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

```
#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 C/C++ Program will look like This

```
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?

Here is how you create a Compute Pipeline Data Structure

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

Highlighted boxes are ones that the Graphics Pipeline Data Structure also has.
Note how less complicated this is!
A Reminder about Data Buffers

Creating a Shader Storage Buffer

VkBuffer PosBuffer;

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

result = vkCreateBuffer ( LogicalDevice, IN &vbc, 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
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;
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

```cpp
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
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 iont32_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 );

#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: 5 Work Groups

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

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

\[
5 = \frac{20}{4}
\]
The Data Needs to be Divided into Large Quantities call Work-Groups, each of which is further Divided into Smaller Units Called Work-Items

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

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

\[ 5 \times 4 = \frac{20 \times 12}{4 \times 3} \]

20x12 (=240) total items to compute:

A Mechanical Equivalent…
The Particle System Compute Shader – The Physics

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

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

cost 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;

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

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)
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 );
}
```

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

**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);

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:

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

Displaying the Particles

```c
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

```c
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

```c
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;
vpiasci.pVertexBindingDescriptions = vvibd;
vpvisci.vertexAttributeDescriptionCount = 3;
vpiasci.pVertexAttributeDescriptions = vviad;
```

```c
VkPipelineInputAssemblyStateCreateInfo vpiasci;  // used to describe input assembly state
vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
vpiasci.pNext = nullptr;
vpiasci.flags = 0;
vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_POINT_LIST;
```
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 );
```

Telling the Pipeline about its Input

Setting a Pipeline Barrier so the Drawing Waits for the Compute

```
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 };  
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

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
);