Introduction to the Vulkan Graphics API

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

Ongoing Notes and Code

The notes and code presented here are constantly being updated.

Go to:

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

for all the latest versions.

3

Introduction to the Vulkan Graphics API

SIGGRAPH Asia '18 Courses, December 4-7, 2018, Tokyo, Japan
ACM 978-1-4503-6026-5/18/12 DOI 10.1145/3277644.3277800

4

Introduction

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

Acknowledgements

5

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!

Oregon State University

Ali Alsalehy	Alan Neads
Natasha Anisimova	Raja Petroff
Jianchang Bi	Bei Rong
Christopher Cooper	Lawrence Roy
Richard Cunard	Lily Shellhammer
Braxton Cuneo	Hannah Solorzano
Benjamin Fields	Jian Tang
Trevor Hammock	Glenn Upthagrove
Zach Lerew	Logan Wingard
Victor Li	

Second, thanks to NVIDIA! The GeForce 1080ti cards are what made this course possible.

NVIDIA

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

KHRONOS GROUP

SIGGRAPH ASIA 2018 TOKYO

mjb – September 19, 2018

What Prompted the Move to Vulkan?

6

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.

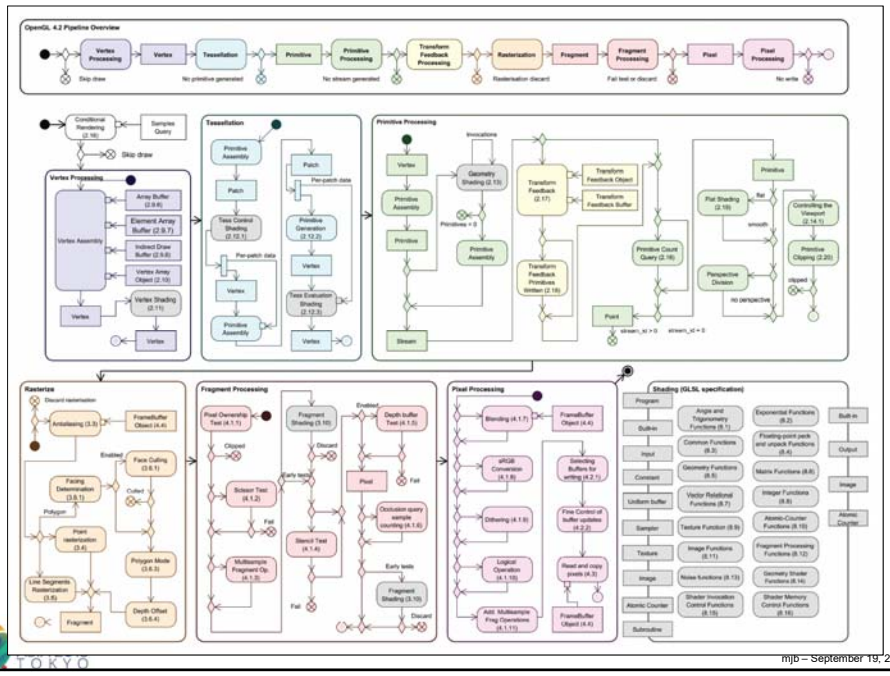
As an aside, the Vulkan development effort was originally called **glNext**, which created the false impression that this was a replacement for OpenGL. It's not.

SIGGRAPH ASIA 2018 TOKYO

mjb – September 19, 2018

OpenGL 4.2 Pipeline Flowchart

7



Why is it so important to keep the GPU Busy?

8

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?

9

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)

Why Name it after the God of the Forge?

10

Who is the Khronos Group?

11

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.

Playing "Where's Waldo" with Khronos Membership

12

Who's Been Specifically Working on Vulkan?

13

Vulkan

14

- Largely 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 – Vulkan can crash
- Goal: higher single-threaded performance than OpenGL can deliver
- Goal: able to do multithreaded graphics
- Goal: able to handle tiled rendering

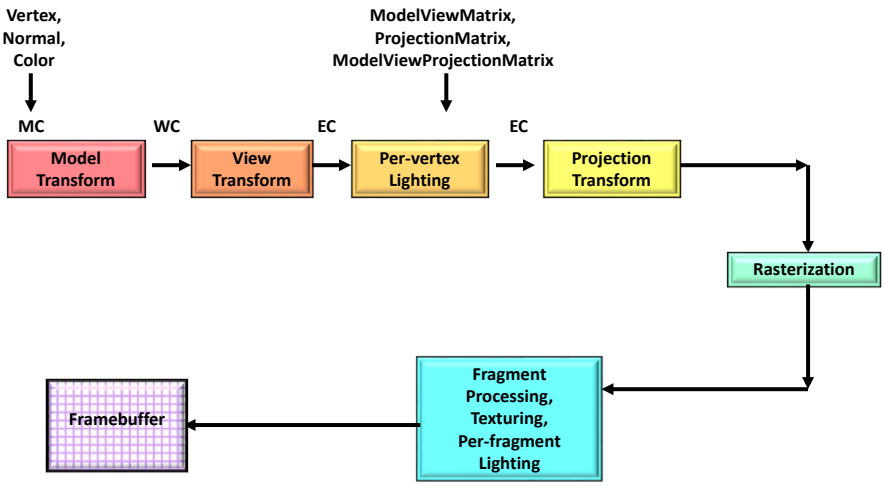
Vulkan Differences from OpenGL

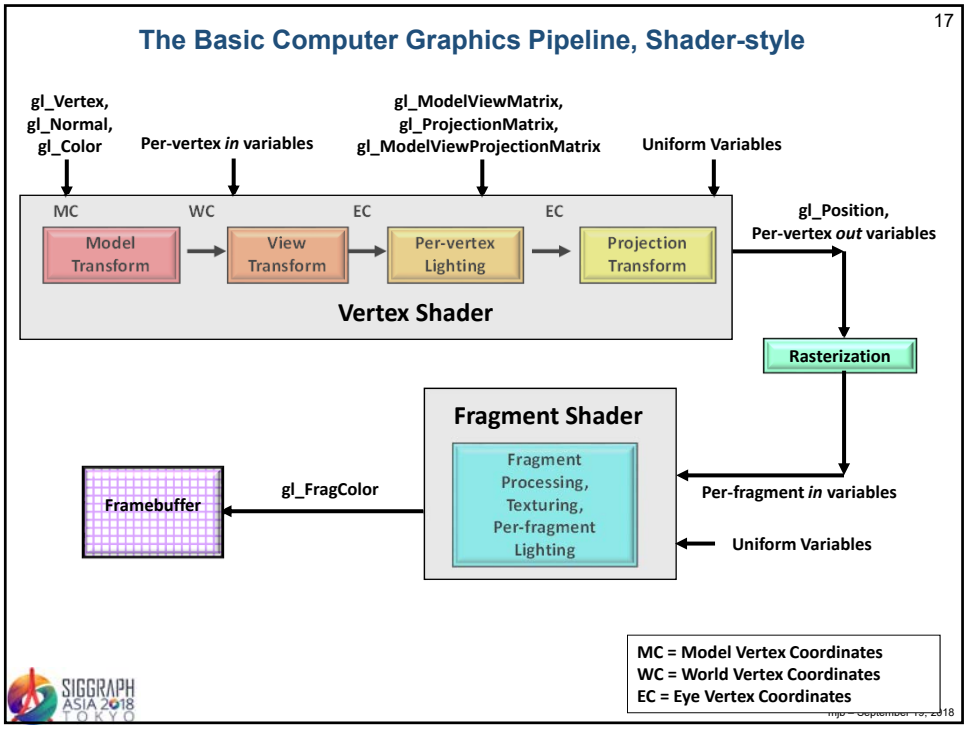
15

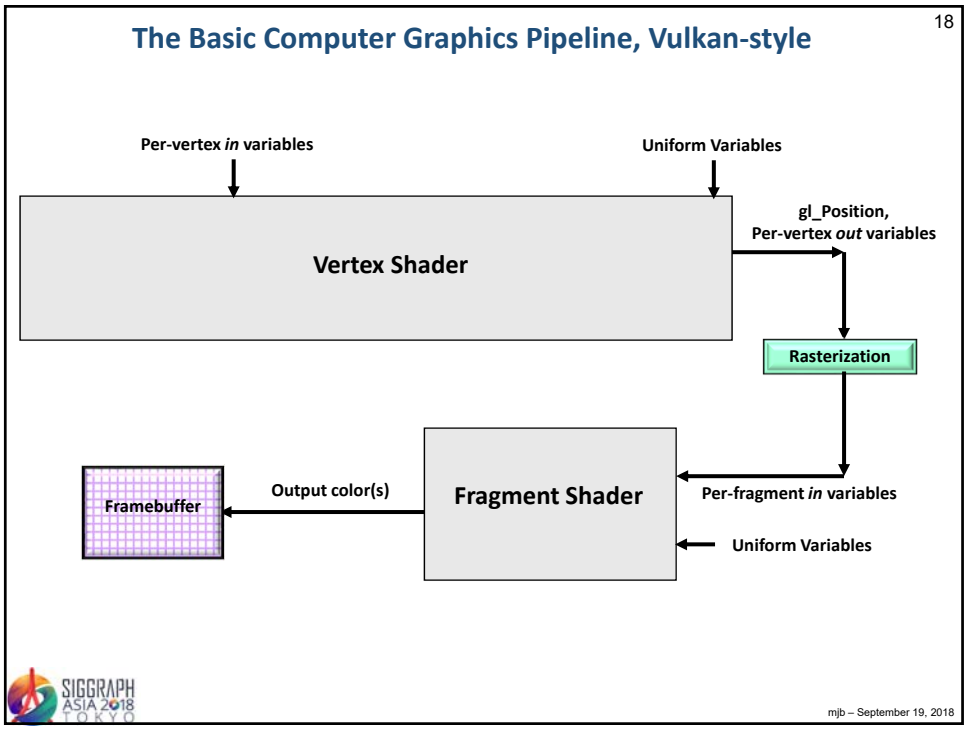
- More low-level information must be provided (by you!) in the application, rather than the driver
- Screen coordinate system is Y-down
- No “current state”, at least not one maintained by the driver
- All of the things that we have talked about being ***deprecated*** in OpenGL are *really* **deprecated**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

The Basic OpenGL Computer Graphics Pipeline, OpenGL-style

16




17
The Basic Computer Graphics Pipeline, Shader-style
gl_Vertex,
gl_Normal,
gl_Color
Per-vertex in variables
gl_ModelViewMatrix,
gl_ProjectionMatrix,
gl_ModelViewProjectionMatrix
Uniform Variables
MC
WC
EC
EC
Model Transform
View Transform
Per-vertex Lighting
Projection Transform
Vertex Shader
gl_Position,
Per-vertex out variables
Rasterization
Fragment Shader
Fragment Processing, Texturing, Per-fragment Lighting
Framebuffer
gl_FragColor
Per-fragment in variables
Uniform Variables
MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates
SIGGRAPH ASIA 2018 TOKYO


18
The Basic Computer Graphics Pipeline, Vulkan-style
Per-vertex in variables
Uniform Variables
Vertex Shader
gl_Position,
Per-vertex out variables
Rasterization
Framebuffer
Output color(s)
Fragment Shader
Per-fragment in variables
Uniform Variables
SIGGRAPH ASIA 2018 TOKYO
mjb – September 19, 2018

A Complete API Redesign

19

OpenGL.	Vulkan™
Originally architected for graphics workstations with direct renderers and split memory	Matches architecture of modern platforms including mobile platforms with unified memory, tiled rendering
Driver does lots of work: state validation, dependency tracking, error checking. Limits and randomizes performance	Explicit API – the application has direct, predictable control over the operation of the GPU
Threading model doesn't enable generation of graphics commands in parallel to command execution	Multi-core friendly with multiple command buffers that can be created in parallel
Syntax evolved over twenty years – complex API choices can obscure optimal performance path	Removing legacy requirements simplifies API design, reduces specification size and enables clear usage guidance
Shader language compiler built into driver. Only GLSL supported. Have to ship shader source	SPIR-V as compiler target simplifies driver and enables front-end language flexibility and reliability
Despite conformance testing, developers must often handle implementation variability between vendors	Simpler API, common language front-ends, more rigorous testing increase cross vendor functional/performance portability

Khronos Group

Moving part of the driver into the application

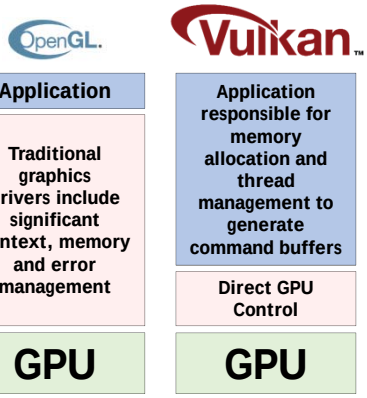
20

Complex drivers lead to driver overhead and cross vendor unpredictability

Error management is always active

Driver processes full shading language source

Separate APIs for desktop and mobile markets



Khronos Group

Simpler drivers for low-overhead efficiency and cross vendor portability

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

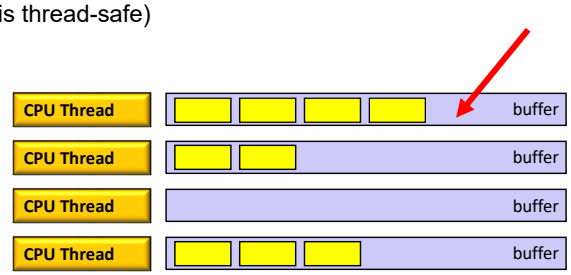
Run-time only has to ingest SPIR-V intermediate language

Unified API for mobile, desktop, console and embedded platforms

Vulkan Highlights: Command Buffers

21

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



Vulkan Highlights: Pipelines

22

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

Querying the Number of Things

23

```
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 Code has a Distinct "Style"

24

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

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

VkMemoryRequirements        vmr;

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

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

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

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

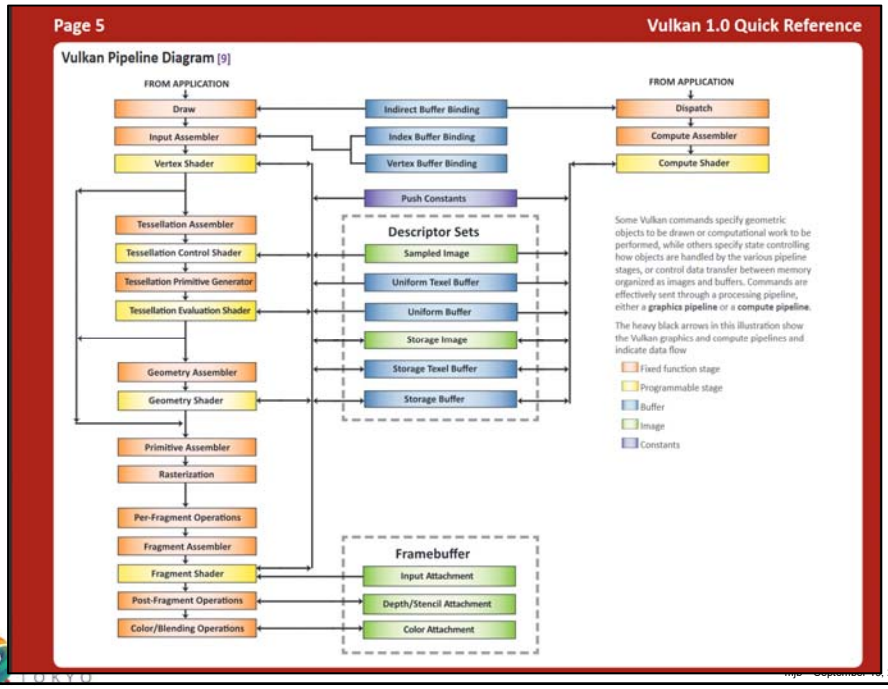
Vulkan Quick Reference Card

25

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

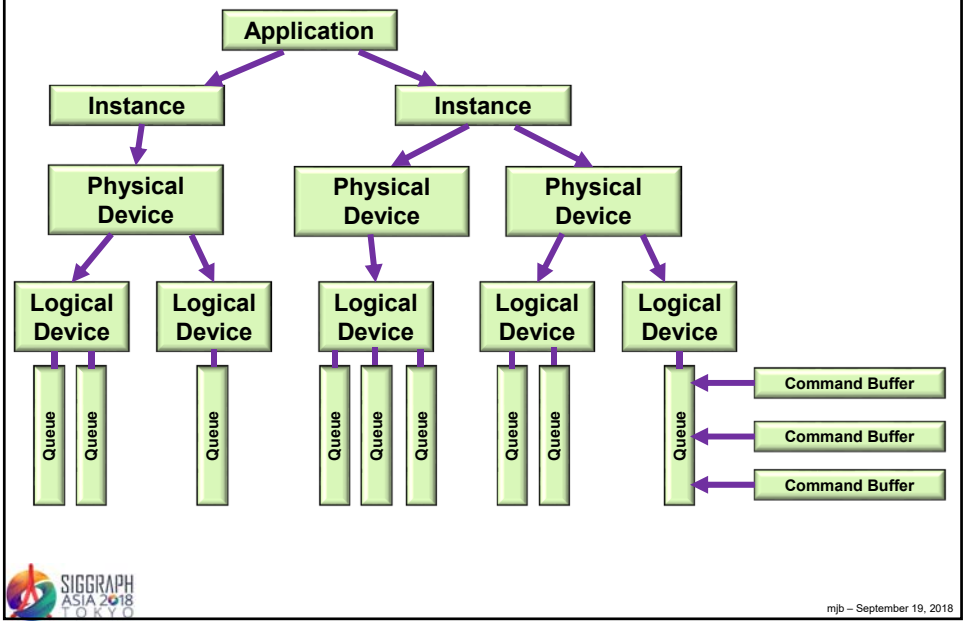
Vulkan Quick Reference Card

26



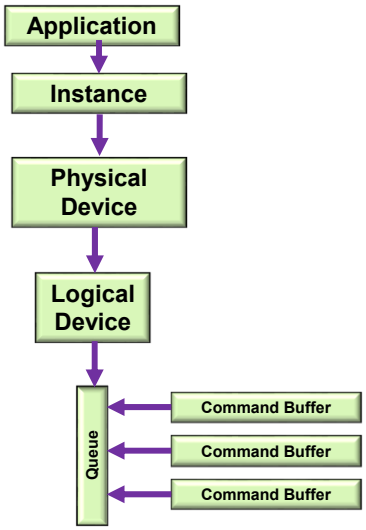
Vulkan Highlights: Overall Block Diagram

27



Vulkan Highlights: a More Typical Block Diagram

28



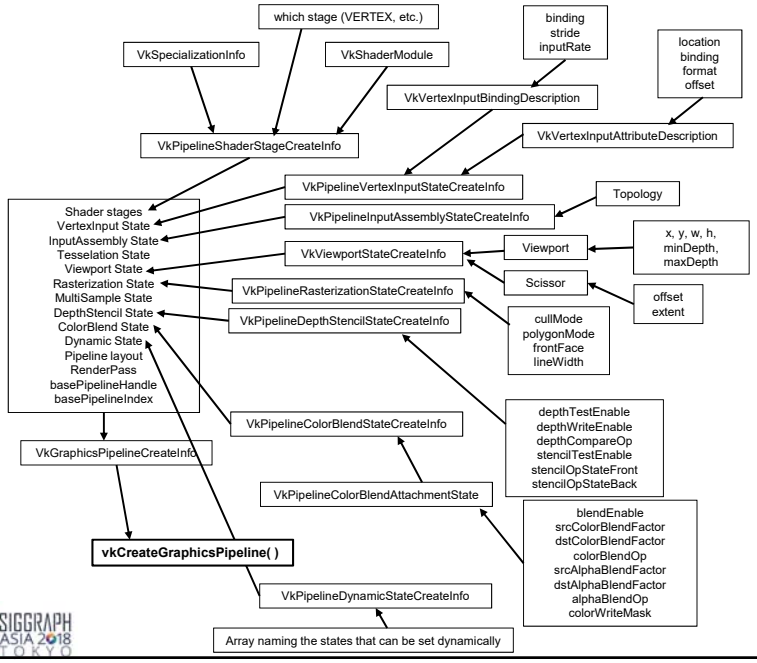
Steps in Creating Graphics using Vulkan

29

1. Create the 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- …

Vulkan: Creating a Pipeline

30



Vulkan GPU Memory

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

From the OpenGL Shader Storage Buffer notes:

```
glGenBuffers( 1, &posSSbo);
glBindBuffer( GL_SHADER_STORAGE_BUFFER, posSSbo );
glBufferData( GL_SHADER_STORAGE_BUFFER, NUM_PARTICLES * sizeof(struct pos), NULL, GL_STATIC_DRAW );

GLint bufMask = GL_MAP_WRITE_BIT | GL_MAP_INVALIDATE_BUFFER_BIT ;      // the invalidate makes a big difference when re-writing

struct pos *points = (struct pos *) glMapBufferRange( GL_SHADER_STORAGE_BUFFER, 0, NUM_PARTICLES * sizeof(struct pos), bufMask );
```

Vulkan Render Passes

- 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
- Multiple render passes can be merged

Vulkan Compute Shaders

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

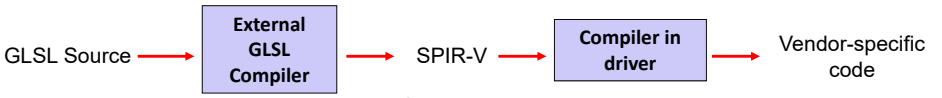
Vulkan Synchronization

- Vulkan tries to run “flat out”
- Therefore, synchronization is the responsibility of the application
- Events can be set, polled, and waited for (much like OpenCL)
- Vulkan does not ever lock – that’s the application’s job
- Threads can concurrently read from the same object
- Threads can concurrently write to different objects

Vulkan Shaders

35

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

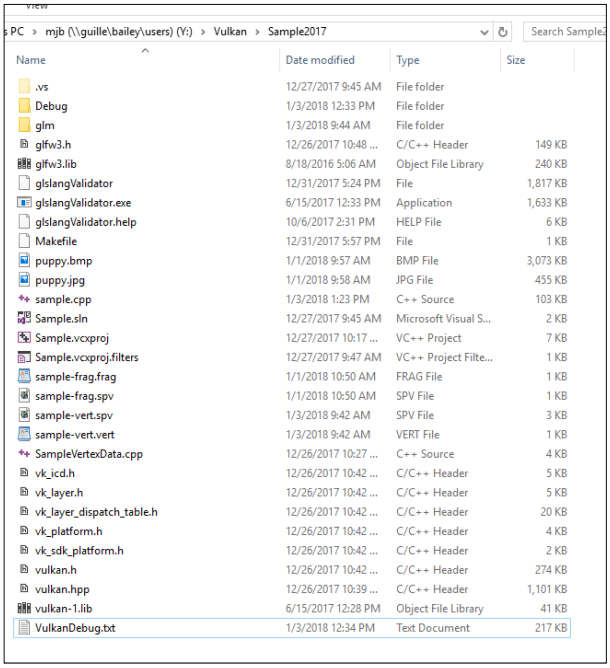


Advantages:

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 Sample2017.zip File Contains This

36



Vertex Buffers

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

What is a Vertex Buffer?

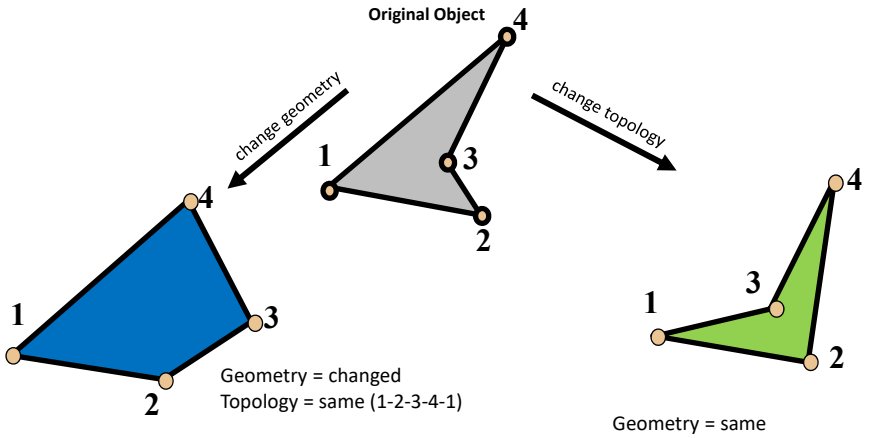
Vertex Buffers are how you draw things in Vulkan. They are very much like Vertex Buffer Objects in OpenGL, but more detail is exposed to you (a lot more…).

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 . . .

39

Geometry vs. Topology



Geometry:

Where things are (e.g., coordinates)

Topology:

How things are connected

40

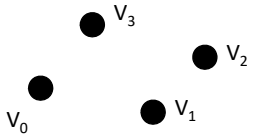
Vulkan Topologies

```
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;
```

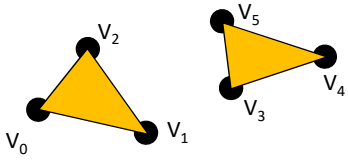
41

Vulkan Topologies – Some OpenGL Topologies are Missing

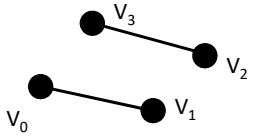
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



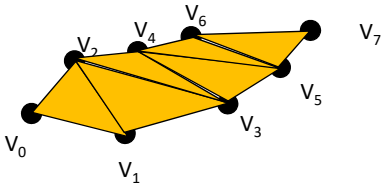
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



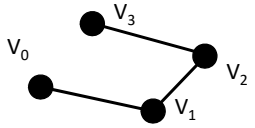
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



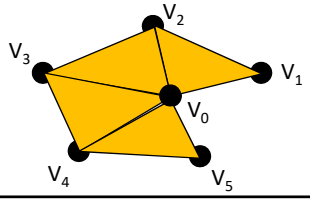
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



42

OpenGL Topologies – Polygon Requirements

Polygons must be:

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

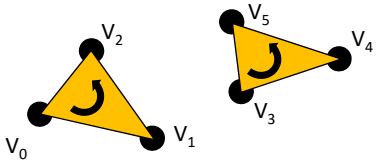
43

Vulkan Topologies – Requirements and Orientation

Polygons must be:
- **Convex** and
- **Planar**

Polygons are traditionally:
- **CCW when viewed from outside the solid object**

GL_TRIANGLES

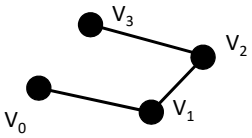


It's not absolutely necessary, but there are possible optimizations if you are ***consistent***

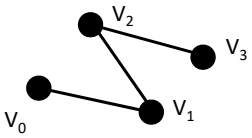
44

OpenGL Topologies – Vertex Order Matters

VK_LINE_STRIP



VK_LINE_STRIP

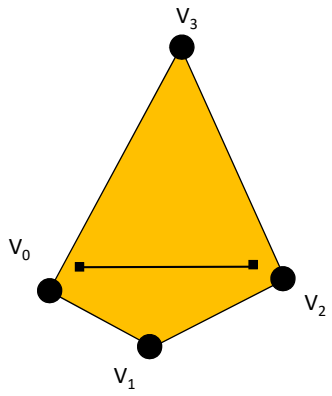


45

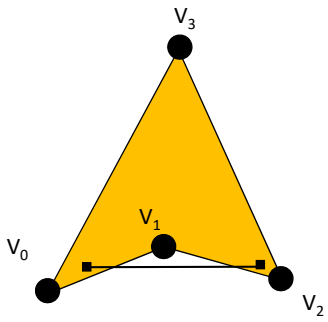
What does "Convex Polygon" Mean?

We can 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.

Convex



Not Convex

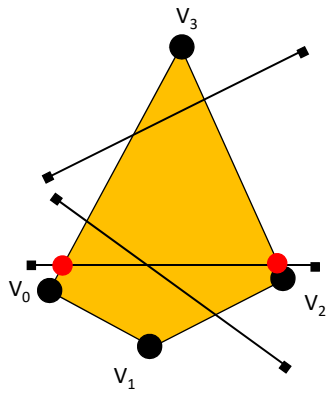


46

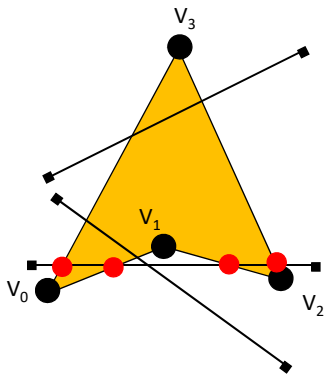
Why is there a Requirement for Polygons to be Convex?

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

Convex



Not Convex

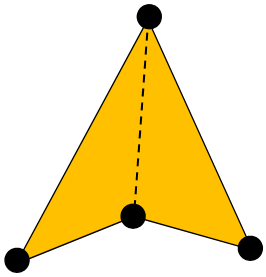


47

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

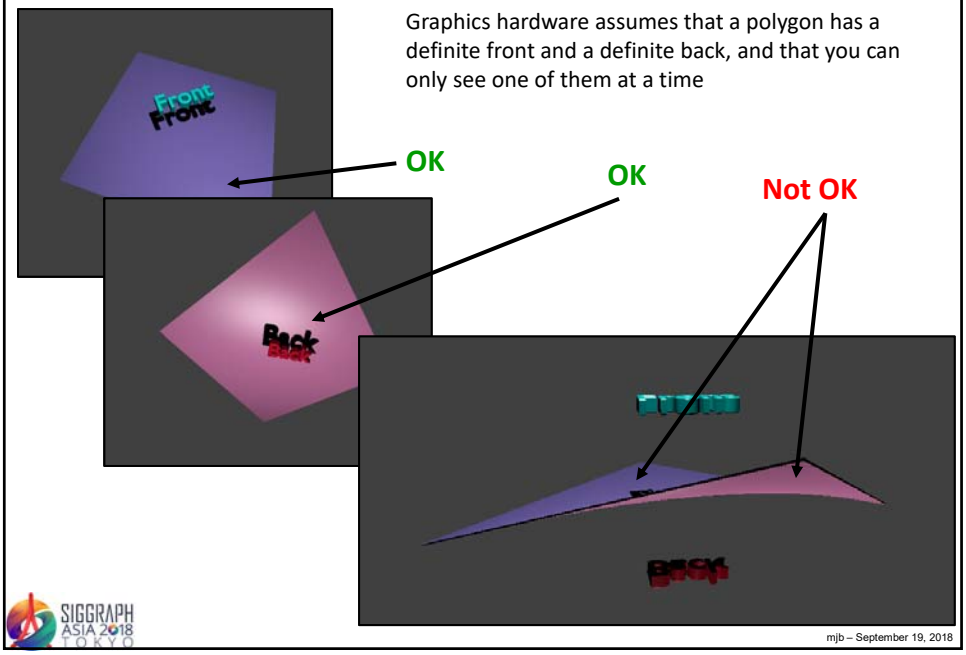


If you ever need to do this, contact me. I have working code …

48

Why is there a Requirement for Polygons to be Planar?

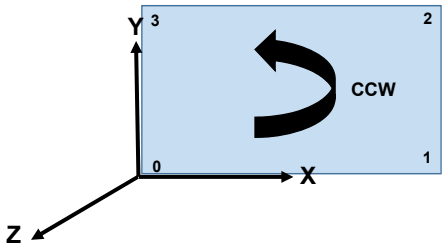
Graphics hardware assumes that a polygon has a definite front and a definite back, and that you can only see one of them at a time



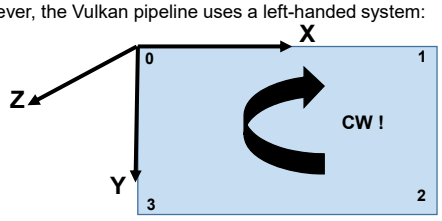
Vertex Orientation Issues

49

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



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



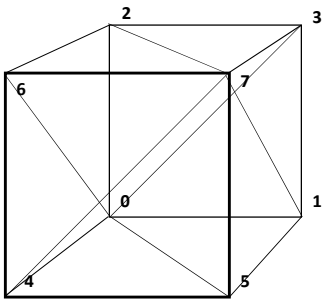
The best way to handle this is to continue to draw in a RH coordinate system and then fix it up in the projection matrix, like this:

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

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

A Colored Cube Example

50



```
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. },
};
```

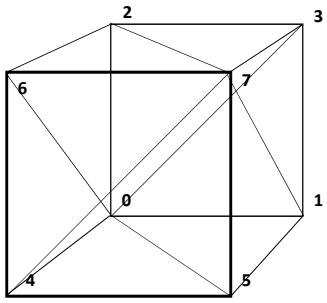
```
static GLfloat CubeVertices[ ][3] =
{
        { -1., -1., -1. },
        {  1., -1., -1. },
        { -1.,  1., -1. },
        {  1.,  1., -1. },
        { -1., -1.,  1. },
        {  1., -1.,  1. },
        { -1.,  1.,  1. },
        {  1.,  1.,  1. }
};
```

```
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 }
};
```

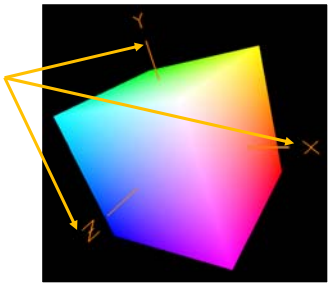
Triangles in an Array of Structures

From the file SampleVertexData.cpp:

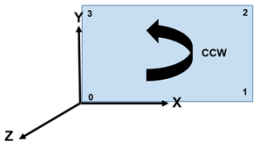
```
struct vertex
{
	glm::vec3	position;
	glm::vec3	normal;
	glm::vec3	color;
	glm::vec2	texCoord;
};

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. }
	},
```

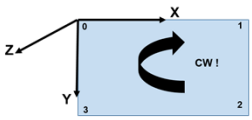


Modeled in right-handed coordinates



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

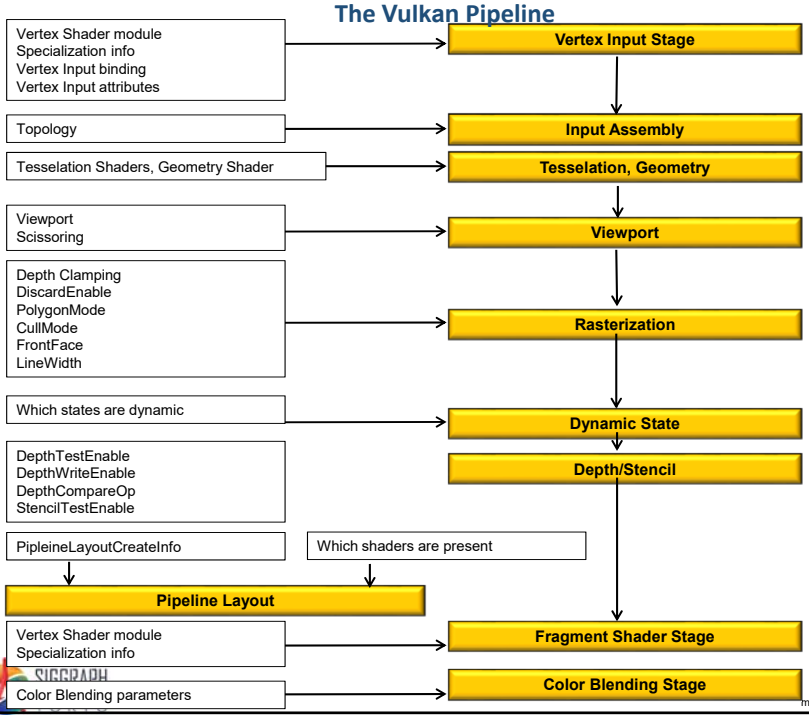

```
MyBuffer          MyVertexDataBuffer;


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;
}
```

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

55



Telling the Pipeline about its Input

56

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

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

vvibd

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

Telling the Pipeline about its Input

57

```
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
```

vviad has 4 elements because we have 4 per-vertex pipeline inputs

Telling the Pipeline about its Input

58

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;;
```

Telling the Pipeline about its Input

59

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 );
```

Telling the Command Buffer what Vertices to Draw

60

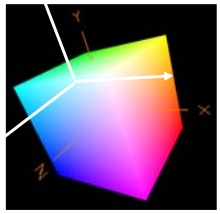
We will come to Command Buffers later, but for now, know that you will specify the vertex buffer that you want drawn.

```
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 );
```

Better to do this than to hard-code a number

61

Drawing

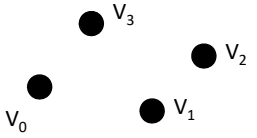


Mike Bailey
Oregon State University
mjb@cs.oregonstate.edu
http://cs.oregonstate.edu/~mjb/vulkan

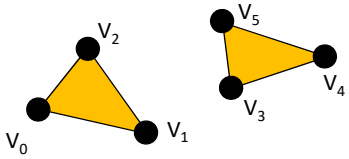
62

Vulkan Topologies

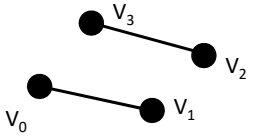
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



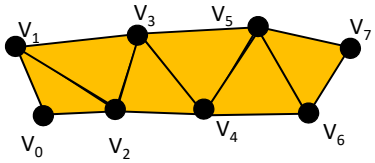
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



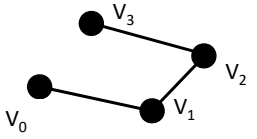
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



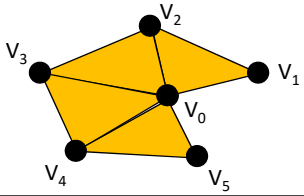
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_LINE_STRIP

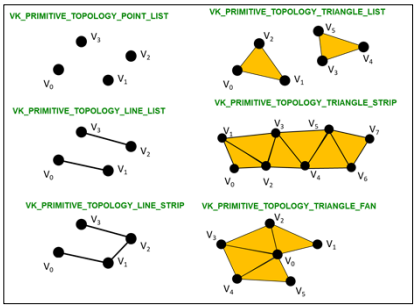


VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



63

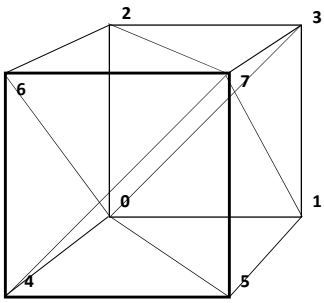
Vulkan Topologies




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


64

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. }
};
```

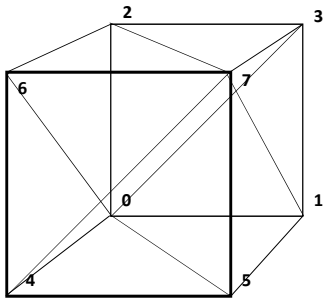
```
static GLuint CubeTriangleIndices[ ][3] =
{
        { 0, 2, 3 },
        { 0, 3, 1 },
        { 4, 5, 7 },
        { 4, 7, 6 },
        { 1, 3, 7 },
        { 1, 7, 5 },
        { 0, 4, 6 },
        { 0, 6, 2 },
        { 2, 6, 7 },
        { 2, 7, 3 },
        { 0, 1, 5 },
        { 0, 5, 4 }
};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

Triangles Represented as an Array of Structures

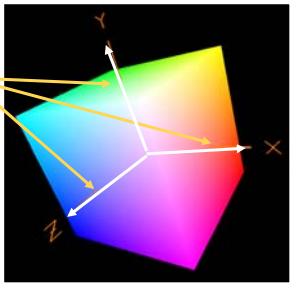
65

From the file **SampleVertexData.cpp**:

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

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

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

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



Modeled in right-handed coordinates

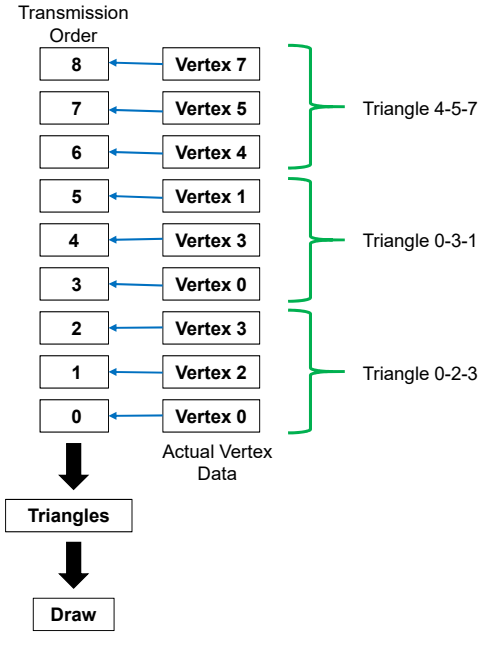


Non-indexed Buffer Drawing

66

From the file **SampleVertexData.cpp**:

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

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

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

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



Filling the Vertex Buffer


```
MyBuffer          MyVertexDataBuffer;


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


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

A 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;
}
```

Telling the Pipeline about its Input

69

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

C/C++:

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

GLSL Shader:

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

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

Telling the Pipeline about its Input

70

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

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

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

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

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

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

Telling the 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.

```
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 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.

```
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 );
```

Telling the Command Buffer what Vertices to Draw

73

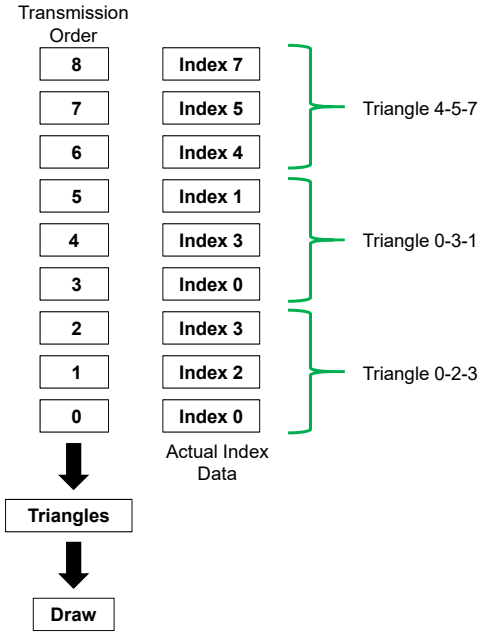
We will come to Command Buffers later, but for now, know that you will specify the vertex buffer that you want drawn.

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

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

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

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

Drawing with an Indexed Buffer

74

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

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


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



Drawing with an Indexed Buffer

75

```
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);
```

Remember that integer-indexed buffers are just BLOBs too.

Drawing with an Indexed Buffer

76

```
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), &MyJustVertexDataBuffer );
Fill05DataBuffer( MyJustVertexDataBuffer,              (void *) JustVertexData );

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

Drawing with an Indexed Buffer

77

```
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;

#ifdef VERTEX_BUFFER
      vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex,
firstInstance );
#endif

#ifdef INDEX_BUFFER
vkCmdDrawIndexed( CommandBuffers[nextImageIndex], indexCount, instanceCount, firstIndex,
vertexOffset, firstInstance );
#endif
```

Note that there is no vertex-count! It is up to you to not exceed the number of vertices with your index numbers!

mjb – September 19, 2018

Indirect Drawing (not to be confused with Indexed)

78

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

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

Compare this with:

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

mjb – September 19, 2018

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

79

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

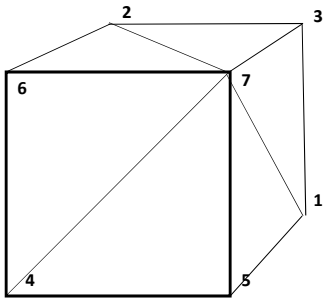
```
typedef struct
VkDrawIndexedIndirectCommand
{
    uint32_t    indexCount;
    uint32_t    instanceCount;
    uint32_t    firstIndex;
    int32_t     vertexOffset;
    uint32_t    firstInstance;
} VkDrawIndexedIndirectCommand;
```

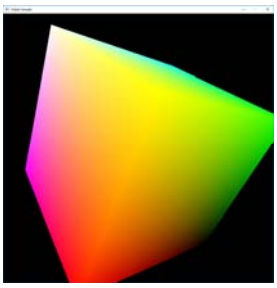
Compare this with:

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

Sometimes the Same Point Needs Multiple Attributes

80





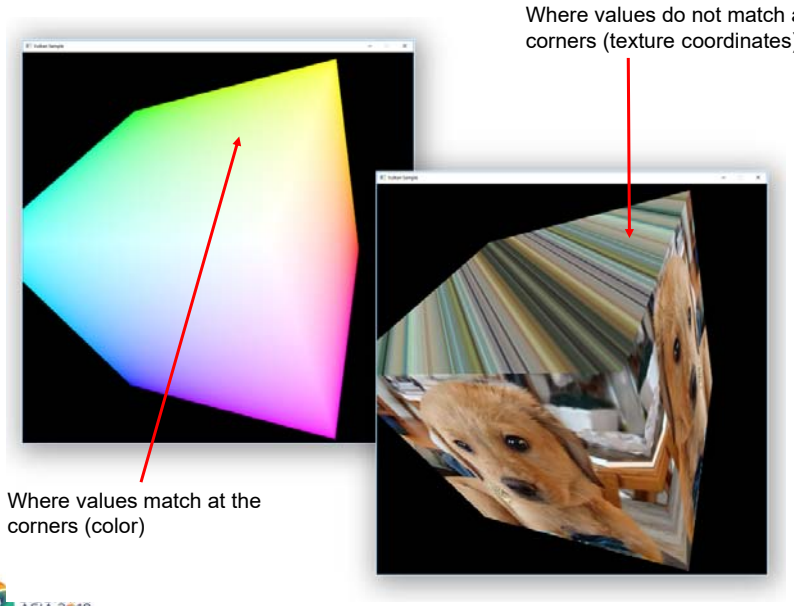
Sometimes a point that is common to multiple faces has the same attributes, no matter what face it is in. Sometimes it doesn't.

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

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

Sometimes the Same Point Needs Multiple Attributes

81



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

82

```
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
v 1.706156 1.293797 -0.037073
v 1.702207 1.290297 -0.040704
v 1.697843 1.285852 -0.040489
v 1.709169 1.295845 -0.029862
v 1.717523 1.288344 -0.029807

. . .

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
vn  0.4573  0.5682 -0.6841
vn  0.5160  0.5538 -0.6535
vn  0.1791  0.2082 -0.9616
vn -0.2167 -0.2250 -0.9499
vn  0.6624  0.6871 -0.2987
```

```
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
vt 0.817383 0.951538
vt 0.810059 0.951385
vt 0.809570 0.955383
vt 0.809082 0.959320
vt 0.811035 0.946381

. . .

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
f 73/73/75 79/79/81 78/78/80
f 79/79/81 73/73/75 74/74/76
f 74/74/76 80/80/82 79/79/81
f 80/80/82 74/74/76 75/75/77
f 75/75/77 81/81/83 80/80/82
```

V / T / N

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

Data Buffers

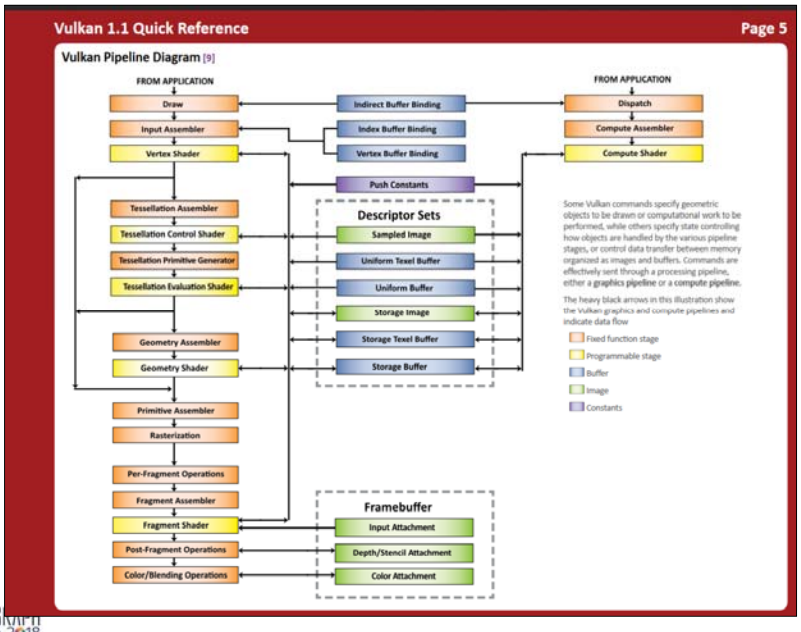
Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

From the Quick Reference Card



Terminology Issues

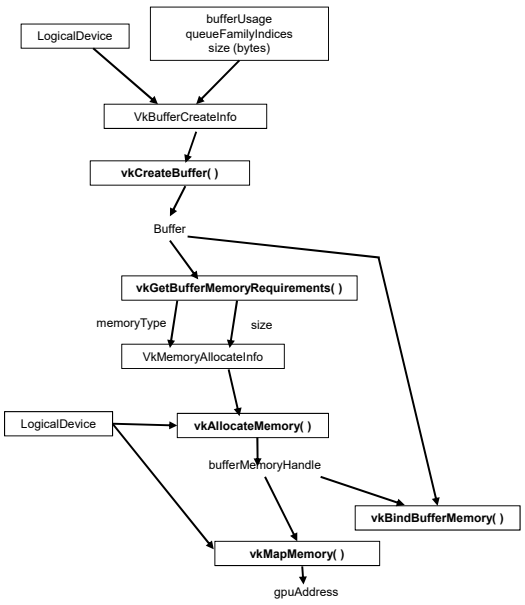
A **Data Buffer** is just a group of contiguous bytes in GPU memory. They have no inherent meaning. The data that is stored there is whatever you want it to be. (This is sometimes called a "Binary Large Object", or "BLOB".)

It is up to you to be sure that the writer and the reader pf 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 have taken to calling these things "Data Buffers" and have even gone to far as to override some of Vulkan's own terminology:

typedef VkBuffer VkDataBuffer;

Vulkan: Buffers



Vulkan: Creating a Data 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;

VkBuffer  Buffer;

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

Doesn't actually allocate memory – just creates a **VkBuffer** data structure

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


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


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

. . .

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

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

. . .

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

        << do the memory copy >>

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

Finding the Right Type of Memory


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

Finding the Right Type of Memory


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

Finding the Right Type of Memory


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

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

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

Something I've Found Useful

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

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

. . .

MyBuffer                      MyMatrixUniformBuffer;
```

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

Initializing a Data Buffer

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

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

Here's the C struct to hold some uniform variables


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

Here's the shader code to access those uniform variables

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

Filling those Uniform Variables

95

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

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

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

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

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

The Parade of Data

96

CPU: ***MyBuffer*** ***MyMatrixUniformBuffer;***

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

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

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

CPU:

struct matBuf ***Matrices;***

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

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

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

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

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

Memory-mapped copy

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

uniform matBuf ***Matrices;***

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

GPU:

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

The Descriptor Set for the Buffer

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

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

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

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

Filling the Data Buffer


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

. . .

MyBuffer                    MyMatrixUniformBuffer;
```

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

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

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

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

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

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

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

Creating and Filling the Data Buffer – the Details


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

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

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

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

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

Copy to GPU Memory via Memory Mapping


```
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.

Shaders and SPIR-V

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

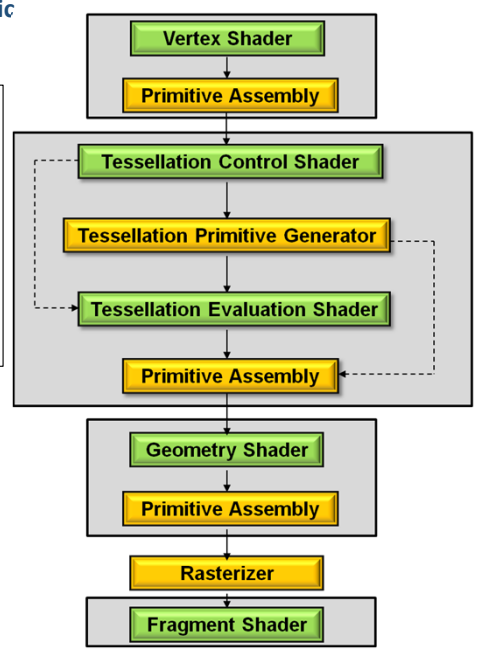
http://cs.oregonstate.edu/~mjb/vulkan

The Shaders' View of the Basic Computer Graphics Pipeline

- In general, you want to have a vertex and fragment shader as a minimum.
- A missing stage is OK. The output from one stage becomes the input of the next stage that is there.
- The last stage before the fragment shader feeds its output variables into the **rasterizer**. The interpolated values then go to the fragment shaders

= Fixed Function

= Programmable



Vulkan Shader Stages

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;
```

Vulkan: GLSL Differences from OpenGL

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

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

Vertex and Instance indices:

gl_VertexIndex
gl_InstanceIndex

These are
gl_VertexID
gl_InstanceID
In OpenGL. The Vulkan names make more sense.

- Both are 0-based

gl_FragColor:

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

Vulkan: GLSL Differences from OpenGL

Shader combinations of separate texture data and samplers:

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

Descriptor Sets:

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

Push Constants:

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

Specialization Constants:

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

- Can only use basic operators, declarations, and constructors
- Only for scalars, but a vector can be constructed from specialization constants

Specialization Constants for Compute Shaders:

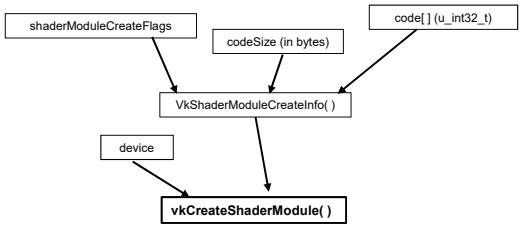
```
layout( local_size_x_id = 8, local_size_y_id = 16 );
```

- gl_WorkGroupSize.z is still as it was

Vulkan: Shaders' use of Layouts for Uniform Variables


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

All opaque (non-sampler) uniform variables must be in block buffers



Vulkan Shader Compiling

107

- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V
- SPIR-V gets turned into fully-compiled code at runtime
- SPIR-V spec has been public for a couple of years –new shader languages are surely being developed
- OpenGL and OpenCL will be moving to SPIR-V as well

Advantages:

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

SPIR-V, from the Khronos Group

108

The first open standard intermediate language for parallel compute and graphics:

- SPIR (**Standard Portable Intermediate Representation**) was initially developed for use by OpenCL and SPIR versions 1.2 and 2.0 were based on LLVM. SPIR has now evolved into a true cross-API standard that is fully defined by Khronos with native support for shader and kernel features – called SPIR-V.
- SPIR-V is the first open standard, cross-API intermediate language for natively representing parallel compute and graphics and is incorporated as part of the core specification of both OpenCL 2.1 and OpenCL 2.2 and the new Vulkan graphics and compute API.
- SPIR-V exposes the machine model for OpenCL 1.2, 2.0, 2.1, 2.2 and Vulkan - including full flow control, and graphics and parallel constructs not supported in LLVM. SPIR-V also supports OpenCL C and OpenCL C++ kernel languages as well as the GLSL shader language for Vulkan.
- SPIR-V 1.1, launched in parallel with OpenCL 2.2, now supports all the kernel language features of OpenCL C++ in OpenCL 2.2, including initializer and finalizer function execution modes to support constructors and destructors. SPIR-V 1.1 also enhances the expressiveness of kernel programs by supporting named barriers, subgroup execution, and program scope pipes.
- SPIR-V is catalyzing a revolution in the language compiler ecosystem - it can split the compiler chain across multiple vendors' products, enabling high-level language front-ends to emit programs in a standardized intermediate form to be ingested by Vulkan or OpenCL drivers. For hardware vendors, ingesting SPIR-V eliminate the need to build a high-level language source compiler into device drivers, significantly reducing driver complexity, and will enable a broad range of language and framework front-ends to run on diverse hardware architectures.
- For developers, using SPIR-V means that kernel source code no longer has to be directly exposed, kernel load times can be accelerated and developers can choose the use of a common language front-end, improving kernel reliability and portability across multiple hardware implementations.

KHRONOS GROUP
CONNECTING SOFTWARE TO SILICON

SPIR

https://www.khronos.org/spir

SPIR-V:
Standard Portable Intermediate Representation for Vulkan

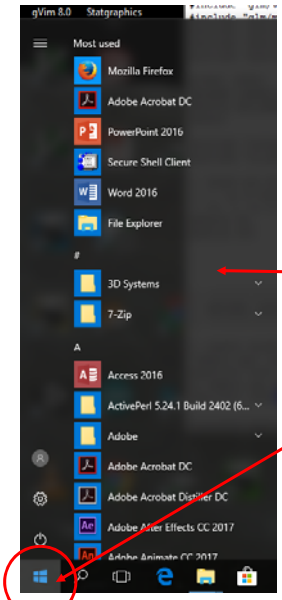
glslangValidator shaderFile -V [-H] [-I<dir>] [-S <stage>] -o shaderBinaryFile.spv

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

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

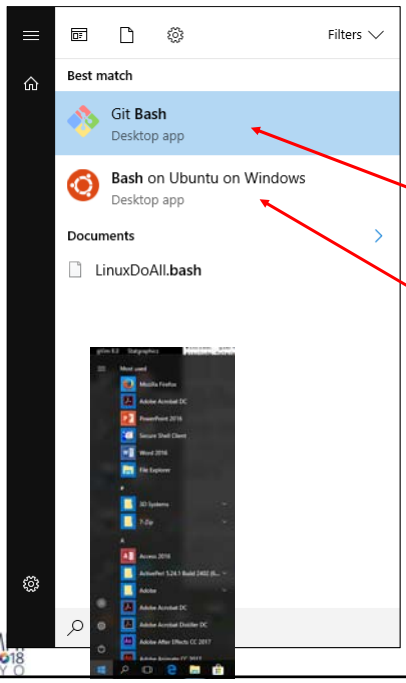
Windows: glslangValidator.exe
Linux: setenv LD_LIBRARY_PATH /usr/local/common/gcc-6.3.0/lib64/

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



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

111



Pick one:

- Can get to your personal folders
- Does not have make

- Cannot get to your personal folders
- Does have make

Running glslangValidator.exe

112

MINGW64:/y/Vulkan/Sample2017

```
ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ !85
glslangValidator.exe -V sample-vert.vert -o sample-vert.spv
sample-vert.vert

ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ !86
glslangValidator.exe -V sample-frag.frag -o sample-frag.spv
sample-frag.frag

ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$
```

You can also run SPIR-V from a Linux Shell


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

$ glslangValidator.exe -V sample-frag.frag -o sample-frag.spv
```

You can also run SPIR-V from a Linux Shell

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

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

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

Specify the output file

How do you know if SPIR-V compiled successfully?

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

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

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

0203 0723 . . .

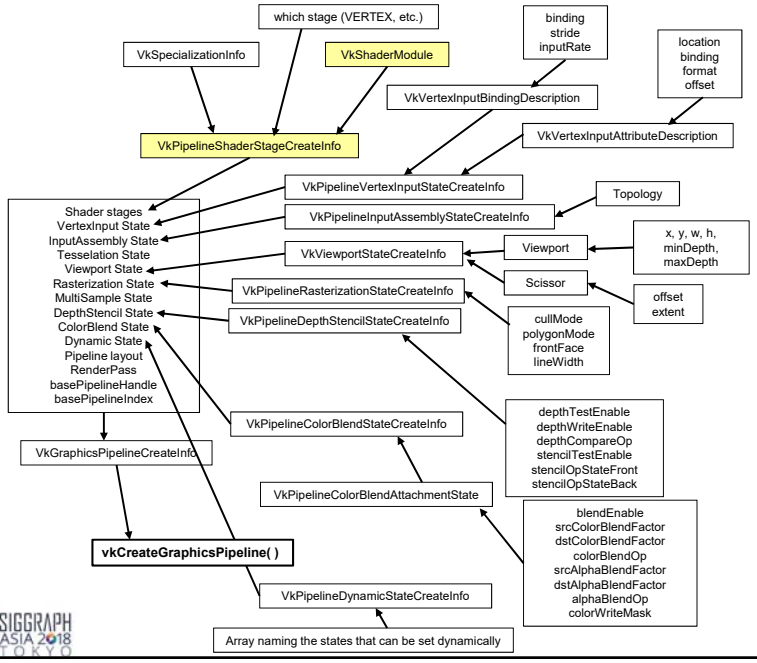
Reading a SPIR-V File into a Vulkan Shader Module


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

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

Reading a SPIR-V File into a Shader Module


```
	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, IN &vsmci, PALLOCATOR, pShaderModule );
	fprintf( FpDebug, "Shader Module '%s' successfully loaded\n", filename.c_str() );
	delete [ ] code;
	return result;
}
```


Vulkan: Creating a Pipeline



You can also take a look at SPIR-V Assembly

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. ☺

For example, if this is your Shader Source


```
#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;
}
```

This is the SPIR-V Assembly, Part I


```
#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
```


This is the SPIR-V Assembly, Part II


```
#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
```

This is the SPIR-V Assembly, Part III


```
#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
```


SPIR-V: Printing the Configuration

glslangValidator –c

```
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
```

SPIR-V: More Information

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

Installing bash on Windows

1.Open **Settings**.
2.Click on **Update & security**.
3.Click on **For Developers**.
4.Under "Use developer features", select the **Developer mode** option to setup the environment to install Bash.
5.On the message box, click **Yes** to turn on developer mode.
6.After the necessary components install, you'll need to restart your computer.
7.Once your computer reboots, open **Control Panel**.
8.Click on **Programs**.
9.Click on **Turn Windows features on or off**.
10.Check the **Windows Subsystem for Linux (beta)** option.
11.Click **OK**.
12.Once the components installed on your computer, click the **Restart now** button to complete the task.

After your computer restarts, you will notice that Bash will not appear in the "Recently added" list of apps, this is because Bash isn't actually installed yet. Now that you have setup the necessary components, use the following steps to complete the installation of Bash.

1.Open Start, do a search for **bash.exe**, and press **Enter**.
2.On the command prompt, type **y** and press **Enter** to download and install Bash from the Windows Store.
3.Then you'll need to create a default UNIX user account. This account doesn't have to be the same as your Windows account. Enter the username in the required field and press **Enter**
(you can't use the username "admin").
4.Close the "bash.exe" command prompt

Now that you completed the installation and setup, you can open the Bash tool from the Start menu like you would with any other app.

https://www.windowscentral.com/how-install-bash-shell-command-line-windows-10

Vulkan Sample Code

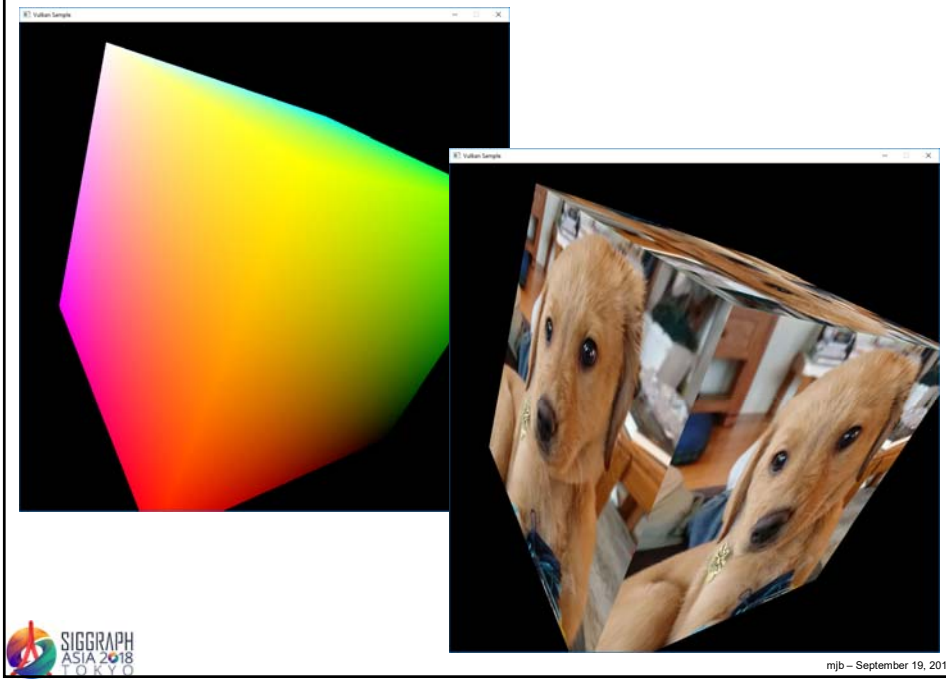
Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

Sample Program Output



Caveats on the Sample Code

- I've written everything out in ***appalling longhand***.
- Everything is in one .cpp file (except the geometry data). It really should be broken up, but this way you can find everything.
- 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 a secret to you.
- I've setup Vulkan structs every time they are used, even though, in many cases, they could have been setup once and then re-used each time.
- At times, I've setup things that didn't need to be setup just to show you what could go there.
- There are good uses for C++ classes and methods here to hide some complexity, but I've not done that.
- I've typedef'ed a couple things to make the Vulkan phraseology more consistent.
- Even though it is not good software style, I have put persistent information in global variables, rather than a separate data structure
- At times, I have copied lines from vulkan.h into the code as comments to show you what certain options could be.
- I've divided functionality up into the pieces that make sense to me. Many other divisions are possible. Feel free to invent your own.

Main Program


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

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

	Reset( );
	InitGraphics( );

	// loop until the user closes the window:

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

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

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

Loop

InitGraphics( ), I

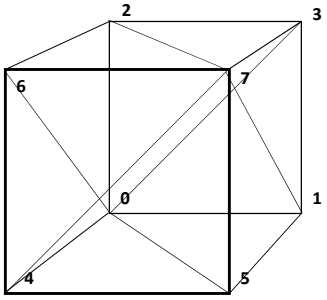

```
void
InitGraphics( )
{
	HERE_I_AM( "InitGraphics" );

	VkResult result = VK_SUCCESS;

	Init01Instance( );

	InitGLFW( );

	Init02CreateDebugCallbacks( );

	Init03PhysicalDeviceAndGetQueueFamilyProperties( );

	Init04LogicalDeviceAndQueue( );

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

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

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

	Init06CommandPool( );
	Init06CommandBuffers( );
```


InitGraphics( ), II


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

	Init08Swapchain( );

	Init09DepthStencilImage( );

	Init10RenderPasses( );

	Init11Framebuffers( );

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

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

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

A Colored Cube

133



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

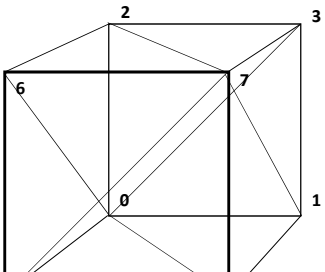
```
static GLfloat CubeVertices[ ][3] =
{
        { -1., -1., -1. },
        {  1., -1., -1. },
        { -1.,  1., -1. },
        {  1.,  1., -1. },
        { -1., -1.,  1. },
        {  1., -1.,  1. },
        { -1.,  1.,  1. },
        {  1.,  1.,  1. }
};
```

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

A Colored Cube

134

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

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

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

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



The Vertex Data is in a Separate File

#include "SampleVertexData.cpp"

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

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

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

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


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

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

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

Vulkan Software Philosophy

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

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

   we would actually say in C:

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

Vulkan Conventions

VkXxx is a typedef, probably a struct

vkXxx( ) is a function call

VK_XXX is a constant

My Conventions

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

The number after "Init" gives you the ordering

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

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

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

"IN" and "OUT" ahead of pointer (address) arguments are just there to let you know how a pointer is used by the function. Otherwise, they have no significance.

```
#define    IN
#define    OUT
```

139

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

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

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

2 calls

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);

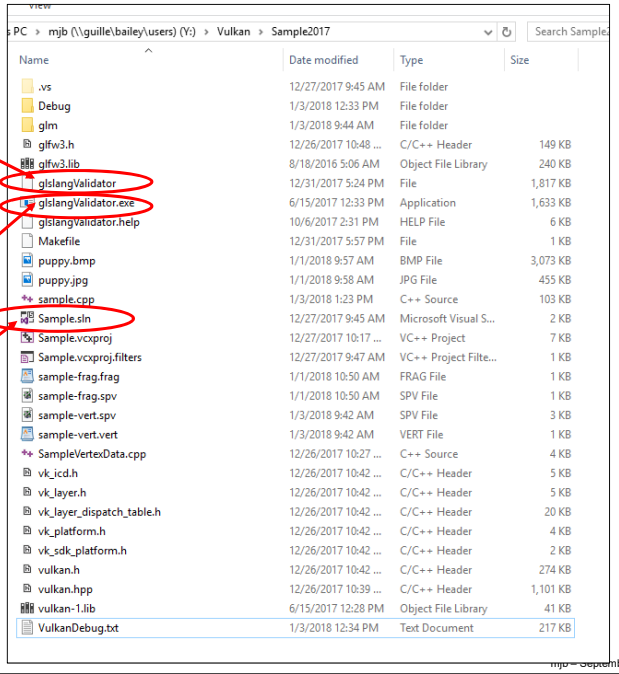
140

Your Sample2017.zip File Contains This

Linux shader compiler

Windows shader compiler

Double-click here to launch Visual Studio 2017 with this solution



Reporting Error Results, I


```
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_KHX, "Invalid External Handle“ },
};
```

Reporting Error Results, II


```
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);
}
```

Extras in the Code

143

```
#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" );
```

144

GLFW

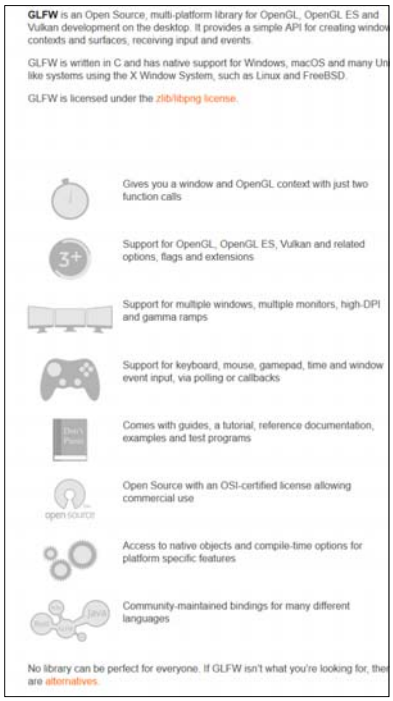
Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

http://www.glfw.org/



Setting Up GLFW


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

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

GLFW Keyboard Callback


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

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

GLFW Mouse Button Callback


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

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

		case GLFW_MOUSE_BUTTON_MIDDLE:
			b = MIDDLE;		break;

		case GLFW_MOUSE_BUTTON_RIGHT:
			b = RIGHT;		break;

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

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

GLFW Mouse Motion Callback

149

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

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

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

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

		if( Scale < MINSCALE )
			Scale = MINSCALE;
	}

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

Looping and Closing GLFW

150

Loop

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

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

GLM

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

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 (with one small exception which can be worked around.

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

You can find it at:

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

You invoke GLM like this:

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

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

Why are we even talking about this?

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

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

Deprecated OpenGL

you would now have to say:

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

GLM

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

The Most Useful GLM Variables, Operations, and Functions

// constructor:

```
glm::mat4( );
glm::vec4( );                  // identity matrix
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  )      // promote vec3 to a vec4 via a constructor
```

// emulating OpenGL transformations *with concatenation*:

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

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

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

The Most Useful GLM Variables, Operations, and Functions

// viewing volume (assign, not concatenate):

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

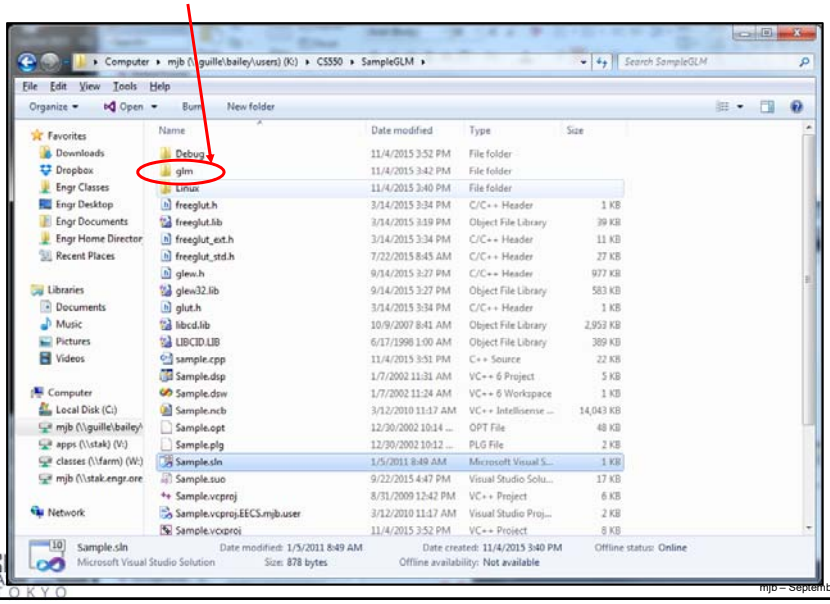
glm::mat4 **glm::frustum**(float left, float right, float bottom, float top, float near, float far);
glm::mat4 **glm::perspective**(float fovy, float aspect, float near, float far);

// viewing (assign, not concatenate):

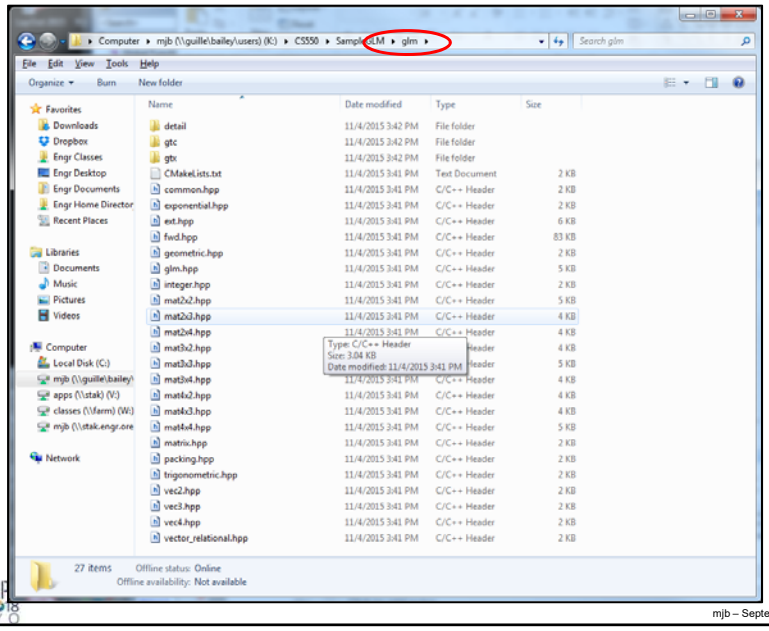
glm::mat4 **glm::lookAt**(glm::vec3 const & eye, glm::vec3 const & look, glm::vec3 const & up);

Installing GLM into your own space

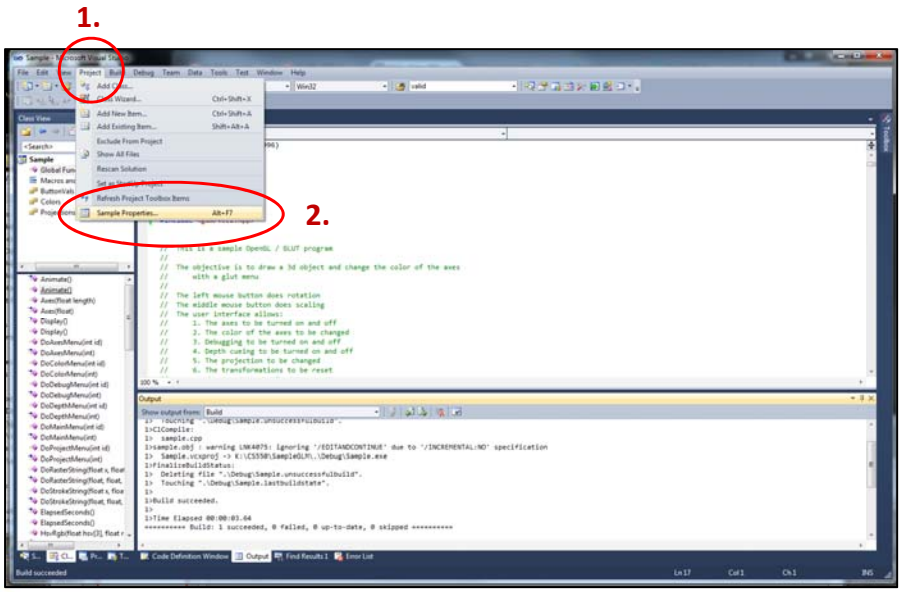
I like to just put the whole thing under my Visual Studio project folder so I can zip up a complete project and give it to someone else.



Here's what that GLM folder looks like



Telling Visual Studio about where the GLM folder is

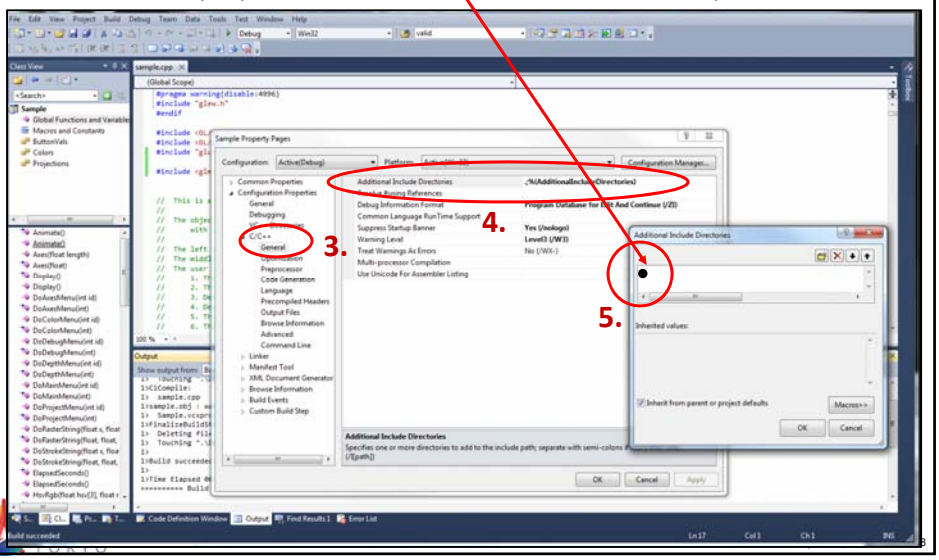


Telling Visual Studio about where the GLM folder is

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

#include <xxx>

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

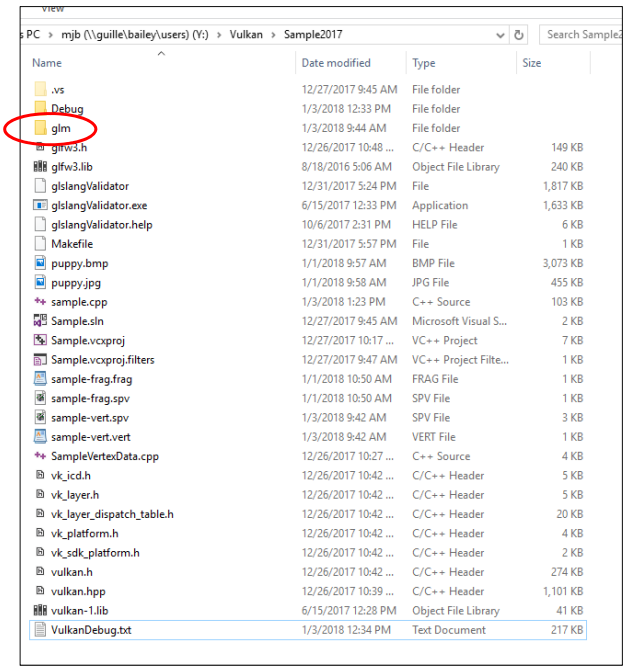


GLM in the Vulkan sample.cpp Program


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

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

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

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

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

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix ) );
Fill05DataBuffer( MyMatrixUniformBuffer, (void *) &Matrices );

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

Your Sample2017.zip File Contains GLM Already

161



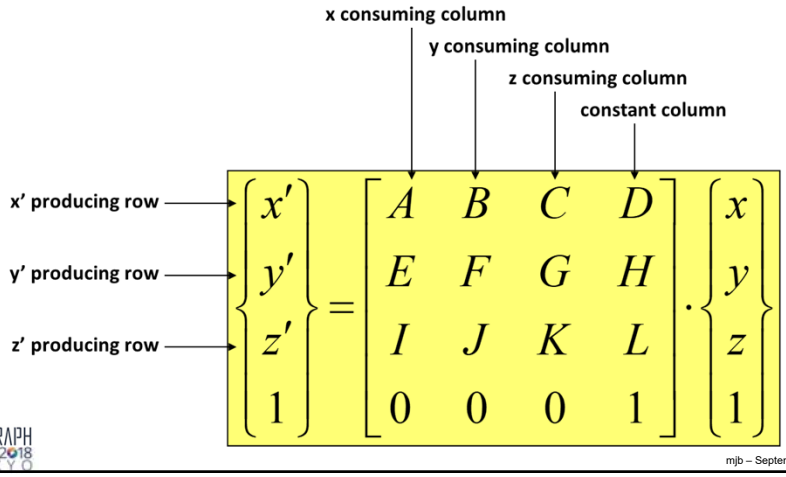
How Does this Matrix Stuff Really Work?

162

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

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:



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

Transformation Matrices

Translation

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

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 X

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

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

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

How it Really Works :-)

$$\begin{bmatrix} \cos 90^\circ & \sin 90^\circ \\ -\sin 90^\circ & \cos 90^\circ \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} a_2 & -a_1 \end{bmatrix}$$

http://xkcd.com

165

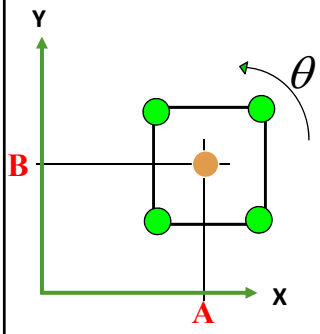
The Rotation Matrix for an Angle (θ) about an Arbitrary Axis (Ax, Ay, Az)

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

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

166

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.

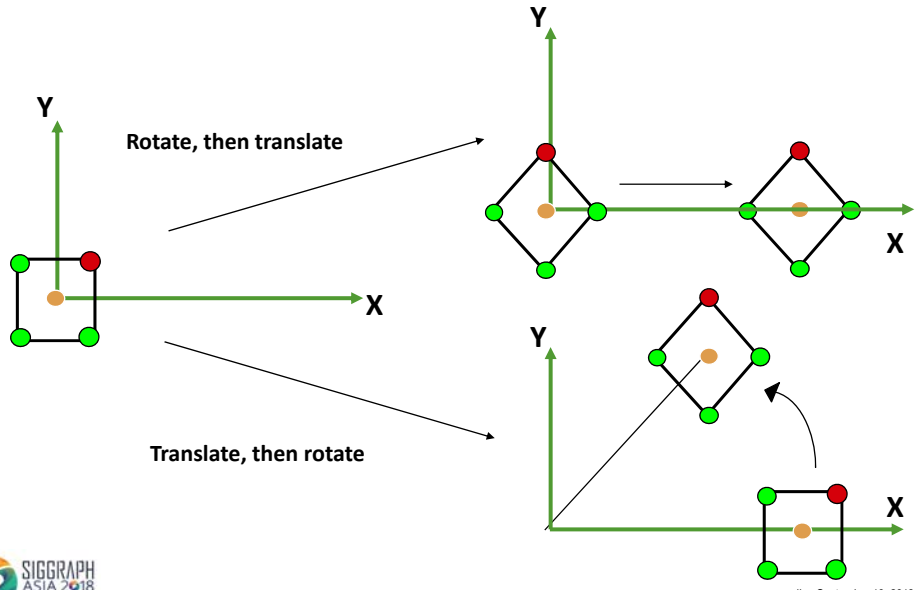
Write it

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left(\boxed{3}\ [T_{+A,+B}] \cdot \left(\boxed{2}\ [R_\theta] \cdot \left(\boxed{1}\ [T_{-A,-B}] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \right) \right) \right)$$

Say it

167

Matrix Multiplication *is not* Commutative



168

Matrix Multiplication *is* Associative

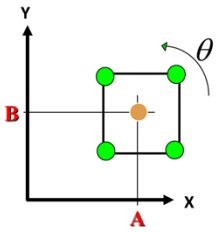
$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left(\left[T_{+A,+B} \right] \cdot \left(\left[R_\theta \right] \cdot \left(\left[T_{-A,-B} \right] \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \right) \right) \right)$$

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

One matrix –
the Current Transformation Matrix, or CTM

169

One Matrix to Rule Them All



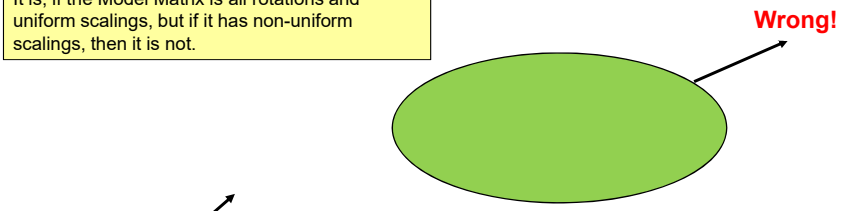
$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \left(\left[T_{+A,+B} \right] \cdot \left[R_{\theta} \right] \cdot \left[T_{-A,-B} \right] \right) \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

```
glm::mat4  Model = glm::mat4( );
Model = glm::translate(Model, glm::vec3( -A, -B, 0. ) );
Model = glm::rotate(Model, thetaRadians, glm::vec3( Ax, Ay, Az ) );
Model = glm::translate(Model, glm::vec3( A, B, 0. ) );

glm::vec3  eye(0.,0.,EYEDIST);
glm::vec3  look(0.,0.,0.);    glm::vec3  up(0.,1.,0.);
glm::mat4 View   = glm::lookAt( eye, look, up );

glm::mat4 Projection = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Projection[1][1] *= -1.;

. . .
glm::mat3 Matrix = Projection * View * Model;
glm::mat3 NormalMatrix = glm::inverseTranspose(  glm::mat3(Model)  );
```

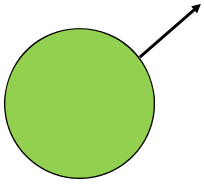
170

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

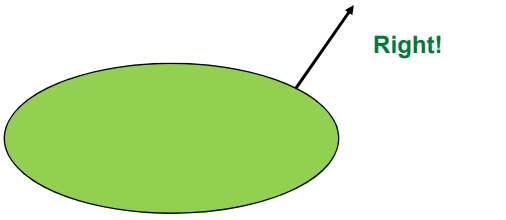
It is, if the Model Matrix is all rotations and uniform scalings, but if it has non-uniform scalings, then it is not.



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



Original object and normal



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

Instancing

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

Instancing – What and why?

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

Must be ≥ 1 Must be ≥ 0

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

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

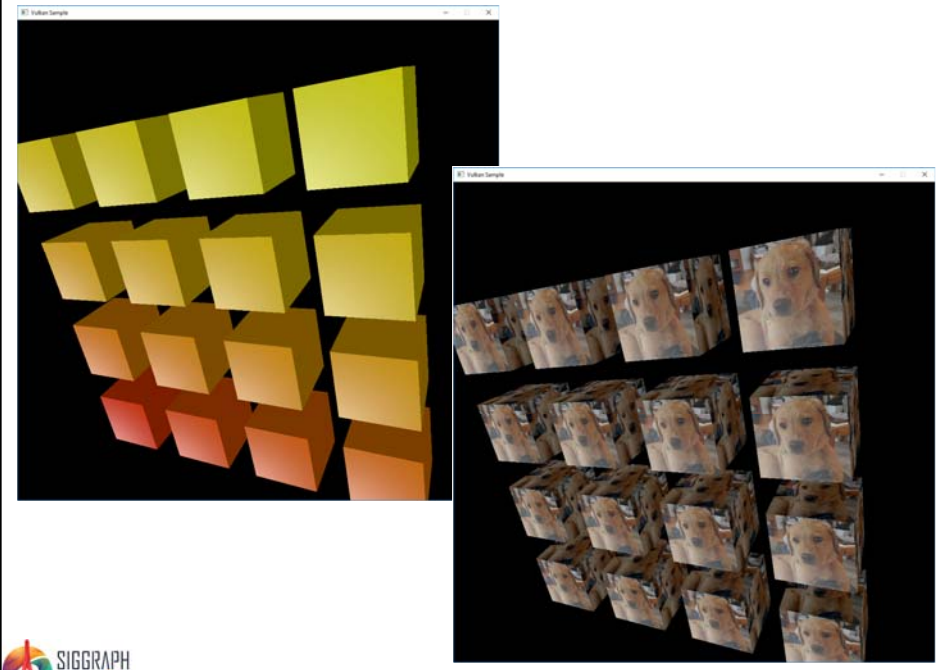
Making each Instance look differently -- Approach #1

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

gl_InstanceIndex starts at 0

In the vertex shader:

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

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

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

gl_Position = PVM * vertex;
```

Making each Instance look differently -- Approach #2

Put the unique characteristics in a uniform buffer and reference them

Still uses **gl_InstanceIndex**

In the vertex shader:

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

out vec3 vColor;

	. . .

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

vColor = Colors.uColors[ index ];

gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
```

Making each Instance look differently -- Approach #3

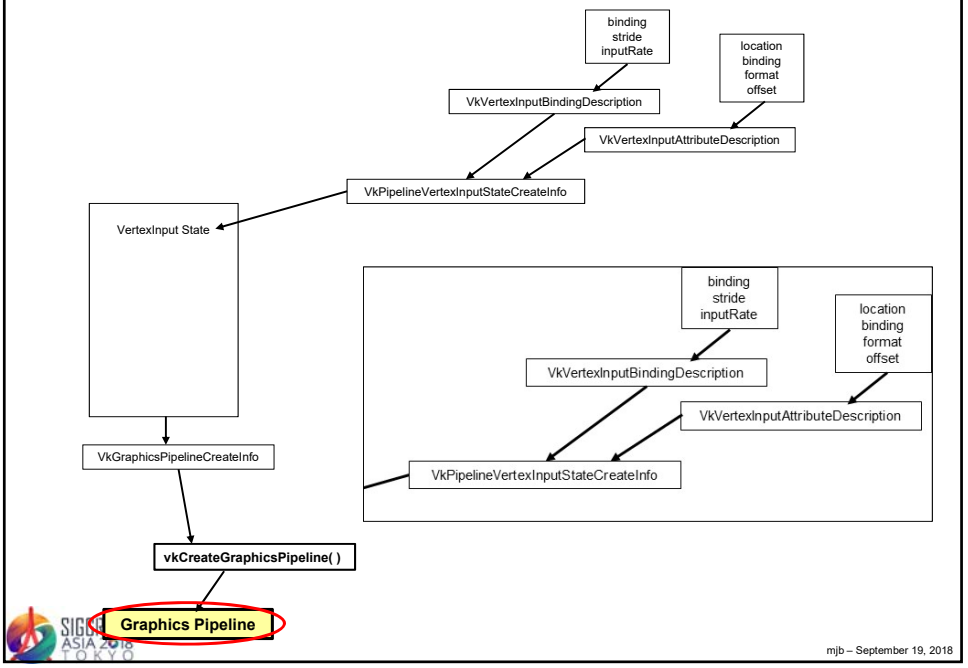
Put a series of unique characteristics in a data buffer, one element per instance.

Read a new characteristic for each instance

Internally uses **gl_InstanceIndex**, but you don't

This is just the Vertex Input State Portion of the Graphics Pipeline Structure

177



How We Constructed the Graphics Pipeline Structure Before

178

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

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

How We Constructed the Graphics Pipeline Structure Before


```
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 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
```

How We Constructed the Graphics Pipeline Structure Before


```
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;
```

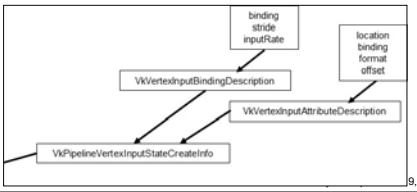
```
VkGraphicsPipelineCreateInfo		vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
        vgpci.flags = 0;
        . . .
        vgpci.pVertexInputState = &vpvisci;
        . . .

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

How We Construct the Graphics Pipeline Structure Now

Let's assign a different color per Instance.
Create a data buffer with one glm::vec3 (to hold r, g, b) for each Instance.

```
VkVertexInputBindingDescription		vvibd[2];
	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;

	vvibd[1].binding = 1;				// which binding # this is
	vvibd[1].stride = sizeof( glm::vec3 );		// bytes between successive entries
	vvibd[1].inputRate = VK_VERTEX_INPUT_RATE_INSTANCE;
```

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



How We Construct the Graphics Pipeline Structure Now

Let's assign a different color per Instance.
Create a data buffer with one glm::vec3 (to hold r, g, b) for each Instance.

```
VkVertexInputAttributeDescription		vviad[5];
		// 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 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[5].location = 0;		// location in the layout decoration
	vviad[5].binding = 1;		// which binding description this is part of
	vviad[5].format = VK_FORMAT_VEC3;	// r, g, b
	vviad[5].offset = 0;		// just one element, so offset is 0
```

How We Construct the Graphics Pipeline Structure Now

Let's assign a different color per Instance.
Create a data buffer with one glm::vec3 (to hold r, g, b) for each Instance.

```
VkPipelineVertexInputStateCreateInfo            vpvisci;
        vpvisci.sType = VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO;
        vpvisci.pNext = nullptr;
        vpvisci.flags = 0;

        vpvisci.vertexBindingDescriptionCount = 2;
        vpvisci.pVertexBindingDescriptions = vvibd;

        vpvisci.vertexAttributeDescriptionCount = 5;
        vpvisci.pVertexAttributeDescriptions = vviad;
```

Note: same names as before, but different sizes

```
VkGraphicsPipelineCreateInfo                    vgpci;
                vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
                vgpci.pNext = nullptr;
                vgpci.flags = 0;
                . . .
                vgpci.pVertexInputState = &vpvisci;
                 . . .

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

How We Write the Vertex Shader Now


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

        . . .

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

layout( location = 4 ) in vec3 aInstanceColor;

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

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

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

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

Descriptor Sets

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

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 bunch of related uniform variables all at once?

```
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;
```

In OpenGL, these are all in one set. They all get bound, whether you need them here or not.

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:

1. Related uniform variables can be updated as a group, gaining efficiency.
2. 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.
3. Values for the shaders' uniform buffer variables can be compartmentalized into what quantities change often and what change seldom (scene-level, model-level, draw-level), so that uniform variables need to be re-written no more often than is necessary.

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

Descriptor Sets

Our example will assume the following shader uniform variables:

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

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
        float  uKa, uKd, uKs, uShininess;
        vec4 uLightPos;
        vec4 uLightSpecularColor;
        vec4 uEyePos;
} Light;


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

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

Descriptor Sets

189

CPU:

Uniform data created in a C++ data structure

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

GPU:

Uniform data in a "blob"*

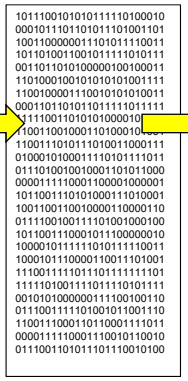
- Knows where the data starts
- Knows the data's size
- Doesn't know the CPU or GPU data structure

GPU:

Uniform data used in the shader

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

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

struct lightBuf
{
	float uKa, uKd, uKs, uShininess;
	glm::vec4 uLightPos;
	glm::vec4 uLightSpecularColor;
	glm::vec4 uEyePos;};

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



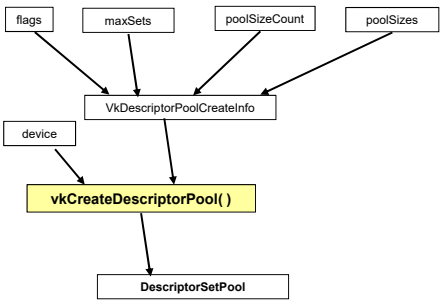
* "binary large object"

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

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
	float  uKa, uKd, uKs, uShininess;
	vec4 uLightPos;
	vec4 uLightSpecularColor;
	vec4 uEyePos; ;
} Light;

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

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

Step 1: Descriptor Set Pools

190

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



191

```
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;
}
```

192

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://discoveringegypt.com

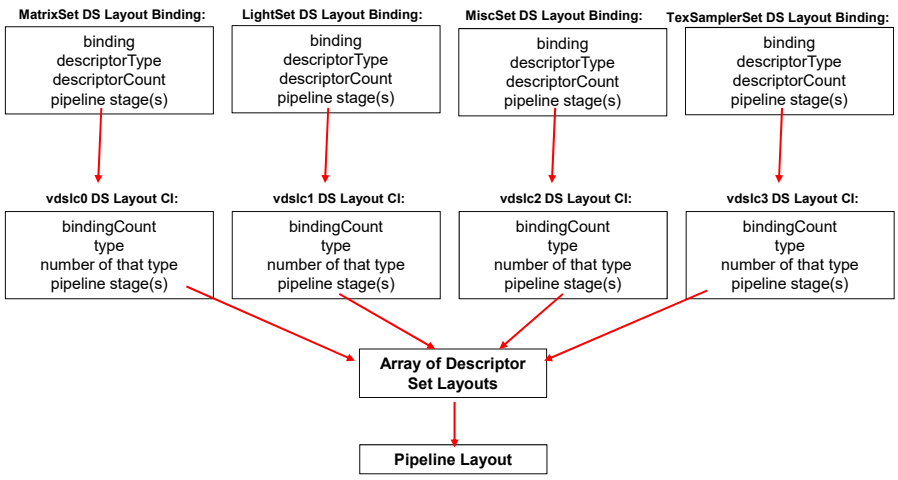
```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
		float  uKa, uKd, uKs, uShininess;
		vec4 uLightPos;
		vec4 uLightSpecularColor;
		vec4 uEyePos; ;
} Light;

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

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

MatrixSet DS Layout Binding:	LightSet DS Layout Binding:	MiscSet DS Layout Binding:	TexSamplerSet DS Layout Binding:
binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)

```
VkResult
Init13DescriptorSetLayouts( )
{
	VkResult result;

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

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

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

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

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


Step 2: Define the Descriptor Set Layouts



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

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

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

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

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

return result;
}
```

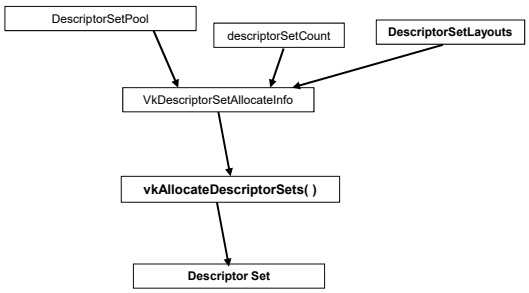
Array of Descriptor Set Layouts

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


```
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;
}
```

Array of Descriptor Set Layouts

Step 4: Allocating the Memory for Descriptor Sets



Step 4: Allocating the Memory for Descriptor Sets


```
VkResult
Init13DescriptorSets( )
{
	VkResult result;

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

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

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

199

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

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

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

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

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

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

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

This struct identifies what texture sampler and image view it owns

Good to use ***sizeof***

mjb – September 19, 2018

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

200

```
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 tto

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

mjb – September 19, 2018

Step 5: Tell the Descriptor Sets where their data is

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

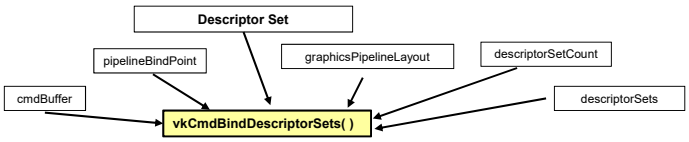
This struct links a Descriptor Set to the image it is pointing to

```
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 );
```

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


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

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

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




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


The Graphics Pipeline

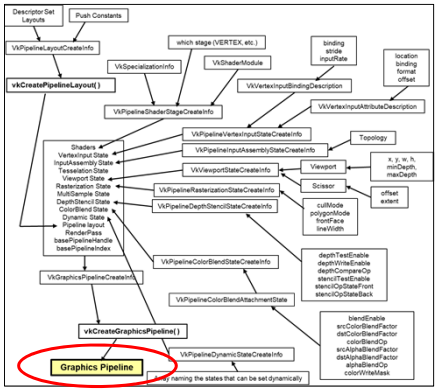
Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

What is the Vulkan Graphics Pipeline?



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

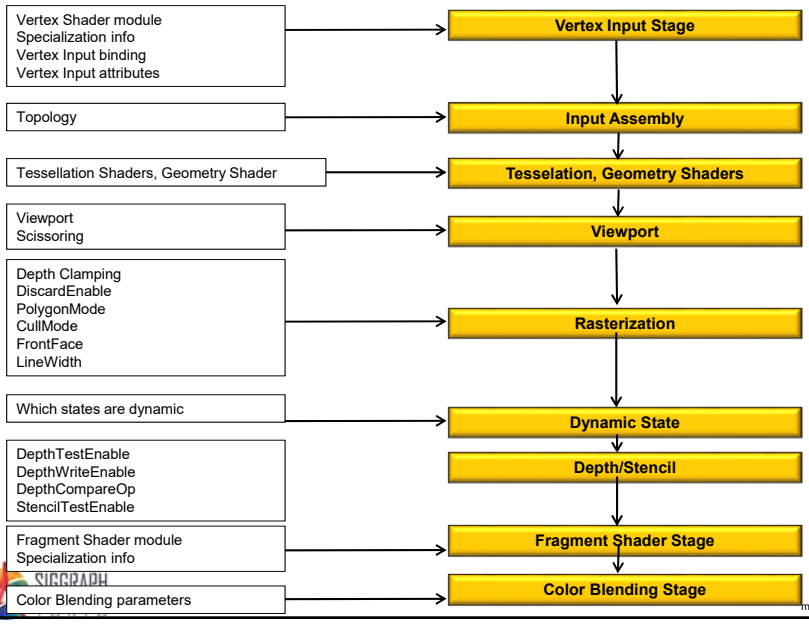
There is also a Vulkan Compute Pipeline – we will get to that later.

Here's what you need to know:

1. The Vulkan Graphics Pipeline is like what OpenGL would call "The State", or "The Context".
2. There's a lot that goes into it.
3. For the most part, the Graphics Pipeline is meant to be immutable – that is, once this combination of state variables is combined into a Pipeline, that Pipeline never gets changed. To make new combinations of state variables, create a new Graphics Pipelines.
4. The shaders get compiled the rest of the way when their Graphics Pipeline gets created.

Graphics Pipeline Stages and what goes into Them

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

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

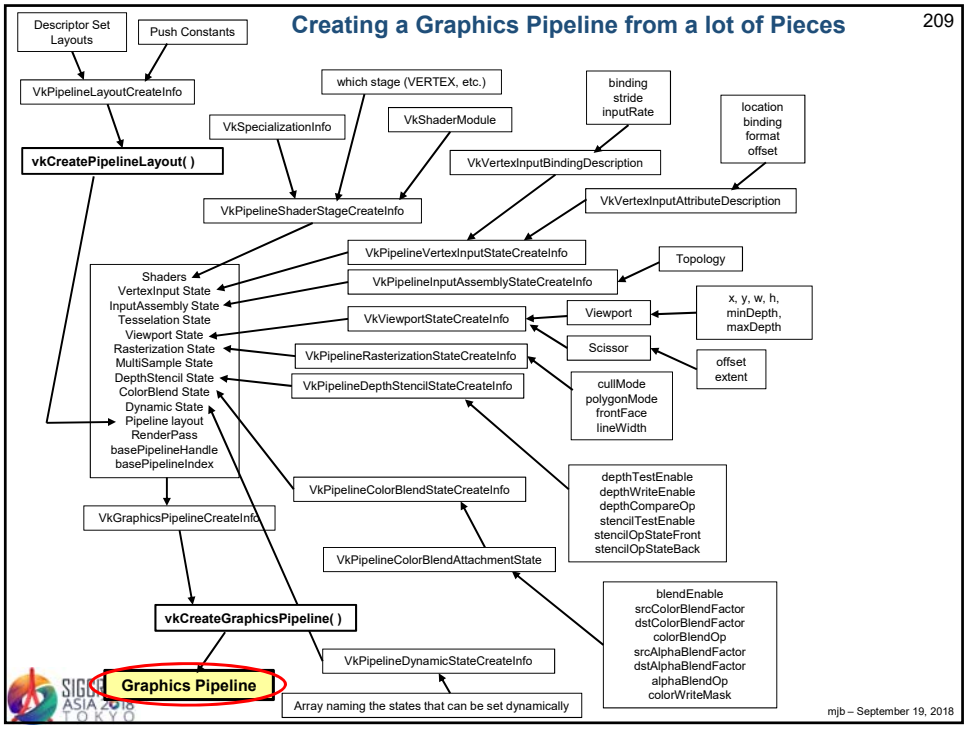
```
VkResult
Init14GraphicsPipelineLayout( )
{
	VkResult result;

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

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

	return result;
}
```

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

Vulkan: A Pipeline Records the Following Items:

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

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



Creating a Typical Graphics Pipeline


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

        . . .
```

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

Link in the Shaders


```
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;
#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[0].module = vertexShader;
        vpssci[0].pName = "main";
        vpssci[0].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

        vpssci[1].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci[1].pNext = nullptr;
        vpssci[1].flags = 0;
        vpssci[1].stage = VK_SHADER_STAGE_FRAGMENT_BIT;
        vpssci[1].module = fragmentShader;
        vpssci[1].pName = "main";
        vpssci[1].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

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

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

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

Link in the Per-Vertex Attributes


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

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

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

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

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

213

```
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

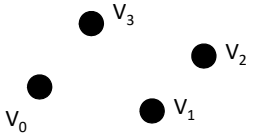
Geometry Shader info

mjb – September 19, 2018

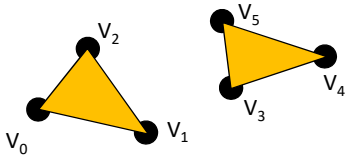
214

Options for vpiasci.topology

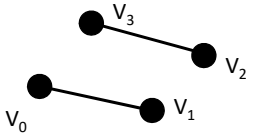
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



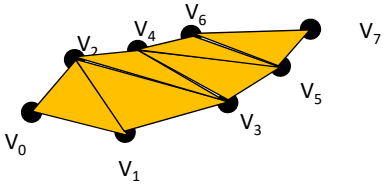
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



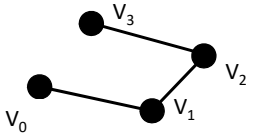
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



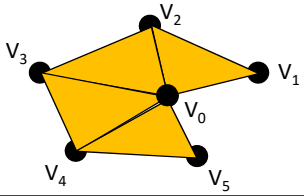
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



mjb – September 19, 2018

What is "Primitive Restart Enable"?


```
vpiasci.primitiveRestartEnable = VK_FALSE;
```

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

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

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

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

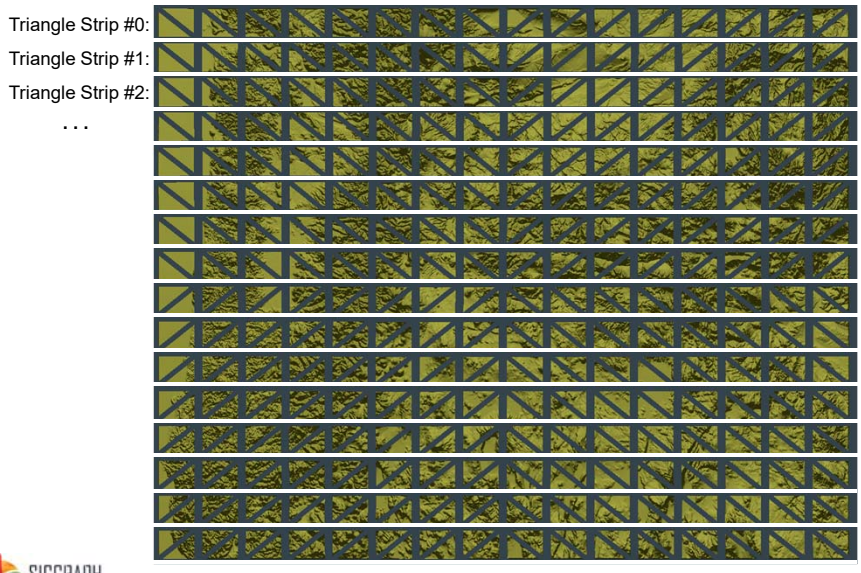
When using the primitive restart code, the easy way to do it is like this:

```
short int restartIndex = ~0;
```

or,

```
int restartIndex = ~0;
```

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



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

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

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

Declare the viewport information

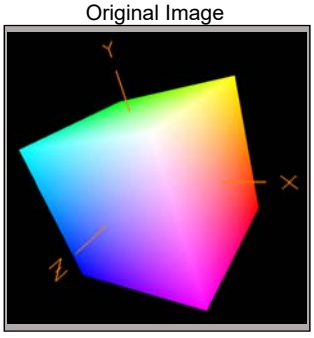
Declare the scissoring information

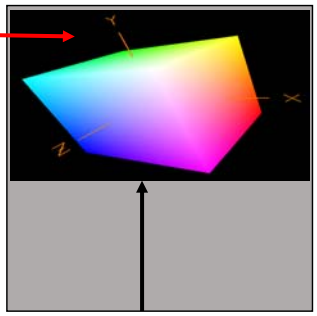
Group the viewport and scissor information together

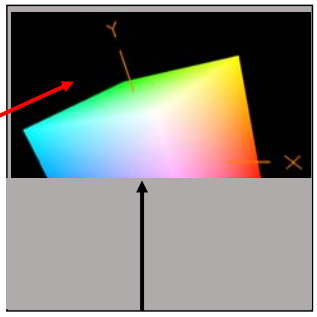
What is the Difference Between Changing the Viewport and Changing the Scissoring?

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

Setting the Rasterizer State


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

Declare information about how the rasterization will take place

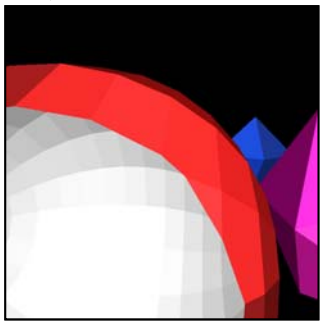
What is "Depth Clamp Enable"?

vprsci.depthClampEnable = VK_FALSE;

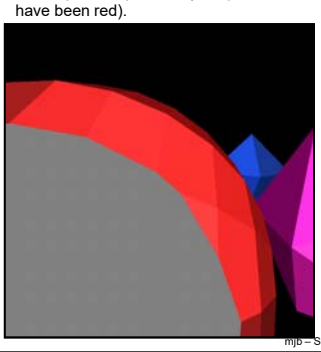
Depth Clamp Enable causes the fragments that would normally have been discarded because they are closer to the viewer than the near clipping plane to instead get projected to the near clipping plane and displayed.

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

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



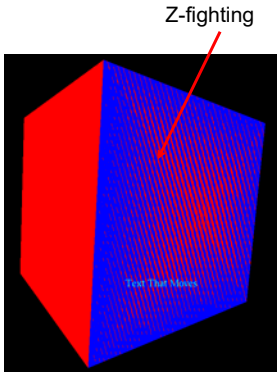
The gray area shows what would happen with depthClampEnable (except it would have been red).



What is "Depth Bias Enable"?


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

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



MultiSampling State


```
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

Color Blending State for each Color Attachment

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

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

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

Color Blending State for each Color Attachment


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

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

Which Pipeline Variables can be Set Dynamically?


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

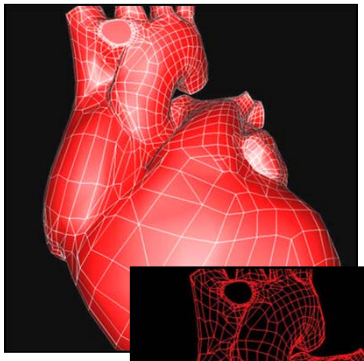
Stencil Operations for Front and Back Faces


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

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

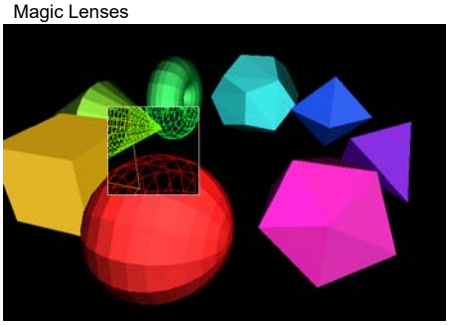
Uses for Stencil Operations

227

Polygon edges without Z-fighting



Magic Lenses



mjb – September 19, 2018

Operations for Depth Values

228

```
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;
```

mjb – September 19, 2018

Putting it all Together! (finally…)


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

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

    return result;
}
```

Group all of the individual state information and create the pipeline

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


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

231

Queues and Command Buffers

Mike Bailey

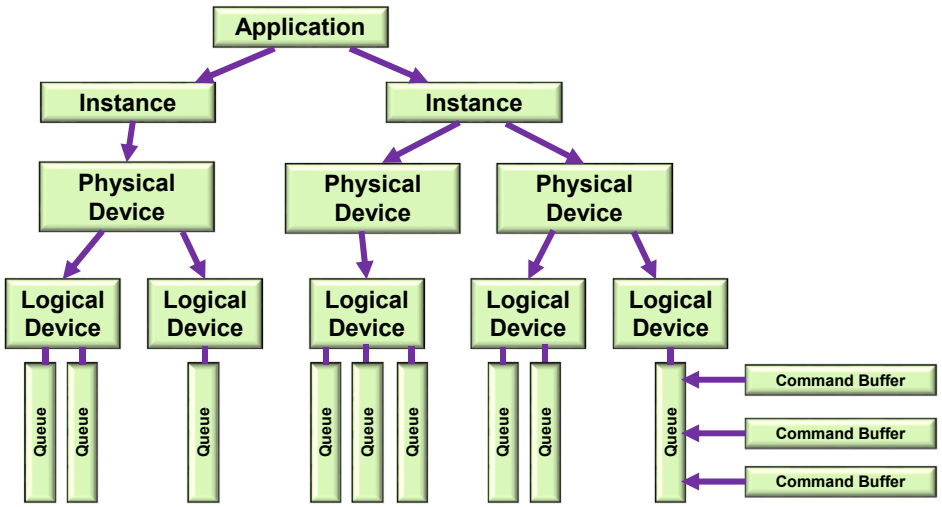
Oregon State University

mjb@cs.oregonstate.edu

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

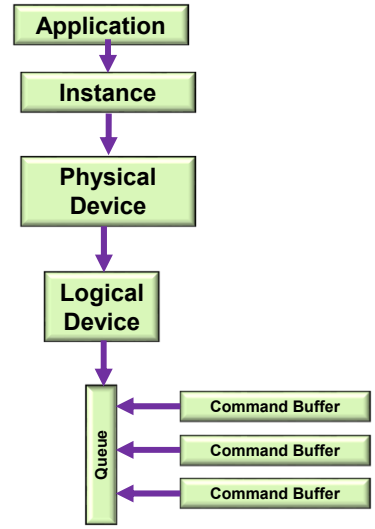
232

Vulkan: Overall Block Diagram



Vulkan: a More Typical (and Simplified) Block Diagram

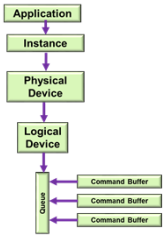
233

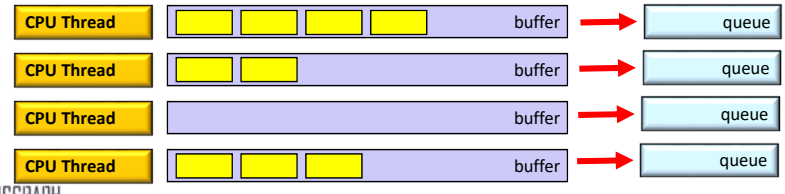


Vulkan Queues and Command Buffers

234

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





Querying what Queue Families are Available

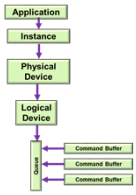

```
uint32_t  count;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *) nullptr );

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

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

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

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


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

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

Creating a Logical Device Queue Needs to Know Queue Family Information



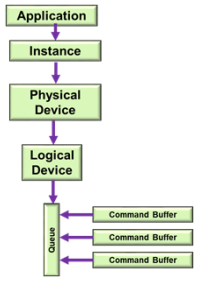

```
float   queuePriorities[ ] =
{
        1.                  // one entry per queueCount
};

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

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

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

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

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

Creating the Command Pool as part of the Logical Device


```
VkResult
Init06CommandPool( )
{
        VkResult result;

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

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

        return result;
}
```

Creating the Command Buffers

239



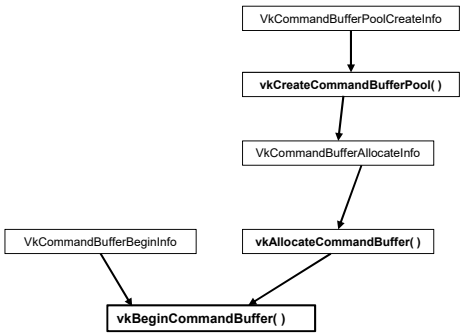

```
VkResult
Init06CommandBuffers( )
{
	VkResult result;

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

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

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


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

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

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

	return result;
}
```

Beginning a Command Buffer

240

```
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] );
```

Beginning a Command Buffer



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


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

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


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


```
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 );
```

245

```
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 );
```

246

```
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] );
```

Submitting a Command Buffer to a Queue for Execution


```
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;
```

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, &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 );
```

Create fence

Get the queue

Fill in the queue information

Submit the queue

Wait for the fence

The Swap Chain

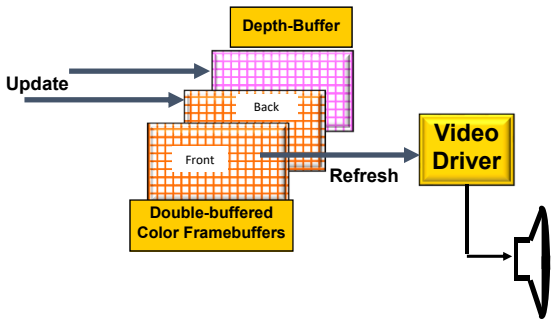
Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

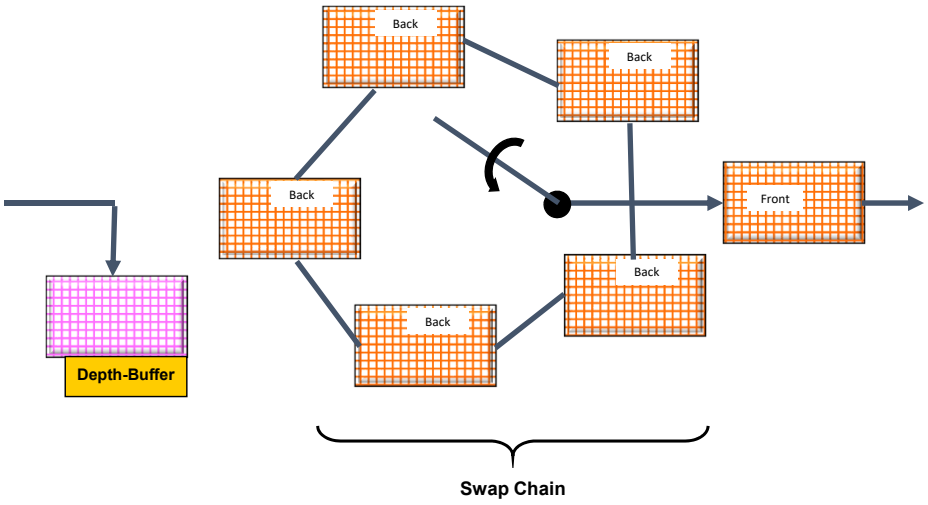
http://cs.oregonstate.edu/~mjb/vulkan

How We Think of OpenGL Framebuffers



251

Vulkan Thinks of it as a Ring Buffer



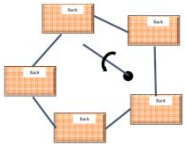
252

What is a Swap Chain?

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

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

Swap Chains are arranged as a ring buffer



Swap Chains are tightly coupled to the window system.

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

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

What is a Swap Chain?

253

Because it has the word “chain” in it, let’s try to visualize the Swap Chain as a physical chain.

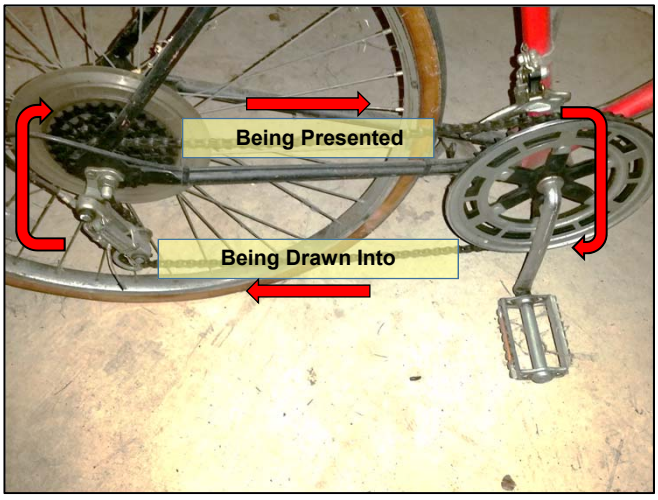
A bicycle chain isn’t far off. A bicycle chain goes around and around, each section of the chain taking its turn on the gear teeth, off the gear teeth, on, off, on, off, etc.

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

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

What is a Swap Chain?

254



This is a pretty good analogy, except that there can be many more images in the ring buffer than are being shown here.

We Need to Find Out What our Display Capabilities Are

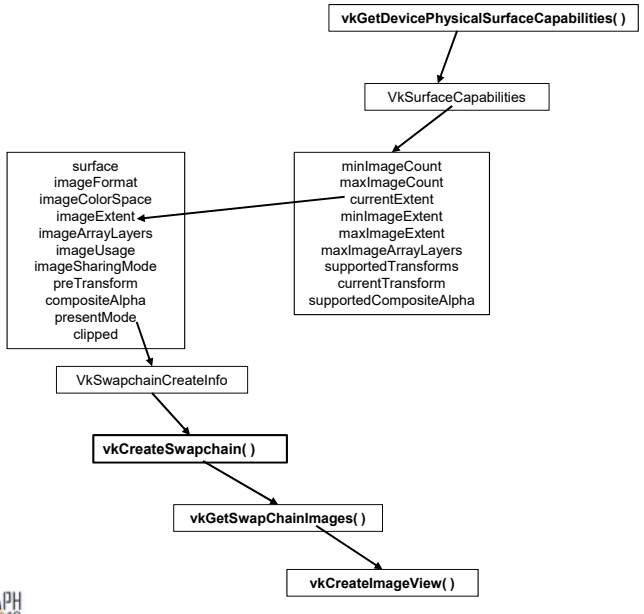

```
VkSurfaceCapabilitiesKHR                vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;
fprintf( FpDebug, "\nvkGetPhysicalDeviceSurfaceCapabilitiesKHR:\n" );

        . . .

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


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

        . . .

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

        . . .
```

We Need to Find Out What our Display Capabilities Are

VulkanDebug.txt output:

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

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


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


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

Creating a Swap Chain



Creating a Swap Chain


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

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

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

Creating the Swap Chain Images and Image Views

259

```
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

260

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

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

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

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

        . . .

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

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

        . . .

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

Rendering into the Swap Chain, II


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

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

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

    . . .

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

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

Rendering into the Swap Chain, III


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

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

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

Rendering

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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


```
VkPipelineRasterizationStateCreateInfo		vprsci;

. . .

vprsci.cullMode = VK_CULL_MODE_NONE
vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;


Matrices.uProjectionMatrix[1][1] *= -1.;
```

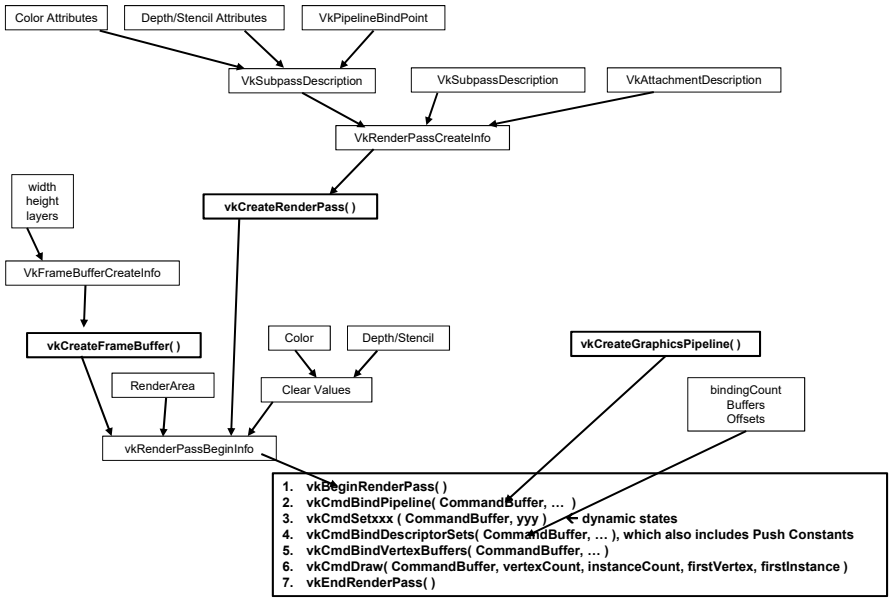
New Stuff – Don't Know Where to Put it Yet

You can create multiple viewports

A single renderpass can consist of multiple subpasses.

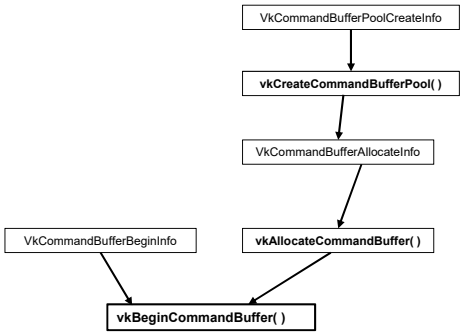
Subpasses are rendering operations that depend on the contents of the framebuffer from previous passes.

Vulkan: Drawing



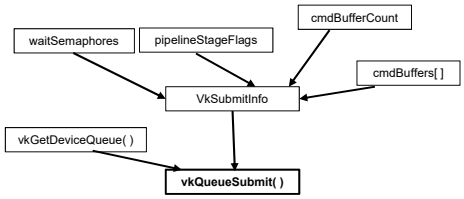
Vulkan: Beginning a Command Buffer

267



Vulkan: Submitting to a Queue

268



269

```
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 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 );
```

270

```
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 );

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

271

```
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, &scissor );


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

//vkCmdBindPushConstants( CommandBuffers[nextImageIndex], PipelineLayout, VK_SHADER_STAGE_ALL,
                        offset, size, void *values );
```

272

```
 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] );

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

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 );     // 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 );

vkDestroySemaphore( LogicalDevice, imageReadySemaphore, PALLOCATOR );
```


Textures

Mike Bailey

Oregon State University

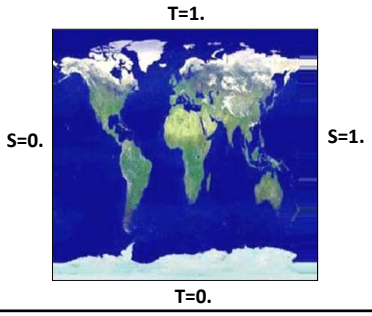
mjb@cs.oregonstate.edu

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

The Basic Idea

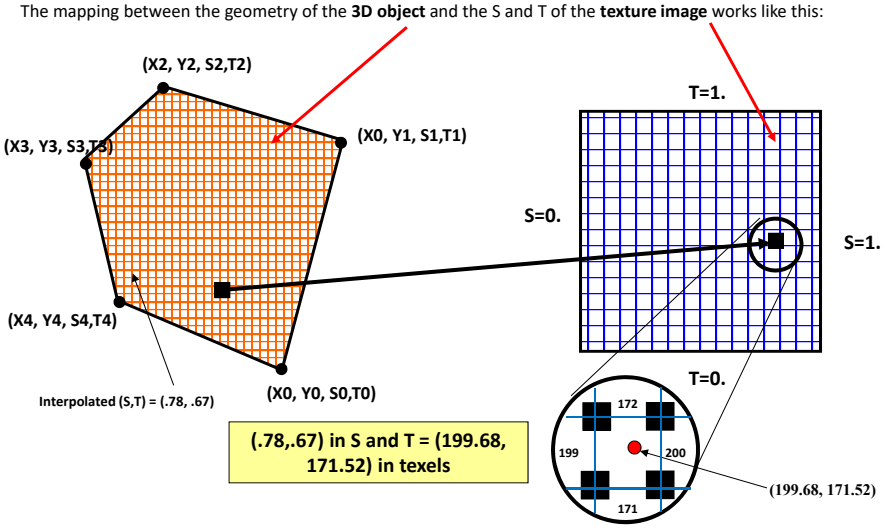
Texture mapping is a computer graphics operation in which a separate image, referred to as the **texture**, is stretched onto a piece of 3D geometry and follows it however it is transformed. This image is also known as a ***texture map***. This can be most any image. At one time, some graphics hardware required the image's pixel dimensions to be a ***power of two***. This restriction has been lifted on most (all?) graphics cards, but just to be safe… The X and Y dimensions did not need to be the *same* power of two, just a power of two. So, a 128x512 image would have been OK; a 129x511 image might not have.

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

Enable texture mapping:

```
glEnable( GL_TEXTURE_2D );
```

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

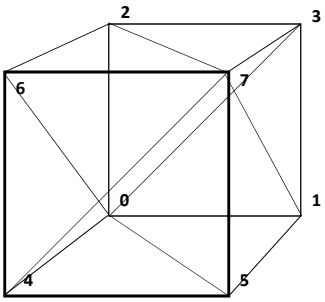
```
glBegin( GL_POLYGON );
        glTexCoord2f( s0, t0 );
        glNormal3f( nx0, ny0, nz0 );
        glVertex3f( x0, y0, z0 );

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

        . . .
glEnd( );
```

Disable texture mapping:

```
glDisable( GL_TEXTURE_2D );
```

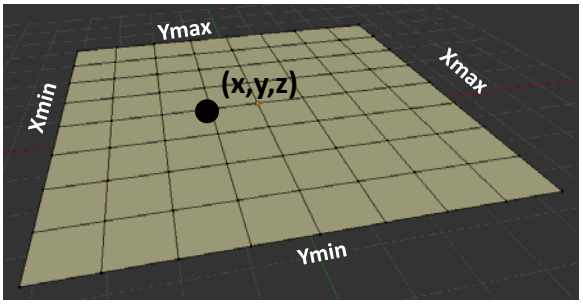
Triangles in an Array of Structures


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

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

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

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



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

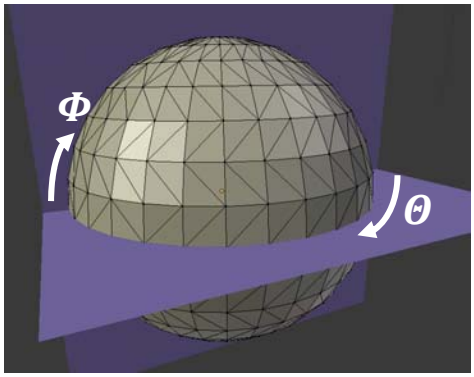
The easiest way to figure out what s and t are at a particular vertex is to figure out what fraction across the object the vertex is living at. For a plane,



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

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

Or, for a sphere,



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

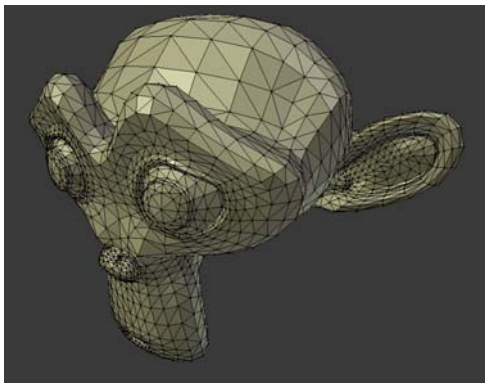
From the Sphere code:

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

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

281

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



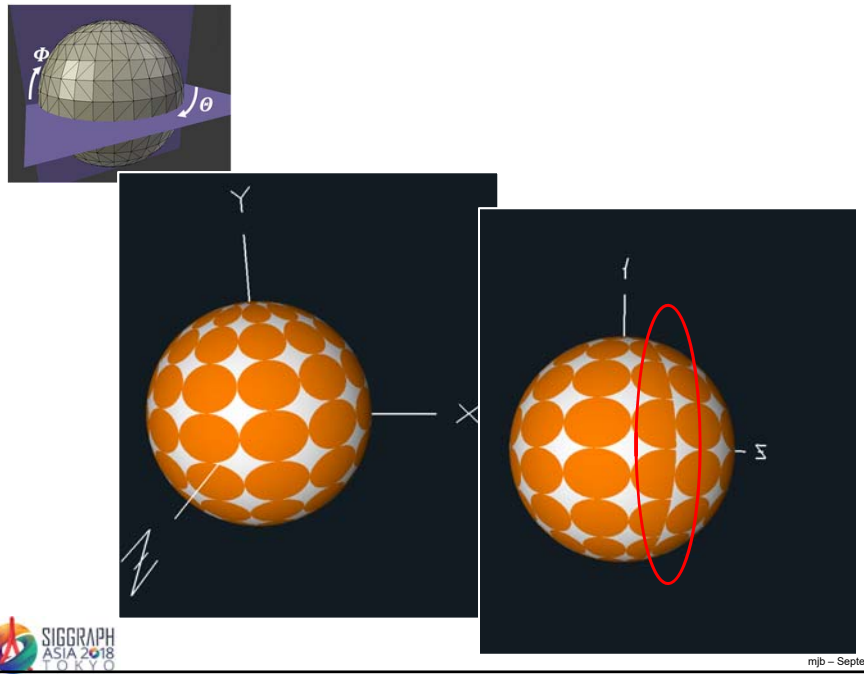
$s = ?$ $t = ?$

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

282

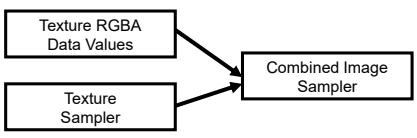
Be careful where *s* abruptly transitions from 1. back to 0.

283



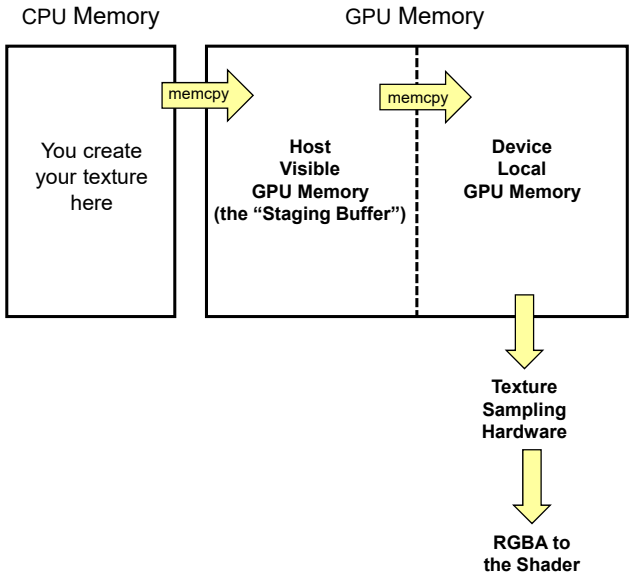
284

```
VkDescriptorSetLayoutBinding          TexSamplerSet[1];
        TexSamplerSet[0].binding              = 0;
        TexSamplerSet[0].descriptorType       = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
                                // uniform sampler2D uSampler
                                // vec4 rgba = texture( uSampler, vST );
        TexSamplerSet[0].descriptorCount      = 1;
        TexSamplerSet[0].stageFlags           = VK_SHADER_STAGE_FRAGMENT_BIT;
        TexSamplerSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    . . .

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

    . . .

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 = &vdii0;
        vwds3.pTexelBufferView = (VkBufferView *)nullptr;
```



Memory Types

285



Memory Types

286

NVIDIA Discrete Graphics:

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

Intel Integrated Graphics:

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

Texture Sampling Parameters

287

```
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 );
```

OpenGL

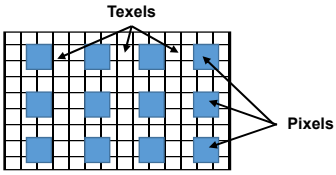
```
VkSamplerCreateInfo                     vsci;
        vsci.magFilter = VK_FILTER_LINEAR;
        vsci.minFilter  = VK_FILTER_LINEAR;
        vsci.mipmapMode    = VK_SAMPLER_MIPMAP_MODE_LINEAR;
        vsci.addressModeU  = VK_SAMPLER_ADDRESS_MODE_REPEAT;
        vsci.addressModeV  = VK_SAMPLER_ADDRESS_MODE_REPEAT;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

        . . .

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

Vulkan

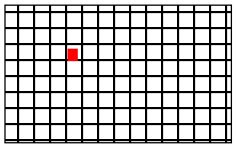
Textures' Undersampling Artifacts

288

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.

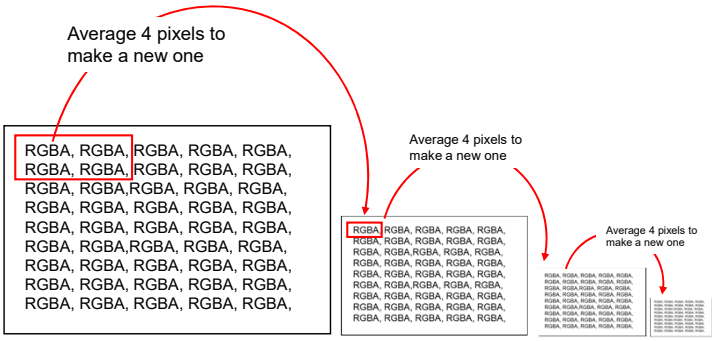


Consider a texture that consists of one red texel and all the rest white. It is easy to imagine an object rendered with that texture as ending up all *white*, with the red texel having never been included in the final image. The solution is to create lower-resolutions of the same texture so that the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



Texture Mip*-mapping

289



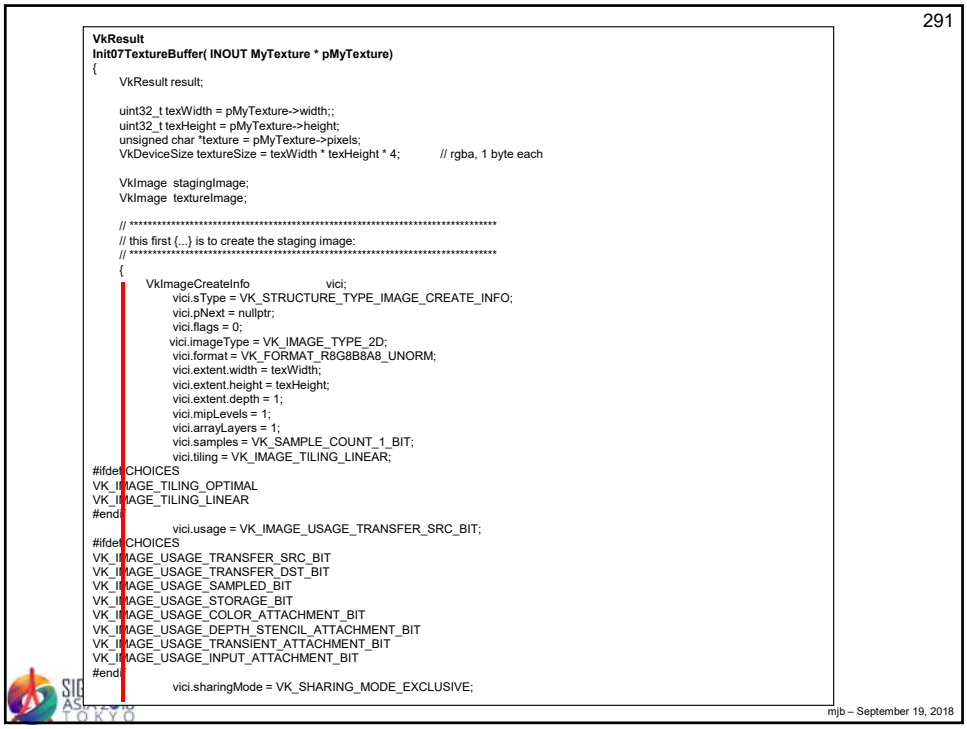
- Total texture storage is ~ 2x what it was without mip-mapping
- Graphics hardware determines which level to use based on the texels : pixels ratio.
- In addition to just picking one mip-map level, the rendering system can sample from two of them, one less that the T:P ratio and one more, and then blend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

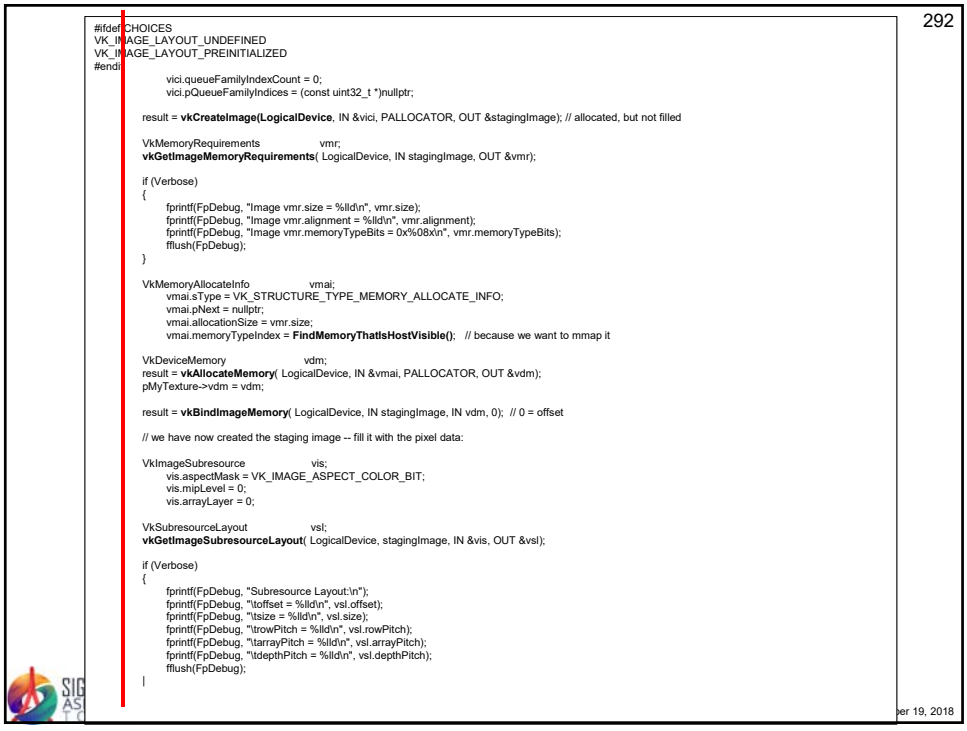
* Latin: *multim in parvo*, “many things in a small place”

290

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

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

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

enable comparison against a reference value during lookups


291
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;
mjb – September 19, 2018


292
#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);
}
er 19, 2018

293

```
	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);

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

294

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

295

```
// 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 = 0;
		vimb.dstAccessMask = 0T;
		vimb.subresourceRange = visr;

	vkCmdPipelineBarrier( TextureCommandBuffer,
			VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_FRAG<EMT_SHADER_BIT, 0,
			0, (VkMemoryBarrier *)nullptr,
			0, (VkBufferMemoryBarrier *)nullptr,
			1, IN &vimb );
}
// *************************************************************************
```

296

```
// *************************************************************************
// 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 = 0;
		vimb.subresourceRange = visr;

	vkCmdPipelineBarrier( TextureCommandBuffer,
		VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_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;
```

297

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

298

```
// ********************************************************************************
// 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:

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

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

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

	return result;
}
```

Note that, at this point, the CPU buffer and the GPU Staging Buffer are no longer needed, and can be destroyed.

Reading in a Texture from a BMP File

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

...

MyTexture	MyPuppyTexture;
```

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

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

301

Physical Devices

Mike Bailey

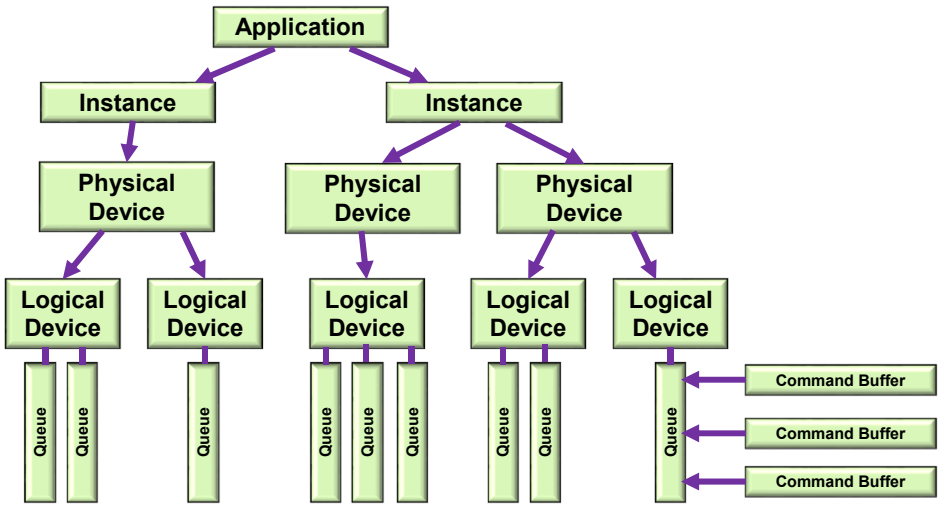
Oregon State University

mjb@cs.oregonstate.edu

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

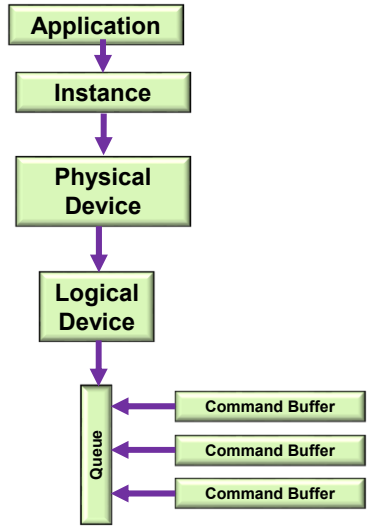
302

Vulkan: Overall Block Diagram



303

Vulkan: a More Typical (and Simplified) Block Diagram



304

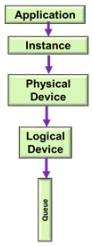
Querying the Number of Physical Devices

```
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




```
VkResult result = VK_SUCCESS;

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

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

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

Which Physical Device to Use, I


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

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

Asking About the Physical Device's Features


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

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

Here's What the NVIDIA 1080ti Produced


```
vkEnumeratePhysicalDevices:

Device  0:
        API version: 4194360
        Driver version: 4194360
        Vendor ID: 0x10de
        Device ID: 0x1b06
        Physical Device Type: 2 = (Discrete GPU)
        Device Name: GeForce GTX 1080 Ti
        Pipeline Cache Size: 13
Device #0 selected ('GeForce GTX 1080 Ti')

Physical Device Features:
geometryShader =  1
tessellationShader =  1
multiDrawIndirect =  1
wideLines =  1
largePoints =  1
multiViewport =  1
occlusionQueryPrecise =  1
pipelineStatisticsQuery =  1
shaderFloat64 =  1
shaderInt64 =  1
shaderInt16 =  0
```

Here's What the Intel HD Graphics 520 Produced


```
vkEnumeratePhysicalDevices:

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

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

Which Physical Device to Use, II


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

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

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

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

Asking About the Physical Device's Different Memories


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

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

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

Here's What I Got


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

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

Asking About the Physical Device's Queue Families


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

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

Here's What I Got


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

315

Logical Devices

Mike Bailey

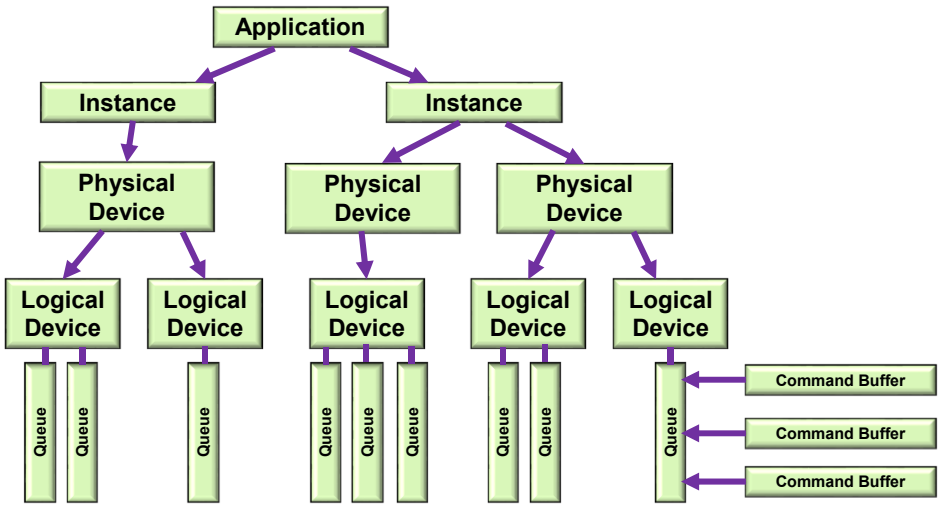
Oregon State University

mjb@cs.oregonstate.edu

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

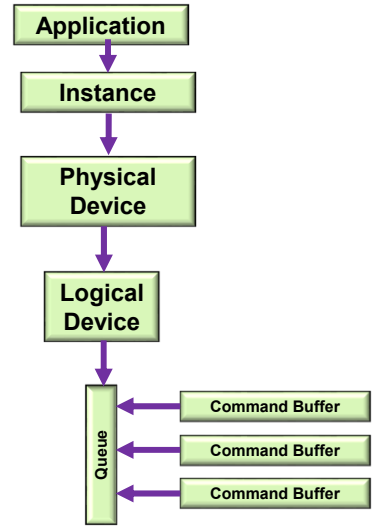
316

Vulkan: Overall Block Diagram



Vulkan: a More Typical (and Simplified) Block Diagram

317



Looking to See What Device Layers are Available

318

```
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);
```

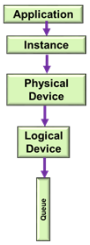
Looking to See What Device Extensions are Available


```
// 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


```
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':
```

Vulkan: Specifying a Logical Device Queue




```
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;
```

Vulkan: Creating a Logical Device


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

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

Vulkan: Creating the Logical Device's Queue


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

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

Layers and Extensions

Mike Bailey

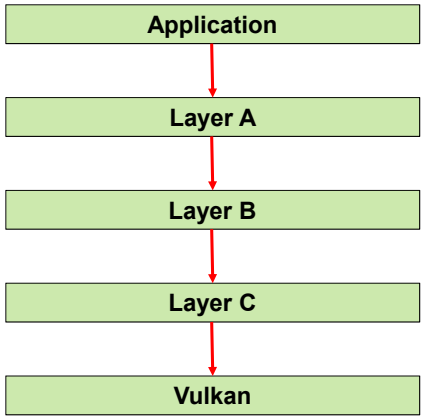
Oregon State University

mjb@cs.oregonstate.edu

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

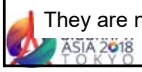
Vulkan Layers

325



Layers are code that can be installed between the Application and Vulkan. Normally, Vulkan is meant to run "flat out". Layers can take the extra time to perform useful functions like printing debugging messages, printing function calls, etc.

They are not always necessary, but when you need them, you will be really glad they are there!



Looking to See What Instance Layers and Instance Extensions are Available

326

```
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 );
```

327

```
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'
```

328

```
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'
```

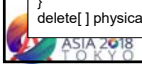
Looking to See What Extensions are Both Wanted and Available


```
// 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

331

```
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;
```



332

```
 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;
```

```
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",
};
```


```
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;
```

335

```
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':
```

336

```
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':
```

337

Synchronization

Mike Bailey

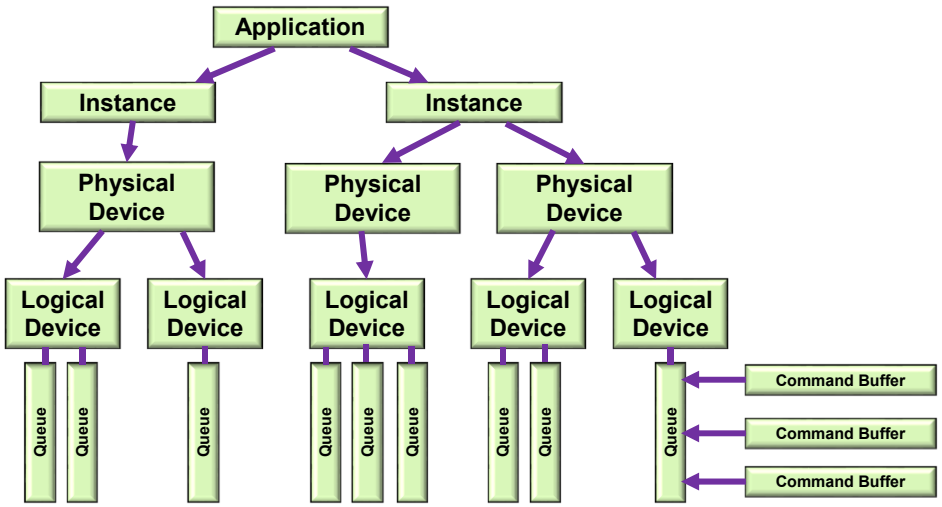
Oregon State University

mjb@cs.oregonstate.edu

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

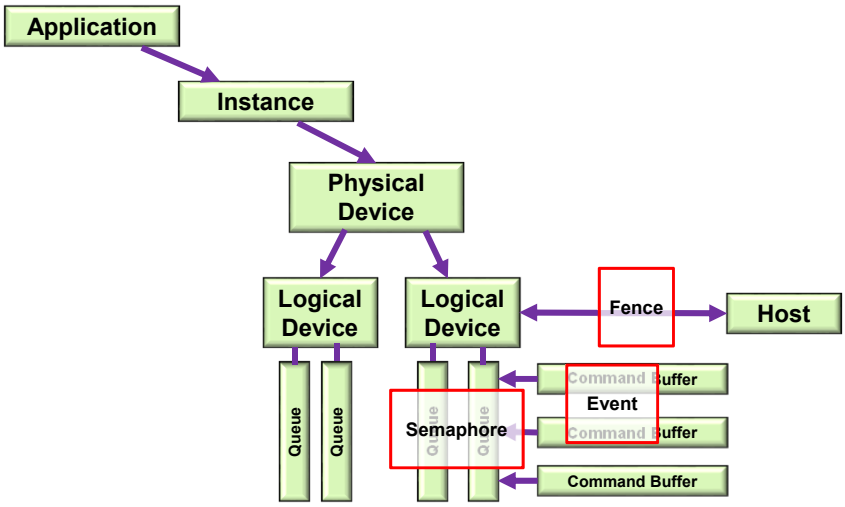
338

Remember the Overall Block Diagram?



Vulkan Highlights: Overall Block Diagram

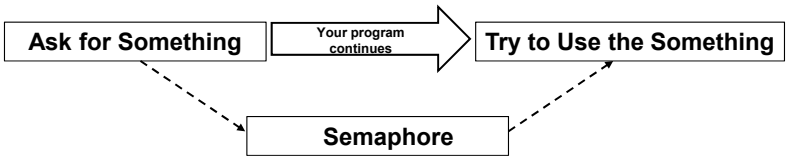
339



Semaphores

340

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



Creating a Semaphore


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

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

Semaphores Example during the Render Loop


```
VkSemaphore imageReadySemaphore;

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

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

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

    . . .

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

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

Could be an array of semaphores

Fences

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

Fences


```
#define VK_FENCE_CREATE_UNSIGNALED_BIT        0

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

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

        , , ,

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

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

Could be an array of fences

Fence Example


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

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;

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

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

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

        . . .

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

        . . .

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

Events

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

Controlling Events from the Host

347

```
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 CPU cannot *block* waiting for an event, but it can test for one

Controlling Events from the Device

348

```
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 GPU cannot *test* for an event, but it can block waiting for one

Pipeline Barriers:
A case of Gate-ing and Wait-ing

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

From the Command Buffer Notes:
These are the Commands that can be entered into the Command Buffer, I

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

We don't any one of these commands to have to wait on a previous command unless you say so. In general, we want all of these commands to be able to run **"flat-out".**

But, if we do that, surely there will be nasty **race conditions**!

From the Command Buffer Notes: These are the Commands that can be entered into the Command Buffer, II


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

We don't any one of these commands to have to wait on a previous command unless you say so. In general, we want all of these commands to be able to run **"flat-out".**

But, if we do that, surely there will be nasty **race conditions**!

Potential Memory Race Conditions that Pipeline Barriers can Prevent

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

Note: there is no problem with Read-then-Read (RtR) as no data has been changed

vkCmdPipelineBarrier( ) Function Call

353

A **Pipeline Barrier** is a way to establish a memory dependency between commands that were submitted before the barrier and commands that are submitted after the barrier

```
vkCmdPipelineBarrier( commandBuffer,
        srcStageMask,
        dstStageMask,
        VK_DEPENDENCY_BY_REGION_BIT,
        memoryBarrierCount,             pMemoryBarriers,
        bufferMemoryBarrierCount,       pBufferMemoryBarriers,
        imageMemoryBarrierCount,        pImageMemoryBarriers
);
```

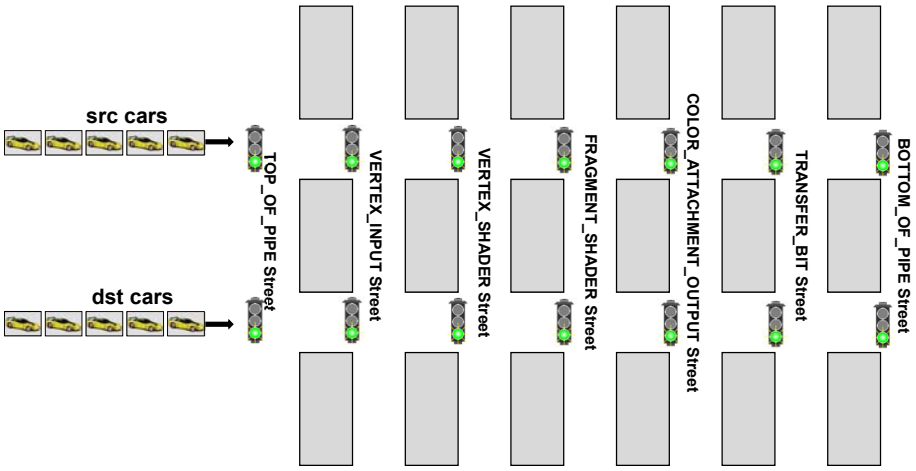
Guarantee that this pipeline stage has completely generated one set of data before …

… allowing this pipeline stage to consume it

Defines what data we will be blocking/un-blocking on

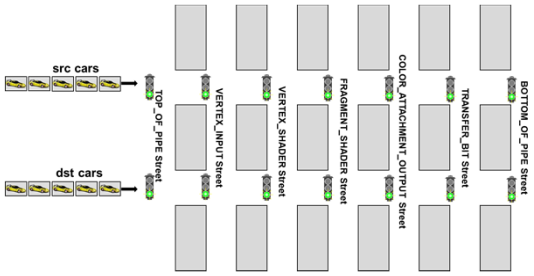
The Scenario

354



The Scenario Rules

355



1. The cross-streets are named after pipeline stages
2. All traffic lights start out green ("we want all of these commands to be able to run flat-out")
3. There are special sensors at all intersections that will know when the ***first car in the src group*** enters that intersection
4. There are connections from those sensors to the traffic lights so that when the ***first car in the src group*** enters its intersection, the ***dst*** traffic light will be turned red
5. When the ***last car in the src group*** completely makes it through its intersection, the ***dst*** traffic light can be turned back to green
6. The Vulkan command pipeline ordering is this: (1) the **src** cars get released, (2) the pipeline barrier is invoked (which turns some lights red), (3) the **dst** cars get released (which end up being stopped by a red light somewhere), (4) the src cars clear their intersection, (5) the dst cars get released

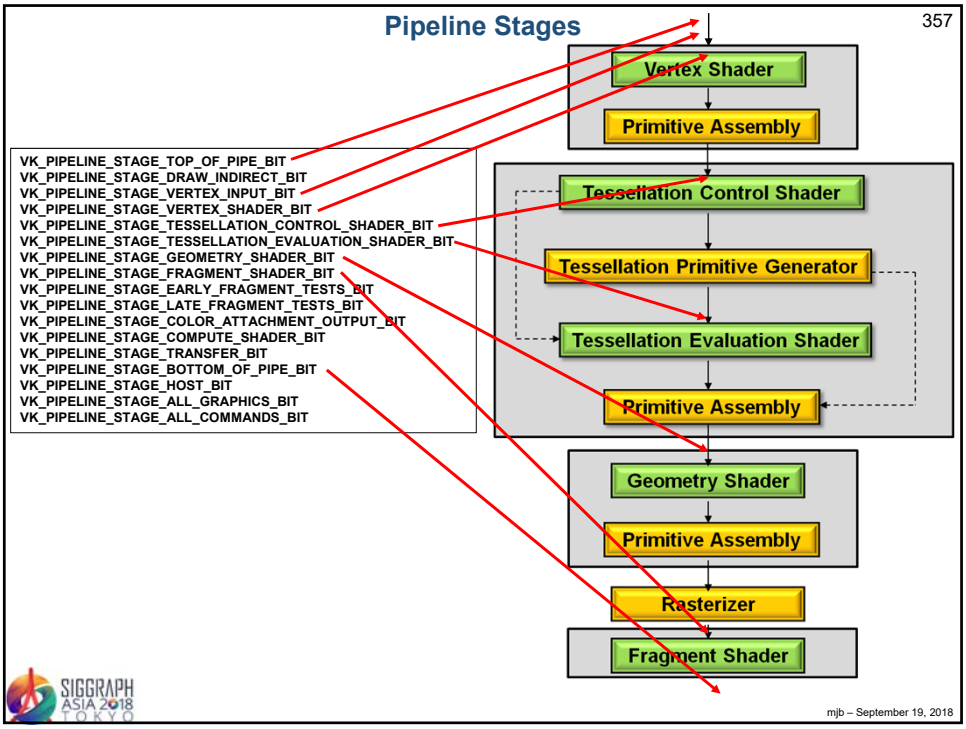
Pipeline Stage Masks – Where in the Pipeline is this Memory Data being Generated or Consumed?

356

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
- VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
- VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
- VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
- VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
- VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
- VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
- VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
- VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
- VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
- VK_PIPELINE_STAGE_TRANSFER_BIT
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT
- VK_PIPELINE_STAGE_HOST_BIT
- VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
- VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Pipeline Stages

357



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

358

VK_ACCESS_INDIRECT_COMMAND_READ_BIT
VK_ACCESS_INDEX_READ_BIT
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT
VK_ACCESS_UNIFORM_READ_BIT
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT
VK_ACCESS_SHADER_READ_BIT
VK_ACCESS_SHADER_WRITE_BIT
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT
VK_ACCESS_TRANSFER_READ_BIT
VK_ACCESS_TRANSFER_WRITE_BIT
VK_ACCESS_HOST_READ_BIT
VK_ACCESS_HOST_WRITE_BIT
VK_ACCESS_MEMORY_READ_BIT
VK_ACCESS_MEMORY_WRITE_BIT

Pipeline Stages and what Access Operations can Happen There

359

		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														●	●		

mjb – September 19, 2018

Access Operations and what Pipeline Stages they can be used In

360

		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															

mjb – September 19, 2018

Example: Be sure we are done writing an output image before using it for something else

361

Stages

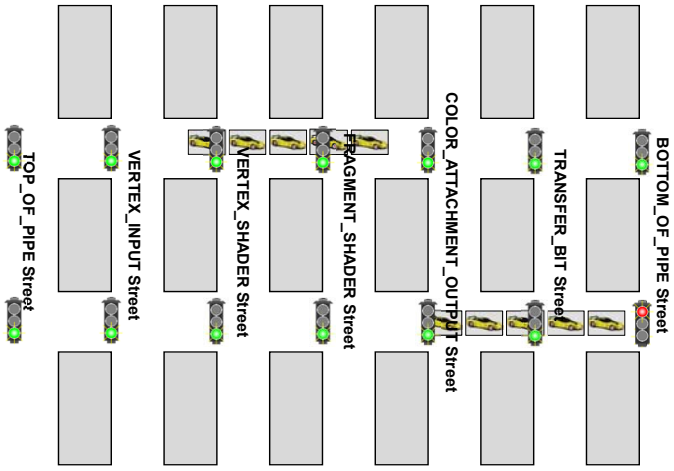
VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT ← src
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT ← dst
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

The Scenario

362

src cars are generating the image

dst cars are doing something with that image



Example: Don't read a buffer back to the host until a shader is done writing it

VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
VK_PIPELINE_STAGE_VERTEX_SHADER_BIT ← **src**
VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT ← **dst**
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

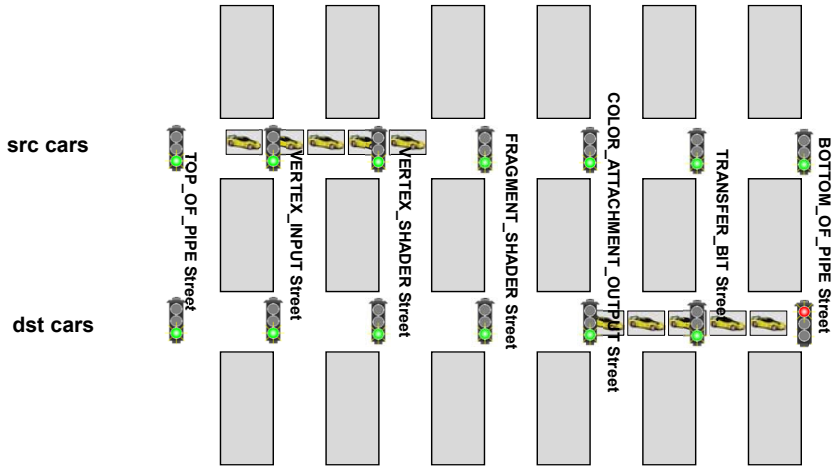
Stages

VK_ACCESS_INDIRECT_COMMAND_READ_BIT
VK_ACCESS_INDEX_READ_BIT
VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT
VK_ACCESS_UNIFORM_READ_BIT
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT
VK_ACCESS_SHADER_READ_BIT
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

Access types

dst (no access setting needed)

The Scenario



VkImageLayout – How an Image gets Laid Out in Memory depends on how it will be Used


```
VkImageMemoryBarrier            vimb'
        vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
        vimb.pNext = nullptr;
        vimb.srcAccessMask = ??;
        vimb.dstAccessMask = ??;
        vimb.oldLayout   = ??;
        vimb.newLayout = ??;
        vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
        vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
        vimb.image = ??;
        vimb.subresourceRange = visr;
```

VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_GENERAL
VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL ← Used as a color attachment
VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL
VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL ← Read into a shader as a texture
VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL ← Copy from
VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL ← Copy to
VK_IMAGE_LAYOUT_PREINITIALIZED
VK_IMAGE_LAYOUT_PRESENT_SRC_KHR ← Show image to viewer
VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR

Here, the use of vkCmdPipelineBarrier( ) is to simply change the layout of an image

Push Constants

Mike Bailey
Oregon State University
mjb@cs.oregonstate.edu
http://cs.oregonstate.edu/~mjb/vulkan

Push Constants

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

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

Push Constants

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

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

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

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

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

size is in bytes

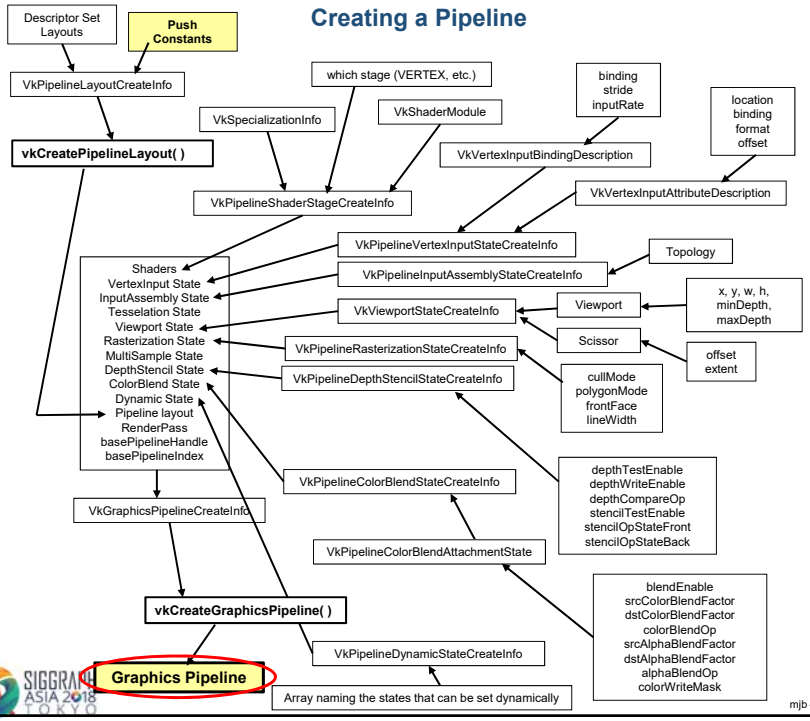
pValues is a void * pointer to the data, which in this 4x4 matrix example, would be of type **glm::mat4**.

Setting up the Push Constants for the Pipeline Structure

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

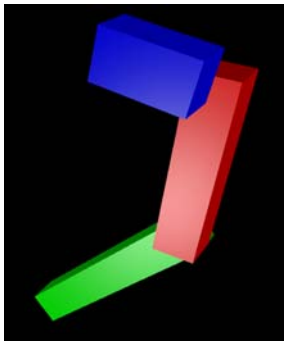
```
VkPushConstantRange                 vpcr[1];
    vpcr[0].stageFlags =
            VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
          | VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
    vpcr[0].offset = 0;
    vpcr[0].size = sizeof( glm::mat4 );

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

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


Creating a Pipeline



An Robotic Example using Push Constants

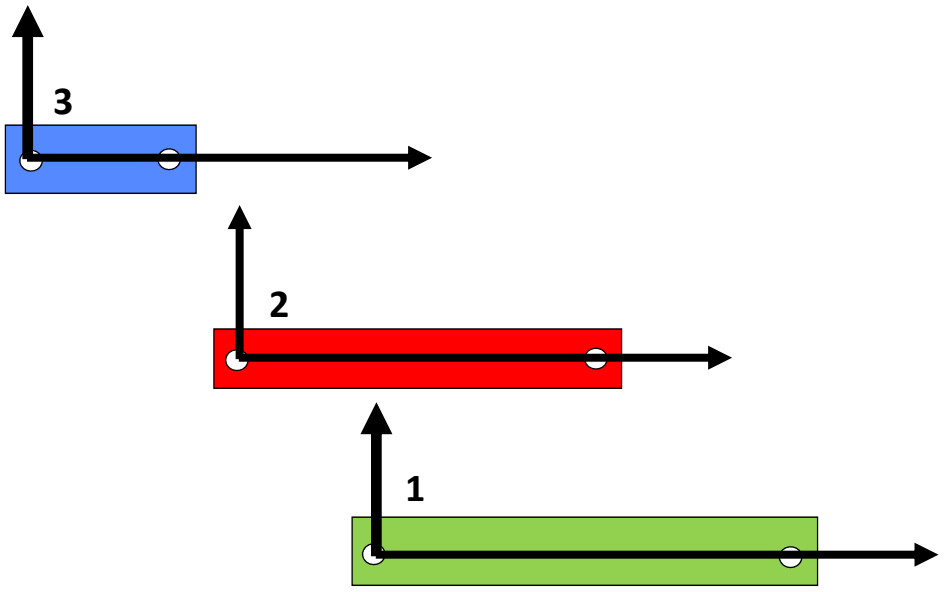
A robotic animation (i.e., a hierarchical transformation system)



Where each arm is represented by:

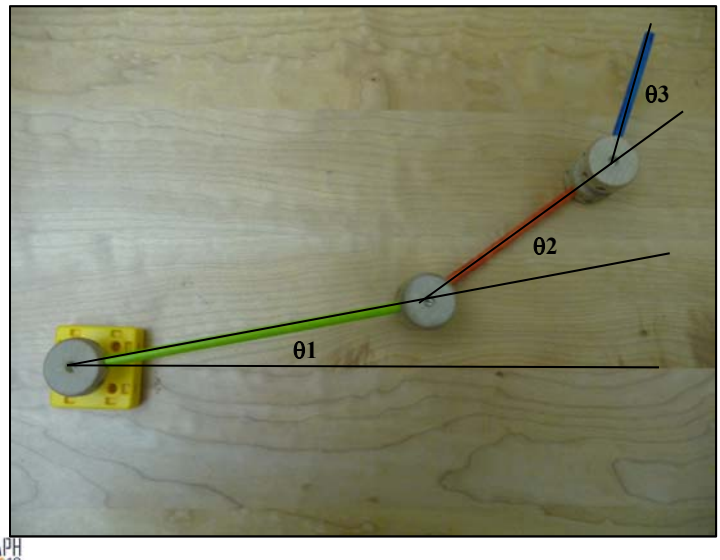
```
struct arm
{
        glm::mat4   armMatrix;
        glm::vec3   armColor;
        float          armScale;     // scale factor in x
};

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


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



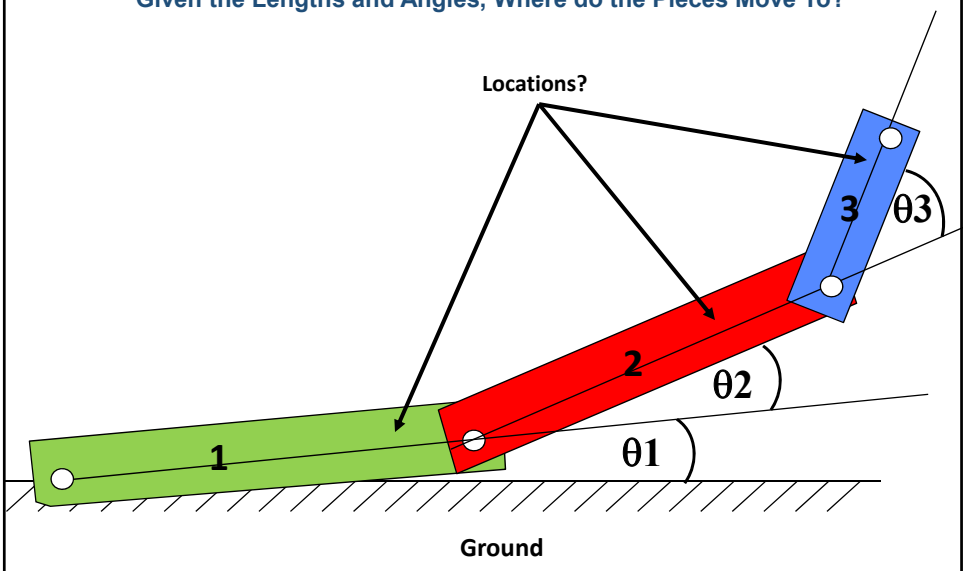
Forward Kinematics:
Hook the Pieces Together, Change Parameters, and Things Move
(All Young Children Understand This)

373



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

374



375

Positioning Part #1 With Respect to Ground

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

Write it

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

Say it

376

Why Do We Say it Right-to-Left?

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 multiples it *last*

377

Positioning Part #2 With Respect to Ground

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

Write 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

378

Positioning Part #3 With Respect to Ground

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 $T_{1/G}$

Write 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

In the *Reset* Function


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

. . .

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

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

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

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

Setup the Push Constant for the Pipeline Structure

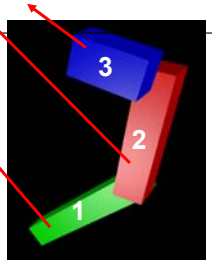

```
VkPushConstantRange                 vpcr[1];
        vpcr[0].stageFlags =
                VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
              | VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
        vpcr[0].offset = 0;
        vpcr[0].size = sizeof( struct arm );

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

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

In the *UpdateScene* Functiom


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

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

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

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

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

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

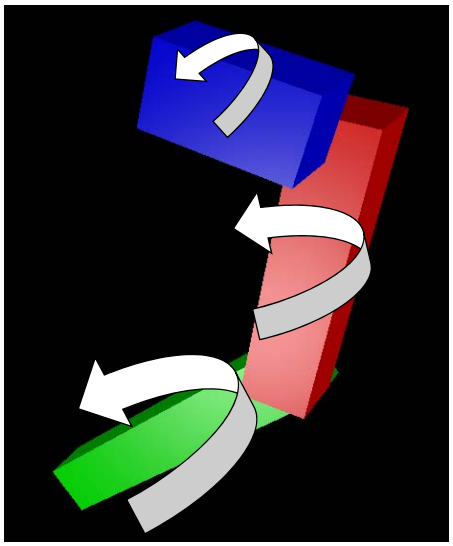
In the *RenderScene* Function


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

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

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


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


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



In the Vertex Shader


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

layout( location = 0 ) in vec3 aVertex;

	. . .

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

	. . .

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

385

Antialiasing and Multisampling

Mike Bailey

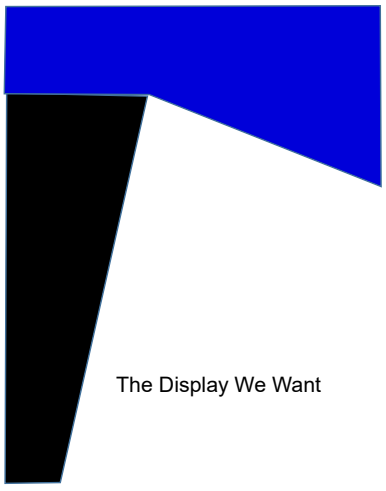
Oregon State University

mjb@cs.oregonstate.edu

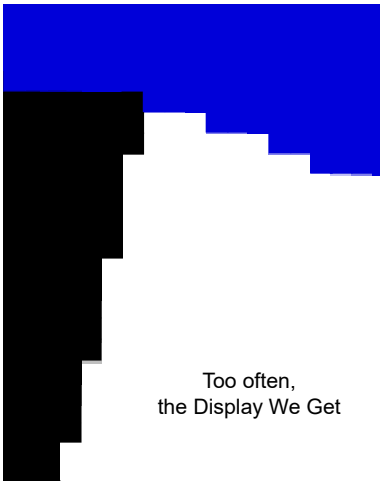
http://cs.oregonstate.edu/~mjb/vulkan

386

Aliasing



The Display We Want

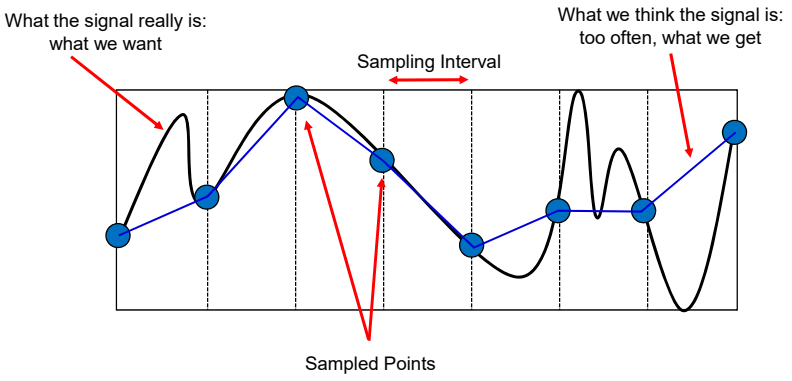


Too often,
the Display We Get

387

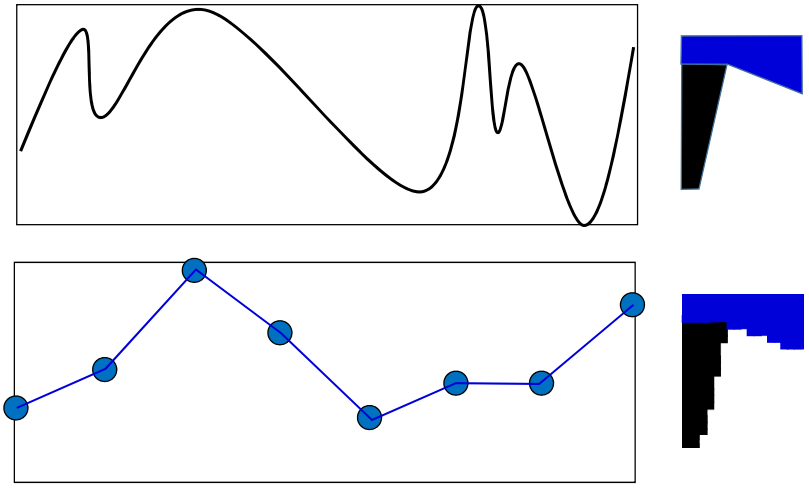
Aliasing

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



388

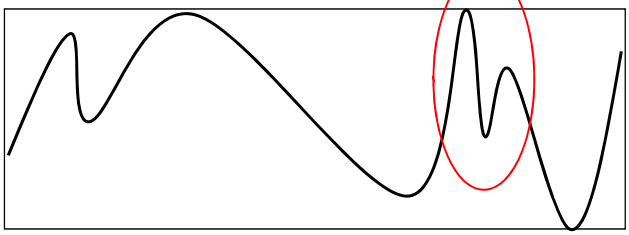
Aliasing



389

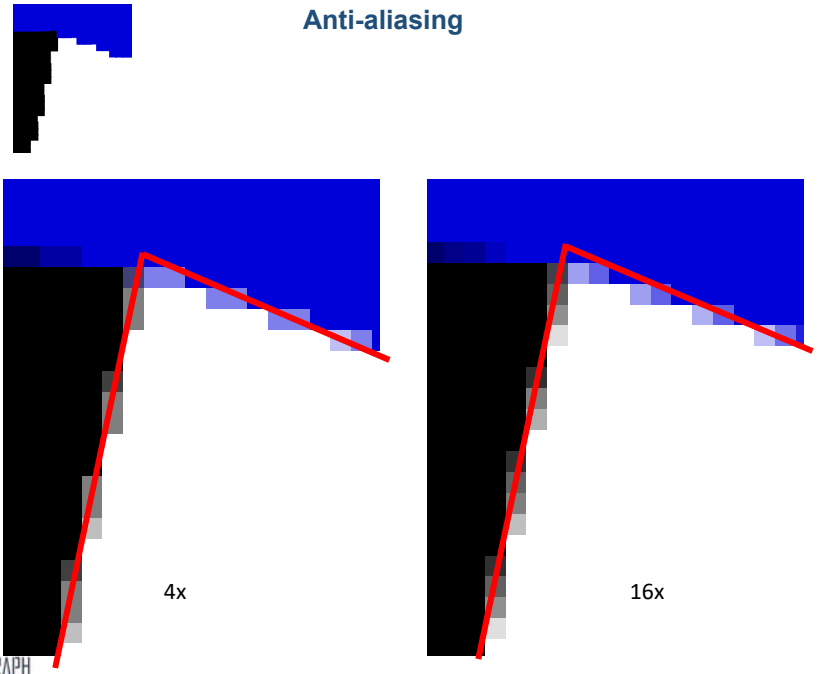
Nyquist Criterion

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



390

Anti-aliasing



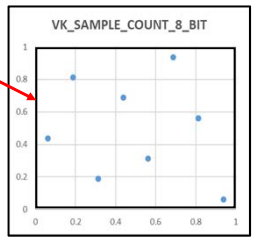
MultiSampling

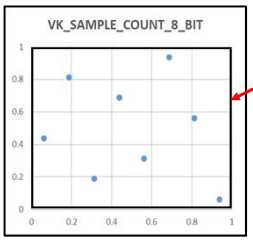
391

Multisampling is a computer graphics technique to improve the quality of your output image by looking inside every pixel to see what the rendering is doing there. There are two approaches:

1. **Supersampling**: Pick some number of unique sub-pixels within a pixel, render the image at each of these individual sub-pixels (including depth and stencil tests), then average them together. This results in lots of renders.

One entire pixel





One entire pixel

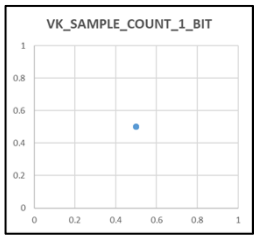
2. **Multisampling**: Perform a single color render for the one entire pixel. Then, pick some number of unique sub-pixels within that pixel and perform depth and stencil tests there. Assign the single color to all the sub-pixels that made it through the depth and stencil tests

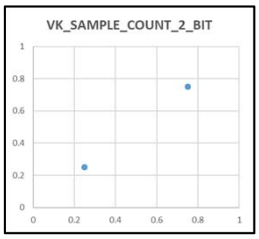
Note: per-sample depth and stencil tests are performed first to decide which color renders actually should be done

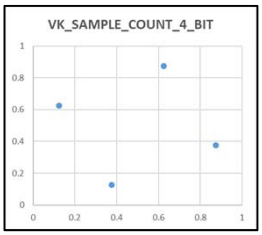
mjb – September 19, 2018

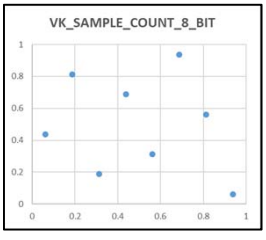
Vulkan Distribution of Sampling Points within a Pixel

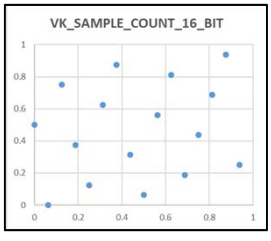
392











mjb – September 19, 2018

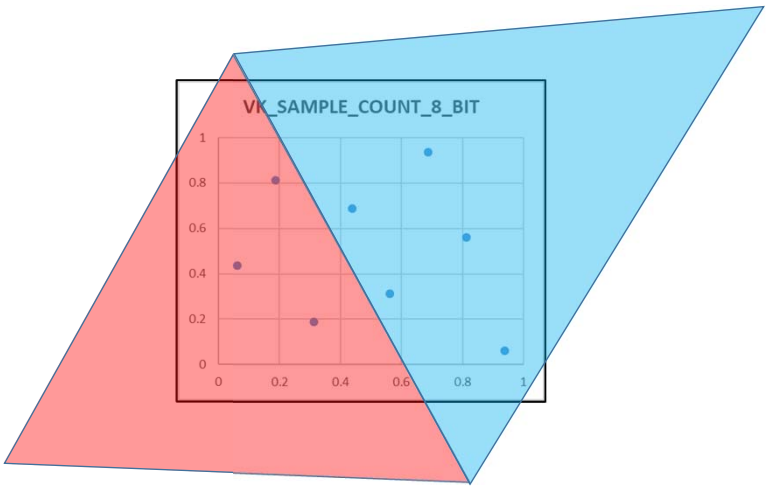
Vulkan Distribution of Sampling Points within a Pixel

393

VK_SAMPLE_COUNT_1_BIT	VK_SAMPLE_COUNT_2_BIT	VK_SAMPLE_COUNT_4_BIT	VK_SAMPLE_COUNT_8_BIT	VK_SAMPLE_COUNT_16_BIT
(0.5,0.5)	(0.25,0.25)	(0.375, 0.125)	(0.5625, 0.3125)	(0.5625, 0.5625)
	(0.75,0.75)	(0.875, 0.375)	(0.4375, 0.6875)	(0.4375, 0.3125)
		(0.125, 0.625)	(0.8125, 0.5625)	(0.3125, 0.625)
		(0.625, 0.875)	(0.3125, 0.1875)	(0.75, 0.4375)
			(0.1875, 0.8125)	(0.1875, 0.375)
			(0.0625, 0.4375)	(0.625, 0.8125)
			(0.6875, 0.9375)	(0.8125, 0.6875)
			(0.9375, 0.0625)	(0.6875, 0.1875)
				(0.375, 0.875)
				(0.5, 0.0625)
				(0.25, 0.125)
				(0.125, 0.75)
				(0.0, 0.5)
				(0.9375, 0.25)
				(0.875, 0.9375)
				(0.0625, 0.0)

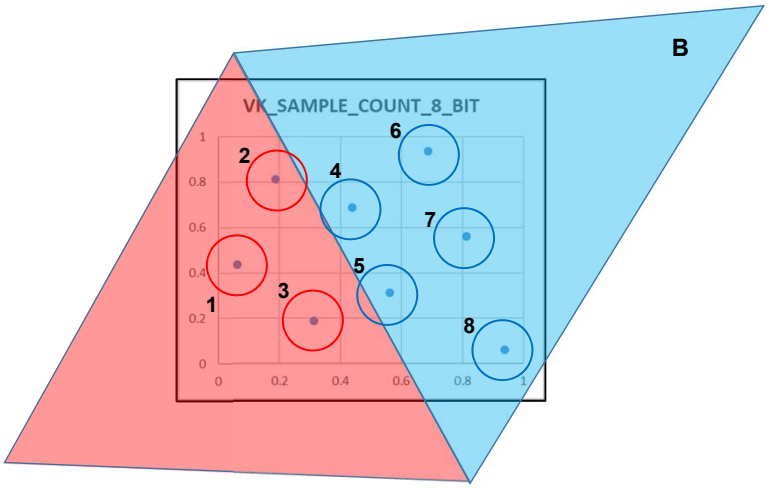
Consider Two Triangles Whose Edges Pass Through the Same Pixel

394



395

Supersampling

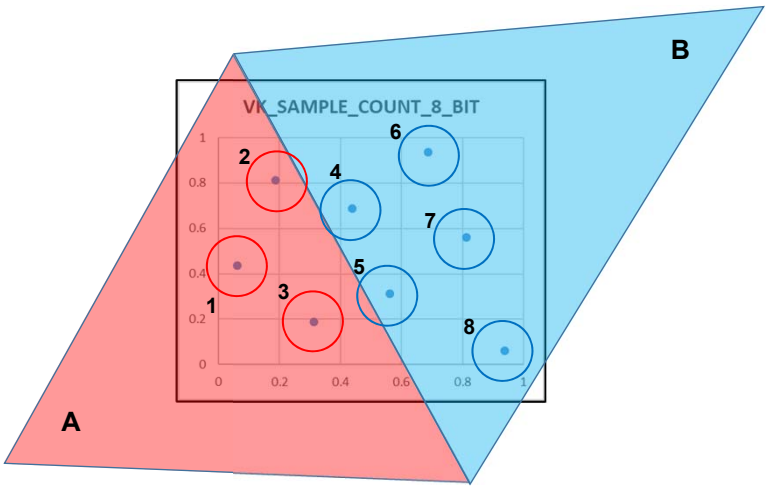


$$Final\ Pixel\ Color = \frac{\sum_{i=1}^{8} Color\ sample\ from\ subpixel_i}{8}$$

Fragment Shader calls = 8

396

Multisampling



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

Fragment Shader calls = 2

Setting up the Image

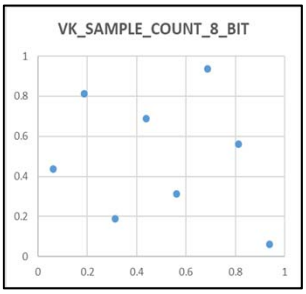

```
VkPipelineMultisampleStateCreateInfo            vpmsci;
        vpmsci.sType = VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO;
        vpmsci.pNext = nullptr;
        vpmsci.flags = 0;
        vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_8_BIT;
        vpmsci.sampleShadingEnable = VK_TRUE;
        vpmsci.minSampleShading = 0.5f;
        vpmsci.pSampleMask = (VkSampleMask *)nullptr;
        vpmsci.alphaToCoverageEnable = VK_FALSE;
        vpmsci.alphaToOneEnable = VK_FALSE;

 VkGraphicsPipelineCreateInfo                   vgpci;
        vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
        vgpci.pNext = nullptr;
    . . .
        vgpci.pMultisampleState = &vpmsci;

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

How dense is the sampling

VK_TRUE means to allow some sort of multisampling to take place

Setting up the Image


```
VkPipelineMultisampleStateCreateInfo            vpmsci;
        . . .
        vpmsci.minSampleShading = 0.5;
        . . .
```



At least this fraction of samples will get their own fragment shader calls (as long as they pass the depth and stencil tests).

0. produces simple multisampling

(0.,1.) produces partial supersampling

1. Produces complete supersampling

399

Setting up the Image

```
VkAttachmentDescription                 vad[2];
        vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
        vad[0].samples = VK_SAMPLE_COUNT_8_BIT;
        vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
        vad[0].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
        vad[0].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[0].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[0].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[0].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
        vad[0].flags = 0;

        vad[1].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
        vad[1].samples = VK_SAMPLE_COUNT_8_BIT;
        vad[1].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
        vad[1].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[1].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[1].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[1].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[1].finalLayout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
        vad[1].flags = 0;

VkAttachmentReference                   colorReference;
        colorReference.attachment = 0;
        colorReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   depthReference;
        depthReference.attachment = 1;
        depthReference.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
```

400

Setting up the Image

```
VkSubpassDescription                    vsd;
        vsd.flags = 0;
        vsd.pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd.inputAttachmentCount = 0;
        vsd.pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd.colorAttachmentCount = 1;
        vsd.pColorAttachments = &colorReference;
        vsd.pResolveAttachments = (VkAttachmentReference *)nullptr;
        vsd.pDepthStencilAttachment = &depthReference;
        vsd.preserveAttachmentCount = 0;
        vsd.pPreserveAttachments = (uint32_t *)nullptr;

VkRenderPassCreateInfo                  vrpci;
        vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
        vrpci.pNext = nullptr;
        vrpci.flags = 0;
        vrpci.attachmentCount = 2;              // color and depth/stencil
        vrpci.pAttachments = vad;
        vrpci.subpassCount = 1;
        vrpci.pSubpasses = &vsd;
        vrpci.dependencyCount = 0;
        vrpci.pDependencies = (VkSubpassDependency *)nullptr;


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

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

```
VIOffset3D                          vo3;
        vo3.x = 0;
        vo3.y = 0;
        vo3.z = 0;

VkExtent3D                          ve3;
        ve3.width = Width;
        ve3.height = Height;
        ve3.depth = 1;

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

VkImageResolve                      vir;
        vir.srcSubresource = visl;
        vir.srcOffset = vo3;
        vir.dstSubresource = visl;
        vir.dstOffset = vo3;
        vir.extent = ve3;

vkCmdResolveImage( cmdBuffer, srcImage, srcImageLayout,  dstImage, dstImageLayout, 1, &vir  );
```

Multipass Rendering

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

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

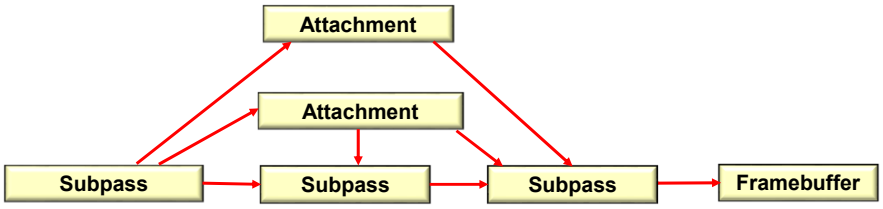
403

"[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:



Back in Our Single-pass Days

404

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 that.

Back in Our Single-pass Days, I

405

```
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;
```

Back in Our Single-pass Days, II

406

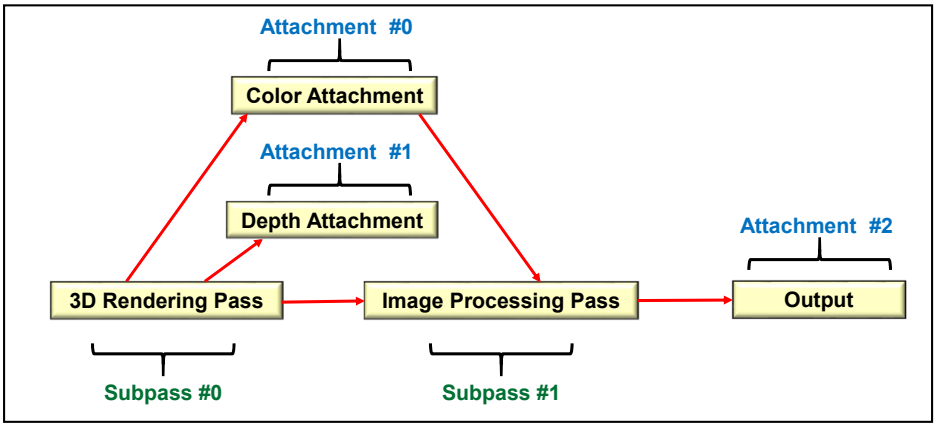
```
VkSubpassDescription                    vsd;
        vsd.flags = 0;
        vsd.pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd.inputAttachmentCount = 0;
        vsd.pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd.colorAttachmentCount = 1;
        vsd.pColorAttachments = &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 );
```

Multipass Rendering

407

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.

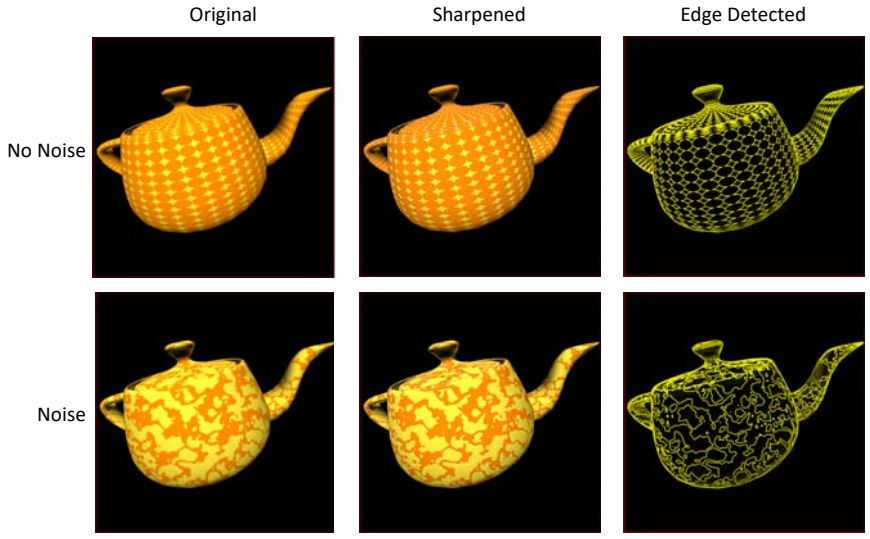
In this case, we will look at following up a 3D rendering with some image processing on the outcome.



Notice how close this resembles a Directed Acyclic Graph (DAG) data structure: nodes connected by arrows that point in one direction

Multipass Algorithm to Render and then Image Process

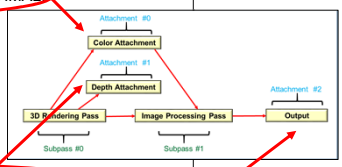
408



Multipass, I

409

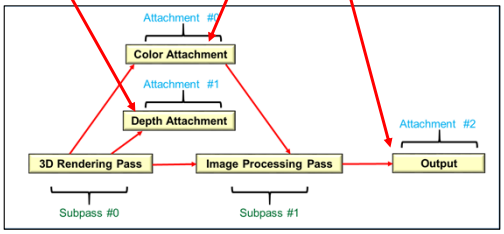
```
VkAttachmentDescription                 vad [ 3 ];
        vad[0].flags = 0;
        vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
        vad[0].samples = VK_SAMPLE_COUNT_1_BIT;
        vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
        vad[0].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
        vad[0].stencilLoadOp = 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_COLOR_ATTACHMENT_OPTIMAL;

        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;

        vad[2].flags = 0;
        vad[2].format = VK_FORMAT_B8G8R8A8_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_DONT_CARE;
        vad[2].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
        vad[2].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
        vad[2].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
        vad[2].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
```



Multipass, II

410

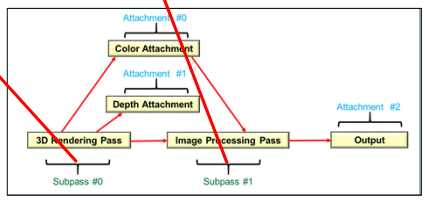
```
VkAttachmentReference                   colorReference;
        colorReference.attachment = 0;
        colorReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   depthReference;
        depthReference.attachment = 1;
        depthReference.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;

VkAttachmentReference                   outputReference;
        outputReference.attachment = 2;
        outputReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;
```



Multipass, III

411

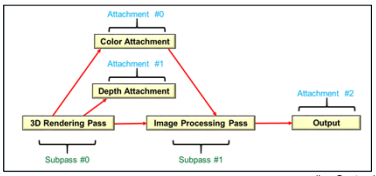
```
VkSubpassDescription                    vsd[2];
        vsd[0].flags = 0;
        vsd[0].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
        vsd[0].inputAttachmentCount = 0;
        vsd[0].pInputAttachments = (VkAttachmentReference *)nullptr;
        vsd[0].colorAttachmentCount = 1;
   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



Multipass, IV

412

```
VkSubpassDependency                     vsdp[1];
        vsdp[0].srcSubpass  = 0;                        // 3D rendering
        vsdp[0].dstSubpass = 1;                         // Image processing
        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;


VkRenderPassCreateInfo                  vrpci;
        vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
        vrpci.pNext = nullptr;
        vrpci.flags = 0;
        vrpci.attachmentCount = 3;   // color, depth/stencil, output
        vrpci.pAttachments = vad;
        vrpci.subpassCount = 2;
        vrpci.pSubpasses = vsd;
        vrpci.dependencyCount = 1;
        vrpci.pDependencies = vsdp;


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

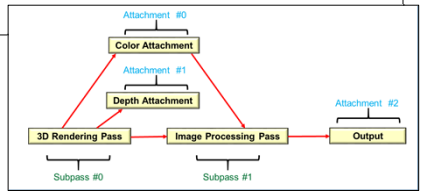


Placing a Pipeline Barrier so an Image is not used before it is Ready


```
VkImageMemoryBarrier            vimb;
        vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
        vimb.pNext = nullptr;
        vimb.oldLayout   = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_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 = VK_ACCESS_COLOR_ATTACHMENT_OUTPUT_BIT;
        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);
```

Multipass, V


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

// first subpass 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 );

// second subpass is started here – doesn't need any new drawing vkCmd's

. . .

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );
```



Dynamic State Variables

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

Creating a Pipeline with Dynamically Changeable State Variables

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

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

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

Which Pipeline State Variables can be Changed Dynamically

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

VK_DYNAMIC_STATE_VIEWPORT
VK_DYNAMIC_STATE_SCISSOR
VK_DYNAMIC_STATE_LINE_WIDTH
VK_DYNAMIC_STATE_DEPTH_BIAS
VK_DYNAMIC_STATE_BLEND_CONSTANTS
VK_DYNAMIC_STATE_DEPTH_BOUNDS
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK
VK_DYNAMIC_STATE_STENCIL_REFERENCE

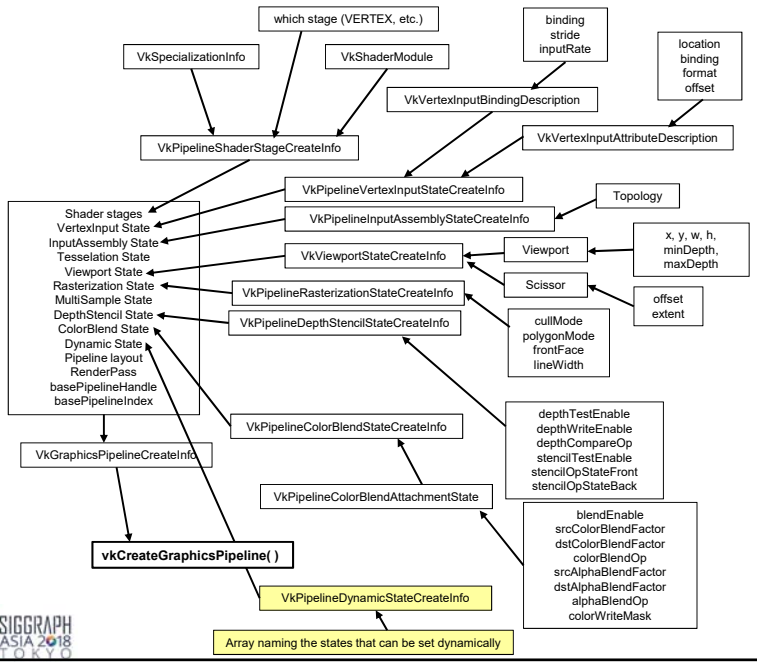
Creating a Pipeline


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


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


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


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

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

Creating a Pipeline

419



Filling State Variables in the Command Buffer

420

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 );
```

Getting Information Back from the Graphics System

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu

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

Setting up Query Pools

There are 3 types of Queries: **Occlusion, Pipeline Statistics, and Timestamp**

Vulkan requires you to first setup “Query Pools”, some for each specific type

This indicates that Vulkan thinks that Queries are time-consuming (relatively) to setup, and thus better to set them up in program-setup than in program-runtime

Setting up Query Pools


```
VkQueryPoolCreateInfo                   vqpci;
        vqpci.sType = VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO;
        vqpci.pNext = nullptr;
        vqpci.flags = 0;
        vqpci.queryType = << one of: >>
                VK_QUERY_TYPE_OCCLUSION
                VK_QUERY_TYPE_PIPELINE_STATISTICS
                VK_QUERY_TYPE_TIMESTAMP
        vqpci.queryCount = 3;
        vqpci.pipelineStatistics = 0;   // bitmask of what stats you are querying for if you
                                        // are doing a pipeline statistics query
VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT
VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT

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

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

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

Resetting, Filling, and Examining a Query Pool


```
vkCmdResetQueryPool( CommandBuffer, occlusionQueryPool, 0, 3 );

vkCmdBeginQuery( CommandBuffer, occlusionQueryPool, 0, VK_QUERY_CONTROL_PRECISE_BIT );

        . . .

vkCmdEndQuery( CommandBuffer, occlusionQueryPool, 0 );

result = vkGetQueryPoolResults( LogicalDevice, occlusionQueryPool, 0, 1, DATASIZE, data, stride, flags );
                // VK_QUERY_RESULT_64_BIT
                // VK_QUERY_RESULT_WAIT_BIT
                // VK_QUERY_RESULT_WITH_AVAILABILTY_BIT
                // VK_QUERY_RESULT_PARTIAL_BIT
                // stride is # of bytes in between each result


vkCmdCopyQueryPoolResults( CommandBuffer, occlusionQueryPool, 0, 1, buffer, 0, stride, flags );
                // VK_QUERY_RESULT_64_BIT
                // VK_QUERY_RESULT_WAIT_BIT
                // VK_QUERY_RESULT_WITH_AVAILABILTY_BIT
                // VK_QUERY_RESULT_PARTIAL_BIT
                // stride is # of bytes in between each result
```

Occlusion Query

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

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

Some hints:

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

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


vkCmdCopyQueryPoolResults( CommandBuffer, occlusionQueryPool, 0, 1,
                                buffer, 0, 0, VK_QUERY_RESULT_WAIT_BIT );
```

Pipeline Statistics Query

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

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


vkCmdCopyQueryPoolResults( CommandBuffer, occlusionQueryPool, 0, 1,
                                buffer, 0, 0, VK_QUERY_RESULT_WAIT_BIT );


VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT
VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT
VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT
VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT
VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT
```

Timestamp Query

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

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


vkCmdCopyQueryPoolResults( CommandBuffer, timestampQueryPool, 0, 1,
                                buffer, 0, 0,
                                 VK_QUERY_RESULT_64_BIT | VK_QUERY_RESULT_WAIT_BIT );
```

Timestamp Query

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

Even though the stages are “bits”, you are supposed to only specify one of them

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

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

Compute Shaders

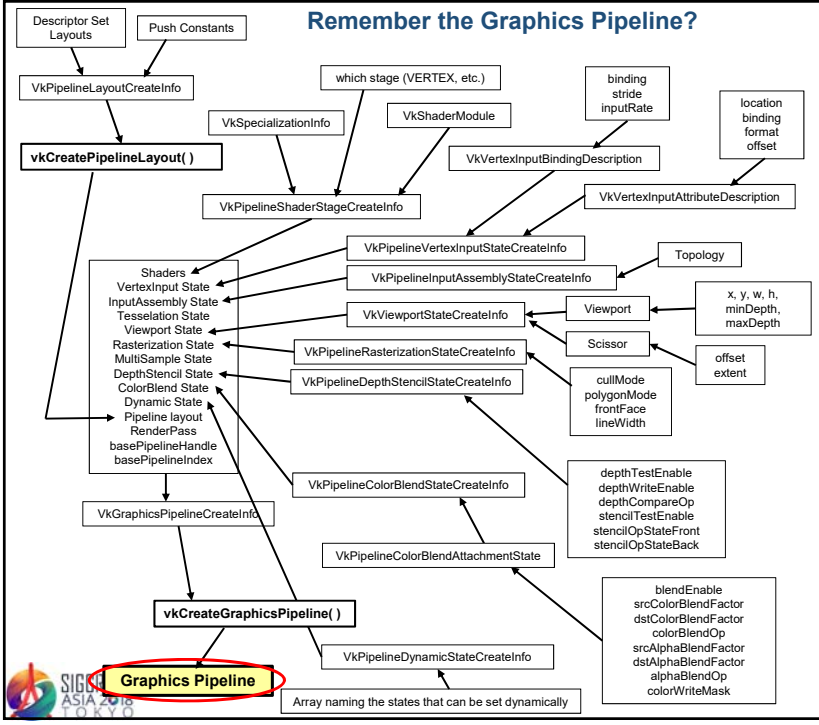
Mike Bailey

Oregon State University

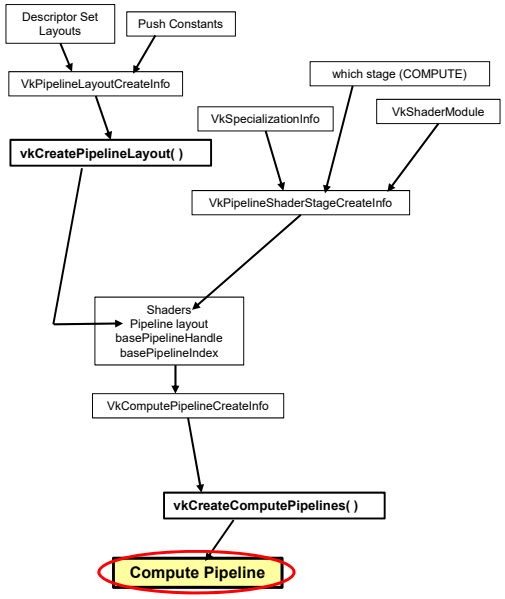
mjb@cs.oregonstate.edu

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

Remember the Graphics Pipeline?



Here is how you create a much-simpler Compute Pipeline



Start with Creating the Data Buffers

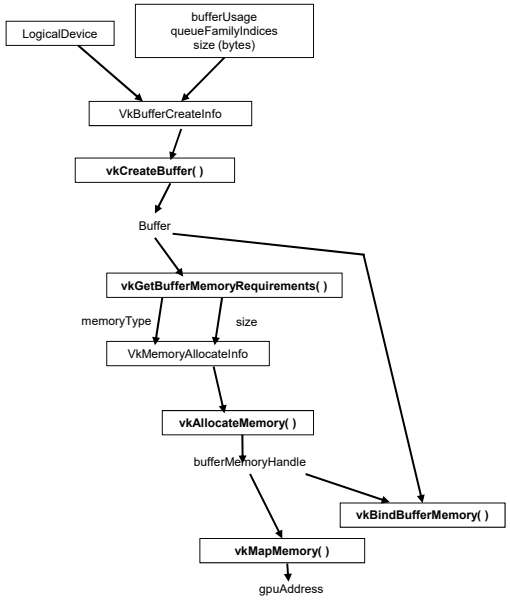
This is a Particle System application, so we need Positions, Velocities, and (possibly) Colors

1
2
3

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

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

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

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

A Reminder about Data Buffers



Creating a Shader Storage Buffer


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

VkBuffer  Buffer;

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

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

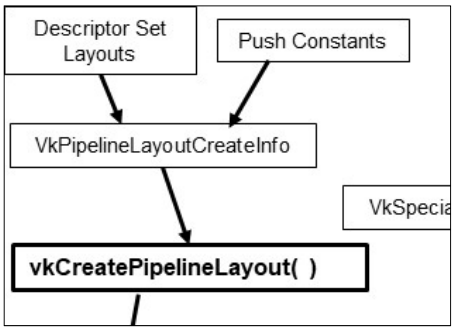

```
VkMemoryRequirements		vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );


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

. . .

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

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

. . .

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

	<< do the memory copy >>

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

Fill the Data Buffer


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

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

And, since we have Data Buffers, we will need Descriptor Sets to Create the Pipeline Layout

437



Create the Compute Pipeline Layout

438

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

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

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

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

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

Create the Compute Pipeline


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


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

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

The Particle System Compute Shader -- Setup


```
#version 430
#extension GL_ARB_compute_shader :  enable

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

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

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

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

The Particle System Compute Shader – The Physics

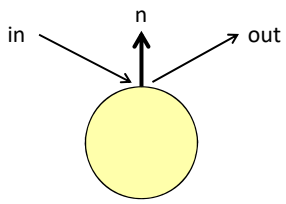

```
#define POINT               vec3
#define VELOCITY            vec3
#define VECTOR              vec3
#define SPHERE              vec4

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

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

      . . .

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

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

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

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

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

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

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


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

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

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



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


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

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

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

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

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

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

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

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

Dispatching the Compute Shader from the Command Buffer

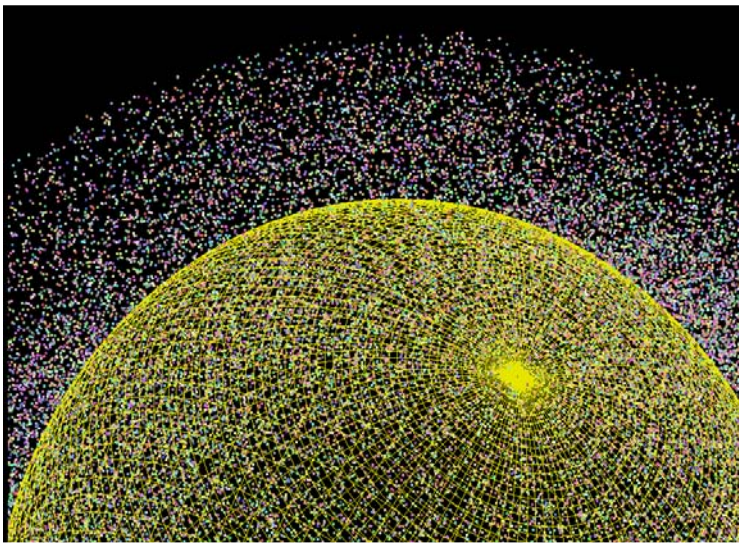

```
const int NUM+PARTICLES        = 1000000;
const int NUM_WORK_ITEMS     = 64;
const int NUM_WORK_GROUPS = NUM_PARTICLES / NUM_WORK_ITEMS;

      . . .

vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );

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

Or,

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

vkCmdDispatchIndirect( CommandBuffer, Buffer, 0 );              // offset
```

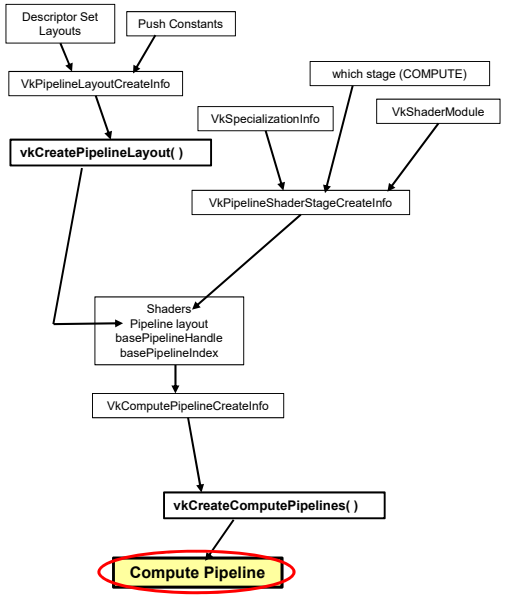
The Bouncing Particle System Compute Shader – What Does It Look Like?

445



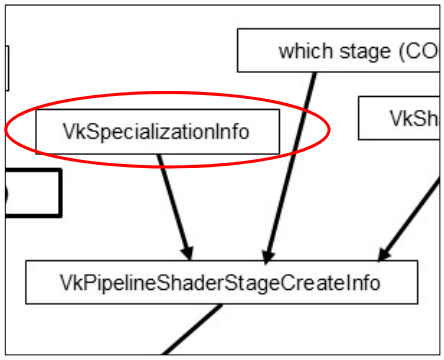
Remember the Compute Pipeline?

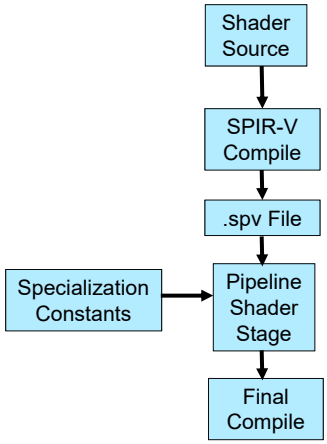
446



Specialization Constants

447





- A Specialization Constant is a way of injecting an integer or Boolean constant into an .spv-compiled version of a shader right before the final compilation.
- That final compilation happens when you call **vkCreateComputePipelines( )**
- Without Specialization Constants, you would have to commit to a final value before the SPIR-V compile was done, which could have been a long time ago

mjb – September 19, 2018

Specialization Constants

448

In the compute shader

```
layout( constant_id = 0 )  const int numXworkItems = 32;

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

In the C/C++ program:

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

int numXworkItems = 64;

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

mjb – September 19, 2018

Linking the Specialization Constants into the Compute Pipeline

449

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

int numXworkItems = 64;

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

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

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

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


A Wrap-up: Here are some good Vulkan References

450

- Graham Sellers, *Vulkan Programming Guide*, Addison-Wesley, 2017.
- Pawel Lapinski, *Vulkan Cookbook*, Packt, 2017.
- Kenwright, *Introduction to Computer Graphics and the Vulkan API*, 2017.

The notes and code presented here are constantly being updated. Go to:

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

for all the latest versions.

Mike Bailey

Oregon State University

mjb@cs.oregonstate.edu