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

The Compute Shader Moves the Particles by Recomputing the Position and Velocity Buffers

The Rendering Draws the Particles by Reading the Position and Color Buffers
This is a Particle System application, so we need Positions, Velocities, and (possibly) Colors

```c
#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

```cpp
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 Vulkan examines the size of this buffer’s data store.
Remember the Graphics Pipeline Data Structure?

- VkPipelineLayoutCreateInfo
- VkPipelineShaderStageCreateInfo
- VkPipelineInputStateCreateInfo
- VkPipelineRasterizationStateCreateInfo
- VkPipelineColorBlendStateCreateInfo
- VkPipelineDynamicStateCreateInfo
- VkPipelineLayoutCreateInfo

Highlight boxes are ones that the Compute Pipeline Data Structure also has.
Here is how you create a Compute Pipeline Data Structure

- VkPipelineLayoutCreateInfo
- VkPipelineShaderStageCreateInfo
- VkSpecializationInfo
- VkShaderModule

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

Note how less complicated this is!
A Reminder about Data Buffers

- LogicalDevice
  - bufferUsage
  - queueFamilyIndices
  - size (bytes)

- VkBufferCreateInfo

- vkCreateBuffer()

- Buffer

- VkGetBufferMemoryRequirements(
  - memoryType
  - size)

- VkMemoryAllocateInfo

- vkAllocateMemory()

- LogicalDevice

- vkBindBufferMemory()

- VkMapMemory(
  - bufferMemoryHandle
  - gpuAddress)
Creating a Shader Storage Buffer

VkBuffer PosBuffer;

\ldots

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 int32_t) nullptr;

result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &PosBuffer );
Allocating Memory for a Buffer, Binding a Buffer to Memory, and Filling the Buffer

```c
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
```
Create the Compute Pipeline Layout

```c
struct ComputeSet[3];

// ComputeSet[0]
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]
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]
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;
vdslc.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
vdslc.pNext = nullptr;
vdslc.flags = 0;
vdslc.bindingCount = 3;
vdslc.pBindings = &ComputeSet[0];
```
Create the Compute Pipeline Layout

```c
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 );
```
Create the Compute Pipeline

```cpp
VkPipeline 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 );
```
Creating a Vulkan Data Buffer

```c
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 int32_t) nullptr;

    result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &posBuffer );
```
Allocating Memory and Binding the Buffer

```c
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;
```
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 );
```c
#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:

\[ \text{#WorkGroups} = \frac{\text{GlobalInvocationSize}}{\text{WorkGroupSize}} \]

\[ 5 \times 4 = \frac{20}{4} \]

The Invocation Space can be 1D, 2D, or 3D. This one is 1D.
The Data Needs to be Divided into Large Quantities called Work-Groups, each of which is further Divided into Smaller Units Called Work-Items.

20x12 (=240) total items to compute:

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

\[
\text{#WorkGroups} = \frac{\text{GlobalInvocationSize}}{\text{WorkGroupSize}}
\]

\[
5 \times 4 = \frac{20 \times 12}{4 \times 3}
\]
A Mechanical Equivalent…

“Work Group”

“Work Items”
# 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)

POINT 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;

\[
p' = p + v \cdot t + \frac{1}{2} G \cdot t^2
\]
\[
v' = v + G \cdot t
\]
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 v, PLANE pl)
{
    VECTOR n = normalize( VECTOR( pl.xyz ) );
    return Bounce( v, 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)
The Particle System Compute Shader – How About Introducing a Bounce?

```
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 );
}
```
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;

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

```c
#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:

```c
layout(local_size_x = 64, local_size_y = 1, local_size_z = 1) in;
```
Displaying the Particles

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;
Displaying the Particles

```
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
```
Telling the Pipeline about 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 = 3;
vpvisci.pVertexBindingDescriptions = vvibd;
vpvisci.vertexAttributeDescriptionCount = 3;
vpvisci.pVertexAttributeDescriptions = vviad;

VkPipelineInputAssemblyStateCreateInfo vpiasci;
vpiasi.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
vpiasi.pNext = nullptr;
vpiasi.flags = 0;
vpiasi.topology = VK_PRIMITIVE_TOPOLOGY_POINT_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 vertex input.

```c
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 = &vpdsscii;
    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 );
```
Setting a Pipeline Barrier so the Drawing Waits for the Compute

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

vkCmdBindVertexBuffer(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
Setting a Pipeline Barrier so the Compute Waits for the Drawing

```cpp
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
);
```