A Review of OpenGL Compute Shaders

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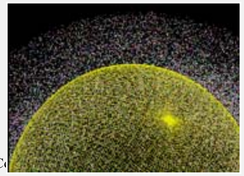
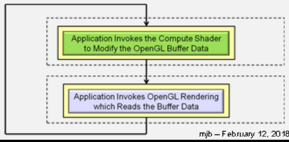
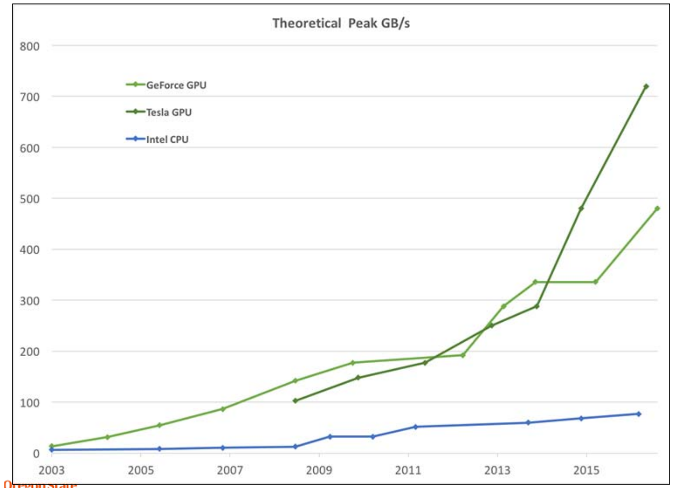






Why have GPUs Been Outpacing CPUs in Performance?

Due to the nature of graphics computations, GPU chips are customized to handle **streaming data**.

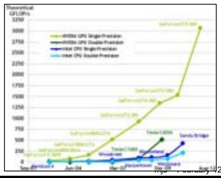
Another reason is that GPU chips do not need the significant amount of **cache** space that occupies much of the real estate on general-purpose CPU chips. The GPU die real estate can then be re-targeted to hold more cores and thus to produce more processing power.

Another reason is that general CPU chips contain on-chip logic to do **branch prediction.** This, too, takes up chip die space.

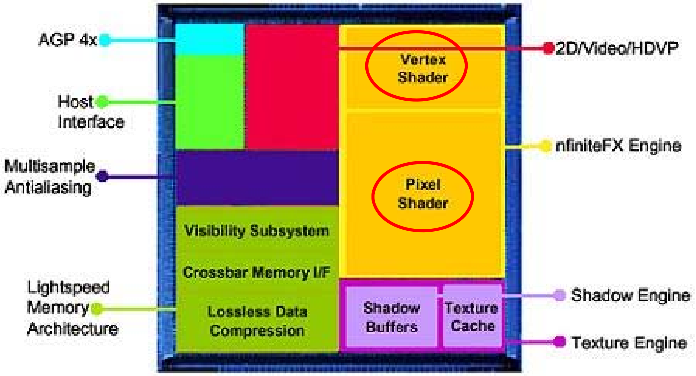
Another reason is that general CPU chips contain on-chip logic to process instructions **out-of-order** if the CPU is blocked and is waiting on something (e.g., a memory fetch). This, too, takes up chip die space.

So, which is better, CPU or GPU?

It depends on what you are trying to do!

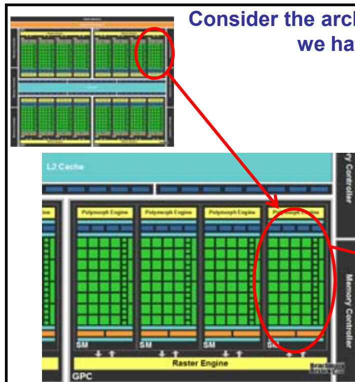


Originally, GPU Devices were very task-specific



Today's GPU Devices are less task-specific

Consider the architecture of the NVIDIA Titan Black we have in our *rabbit* System



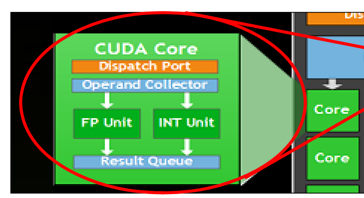
15 Streaming Multiprocessors (SMs) / chip

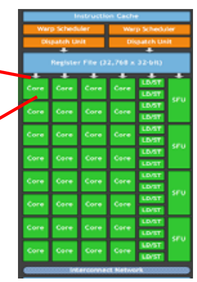
192 cores / SM

Wow! 2880 cores / chip? Really?

The “Core-Score”. How can this be?

What is a “Core” in the GPU Sense?



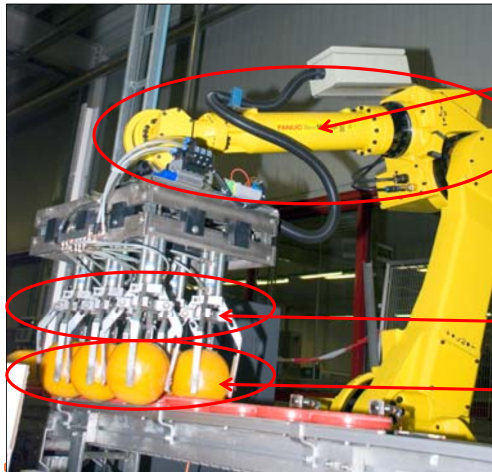


Look closely, and you'll see that NVIDIA really calls these “CUDA Cores”

Look even more closely and you'll see that these CUDA Cores have no control logic – they are **pure compute units**. (The surrounding SM has the control logic.)

Other vendors refer to these as “Lanes”. You might also think of them as 192-way SIMD.

A Mechanical Equivalent…



“Streaming Multiprocessor”

“CUDA Cores”

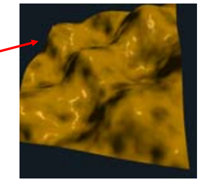
“Data”

http://news.cision.com

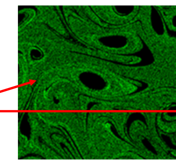
How Can You Gain Access to that GPU Power?

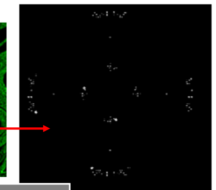
There are three ways:

1. Write a graphics display program (≥ 1985)



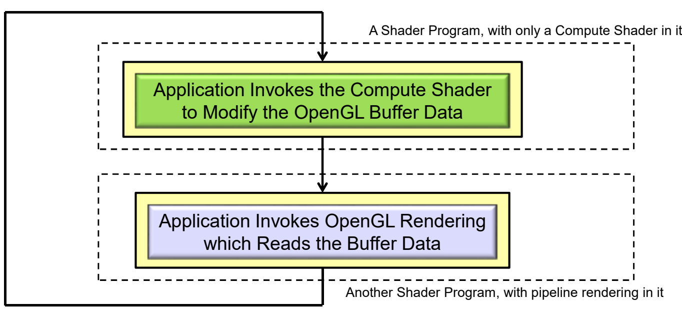
2. Write an application that looks like a graphics display program, but uses the fragment shader to do some computation (≥ 2002)





3. Write in OpenCL (or CUDA), which looks like C++ (≥ 2006)

OpenGL Compute Shader – the Basic Idea



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

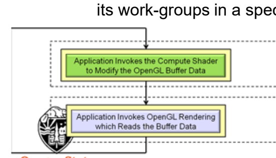
Not much:

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.



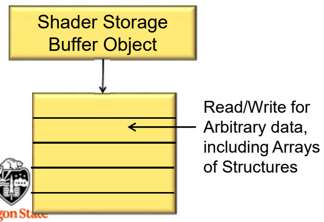
More information on items 3 and 4 are coming up . . .

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."

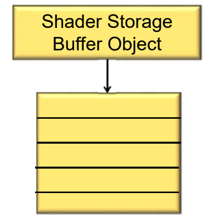
OpenCL programs have access to general arrays of data, and also access to OpenGL arrays of data in the form of buffer objects. Compute Shaders, looking like other shaders, haven't had *direct* access to general arrays of data (hacked access, yes; direct access, no). But, because Compute Shaders represent 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!

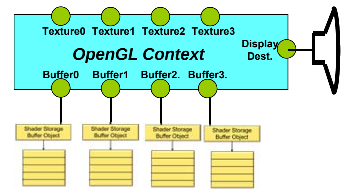


Shader Storage Buffer Objects are created with arbitrary data (same as other buffer objects), but what is new is that the shaders can read and write them in the same C-like way as they were created, including treating parts of the buffer as an array of structures – perfect for data-parallel computing!

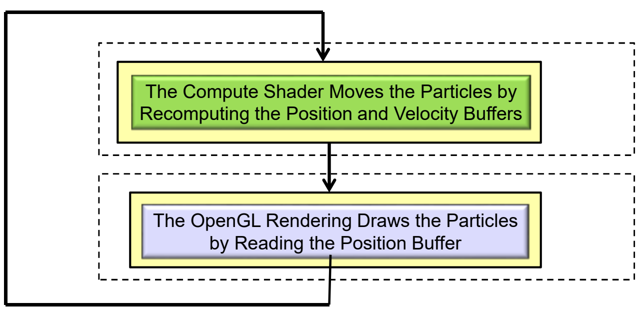
Passing Data to the Compute Shader Happens with a Cool New Buffer Type – the *Shader Storage Buffer Object*



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.



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

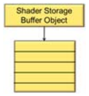


Setting up the Shader Storage Buffer Objects in Your C Program

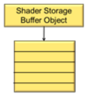

```
#define NUM_PARTICLES       1024*1024       // total number of particles to move
#define WORK_GROUP_SIZE          128        // # work-items per work-group

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;
```

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 need to be done for the color shader storage buffer object

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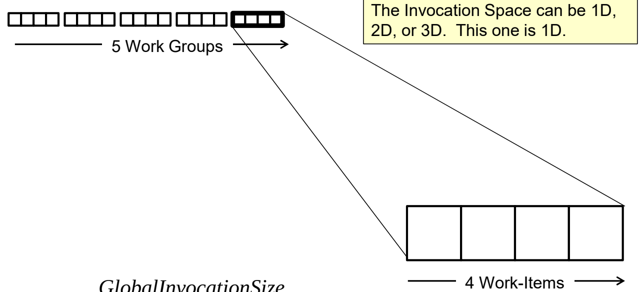
The Data Needs to be Divided into Large Quantities call *Work-Groups*, each of which is further Divided into Smaller Units Called *Work-Items*

20 total items to compute:

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



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

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

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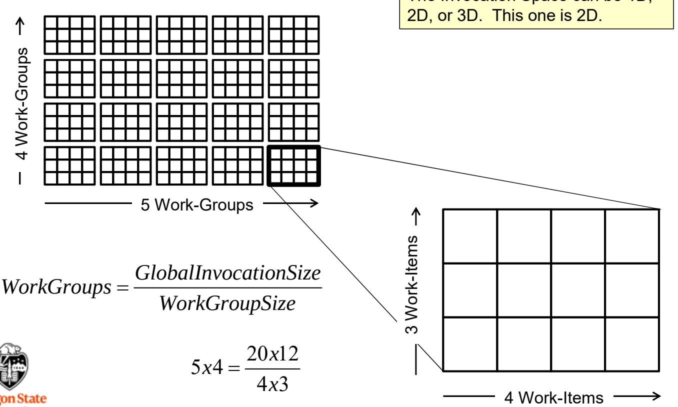
The Data Needs to be Divided into Large Quantities call Work-Groups, each of which is further Divided into Smaller Units Called Work-Items

20x12 (=240) total items to compute:

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



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

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

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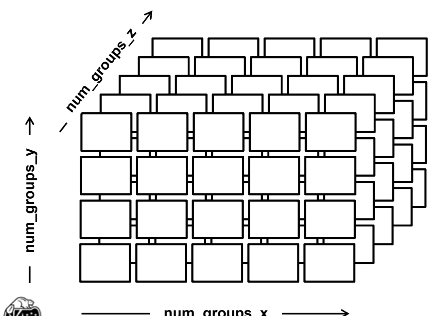
Running the Compute Shader from the Application


```
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

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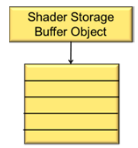
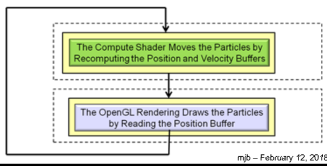
Invoking the Compute Shader in Your C Program


```
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 );
```





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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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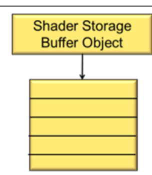
The Particle System Compute Shader -- Setup


```
#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
};

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.



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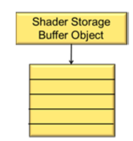
The Particle System Compute Shader – The Physics


```
#define POINT    vec3
#define VECTOR   vec3
#define SPHERE   vec4

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

        . . .

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

POIINT   p = Positions[ gid ].xyz;
VECTOR   v = Velocities[ gid ].xyz;

POINT    pp = p + v*DT + .5*DT*DT*G;
VECTOR   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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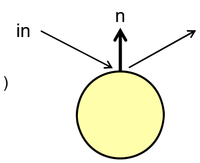
```
const SPHERE S =  vec4( -100., -800., 0.,  600. );      // x, y, z, r
                                                        // (could also have passed this in)
VECTOR
Bounce( VECTOR vin, VECTOR n )
{
        VECTOR vout = reflect( vin, n );
        return vout;
}

VECTOR
BounceSphere( POINT p, VECTOR 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  );
}
```



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;
VECTOR v  = Velocities[  gid  ].xyz;

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

if(  IsInsideSphere( pp, S )  )
{
        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, nobody will ever know…

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

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