1

Vulkan

Compute Shaders

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

The Example We Are Going to Use Here is a *Particle System*

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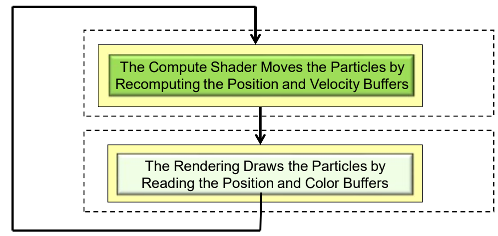

The Data in your C/C++ Program will look like This

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

```
#define NUM_PARTICLES                 (1024*1024)   // total number of particles to move
#define NUM_WORK_ITEMS_PER_GROUP          64        // # work-items per work-group
#define  NUM_X_WORK_GROUPS            ( NUM_PARTICLES / NUM_WORK_ITEMS_PER_GROUP )


struct pos
{
        glm::vec4;  // positions
};

struct vel
{
        glm::vec4;  // velocities
};

struct col
{
        glm::vec4;  // colors
};
```

Note that .w and .vw are not actually needed. But, by making these structure sizes a multiple of 4 floats, it doesn't matter if they are declared with the std140 or the std430 qualifier. I think this is a good thing.

The Data in your Compute Shader will look like This

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

2
```
layout( std140, set = 0, binding = 1 )  buffer  Vel
{
        vec4  Velocities[   ];      // array of structures
};
```

3
```
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 Vulkan examines the size of this buffer's data store.

Remember the Graphics Pipeline Data Structure?

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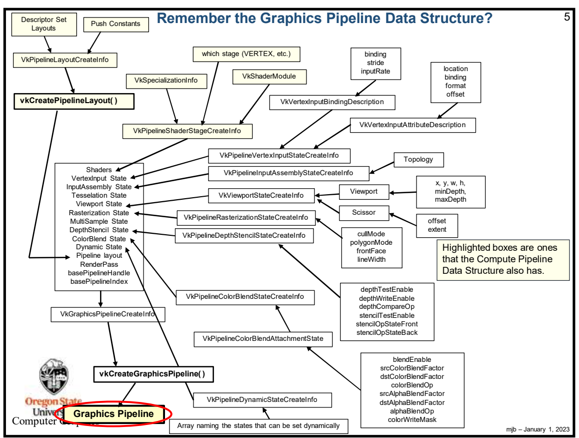

Here is how you create a Compute Pipeline Data Structure

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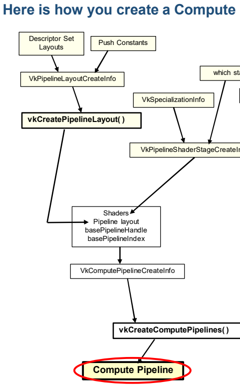

Highlighted boxes are ones that the Graphics Pipeline Data Structure also has

Note how less complicated this is!

A Reminder about Data Buffers

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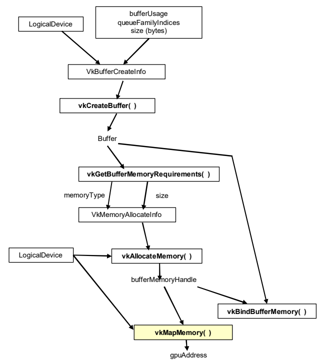

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Creating a Shader Storage Buffer

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```
VkBuffer  PosBuffer;
. . .

VkBufferCreateInfo  vbci;
        vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
        vbci.pNext = nullptr;
        vbci.flags = 0;
        vbci.size = NUM_PARTICLES * sizeof( glm::vec4 );
        vbci.usage = VK_USAGE_STORAGE_BUFFER_BIT;
        vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
        vbci.queueFamilyIndexCount = 0;
        vbci.pQueueFamilyIndices = (const iont32_t) nullptr;

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

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Allocating Memory for a Buffer, Binding a Buffer to Memory, and Filling the Buffer

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```
VkMemoryRequirements          vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, PosBuffer, 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, PosBuffer, IN vdm, 0 );        // 0 is the offset
```

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Create the Compute Pipeline Layout

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

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

        ComputeSet[2].binding              = 2;
        ComputeSet[2].descriptorType       = VK_DESCRIPTOR_TYPE_STORAGE_BUFFER;
        ComputeSet[2].descriptorCount      = 1;
        ComputeSet[2].stageFlags           = VK_SHADER_STAGE_COMPUTE_BIT;
        ComputeSet[2].pImmutableSamplers = (VkSampler *)nullptr;

VkDescriptorSetLayoutCreateInfo         vdslc;
        vdslc0.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
        vdslc0.pNext = nullptr;
        vdslc0.flags = 0;
        vdslc0.bindingCount = 3;
        vdslc0.pBindings = &ComputeSet[0];
```

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Create the Compute Pipeline Layout

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```
VkPipelineLayout          ComputePipelineLayout;
VkDescriptorSetLayout     ComputeSetLayout;

. . .

result = vkCreateDescriptorSetLayout( LogicalDevice, IN &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 );
```

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Create the Compute Pipeline

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```
VkPipeline                 ComputePipeline;
. . .

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


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

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

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Creating a Vulkan Data Buffer


```
VkBuffer  Buffer;

VkBufferCreateInfo  vbci;
        vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
        vbci.pNext = nullptr;
        vbci.flags = 0;
        vbci.size = NUM_PARTICLES * sizeof( glm::vec4 );
        vbci.usage = VK_USAGE_STORAGE_BUFFER_BIT;
        vbci.sharingMode = VK_SHARING_MODE_CONCURRENT;
        vbci.queueFamilyIndexCount = 0;
        vbci.pQueueFamilyIndices = (const iont32_t) nullptr;

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


Allocating Memory and Binding the Buffer


```
VkMemoryRequirements           vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, posBuffer, 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, posBuffer, IN vdm, 0 );          // 0 is the offset

MyBuffer   myPosBuffer;
        myPosBuffer.size    = vbci.size;
        myPosBuffer.buffer = PosBuffer;
        myPosBuffer.vdm    = vdm;
```


Fill the Buffers


```
struct pos * positions;
vkMapMemory( LogicalDevice, IN myPosBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT (void *) &positions );
for( int i = 0; i < NUM_PARTICLES; i++ )
{
          positions[ i ].x = Ranf( XMIN, XMAX );
          positions[ i ].y = Ranf( YMIN, YMAX );
          positions[ i ].z = Ranf( ZMIN, ZMAX );
          positions[ i ].w = 1.;
    }
vkUnmapMemory( LogicalDevice, IN myPosBuffer.vdm );


struct vel * velocities;
vkMapMemory( LogicalDevice, IN myVelBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT (void *) &velocities );
for( int i = 0; i < NUM_PARTICLES; i++ )
{
           velocities[ i ].x = Ranf( VXMIN, VXMAX );
           velocities[ i ].y = Ranf( VYMIN, VYMAX );
           velocities[ i ].z = Ranf( VZMIN, VZMAX );
           velocities[ i ].w = 0.;
}
vkUnmapMemory( LogicalDevice, IN myVelBuffer.vdm );


struct col * colors;
vkMapMemory( LogicalDevice, IN myColBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT (void *) &colors );
for( int i = 0; i < NUM_PARTICLES; i++ )
{
           colors[ i ].r =  Ranf( .3f, 1. );
           colors[ i ].g = Ranf( .3f, 1. );
           colors[ i ].b = Ranf( .3f, 1. );
           colors[ i ].a = 1.;
}
vkUnmapMemory( LogicalDevice, IN myColBuffer.vdm );
```


Fill the Buffers


```
#include <stdlib.h>

#define TOP     2147483647.           // 2^31 - 1

float
Ranf( float low, float high )
{
        long random( );        // returns integer 0 - TOP

        float r = (float)rand( );
        return  low  +  r * ( high - low ) / (float)RAND_MAX ;
}
```


The Particle System Compute Shader

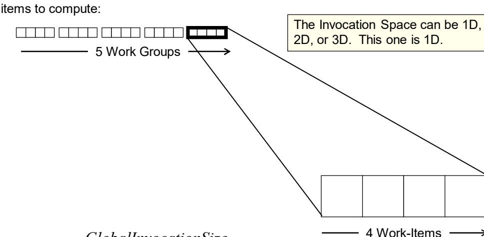

```
layout( std140, set = 0, binding = 0 )  buffer  Pos
{
        vec4  Positions[  ];              // array of structures
};

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

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

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

This is the number of **work-items per work-group**, set in the compute shader.
The number of work-groups is set in the
vkCmdDispatch(commandBuffer, workGroupCountX, workGroupCountY, workGroupCountZ);
function call in the application program.

The Data gets Divided into Large Quantities call *Work-Groups*, each of which is further Divided into Smaller Units Called *Work-Items*

20 total items to compute:

The Invocation Space can be 1D, 2D, or 3D. This one is 1D.



$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

$$5 = \frac{20}{4}$$

The Data Needs to be Divided into Large Quantities call Work-Groups, each of which is further Divided into Smaller Units Called Work-Items

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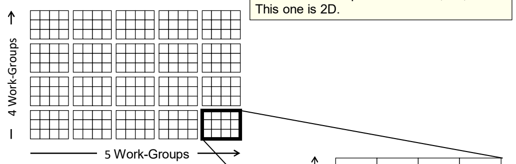
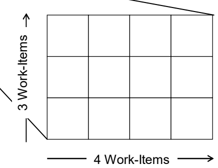
20x12 (=240) total items to compute:

The Invocation Space can be 1D, 2D, or 3D. This one is 2D.



$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

$$5x4 = \frac{20x12}{4x3}$$



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A Mechanical Equivalent…

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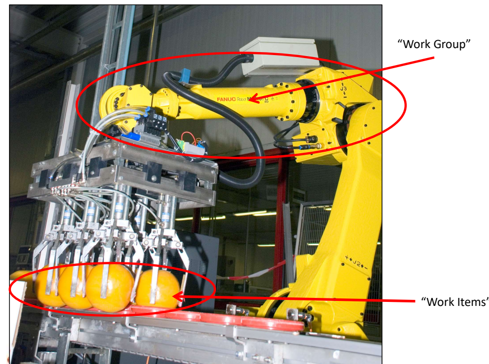

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The Particle System Compute Shader – The Physics

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```
#define POINT           vec3
#define VELOCITY        vec3
#define VECTOR          vec3
#define SPHERE          vec4        // xc, yc, zc, r
#define PLANE           vec4        // a, b, c, d

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;       //where I am in the global dataset (6 in this example)
                                          // (as a 1d problem, the .y and .z are both 1)

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;
```

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

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

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

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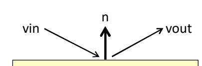
```
VELOCITY
Bounce( VELOCITY vin, VECTOR n )
{
    VELOCITY vout = reflect( vin, n );
    return vout;
}

// plane equation: Ax + By + Cz + D = 0
// ( it turns out that (A,B,C) is the normal )

VELOCITY
BouncePlane( POINT p, VELOCITY vin, PLANE pl )
{
    VECTOR n = normalize( VECTOR( pl.xyz ) );
    return Bounce( vin, n );
}

bool
IsUnderPlane( POINT p, PLANE pl )
{
    float r = pl.x*p.x + pl.y*p.y + pl.z*p.z + pl.w;
    return ( r < 0. );
}
```



Note: a surface in the x-z plane has the equation:
0x + 1y + 0z + 0 = 0
and thus its normal vector is (0,1,0)

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

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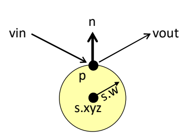
```
VELOCITY
BounceSphere( POINT p, VELOCITY vin, SPHERE s )
{
    VECTOR n = normalize( p - s.xyz );
    return Bounce( vin, n );
}

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



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

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

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

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

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

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

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

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

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

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Dispatching the Compute Shader from the Command Buffer

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```
#define  NUM_PARTICLES                    (1024*1024)
#define  NUM_WORK_ITEMS_PER_GROUP          64
#define  NUM_X_WORK_GROUPS                ( NUM_PARTICLES / NUM_WORK_ITEMS_PER_GROUP )

    . . .

vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );

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

This is the number of work-groups, set in the application program.
The number of work-items per work-group is set in the layout in the compute shader:

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

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Displaying the Particles

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```
VkVertexInputBindingDescription          vvibd[3];     // one of these per buffer data buffer
        vvibd[0].binding = 0;                          // which binding # this is
        vvibd[0].stride = sizeof( struct pos );        // bytes between successive structs
        vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;

        vvibd[1].binding = 1;
        vvibd[1].stride = sizeof( struct vel );
        vvibd[1].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;

        vvibd[2].binding = 2;
        vvibd[2].stride = sizeof( struct col );
        vvibd[2].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
```

```
layout( location = 0 ) in vec4 aPosition;
layout( location = 1 ) in vec4 aVelocity;
layout( location = 2 ) in vec4 aColor;
```

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Displaying the Particles

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```
VkVertexInputAttributeDescription        vviad[3];        // array per vertex input attribute
        // 3 = position, velocity, color
        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_VEC4;       // x, y, z, w
        vviad[0].offset = offsetof( struct pos, pos );   // 0

        vviad[1].location = 1;
        vviad[1].binding = 0;
        vviad[1].format = VK_FORMAT_VEC4;       // nx, ny, nz
        vviad[1].offset = offsetof( struct vel, vel );   // 0

        vviad[2].location = 2;
        vviad[2].binding = 0;
        vviad[2].format = VK_FORMAT_VEC4;       // r, g, b, a
        vviad[2].offset = offsetof( struct col, col );   // 0
```

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Telling the Pipeline about its Input

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```
VkPipelineVertexInputStateCreateInfo          vpvisci;       // used to describe the input vertex attributes
        vpvisci.sType = VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO;
        vpvisci.pNext = nullptr;
        vpvisci.flags = 0;
        vpvisci.vertexBindingDescriptionCount = 3;
        vpvisci.pVertexBindingDescriptions = vvibd;
        vpvisci.vertexAttributeDescriptionCount = 3;
        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_POINT_LIST;
```

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Telling the Pipeline about its Input

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

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

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

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Setting a Pipeline Barrier so the Drawing Waits for the Compute

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

const uint32 bufferMemoryBarrierCount = 1;
vkCmdPipelineBarrier
(
        commandBuffer,
        VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT, VK_PIPELINE_STAGE_VERTEX_INPUT_BIT,
        VK_DEPENDENCY_BY_REGION_BIT, 0, nullptr,   bufferMemoryBarrierCount, IN &vbmb, 0,nullptr
);
```

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Drawing

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```
VkBuffer buffers[ ] = MyPosBuffer.buffer, MyVelBuffer.buffer, MyColBuffer.buffer };
size_t      offsets[ ] = { 0, 0, 0 };

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 3, buffers, offsets );

const uint32_t  vertexCount = NUM_PARTICLES;
const uint32_t  instanceCount = 1;
const uint32_t  firstVertex = 0;
const uint32_t  firstInstance = 0;

vkCmdDraw( CommandBuffers[nextImageIndex], NUM_PARTICLES, 1, 0, 0 );
                        // vertexCount, instanceCount, firstVertex, firstInstance
```

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Setting a Pipeline Barrier so the Compute Waits for the Drawing

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```
VkBufferMemoryBarrier                 vbmb;
        vbmb.sType = VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER;
        vbmb.pNext = nullptr;
        vbmb.srcAccessFlags = 0;
        vbmb.dstAccessFlags = VK_ACCESS_UNIFORM_READ_BIT;
        vbmb.srcQueueFamilyIndex = 0;
        vbmb.dstQueueFamilyIndex = 0;
        vbmb.buffer =
        vbmb.offset = 0;
        vbmb.size = ??

const uint32 bufferMemoryBarrierCount = 1;
vkCmdPipelineBarrier
(
        commandBuffer,
        VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT, VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT,
        VK_DEPENDENCY_BY_REGION_BIT, 0,  nullptr,    bufferMemoryBarrierCount
        IN &vbmb,    0,   nullptr
);
```

Oregon State University Computer Graphics

mjb – January 1, 2023