An Introduction to Shader-Based OpenGL Programming

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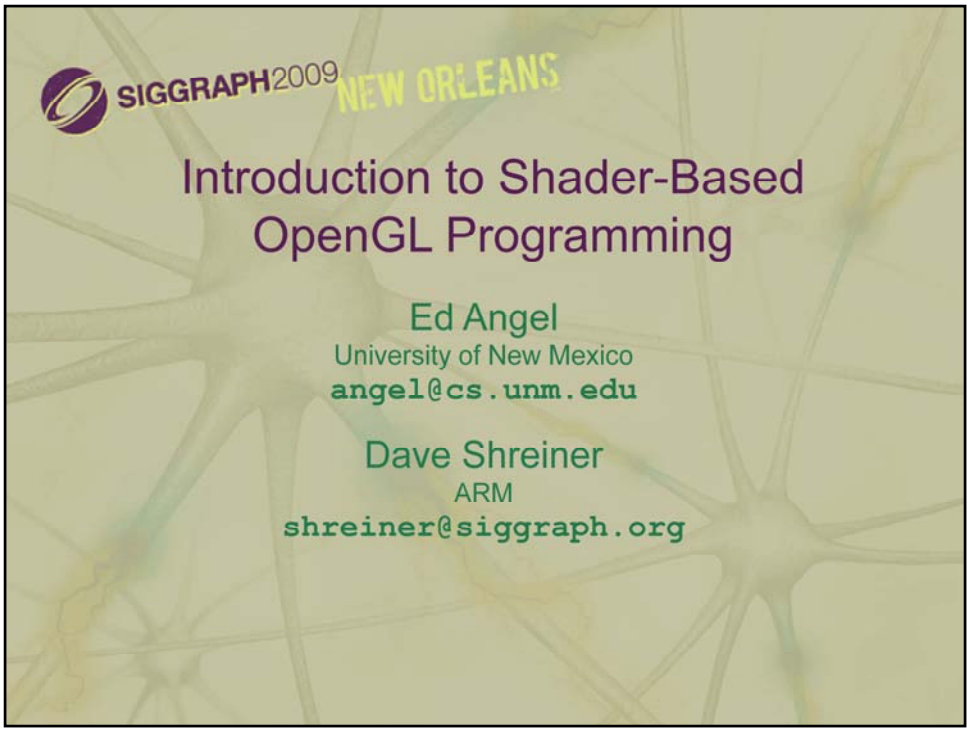
Table of Contents

Notes

Program Listings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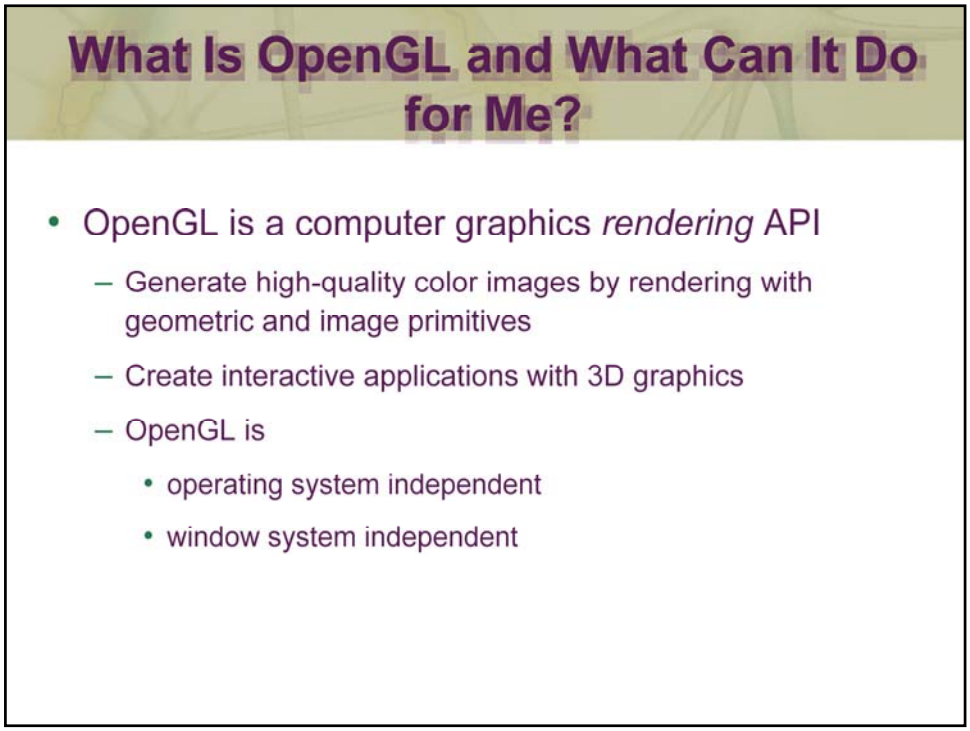
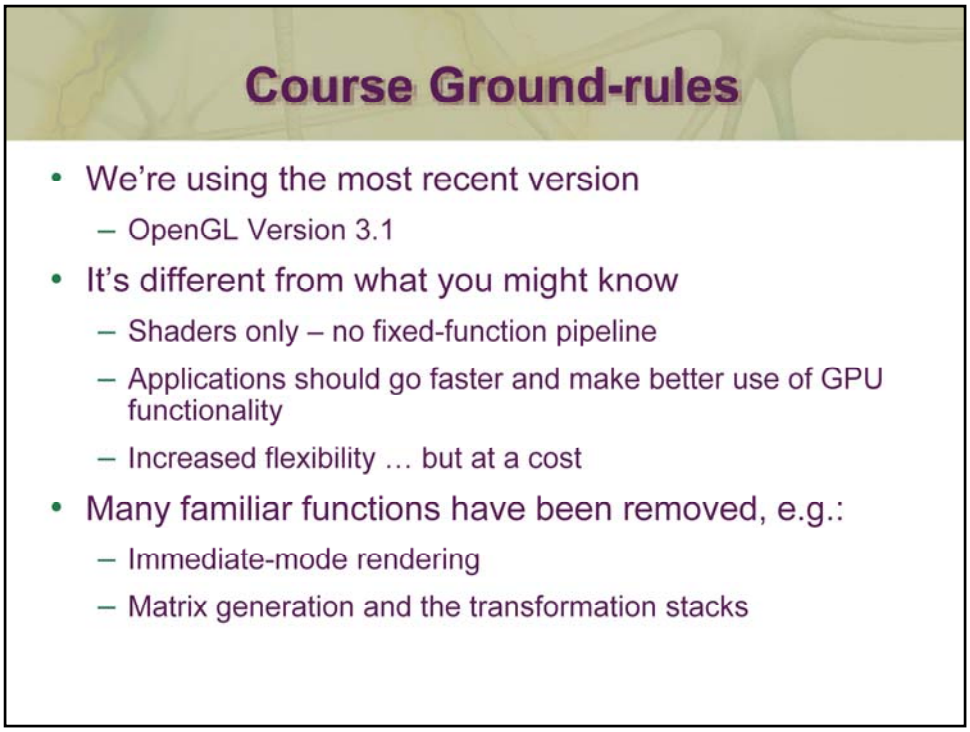


OpenGL is a library for doing computer graphics. By using it, you can create interactive applications that render high-quality color images composed of 3D geometric objects and images.

OpenGL is window and operating system independent. As such, the part of your application which does rendering is platform independent. However, in order for OpenGL to be able to render, it needs a window to draw into. Generally, this is controlled by the windowing system on whatever platform you are working on.



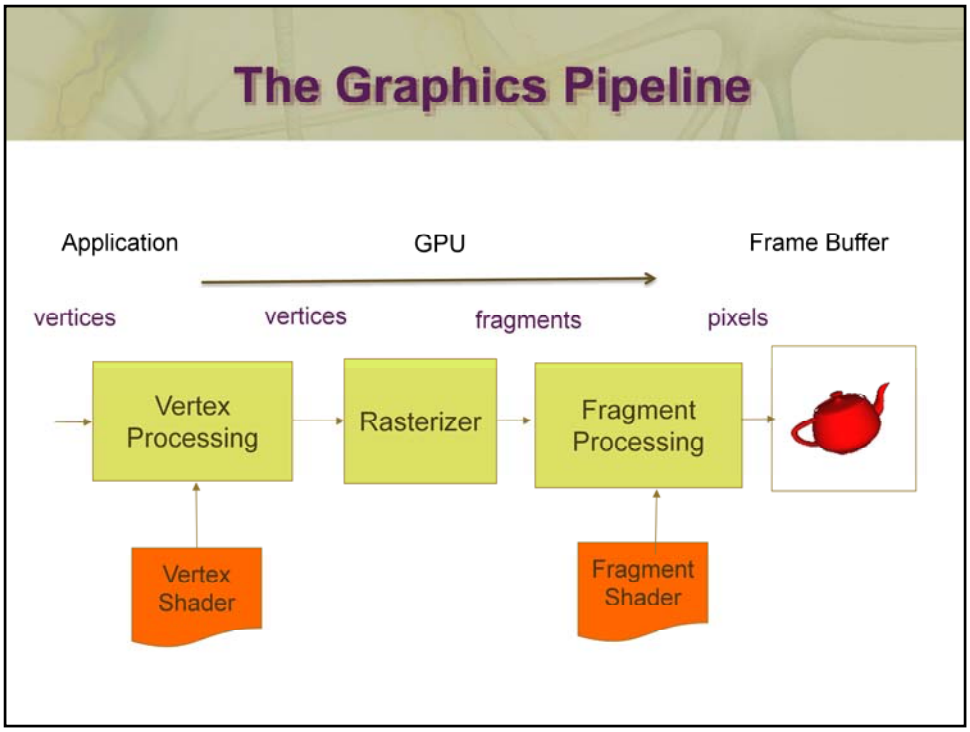
OpenGL 3.1 is the first version of OpenGL not to be backwards compatible with previous version. This version removed a lot of older-style functionality, like the immediate-mode rendering interface (e.g., `glBegin()` / `glEnd()` rendering), the matrix transformation stack, and vertex lighting, to name a few features. The idea was to move all applications to shader-based rendering, which can better leverage GPUs, and removed the less efficient methods and functions to help application developer's get the best performance from their hardware. Additionally, shaders provide considerably more flexibility in how we do graphics. We're no longer constrained by the features implemented in the core of OpenGL, but can completely control how we render.

For the purposes of this course, we don't assume you know anything about OpenGL, just that you know a little about computer graphics. We'll take you step-by-step in constructing an application that renders 3D, moving, shaded objects.

Syllabus

- Getting Started
- Working with Objects
- OpenGL Shading Language
- Transformations
- Lighting
- Texture Mapping
- Application Examples

Getting Started



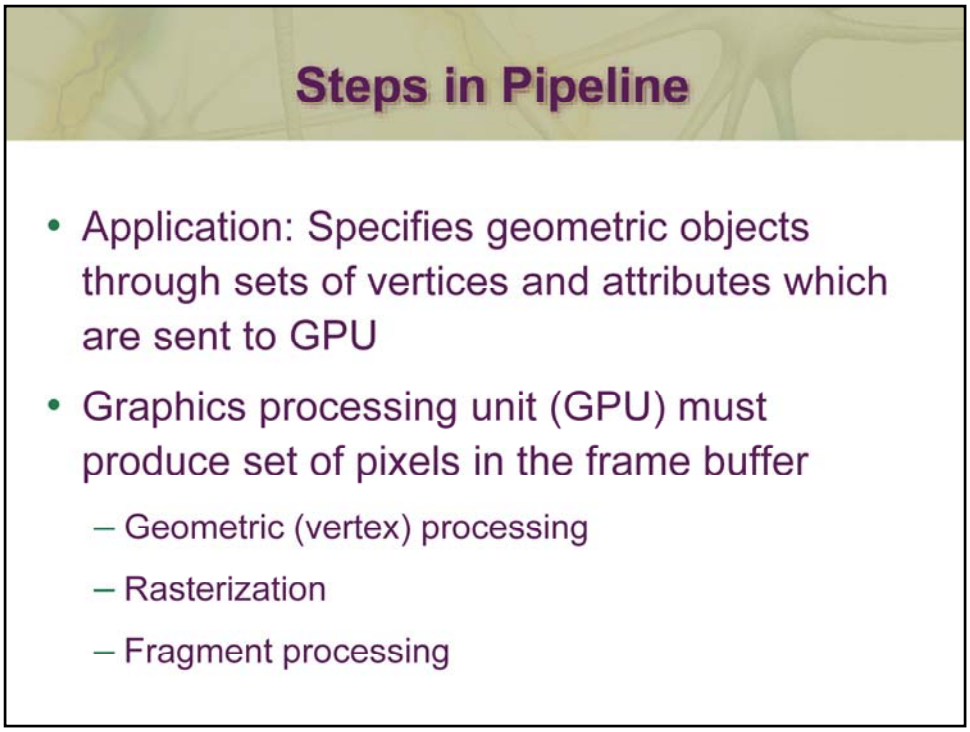
Here we show a simplified version of the OpenGL pipeline, which specifically processes geometry. All OpenGL programs use this pipeline, and with OpenGL Version 3.1, you get to configure the operation of the pipeline by writing shaders which are executed by the various stages of the pipeline.

You can see that a *vertex shader* is used by the vertex processing phase, which accepts vertices as its input, processes them, and passes them into the next phase of the pipeline.

The *rasterizer* is the part of the pipeline that determines which pixels on the screen should be colored in based on the *geometric primitive* that the vertex processing phase finished with. The output of the rasterizer are *fragments,* which are passed into the fragment processing phase of the pipeline. Each fragment references a location in the window, which the fragment processing phase determines the color for.

The fragment processing phase takes a *fragment shader* which is executed for ever fragment from the input geometric primitive. The fragment shader's job is to *shade* (compute the color of) a pixel and then pass it into the fragment testing pipeline to determine if the color should be displayed in the window (i.e., written into the *framebuffer*).

The framebuffer contains the final image after all of the geometric primitives are processed and shaded.

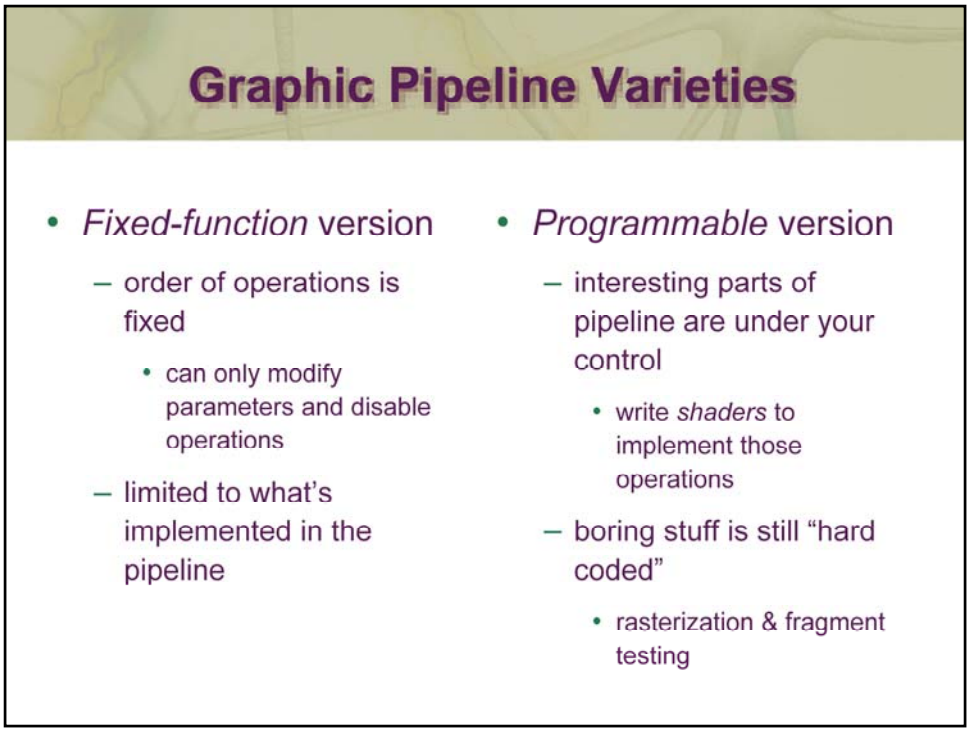


Attributes such as colors, texture coordinates and lighting normals determine how a geometric object is displayed.

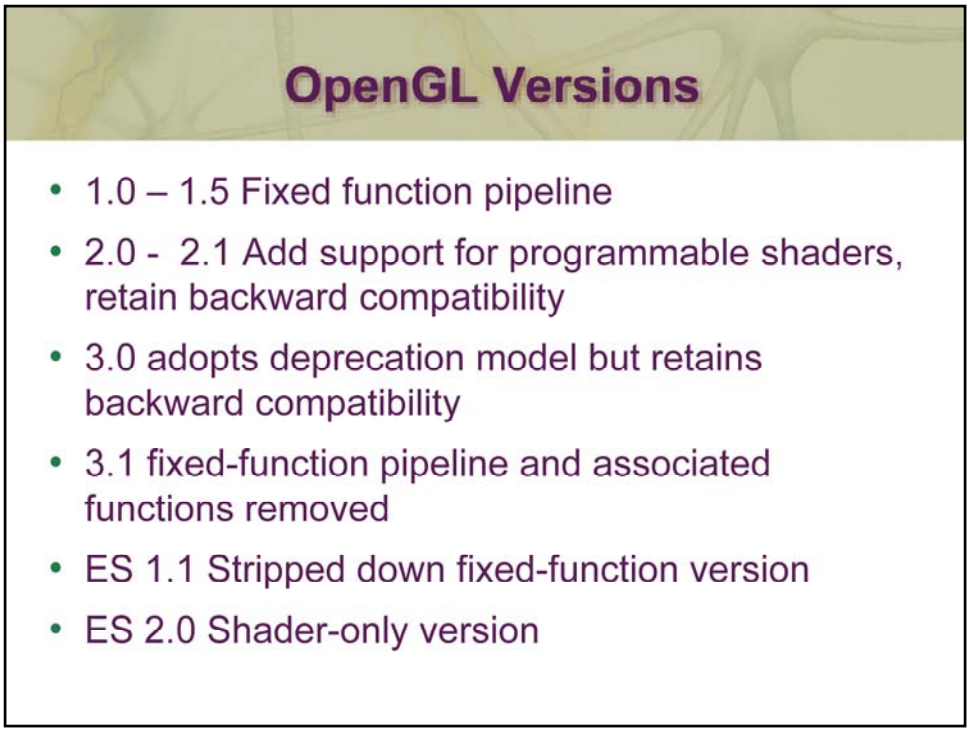
Geometry processing includes coordinate transformations, per-vertex lighting, clipping and primitive assembly.

The rasterizer generates fragments that correspond to pixel locations interior to the geometric objects that haven't be clipped. Fragments are potential pixels can appear on the display but may not due to later processing such as hidden surface removal. The rasterizer must interpolate vertex attributes to determine values such as texture coordinates for each fragment.

Fragment processing produces a color for each fragment and includes hidden surface removal, per fragment lighting, and application of textures.

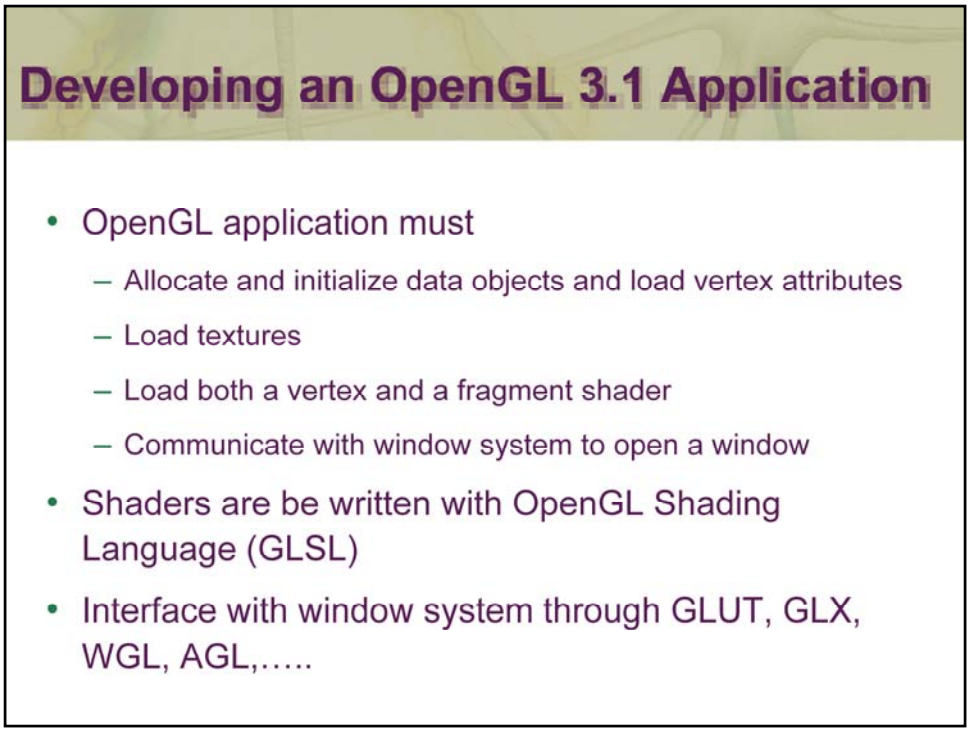


This course concentrates on the programmable version of OpenGL.



OpenGL 3.0 introduced versioned contexts so that application programs could specify which version of OpenGL is being requested.

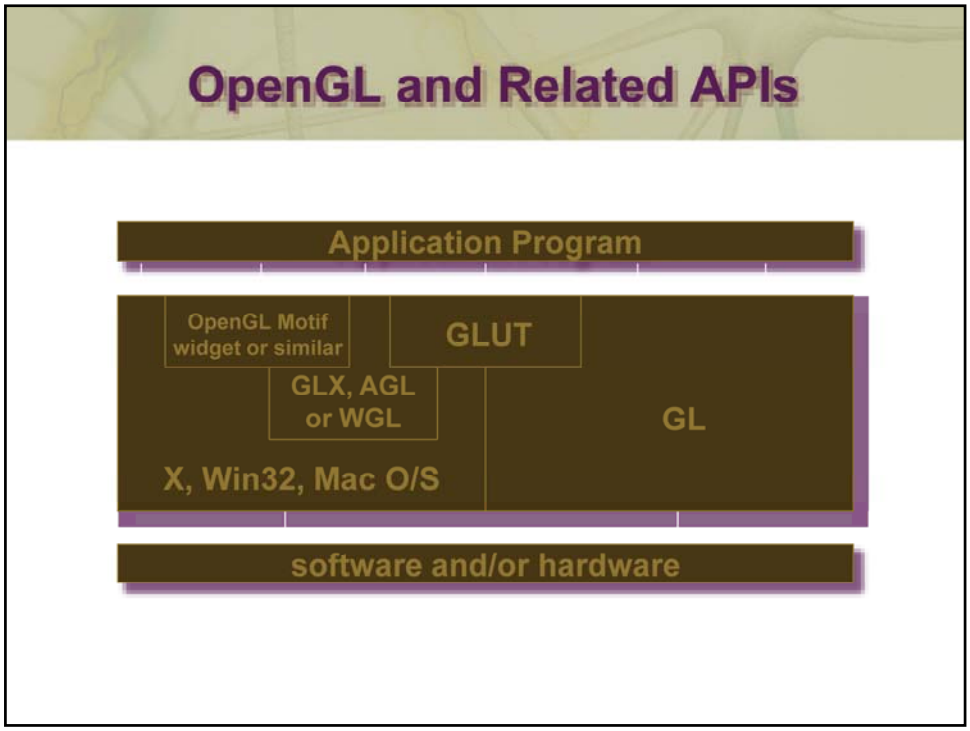
Most of the fixed-function pipeline functions were marked as deprecated in 3.0. This removed much of the default functionality and state. These functions were removed from 3.1 although they are available in an ARB extension that will likely be supported on most implementations.



In OpenGL 3.1, almost all data is stored in *objects*, which is memory that OpenGL manages on your behalf. You can think of if roughly liked calling `malloc()`, where you specify how much memory you need. Once you've allocated your objects, you'll need to load it with data, like *vertex attributes*. It's also quite likely you'll use *textures*, which is also data you'll pass to OpenGL to manage, and use to draw your scene.

Next, you'll need to configure how the OpenGL pipeline should process data. You do this by specifying vertex and fragment *shaders*, which are small programs written in the OpenGL Shading Language (commonly called "GLSL"). These shaders are compiled and linked like any compiled program. However, the entire compilation process is done by calling functions inside of your application.

For the purposes of this class, we use an open-source library for managing windows named **Freeglut**. It allows you to easily port the same source code to any of the popular operating systems: Microsoft Windows, Apple's Mac OS X, and Linux. Each of the different operating systems has a specific library that is used to enable OpenGL rendering within its windowing system. For instance, you would use Microsoft Windows' methods to open a window, and then use WGL – the specific OpenGL windowing interface on Microsoft Windows – to modify that window to be able to use OpenGL. Likewise, Mac OS X there's AGL which serves the same purpose, as does GLX on Linux for the X Window System.

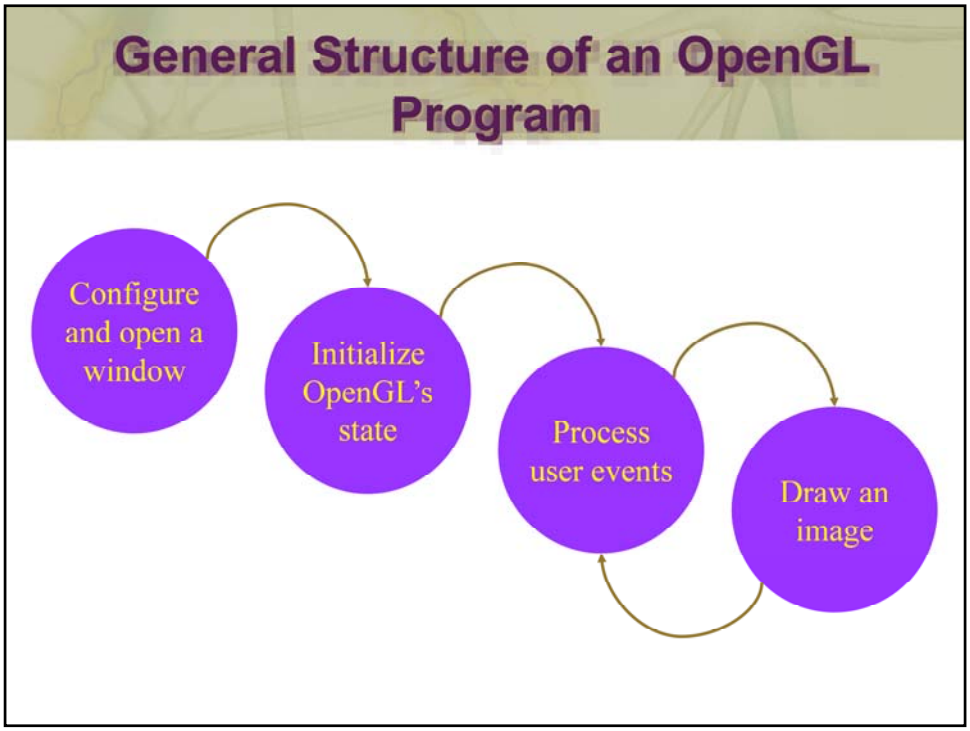


The above diagram illustrates the relationships of the various libraries and window system components.

Generally, applications which require more user interface support will use a library designed to support those types of features (i.e., buttons, menu and scroll bars, etc.) such as Motif or the Win32 API.

Prototype applications, or ones which do not require all the bells and whistles of a full GUI, may choose to use GLUT instead because of its simplified programming model and window system independence.

The OpenGL Utility Library (GLU) contained many helpful functions that were constructed from GL including quadrics, some additional viewing functions, and tessellation code. However, most GLU functions require OpenGL functions that have been removed from OpenGL 3.1 so this library will no longer be useful (although much of it could probably be recreated without the deprecated functions).



OpenGL was primarily designed to be able to draw high-quality images fast enough so that an application could draw many of them a second, and provide the user with an interactive application, where each *frame* could be customized by input from the user.

The general flow of an interactive application, including OpenGL applications is:

1. Configure and open a window suitable for drawing OpenGL into.
2. Initialize any OpenGL state that you will need to use throughout the application.
3. Process any events that the user might have entered. These could include pressing a key on the keyboard, moving the mouse, or even moving or resizing the application's window.
4. Draw your 3D image using OpenGL with values that may have been entered from the user's actions, or other data that the program has available to it.

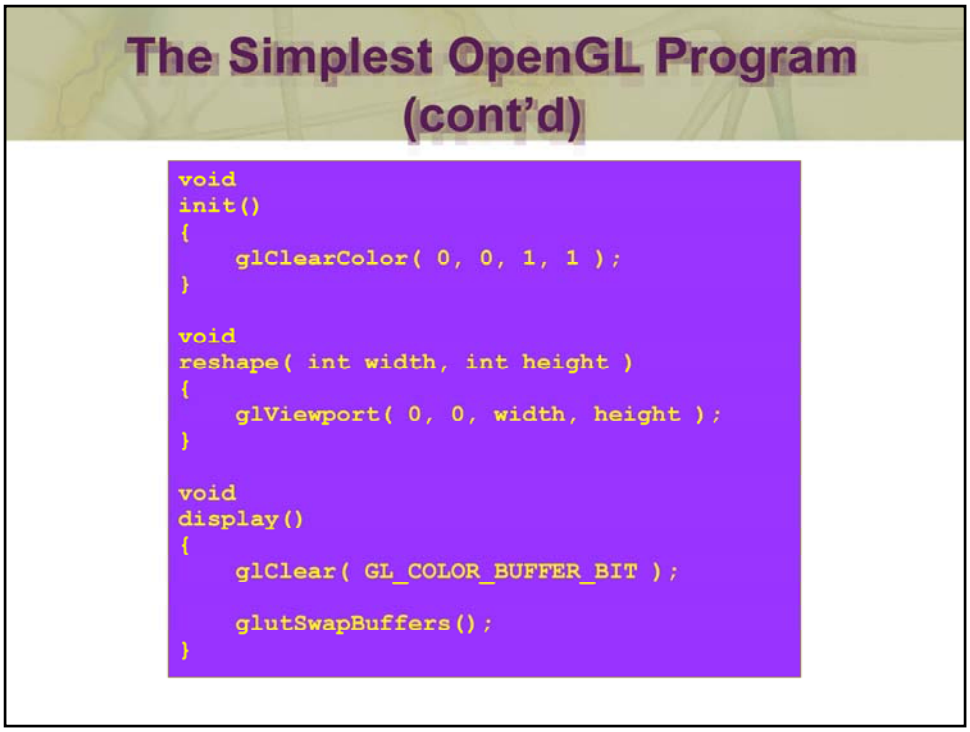
This slide contains the program statements for the `main()` routine of a C program that uses OpenGL and GLUT. For the most part, all of the programs you will see today, and indeed may of the programs available as examples of OpenGL programming that use GLUT will look very similar to this program.

All GLUT-based OpenGL programs begin with configuring the GLUT window that gets opened.

Next, in the routine `init()` (detailed on the following slide), "global" OpenGL state is configured. By "global", we mean state that will be left on for the duration of the application. By setting that state once, we can make our OpenGL applications run as efficiently as possible. As we shall later, the shaders must be read, compiled, and linked.

After initialization, we set up our GLUT *callback functions*, which are routines that you write to have OpenGL draw objects and other operations. Callback functions, if you're not familiar with them, make it easy to have a generic library (like GLUT), that can easily be configured by providing a few routines of your own construction.

Finally, as with all interactive programs, the event loop is entered. For GLUT-based programs, this is done by calling `glutMainLoop()`. As `glutMainLoop()` never exits (it is essentially an infinite loop), any program statements that follow `glutMainLoop()` will never be executed.



Here is the remainder of the program. While it's not very impressive, it's the fundamental structure of every OpenGL program.

We use the `init()` routine configure settings that aren't going to change across the execution of a program. In this case, we show our first OpenGL routine, `glClearColor()`, which specifies the color that the window will show when it's cleared.

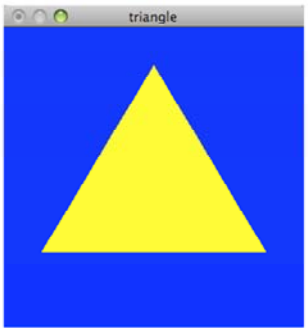
Next, we set up the `glutReshapeFunc()` callback, which we name reshape() (you'll see a pattern here ☺). In this case, we merely reconfigure the *viewport* based on the values the windowing system provide to us (which GLUT passes on for our use). We'll discuss the viewport and its importance later.

Finally, we specify the `glutReshapeFunc()` callback – `display()` – which is were we'll do all of our drawing. For this simple application, we do to rendering operations:

1. we clear the window using the OpenGL routine `glClear()`. You'll notice that it takes a parameter that specifies we want to clear the color buffer. We'll see that there are other buffers for our use in a bit.
2. finally, we *swap the buffers* by calling `glutSwapBuffers()`. We'll talk more about *double-buffered rendering* later as well.

Drawing a Triangle - A More Realistic Example

- Steps to drawing any object
  1. Load object data
  2. Initialize shaders
  3. Draw



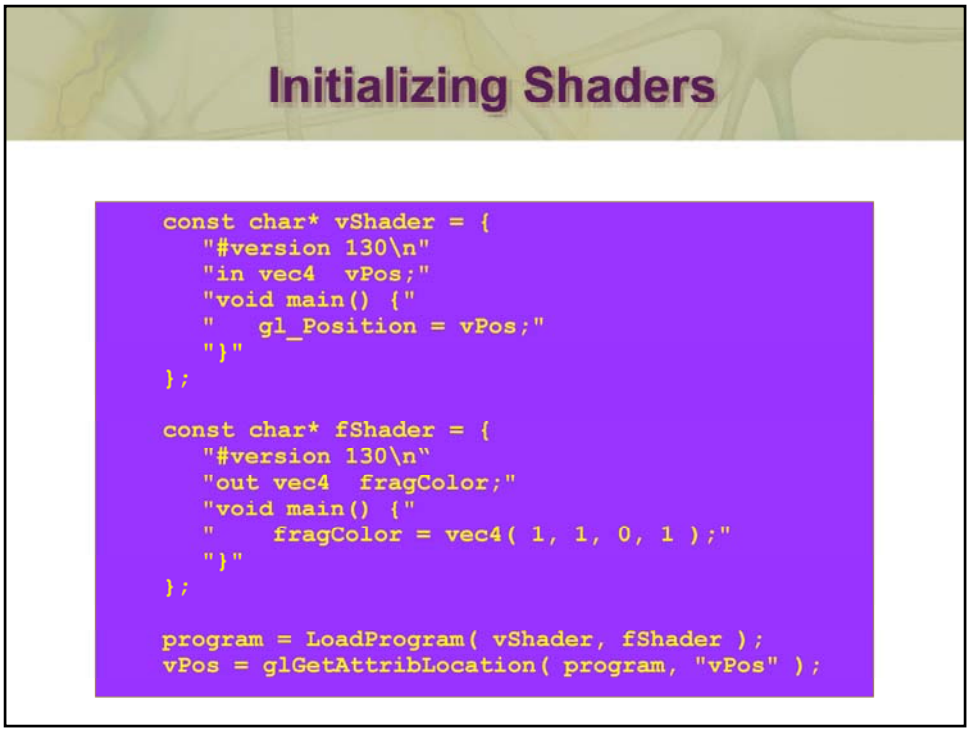
The first example we demonstrated wasn't too visually captivating. Here we'll show what's required to actually draw something.

This example shows loading object data, initializing the required shaders, and rendering. Every application leverages these steps – just with more data and complex shaders. We'll discuss the specifics of the process in more detail as we proceed.

Loading Vertex Data

```
void
init()
{
    //
    // --- Load vertex data ---
    //
    GLfloat  vertices[][4] = {
       { -0.75, -0.5,  0.0, 1.0 },
       {  0.75, -0.5,  0.0, 1.0 },
       {  0.0,   0.75, 0.0, 1.0 }
    };

    glGenBuffers( 1, &buffer );
    glBindBuffer( GL_ARRAY_BUFFER, buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(vertices),
                  vertices, GL_STATIC_DRAW );
```

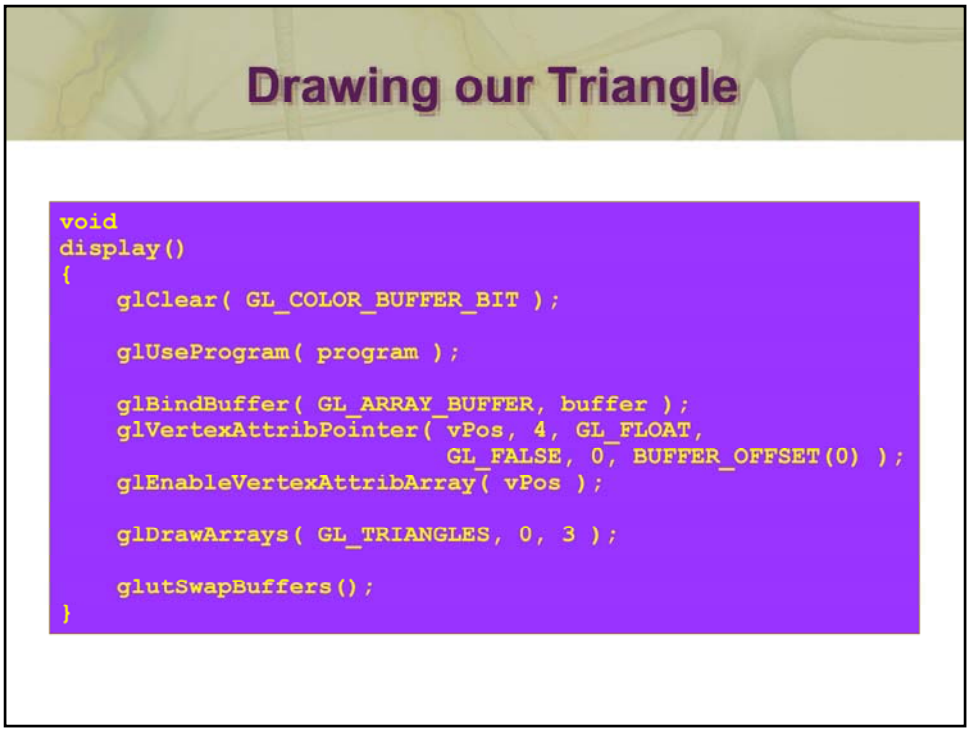
Here we see one method of specifying the data we use to represent objects. We'll cover this method, and the others, in the next section.



Here are examples of the types of shaders that OpenGL requires. The variable vShader contains the source to our *vertex shader*. This is about the simplest vertex shader you can have. Similarly, the variable fShader contains the source of our *fragment shader* which determines the color of the pixel. Here, we set the color of all the pixels to a constant color.

We pass the shaders into a helper routine we've written for the course named `LoadProgram()`, which takes a vertex shader and a fragment shader, and creates a GLSL "program" from them. We'll show the internals of `LoadProgram()` later, but assuming that there aren't errors in your shaders (they're really small programs that get compiled, and can have errors – `LoadProgram()` will report them to you if there's a problem), it will create a usable shader program we'll use later.

The last line retrieves information about a variable in (in this case, the variable "vPos") that we'll need later when it comes time render. For the curious, all variables labeled "in" in a vertex shader are assigned a *location index* that we need to initialize to pass data into. We'll see how we use those values when we draw on the next slide.



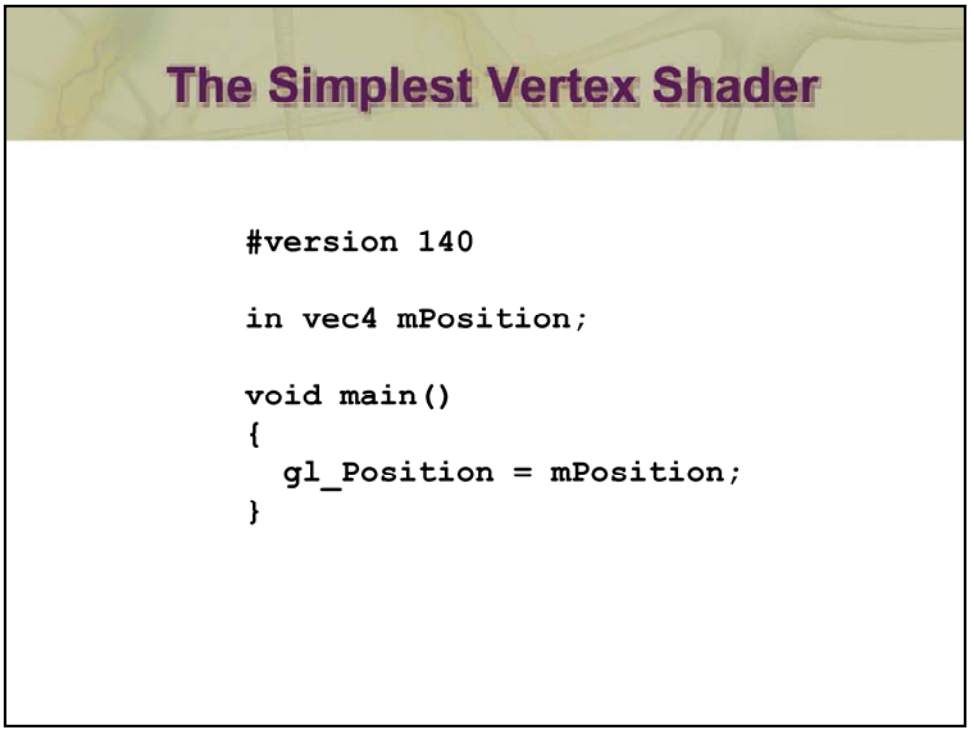
Here is the entirety of our routine for drawing. As you've seen, we first clear the window by calling `glClear()`.

Next, we enable the shader program that we initialized in `init()` previously. After this, all data is processed by that program until we turn it off, or switch to using another shader program.

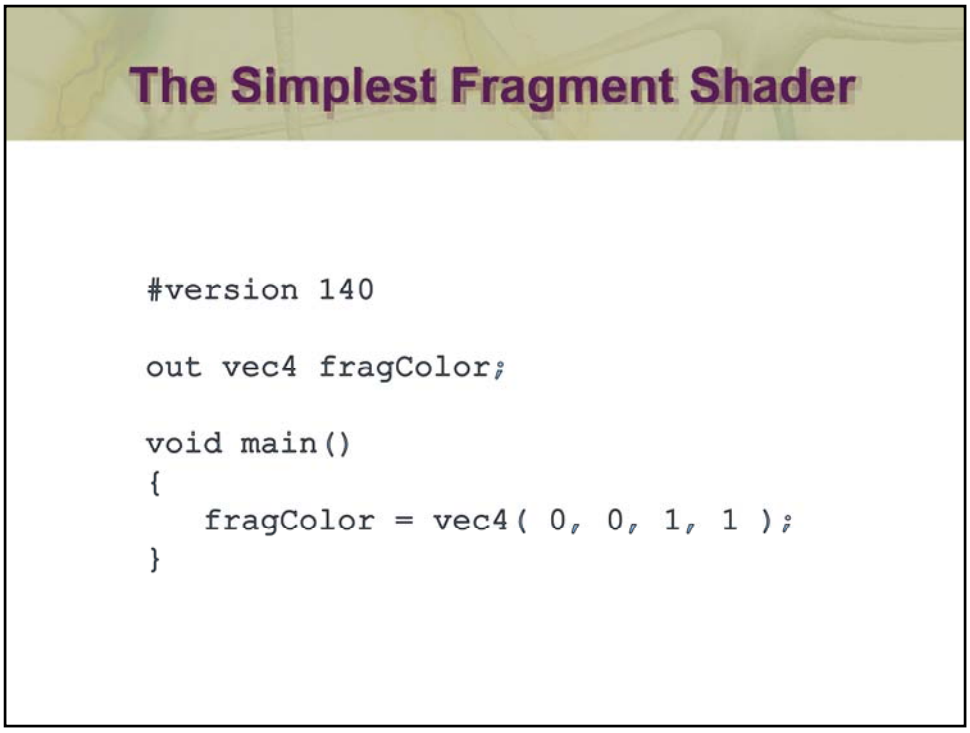
Next, we tell OpenGL where to find the data for our object, and use the location value – *vPos* – that we retrieved in `init()` to associate our data with a variable in a shader. After making the association, we tell OpenGL that it should use the data for that connection. That might seem redundant, but it's really an option for flexibility. Depending on how you will want to draw something, you may find it simpler to load lots of data for an object, and switch between subsets of that data as you draw different versions of it. We'll show you how you might do that in just a bit.

We draw the object by calling `glDrawArrays()`, in this case specifying that we'd like to draw triangles. It's just one method of drawing objects. We'll see other methods in the next section.

Finally, we swap the buffers, just like you had seen previously. After the buffer swap, our completed image is shown in the screen.



The vertex shader must output the vertex's position for the rasterizer. Here we use the special variable *gl_Position*. A more realistic vertex shader would also do a coordinate transformation since the input position would likely be in an application-defined coordinate system (e.g., model coordinates) while *gl_Position* must be in clip coordinates. In addition, most vertex shaders would also process other per-vertex attributes such as colors.



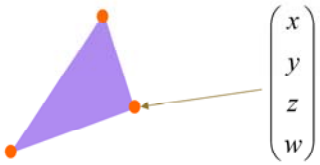
OpenGL differentiates between *pixels*, which are the final pixel colors stored in the framebuffer, and *fragments* which are candidate pixels, but still need to have some more work done to them.

A fragment's color is computed by a *fragment shader*. Inside of the fragment shader, you are provided with some generated information (like the fragment's framebuffer location as computed by the *rasterizer*), as well as any information you pass into the shader through variables.

Working With Objects

Representing Geometry

- We represent geometric primitives by their *vertices*

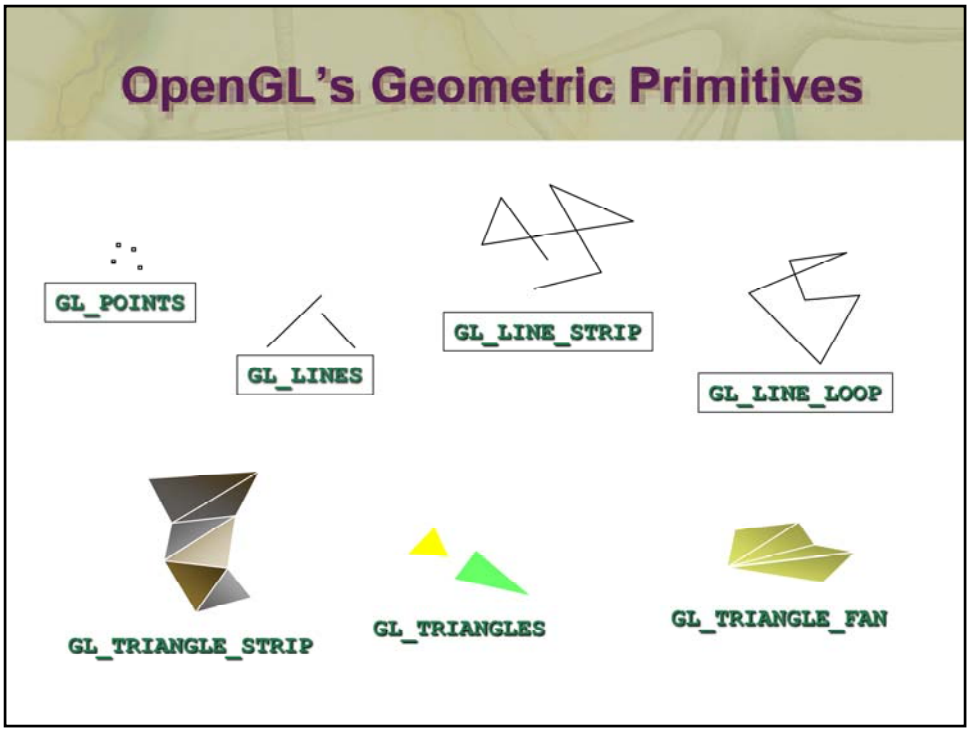


- A vertex is a point in space
  - specified as *homogenous coordinates*
    - 4-tuple of floating-point values
    - most "vertex data" are homogenous coordinates
      - makes the math easier

We describe geometric primitives by their vertices, which are either a single point, the endpoints of a line, or the corners of a triangle. A vertex is a set of four floating-point values, which we term a *homogenous coordinate*. The homogeneity relates to mathematics we use for processing—the subject of a future slide.

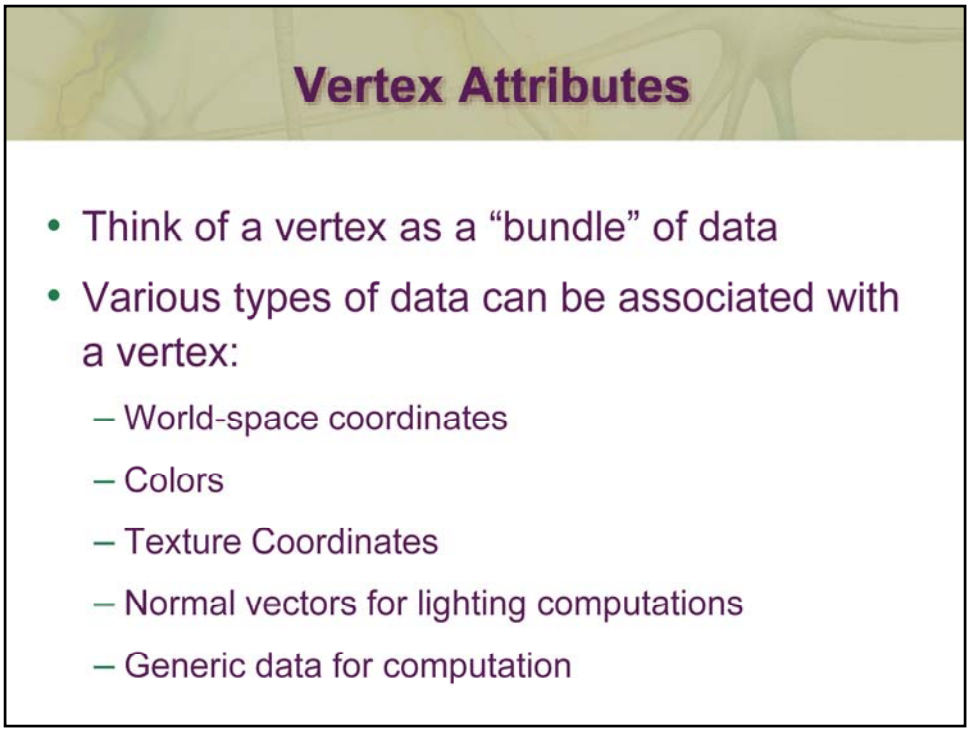
For a vertex, the x-, y-, and z-coordinates describe the vertex's location in 3D space with respect to an origin (of your choosing). The w-coordinate is generally just set to the value 1.0. It's role will become clearer a little farther on.

We group vertices together to form our geometric primitives.



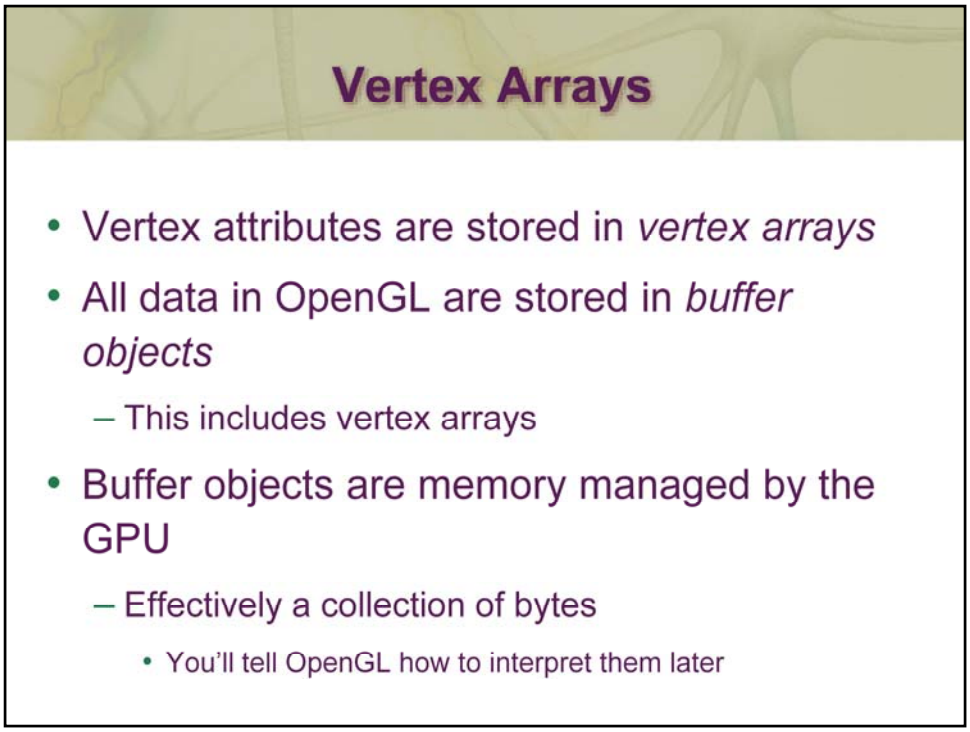
OpenGL is a low-level rendering library, and as such, doesn't know how to draw too many things. In fact, it really only knows how to draw single points, line segments (which might be connected to one another), and triangles (again, which may share boundaries between two triangles). Above are the seven *primitives* that OpenGL knows how to render. These primitives specify how OpenGL should group your processed vertices to form a rendered shape. Your job is to use collections of these shapes to form *geometric objects* , through a process called *modeling*.

For those of you with familiar with pervious versions of OpenGL, there were ten geometric primitives. OpenGL Version 3.1 removed support GL_QUADS, GL_QUAD_STRIP, and GL_POLYGONs, as they can easily be rendered using the above primitives (a quad is two triangles; a quad strip is just a triangle strip; and a polygon just a triangle fan).

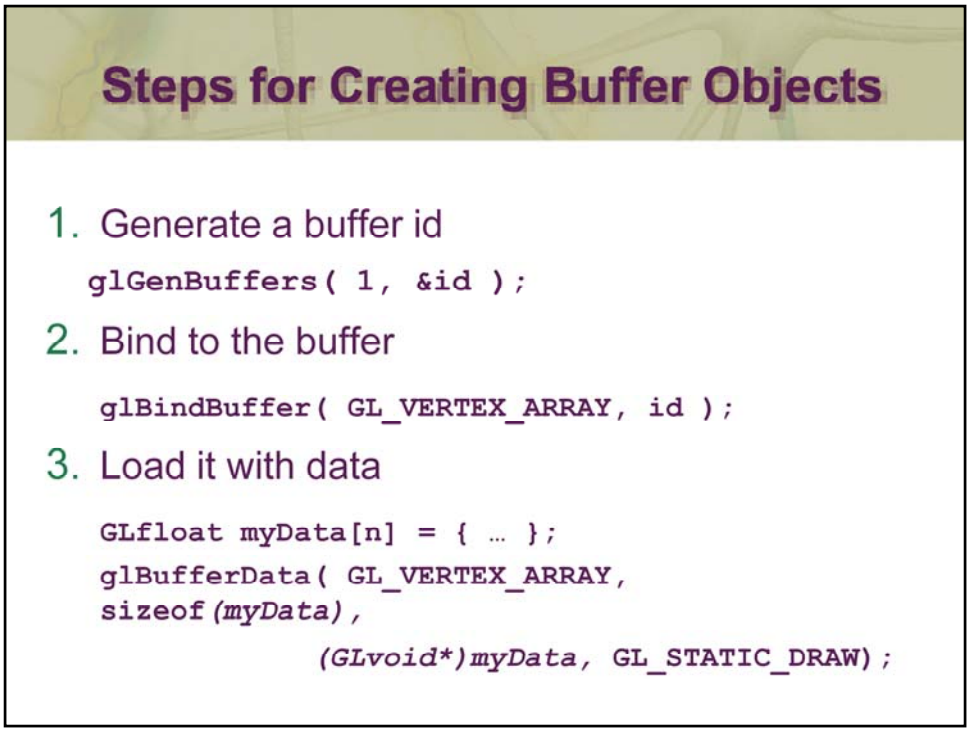


A vertex is a “bundle” of data that is collectively presented to you in a vertex shader. You determine the data in the bundle by specifying its *vertex attributes*. Attributes can be any type of data; floating-point or integer; scalar, vectors, or matrices; or even user-defined structures, and it’s up to your vertex shader to process the data, and set up the values required for the fragment shader.

Some vertex attributes have particular uses–like specifying the location of a vertex in space, or its color–which are used in “classic” computer graphics computations, while other data are values that only have meaning to you, and you’ll process in your shader for your own purposes.



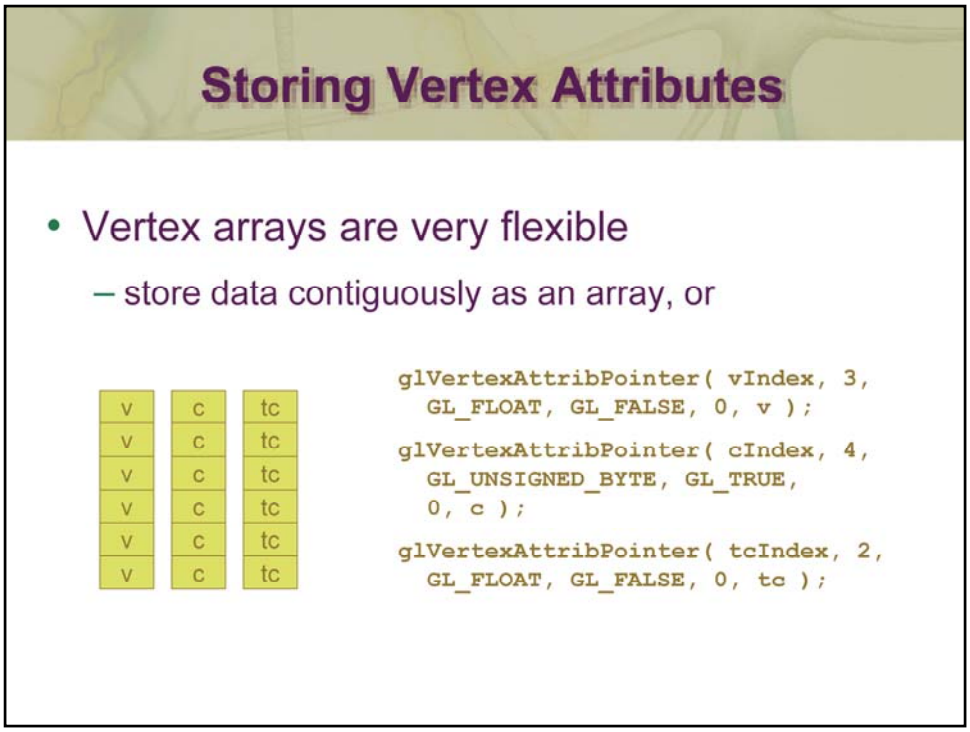
Vertices need to be stored in *vertex arrays*, which are just vectors of vertex data. They, like all data in OpenGL, are stored in buffers managed by OpenGL called *buffer objects*. You can think of buffer objects like dynamic memory allocated by the GPU–it's a bucket of bytes that you dump data into, and then you tell OpenGL how to interpret those bytes as data values.



Buffer objects—specifically *vertex buffer objects* (commonly called VBOs)—are used required for holding vertex attribute data. Creating and loading data into a VBO is a simple process of generating a unique buffer name, binding to the buffer, and loading the data. At this point, the data in the buffer hasn't been mapped to anything useful for OpenGL. We'll need to do a little extra work to get that to occur.

There are numerous different types of buffers that we'll encounter. GL_VERTEX_ARRAY is one specifically for holding vertex attribute data.

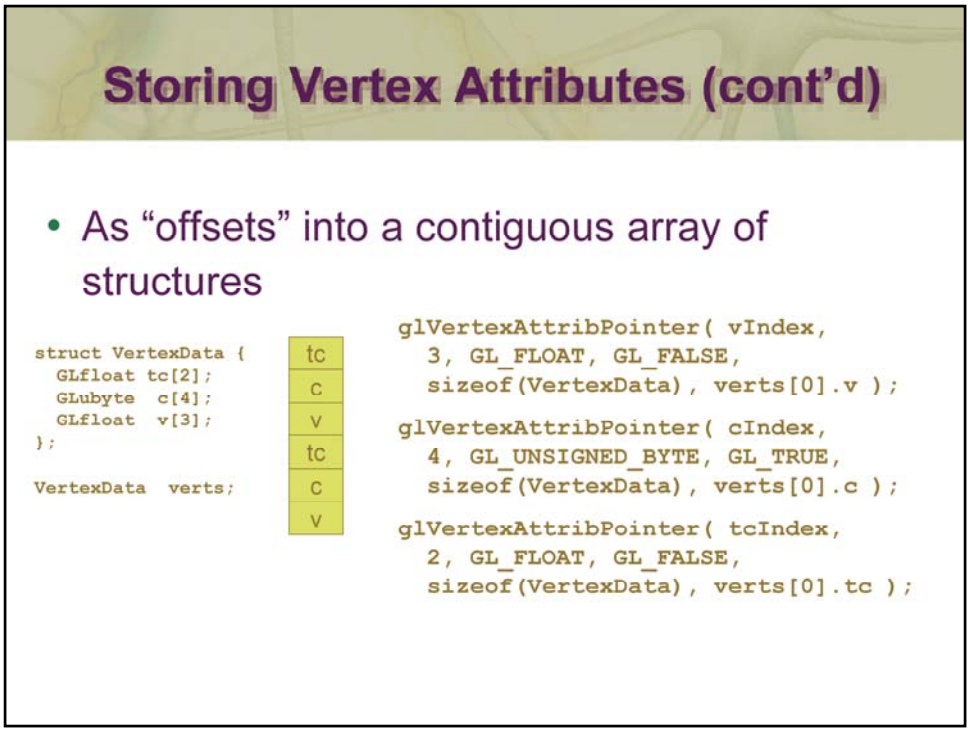
All of our sample programs will contain variations on this theme, depending on the types data that is required by the object.



We need to tell OpenGL where to find the relevant data inside of a buffer object, and the routine `glVertexAttribPointer()` is used to provide the meta-data required for OpenGL. There are two ways to organize vertex attribute data: as contiguous arrays of attributes (commonly called a "structure of arrays"), or as an array of bundles of vertex data (the "array of structures" method).

Here we demonstrate the contiguous array method, providing three sets of data for each vertex: "v", "c", and "tc". Each call to `glVertexAttribPointer()` provides information about the number of components (e.g., three for "v"), the associated type for each element, whether integer values should be mapped into a floating-point value in the range [0, 1], the number of bytes between successive elements (here "0" is a special value indicating that the data is tightly packed, and normal pointer incrementing [as you would do in C programs, for example] is sufficient).

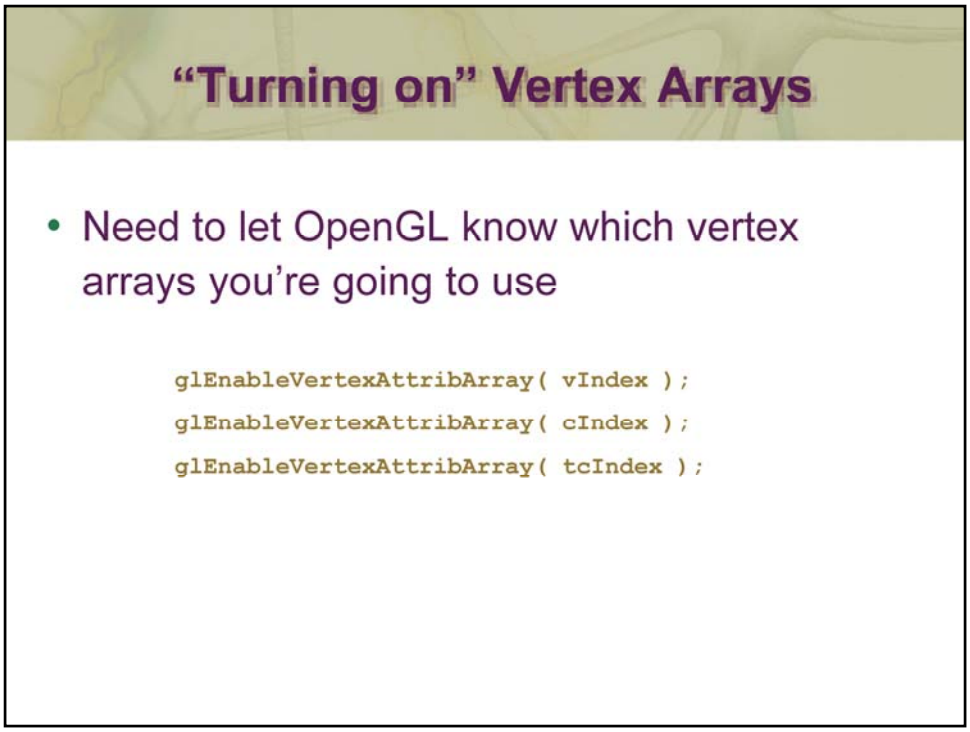
The program **`color-draw-arrays.c`** demonstrates setting up vertex attributes in this manner.



By comparison to the previous slide demonstrating contiguous arrays of data, here we tell OpenGL that all of the vertex attributes for a vertex are contiguous in memory – the array of structures approach. In this case, the only differences in our `glVertexAttribPointer()` calls is that the distance to find successive elements is the size of the "structure", and the differing offsets required to tell OpenGL where in the buffer to find the initial data values.

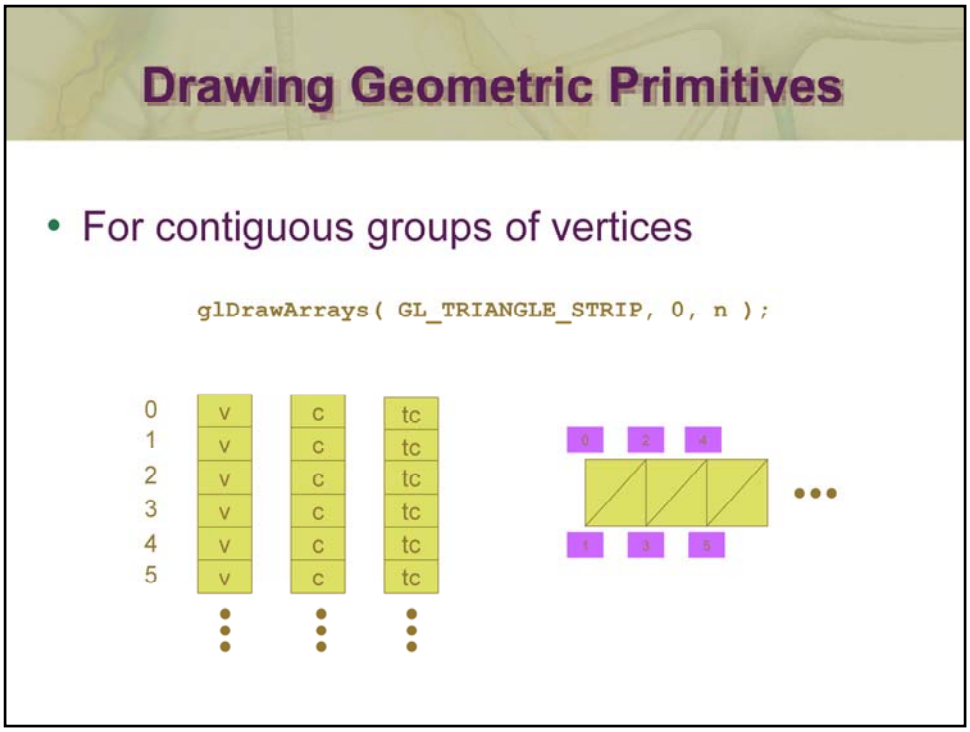
Generally speaking, this method may provide better performance than the previous method due to memory caching in modern computer systems.

The program **`AOS-color-draw-arrays.c`** (where the "AOS" is a mnemonic for Arrays-of-structures) demonstrates storing data in this manner.



The final step in preparing you data for processing by OpenGL (i.e., sending it down for rendering) is to specify which vertex attributes you'd like issued to the graphics pipeline. While this might seem superfluous, it allows you to specify multiple collections of data, and choose which ones you'd like to use at any given time.

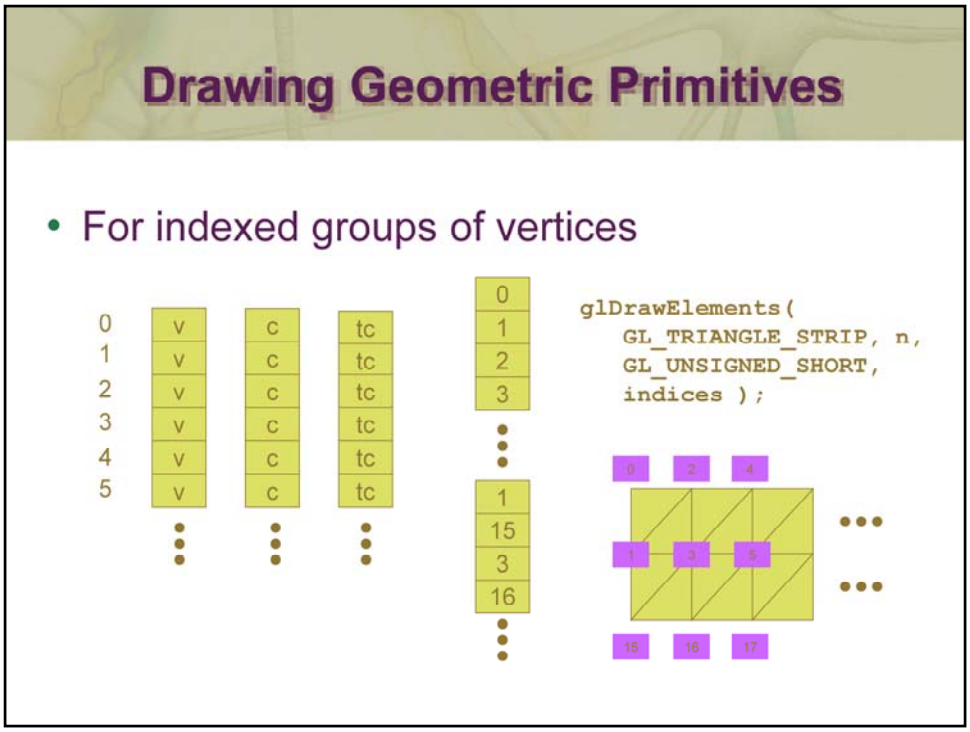
Each of the attributes that we enable must be associated with an "in" variable of the currently bound vertex shader. As you might recall from our **`triangle.cxx`** example, each of those vertex attribute locations was retrieved from the compiled shader by calling `glGetAttribLocation()`. We discuss this call in the shader section.



In order to initiate the rendering of primitives, you need to issue a drawing routine. While there are many routines for this in OpenGL, we'll discuss the most fundamental ones. The simplest routine is `glDrawArrays()`, to which you specify what type of graphics primitive you want to draw (e.g., here we're rending a triangle strip), which vertex in the enabled vertex attribute arrays to start with, and how many vertices to send.

This is the simplest way of rendering geometry in OpenGL Version 3.1. You merely need to store you vertex data in sequence, and then `glDrawArrays()` takes care of the rest. However, in some cases, this won't be the most memory efficient method of doing things. Many geometric objects share vertices between geometric primitives, and with this method, you need to replicate the data once for each vertex. We'll see a more flexible, in terms of memory storage and access in the next slides.

The programs **`color-draw-arrays.cxx`** and **`AOS-color-draw-arrays.cxx`** demonstrate using `glDrawArrays()` with the different methods of storing data in vertex attribute arrays.



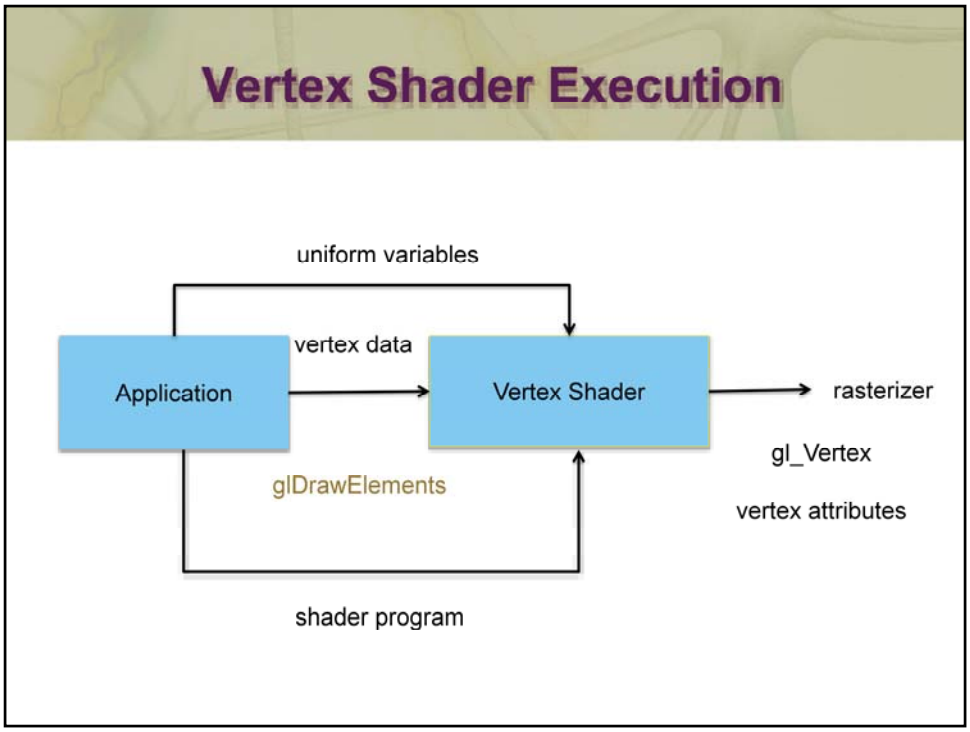
The other very common way to rendering geometry is by using *indexed primitives*, where access to vertices is done by providing a list of indices into the array of vertex values. The routine `glDrawElements()` does this. As you can see, it takes which primitive type to render, and a count of how many vertices should be rendered, just like `glDrawArrays()`. However, you also pass in an array of values representing the vertex indices to be processed, including a token describing the type of that array (GL_UNSIGNED_BYTE, GL_UNSIGNED_SHORT, GL_UNSIGNED_INT are accepted).

The program **`draw-elements.cxx`** demonstrates using `glDrawElements()` with multiple vertex attribute streams.

Shaders and GLSL

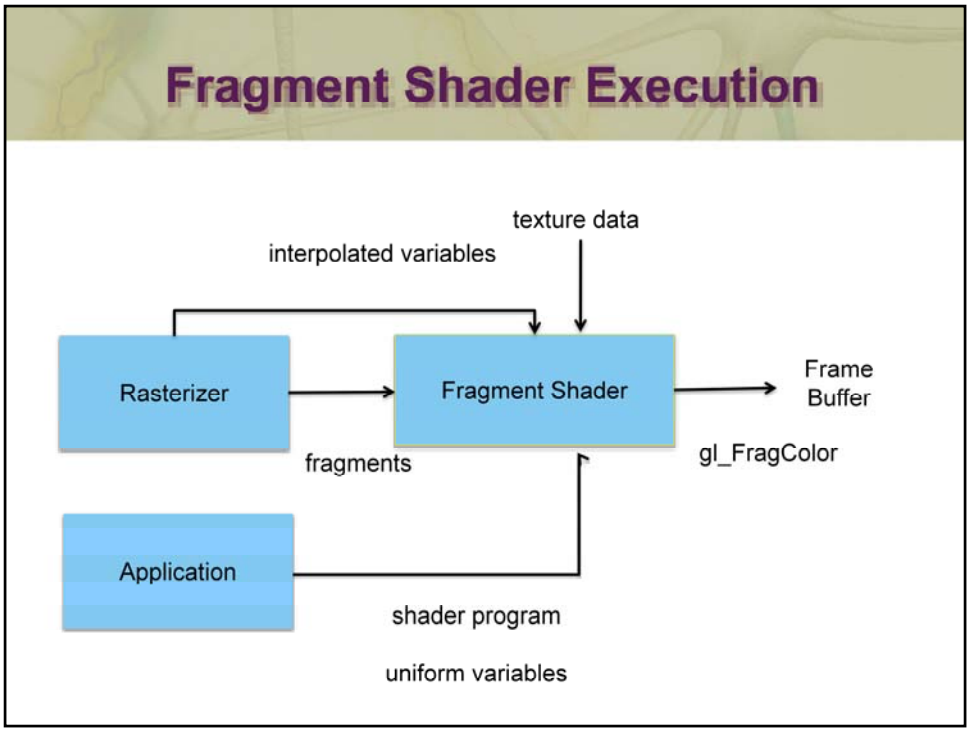
Where the work gets done

- Application sets parameters, sends data to GPU, and loads shaders
- Shaders do the work
- Shaders can be written in a C-like language called the OpenGL Shading Language (GLSL) that is part of OpenGL

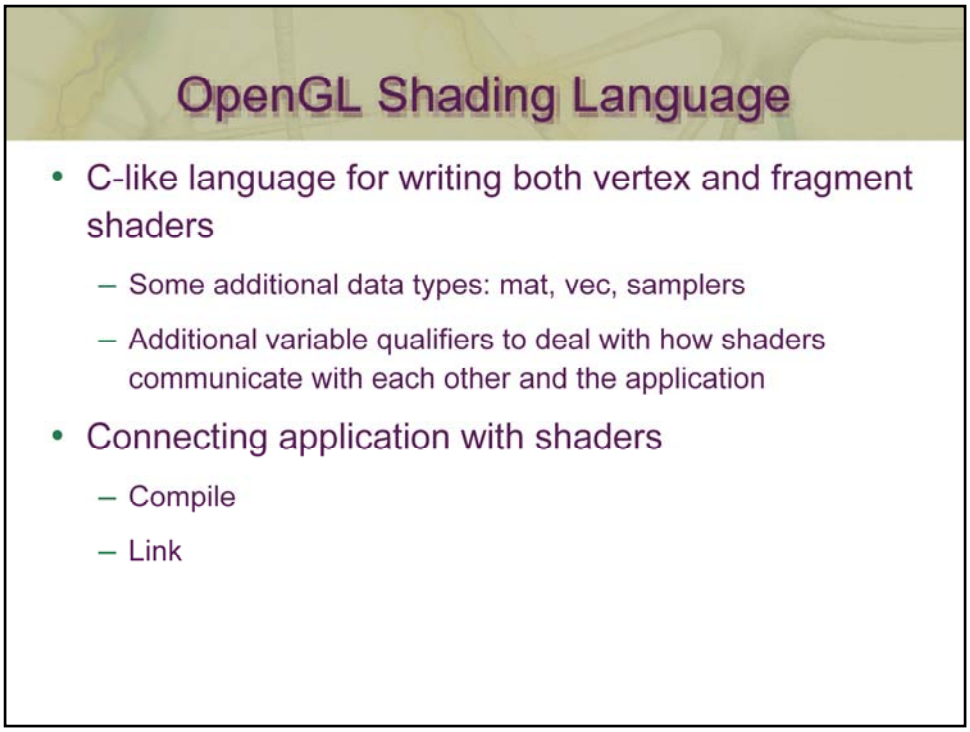


Vertex data (positions, colors, and texture coordinates, for example) are loaded onto GPU. When application issues a drawing command, each vertex generates an execution of the vertex shader. The vertex shader outputs a position and other per vertex variables that will be interpolated by the rasterizer.

Uniform variables are set by the application and remain unchanged through an execution of `glDrawElements()`.

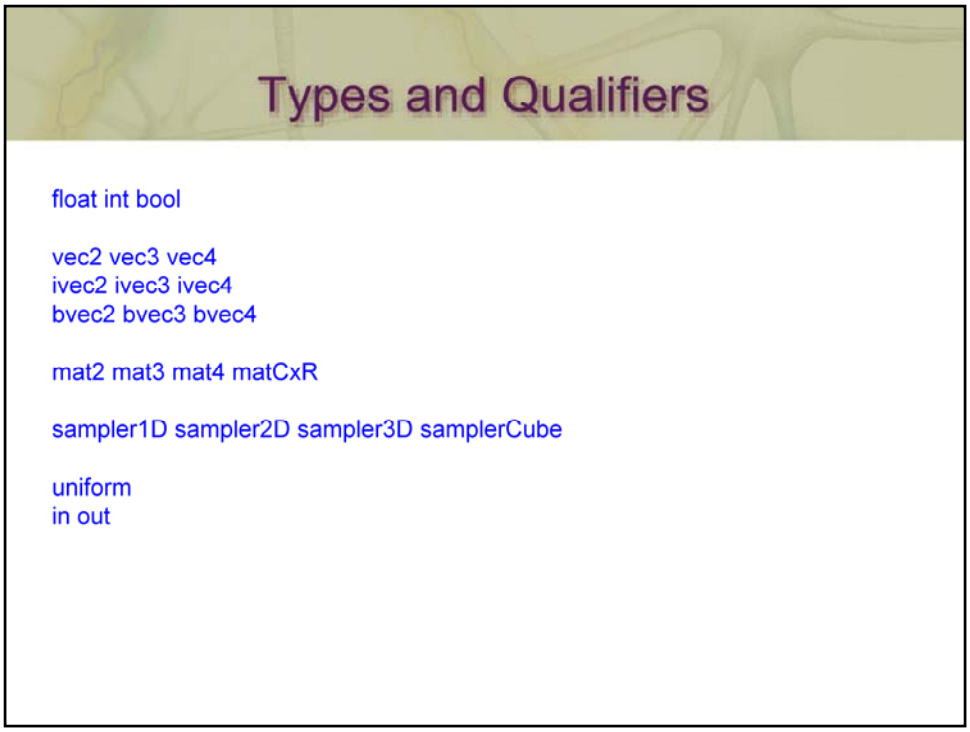


Each fragment generated by the rasterizer starts the execution of a fragments shader. Vertex attributes from the vertex shader are interpolated by the rasterizer to provide per-fragment values. For example, we can set a texture coordinate for each vertex in the application and put these data into vertex arrays. The vertex processor can process these values (or just pass them on) and output them as input to the rasterizer which will interpolate a value for each fragment.

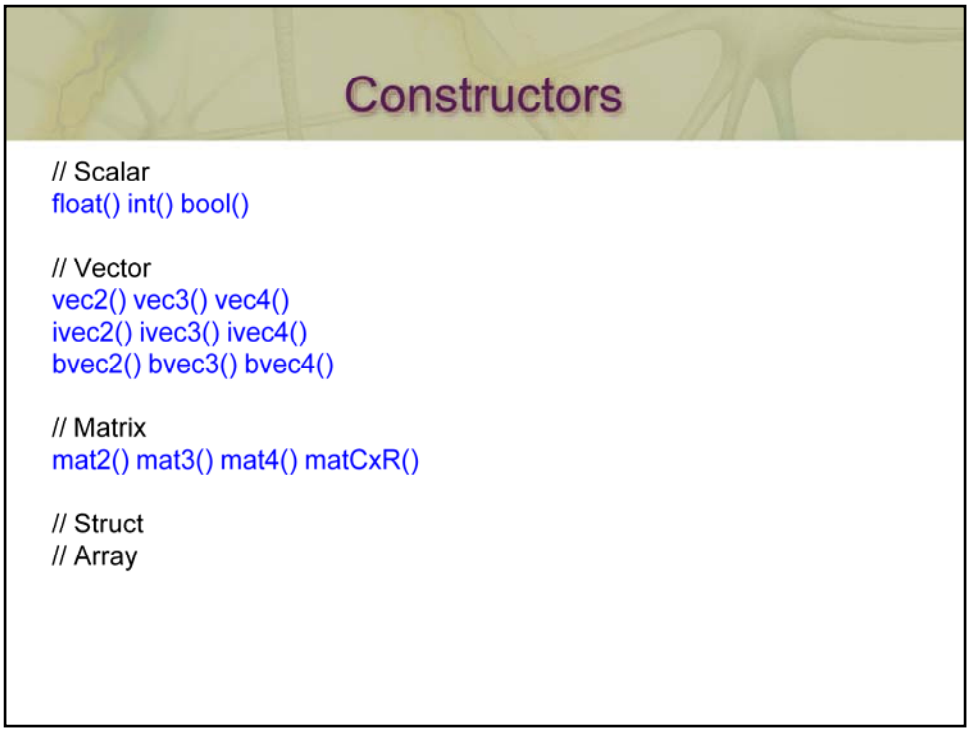


Specifications are at: http://www.khronos.org/registry/

(http://www.opengl.org/registry/ and http://www.khronos.org/registry/gles/)

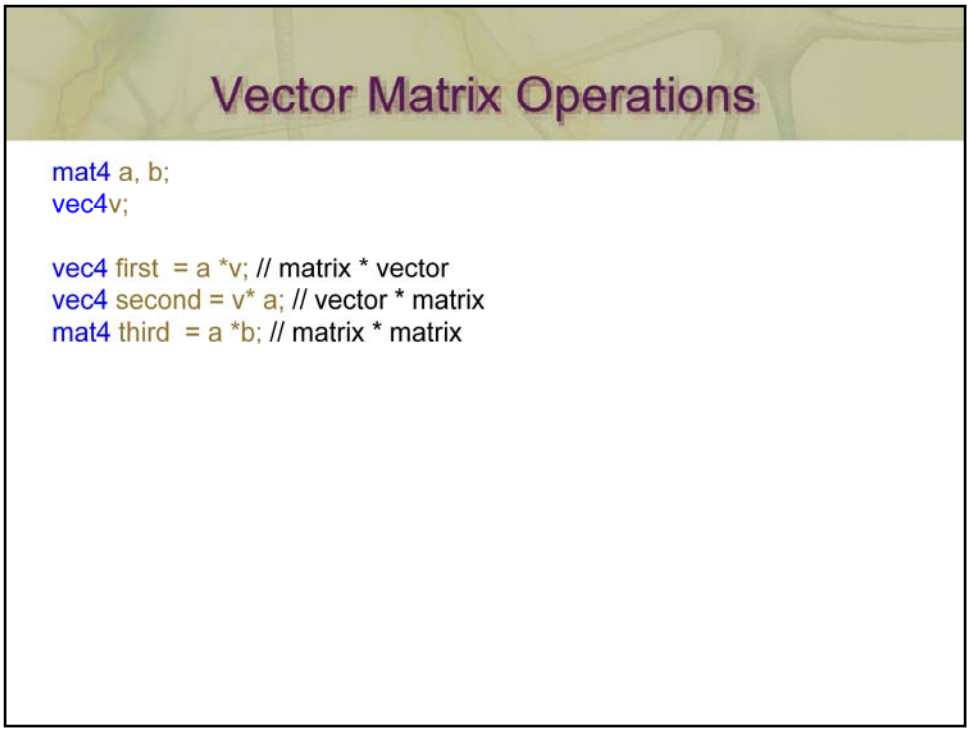


Here we some of the basic types and qualifiers used in GLSL. Since GLSL is very close to C (and C++ in some instances), we don't dwell on the language constructs.

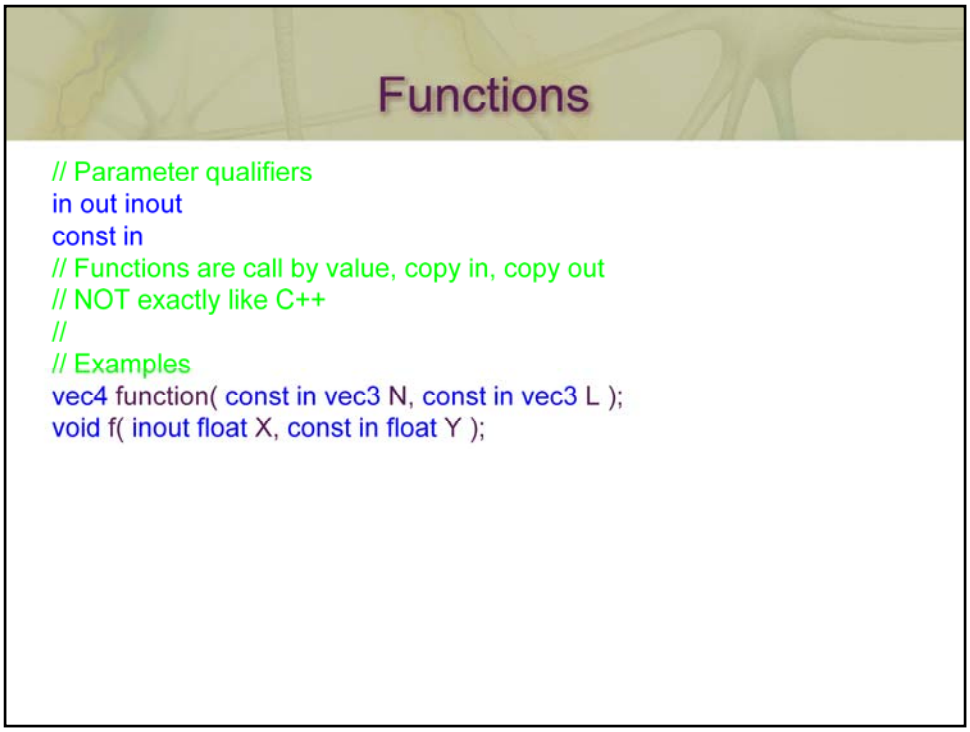


Compound types, like vectors and matrices, require *construction.* They're not arrays like in C – they're more like classes in C++. Both for creating one of these types, as well as converting between them (e.g., a collection of vectors can be used to initialize a matrix) is required in GLSL.

In addition to being able to use vectors like arrays in C (i.e., index into the using a ‘[]-type construction) , alternate access methods similar to accessing fields in a structure are available. The multiple forms enhance readability of code. Use rgba for color, xyxw for positions, stpg for textures but there is no semantic distinctions; you could just as easily use xyzw for colors as the rgba swizzlers.



Note that operations are overloaded so both vA and Av are valid but the results are different.



Overloading, restriction is that function prototypes are at global (or outside global) scope.

Built-In Variables

```
// Vertex
vec4  gl_Position;        // must be written to
float gl_PointSize;// may be written to

// Fragment
vec4gl_FragCoord;// may be read from
bool gl_Frontfacing;// may be read from
vec4gl_FragColor;        // may be written to
vec4gl_FragData[i];// may be written to
float gl_FragDepth;// may be written to
```

In earlier versions of OpenGL, almost all OpenGL state variables were available to shaders as built in variables. However most have been deprecated.

Built-in Functions

```
// angles and trigonometry
// exponential
// common
// interpolations
// geometric
// vector relational
// texture
// shadow
// noise

// fragment
genType dFdx(genType P );
genType dFdy(genType P );
genType fwidth(genType P );
```

radians, degrees, sin, cos, tan, asin, acos, atan, atan

pow, exp2, log2, sqrt, inversesqrt

abs, sign, floor, ceil, fract, mod, min, max, clamp

mix, step, smoothstep

length, distance, dot, cross, normalize, faceforward, reflect

lessThan, lessThanEqual, greaterThan, greaterThanEqual, equal, notEqual, any, all

Simple Example

- Rotate vertices continuously around z axis
- Three approaches
  - All use idle callback to regenerate geometry
  1. Generate new vertices in application
  2. Reposition original vertices in shader
  3. Send transformation matrices to shader
  - For now we'll do 2.

Since we have yet to cover transformations and shading, we'll specify vertices in clip coordinates. If all the vertices are in cube centered the origin with corners at (-1,-1,-1) and (1,1,1), none of the geometry will be clipped out. In this example we will place all the vertices in the plane z = 0 and color all fragments with the same color.

Application Callbacks

```
static void draw()
{
   glClear(GL_COLOR_BUFFER_BIT);
   glUniform1f(timeParam, 0.001*glutGet(GLUT_ELAPSED_TIME));
   glDrawArrays(GL_TRIANGLES, 0, 3);
   glutSwapBuffers();
}

static void idle()
{
   glutPostRedisplay();  // schedule another call to draw()
}
```

Once the vertex array is created as part of initialization the application simply redraws the array as fast as possible through the idle callback. Note that this example is not very efficient since we are sending the same data to the GPU each time rather than storing it there as a vertex buffer object.

GLUT_ELAPSED_TIME is the elapsed time in milliseconds. It is put into an application variable timeParam which is aligned with the time variable in the shader. We will see the details in a few slides.

Vertex Shader

```
in vec4 vPosition;
uniform float time;
uniform mat4 MVP;

void main()
{
  gl_Position = MVP*vPosition;
  gl_Position.x = cos(time)*vPosition.x+sin(time)*vPosition.y;
  gl_Position.y = sin(time)*vPosition.x+cos(time)*vPosition.y

// color computation

}
```

MVP is the model-view projection matrix which converts from vertex positions from model coordinates to clip coordinates. In this example it is computed in the application.

Fragment Shader

```
out vec4 fragColor;

void main()
{
    fragColor = vec4 ( 1.0, 0.0, 0.0, 1.0 );
}
```

In general, we would compute colors for each fragment using a lighting model.

Colors are specified in RGBA space where A is the opacity.

Creating a Shader Program

- Similar to compiling a “C” program
  - compile, and link
- Multi-step process
  1. create and compile shader objects
  2. attach shader objects to program
  3. link objects into executable program
- This is what `LoadProgram()` does

Shader Compilation (Part 1)

- Create and compile a Shader

```
GLuint shader = glCreateShader( shaderType );
const char* str = "void main() {…}";
glShaderSource( shader, 1, &str, NULL );
glCompileShader( shader );
```

- *shaderType* is either
  - GL_VERTEX_SHADER
  - GL_FRAGMENT_SHADER

```
const GLchar* vSource[] = {
   “in vec4 vPos; ”
   "uniform float time;”
   "void main()”
   "{”
   "   gl_Position.x = cos(time)*vPos.x-sin(time)*vPos.y;”
   "   gl_Position.y = sin(time)*vPos.x+cos(time)*vPos.y;”
   "   gl_Position.zw = vPos.zw;”
   "}"
 };

const GLchar*  fSource[] = {
   “out vec4 fragColor;”
   "void main()”
   "{"
   "  fragColor = vec4( 1.0, 0.0, 0.0, 1.0 );”
   "} "
 };

GLuintvShader, fShader;
    /* create program and shader objects */
vShader = glCreateShader(GL_VERTEX_SHADER);
fShader = glCreateShader(GL_FRAGMENT_SHADER);


glCompileShader(vShader);
glCompileShader(fShader);

/* check for errors here */
```

Shader Compilation (Part 2)

- Checking to see if the shader compiled

```
GLint  compiled;
glGetShaderiv( shader, GL_COMPILE_STATUS, &compiled );
if ( !compiled ) {
  GLint len;
  glGetShaderiv( shader, GL_INFO_LOG_LENGTH, &len );
  std::string  msgs( ' ', len );
  glGetShaderInfoLog( shader, len, &len, &msgs[0] );
  std::cerr << msgs << std::endl;
  throw shader_compile_error;
}
```

Shader Program Linking (Part 1)

- Create an empty program object

```
GLuint  program = glCreateProgram();
```

- Associate shader objects with program

```
glAttachShader( program, vertexShader );
glAttachShader( program, fragmentShader );
```

- Link program

```
glLinkProgram( program );
```

Shader Program Linking (Part 2)

- Making sure it worked

```
GLint  linked;
glGetProgramiv( program, GL_LINK_STATUS, &linked );
if ( !linked ) {
  GLint len;
  glGetProgramiv( program, GL_INFO_LOG_LENGTH, &len );
  std::string  msgs( ' ', len );
  glGetProgramInfoLog( program, len, &len, &msgs[0] );
  std::cerr << msgs << std::endl;
  throw shader_link_error;
}
```

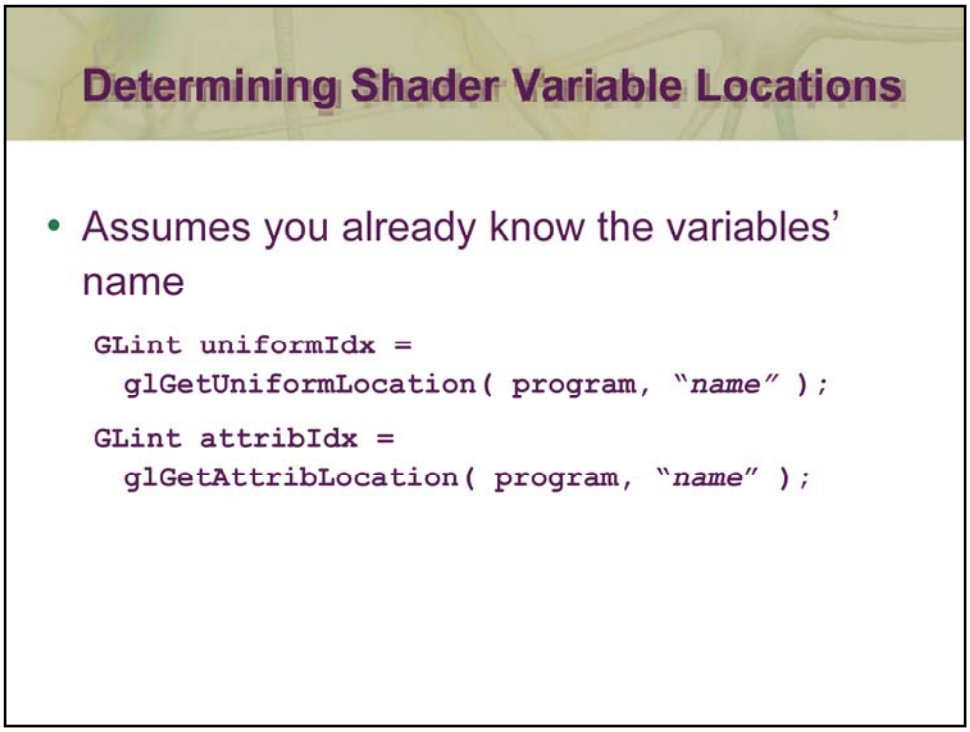
Using Shaders in an Application

- Need to turn on the appropriate shader

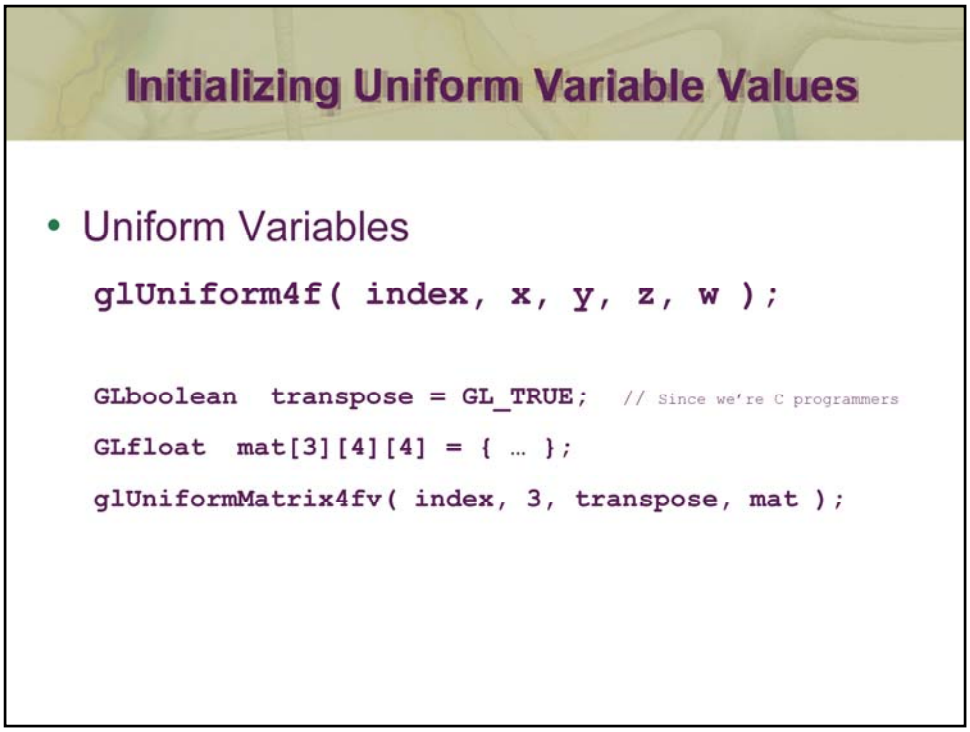
```
glUseProgram( program );
```

Associating Shader Variables and Data

- Need to associate a shader variable with an OpenGL data source
  - vertex shader attributes → app vertex attributes
  - shader uniforms → app provided uniform values
- OpenGL relates shader variables to indices for the app to set
- Two methods for determining variable/index association
  - specify association before program linkage
  - query association after program linkage



As you've seen us use multiple times, when we need to initialize data for a shader, we first have to find that variables associated index so that we can load data into its location. Given the two types of variables we need to initialize – vertex attributes and uniforms – each of the respective commands above retrieve the index for us. Using these routines require the that the shader has been linked, as that's when OpenGL assigns indices to variables.



GLint timeParam = glGetUniformLocation(program, "time"); /* time in vertex shader */

GLint loc = glGetAttribLocation(program, "vPosition"); /* vertex locations in vertex shader */

glEnableVertexAttribArray(loc);

glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 0,0);

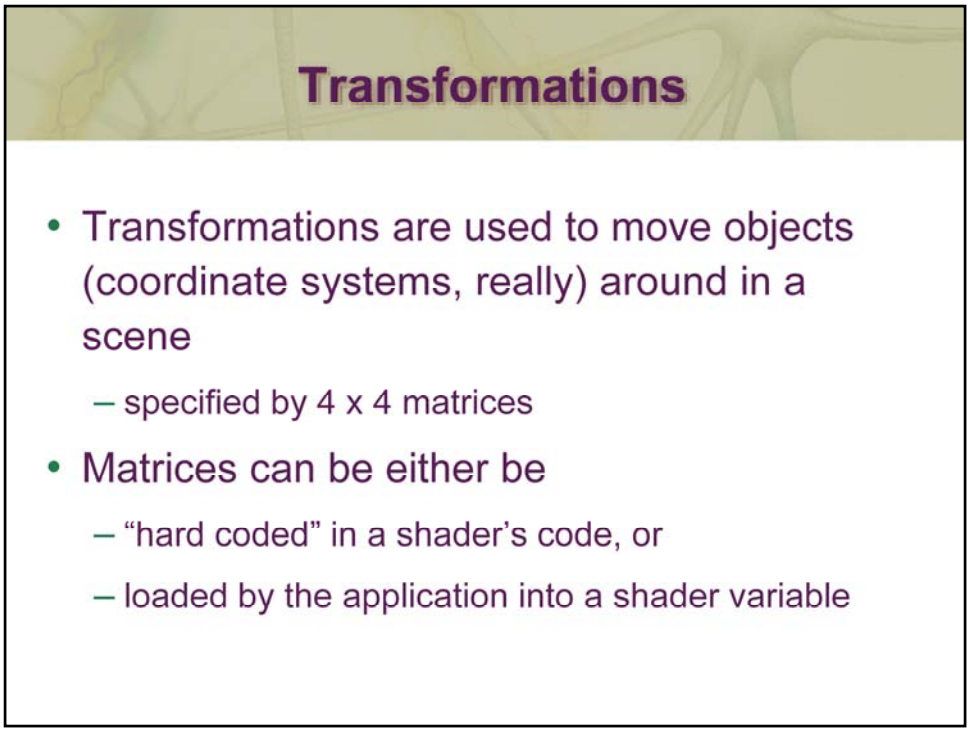
In draw() callback we send the time by

glUniform1f(timeParam, 0.001*glutGet(GLUT_ELAPSED_TIME));

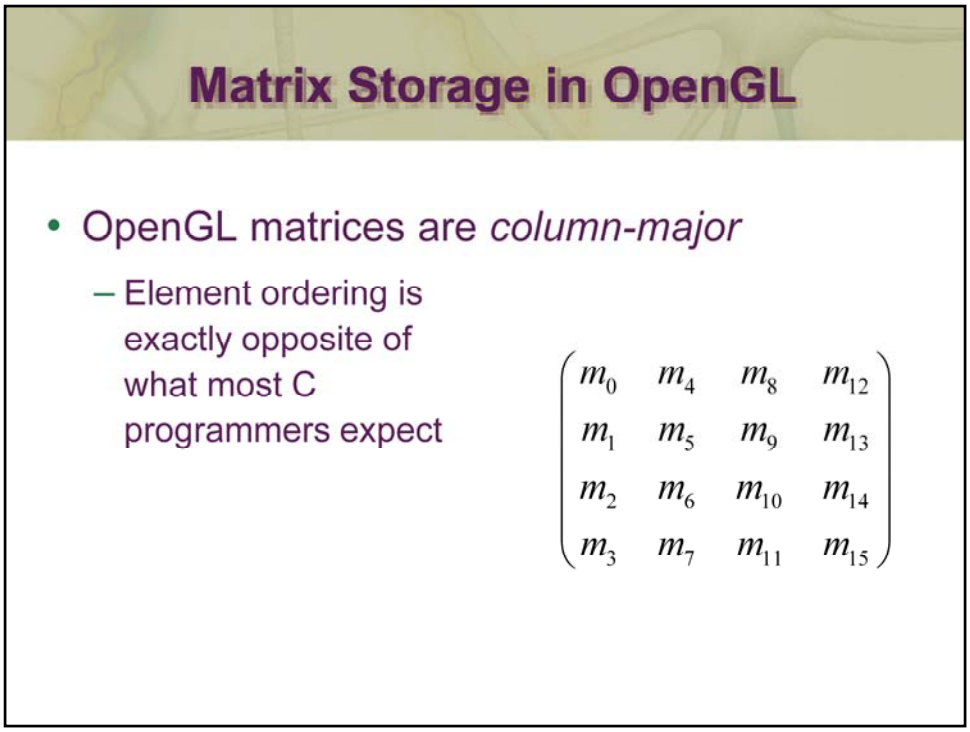
The vertex data is in the buffer object

```
/* Triangle Data */
GLfloat vVertices[][3] = {  {0.0f,  -0.5f, 0.0f},
                            {0.5f, 0.0f, 0.0f},
                             {0.0f, 0.5f, 0.0f} };
GLubyte indices[] = {0, 1, 2};
```

Transformations

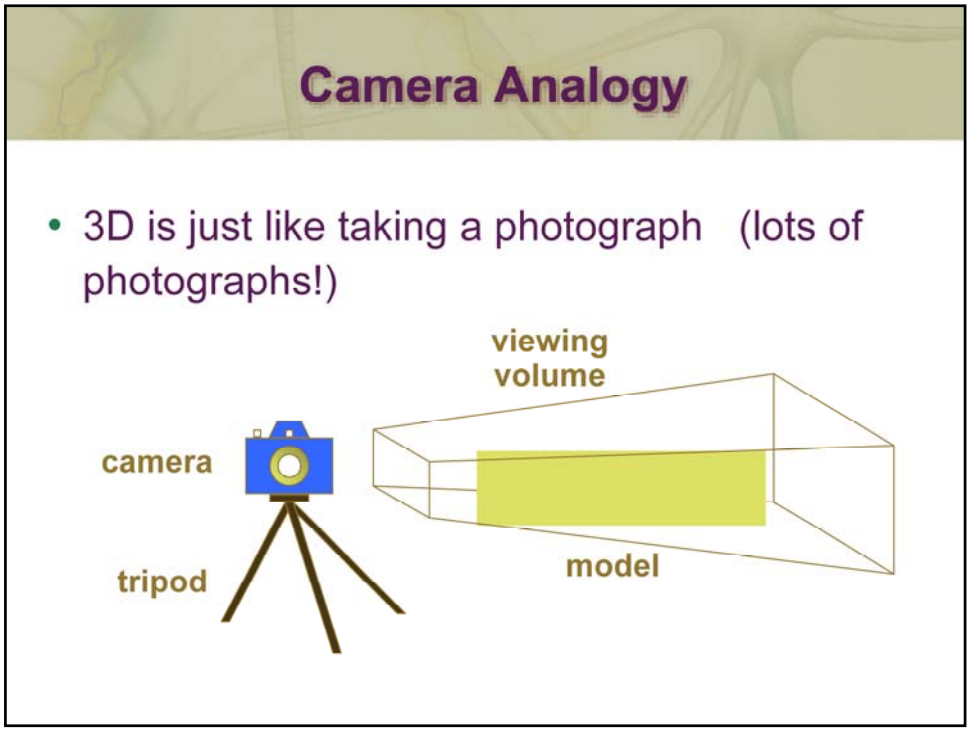


Transformations are fundamental to computer graphics, and OpenGL leverages them quite heavily. The most common use is for manipulating the position and orientation of 3D objects, but they also find applications in modifying colors, and other vector quantities used in graphics. For OpenGL, transformations are represented by 4 × 4 matrices. These matrices are applied in shaders, and can either be static (e.g., “hard coded” in a shader’s source code), or loaded dynamically by the application into a shader variable.



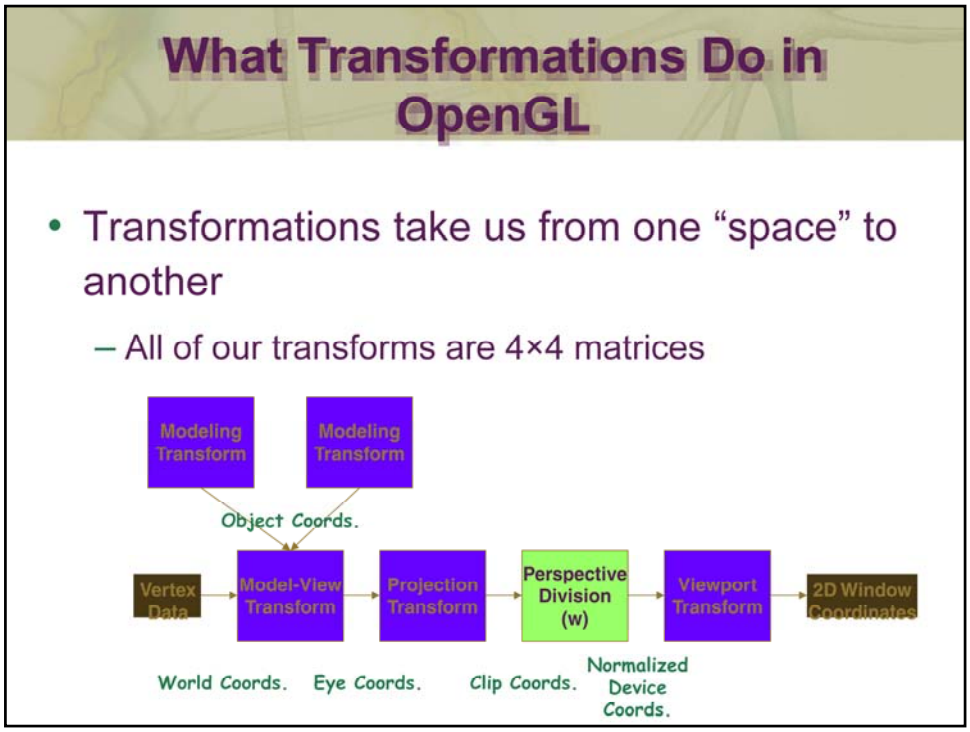
OpenGL matrices are generally considered to be column-major, which causes some trepidation for C programmers, as it's exactly the opposite indexing of what we're all used to. There are multiple solutions to this issue:

- You can orient your values in your code to match what OpenGL requires
- Most routines that load matrix values in OpenGL have a transpose parameter to say that the data should be transposed when loaded
- You can transpose matrices in your shader using the transpose() method
- Finally, you can specify that a matrix is row_major in the shader, however, this causes the matrix to truly be considered row major, and not merely transposed, and as such you need to reverse the order of the multiplicands in your vector-matrix and matrix-matrix multiplications.



OpenGL uses a *synthetic camera model* for specifying how a set of 3D objects are viewed. The model effectively uses three conceptual parts, each of which is represented by a matrix:

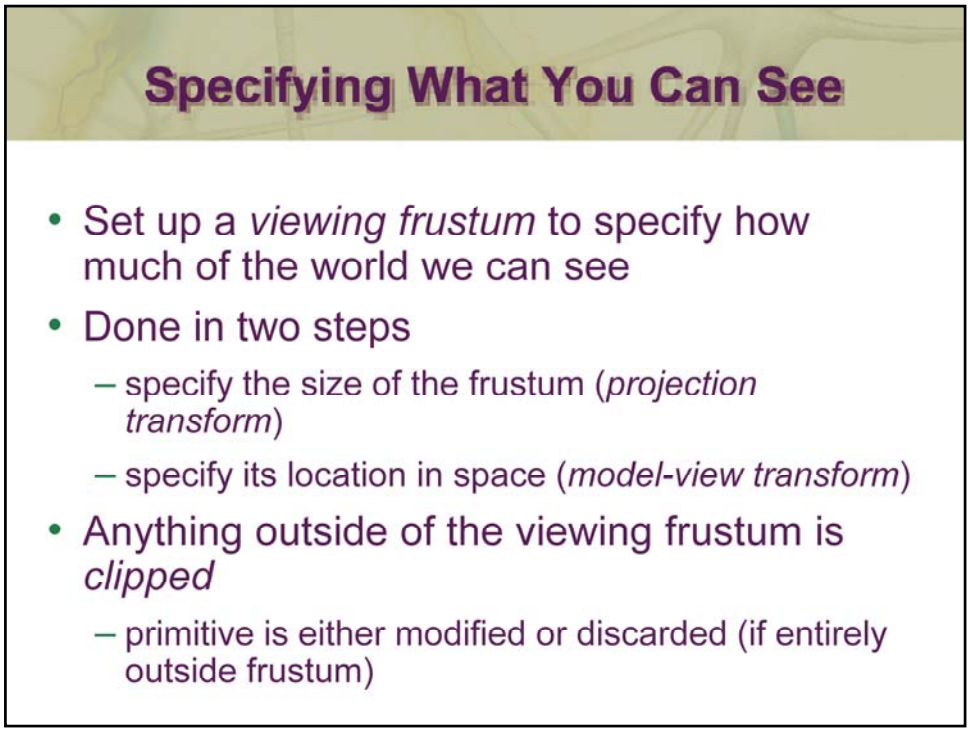
- The *projection transformation* which specifies how much of the world is visible. It's like setting the field-of-view on a camera lens
- The *viewing transformation* which controls the placement and orientation of the camera in the world
- Finally, *modeling transformations* are used to control the placement and orientation of objects in the world



The processing required for converting a vertex from 3D space into a 2D window coordinate is done by the transform stage of the graphics pipeline. The operations in that stage are illustrated above. The purple boxes represent a matrix multiplication operation. In graphics, all of our matrices are 4×4 matrices (they're homogenous, hence the reason for homogenous coordinates).

When we want to draw an geometric object, like a chair for instance, we first determine all of the vertices that we want to associate with the chair. Next, we determine how those vertices should be grouped to form geometric primitives, and the order we're going to send them to the graphics subsystem. This process is called *modeling*. Quite often, we'll model an object in its own little 3D coordinate system. When we want to add that object into the scene we're developing, we need to determine its *world coordinates.* We do this by specifying a *modeling transformation*, which tells the system how to move from one coordinate system to another.

Modeling transformations, in combination with *viewing* transforms, which dictate where the viewing frustum is in world coordinates, are the first transformation that a vertex goes through. Next, the *projection transform* is applied which maps the vertex into another space called *clip coordinates,* which is where clipping occurs. After clipping, we divide by the *w* value of the vertex, which is modified by projection. This division operation is what allows the farther-objects-being-smaller activity. The transformed, clipped coordinates are then mapped into the window.

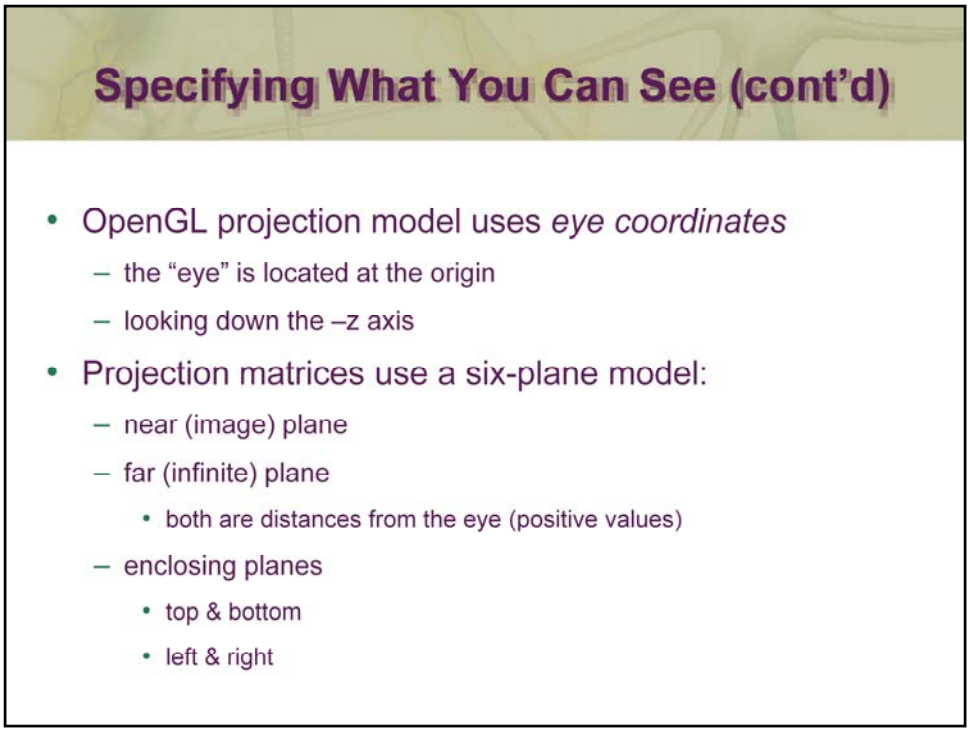


Another essential part of the graphics processing is setting up how much of the world we can see. We construct a *viewing frustum*, which defines the chunk of 3-space that we can see. There are two types of views: a *perspective view*, which you're familiar with as it's how your eye works, is used to generate frames that match your view of reality–things farther from your appear smaller. This is the type of view used for video games, simulations, and most graphics applications in general.

The other view, *orthographic*, is used principally for engineering and design situations, where relative lengths and angles need to be preserved.

For a perspective, we locate the eye at the apex of the frustum pyramid. We can see any objects which are between the two planes perpendicular to eye (they're called the *near* and *far* clipping planes, respectively). Any vertices between near and far, and inside the four planes that connect them will be rendered. Otherwise, those vertices are *clipped* out and discarded. In some cases a primitive will be entirely outside of the view, and the system will discard it for that frame. Other primitives might intersect the frustum, which we *clip* such that the part of them that's outside is discarded and we create new vertices for the modified primitive.

While the system can easily determine which primitive are inside the frustum, it's wasteful of system bandwidth to have lots of primitives discarded in this manner. We utilize a technique named *culling* to determine exactly which primitives need to be sent to the graphics processor, and send only those primitives to maximize its efficiency.



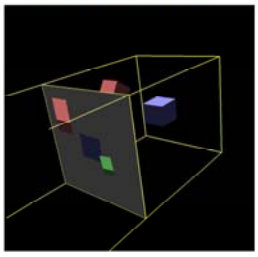
Viewing frusta are usually specified by six parameters, which are combined to set the six clipping planes of the viewing frustum.

OpenGL "sets up" the viewing frustum in *eye coordinates*, where the eye is located at the origin, and looking down the negative z-axis. From that the clipping planes of the frustum are configured.

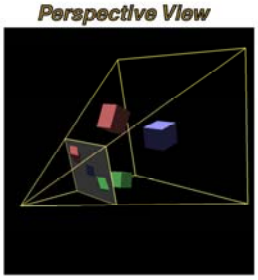
There are two types of projections, as we'll see on the following page.

Specifying What You Can See (cont'd)

Orthographic View



Perspective View



$$O = \begin{pmatrix} \frac{2}{r-l} & 0 & 0 & \frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & \frac{t+b}{t-b} \\ 0 & 0 & \frac{-2}{f-n} & \frac{f+n}{f-n} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

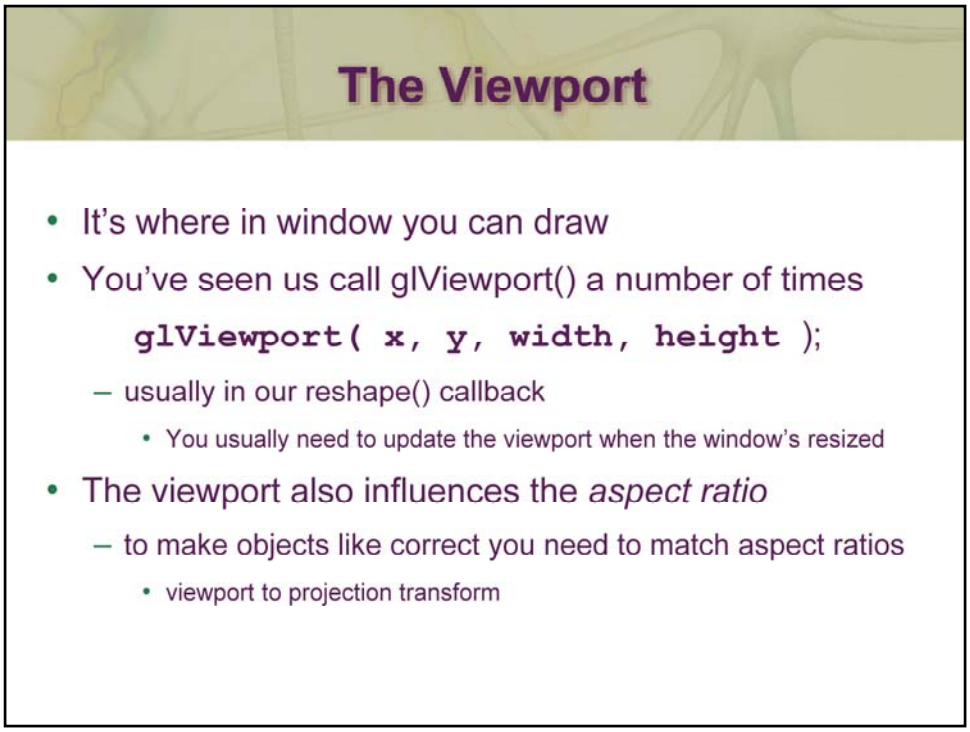
$$P = \begin{pmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & \frac{-(f+n)}{f-n} & \frac{-2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

There are two types of projections that are generally used in computer graphics:

- *orthographic projections* which are generally used in science and engineering applications – those that require angels to be preserved during rendering
- *perspective projections* which mimic how the eye works – objects seem to decrease in size the farther from the viewer that are

Here we show how the matrices are constructed from the six values we described on the previous page: the near and far clipping planes; and the left, right, top, and bottom values used to compute the planes for the types of projections. In either case, the near and far clipping planes represent the "front" (where the *imaging plane*, or where the image is projected to) and "back" clipping planes located along the line of sight. The other values are used to compute the "box" enclosing the viewable region. For orthographic projections, this really defined a parallelepiped in 3D, where for perspective projections, it forms a pyramid with the eye located at the apex (which is coincident with the eye-space coordinate space origin).

Don't fret about constructing those matrices, we have helper routines that take care of making them for you ☺



The viewport is the part of the window you can draw into. Generally, it's a subset of the pixels inside of the window, and is controlled by calling the `glViewport()` routine, which takes the lower-left corner in window coordinates, and the width and height of the viewport in pixels.

Any time you find a width and height in OpenGL, you should also consider their ratio, usually termed the *aspect ratio*, and is the ratio of the width to the height. In order have geometric objects "look right" – like having squares look square and sphere look round and not oblong – various aspect ratios need to match. In particular, the aspect ratio of the viewport should match the viewport of the projection transformation.

Viewing Transformations

- Position the camera/eye in the scene
  - place the tripod down; aim camera
- To "fly through" a scene
  - change viewing transformation and redraw scene

```
LookAt( eyex, eyey, eyez,
  lookx, looky, lookz,
  upx, upy, upz )
```

  - up vector determines unique orientation
  - careful of degenerate positions

A common way to navigate a scene is as if you're flying. The `LookAt()` routine is one that we've implemented based on a routine named `gluLookAt()` from OpenGL's old utility library. It takes three sets of parameters: where your eye is (eye_*); a point you're looking towards ($look_*$), and a vector in the local coordinate system representing which direction is "up" in the scene. Please see our Transform.h file for implementation details.

Creating the LookAt Matrix

$$\hat{n} = \frac{\overrightarrow{look} - \overrightarrow{eye}}{\left\| \overrightarrow{look} - \overrightarrow{eye} \right\|}$$

$$\hat{u} = \frac{\hat{n} \times \overrightarrow{up}}{\left\| \hat{n} \times \overrightarrow{up} \right\|}$$

$$\hat{v} = \hat{u} \times \hat{n}$$

$$\Rightarrow \begin{pmatrix} u_x & u_y & u_z & 0 \\ v_x & v_y & v_z & 0 \\ -n_x & -n_y & -n_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Then we translate to the eye's position
  - we'll use the Translation matrix on the next page

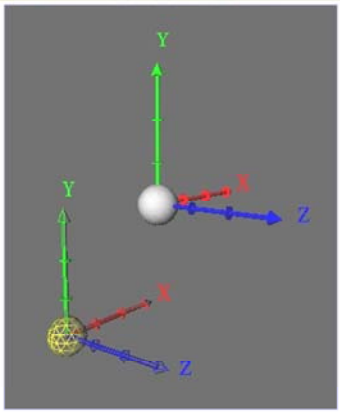
Here we create an *ortho-normal basis* (a fancy name for three vectors that are perpendicular to each other, and each have unit length). Those three vectors form the necessary rotation to orientate our world scene to eye coordinates.

The final operation in completing the `LookAt()` function's transform is to translate to the eye's position . Please see the implementation in Transform.h for more details.

Translation

- Move the origin to a new location

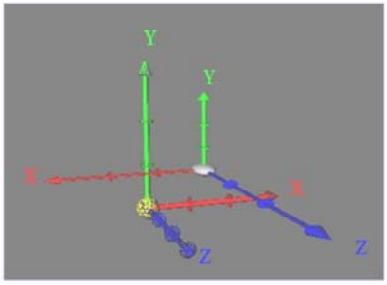
$$T(t_x, t_y, t_z) = \begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Scale

- Stretch, mirror or decimate a coordinate direction

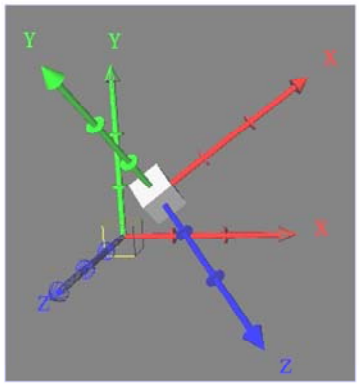
$$S(s_x, s_y, s_z) = \begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Note, there's a translation applied here to make things easier to see

Rotation

- Rotate coordinate system about an axis in space



Note, there's a translation applied here to make things easier to see

Rotation (cont'd)

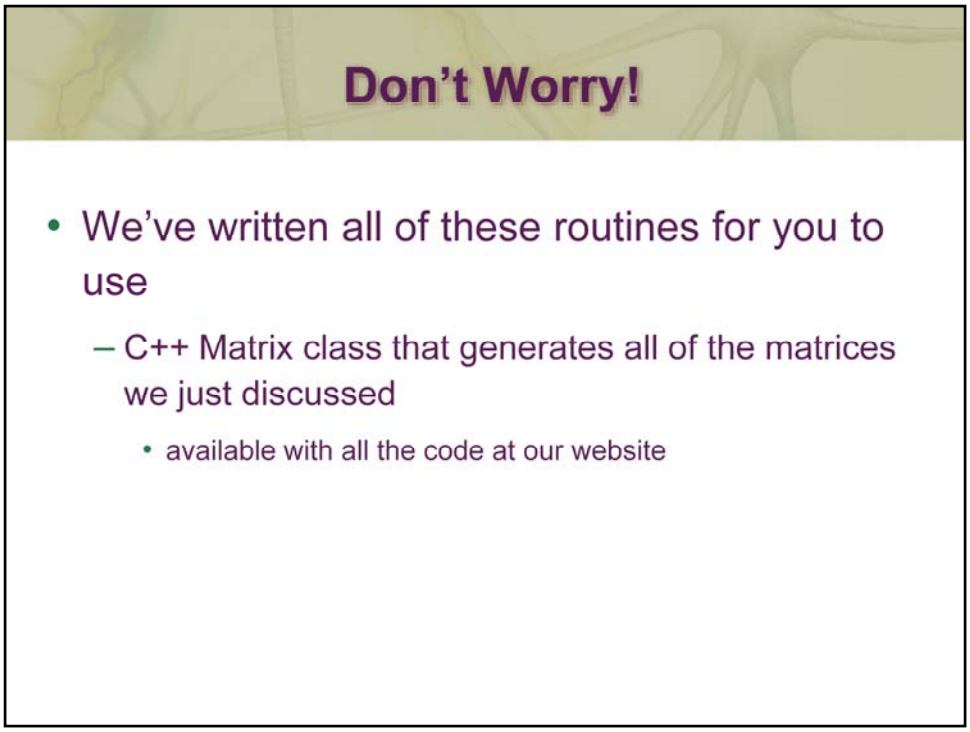
$$\vec{v} = \begin{pmatrix} x & y & z \end{pmatrix}$$

$$\vec{u} = \frac{\vec{v}}{\|\vec{v}\|} = \begin{pmatrix} x' & y' & z' \end{pmatrix}$$

$$M = \vec{u}^t\vec{u} + \cos(\theta)(I - \vec{u}^t\vec{u}) + \sin(\theta)S$$

$$S = \begin{pmatrix} 0 & -z' & y' \\ z' & 0 & -x' \\ -y' & x' & 0 \end{pmatrix}$$

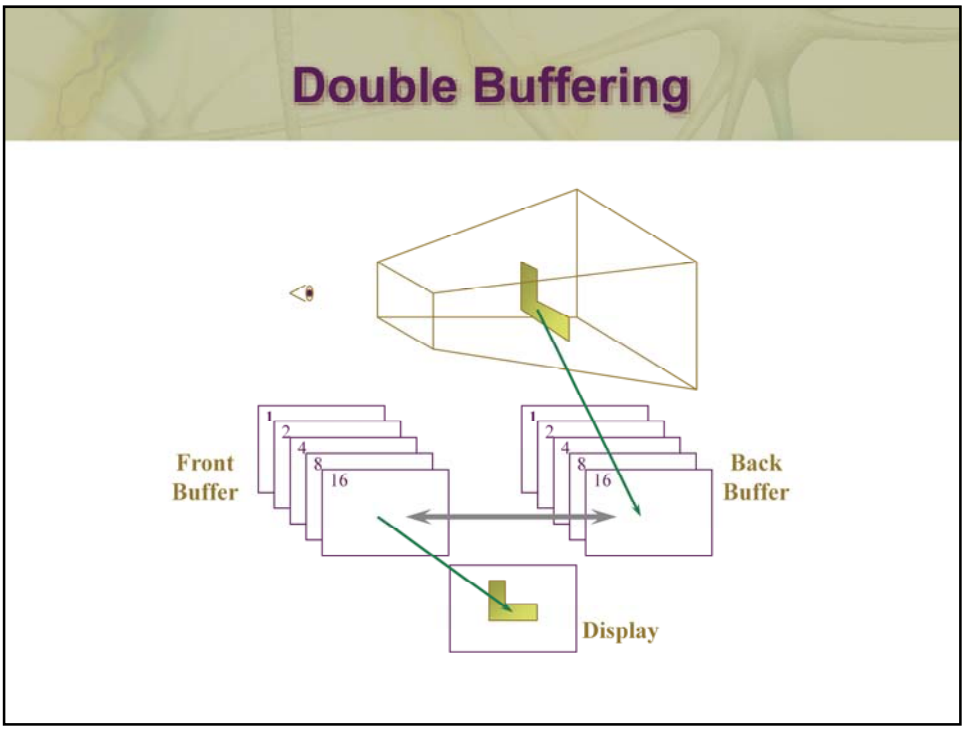
$$R_{\vec{v}}(\theta) = \begin{pmatrix} & M & & 0 \\ & & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



We know all that matrix math could be intimidating if you're not too familiar with linear algebra. We've written a header file, Transform.h, that takes implements all of those routines, manages the row and column ordering of the matrices, and makes it very easy to integrate them with your shaders.

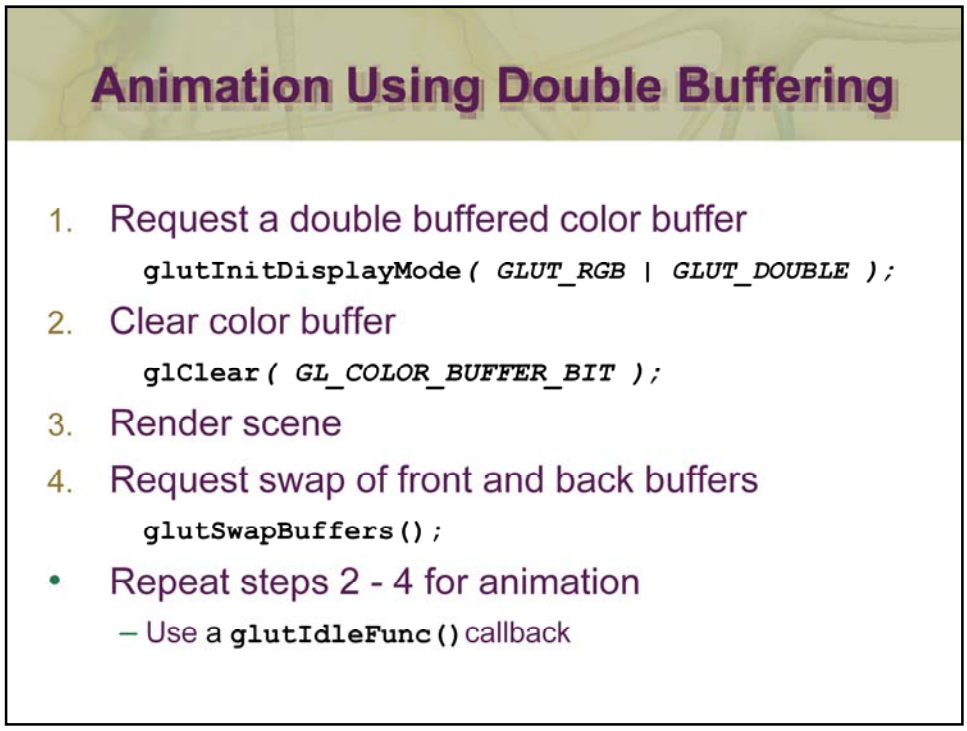
For example, you might want to use a perspective projection matrix in shader. Here's how you'd do that with our code (this assumes your shader has a variable named "P" for the projection matrix):

```
projIndex = glGetUniformLocation( program, "P" );

Matrix p = Perspective( 120.0, aspectRatio, zNear, zFar );

glUniformMatrix4fv( projIndex, 1,
        /* transpose matrix? */ GL_FALSE, p );
```



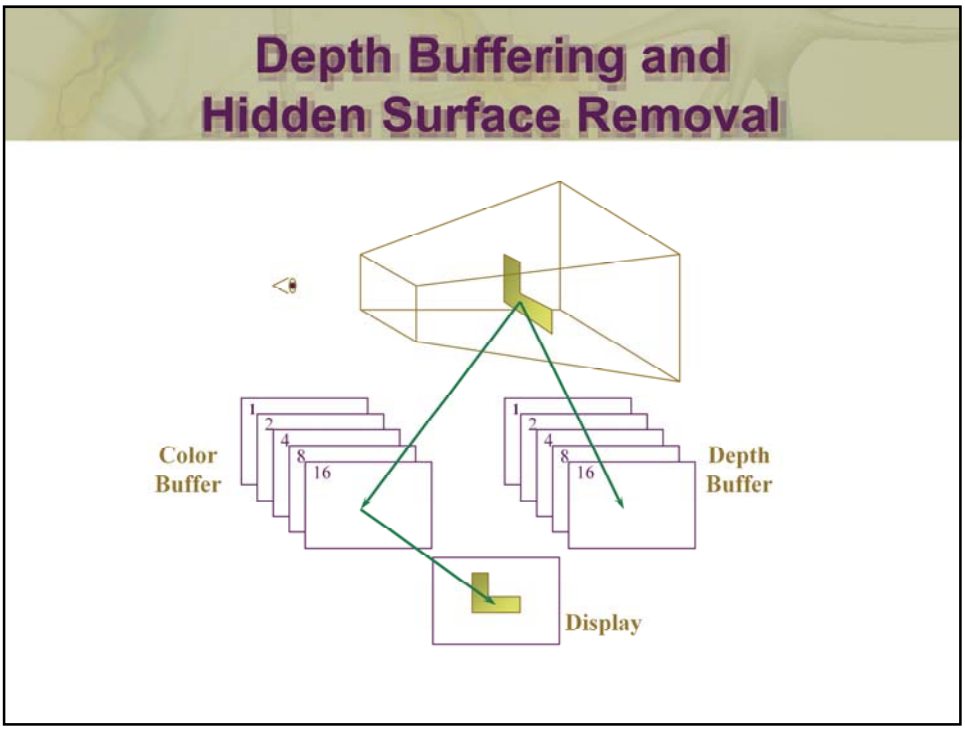
Double buffer is a technique for tricking the eye into seeing smooth animation of rendered scenes. The color buffer is usually divided into two equal halves, called the *front buffer* and the *back buffer.*

The front buffer is displayed while the application renders into the back buffer. When the application completes rendering to the back buffer, it requests the graphics display hardware to swap the roles of the buffers, causing the back buffer to now be displayed, and the previous front buffer to become the new back buffer.



Requesting double buffering in GLUT is simple. Adding `GLUT_DOUBLE` to your `glutInitDisplayMode()` call will cause your window to be double buffered.

When your application is finished rendering its current frame, and wants to swap the front and back buffers, the `glutSwapBuffers()` call will request the windowing system to update the window's color buffers.

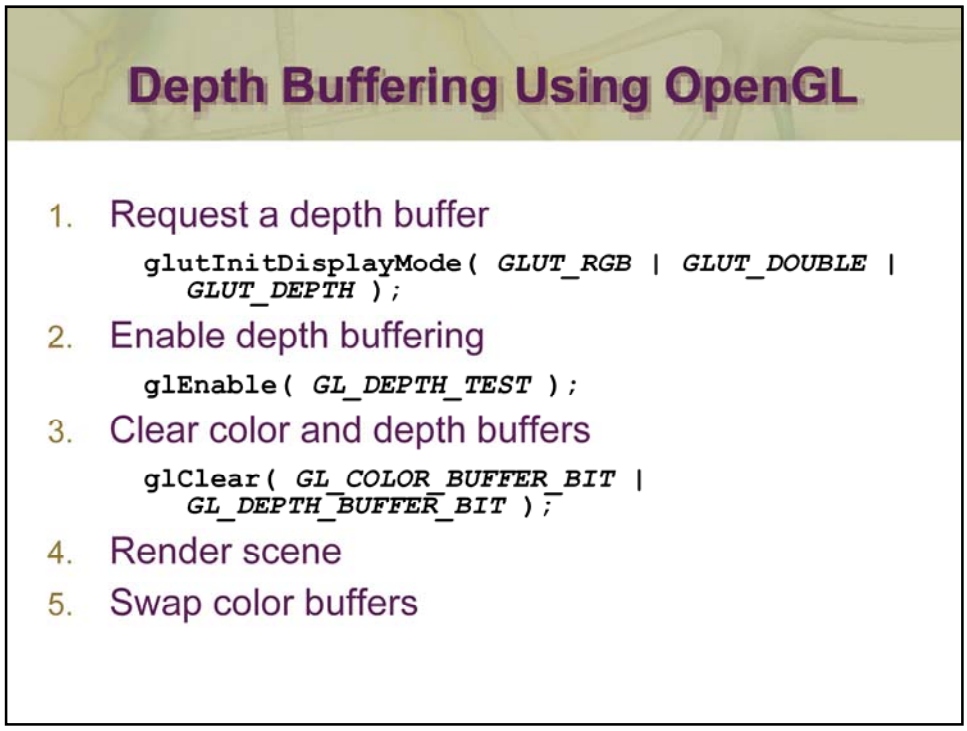


Depth buffering is a technique to determine which primitives in your scene are occluded by other primitives. As each pixel in a primitive is rasterized, its distance from the eyepoint (depth value), is compared with the values stored in the depth buffer. If the pixel's depth value is less than the stored value, the pixel's depth value is written to the depth buffer, and its color is written to the color buffer.

The depth buffer algorithm is:

```
if ( pixel->z < depthBuffer(x,y)->z ) {
   depthBuffer(x,y)->z = pixel->z;
   colorBuffer(x,y)->color = pixel->color;
}
```

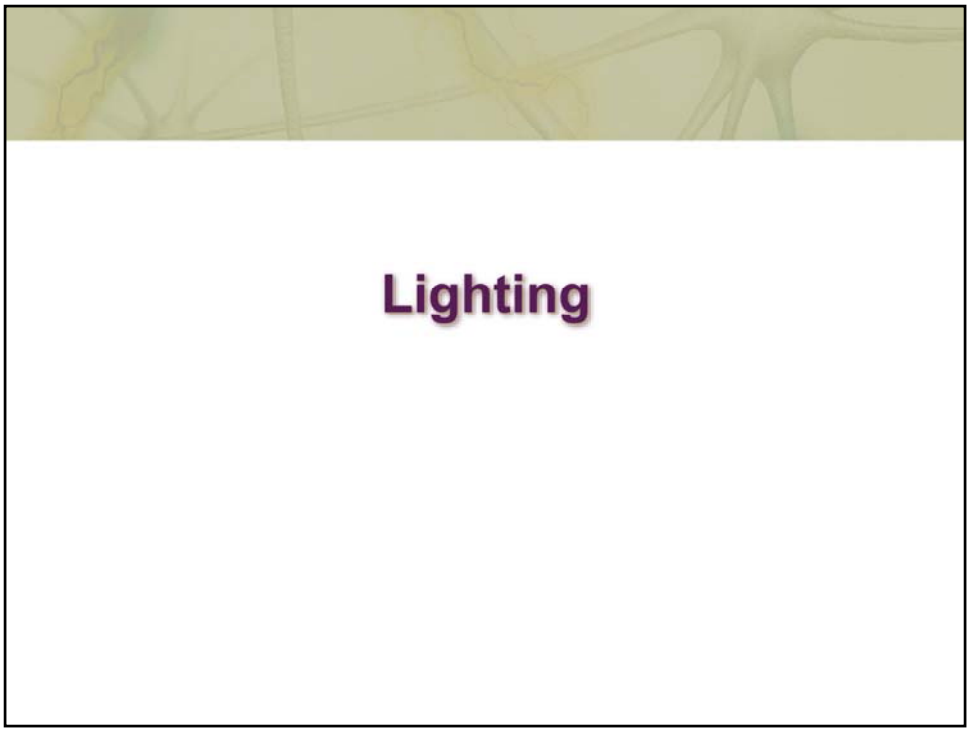
OpenGL depth values range from [0.0, 1.0], with 1.0 being essentially infinitely far from the eyepoint. Generally, the depth buffer is cleared to 1.0 at the start of a frame.



Enabling depth testing in OpenGL is very straightforward.

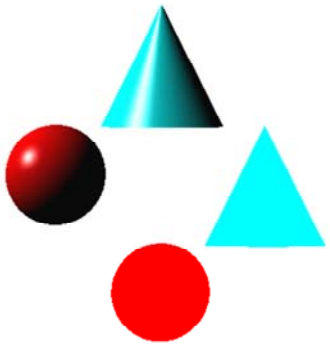
A depth buffer must be requested for your window, once again using the `glutInitDisplayMode()`, and the `GLUT_DEPTH` bit.

Once the window is created, the depth test is enabled using `glEnable( GL_DEPTH_TEST )`.


Lighting

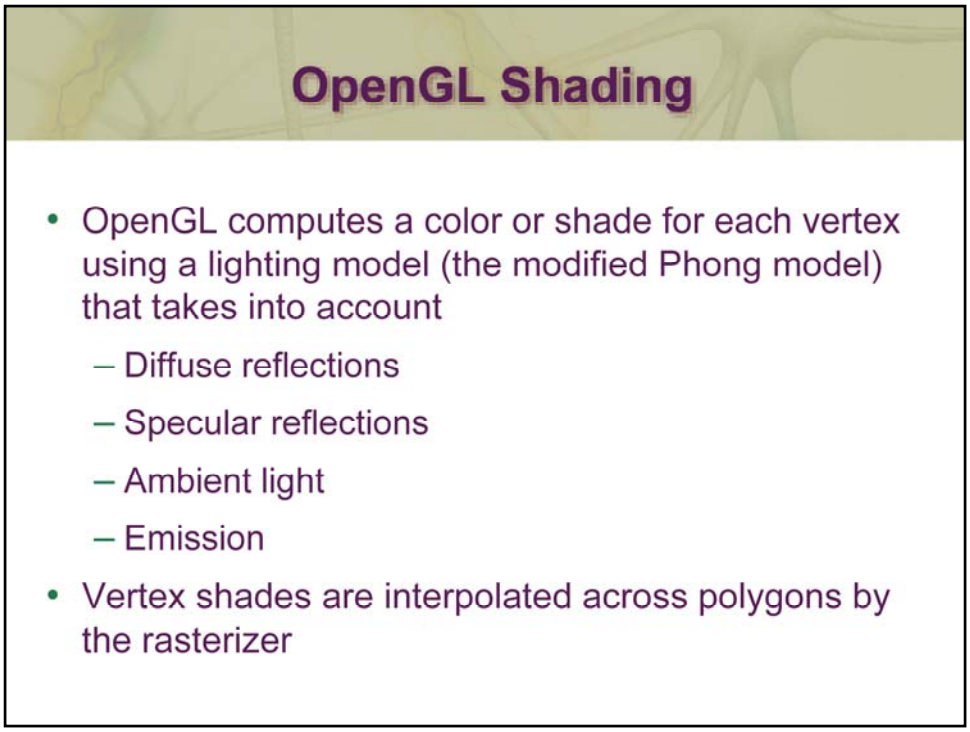
Lighting Principles

- Lighting simulates how objects reflect light
  - material composition of object
  - light's color and position
  - global lighting parameters
    - ambient light
    - two sided lighting

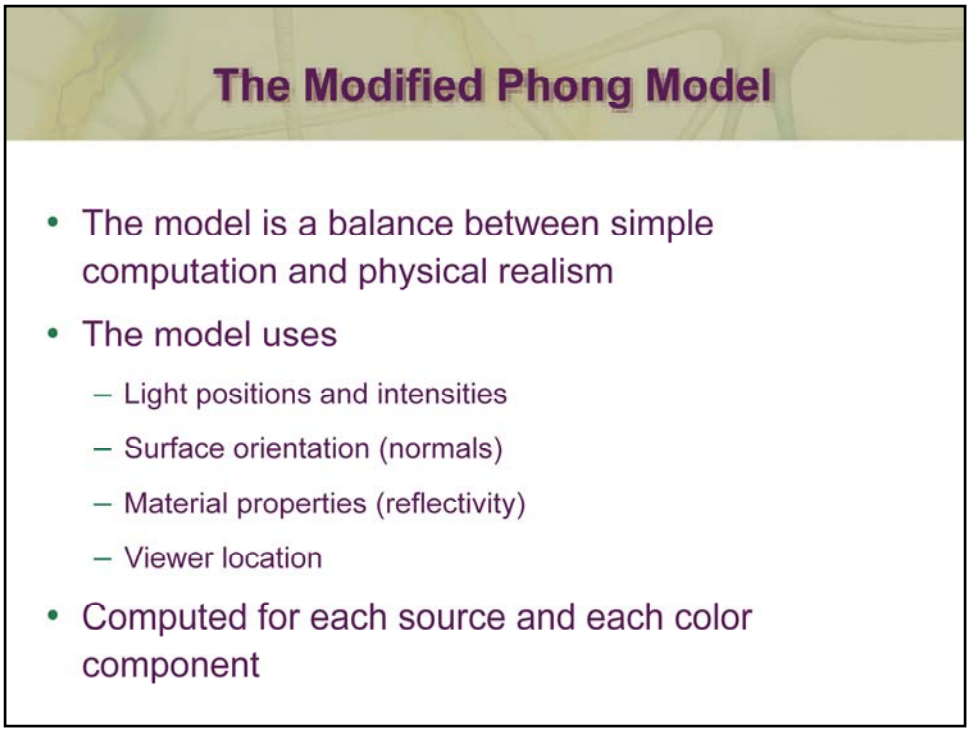


Lighting is an important technique in computer graphics. Without lighting, objects tend to look like they are made out of plastic.

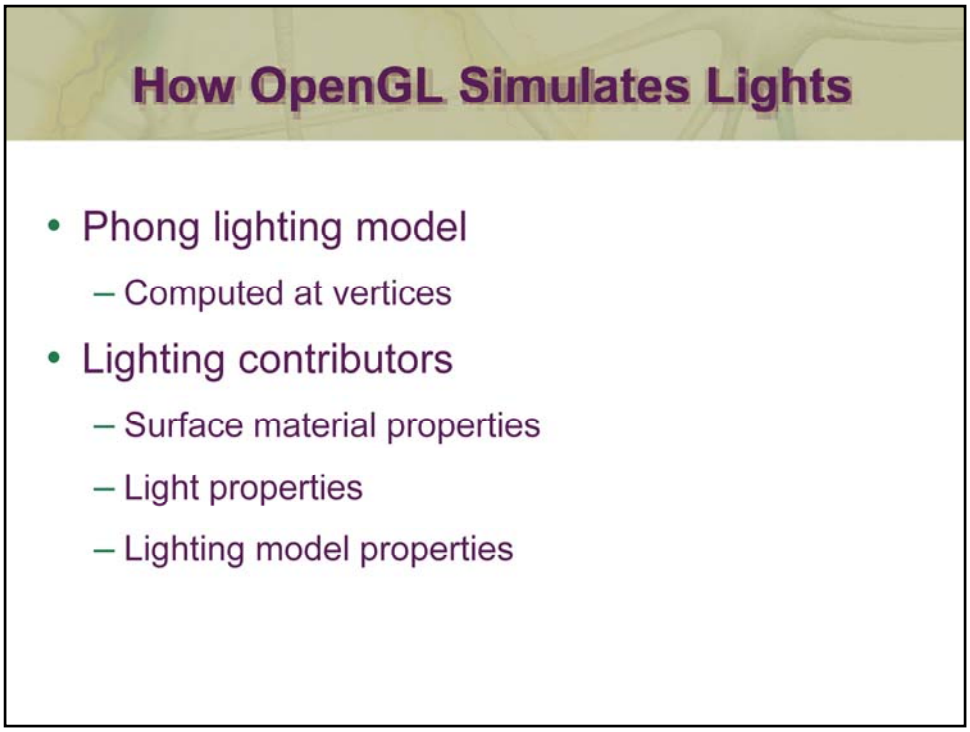
OpenGL divides lighting into three parts: material properties, light properties and global lighting parameters.



OpenGL can use the shade at one vertex to shade an entire polygon (constant shading) or interpolated the shades at the vertices across the polygon (smooth shading), the default.



The orientation of a surface is specified by the normal at each point. For a flat polygon the normal is constant over the polygon. Because normals are specified by the application program and can be changed between the specification of vertices, when we shade a polygon it can appear to be curved.



Classically, OpenGL lighting was based on the Phong lighting model. At each vertex in the primitive, a color is computed using that primitives material properties along with the light settings.

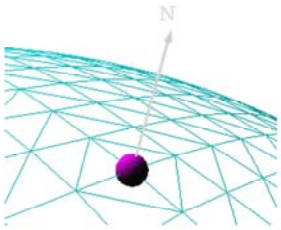
The color for the vertex is computed by adding four computed colors for the final vertex color. The four contributors to the vertex color are:

- *Ambient* is color of the object from all the undirected light in a scene.
- *Diffuse* is the base color of the object under current lighting. There must be a light shining on the object to get a diffuse contribution.
- *Specular* is the contribution of the shiny highlights on the object.
- *Emission* is the contribution added in if the object emits light (i.e., glows)

Since we need to do this in shaders, we'll discuss this model as it provides a nice description, but please realize there are more accurate lighting models available you could implement in your shaders.

Surface Normals

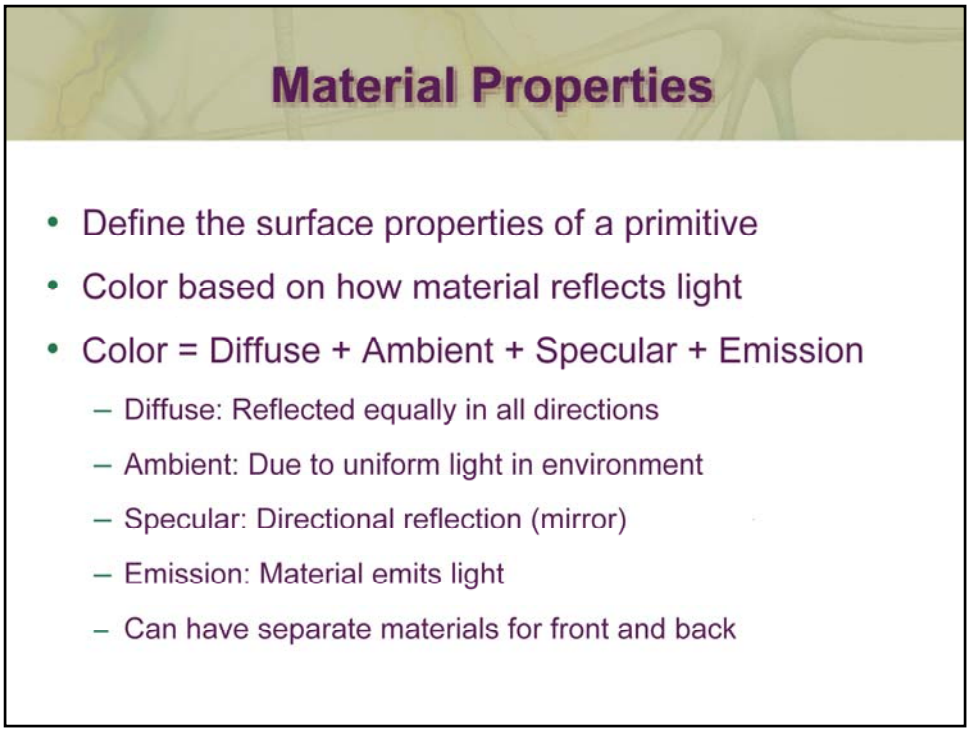
- Normals define how a surface reflects light
  - Specify normals as vertex attributes
  - Use *unit* normals for proper lighting
    - scaling affects a normal's length



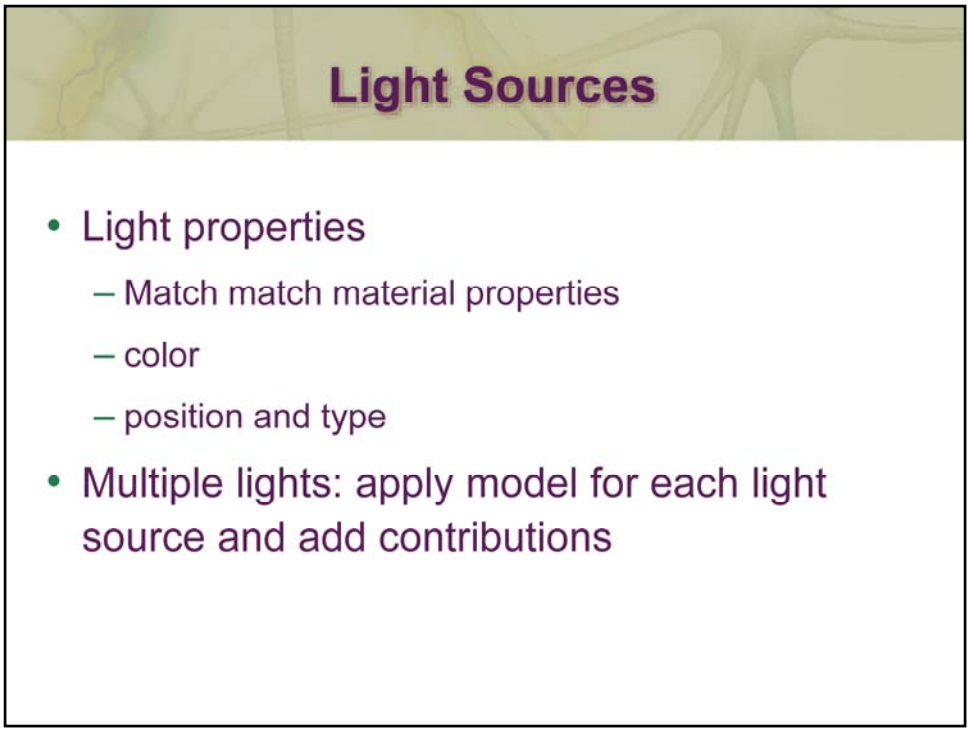
The lighting normal tells OpenGL how the object reflects light around a vertex. If you imagine that there is a small mirror at the vertex, the lighting normal describes how the mirror is oriented, and consequently how light is reflected.

Usually, lighting normals are provided with a vertex (they might also be generated in the vertex shader, like for algebraic shapes, for example).

The mathematics of lighting also rely on the fact it's a *normalized vector*, which has a length of one, to generate correct results. If your normals don't have unit length being passed into a shader, you can use the **normalize()** routine within your shader to make the vector have unit length.

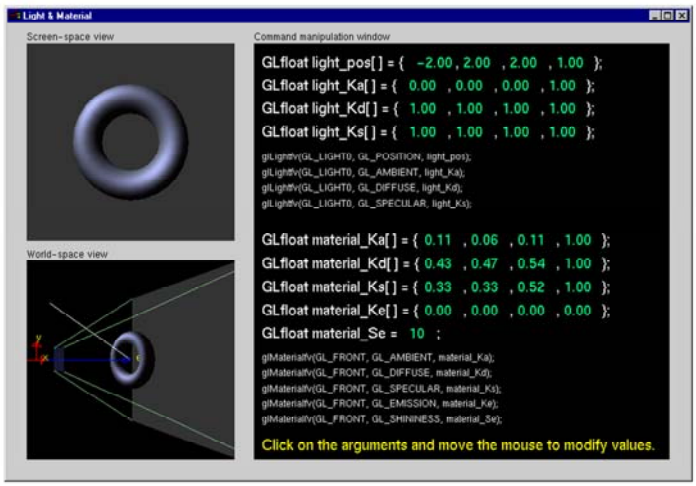


Material properties describe the color and surface properties of a material (dull, shiny, etc.). OpenGL supports material properties for both the front and back of objects, as described by their vertex winding.



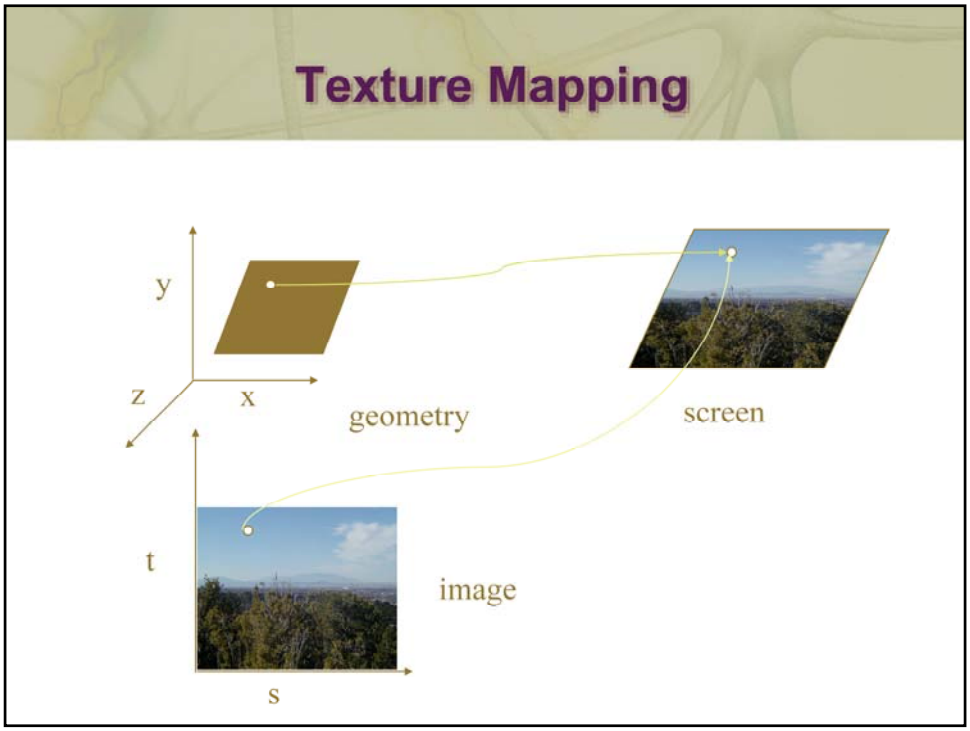
Generally, lights have a matching set of color properties to the material properties, i.e., diffuse, specular, etc. components. In addition – and more importantly – lights have positions and types. The classic OpenGL lighting model includes two types of lights: directional and point lights. *Directional lights* are like the sun, where all the light rays are parallel and coming from the same direction. Conversely, point lights are like light bulbs, they emit light spherically from a point in space.

Light Material Tutorial



This tutorial is based on fixed-function OpenGL, but provides a useful and descriptive context for discussing lighting computations in OpenGL. With shaders, all of the computation that's done for lighting must be done in the shader, including specifying variables for the different types of properties and such.

Texture Mapping



Textures are images that can be pasted on geometry and can be one, two, or three dimensional. By convention, the coordinates of the image are *s*, *t*, *r* and *q*. Thus for the two dimensional image above, a point in the image is given by its (*s, t*) values with (*0, 0*) in the lower-left corner and (*1, 1*) in the top-right corner.

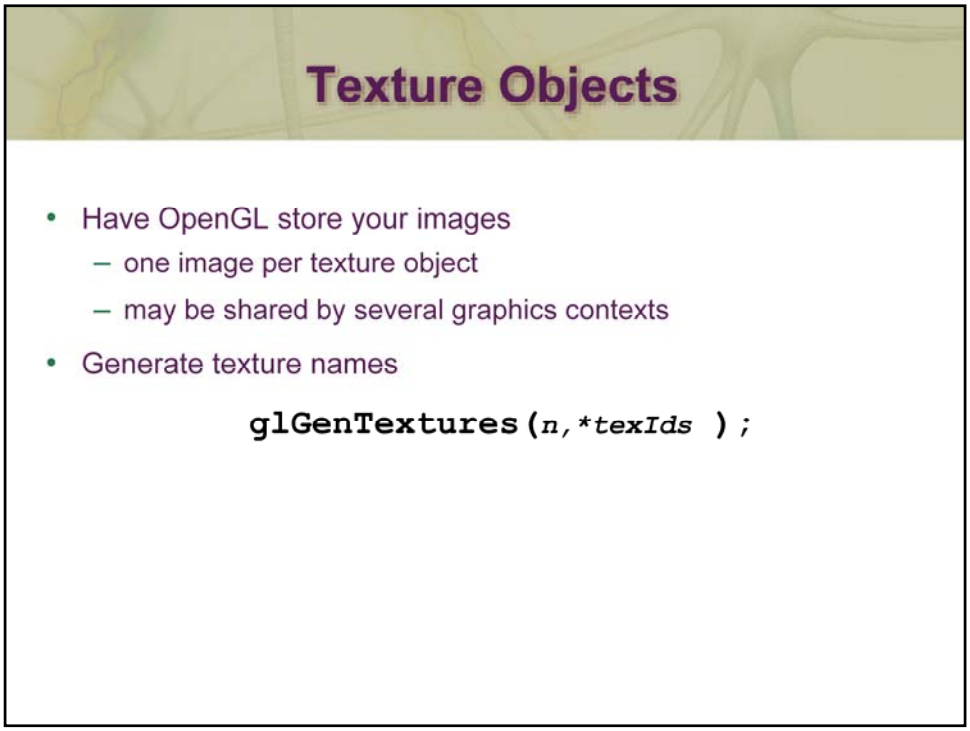
A texture map for a two-dimensional geometric object in (*x, y, z*) world coordinates maps a point in (*s, t*) space to a corresponding point on the screen.

In the simplest approach, we must perform these three steps.

Textures reside in texture memory. When we assign an image to a texture it is copied from processor memory to texture memory where pixels are formatted differently.

Texture coordinates are actually part of the state as are other vertex attributes such as color and normals. As with colors, OpenGL interpolates texture inside geometric objects.

Because textures are really discrete and of limited extent, texture mapping is subject to aliasing errors that can be controlled through filtering.



The first step in creating texture objects is to have OpenGL reserve some indices for your objects. `glGenTextures()` will request *n* texture ids and return those values back to you in `texIds`.

To begin defining a texture object, you call `glBindTexture()` with the id of the object you want to create. The target is one of `GL_TEXTURE_{123}D()`. All texturing calls become part of the object until the next `glBindTexture()` is called.

To have OpenGL use a particular texture object, call `glBindTexture()` with the target and id of the object you want to be active.

To delete texture objects, use `glDeleteTextures()`.

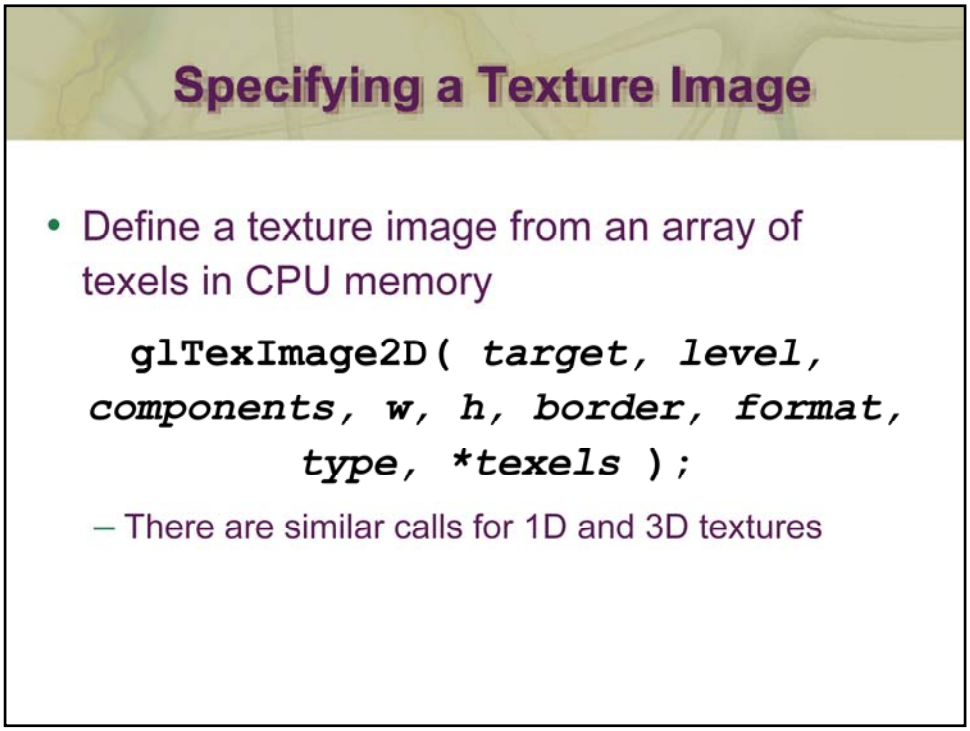
Texture Objects (cont'd.)

- Create texture objects with texture data and state

```
glBindTexture( target, id );
```

- Bind textures before using

```
glBindTexture( target, id );
```

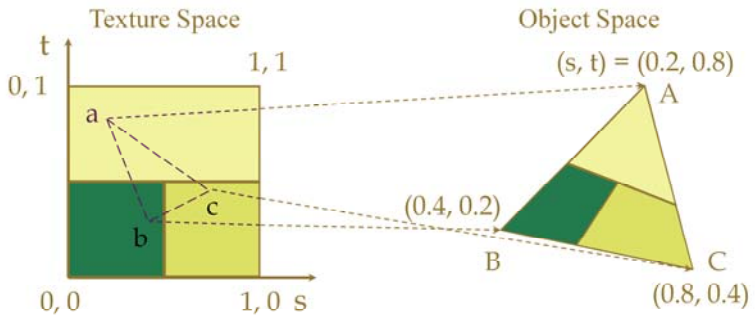


Specifying the texels for a texture is done using the `glTexImage{123}D()` call. This will transfer the texels in CPU memory to OpenGL, where they will be processed and converted into an internal format.

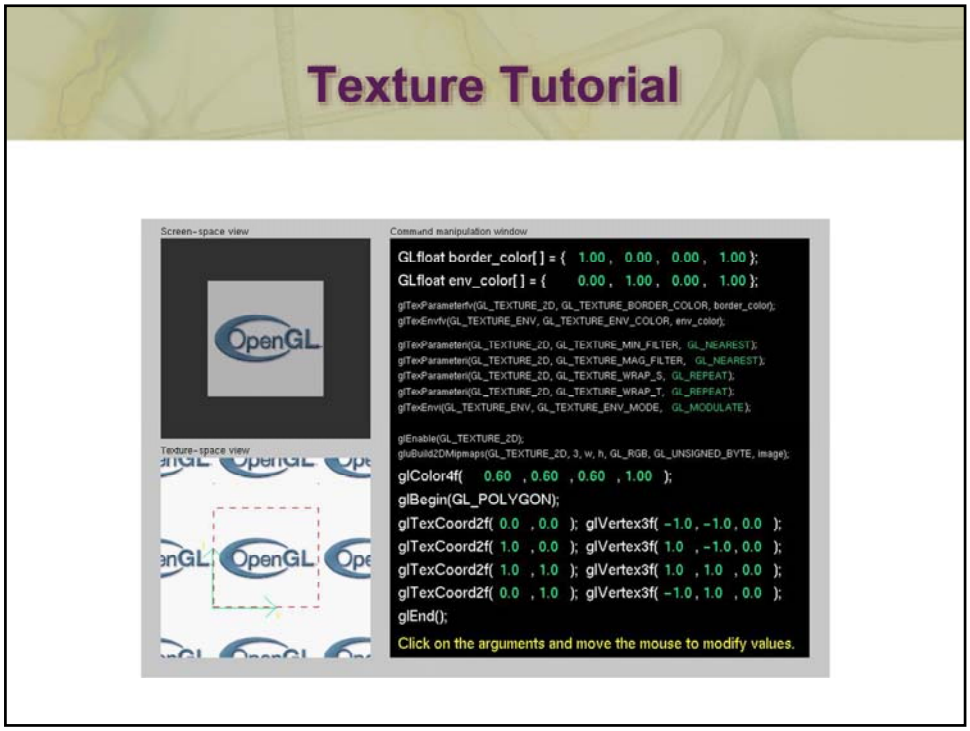
The level parameter is used for defining how OpenGL should use this image when mapping texels to pixels. Generally, you'll set the level to 0, unless you are using a texturing technique called mipmapping, which we will discuss in the next section.

Mapping a Texture

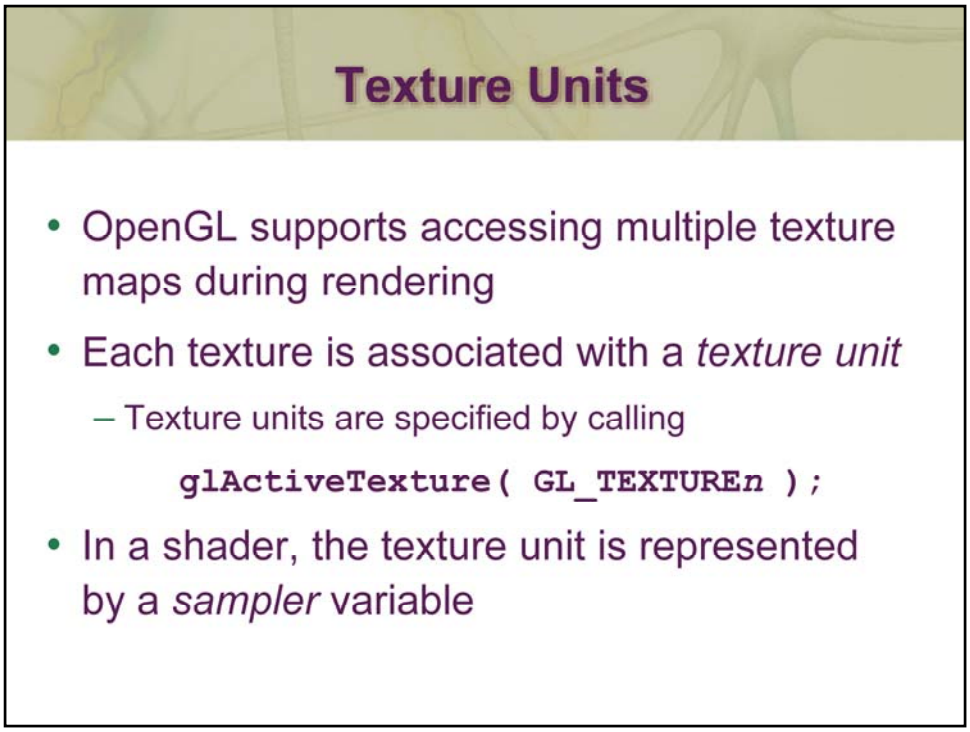
- Based on parametric texture coordinates
- Specify a texture coordinate for each vertex



When you want to map a texture onto a geometric primitive, you need to provide texture coordinates. Just like a vertex's positional data, or lighting normal, texture coordinates are just another (or part of a set of) vertex attributes. Valid texture coordinates are between 0 and 1, for each texture dimension, and the default texture coordinate is (0, 0, 0, 1).



Like our other tutorials, this one reflects using the older fixed-function methods of doing texture mapping. However the concepts are still relevant and hopefully illustrative.



During rendering, you can sample multiple textures and apply them to a single geometric object. This is a handy technique as often, you'll have a texture map for the surfaces appearance, another one for controlling the surfaces roughness (these are commonly called *gloss maps* – think of being a map of where a surface has shown wear or is still shiny and reflective), still more for light maps, or transparency maps.

Each texture map needs to be associated with its own *texture unit*, which is capable of storing a single (perhaps mipmapped) texture. To switch between different texture units, call `glActiveTexture()` passing the token GL_TEXTURE*n*, where n runs form zero to one less than the number of supported texture units.

Inside of your shader, you'll access a particular texture unit using a *sampler*. Samplers are uniform variables, whose type must match the type of texture bound to that texture unit. The available types of texture samplers are: **sampler1D**, **sampler2D**, **sampler3D**, **samplerCube** (and a few more advanced versions). When you load a texture, the call and type of texture (e.g., calling glTexture2D() with GL_TEXTURE_2D) specifies which type of sampler is capable of accessing that texture. In this case, you'd use a sampler2D to access the texture. The final issue is that you need to associate the texture unit's number (the *n* you specified when calling `glActiveTexture()`) with the sampler. Being a uniform, you do that by loading a uniform variable with the texture unit's number. For example, in the shader, say we declare "uniform sampler2D tex;". If we've loaded a two-dimensional texture into texture unit four, we'd need to do the following:

```
GLuint  texLoc = glGetUniformLocation( program, "tex" );
glUniform1i( texLoc, 4 );
```

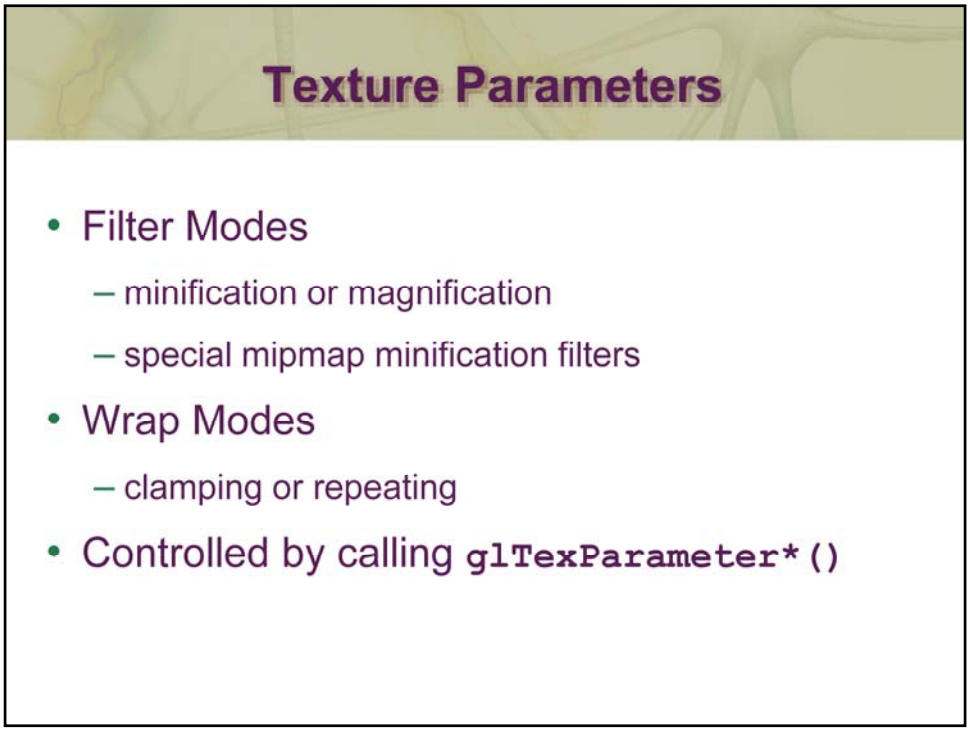
After doing that, we can access the texture from our shader.

Sampling a Texture

- Inside of your shader, to retrieve a texel, you'll call `texture2D()`
  - or the suitable call to match the texture's type

```
uniform sampler2D  tex;

in vec2 tc; // texture coordinates
out vec4 color;

void main()
{
    color = texture2D( tex, tc );
}
```

From within a shader, to access a texture you need a suitable sampler and the appropriate texture coordinates. With those elements, it's as simple as calling **texture2D()** (or the appropriate call to match the type of texture stored in the texture unit). The value returned will be a four-component color that's been processed by the texture retrieval system (including *filtering* and *wrapping* the texture).

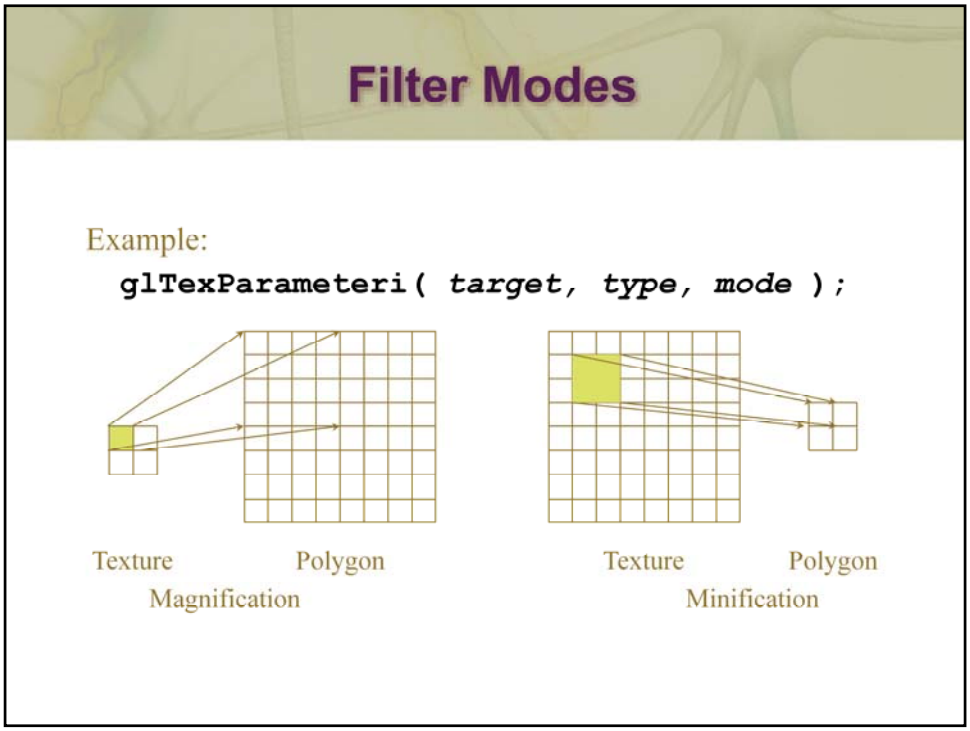


Textures and the objects being textured are rarely the same size (in pixels). Filter modes determine the methods used by how texels should be expanded
(magnification), or shrunk (minification) to match a pixel's size. An additional technique, called mipmapping is a special instance of a minification filter.

Wrap modes determine how to process texture coordinates outside of the [0,1] range. The available modes are:

`GL_CLAMP` - clamp any values outside the range to closest valid value,
causing the edges of the texture to be "smeared" across the primitive

`GL_REPEAT` - use only the fractional part of the texture coordinate,
causing the texture to repeat across an object.



Filter modes control how pixels are minified or magnified. Generally a color is computed using the nearest texel or by a linear average of several texels.

The filter type, above is one of `GL_TEXTURE_MIN_FILTER` or `GL_TEXTURE_MAG_FILTER`.

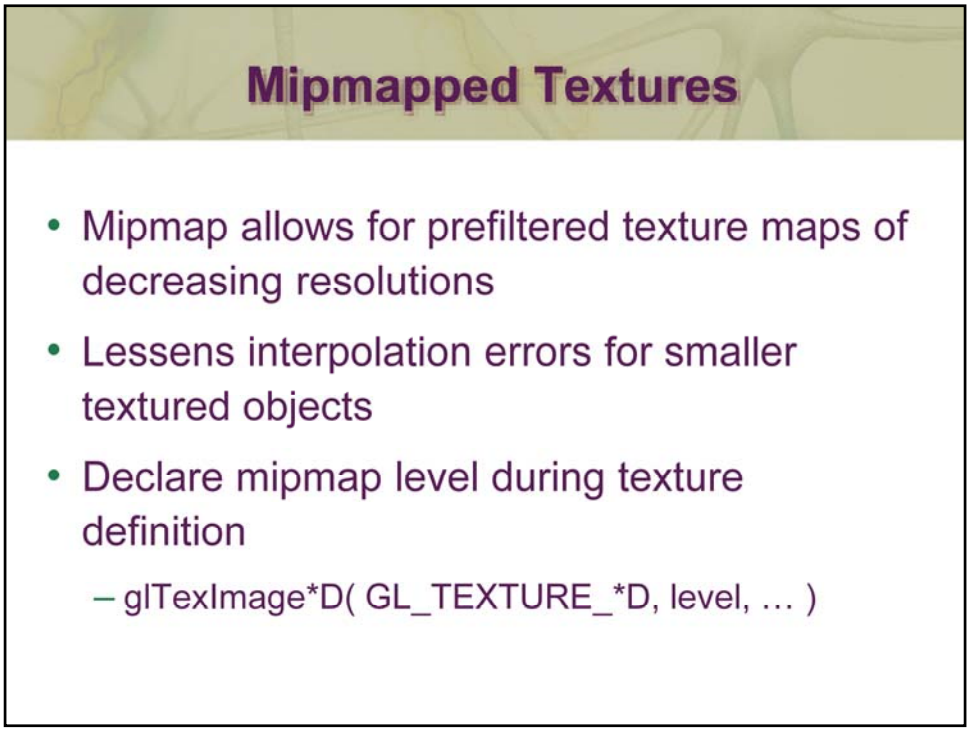
The mode is one of `GL_NEAREST`, `GL_LINEAR`, or special modes for mipmapping. Mipmapping modes are used for minification only, and can have values of:
`GL_NEAREST_MIPMAP_NEAREST`

`GL_NEAREST_MIPMAP_LINEAR`

`GL_LINEAR_MIPMAP_NEAREST`

`GL_LINEAR_MIPMAP_LINEAR`

Full coverage of mipmap texture filters is outside the scope of this course.



As primitives become smaller in screen space, a texture may appear to shimmer as the minification filters creates rougher approximations. Mipmapping is an attempt to reduce the shimmer effect by creating several approximations of the original image at lower resolutions.

Each mipmap level should have an image which is one-half the height and width of the previous level, to a minimum of one texel in either dimension. For example, level 0 could be 32 x 8 texels. Then level 1 would be 16 x 4; level 2 would be 8 x 2; level 3, 4 x 1; level 4, 2 x 1, and finally, level 5, 1 x 1.

Wrapping Mode

- Example:

```
glTexParameteri( GL_TEXTURE_2D,
     GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D,
     GL_TEXTURE_WRAP_T, GL_REPEAT )
```

Wrap mode determines what should happen if a texture coordinate lies outside of the [0,1] range. If the `GL_REPEAT` wrap mode is used, for texture coordinate values less than zero or greater than one, the integer is ignored and only the fractional value is used.

If the `GL_CLAMP` wrap mode is used, the texture value at the extreme (either 0 or 1) is used.

Application Examples

Shader Examples

- Vertex Shaders
  - Moving vertices: height fields
  - Per vertex lighting: height fields
  - Per vertex lighting: cartoon shading
- Fragment Shaders
  - Per vertex vs. per fragment lighting: cartoon shader
  - Samplers: reflection Map
  - Bump mapping

101

Height Fields

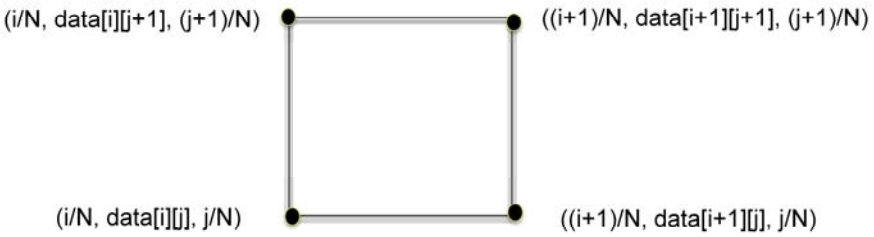
- A **height field** is a function $y = f(x,z)$ where the y value represents a quantity such as the height above a point in the x-z plane.
- Heights fields are usually rendered by sampling the function to form a rectangular mesh of triangles or rectangles from the samples $y_{ij} = f(x_i, y_j)$

Displaying a Height Field

- Defining a rectangular mesh

```
for(i=0;i<N;i++) for(j=0;j<N;j++) data[i][j]=f( i, j, time);
```

- Displaying a mesh with quad line loops

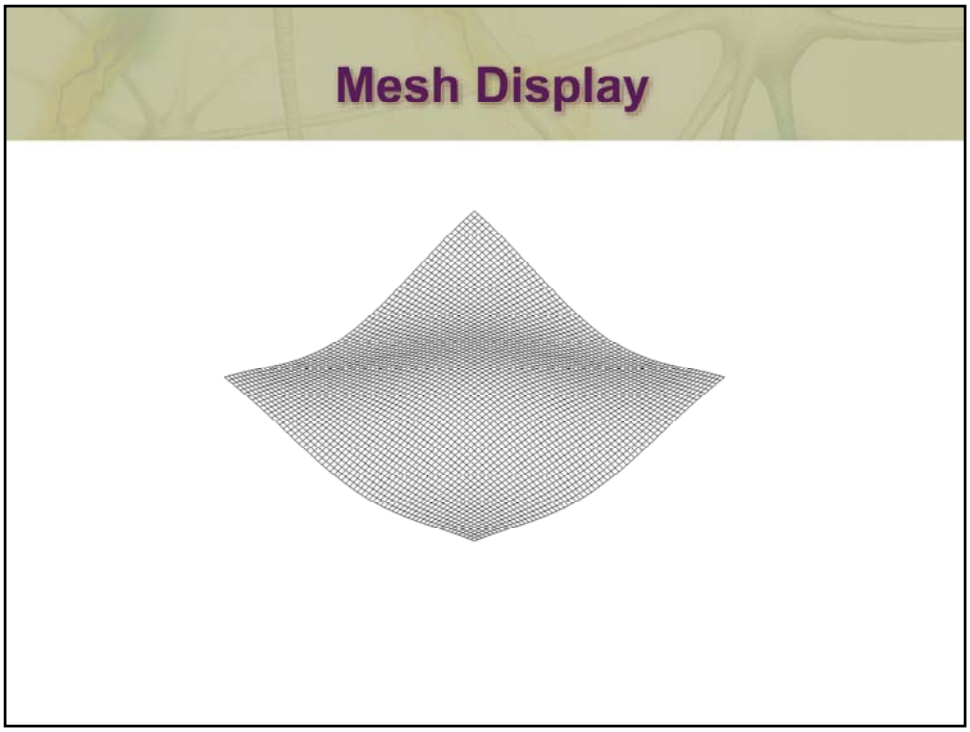


- Each quad can be filled with two triangles

Time varying vertex shader

```
uniform float time; /* in milliseconds */
uniform mat4 modelViewProjection;
in vec4 mPosition;

void main()
{
    vec4  t =mPosition;
    t.y = 0.1*sin(0.001*time
          + 5.0*mPosition.x)*sin(0.001)*time
          + 5.0*mPosition.z);
    gl_Position = modelViewProjectionMatrix* t;
}
```

This is the shader from are earlier example with the addition of the modelviewprojection matrix to allow for viewing and transformation from model coordinates. Shading is left to the fragment shader.



To achieve this output all the fragment shader can be as simple as our trivial example that colors each fragment with the same color.

```
void main()
{
    gl_FragColor = vec4 ( 0.0, 0.0, 0.0, 1.0 );
}
```

Such a simple coloring will not be adequate if we are to fill the polygons.

Adding Lighting

- Solid Mesh: convert each quad to two triangles
- We must add lighting
- Must do per vertex lighting in shader if we use a vertex shader for time-varying mesh

If we don't add lighting, we will see a solid black mesh and won't be able to see shape.

106

Mesh Shader

```
uniform float time;
uniform mat4 modelViewProjectionMatrix, modelViewMatrix;
uniform mat3 normalMatrix;
uniform vec4 lightSourcePosition;
uniformvec4 specularLightProduct, diffuseLightproduct;
uniform float shininess;
uniform vec3 mNormal;
in vec4 mPosition;
out vec4 frontColor;
```

Details of lighting model are not important to here. The model includes the standard modified Phong diffuse and specular terms without distance.

Note that we do the lighting in eye coordinates and therefore must compute the eye position in this frame.

All the light and material properties are set in the application and sent to the shader.

time: same as in previous example

modelViewProjection matrix: product of modelview and projection matrices

modelViewMatrix: need to convert normal to eye coordinates

normalMatrx: inverse transpose of the upper left 3 x 3 part of the model view matrix needed to preserve angle between normal and light source when going to object coordinates

lightSourcePosition: in eye coordinates

specularLightProduct, diffuseLightProduct: vectors of product of component of light sources and material reflectivity

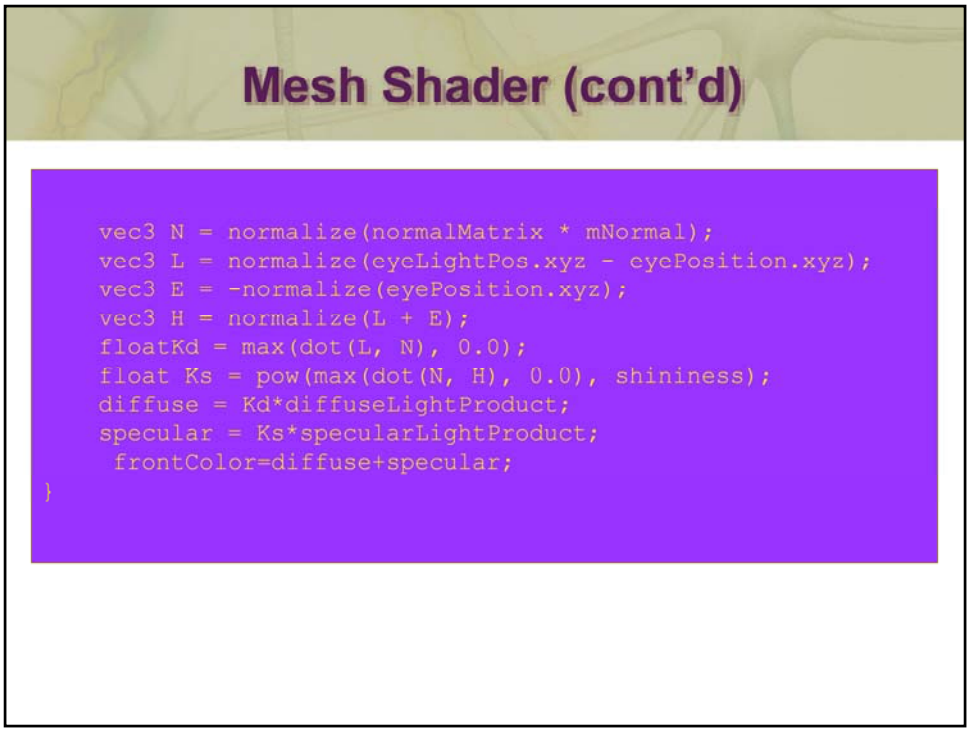
mNormal: normal in object coordinates

107

Mesh Shader (cont'd)

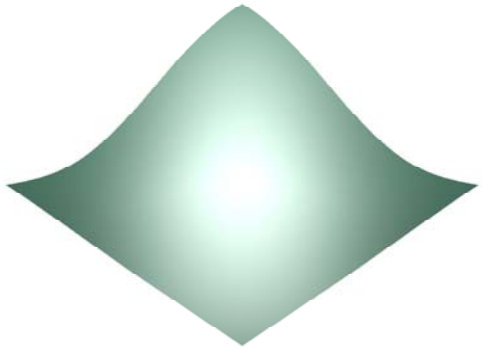
```
void main()
{
    vec4  t = mPosition;
    t.y = 0.1*sin(0.001*time+5.0*mPosition.x)
            *sin(0.001*time+5.0*mPosition.z);
    gl_Position = modelViewProjectionMatrix * t;

    vec4 diffuse;
    vec4 specular;
    vec4 eyePosition = modelViewMatrix * mPosition;
    vec4 eyeLightPos = lightSourcePosition;
```

Output position computed as before



Computation of shades using Blinn-Phong model without ambient term and distance terms

Shaded Mesh



Cartoon Shader

- This vertex shader uses only two colors but the color used is based on the orientation of the surface with respect to the light source
- Normal vector provided by the application
- A third color (black) is used for a silhouette edge

In this example, we use some of the standard diffuse computation to find the cosine of the angle between the light vector and the normal vector. Its value determines whether we color with red or yellow.

A silhouette edge is computed as in the previous example.

111

Cartoon Shader

```
in vec4 mPosition;
out vec4 vColor;
attribute mat4 modelViewProjectionMatrix;
attribute mat4 modelViewMatrix, normalMatrix;
attribute vec4 lightSourcePosition, mNormal;

void main()
{
    const vec4 yellow = vec4(1.0, 1.0, 0.0, 1.0);
    const vec4 red = vec4(1.0, 0.0, 0.0, 1.0);
    gl_Position =modelViewProjectionMatrix*mPosition;
    vec4 eyePosition =modelViewMatrix*mPosition;
    vec4 eyeLightPos =lightSourcePosition;
    vec3 N = normalize(normalMatrix*mNormal);
    vec3 L = normalize(eyeLightPos.xyz - eyePosition.xyz);
    floatKd = max(dot(L, N), 0.0);
    vColor = Kd > 0.6 ? yellow : red;
}
```

Adding a Silhouette Edge

```
const vec4 black = vec4(0.0, 0.0, 0.0, 1.0);

vec3 E = -normalize(eyePosition.xyz);

if(abs(dot(E,N))<0.25)    vColor= black;
```

The idea is that if the angle between the eye vector and the surface normal is small, we are near an edge.

113

Smoothing

- We can get rid of some of the jaggedness using the mix function in the shader

```
vColor=  mix(yellow, red, Kd);
```

But we do even better if we use a fragment shader

114

Fragment Shader Examples

- Per fragment lighting: Cartoon shader
- Texture Mapping: Reflection Map
- Bump Mapping

Per-Fragment Cartoon Vertex Shader

```
in vec4 mPosition;
out vec3 N;
out vec3 L;
out vec3 E;
attribute vec4 lightSourcePosition, mNormal;
attribute mat4 normalMatrix, modelViewProjectionMatrix;

void main()
{
    gl_Position =modelViewProjectionMatrix*mPosition;

    vec4 eyePosition = gl_ModelViewMatrix *mPosition;
    vec4 eyeLightPos =lightSourcePosition;

    N = normalize(normalMatrix*mNormal);
    L = normalize(eyeLightPos.xyz - eyePosition.xyz);
    E = -normalize(eyePosition.xyz);
}
```

Basic job of the vertex shader is to:

Compute position in clip coordinates

Pass normal, light and eye vectors to the rasterizer

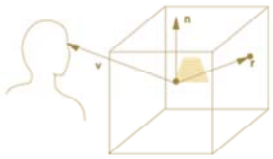
Cartoon Fragment Shader

```
in vec3 N;
in vec3 L;
in vec3 E;

void main()
{
    const vec4 yellow = vec4(1.0, 1.0, 0.0, 1.0);
    const vec4 red = vec4(1.0, 0.0, 0.0, 1.0);
    const vec4 black = vec4(0.0, 0.0, 0.0, 1.0);

    float Kd = max(dot(L, N), 0.0);
    gl_FragColor = mix(red, yellow, Kd);
    if(abs(dot(E,N))<0.25) gl_FragColor = black;
}
```

Cartoon Fragment Shader Result

Reflection Map

- Specify a cube map in application
- Use reflect function in vertex shader to compute view direction
- Apply texture in fragment shader



Reflection Map Vertex Shader

```
in vec4 mPosition;
out vec3 R;
attribute mat4 modelViewProjectionMatrix, normalMatrix;
attribute vec4 mNormal;

void main()
{
    gl_Position =modelViewProjectionMatrix*mPosition;

    vec3 N = normalize(normalMatrix*mNormal);
    vec4 eyePos =modelViewMatrix*mPosition;

    R = reflect(eyePos.xyz, N);
}
```

Reflection Map Fragment Shader

```
in vec3 R;
uniform samplerCube texMap;

void main()
{
     vec4 texColor = textureCube(texMap, R);

     gl_FragColor = texColor;
}
```

The rasterizer interpolates both the texture coordinates and reflection vector to get the respective values for the fragment shader.

Note that all the texture definitions and parameters are in the application program.

Reflection mapped teapot

Bump Mapping

- Vary normal in fragment shader so that lighting changes for each fragment
- Application: specify texture maps that describe surface variations
- Vertex Shader: calculate vertex lighting vectors and transform to texture space
- Fragment Shader: calculate normals from texture map and shade each fragment

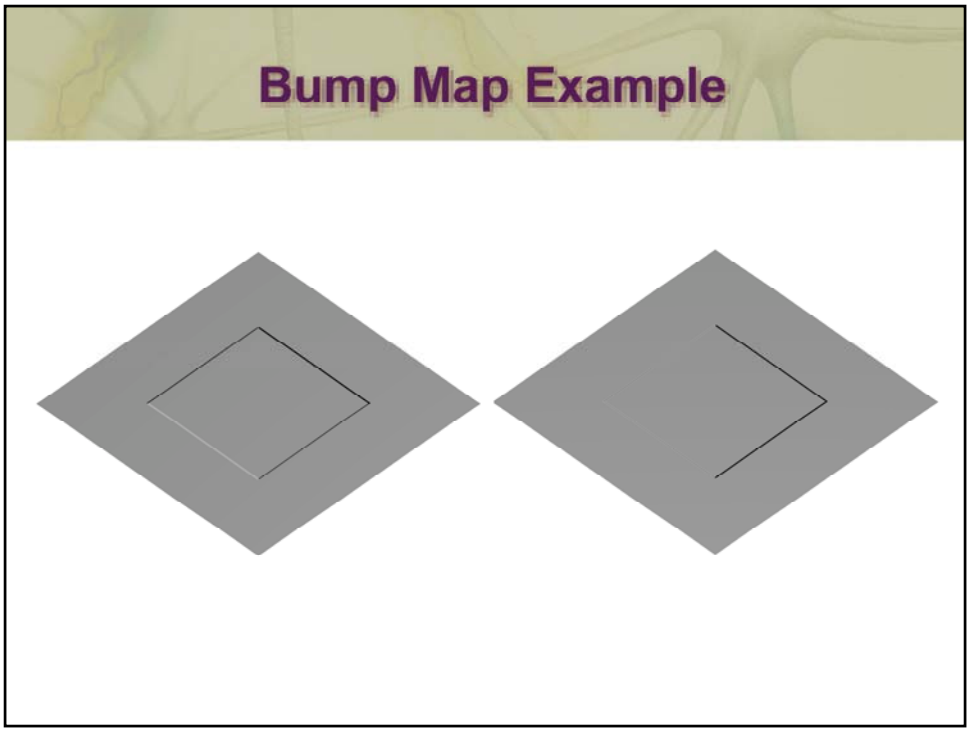
Details are a little complex

Need lighting model

Usually do computations in a local frame that changes for each fragment

Put code in an appendix

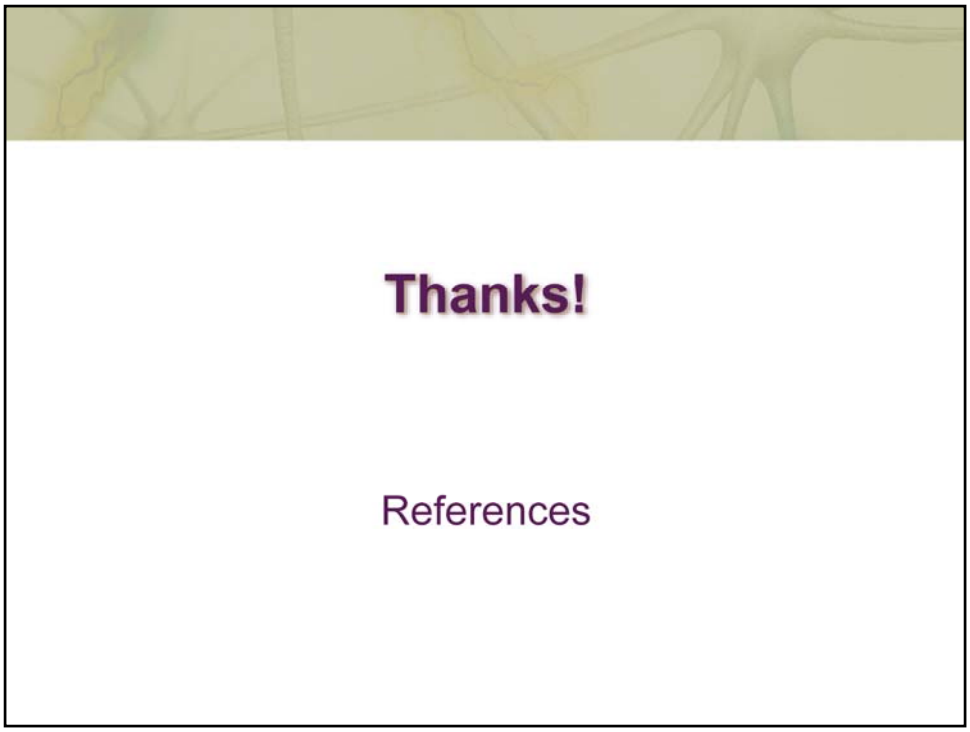
123



Single rectangle with moving light source.

Bump map is derived from a texture map with which is a step function.

124

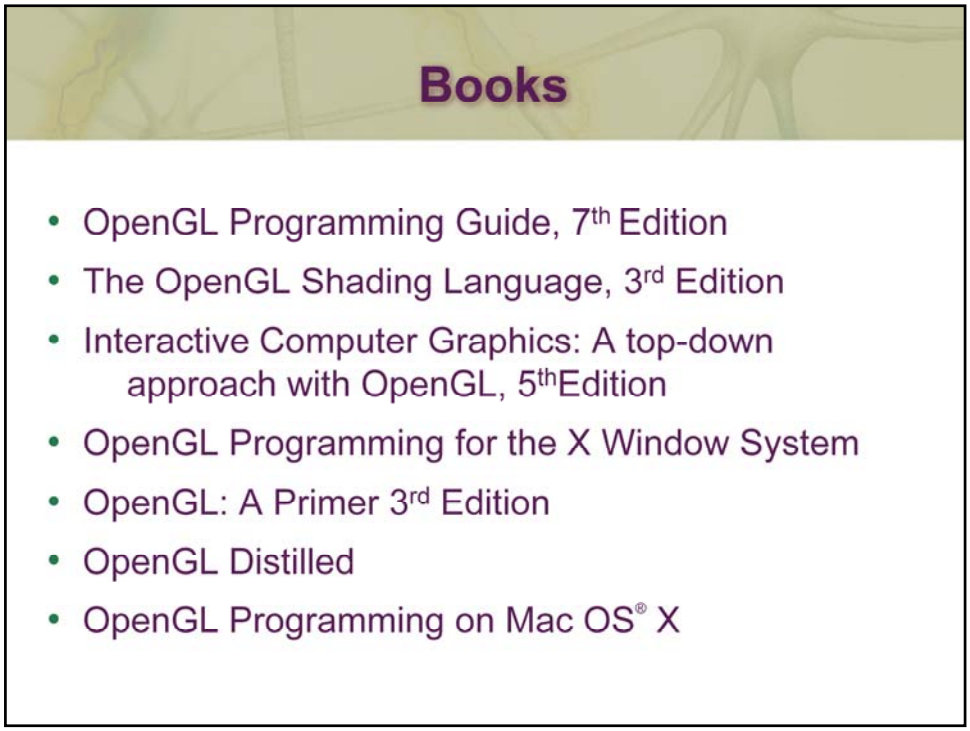

Thanks!
References

Course Resources

- `http://www.opengl-redbook.com/s2009`
  - Updated notes
  - Presentation slides
  - Code examples

On-Line Resources

- **http://www.opengl.org**
  - start here; up to date specification and lots of sample code
  - online “man pages” for all OpenGL functions
- **http://www.mesa3d.org/**
  - Brian Paul’s Mesa 3D
- **http://www.cs.utah.edu/~narobins/opengl.html**
  - very special thanks to Nate Robins for the OpenGL Tutors
  - source code for tutors available here!



The OpenGL Programming Guide– often referred to as the "Red Book" due to the color of its cover – discusses all aspects of OpenGL programming, discussing all of the features of OpenGL in detail.

Mark Kilgard's *OpenGL Programming for the X Window System*, is the "Green Book", and Ron Fosner's *OpenGL Programming for Microsoft Windows*, which has a white cover is sometimes called the "Alpha Book." *The OpenGL Shading Language*, by Randi Rost, Barthold Litchenbelt, and John Kessenich, is the "Orange Book."

All of the OpenGL programming series books, along with *Interactive Computer Graphics: A top-down approach with OpenGL*, *OpenGL: A Primer, and OpenGL Distilled* are published by Addison Wesley Publishers.

Program Listing

triangle.cxx

```
//////////////////////////////////////////////////////////////////////////
//
//  triangle.cxx - draw a single triangle in normalized-device coordinates
//

#include <stdlib.h>
#include <GL/glew.h>
#ifdef MACOSX
#include <GLUT/glut.h>
#else
#include <GL/freeglut.h>
#endif

#include "LoadProgram.h"

#define BUFFER_OFFSET( offset )   ((GLvoid*) offset)

GLuint  buffer;
GLuint  vPos;
GLuint  program;


//----------------------------------------------------------------------------

void
init()
{
    //
    // --- Load vertex data ---
    //
    GLfloat  vertices[][4] = {
       { -0.75, -0.5,  0.0, 1.0 },
       {  0.75, -0.5,  0.0, 1.0 },
       {  0.0,   0.75, 0.0, 1.0 }
    };

    glGenBuffers( 1, &buffer );
    glBindBuffer( GL_ARRAY_BUFFER, buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(vertices),
                  vertices, GL_STATIC_DRAW );

    //
    // --- Load shaders ---
    //

#if GLSL_VERSION == 130
    const char* vShader = {
       "#version 130\n"
       ""
       "in vec4  vPos;"
       ""
       "void main() {"
       "   gl_Position = vPos;"
       "}"
    };

    const char* fShader = {
       "#version 130\n"
```

```
        ""
        "out vec4  fColor;"
        ""
        "void main() {"
        "    fColor = vec4( 1, 1, 0, 1 );"
        "}"
    };
#else
     const char* vShader = {
    "attribute vec4  vPos;"
    ""
    "void main() {"
    "   gl_Position = vPos;"
    "}"
    };

    const char* fShader = {
        "void main() {"
        "    gl_FragColor = vec4( 1, 1, 0, 1 );"
        "}"
    };
#endif //  SHADER_VERSION == 130


    program = LoadProgram( vShader, fShader );

    vPos = glGetAttribLocation( program, "vPos" );

    glClearColor( 0.0, 0.0, 1.0, 1.0 );
}

//----------------------------------------------------------------------------

void
display()
{
    glClear( GL_COLOR_BUFFER_BIT );

    glUseProgram( program );

    glBindBuffer( GL_ARRAY_BUFFER, buffer );
    glVertexAttribPointer( vPos, 4, GL_FLOAT, GL_FALSE, 0, BUFFER_OFFSET(0) );
    glEnableVertexAttribArray( vPos );
    glDrawArrays( GL_TRIANGLES, 0, 3 );

    glutSwapBuffers();
}

//----------------------------------------------------------------------------

void
reshape( int width, int height )
{
    glViewport( 0, 0, width, height );
}

//----------------------------------------------------------------------------

void
keyboard( unsigned char key, int x, int y )
{
```

```
    switch( key ) {
       case 033: // Escape Key
           exit( EXIT_SUCCESS );
           break;
    }

    glutPostRedisplay();
}

//---------------------------------------------------------------------------

int
main( int argc, char* argv[] )
{
    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE );
//     glutInitContextVersion( 3, 0 );
    glutCreateWindow( argv[0] );

    glewInit();

    init();

    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutKeyboardFunc( keyboard );

    glutMainLoop();
}
```

color-draw-arrays.cxx

```
//////////////////////////////////////////////////////////////////////////
//
//  color-draw-arrays.cxx - draw a cube using glDrawArrays() with two
//    vertex attribute arrays enabled: one for positions, and the other
//    for colors.
//

#include <stdlib.h>
#include <GL/glew.h>
#ifdef MACOSX
#include <GLUT/glut.h>
#else
#include <GL/freeglut.h>
#endif

#include "LoadProgram.h"

#define BUFFER_OFFSET( offset )   ((GLvoid*) offset)

GLuint  vbo;
GLuint  program;

GLuint    vPos, vColor;
GLintptr  colorOffset;

//----------------------------------------------------------------------------

void
init()
{
    GLfloat vertices[] = {
        1.0, 0.0, 0.0,  /* Index 4 */
        1.0, 0.0, 1.0,  /* Index 5 */
        1.0, 1.0, 1.0,  /* Index 7 */

        1.0, 0.0, 0.0,  /* Index 4 */
        1.0, 1.0, 1.0,  /* Index 7 */
        1.0, 1.0, 0.0,  /* Index 6 */

        0.0, 0.0, 0.0,  /* Index 0 */
        0.0, 1.0, 0.0,  /* Index 2 */
        0.0, 1.0, 1.0,  /* Index 3 */

        0.0, 0.0, 0.0,  /* Index 0 */
        0.0, 1.0, 1.0,  /* Index 3 */
        0.0, 0.0, 1.0,  /* Index 1 */

        0.0, 1.0, 0.0,  /* Index 2 */
        1.0, 1.0, 0.0,  /* Index 6 */
        1.0, 1.0, 1.0,  /* Index 7 */

        0.0, 1.0, 0.0,  /* Index 2 */
        1.0, 1.0, 1.0,  /* Index 7 */
        0.0, 1.0, 1.0,  /* Index 3 */

        0.0, 0.0, 0.0,  /* Index 0 */
        0.0, 0.0, 1.0,  /* Index 1 */
```

```
            1.0, 0.0, 1.0,  /* Index 5 */
60
            0.0, 0.0, 0.0,  /* Index 0 */
            1.0, 0.0, 1.0,  /* Index 5 */
            1.0, 0.0, 0.0,  /* Index 4 */

65          0.0, 0.0, 0.0,  /* Index 0 */
            1.0, 0.0, 0.0,  /* Index 4 */
            1.0, 1.0, 0.0,  /* Index 6 */

            0.0, 0.0, 0.0,  /* Index 0 */
70          1.0, 1.0, 0.0,  /* Index 6 */
            0.0, 1.0, 0.0,  /* Index 2 */

            0.0, 0.0, 1.0,  /* Index 1 */
            0.0, 1.0, 1.0,  /* Index 3 */
75          1.0, 1.0, 1.0,  /* Index 7 */

            0.0, 0.0, 1.0,  /* Index 1 */
            1.0, 1.0, 1.0,  /* Index 7 */
            1.0, 0.0, 1.0,  /* Index 5 */
80      };

        GLfloat colors[] = {
            1.0, 0.0, 0.0,  /* Index 4 */
            1.0, 0.0, 1.0,  /* Index 5 */
85          1.0, 1.0, 1.0,  /* Index 7 */

            1.0, 0.0, 0.0,  /* Index 4 */
            1.0, 1.0, 1.0,  /* Index 7 */
            1.0, 1.0, 0.0,  /* Index 6 */
90
            0.0, 0.0, 0.0,  /* Index 0 */
            0.0, 1.0, 0.0,  /* Index 2 */
            0.0, 1.0, 1.0,  /* Index 3 */

95          0.0, 0.0, 0.0,  /* Index 0 */
            0.0, 1.0, 1.0,  /* Index 3 */
            0.0, 0.0, 1.0,  /* Index 1 */

            0.0, 1.0, 0.0,  /* Index 2 */
100         1.0, 1.0, 0.0,  /* Index 6 */
            1.0, 1.0, 1.0,  /* Index 7 */

            0.0, 1.0, 0.0,  /* Index 2 */
            1.0, 1.0, 1.0,  /* Index 7 */
105         0.0, 1.0, 1.0,  /* Index 3 */

            0.0, 0.0, 0.0,  /* Index 0 */
            0.0, 0.0, 1.0,  /* Index 1 */
            1.0, 0.0, 1.0,  /* Index 5 */
110
            0.0, 0.0, 0.0,  /* Index 0 */
            1.0, 0.0, 1.0,  /* Index 5 */
            1.0, 0.0, 0.0,  /* Index 4 */

115         0.0, 0.0, 0.0,  /* Index 0 */
            1.0, 0.0, 0.0,  /* Index 4 */
            1.0, 1.0, 0.0,  /* Index 6 */

            0.0, 0.0, 0.0,  /* Index 0 */
```

```
        1.0, 1.0, 0.0,  /* Index 6 */
        0.0, 1.0, 0.0,  /* Index 2 */

        0.0, 0.0, 1.0,  /* Index 1 */
        0.0, 1.0, 1.0,  /* Index 3 */
        1.0, 1.0, 1.0,  /* Index 7 */

        0.0, 0.0, 1.0,  /* Index 1 */
        1.0, 1.0, 1.0,  /* Index 7 */
        1.0, 0.0, 1.0,  /* Index 5 */
    };

    //
    // --- Load vertex data ---
    //

    glGenBuffers( 1, &vbo );
    glBindBuffer( GL_ARRAY_BUFFER, vbo );
    glBufferData( GL_ARRAY_BUFFER, sizeof(vertices) + sizeof(colors),
                  NULL, GL_STATIC_DRAW );

    colorOffset = sizeof(vertices );

    glBufferSubData( GL_ARRAY_BUFFER, 0, sizeof(vertices), vertices );
    glBufferSubData( GL_ARRAY_BUFFER, colorOffset, sizeof(colors), colors );

    //
    // --- Load shaders ---
    //

#if SHADER_VERSION == 130
    const char* vShader = {
        "#version 130\n"
        ""
        "in vec3   vPos;"
        "in vec3   vColor;"
        "out vec4  oColor;"
        ""
        "void main() {"
        "   oColor = vec4( vColor, 1 );"
        "   gl_Position = vec4( vPos, 1 );"
        "}"
    };

    const char* fShader = {
        "#version 130\n"
        ""
        "in  vec4  color;"
        "out vec4  fColor;"
        ""
        "void main() {"
        "    fColor = color;"
        "}"
    };
#else
     const char* vShader = {
        "attribute vec3  vPos;"
        "attribute vec3  vColor;"
        "varying   vec4  color;"
        ""
        "void main() {"
```

```
           "   color = vec4( vColor, 1 );"
           "   gl_Position = vec4( vPos, 1 );"
           "}"
       };

       const char* fShader = {
           "varying vec4 color;"
           ""
           "void main() {"
           "    gl_FragColor = color;"
           "}"
       };
#endif //  SHADER_VERSION == 130

    program = LoadProgram( vShader, fShader );

    vPos = glGetAttribLocation( program, "vPos" );
    vColor = glGetAttribLocation( program, "vColor" );

    glClearColor( 0.0, 0.0, 1.0, 1.0 );
}

//----------------------------------------------------------------------------

void
display()
{
    glClear( GL_COLOR_BUFFER_BIT );

    glUseProgram( program );

    glColor3f( 1, 1, 1 );

    glBindBuffer( GL_ARRAY_BUFFER, vbo );
    glVertexAttribPointer( vPos, 3, GL_FLOAT, GL_FALSE, 0, BUFFER_OFFSET(0) );
    glVertexAttribPointer( vColor, 3, GL_FLOAT, GL_FALSE, 0,
                           BUFFER_OFFSET(colorOffset) );
    glEnableVertexAttribArray( vPos );
    glEnableVertexAttribArray( vColor );

    glDrawArrays( GL_TRIANGLES, 0, 36 );

    glBindBuffer( GL_ARRAY_BUFFER, 0 );

    glutSwapBuffers();
}

//----------------------------------------------------------------------------

void
reshape( int width, int height )
{
    glViewport( 0, 0, width, height );
}

//----------------------------------------------------------------------------

void
keyboard( unsigned char key, int x, int y )
{
    switch( key ) {
```

```
            case 033: // Escape Key
                exit( EXIT_SUCCESS );
                break;
245     }

        glutPostRedisplay();
    }

250 //---------------------------------------------------------------------------

    int
    main( int argc, char* argv[] )
    {
255     glutInit( &argc, argv );
        glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE );
    //     glutInitContextVersion( 3, 0 );
        glutCreateWindow( argv[0] );

260     glewInit();

        init();

        glutDisplayFunc( display );
265     glutReshapeFunc( reshape );
        glutKeyboardFunc( keyboard );

        glutMainLoop();
    }
270
```

AOS-color-draw-arrays.cxx

```
//////////////////////////////////////////////////////////////////////////
//
//  AOS-color-draw-arrays.cxx - demonstrates using the Array-of-structures
//    (AOS) methods of storing data in vertex attributes.  The cube is
//    rendering using the glDrawArrays() method.
//

#include <stdlib.h>
#include <GL/glew.h>
#ifdef MACOSX
#include <GLUT/glut.h>
#else
#include <GL/freeglut.h>
#endif

#include "LoadProgram.h"

#define BUFFER_OFFSET( offset )   ((GLvoid*) offset)

GLuint  vbo;
GLuint  program;

GLuint    vPos, vColor;
GLintptr  vertexOffset;

struct VertexData {
    GLfloat  color[3];
    GLfloat  vertex[3];

    VertexData( GLfloat x, GLfloat y, GLfloat z ) {
       color[0]  = x;  color[1]  = y;  color[2]  = z;
       vertex[0] = x;  vertex[1] = y;  vertex[2] = z;
    }
};

//----------------------------------------------------------------------------

void
init()
{
    VertexData  vertexData[] = {
       VertexData( 1.0, 0.0, 0.0 ),  /* Index 4 */
       VertexData( 1.0, 0.0, 1.0 ),  /* Index 5 */
       VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */

       VertexData( 1.0, 0.0, 0.0 ),  /* Index 4 */
       VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */
       VertexData( 1.0, 1.0, 0.0 ),  /* Index 6 */

       VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
       VertexData( 0.0, 1.0, 0.0 ),  /* Index 2 */
       VertexData( 0.0, 1.0, 1.0 ),  /* Index 3 */

       VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
       VertexData( 0.0, 1.0, 1.0 ),  /* Index 3 */
       VertexData( 0.0, 0.0, 1.0 ),  /* Index 1 */
```

```
            VertexData( 0.0, 1.0, 0.0 ),  /* Index 2 */
            VertexData( 1.0, 1.0, 0.0 ),  /* Index 6 */
            VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */

            VertexData( 0.0, 1.0, 0.0 ),  /* Index 2 */
            VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */
            VertexData( 0.0, 1.0, 1.0 ),  /* Index 3 */

            VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
            VertexData( 0.0, 0.0, 1.0 ),  /* Index 1 */
            VertexData( 1.0, 0.0, 1.0 ),  /* Index 5 */

            VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
            VertexData( 1.0, 0.0, 1.0 ),  /* Index 5 */
            VertexData( 1.0, 0.0, 0.0 ),  /* Index 4 */

            VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
            VertexData( 1.0, 0.0, 0.0 ),  /* Index 4 */
            VertexData( 1.0, 1.0, 0.0 ),  /* Index 6 */

            VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
            VertexData( 1.0, 1.0, 0.0 ),  /* Index 6 */
            VertexData( 0.0, 1.0, 0.0 ),  /* Index 2 */

            VertexData( 0.0, 0.0, 1.0 ),  /* Index 1 */
            VertexData( 0.0, 1.0, 1.0 ),  /* Index 3 */
            VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */

            VertexData( 0.0, 0.0, 1.0 ),  /* Index 1 */
            VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */
            VertexData( 1.0, 0.0, 1.0 ),  /* Index 5 */
        };

        vertexOffset = sizeof(vertexData[0].color);

        //
        // --- Load vertex data ---
        //

        glGenBuffers( 1, &vbo );
        glBindBuffer( GL_ARRAY_BUFFER, vbo );
        glBufferData( GL_ARRAY_BUFFER, sizeof(vertexData),
                      vertexData, GL_STATIC_DRAW );

        //
        // --- Load shaders ---
        //

    #if SHADER_VERSION == 130
        const char* vShader = {
            "#version 130\n"
            ""
            "in vec3   vPos;"
            "in vec3   vColor;"
            "out vec4  oColor;"
            ""
            "void main() {"
            "   oColor = vec4( vColor, 1 );"
            "   gl_Position = vec4( vPos, 1 );"
            "}"
        };
```

```
120
        const char* fShader = {
           "#version 130\n"
           ""
           "in  vec4  color;"
125        "out vec4  fColor;"
           ""
           "void main() {"
           "    fColor = color;"
           "}"
130     };
    #else
            const char* vShader = {
           "attribute vec3  vPos;"
           "attribute vec3  vColor;"
135        "varying   vec4  color;"
           ""
           "void main() {"
           "   color = vec4( vColor, 1 );"
           "   gl_Position = vec4( vPos, 1 );"
140        "}"
        };

        const char* fShader = {
           "varying vec4 color;"
145        ""
           "void main() {"
           "    gl_FragColor = color;"
           "}"
        };
150 #endif //  SHADER_VERSION == 130

        program = LoadProgram( vShader, fShader );

        vPos = glGetAttribLocation( program, "vPos" );
155     vColor = glGetAttribLocation( program, "vColor" );

        glClearColor( 0.0, 0.0, 1.0, 1.0 );
    }

160 //----------------------------------------------------------------------------

    void
    display()
    {
165     glClear( GL_COLOR_BUFFER_BIT );

        glUseProgram( program );

        glColor3f( 1, 1, 1 );
170
        glBindBuffer( GL_ARRAY_BUFFER, vbo );
        glVertexAttribPointer( vColor, 3, GL_FLOAT, GL_FALSE,
                               sizeof(VertexData), BUFFER_OFFSET(0) );
        glVertexAttribPointer( vPos, 3, GL_FLOAT, GL_FALSE,
175                            sizeof(VertexData), BUFFER_OFFSET(vertexOffset) );
        glEnableVertexAttribArray( vPos );
        glEnableVertexAttribArray( vColor );

        glDrawArrays( GL_TRIANGLES, 0, 36 );
180
```

```
    glBindBuffer( GL_ARRAY_BUFFER, 0 );

    glutSwapBuffers();
}

//----------------------------------------------------------------------------

void
reshape( int width, int height )
{
    glViewport( 0, 0, width, height );
}

//----------------------------------------------------------------------------

void
keyboard( unsigned char key, int x, int y )
{
    switch( key ) {
       case 033: // Escape Key
           exit( EXIT_SUCCESS );
           break;
    }

    glutPostRedisplay();
}

//----------------------------------------------------------------------------

int
main( int argc, char* argv[] )
{
    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE );
//     glutInitContextVersion( 3, 0 );
    glutCreateWindow( argv[0] );

    glewInit();

    init();

    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutKeyboardFunc( keyboard );

    glutMainLoop();
}
```

Draw-elements.cxx

```
//////////////////////////////////////////////////////////////////////////
//
//  draw-elements.cxx - render a cube using glDrawElements() indexing into
//    a set of vertex attributes stored in array-of-structures (AOS) storage.
//

#include <stdlib.h>
#include <GL/glew.h>
#ifdef MACOSX
#include <GLUT/glut.h>
#else
#include <GL/freeglut.h>
#endif

#include "LoadProgram.h"

#define BUFFER_OFFSET( offset )   ((GLvoid*) offset)

enum { Vertices, Indices, NumBuffers };

GLuint  buffers[NumBuffers];
GLuint  program;

GLuint    vPos, vColor;
GLintptr  vertexOffset;

struct VertexData {
    GLfloat  color[3];
    GLfloat  vertex[3];

    VertexData( GLfloat x, GLfloat y, GLfloat z ) {
       color[0]  = x;  color[1]  = y;  color[2]  = z;
       vertex[0] = x;  vertex[1] = y;  vertex[2] = z;
    }
};

//----------------------------------------------------------------------------

void
init()
{
    VertexData  vertexData[] = {
       VertexData( 0.0, 0.0, 0.0 ),  /* Index 0 */
       VertexData( 0.0, 0.0, 1.0 ),  /* Index 1 */
       VertexData( 0.0, 1.0, 0.0 ),  /* Index 2 */
       VertexData( 0.0, 1.0, 1.0 ),  /* Index 3 */
       VertexData( 1.0, 0.0, 0.0 ),  /* Index 4 */
       VertexData( 1.0, 0.0, 1.0 ),  /* Index 5 */
       VertexData( 1.0, 1.0, 0.0 ),  /* Index 6 */
       VertexData( 1.0, 1.0, 1.0 ),  /* Index 7 */
    };

    GLubyte indices[] = {
       4, 5, 7, // +X face
       4, 7, 6,
       0, 2, 3, // -X face
       0, 3, 1,
       2, 6, 7, // +Y face
```

```
            2, 7, 3,
            0, 1, 5, // -Y face
            0, 5, 4,
            0, 4, 6, // +Z face
            0, 6, 2,
            1, 3, 7, // -Z face
            1, 7, 5
        };

        vertexOffset = sizeof(vertexData[0].color);

        //
        // --- Load vertex data ---
        //

        glGenBuffers( NumBuffers, buffers );
        glBindBuffer( GL_ARRAY_BUFFER, buffers[Vertices] );
        glBufferData( GL_ARRAY_BUFFER, sizeof(vertexData),
                      vertexData, GL_STATIC_DRAW );

        glBindBuffer( GL_ELEMENT_ARRAY_BUFFER, buffers[Indices] );
        glBufferData( GL_ELEMENT_ARRAY_BUFFER, sizeof(indices),
                      indices, GL_STATIC_DRAW );

        //
        // --- Load shaders ---
        //

    #if SHADER_VERSION == 130
        const char* vShader = {
            "#version 130\n"
            ""
            "in vec3   vPos;"
            "in vec3   vColor;"
            "out vec4  oColor;"
            ""
            "void main() {"
            "   oColor = vec4( vColor, 1 );"
            "   gl_Position = vec4( vPos, 1 );"
            "}"
        };

        const char* fShader = {
            "#version 130\n"
            ""
            "in  vec4  color;"
            "out vec4  fColor;"
            ""
            "void main() {"
            "    fColor = color;"
            "}"
        };
    #else
         const char* vShader = {
            "attribute vec3  vPos;"
            "attribute vec3  vColor;"
            "varying   vec4  color;"
            ""
            "void main() {"
            "   color = vec4( vColor, 1 );"
            "   gl_Position = vec4( vPos, 1 );"
```

```
        "}"
    };

    const char* fShader = {
        "varying vec4 color;"
        ""
        "void main() {"
        "    gl_FragColor = color;"
        "}"
    };
#endif //  SHADER_VERSION == 130

    program = LoadProgram( vShader, fShader );

    vPos = glGetAttribLocation( program, "vPos" );
    vColor = glGetAttribLocation( program, "vColor" );

    glClearColor( 0.0, 0.0, 1.0, 1.0 );
}

//----------------------------------------------------------------------------

void
display()
{
    glClear( GL_COLOR_BUFFER_BIT );

    glUseProgram( program );

    glColor3f( 1, 1, 1 );

    glBindBuffer( GL_ARRAY_BUFFER, buffers[Vertices] );
    glVertexAttribPointer( vColor, 3, GL_FLOAT, GL_FALSE,
                           sizeof(VertexData), BUFFER_OFFSET(0) );
    glVertexAttribPointer( vPos, 3, GL_FLOAT, GL_FALSE,
                           sizeof(VertexData), BUFFER_OFFSET(vertexOffset) );
    glEnableVertexAttribArray( vPos );
    glEnableVertexAttribArray( vColor );

    glBindBuffer( GL_ELEMENT_ARRAY_BUFFER, buffers[Indices] );
    glDrawElements( GL_TRIANGLES, 36, GL_UNSIGNED_BYTE, BUFFER_OFFSET(0) );

    glBindBuffer( GL_ARRAY_BUFFER, 0 );
    glBindBuffer( GL_ELEMENT_ARRAY_BUFFER, 0 );

    glutSwapBuffers();
}

//----------------------------------------------------------------------------

void
reshape( int width, int height )
{
    glViewport( 0, 0, width, height );
}

//----------------------------------------------------------------------------

void
keyboard( unsigned char key, int x, int y )
{
```

```
    switch( key ) {
       case 033: // Escape Key
           exit( EXIT_SUCCESS );
           break;
    }

    glutPostRedisplay();
}

//---------------------------------------------------------------------------

int
main( int argc, char* argv[] )
{
    glutInit( &argc, argv );
    glutInitDisplayMode( GLUT_RGBA | GLUT_DOUBLE );
//     glutInitContextVersion( 3, 0 );
    glutCreateWindow( argv[0] );

    glewInit();

    init();

    glutDisplayFunc( display );
    glutReshapeFunc( reshape );
    glutKeyboardFunc( keyboard );

    glutMainLoop();
}
```

LoadProgram.h

```
////////////////////////////////////////////////////////////////////////////
//
//  --- LoadProgram.h ---
//
////////////////////////////////////////////////////////////////////////////

#ifndef __LOADPROGRAM_H__
#define __LOADPROGRAM_H__

//----------------------------------------------------------------------------

#ifdef __cplusplus
extern "C" {
#endif /* __cplusplus */

extern GLuint LoadProgram( const char*, const char* );
extern GLuint LoadTransformFeedbackShader( const char*, GLsizei,
                                           const char** );

#ifdef __cplusplus
};
#endif /* __cplusplus */

//----------------------------------------------------------------------------

#endif // !__LOADPROGRAM_H__
```

LoadProgram.c

```
////////////////////////////////////////////////////////////////////////
//
//  --- LoadProgram.c ---
//
////////////////////////////////////////////////////////////////////////

#include <stdio.h>
#include <stdlib.h>
#ifdef MACOS
#include <OpenGL/OpenGL.h>
#else
#include <GL/glew.h>
#endif
#include "CheckError.h"

/*--------------------------------------------------------------------*/

GLuint
LoadProgram( const char* vShader, const char* fShader )
{
    GLuint  shader, program;
    GLint   completed;

    program = glCreateProgram();

    /*----------------------------------------------------------------
    **
    **  --- Load and compile the vertex shader ---
    */

    if ( vShader != NULL ) {
       shader = glCreateShader( GL_VERTEX_SHADER );
       glShaderSource( shader, 1, &vShader, NULL );
       glCompileShader( shader );
       glGetShaderiv( shader, GL_COMPILE_STATUS, &completed );

       if ( !completed ) {
           GLint  len;
           char*  msg;

           glGetShaderiv( shader, GL_INFO_LOG_LENGTH, &len );
           msg = (char*) malloc( len );
           glGetShaderInfoLog( shader, len, &len, msg );
           fprintf( stderr, "Vertex shader compilation failure:\n%s\n", msg );
           free( msg );

           glDeleteProgram( program );

           exit( EXIT_FAILURE );
       }

       glAttachShader( program, shader );

       CheckError();
    }

    /*----------------------------------------------------------------
    **
```

```
        **  --- Load and compile the fragment shader ---
60      */

        if ( fShader != NULL ) {
           shader = glCreateShader( GL_FRAGMENT_SHADER );
           glShaderSource( shader, 1, &fShader, NULL );
65         glCompileShader( shader );
           glGetShaderiv( shader, GL_COMPILE_STATUS, &completed );

           if ( !completed ) {
               GLint  len;
70             char*  msg;

               glGetShaderiv( shader, GL_INFO_LOG_LENGTH, &len );
               msg = (char*) malloc( len );
               glGetShaderInfoLog( shader, len, &len, msg );
75             fprintf( stderr, "Fragment shader compilation failure:\n%s\n",
                        msg );
               free( msg );

               glDeleteProgram( program );
80
               exit( EXIT_FAILURE );
           }

           glAttachShader( program, shader );
85
           CheckError();
        }

        /*-------------------------------------------------------------------
90      **
        **  --- Link program ---
        */

        glLinkProgram( program );
95      glGetProgramiv( program, GL_LINK_STATUS, &completed );

        if ( !completed ) {
           GLint  len;
           char*  msg;
100
           glGetProgramiv( program, GL_INFO_LOG_LENGTH, &len );
           msg = (char*) malloc( len );
           glGetProgramInfoLog( program, len, &len, msg );
           fprintf( stderr, "Program link failure:\n%s\n", msg );
105        free( msg );

           glDeleteProgram( program );

           exit( EXIT_FAILURE );
110     }

        CheckError();

        return program;
115  }
```