How to Use and Teach OpenGL Compute Shaders

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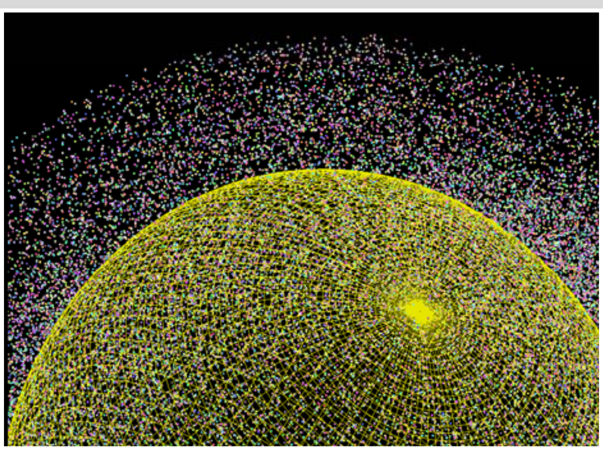
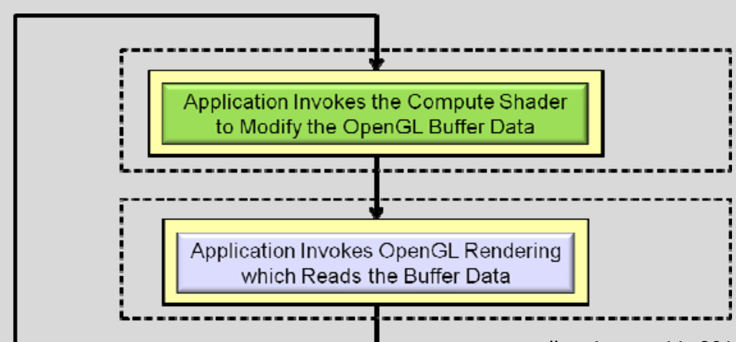
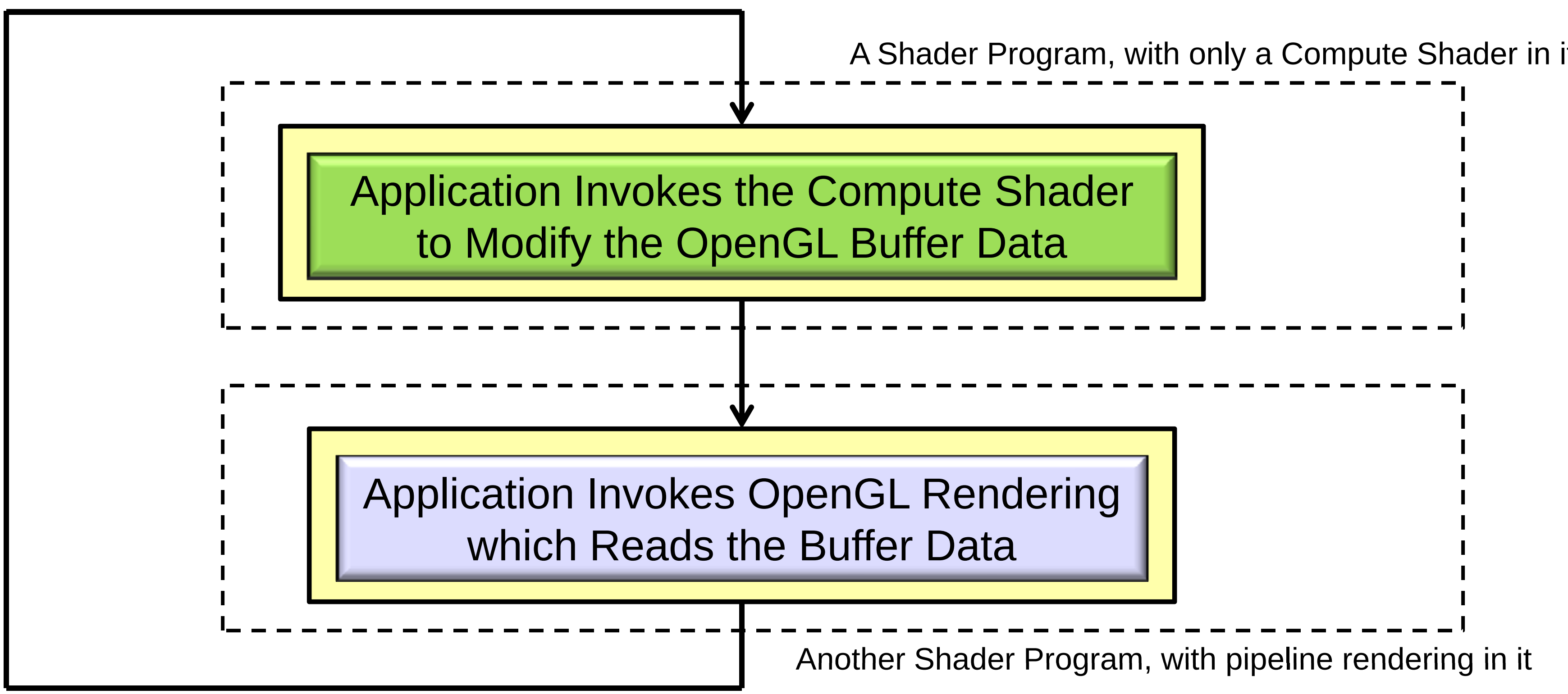




OpenGL Compute Shader – the Basic Idea



Why Not Just Use OpenCL Instead?

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

I suspect that 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. I hope I'm right.

If I Know GLSL,
What Do I Need to Do Differently to Write a Compute Shader?

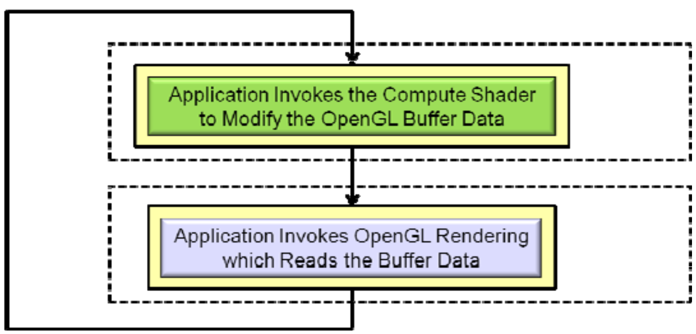
Not much:

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. (why?)

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.



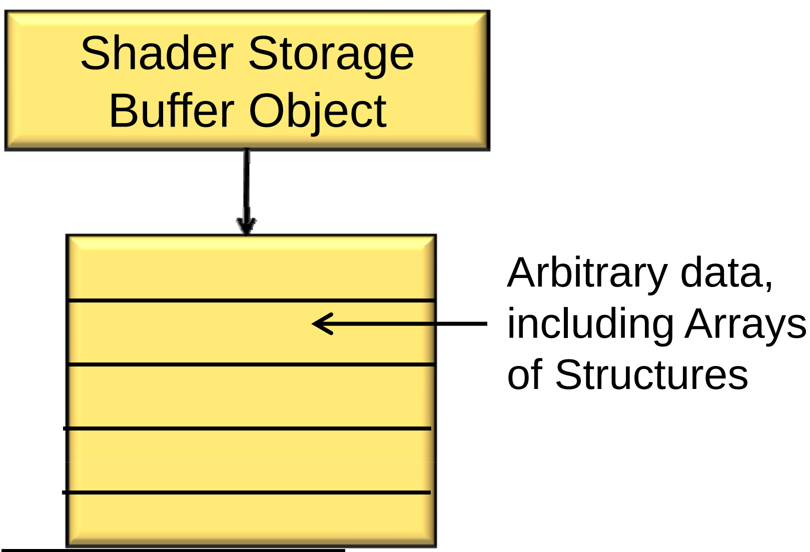
More information on items 3 and 4 are coming up . . .

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.”

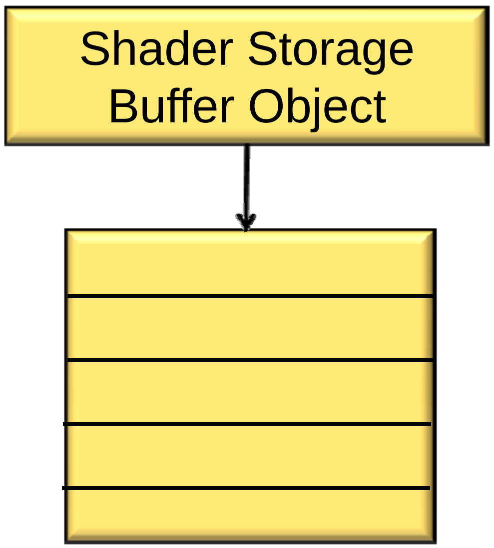
OpenCL programs have access to general arrays of data, and also access to OpenGL arrays of data in the form of buffer objects. Compute Shaders, looking like other shaders, haven’t had *direct* access to general arrays of data (hacked access, yes; direct access, no). But, because Compute Shaders represent opportunities for massive data-parallel computations, that is exactly what you want them to use.

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

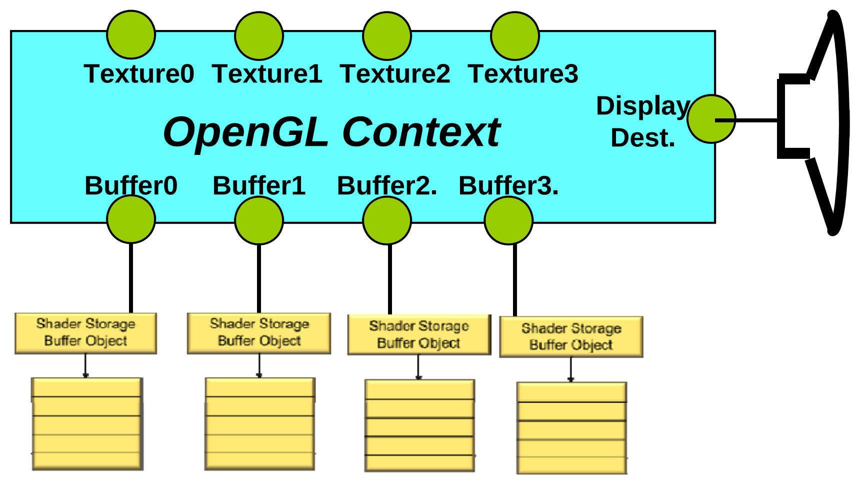


Shader Storage Buffer Objects are created with arbitrary data (same as other buffer objects), but what is new is that the shaders can read and write them in the same C-like way as they were created, including treating parts of the buffer as an array of structures – perfect for data-parallel computing!

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

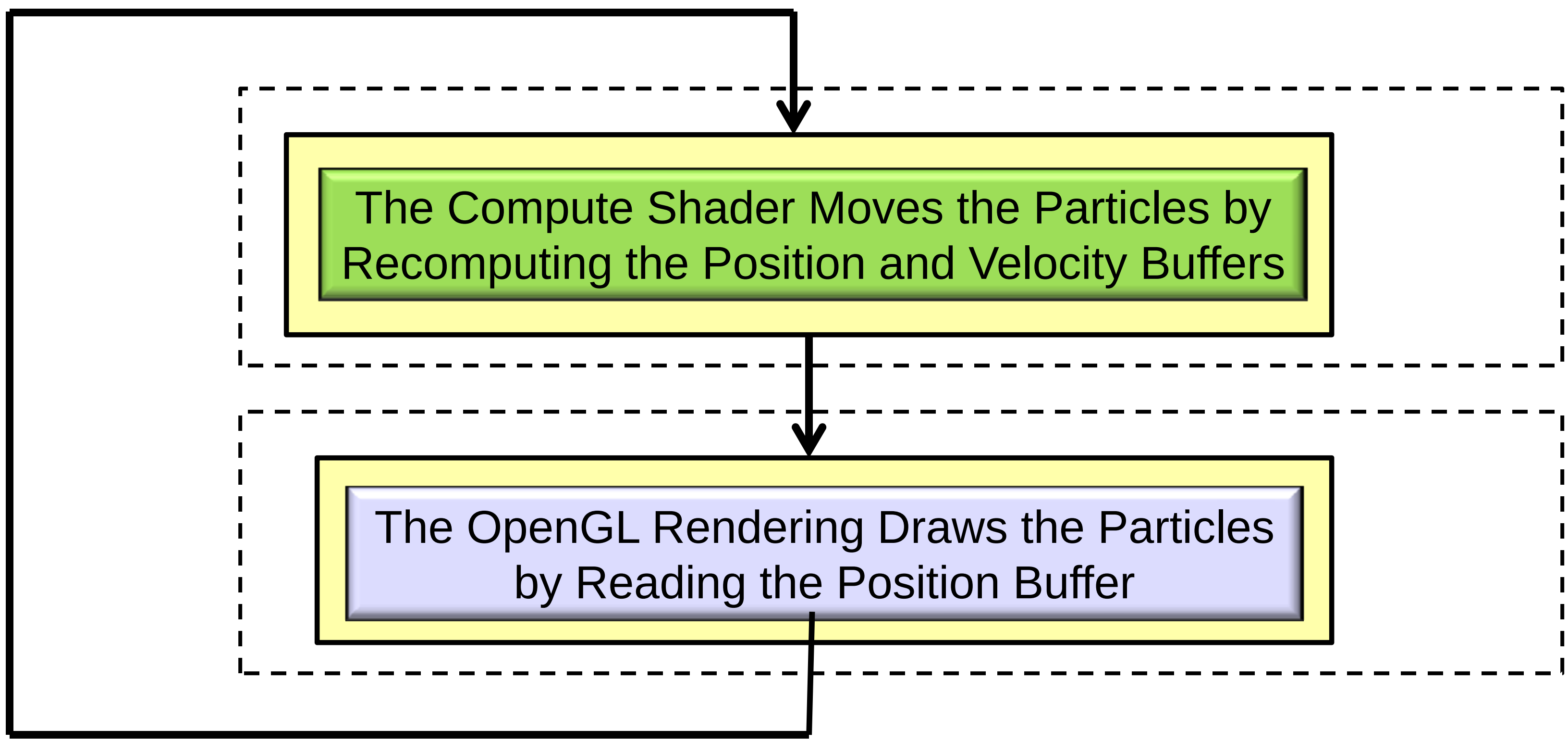


And, like other OpenGL buffer types, Shader Storage Buffer Objects can be bound to indexed binding points, making them easy to access from inside the Compute Shaders.



(Any resemblance this diagram has to a mother sow is accidental, but not entirely inaccurate…)

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



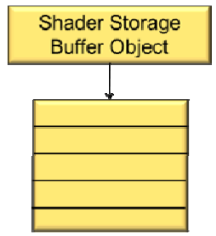
Setting up the Shader Storage Buffer Objects in Your C Program

```
#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;
```

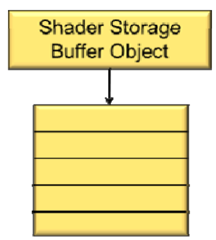
Note that .w and .vw are not actually needed. But, by making these structure sizes a multiple of 4 floats, it doesn't matter if they are declared with the std140 or the std430 qualifier. I think this is a good thing. (is it?)

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 );
```

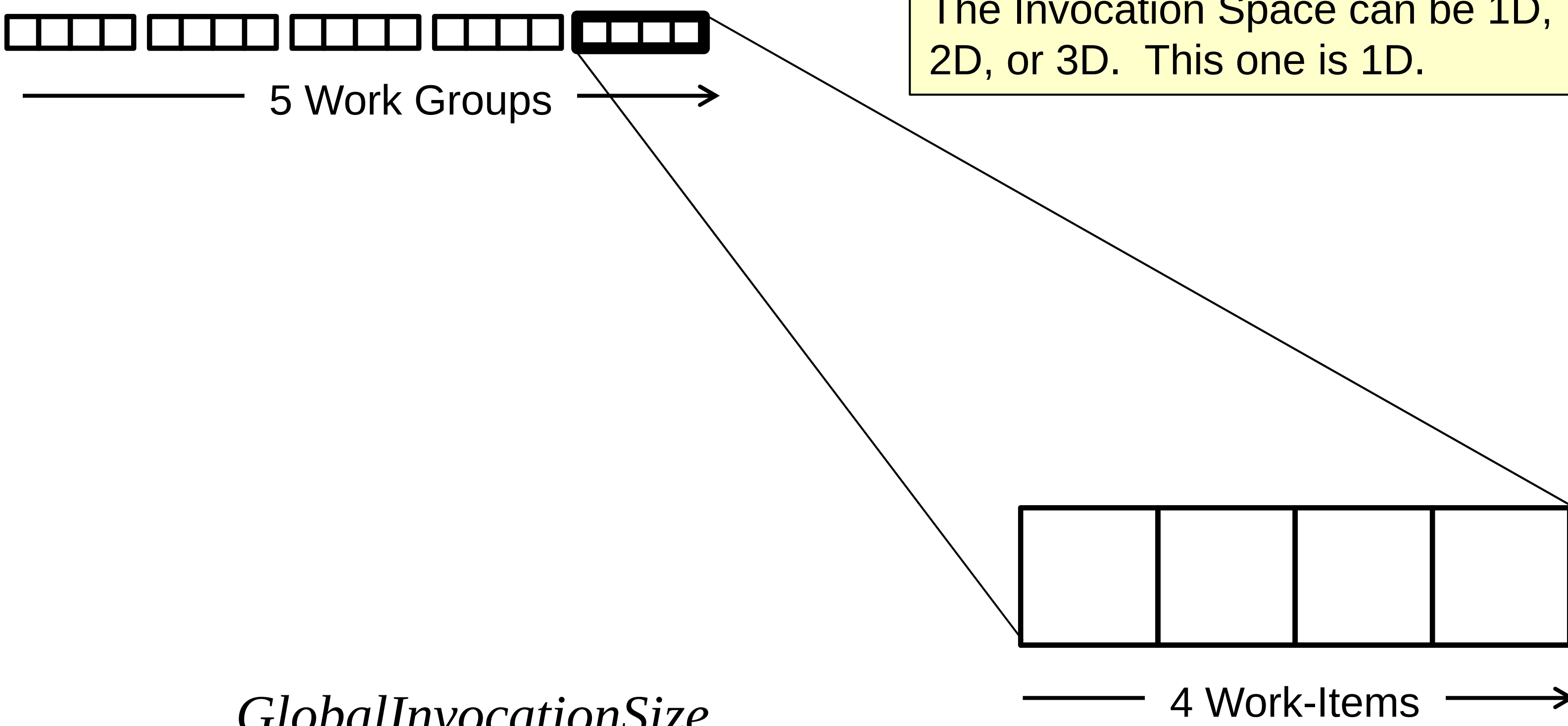


The same would possibly need to be done for the color shader storage buffer object

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.



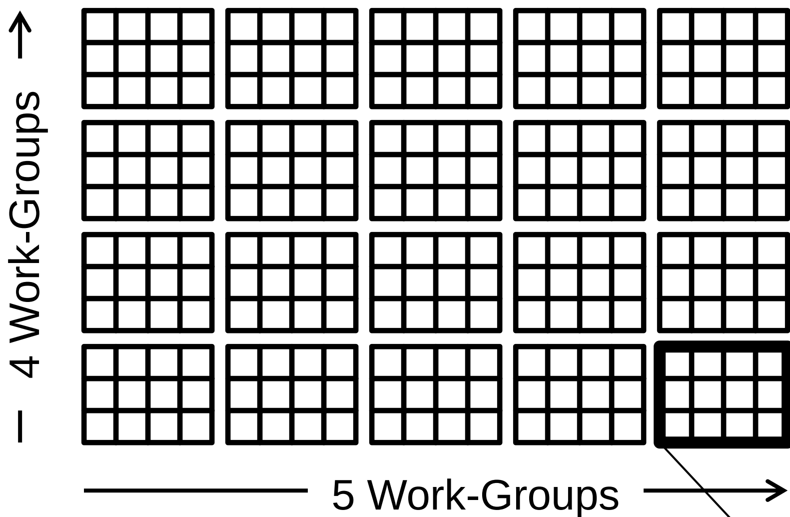
$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

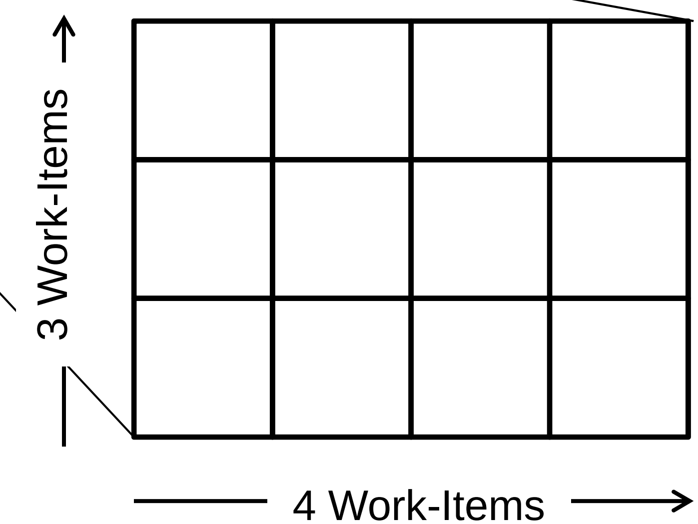
$$5x4 = \frac{20}{4}$$

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.



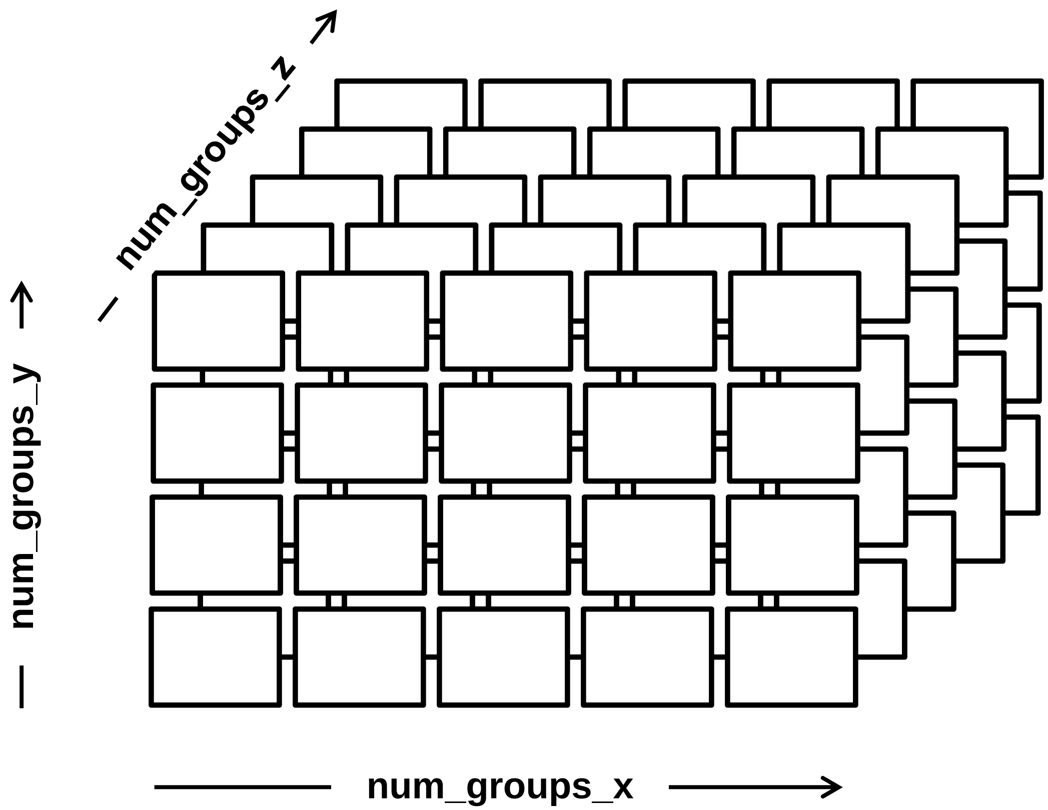


$$\#WorkGroups = \frac{GlobalInvocationSize}{WorkGroupSize}$$

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

Running the Compute Shader from the Application

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

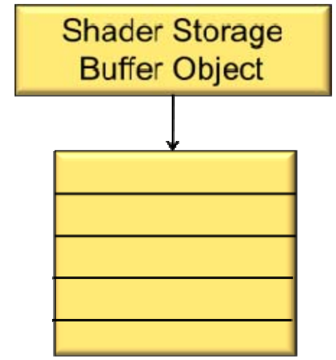


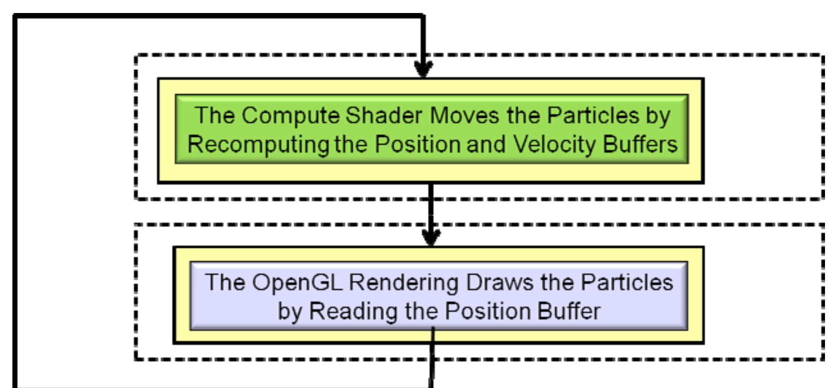
If the problem is 2D, then
num_groups_z = 1

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 );
```





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

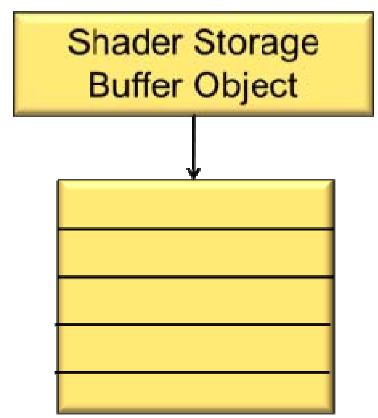
gl_GlobalInvocationID = gl_WorkGroupID * gl_WorkGroupSize + gl_LocalInvocationID

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

The Particle System Compute Shader -- Setup

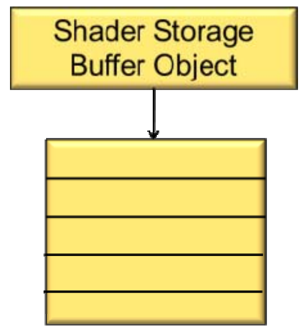
```
#version 430 compatibility
#extension GL_ARB_compute_shader :                    enable
#extension GL_ARB_shader_storage_buffer_object :   enable;

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
};

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

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.



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;
```

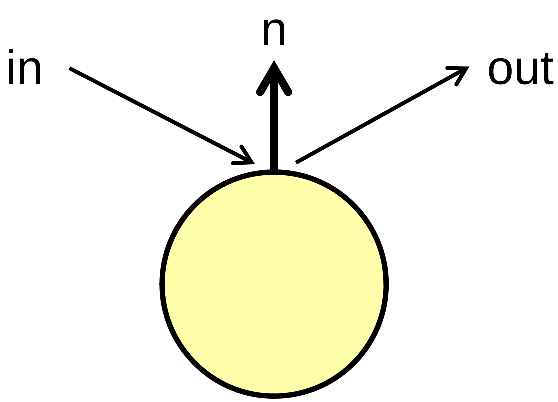


$$p' = p + v \cdot t + \frac{1}{2} G \cdot t^2$$

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

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  );
}
```



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

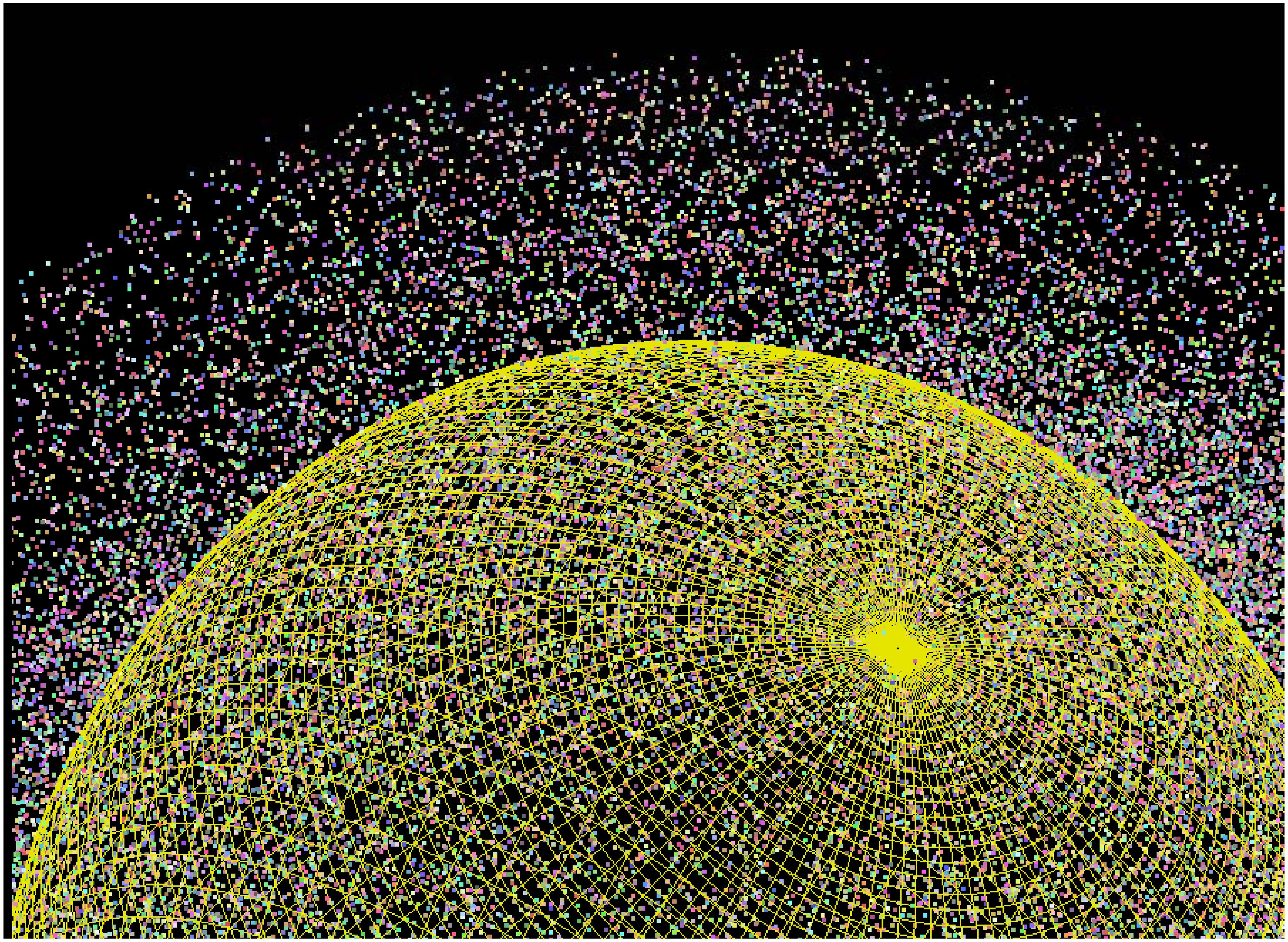
```
uint  gid = gl_GlobalInvocationID.x;            // the .y and .z are both 1 in this case

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…

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



Personally, I Think this is a Better Way of Dispatching the Compute Shader from the Application

In your C/C++ code, replace:

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

with:

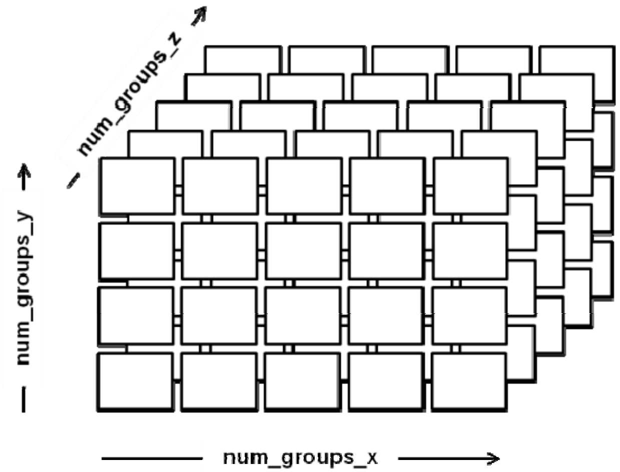
```
void  glDispatchComputeGroupSize(
            num_groups_x,       num_groups_y,        num_groups_z,
            work_group_size_x, work_group_size_y, work_group_size_z  );
```

And, in your shader code, replace:

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

with:

```
layout( local_size_variable )   in;
```

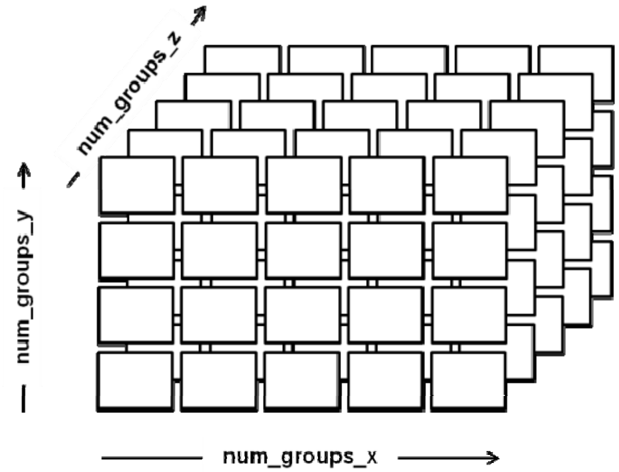


Personally, I Think this is a Better Way of Dispatching the Compute Shader from the Application

I like this better because you can experiment with changing work group sizes by changing a value in only one place, not two:

Run your timing experiments by changing this one number

```
#define NUMPARTICLES            1024*1024
#define WORK_GROUP_SIZE         128
#define NUMGROUPS               ( NUMPARTICLES / WORK_GROUP_SIZE )

void  glDispatchComputeGroupSize(
          NUMGROUPS,            1,    1,
          WORK_GROUP_SIZE,  1,    1  );
```



In the other way of dispatching a compute shader, you would have modified the parallel parameters by changing values in *both* the C/C++ code *and* in the shader code.

Other Useful Stuff –
Copying Global Data to a Local Array Shared by the Entire Work-Group

There are some applications, such as image convolution, where threads within a work-group need to operate on each other's input or output data. In those cases, it is usually a good idea to create a local shared array that all of the threads in the work-group can access. You do it like this:

```
layout( std140, binding=6 )  buffer  Col
{
		vec4  Colors[  ];
};

layout(  shared )  vec4 rgba[ gl_WorkGroupSize.x ];

uint  gid = gl_GlobalInvocationID.x;
uint  lid  = gl_LocalInvocationID.x;

rgba[ lid ] = Colors[ gid ];

memory_barrier_shared(  );

		<< operate on the rgba array elements >>

Colors[ gid ] = rgba[ lid ];
```

Other Useful Stuff –
Getting Information Back Out

There are some applications it is useful to be able to return some numerical information about the running of the shader back to the application program. For example, here's how to count the number of bounces:

Application Program

```
glGenBuffers( 1, &countBuffer);
glBindBufferBase( GL_ATOMIC_COUNTER_BUFFER, 7, countBuffer);
glBufferData(GL_ATOMIC_COUNTER_BUFFER, sizeof(GLuint), NULL, GL_DYNAMIC_DRAW);

GLuint zero = 0;
glBufferSubData(GL_ATOMIC_COUNTER_BUFFER, 0, sizeof(GLuint), &zero);
```

Compute Shader

```
layout( std140, binding=7 ) buffer { atomic_uint  bounceCount };

if(  IsInsideSphere( pp, SPHERE )  )
{
        vp = BounceSphere( p, v, SPHERE );
        pp = p + vp*DT + .5*DT*DT*G;
        atomicCounterIncrement(  bounceCount  );
}
```

Application Program

```
glBindBuffer( GL_SHADER_STORAGE_BUFFER, countBuffer );
GLuint *ptr = (GLuint *) glMapBuffer( GL_SHADER_STORAGE_BUFFER, GL_READ_ONLY );
GLuint  bounceCount = ptr[ 0 ];
glUnmapBuffer( GL_SHADER_STORAGE_BUFFER );
fprintf( stderr, "%d bounces\n", bounceCount );
```

Other Useful Stuff – Getting Information Back Out

Another example would be to count the number of fragments drawn so we know when all particles are outside the viewing volume, and can stop animating:

Application Program

```
glGenBuffers( 1, &particleBuffer);
glBindBufferBase( GL_ATOMIC_COUNTER_BUFFER, 8, particleBuffer);
glBufferData(GL_ATOMIC_COUNTER_BUFFER, sizeof(GLuint), NULL, GL_DYNAMIC_DRAW);

GLuint zero = 0;
glBufferSubData(GL_ATOMIC_COUNTER_BUFFER, 0, sizeof(GLuint), &zero);
```

Fragment Shader

```
layout( std140, binding=8 ) buffer { atomic_uint  particleCount };

atomicCounterIncrement(  particleCount  );
```

Application Program

```
glBindBuffer( GL_SHADER_STORAGE_BUFFER, particleBuffer );
GLuint *ptr = (GLuint *) glMapBuffer( GL_SHADER_STORAGE_BUFFER, GL_READ_ONLY );
GLuint  particleCount = ptr[ 0 ];
glUnmapBuffer( GL_SHADER_STORAGE_BUFFER );
If( particleCount  ==  0 )
        DoAnimate = false;                    // stop animating
```

Other Useful Stuff –
Getting Information Back Out

While we are at it, there is a cleaner way to set all values of a buffer to a preset value. In the previous example, we cleared the *countBuffer* by saying:

Application Program

```
glBindBufferBase( GL_ATOMIC_COUNTER_BUFFER, 7, countBuffer);
GLuint zero = 0;
glBufferSubData(GL_ATOMIC_COUNTER_BUFFER, 0, sizeof(GLuint), &zero);
```

We could have also done it by using a new OpenGL 4.3 feature, *Clear Buffer Data*, which sets all values of the buffer object to the same preset value. This is analogous to the C function *memset( )*.

Application Program

```
glBindBufferBase( GL_ATOMIC_COUNTER_BUFFER, 7, countBuffer);
GLuint zero = 0;
glClearBufferData( GL_ATOMIC_COUNTER_BUFFER, GL_R32UI, GL_RED, GL_UNSIGNED_INT,  &zero );
```

Presumably this is faster than using *glBufferSubData*, especially for *large-sized* buffer objects (unlike this one).

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