Introduction to the OpenGL Shading Language (GLSL)

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The Basic Computer Graphics Pipeline, OpenGL-style

- Vertex, Normal, Color
  - MC
- Model Transform
- WC
- View Transform
- EC
- Per-vertex Lighting
- EC
- Projection Transform
- Projection
- Rasterization
- Fragment Processing, Texturing, Per-fragment Lighting
- Framebuffer

MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates
The Basic Computer Graphics Pipeline, Shader-style

**Vertex Shader**
- **Per-vertex in variables:** gl_Vertex, gl_Normal, gl_Color
- **Uniform Variables:** gl_ModelViewMatrix, gl_ProjectionMatrix, gl_ModelViewProjectionMatrix
- **Per-vertex out variables:** gl_Position

**Fragment Shader**
- **Per-fragment in variables:** gl_FragColor
- **Uniform Variables:**
  - Fragment Processing, Texturing, Per-fragment Lighting

**Rasterization**
- MC = Model Vertex Coordinates
- WC = World Vertex Coordinates
- EC = Eye Vertex Coordinates
The Basic Computer Graphics Pipeline, Shader-style

- **Per-vertex in variables**: `gl_Vertex`, `gl_Normal`, `gl_Color`
- **Uniform Variables**: `gl_ModelViewMatrix`, `gl_ProjectionMatrix`, `gl_ModelViewProjectionMatrix`
- **Per-vertex out variables**: `gl_Position`
- **Per-fragment in variables**: `gl_FragColor`
- **Uniform Variables**

**Shaders**

- **Vertex Shader**
- **Fragment Shader**

**Framebuffer**

[Diagram of the basic computer graphics pipeline showing the flow of data through the vertex shader, fragment shader, and framebuffer.]
### GLSL Variable Types

**attribute**

These are per-vertex *in* variables. They are assigned *per-vertex* and passed into the vertex shader, usually with the intent to interpolate them through the rasterizer.

**uniform**

These are “global” values, assigned and left alone for a group of primitives. They are read-only accessible from all of your shaders. **They cannot be written to from a shader.**

**out / in**

These are passed from one shader stage to the next shader stage. In our case, *out* variables come from the vertex shader, are interpolated in the rasterizer, and go *in* to the fragment shader. Attribute variables are *in* variables to the vertex shader.
GLSL Shaders Are Like C With Extensions for Graphics:

- Types include int, ivec2, ivec3, ivec4
- Types include float, vec2, vec3, vec4
- Types include mat2, mat3, mat4
- Types include bool, bvec2, bvec3, bvec4
- Types include sampler to access textures
- Vector components are accessed with [index], .rgba, .xyzw, or.stpq
- You can ask for parallel SIMD operations (doesn’t necessarily do it in hardware):
  ```
  vec4 a, b, c;
  a = b + c;
  ```
- Vector components can be “swizzled” ( c1.rgba = c2.abgr )
- Type qualifiers: const, attribute, uniform, in, out
- Variables can have “layout qualifiers” (more on this later)
- The **discard** operator is used in fragment shaders to get rid of the current fragment
The *discard* Operator Halts Production of the Current Fragment

```cpp
if( random_number < 0.5 )
    discard;
```
GLSL Shaders Are Missing Some C-isms:

- No type casts -- use constructors instead: `int i = int( x );`
- Only some amount of automatic promotion (don’t rely on it!)
- No pointers
- No strings
- No enums
- Can only use 1-D arrays (no bounds checking)

**Warning:** integer division is still integer division!

```cpp
float f = float( 2 / 4 ); // still gives 0. like C, C++, Python, Java
```
The Shaders’ View of the Basic Computer Graphics Pipeline

• A missing stage is OK. The output from one stage becomes the input of the next stage that is there.

• The last stage before the fragment shader feeds its output variables into the rasterizer. The interpolated values then go to the fragment shader.

We are just going to cover these two
A GLSL Vertex Shader Replaces These Operations:

- Vertex transformations
- Normal transformations
- Normal unitization (normalization)
- Computing per-vertex lighting
- Taking per-vertex texture coordinates (s, t) and passing them through the rasterizer to the fragment shader
Built-in Vertex Shader Variables You Will Use a Lot:

vec4 gl_Vertex
vec3 gl_Normal
vec4 gl_Color
vec4 gl_MultiTexCoord0
mat4 gl_ModelViewMatrix
mat4 gl_ProjectionMatrix
mat4 gl_ModelViewProjectionMatrix
mat4 gl_NormalMatrix (this is the transpose of the inverse of the MV matrix)

vec4 gl_Position

Note: while this all still works, OpenGL now prefers that you pass in all the above variables (except gl_Position) as user-defined attribute variables. We'll talk about this later. For now, we are going to use the easiest way possible.
A GLSL Fragment Shader Replaces These Operations:

- Color computation
- Texturing
- Handling of per-fragment lighting
- Color blending
- Discarding fragments

Built-in Fragment Shader Variables You Will Use a Lot:

`vec4 gl_FragColor`

Note: while this all still works, OpenGL now prefers that you pass in all the above variables (except `gl_Position`) as user-defined `attribute` variables. We’ll talk about this later. For now, we are going to use the easiest way possible.
My Own Variable Naming Convention

With 7 different places that GLSL variables can be written from, I decided to adopt a naming convention to help me recognize what program-defined variables came from what sources:

<table>
<thead>
<tr>
<th>Beginning letter(s)</th>
<th>Means that the variable …</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Is a per-vertex attribute from the application</td>
</tr>
<tr>
<td>u</td>
<td>Is a uniform variable from the application</td>
</tr>
<tr>
<td>v</td>
<td>Came from the vertex shader</td>
</tr>
<tr>
<td>tc</td>
<td>Came from the tessellation control shader</td>
</tr>
<tr>
<td>te</td>
<td>Came from the tessellation evaluation shader</td>
</tr>
<tr>
<td>g</td>
<td>Came from the geometry shader</td>
</tr>
<tr>
<td>f</td>
<td>Came from the fragment shader</td>
</tr>
</tbody>
</table>

This isn’t part of “official” OpenGL – it is my way of handling the confusion
# The Minimal Vertex and Fragment Shader

### Vertex shader:

```cpp
#version 330 compatibility

void main( )
{
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

This makes sure that each vertex gets transformed.

### Fragment shader:

```cpp
#version 330 compatibility

void main( )
{
  gl_FragColor = vec4( .5, 1., 0., 1. );
}
```

This assigns a fixed color and alpha to each fragment drawn.

Not terribly useful …
A Reminder of what a Rasterizer does

There is a piece of hardware called the **Rasterizer**. Its job is to interpolate a line or polygon, defined by vertices, into a collection of **fragments**. Think of it as filling in squares on graph paper.

A fragment is a “pixel-to-be”. In computer graphics, “pixel” is defined as having its full RGBA already computed. A fragment does not yet but all of the information needed to compute the RGBA is there.

A fragment is turned into a pixel by the **fragment processing** operation.

Rasterizers interpolate built-in variables, such as the (x,y) position where the pixel will live and the pixel’s z-coordinate. They can also interpolate user-defined variables as well.
A Little More Interesting

Vertex shader:

```glsl
#version 330 compatibility
out vec3 vColor;

void main()
{
    vec4 pos = gl_Vertex;
vColor = pos.xyz;    // set rgb from xyz!
gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```glsl
#version 330 compatibility
in vec3 vColor;

void main()
{
    gl_FragColor = vec4( vColor, 1.);
}
```
vColor = gl_Vertex.xyz;
Vertex shader:

```cpp
#version 330 compatibility
out vec3 vColor;

void
main( )
{
  vec4 pos = gl_ModelViewMatrix * gl_Vertex;
  vColor = pos.xyz; // set rgb from xyz!
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```cpp
#version 330 compatibility
in vec3 vColor;

void
main( )
{
  gl_FragColor = vec4( vColor, 1. );
}
```
What's Different About This?

Set the color from the **pre-transformed (MC)** $xyz$:

```cpp
#version 330 compatibility
out vec3 vColor;

void main() {
    vec4 pos = gl_Vertex;
    vColor = pos.xyz; // set rgb from xyz!
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Set the color from the **post-transformed (WC/EC)** $xyz$:

```cpp
#version 330 compatibility
out vec3 vColor;

void main() {
    vec4 pos = gl_ModelViewMatrix * gl_Vertex;
    vColor = pos.xyz; // set rgb from xyz! why? who cares?
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```
Setting rgb From xyz, II

\[ vColor = ( \text{gl\_ModelViewMatrix} \times \text{gl\_Vertex} ).\text{xyz}; \]
Setting rgb From xyz

\[ v\text{Color} = \text{gl\_Vertex}.xyz; \]

\[ v\text{Color} = (\ \text{gl\_ModelViewMatrix} \times \text{gl\_Vertex}).xyz; \]
Vertex shader:

```cpp
#version 330 compatibility

out vec2 vST; // texture coords
out vec3 vN; // normal vector
out vec3 vL; // vector from point to light
out vec3 vE; // vector from point to eye

const vec3 LIGHTPOSITION = vec3( 5., 5., 0. );

void main( )
{
    vST = gl_MultiTexCoord0.st;
    vec4 ECposition = gl_ModelViewMatrix * gl_Vertex;
    vN = normalize( gl_NormalMatrix * gl_Normal ); // normal vector
    vL = LIGHTPOSITION - ECposition.xyz; // vector from the point to the light position
    vE = vec3( 0., 0., 0. ) - ECposition.xyz; // vector from the point to the eye position
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Per-fragment Lighting
#version 330 compatibility
uniform float uKa, uKd, uKs; // coefficients of each type of lighting
uniform vec3 uColor; // object color
uniform vec3 uSpecularColor; // light color
uniform float uShininess; // specular exponent
in vec2 vST; // texture cords
in vec3 vN; // normal vector
in vec3 vL; // vector from point to light
in vec3 vE; // vector from point to eye

void main( )
{
    vec3 Normal = normalize(vN);
    vec3 Light   = normalize(vL);
    vec3 Eye     = normalize(vE);

    vec3 ambient = uKa * uColor;

    float d = max( dot(Normal,Light), 0. ); // only do diffuse if the light can see the point
    vec3 diffuse = uKd * d * uColor;

    float s = 0.;
    if( dot(Normal,Light) > 0. ) // only do specular if the light can see the point
    {
        vec3 ref = normalize( reflect( -Light, Normal ) );
        s = pow( max( dot(Eye,ref),0. ), uShininess );
    }
    vec3 specular = uKs * s * uSpecularColor;
    gl_FragColor = vec4( ambient + diffuse + specular, 1. );}
Per-fragment Lighting

All together now!
Within the fragment shader, find out if the current fragment is within a particular rectangle:

```glsl
dot
vec3 myColor = uColor;

if( uS0-uSize/2. <= vST.s && vST.s <= uS0+uSize/2. &&
    uT0-uSize/2. <= vST.t && vST.t <= uT0+uSize/2. )
{
    myColor = vec3( 1., 0., 0. );
}

dot
vec3 ambient = uKa * myColor;
```

Within the fragment shader, find out if the current fragment is within a particular rectangle:
Here’s the cool part: It doesn’t matter (up to the limits of 32-bit floating-point precision) how far you zoom in. You still get an exact crisp edge. This is an advantage of procedural (equation-based) textures, as opposed to texel-based textures.
A C++ Class to Handle the Shaders

Setup:

```
GLSLProgram *Pattern;

...  
Pattern = new GLSLProgram( );
bool valid = Pattern->Create( "pattern.vert", "pattern.frag" );
if( ! valid )
{
  ...
}
```

This loads, compiles, and links the shader. If something went wrong, it prints error messages and returns a value of false.
A C++ Class to Handle the Shaders

Invoking this class in Display():

```c++
float S0, T0;
float Ds, Dt;
float V0, V1, V2;
float ColorR, ColorG, ColorB;

... Pattern->Use( );
Pattern->SetUniformVariable( "uS0", S0 );
Pattern->SetUniformVariable( "uT0", T0 );
Pattern->SetUniformVariable( "uDs", Ds );
Pattern->SetUniformVariable( "uDt", Dt );
Pattern->SetUniformVariable( "uColor", ColorR, ColorG, ColorB );

glBegin( GL_TRIANGLES );
    Pattern->SetAttributeVariable( "aV0", V0 ); // don’t need for Project #5
    glVertex3f( x0, y0, z0 );
    Pattern->SetAttributeVariable( "aV1", V1 ); // don’t need for Project #5
    glVertex3f( x1, y1, z1 );
    Pattern->SetAttributeVariable( "aV2", V2 ); // don’t need for Project #5
    glVertex3f( x2, y2, z2 );

glEnd( );

Pattern->Use( 0 ); // go back to fixed-function OpenGL
```
Setting Up Texturing in Your C/C++ Program

This is the hardware Texture Unit Number. It can be 0-15 (and often a lot higher depending on the graphics card).

```c
// globals:
unsigned char * Texture;
GLuint TexName;

...  
// In InitGraphics( ):
glGenTextures( 1, &TexName );
int nums, numt;
Texture = BmpToTexture( "filename.bmp" , &nums, &numt );
glBindTexture( GL_TEXTURE_2D, TexName );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
glTexImage2D( GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );

...  
// In Display( ):
Pattern->Use( );
glActiveTexture( GL_TEXTURE5 );  // use texture unit 5
glBindTexture( GL_TEXTURE_2D, TexName );
Pattern->SetUniformVariable( "uTexUnit", 5 );  // tell your shader program you are using texture unit 5
    << draw something >>
Pattern->Use( 0 );
```
2D Texturing

Vertex shader:

```glsl
#version 330 compatibility
out vec2 vST;

void main( )
{
    vST = gl_MultiTexCoord0.st;
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```glsl
#version 330 compatibility
in vec2 vST;
uniform sampler uTexUnit;

void main( )
{
    vec3 newcolor = texture( uTexUnit, vST ).rgb;
    gl_FragColor = vec4( newcolor, 1. );
}
```
Hints on Running Shaders on Your Own System

• You need a graphics system that is OpenGL 2.0 or later. Basically, if you got your graphics system in the last 5 years, you should be OK. If you don't have access to such a system, use the CGEL. (The most recent OpenGL level there is 4.6)

• Update your graphics drivers to the most recent level!

• If you are on Windows, you must do the GLEW setup. It looks like this in the sample code:
  
  ```c
  GLenum err = glewInit();
  if( err != GLEW_OK )
  {
    fprintf( stderr, "glewInit Error\n" );
  }
  else
    fprintf( stderr, "GLEW initialized OK\n" );
  
  And, this must come after you've opened a window. (It is this way in the code, but I'm saying this because I know some of you went in and "simplified" the sample code by deleting everything you didn't think you needed.)

• You can use the GLSL C++ class you've been given only after GLEW has been setup. So, initialize your shader program:
  
  ```c
  bool valid = Pattern->Create( "pattern.vert", "pattern.frag" );
  ```

  after successfully initializing GLEW.
Declare the GLSLProgram above the main program (as a global):

GLSLProgram * Pattern;

At the end of InitGraphics( ), create the shader program and setup your shaders:

Pattern = new GLSLProgram( );
bool valid = Pattern->Create( "project.vert", "project.frag" );
if( ! valid ) { . . . }

Use the Shader Program in Display( ):

Pattern->Use( );
Pattern->SetUniformVariable( ... 

Draw the object here

Pattern->Use( 0 ); // return to fixed functionality
**Tips on drawing the object:**

- If you want to key off of s and t coordinates in your shaders, the object had better have s and t coordinates assigned to its vertices – not all do!

- If you want to use surface normals in your shaders, the object had better have surface normals assigned to its vertices – not all do!

- Be sure you explicitly assign *all* of your uniform variables – no error messages occur if you forget to do this – it just quietly screws up.

- The glutSolidTeapot has been textured in patches, like a quilt – cute, but weird

- The MjbSphere( ) function from the texturing project will give you a very good sphere