrier
vkCmdPipelineBarrier2

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

387

vkCmdPreprocessGeneratedCommands
vkCmdPushConstants
vkCmdPushDescriptorSet
vkCmdPushDescriptorSetWithTemplate
vkCmdResetEvent
vkCmdResetEvent2
vkCmdResetQueryPool
vkCmdResolveImage
vkCmdResolveImage2
vkCmdSetBlendConstants
vkCmdSetCheckpoint
vkCmdSetCoarseSampleOrder
vkCmdSetCullMode
vkCmdSetDepthBias
vkCmdSetDepthBiasEnable
vkCmdSetDepthBounds
vkCmdSetDepthBoundsTestEnable
vkCmdSetDepthCompareOp

vkCmdSetDepthTestEnable
vkCmdSetDepthWriteEnable
vkCmdSetDeviceMask
vkCmdSetDiscardRectangle
vkCmdSetEvent
vkCmdSetEvent2
vkCmdSetExclusiveScissor
vkCmdSetFragmentShadingRateEnum
vkCmdSetFragmentShadingRate
vkCmdSetFrontFace
vkCmdSetLineStipple
vkCmdSetLineWidth
vkCmdSetLogicOp
vkCmdSetPatchControlPoints
vkCmdSetPrimitiveRestartEnable
vkCmdSetPrimitiveTopology
vkCmdSetRasterizerDiscardEnable
vkCmdSetRayTracingPipelineStackSize

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

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vkCmdSetSampleLocations
vkCmdSetScissor
vkCmdSetScissorWithCount
vkCmdSetStencilCompareMask
vkCmdSetStencilOp
vkCmdSetStencilReference
vkCmdSetStencilTestEnable
vkCmdSetStencilWriteMask
vkCmdSetVertexInput
vkCmdSetViewport
vkCmdSetViewportShadingRatePalette
vkCmdSetViewportWithCount
vkCmdSetViewportWScaling

vkCmdSubpassShading
vkCmdTraceRaysIndirect2
vkCmdTraceRaysIndirect
vkCmdTraceRays
vkCmdUpdateBuffer
vkCmdWaitEvents
vkCmdWaitEvents2
vkCmdWriteAccelerationStructuresProperties
vkCmdWriteBufferMarker2
vkCmdWriteBufferMarker
vkCmdWriteTimestamp
vkCmdWriteTimestamp2

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vkCmdPipelineBarrier( ) Function Call

A **Pipeline Barrier** is a way to establish a 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
);
```

srcStageMask: Guarantee that *this* pipeline stage is completely done being used by the previous vkCmdxxx before …

dstStageMask: … allowing *this* pipeline stage to be used by the next vkCmdyyy

pMemoryBarriers, pBufferMemoryBarriers, pImageMemoryBarriers: Defines what data we will be blocking on or un-blocking on

The hope is maximize the number of unblocked stages: produce data *early* and consume date *late*

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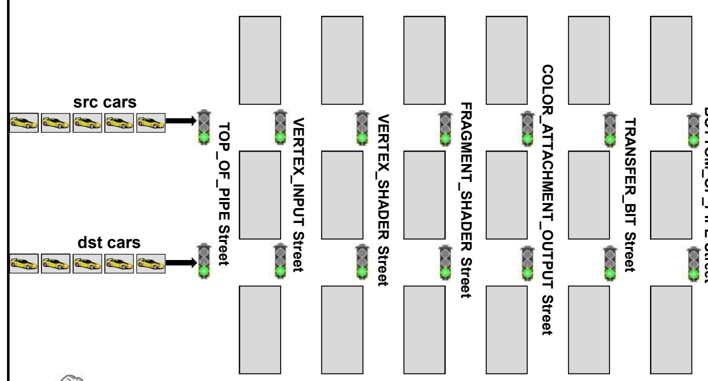
The Scenario



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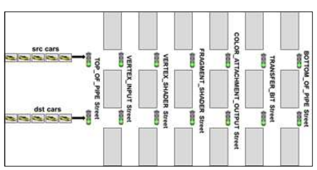
The Scenario

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 ***any car in the src group*** is in that intersection
4. There are connections from those sensors to the traffic lights so that when ***any car in the src group*** is in the intersection, the proper ***dst*** traffic lights will be turned red
5. When the ***last car in the src group*** completely makes it through its intersection, the proper ***dst*** traffic lights are turned back to green
6. The Vulkan command pipeline ordering is this: (1) the **src** cars get released by the previous vkCmdxxx, (2) the pipeline barrier is invoked (which turns some lights red), (3) the dst cars get released by the next vkCmdyyy, (4) the **dst** cars stop at the red light, (5) the **src** cars clear the intersection, (6) the dst lights turn green, (6) the **dst** cars continue.



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Pipeline Stage Masks – Where in the Pipeline is this Memory Data being Generated or Consumed?

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

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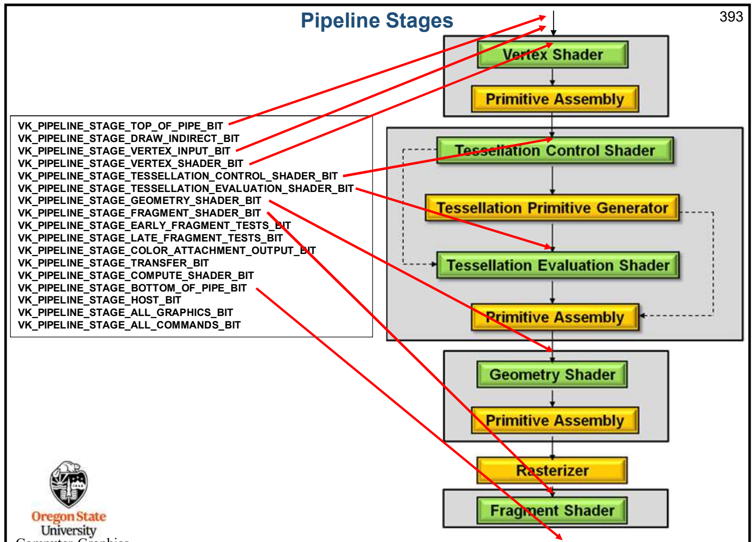
Pipeline Stages



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Access Masks – What are you Interested in Generating or Consuming this Memory for?

- 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

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Pipeline Stages and what Access Operations are Allowed

		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														•	•		

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Access Operations and what Pipeline Stages they can be used In

		1	2	3	4	5	6	7	8	9	10	11	12			
		VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT	VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT	VK_PIPELINE_STAGE_VERTEX_INPUT_BIT	VK_PIPELINE_STAGE_VERTEX_SHADER_BIT	VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT	VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT	VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT	VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT	VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT	VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT	VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT	VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT	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															

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Example #1: Be sure we are done writing an Output image before using it as a Fragment Shader Texture

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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
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, dst
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

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 ← dst
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

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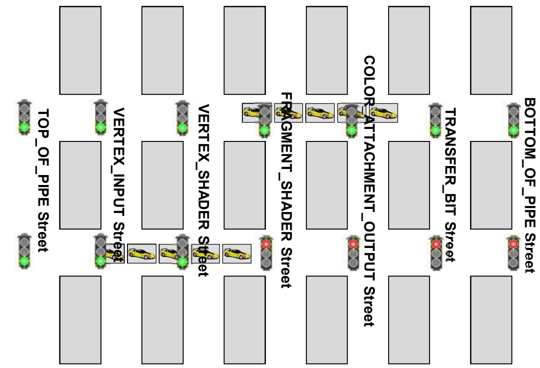
Example #1: The Scenario

398

src cars are generating the image

dst cars are waiting to use that image as a texture



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Example #2: Setting a Pipeline Barrier so the Drawing Waits for the Compute Shader to Finish

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```
VkBufferMemoryBarrier                    vbmb;
        vbmb.sType = VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER;
        vbmb.pNext = nullptr;
        vbmb.srcAccessFlags = VK_ACCESS_SHADER_WRITE_BIT;
        vbmb.dstAccessFlags = VK_ACCESS_SHADER_READ_BIT;
        vbmb.srcQueueFamilyIndex = 0;
        vbmb.dstQueueFamilyIndex = 0;
        vbmb.buffer =
        vbmb.offset = 0;
        vbmb.size = NUM_PARTICLES * sizeof( glm::vec4 );

const uint32 bufferMemoryBarrierCount = 1;

vkCmdPipelineBarrier
(
        commandBuffer,
        VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT,
        VK_PIPELINE_STAGE_VERTEX_SHADER_BIT,
        VK_DEPENDENCY_BY_REGION_BIT,
        0,  nullptr,   bufferMemoryBarrierCount, IN &vbmb,  0,nullptr
);
```

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Example #2: Setting a Pipeline Barrier so the Compute Shader Waits for the Drawing to Finish

400

```
VkBufferMemoryBarrier                    vbmb;
        vbmb.sType = VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER;
        vbmb.pNext = nullptr;
        vbmb.srcAccessFlags = VK_ACCESS_SHADER_WRITE_BIT;
        vbmb.dstAccessFlags = VK_ACCESS_SHADER_READ_BIT;
        vbmb.srcQueueFamilyIndex = 0;
        vbmb.dstQueueFamilyIndex = 0;
        vbmb.buffer =
        vbmb.offset = 0;
        vbmb.size = NUM_PARTICLES * sizeof( glm::vec4 );

const uint32 bufferMemoryBarrierCount = 1;

vkCmdPipelineBarrier
(
        commandBuffer,
        VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT,
        VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT,
        VK_DEPENDENCY_BY_REGION_BIT,
        0,  nullptr,   bufferMemoryBarrierCount, IN &vbmb,    0,     nullptr
);
```

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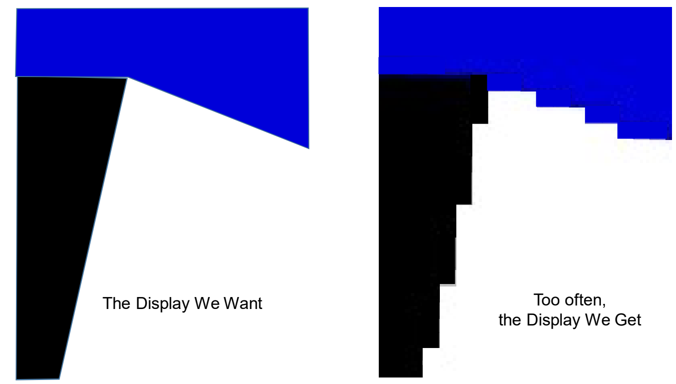
Vulkan

Antialiasing and Multisampling

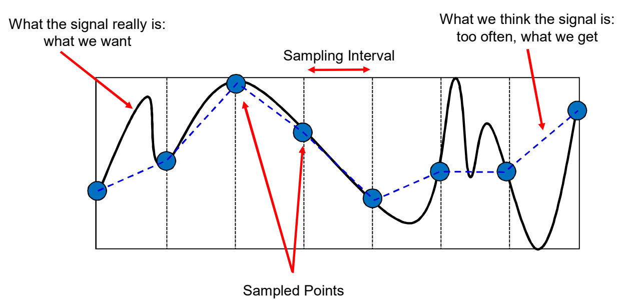
Oregon State University
Mike Bailey
mjb@cs.oregonstate.edu

Aliasing

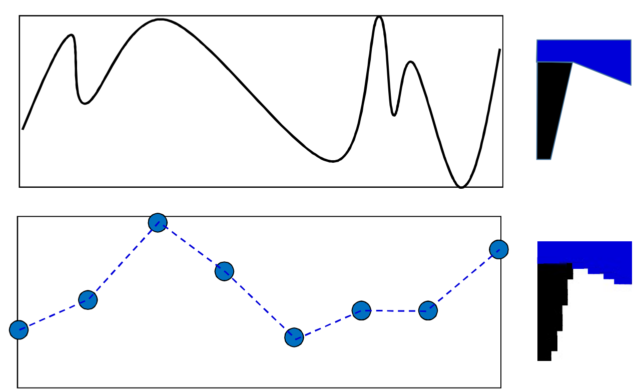


Aliasing

"Aliasing" is a signal-processing term for "under-sampled compared with the frequencies in the signal".

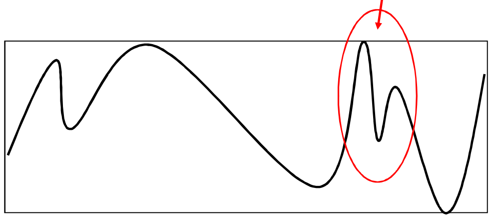


Aliasing



The Nyquist Criterion

"The Nyquist [sampling] rate is twice the maximum component frequency of the function [i.e., signal] being sampled." -- WikiPedia



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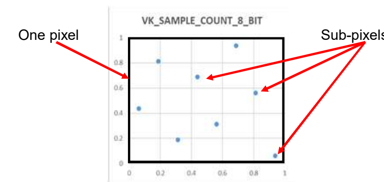
MultiSampling

Oversampling 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 sub-pixels within that pixel that pass the depth and stencil tests. Render the image at each of these sub-pixels. **Results in the best image,but the most rendering time.**



2. **Multisampling**: Pick some number of sub-pixels within that pixel that pass the depth and stencil tests. If any of them pass, then perform a single color render for the one pixel and assign that single color to all the sub-pixels that passed the depth and stencil tests. **Results in a good image, with less rendering time.**

The final step is to average those sub-pixels' colors to produce one final color for this whole pixel. This is called ***resolving*** the pixel.

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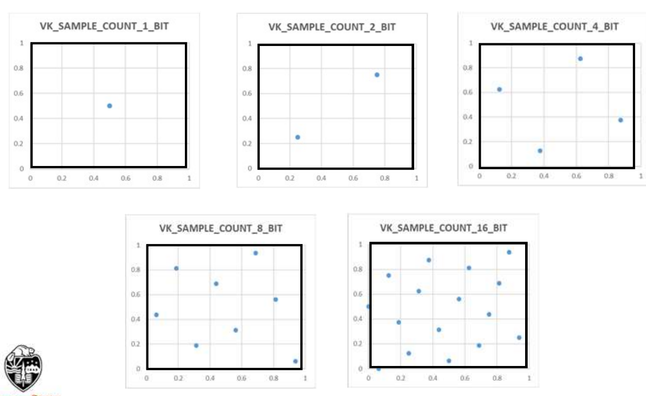
Vulkan Specification Distribution of Sampling Points within a Pixel



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Vulkan Specification Distribution of Sampling Points within a Pixel

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)

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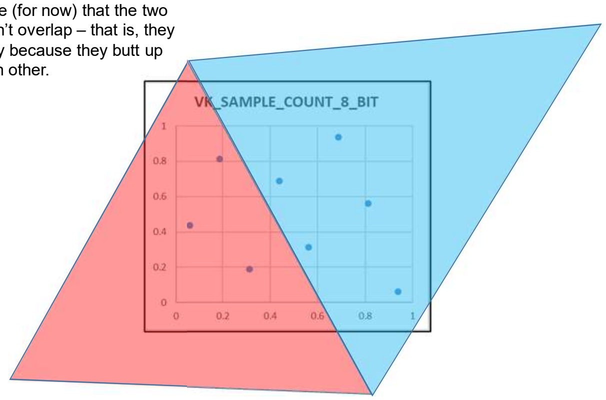
Consider Two Triangles That Pass Through the Same Pixel

Let's assume (for now) that the two triangles don't overlap – that is, they look this way because they butt up against each other.



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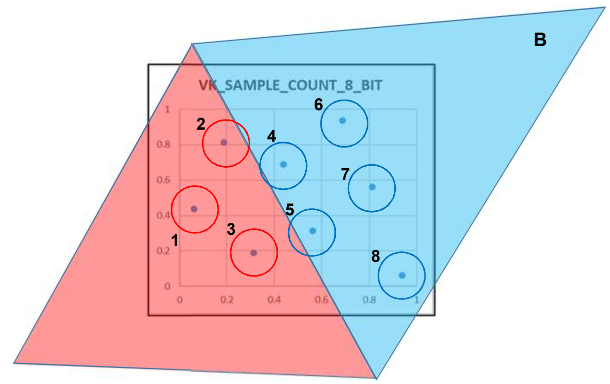
Supersampling



$$Final\ Pixel\ Color = \frac{\sum_{i=1}^{8} Color\ sample\ from\ subpixel_i}{8}$$

 # Fragment Shader calls = 8

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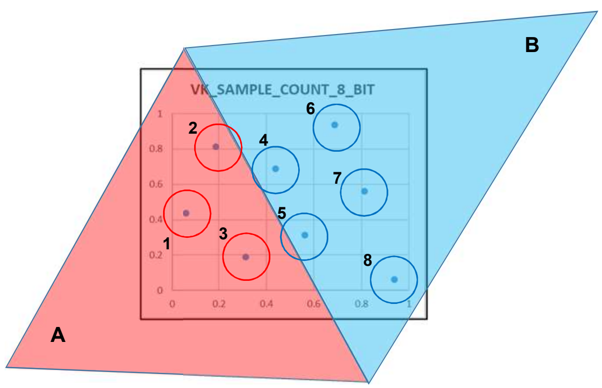
Multisampling



$$Final\ Pixel\ Color = \frac{3 * One\ color\ sample\ from\ A\ +\ 5 * One\ color\ sample\ from\ B}{8}$$

 # Fragment Shader calls = 2

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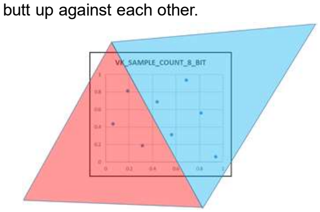
Consider Two Triangles Who Pass Through the Same Pixel

Let's assume (for now) that the two triangles don't overlap – that is, they look this way because they butt up against each other.



Number of Fragment Shader Calls

	Multisampling	Supersampling
Blue fragment shader calls	1	5
Red fragment shader calls	1	3

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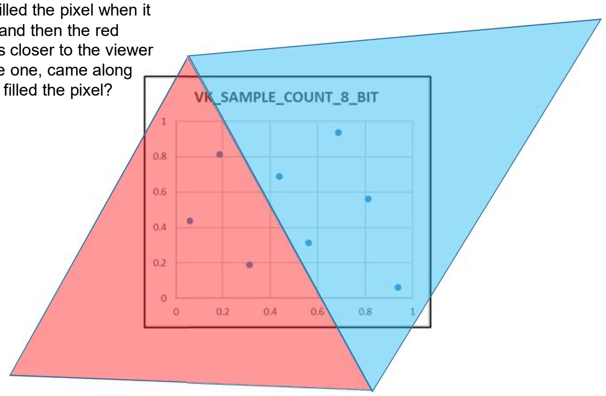
Consider Two Triangles Who Pass Through the Same Pixel

413

Q: What if the blue triangle completely filled the pixel when it was drawn, and then the red one, which is closer to the viewer than the blue one, came along and partially filled the pixel?



A: The ideas are all still the same, but the blue one had to deal with 8 sub-pixels (instead of 5 like before). But, the red triangle came along and obsoleted 3 of those blue sub-pixels. Note that the "resolved" image will still turn out the same as before.

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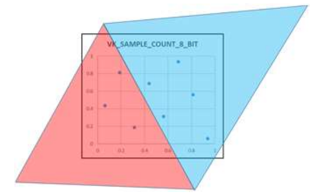
Consider Two Triangles Who Pass Through the Same Pixel

414

What if the blue triangle completely filled the pixel when it was drawn, and then the red one, which is closer to the viewer than the blue one, came along and partially filled the pixel?



Number of Fragment Shader Calls

	Multisampling	Supersampling
Blue fragment shader calls	1	8
Red fragment shader calls	1	3

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Setting up the Image

415

```
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

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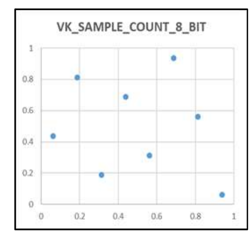
Setting up the Image

416

```
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

417

```
VkAttachmentDescription          vad[2];
        vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;              // 24-bit color
        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;          // 32-bit floating-point depth
        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;
```

to next slide

Com

Setting up the Image

418

```
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 );
```

from previous slide

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Resolving the Image: Converting the Multisampled Image to a VK_SAMPLE_COUNT_1_BIT image

419

```
VlOffset3D                       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, IN &vir );
```

For the *ImageLayout, use VK_IMAGE_LAYOUT_GENERAL

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420

Vulkan.

Multipass Rendering

Oregon State University

Mike Bailey

mjb@cs.oregonstate.edu

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MultiPass.pptx

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Multipass Rendering uses Attachments -- What is a Vulkan *Attachment* Anyway?

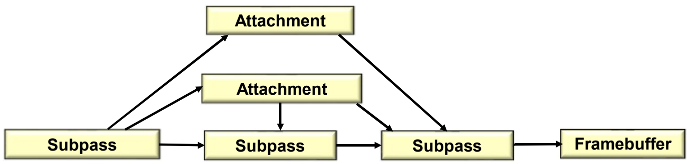
421

"[An attachment is] an image associated with a renderpass that can be used as the input or output of one or more of its subpasses."

-- Vulkan Programming Guide

An attachment can be written to, read from, or both.

For example:



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What is an Example of Wanting to do This?

422

There is a process in computer graphics called ***Deferred Rendering***. The idea is that a game-quality fragment shader takes a long time (relatively) to execute, but, with all the 3D scene detail, a lot of the rendered fragments are going to get z-buffered away anyhow. So, why did we invoke the fragment shaders so many times when we didn't need to?

Here's the trick:

Let's create a grossly simple fragment shader that writes out (into multiple framebuffers) each fragment's:

- position (x,y,z)
- normal (nx,ny,nz)
- material color (r,g,b)
- texture coordinates (s,t)

As well as:

- the current light source positions and colors
- the current eye position

When we write these out, the final framebuffers will contain just information for the pixels that *can be seen*. We then make a second pass running the expensive lighting model *just* for those pixels. This known as the ***G-buffer Algorithm***.

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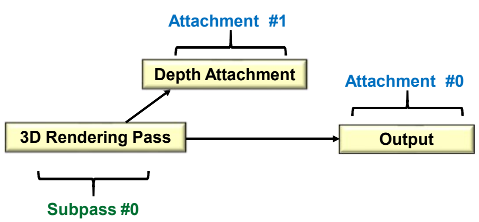
Back in Our Single-pass Days

423

So far, we've only performed single-pass rendering, within a single Vulkan RenderPass.



Here comes a quick reminder of how we did that.

Afterwards, we will extend it.

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Back in Our Single-pass Days, I

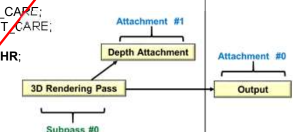
424

```
VkAttachmentDescription                vad [2 ];
        vad[0].flags = 0;
        vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
        vad[0].samples = VK_SAMPLE_COUNT_1_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[1].flags = 0;
        vad[1].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
        vad[1].samples = VK_SAMPLE_COUNT_1_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;

    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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Back in Our Single-pass Days, II

425

```
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 = &vsd;
        vrpci.dependencyCount = 0;
        vrpci.pDependencies = (VkSubpassDependency *)nullptr;

result = vkCreateRenderPass( LogicalDevice, IN &vrpci, PALLOCATOR, OUT &RenderPass );
```

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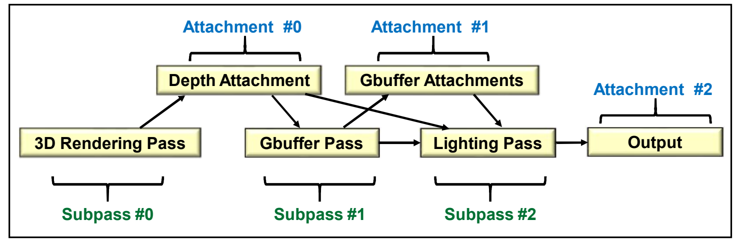
Multipass Rendering

426

So far, we've only performed single-pass rendering, but within a single Vulkan RenderPass, we can also have several subpasses, each of which is feeding information to the next subpass or subpasses. In this case, we will look at following up a 3D rendering with Gbuffer operations.

The Gbuffer algorithm is where you render just the depth in the first pass and use that to limit the number of calls to time-consuming fragment shaders in the second or subsequent passes.



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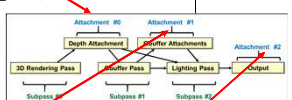
Multipass, I

427

```
VkAttachmentDescription                 vad [ 3 ];
        vad[0].flags = 0;
        vad[0].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
        vad[0].samples = VK_SAMPLE_COUNT_1_BIT;
        vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[0].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        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_UNDEFINED;

        vad[1].flags = 0;
        vad[1].format = VK_FORMAT_R32G32B32A32_UINT;
        vad[1].samples = VK_SAMPLE_COUNT_1_BIT;
        vad[1].loadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        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_UNDEFINED;

        vad[2].flags = 0;
        vad[2].format = VK_FORMAT_R8G8B8A8_SRGB;
        vad[2].samples = VK_SAMPLE_COUNT_1_BIT;
        vad[2].loadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[2].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
        vad[2].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad20].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[2].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[2].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC;
```



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Multipass, II

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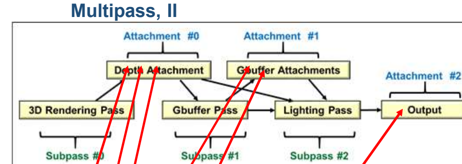


```
VkAttachmentReference                   depthOutput;
        depthOutput.attachment = 0;             // depth
        depthOutput.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   gbufferInput;
        gBufferInput.attachment = 0;            // depth
        gBufferInput.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   gbufferOutput;
        gBufferOutput.attachment = 1;           // gbuffer
        gBufferOutput.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   lightingInput[2];
        lightingInput[0].attachment = 0;        // depth
        lightingInput[0].layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL;
        lightingInput[1].attachment = 1;        // gbuffer
        lightingInput[1].layout = VK_IMAGE_LAYOUT_SHADER_READ_OPTIMAL;

VkAttachmentReference                   lightingOutput;
        lightingOutput.attachment = 2;          // color rendering
        lightingOutput = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;
```

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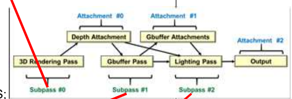
Multipass, III


```
VkSubpassDescription                    vsd[3];
        vsd[0].flags = 0;
        vsd[0].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd[0].inputAttachmentCount = 0;
        vsd[0].pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd[0].colorAttachmentCount = 0;
        vsd[0].pColorAttachments = (VkAttachmentReference *)nullptr;;
        vsd[0].pResolveAttachments = (VkAttachmentReference *)nullptr;
        vsd[0].pDepthStencilAttachment = &depthOutput;
        vsd[0].preserveAttachmentCount = 0;
        vsd[0].pPreserveAttachments = (uint32_t *) nullptr;

        vsd[1].flags = 0;
        vsd[1].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd[1].inputAttachmentCount = 0;
        vsd[1].pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd[1].colorAttachmentCount = 1;
        vsd[1].pColorAttachments = &gBufferOutput;
        vsd[1].pResolveAttachments = (VkAttachmentReference *)nullptr;
        vsd[1].pDepthStencilAttachment = (VkAttachmentReference *) nullptr;
        vsd[1].preserveAttachmentCount = 0;
        vsd[1].pPreserveAttachments = (uint32_t *) nullptr;

        vsd[2].flags = 0;
        vsd[2].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd[2].inputAttachmentCount = 2;
        vsd[2].pInputAttachments = &lightingInput[0];
        vsd[2].colorAttachmentCount = 1;
        vsd[2].pColorAttachments = &lightingOutput;
        vsd[2].pResolveAttachments = (VkAttachmentReference *)nullptr;
        vsd[2].pDepthStencilAttachment = (VkAttachmentReference *) nullptr;
        vsd[2].preserveAttachmentCount = 0;
        vsd[2].pPreserveAttachments = (uint32_t *) nullptr
```



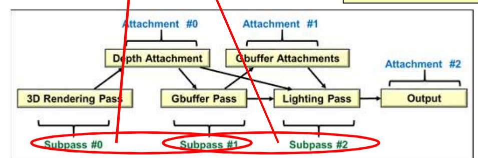
Computer Graphics

Multipass, IV


```
VkSubpassDependency                     vsdp[2];
        vsdp[0].srcSubpass = 0;                         // depth rendering →
        vsdp[0].dstSubpass = 1;                         // → gbuffer
        vsdp[0].srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT;
        vsdp[0].dstStageMask = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
        vsdp[0].srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT;
        vsdp[0].dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
        vsdp[0].dependencyFlags = VK_DEPENDENCY_BY_REGION_BIT;

        vsdp[1].srcSubpass = 1;                         // gbuffer →
        vsdp[1].dstSubpass = 2;                         // → color output
        vsdp[1].srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT;
        vsdp[1].dstStageMask = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
        vsdp[1].srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT;
        vsdp[1].dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
        vsdp[1].dependencyFlags = VK_DEPENDENCY_BY_REGION_BIT;
```

Notice how similar this is to creating a **Directed Acyclic Graph** (DAG).



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Multipass, V


```
VkRenderPassCreateInfo                  vrpci;
        vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
        vrpci.pNext = nullptr;
        vrpci.flags = 0;
        vrpci.attachmentCount = 3;      // depth, gbuffer, output
        vrpci.pAttachments = vad;
        vrpci.subpassCount = 3;
        vrpci.pSubpasses = vsd;
        vrpci.dependencyCount = 2;
        vrpci.pDependencies = vsdp;

result = vkCreateRenderPass( LogicalDevice, IN &vrpci, PALLOCATOR, OUT &RenderPass );
```

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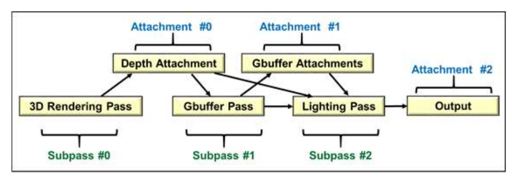
Multipass, VI


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

// subpass #0 is automatically started here

vkCmdBindPipeline( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS,
        GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *) nullptr );
vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, vBuffers, offsets );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );
. . .
vkCmdNextSubpass(CommandBuffers[nextImageIndex], VK_SUBPASS_CONTENTS_INLINE );
// subpass #1 is started here
. . .
vkCmdNextSubpass(CommandBuffers[nextImageIndex], VK_SUBPASS_CONTENTS_INLINE );
// subpass #2 is started here
. . .
vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );
```



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