Introduction to using the OpenGL Shading Language (GLSL)

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The Basic Computer Graphics Pipeline, OpenGL-style

The Basic Computer Graphics Pipeline, Shader-style

The Basic Computer Graphics Pipeline, Shader-style
**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 into the fragment shader.

- **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.

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**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

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**The `discard` Operator Halts Production of the Current Fragment**

```
if( random_number < 0.5 )
  discard;
```

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**GLSL Shaders Are Missing Some C-isms:**

- No type casts -- use constructors instead: `int i = int( x );`
- There is 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!

```
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 interpolating 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`
- `mat3 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 most straightforward way possible.

A GLSL Fragment Shader Replaces These Operations:

- Color computation
- Texturing
- 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 out the fragment color variable as a user-defined out variable. We’ll talk about this later. For now, we are going to use the most straightforward 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/GLSL – it is my way of handling the confusion.

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.

The Minimal Vertex and Fragment Shader

```glsl
#version 330 compatibility

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

Vertex shader:

```glsl
#version 330 compatibility

out vec3 vColor;

void main() {
    vColor = vec3(gl_Position.x, gl_Position.y, 1.);
    gl_FragColor = vec4(vColor, 1.);
}
```

Fragment shader:

A Little More Interesting: Setting rgb from the Untransformed xyz, 1

```glsl
#version 330 compatibility

void main() {
    vec4 pos = gl_Vertex;
    vec4 res = vec4(pos.x, pos.y, pos.z, 1.);
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
    gl_FragColor = vec4(res.r, res.g, res.b, 1.);
}
```

Vertex shader:

```glsl
#version 330 compatibility

in vec3 vColor;

void main() {
    gl_FragColor = vec4(vColor, 1.);
}
```
Setting rgb from the Untransformed xyz, I

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

**Vertex shader:**
```
#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:**
```
#version 330 compatibility
in vec3 vColor;
void main()
{
  gl_FragColor = vec4( vColor, 1.);
}
```

Setting rgb from the Transformed xyz, II

**Vertex shader:**
```
#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:**
```
#version 330 compatibility
in vec3 vColor;
void main()
{
  gl_FragColor = vec4( vColor, 1.);
}
```

What's Different About This?

Set the color from the untransformed (MC) xyz:
```
#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 transformed (WC/EC) xyz:
```
#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;
}
```

Setting rgb from the Transformed xyz, II

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

- $vColor = gl\_Vertex.xyz$;
- $vColor = (gl\_ModelViewMatrix \times gl\_Vertex).xyz$;

### Vertex shader: Per-fragment Lighting

- #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; // eye coordinate position
  | vN = normalize(gl\_NormalMatrix \times gl\_Normal); // normal vector
  | vL = LIGHTPOSITION - ECposition.xyz; // vector from the point
  | vE = vec3(0., 0., 0.) - ECposition.xyz; // vector from the point
  | gl\_Position = gl\_ModelViewProjectionMatrix \times gl\_Vertex;

### Fragment shader: 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 = 0.6;
  | float x = dot(Normal, Light) > 0. ? max(0, dot(reflect(-Light, Normal), Eye)) : 0;
  | vec3 reflect = normalize(reflect(-Light, Normal));
  | vec3 spec = uKs * x * uSpecularColor;
  | gl\_FragColor = vec4(ambient + diffuse + specular, 1.);
Within the fragment shader, find out if the current fragment is within a particular rectangle:

```glsl
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. );
}
vec3 ambient = uKa * myColor;
```

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.

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A C++ Class to Handle the Shaders

Do this in `Display()`:

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

Pattern->Use( ); // no more fixed-function – shaders now handle everything
Pattern->SetUniformVariable( "uS0", S0 );
Pattern->SetUniformVariable( "uT0", T0 );
Pattern->SetUniformVariable( "uDs", Ds );
Pattern->SetUniformVariable( "uDt", Dt );
Pattern->SetUniformVariable( "uColor", ColorR, ColorG, ColorB );
gBegin( GL_TRIANGLES );
Pattern->SetAttributeVariable( "aV0", V0 ); // don't need for Project #5
Pattern->SetAttributeVariable( "aV1", V1 ); // don't need for Project #5
Pattern->SetAttributeVariable( "aV2", V2 ); // don't need for Project #5
gEnd( );
Pattern->UnUse( ); // go back to fixed-function OpenGL
```

---

This loads, compiles, and links the shader. If something went wrong, it prints error messages into the console window and returns a value of false.
Setting Up Texturing in Your C/C++ Program

```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 );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
gTexImage2D( GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );

// In Display( ):
Pattern->Use( );
gActiveTexture( GL_TEXTURE5 ); // use texture unit 5
Pattern->SetUniformVariable( "uTexUnit", 5 ); // tell your shader program you are using texture unit 5
<< draw something >>
Pattern->UnUse( );
```

### 2D Texturing

```c
// In Display( ):
Pattern->Use( );
gActiveTexture( GL_TEXTURE5 ); // use texture unit 5
Pattern->SetUniformVariable( "uTexUnit", 5 ); // tell your shader program you are using texture unit 5
<< draw something >>
Pattern->UnUse( );
```

#### Setting up 2D Texturing in Your C/C++ Program

- **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 );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
  tTexImage2D( GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );
  ```

- **In Display( ):**
  ```
  Pattern->Use( );
  gActiveTexture( GL_TEXTURE5 ); // use texture unit 5
  Pattern->SetUniformVariable( "uTexUnit", 5 ); // tell your shader program you are using texture unit 5
  << draw something >>
  Pattern->UnUse( );
  ```

### 2D Texturing

```c
out  vec2 vST;

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

#### Setting up 2D Texturing in Your C/C++ Program

- **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 );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
  tTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
  tTexImage2D( GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );
  ```

- **In Display( ):**
  ```
  Pattern->Use( );
gActiveTexture( GL_TEXTURE5 ); // use texture unit 5
  Pattern->SetUniformVariable( "uTexUnit", 5 ); // tell your shader program you are using texture unit 5
  << draw something >>
  Pattern->UnUse( );
  ```

### 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. (The most recent OpenGL level is 4.6)
- Update your graphics drivers to the most recent!
- You must do the GLEW setup. It looks like this in the sample code:
  ```
  GLenum err = glewInit( );
  if( err != GLEW_OK )
    {
        fprintf( stderr, "glewInit Error\n" );
    }
  else
    fprintf( stderr, "GLEW initialized OK\n" );
  ```
  This must come after you've opened a window. (It's in this way in the sample code, but I'm saying this because I know some of you go in and "simplify" the sample code by deleting everything you don't think you need.)
- You can use the GLSL C++ class you've been given only after GLEW has been setup. So, initialize your shader program:
  ```
  bool valid = Pattern->Create( "pattern.vert", "pattern.frag" );
  after successfully initializing GLEW.
  ```
1. Declare the GLSLProgram above the main program (as a global):
   
   GLSLProgram * Pattern;

2. At the end of InitGraphics(), create the shader program and setup your shaders:
   
   Pattern = new GLSLProgram();
   bool valid = Pattern->Create("pattern.vert", "pattern.frag");
   if (!valid) { ... }

3. Turn on the shader program in Display(), set shader variables, draw the object, then turn off the shader program:
   
   Pattern->Use();
   Pattern->SetUniformVariable(...)
   Sphere();
   Pattern->UnUse(); // return to the fixed function pipeline

4. When you run your program, be sure to check the console window for shader compilation errors!

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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 (vt) assigned to its vertices – *not all OBJ files do!*

- If you want to use surface normals in your shaders, the object had better have surface normals (vn) assigned to its vertices – *not all OBJ files 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 OsuSphere() function from the texturing project will give you a very good sphere