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OpenGL Compute Shaders

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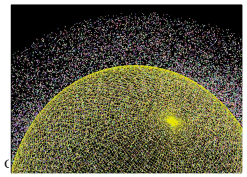
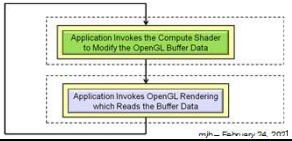
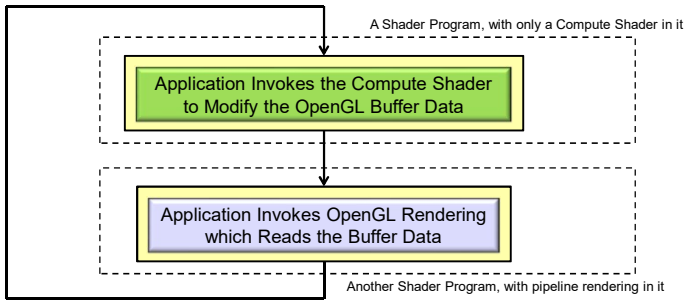




OpenGL Compute Shader – the Basic Idea

2



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OpenGL Compute Shader – the Basic Idea

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Paraphrased from the ARB_compute_shader spec:

Recent graphics hardware has become extremely powerful. A strong desire to harness this power for work that does not fit the traditional graphics pipeline has emerged. To address this, Compute Shaders are a new single-stage program. They are launched in a manner that is essentially stateless. This allows arbitrary workloads to be sent to the graphics hardware with minimal disturbance to the GL state machine.

In most respects, a Compute Shader is identical to all other OpenGL shaders, with similar status, uniforms, and other such properties. It has access to many of the same data as all other shader types, such as textures, image textures, atomic counters, and so on. However, the Compute Shader has no predefined inputs, nor any fixed-function outputs. It cannot be part of a rendering pipeline and its visible side effects are through its actions on shader storage buffers, image textures, and atomic counters.

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Why Not Just Use OpenCL Instead?

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OpenCL is *great*! It does a super job of using the GPU for general-purpose data-parallel computing. And, OpenCL is more feature-rich than OpenGL compute shaders. So, why use Compute Shaders *ever* if you've got OpenCL? Here's what I think:

- OpenCL requires installing a separate driver and separate libraries. While this is not a huge deal, it does take time and effort. When everyone catches up to OpenGL 4.3, Compute Shaders will just "be there" as part of core OpenGL.
- Compute Shaders use the GLSL language, something that all OpenGL programmers should already be familiar with (or will be soon).
- Compute shaders use the same context as does the OpenGL rendering pipeline. There is no need to acquire and release the context as OpenGL+OpenCL must do.
- I'm assuming that calls to OpenGL compute shaders are more lightweight than calls to OpenCL kernels are. (true?) This should result in better performance. (true? how much?)
- Using OpenCL is somewhat cumbersome. It requires a lot of setup (queries, platforms, devices, queues, kernels, etc.). Compute Shaders look to be more convenient. They just kind of flow in with the graphics.

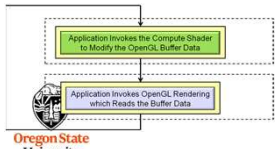
The bottom line is that I continue to use OpenCL for the big, bad stuff. But, for lighter-weight data-parallel computing that interacts with graphics, I use the Compute Shaders.

A good example of a lighter-weight data-parallel graphics-related application is a **particle system**. This will be shown here in the rest of these notes.

If We Know GLSL (and you *do*), What Do We Need to Do Differently to Write a Compute Shader?

Not much!

1. A Compute Shader is created just like any other GLSL shader, except that its type is GL_COMPUTE_SHADER (duh…). You compile it and link it just like any other GLSL shader program.
2. A Compute Shader must be in a shader program all by itself. There cannot be vertex, fragment, etc. shaders in there with it. (I don't understand why this is necessary.)
3. A Compute Shader has access to uniform variables and buffer objects but cannot access any pipeline variables such as attributes or variables from other stages. It stands alone.
4. A Compute Shader needs to declare the number of work-items in each of its work-groups in a special GLSL *layout* statement.



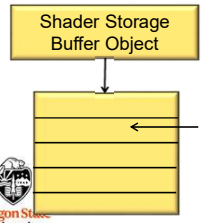
More information on item 4 is coming up . . .

Passing Data to the Compute Shader Happens with a Cool New Buffer Type – the *Shader Storage Buffer Object*

The tricky part is getting data into and out of the Compute Shader. The trickiness comes from the specification phrase: "In most respects, a Compute Shader is identical to all other OpenGL shaders, with similar status, uniforms, and other such properties. It has access to many of the same data as all other shader types, such as textures, image textures, atomic counters, and so on."

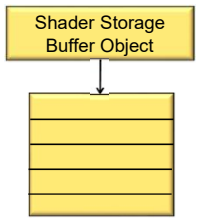
Compute Shaders, looking like other shaders, haven't had *direct* access to general arrays of data (hacked access, yes; direct access, no). But, because Compute Shaders represent opportunities for massive data-parallel computations, that is exactly what you want them to have access to.

Thus, OpenGL 4.3 introduced the **Shader Storage Buffer Object**. This is very cool, and has been needed for a long time!

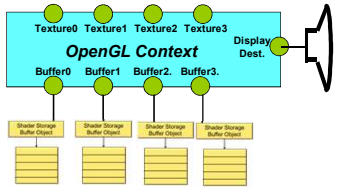


Shader Storage Buffer Objects are created with arbitrary data (same as other buffer objects), but what is new is that the shaders can read and write them in the same C-like way as they were created, including treating parts of the buffer as an array of structures – perfect for data-parallel computing!

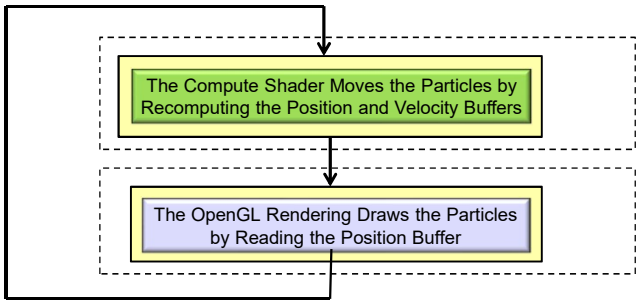
Passing Data to the Compute Shader Happens with a Cool New Buffer Type – the *Shader Storage Buffer Object*



And, like other OpenGL buffer types, Shader Storage Buffer Objects can be bound to the context, making them easy to access from inside the Compute Shaders.



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



Setting up the Shader Storage Buffer Objects in Your C/C++ Program


```
#define NUM_PARTICLES          1024*1024          // total number of particles to move
#define WORK_GROUP_SIZE          128              // # work-items per work-group

struct pos
{
        float x, y, z, w;      // positions
};

struct vel
{
        float vx, vy, vz, vw;  // velocities
};

struct color
{
        float r, g, b, a;      // colors
};

// need to do the following for both position, velocity, and colors of the particles:

GLuint  posSSbo;
GLuint  velSSbo
GLuint  colSSbo;
```

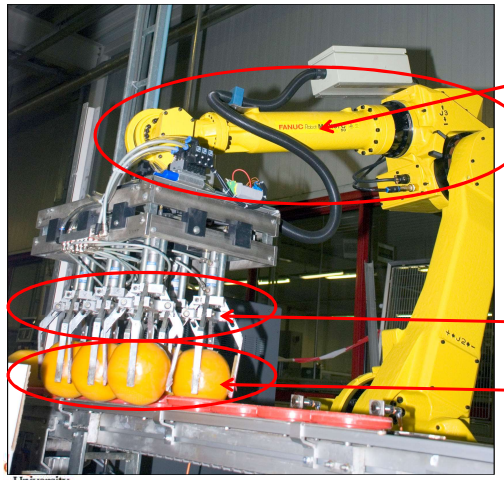
Note that .w and .vw are not actually needed. But, by making these structure sizes a multiple of 4 floats, it doesn't matter if they are declared with the std140 or the std430 qualifier. I think this is a good thing.

Setting up the Shader Storage Buffer Objects in Your C Program


```
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 );
for( int i = 0; i < NUM_PARTICLES; i++ )
{
        points[ i ].x = Ranf( XMIN, XMAX );
        points[ i ].y = Ranf( YMIN, YMAX );
        points[ i ].z = Ranf( ZMIN, ZMAX );
        points[ i ].w = 1.;
}
glUnmapBuffer( GL_SHADER_STORAGE_BUFFER );

glGenBuffers( 1, &velSSbo);
glBindBuffer( GL_SHADER_STORAGE_BUFFER, velSSbo );
glBufferData( GL_SHADER_STORAGE_BUFFER, NUM_PARTICLES * sizeof(struct vel), NULL, GL_STATIC_DRAW );

struct vel *vels = (struct vel *) glMapBufferRange( GL_SHADER_STORAGE_BUFFER, 0, NUM_PARTICLES * sizeof(struct vel), bufMask );
for( int i = 0; i < NUM_PARTICLES; i++ )
{
        vels[ i ].vx = Ranf( VXMIN, VXMAX );
        vels[ i ].vy = Ranf( VYMIN, VYMAX );
        vels[ i ].vz = Ranf( VZMIN, VZMAX );
        vels[ i ].vw = 0.;
}
glUnmapBuffer( GL_SHADER_STORAGE_BUFFER );
```

The same would possibly need to be done for the color shader storage buffer object

A Mechanical Equivalent of a GPU



"Streaming Multiprocessor"

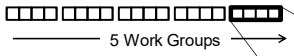
"CUDA Cores"

"Data"

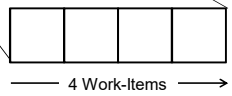
http://news.cision.com

The Data Needs to be 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.



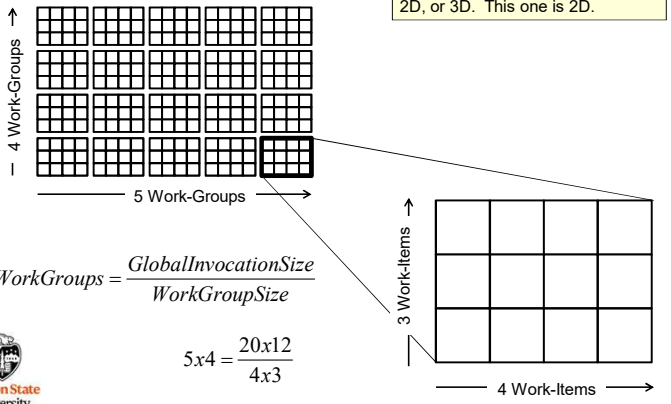
$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

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

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

20x12 (=240) total items to compute:

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

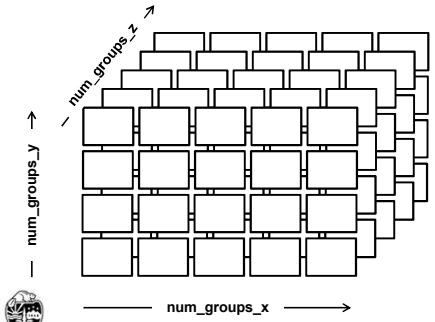


$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

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

Running the Compute Shader from the Application


```
void glDispatchCompute( num_groups_x, num_groups_y, num_groups_z );
```

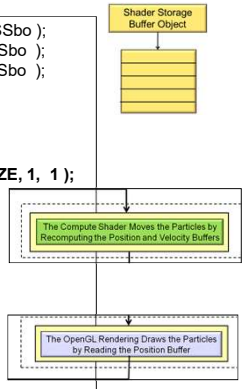


If the problem is 2D, then num_groups_z = 1

If the problem is 1D, then num_groups_y = 1 and num_groups_z = 1

Invoking the Compute Shader in Your C Program


```
glBindBufferBase( GL_SHADER_STORAGE_BUFFER, 4, posSSbo );
glBindBufferBase( GL_SHADER_STORAGE_BUFFER, 5, velSSbo );
glBindBufferBase( GL_SHADER_STORAGE_BUFFER, 6, colSSbo );

. . .

glUseProgram( MyComputeShaderProgram );
glDispatchCompute( NUM_PARTICLES / WORK_GROUP_SIZE, 1, 1 );
glMemoryBarrier( GL_SHADER_STORAGE_BARRIER_BIT );

. . .

glUseProgram( MyRenderingShaderProgram );
glBindBuffer( GL_ARRAY_BUFFER, posSSbo );
glVertexPointer( 4, GL_FLOAT, 0, (void *)0 );
glEnableClientState( GL_VERTEX_ARRAY );
glDrawArrays( GL_POINTS, 0, NUM_PARTICLES );
glDisableClientState( GL_VERTEX_ARRAY );
glBindBuffer( GL_ARRAY_BUFFER, 0 );
```



Using the glslprogram C++ Class to Handle Everything

Setup:

```
GLSLProgram *Particles = new GLSLProgram( );
bool valid = Particles->Create( "particles.cs" );
if( ! valid ) { . . . }
```

Using:

```
Particles->Use( );
Particles->DispatchCompute( NUM_PARTICLES / WORK_GROUP_SIZE, 1, 1 );
Particles->UnUse( );

Render->Use( );                    // draw the particles
. . .
Render->UnUse( );
```

Special Pre-set Variables in the Compute Shader

in	**uvec3**	**gl_NumWorkGroups ;**	Same numbers as in the *glDispatchCompute* call
const	**uvec3**	**gl_WorkGroupSize ;**	Same numbers as in the *layout* local_size_*
in	**uvec3**	**gl_WorkGroupID ;**	Which workgroup this thread is in
in	**uvec3**	**gl_LocalInvocationID ;**	Where this thread is in the current workgroup
in	**uvec3**	**gl_GlobalInvocationID ;**	Where this thread is in *all* the work items
in	**uint**	**gl_LocalInvocationIndex ;**	1D representation of the gl_LocalInvocationID (used for indexing into a shared array)

```
0  ≤  gl_WorkGroupID          ≤  gl_NumWorkGroups – 1

0  ≤  gl_LocalInvocationID    ≤  gl_WorkGroupSize – 1

gl_GlobalInvocationID   =  gl_WorkGroupID * gl_WorkGroupSize  +  gl_LocalInvocationID

gl_LocalInvocationIndex  =  gl_LocalInvocationID.z * gl_WorkGroupSize.y * gl_WorkGroupSize.x  +
                            gl_LocalInvocationID.y * gl_WorkGroupSize.x                       +
                            gl_LocalInvocationID.x
```

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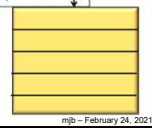
The Particle System Compute Shader -- Setup


```
#version 430 compatibility
#extension GL_ARB_compute_shader :                enable
#extension GL_ARB_shader_storage_buffer_object :  enable;

layout( std140, binding=4 )  buffer  Pos
{
        vec4  Positions[  ];          // array of structures
};

layout( std140, binding=5 )  buffer  Vel
{
        vec4  Velocities[  ];         // array of structures
};

layout( std140, binding=6 )  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.

Shader Storage Buffer Object

layout(local_size_x = 128, local_size_y = 1, local_size_z = 1) in;



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The Particle System Compute Shader – The Physics


```
const  vec3  G     =  vec3( 0., -9.8, 0. );
const  float  DT   =  0.1;

    . . .

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

vec3 p  = Positions[  gid  ].xyz;
vec3 v  = Velocities[  gid  ].xyz;

vec3  pp = p + v*DT + .5*DT*DT*G;
vec3  vp = v + G*DT;

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

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

Shader Storage Buffer Object

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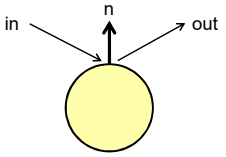
The Particle System Compute Shader – How About Introducing a Bounce?


```
const vec4 Sphere =  vec4( -100., -800., 0.,  600. );    // x, y, z, r
                                                          // (could also have passed this in)
vec3
Bounce( vec3 vin, vec3 n )
{
        vec3 vout = reflect( vin, n );
        return vout;
}

vec3
BounceSphere( vec3 p, vec3 v, vec4 s )
{
        vec3 n = normalize( p - s.xyz );
        return Bounce( v, n );
}

bool
IsInsideSphere( vec3 p, vec4 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?


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

vec3 p  = Positions[  gid  ].xyz;
vec3 v  = Velocities[  gid  ].xyz;

vec3  pp = p + v*DT + .5*DT*DT*G;
vec3  vp = v + G*DT;

if(  IsInsideSphere( pp, Sphere ) )
{
        vp = BounceSphere( p, v, Sphere );
        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, nobody will ever know…

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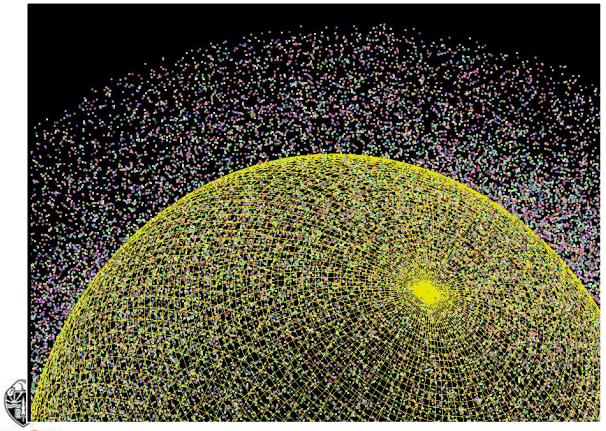
The Bouncing Particle System Compute Shader – What Does It Look Like?



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