Chapter 4

Introduction to OpenGL Programming

Overview

This chapter is supposed to provide a brief overview of some of the most important features of OpenGL. It will include details that go beyond the scope of this class. Some of the topics addressed will be covered in Computer Graphics II, such as lighting, depth buffer, texture mapping, etc. Some topics will be a repeat what was discussed before but in more detail to help you develop 3-D applications based on OpenGL.

Overview

The topics of this chapter are:

- General OpenGL Introduction
- Rendering Primitives
- Rendering Modes
- Lighting
- Texture Mapping
- Additional Rendering Attributes
- Imaging

OpenGL and GLUT Overview

OpenGL and GLUT Overview

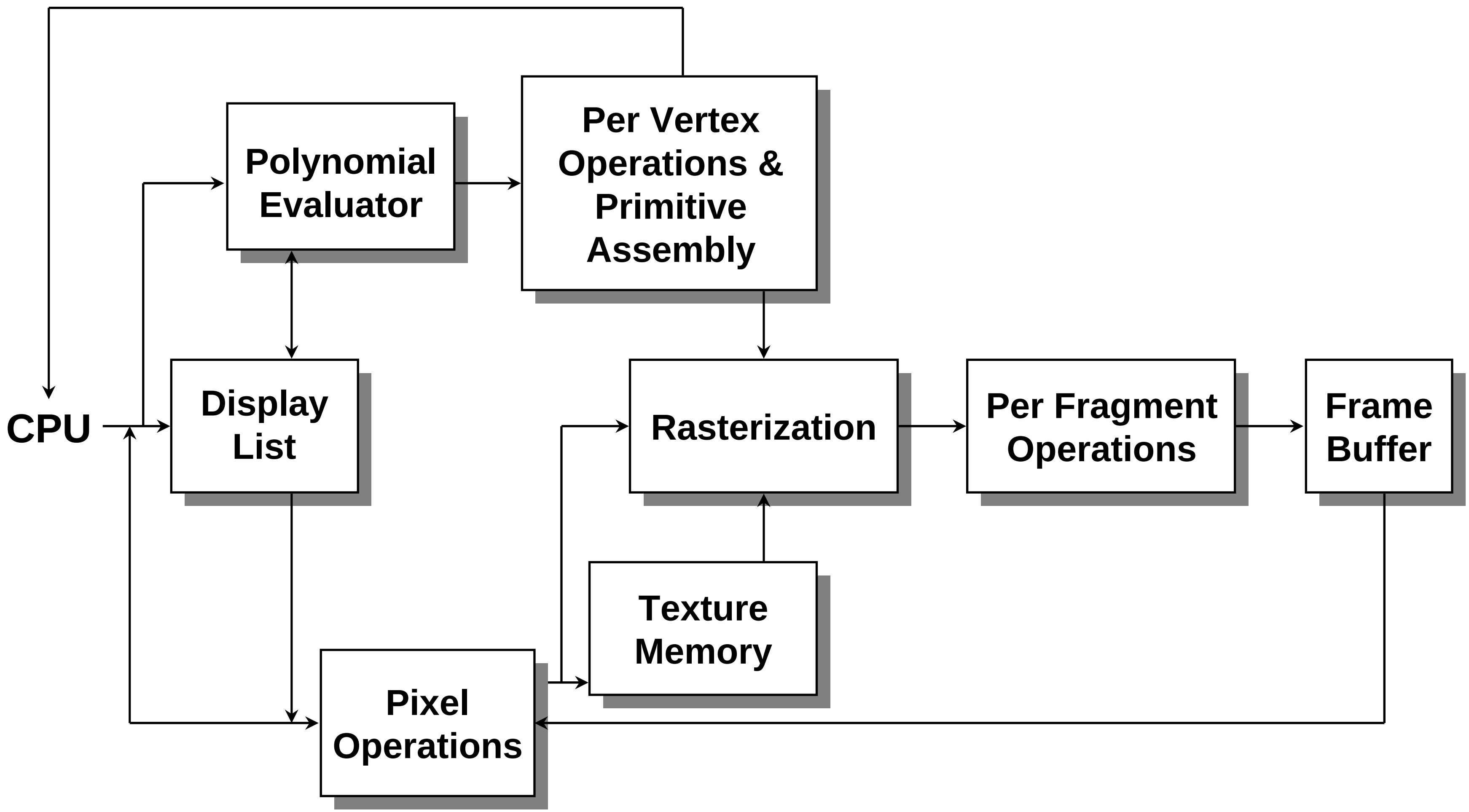
- What is OpenGL & what can it do for me?
- OpenGL in windowing systems
- Why GLUT
- A GLUT program template

What Is OpenGL?

Graphics rendering API

- high-quality color images composed of geometric and image primitives
- window system independent
- operating system independent

OpenGL Architecture



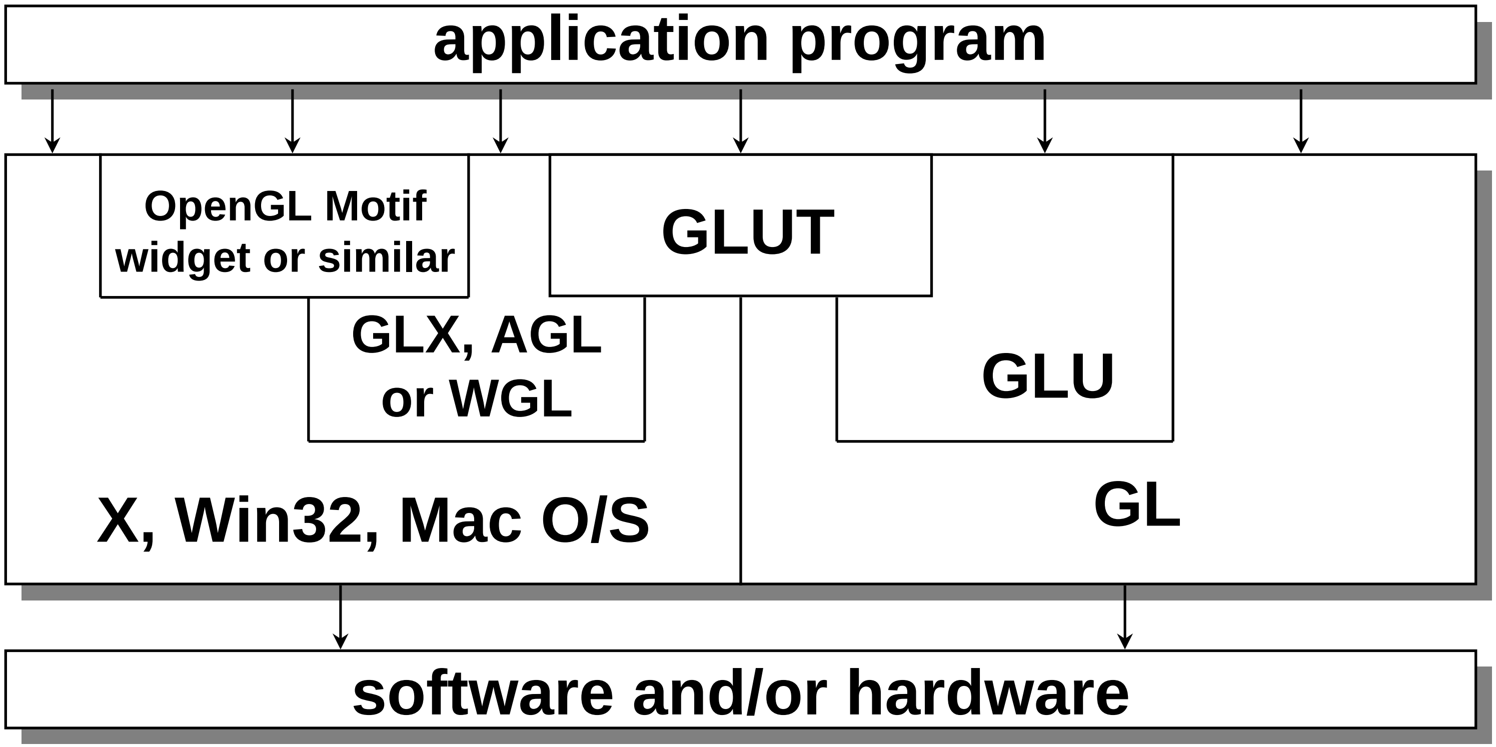
OpenGL as a Renderer

- Geometric primitives
  - points, lines and polygons
- Image Primitives
  - images and bitmaps
  - separate pipeline for images and geometry
    - linked through texture mapping
- Rendering depends on state
  - colors, materials, light sources, etc.

Related APIs

- AGL, GLX, WGL
  - glue between OpenGL and windowing systems
- GLU (OpenGL Utility Library)
  - part of OpenGL
  - NURBS, tessellators, quadric shapes, etc.
- GLUT (OpenGL Utility Toolkit)
  - portable windowing API
  - not officially part of OpenGL

OpenGL and Related APIs



Preliminaries

Headers Files

```
#include <GL/gl.h>
#include <GL/glu.h>
#include <GL/glut.h>
```

Libraries

libGL, libGLU, libglut

Enumerated Types

OpenGL defines numerous types for compatibility

GLfloat, GLint, GLenum, etc.

GLUT Basics

- Application Structure
  - Configure and open window
  - Initialize OpenGL state
  - Register input callback functions
    - render
    - resize
    - input: keyboard, mouse, etc.
  - Enter event processing loop

Sample Program

```
void main( int argc, char** argv )
{
  int mode = GLUT_RGB|GLUT_DOUBLE;
  glutInitDisplayMode( mode );
  glutCreateWindow( argv[0] );
  init();
  glutDisplayFunc( display );
  glutReshapeFunc( resize );
  glutKeyboardFunc( key );
  glutIdleFunc( idle );
  glutMainLoop();
}
```

OpenGL Initialization

Set up whatever state you're going to use

```
void init( void )
{
  glClearColor( 0.0, 0.0, 0.0, 1.0 );
  glClearDepth( 1.0 );

  glEnable( GL_LIGHT0 );
  glEnable( GL_LIGHTING );
  glEnable( GL_DEPTH_TEST );
}
```

GLUT Callback Functions

Routine to call when something happens

- window resize or redraw
- user input
- animation

"Register" callbacks with GLUT

- **glutDisplayFunc(** ***display*** **);**
- **glutIdleFunc(** ***idle*** **);**
- **glutKeyboardFunc(** ***keyboard*** **);**

Rendering Callback

Do all of your drawing here

```
glutDisplayFunc( display );
```

```
void display( void )
{
  glClear( GL_COLOR_BUFFER_BIT );
  glBegin( GL_TRIANGLE_STRIP );
    glVertex3fv( v[0] );
    glVertex3fv( v[1] );
    glVertex3fv( v[2] );
    glVertex3fv( v[3] );
  glEnd();
  glutSwapBuffers();
}
```

Idle Callbacks

Use for animation and continuous update

```
glutIdleFunc( idle );
```

```
void idle( void )
{
  t += dt;
  glutPostRedisplay();
}
```

User Input Callbacks

Process user input

```
glutKeyboardFunc( keyboard );
```

```
void keyboard( char key, int x, int y )
{
  switch( key ) {
    case 'q' : case 'Q' :
      exit( EXIT_SUCCESS );
      break;

    case 'r' : case 'R' :
      rotate = GL_TRUE;
      break;
  }
}
```

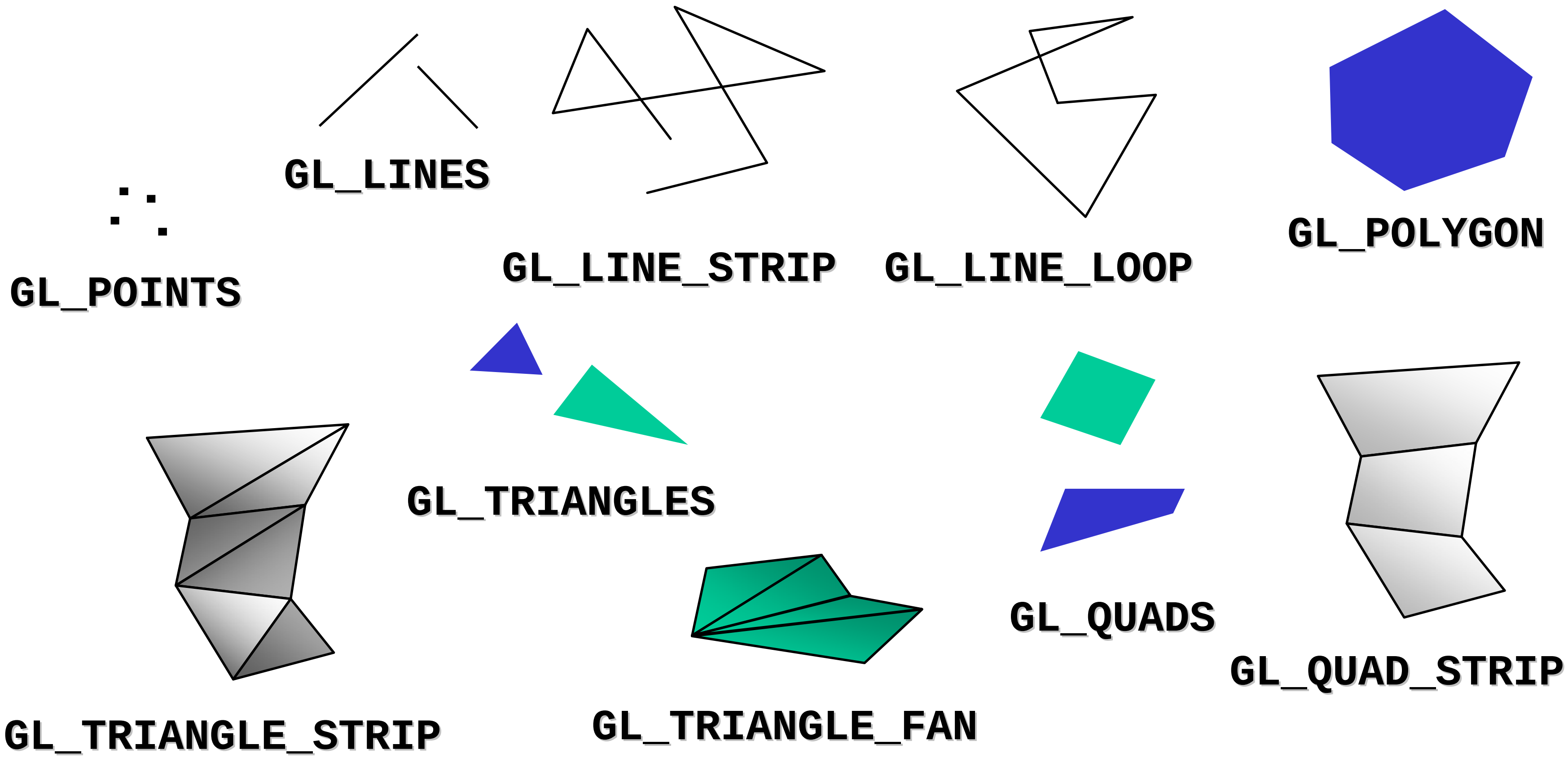
Elementary Rendering

Elementary Rendering

- Geometric Primitives
- Managing OpenGL State
- OpenGL Buffers

OpenGL Geometric Primitives

All geometric primitives are specified by vertices



Simple Example

```
void drawRhombus( GLfloat color[] )
{
    glBegin( GL_QUADS );
    glColor3fv( color );
    glVertex2f( 0.0, 0.0 );
    glVertex2f( 1.0, 0.0 );
    glVertex2f( 1.4, 1.118 );
    glVertex2f( 0.4, 1.118 );
    glEnd();
}
```

OpenGL Command Formats

glVertex3fv(*v*)

Number of components

```
2 - (x,y)
3 - (x,y,z)
4 - (x,y,z,w)
```

Data Type

```
b  - byte
ub - unsigned byte
s  - short
us - unsigned short
i  - int
ui - unsigned int
f  - float
d  - double
```

Vector

omit "v" for scalar form

```
glVertex2f( x, y )
```

Specifying Geometric Primitives

Primitives are specified using

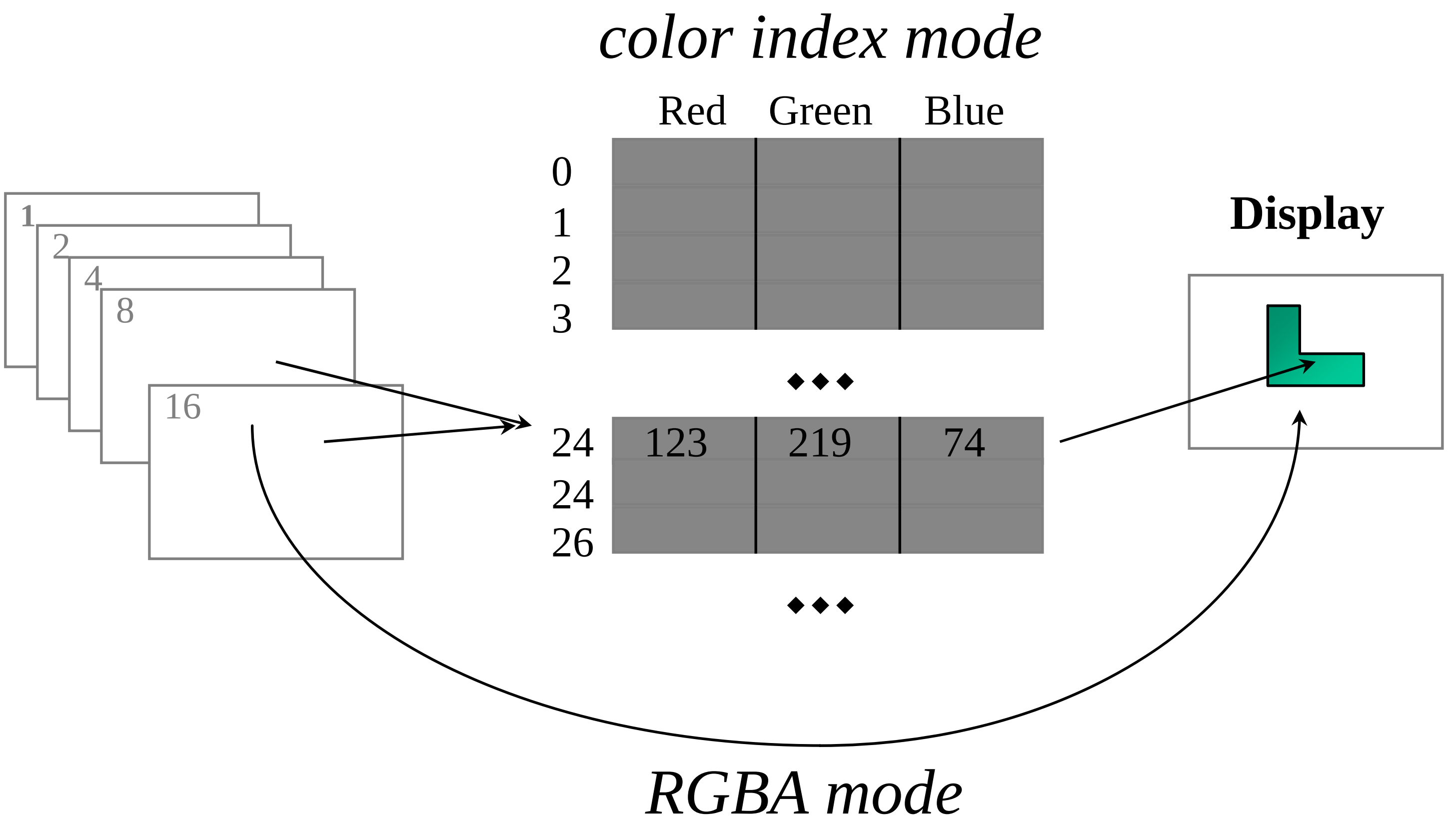
```
glBegin( primType );
glEnd();
```

primType determines how vertices are combined

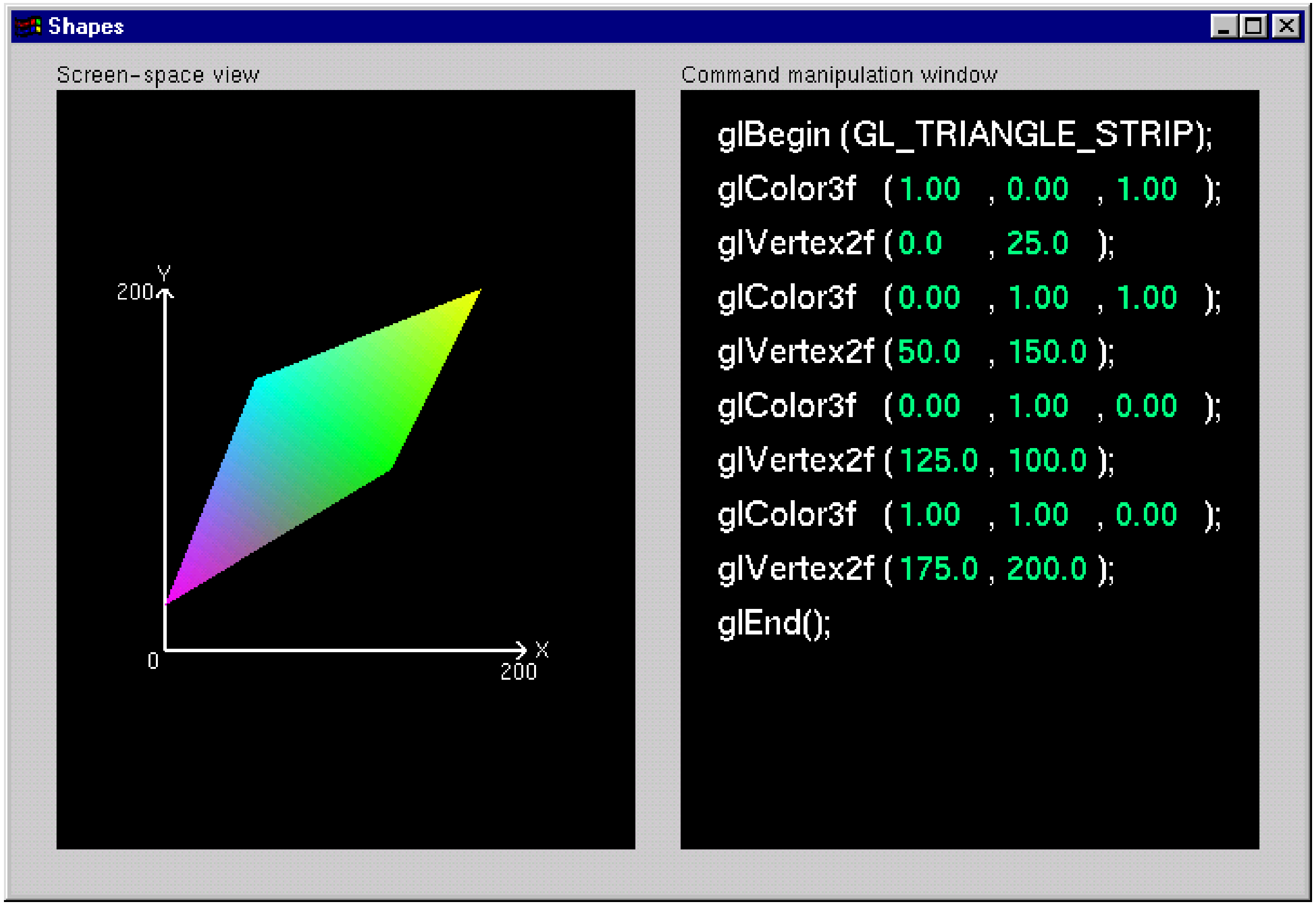
```
GLfloat red, greed, blue;
Glfloat coords[3];
glBegin( primType );
for ( i = 0; i < nVerts; ++i ) {
  glColor3f( red, green, blue );
  glVertex3fv( coords );
}
glEnd();
```

OpenGL Color Models

RGBA or Color Index



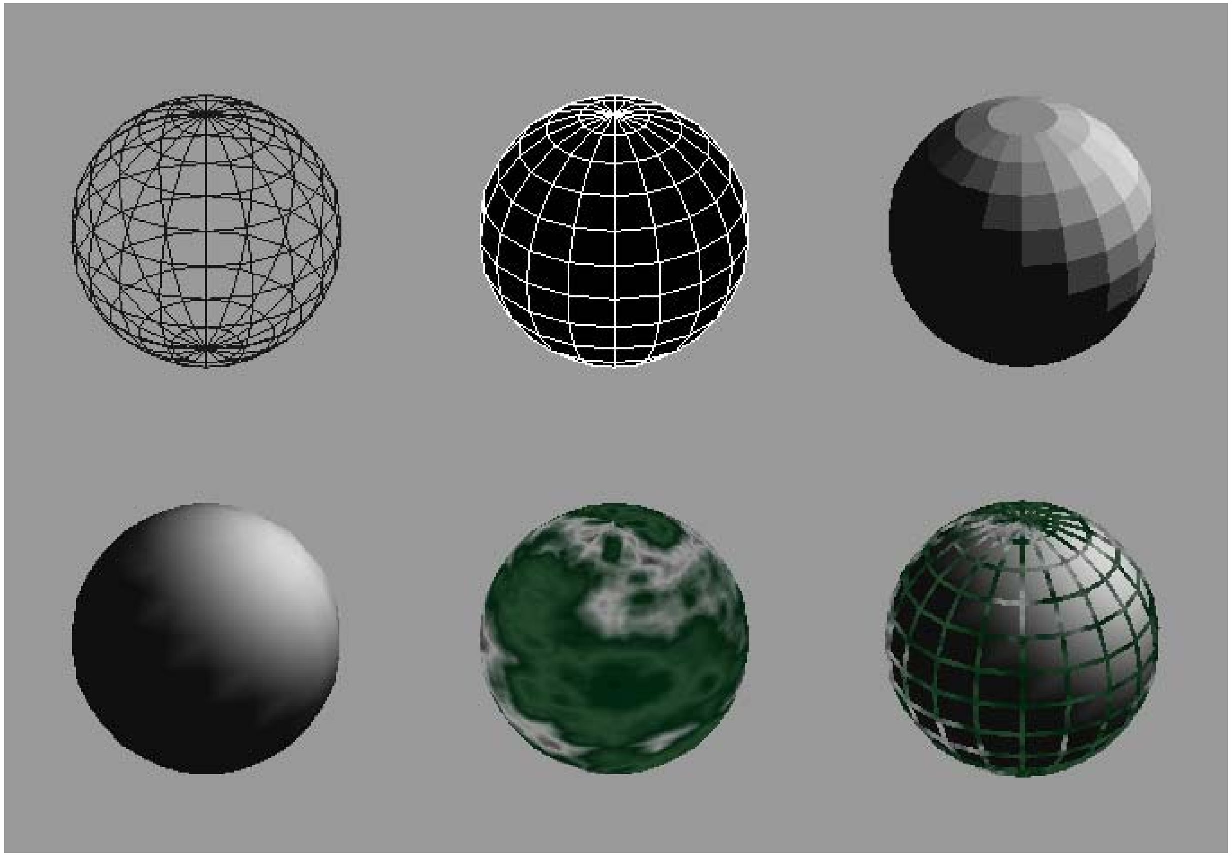
Shapes Tutorial



http://www.xmission.com/~nate/tutors.html

Controlling Rendering Appearance

From Wireframe to Texture Mapped



OpenGL's State Machine

All rendering attributes are encapsulated in the OpenGL State

- rendering styles
- shading
- lighting
- texture mapping

Manipulating OpenGL State

Appearance is controlled by current state

```
for each ( primitive to render ) {
    update OpenGL state if necessary
    render primitive
}
```

Manipulating vertex attributes is most common way to manipulate state

```
glColor*() / glIndex*()
glNormal*()
glTexCoord*()
```

Controlling current state

Setting State

```
glPointSize( size );
glLineStipple( repeat, pattern );
glShadeModel( GL_SMOOTH );
```

Enabling Features

```
glEnable( GL_LIGHTING );
glDisable( GL_TEXTURE_2D );
```

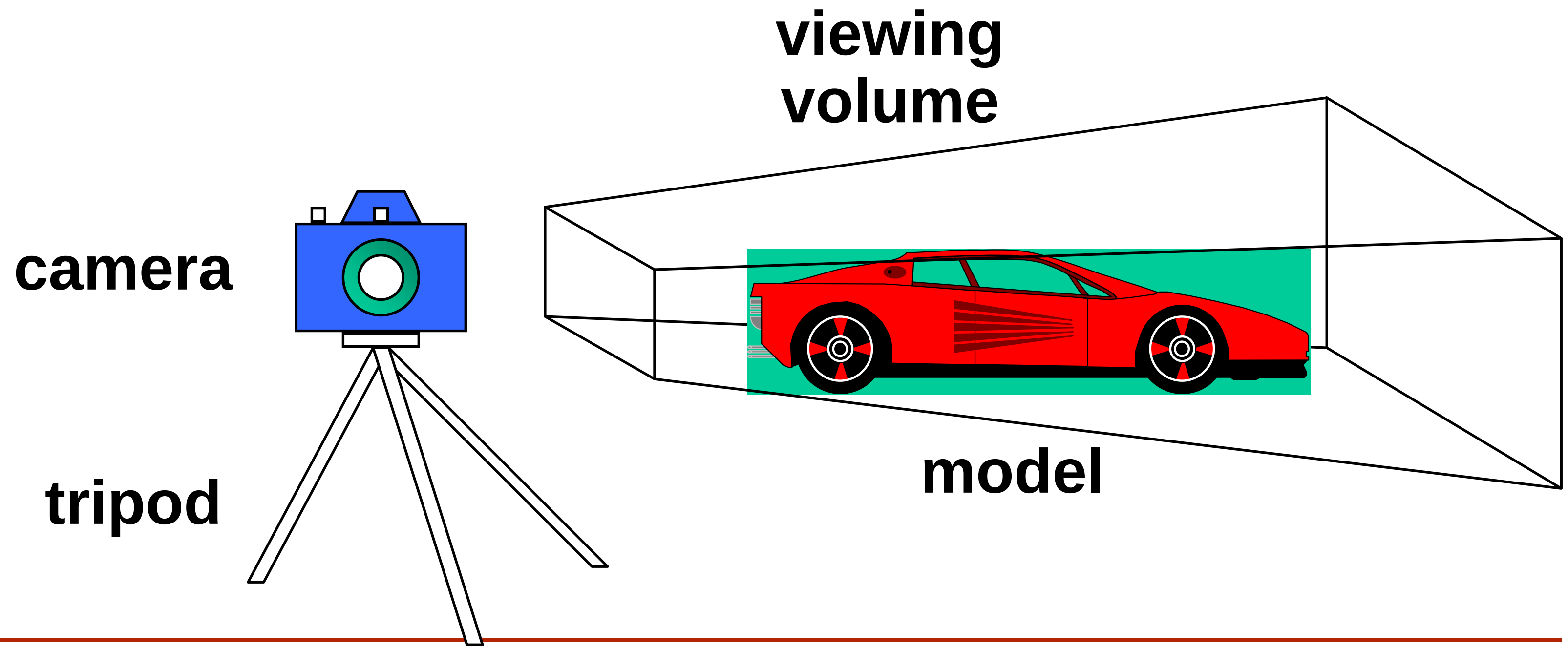
Transformations

Transformations in OpenGL

- Modeling
- Viewing
  - orient camera
  - projection
- Animation
- Map to screen

Camera Analogy

3D is just like taking a photograph (lots of photographs!)



Camera Analogy and Transformations

- Projection transformations
  - adjust the lens of the camera
- Viewing transformations
  - tripod–define position and orientation of the viewing volume in the world
- Modeling transformations
  - moving the model
- Viewport transformations
  - enlarge or reduce the physical photograph

Coordinate Systems and Transformations

- Steps in Forming an Image
  - specify geometry (world coordinates)
  - specify camera (camera coordinates)
  - project (window coordinates)
  - map to viewport (screen coordinates)
- Each step uses transformations
- Every transformation is equivalent to a change in coordinate systems (frames)

Affine Transformations

- Want transformations which preserve geometry
  - lines, polygons, quadrics
- Affine = line preserving
  - Rotation, translation, scaling
  - Projection
  - Concatenation (composition)

Homogeneous Coordinates

Each vertex is a column vector

$$\vec{v} = \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$

w is usually 1.0

all operations are matrix multiplications

directions (directed line segments) can be represented with $w = 0.0$

3D Transformations

A vertex is transformed by 4 x 4 matrices

- all affine operations are matrix multiplications
- all matrices are stored column-major in OpenGL
- matrices are always post-multiplied
- product of matrix and vector is $\mathbf{M}\vec{v}$

$$\mathbf{M} = \begin{bmatrix} m_0 & m_4 & m_8 & m_{12} \\ m_1 & m_5 & m_9 & m_{13} \\ m_2 & m_6 & m_{10} & m_{14} \\ m_3 & m_7 & m_{11} & m_{15} \end{bmatrix}$$

Specifying Transformations

Programmer has two styles of specifying transformations

- specify matrices (`glLoadMatrix, glMultMatrix`)
- specify operation (`glRotate, glOrtho`)

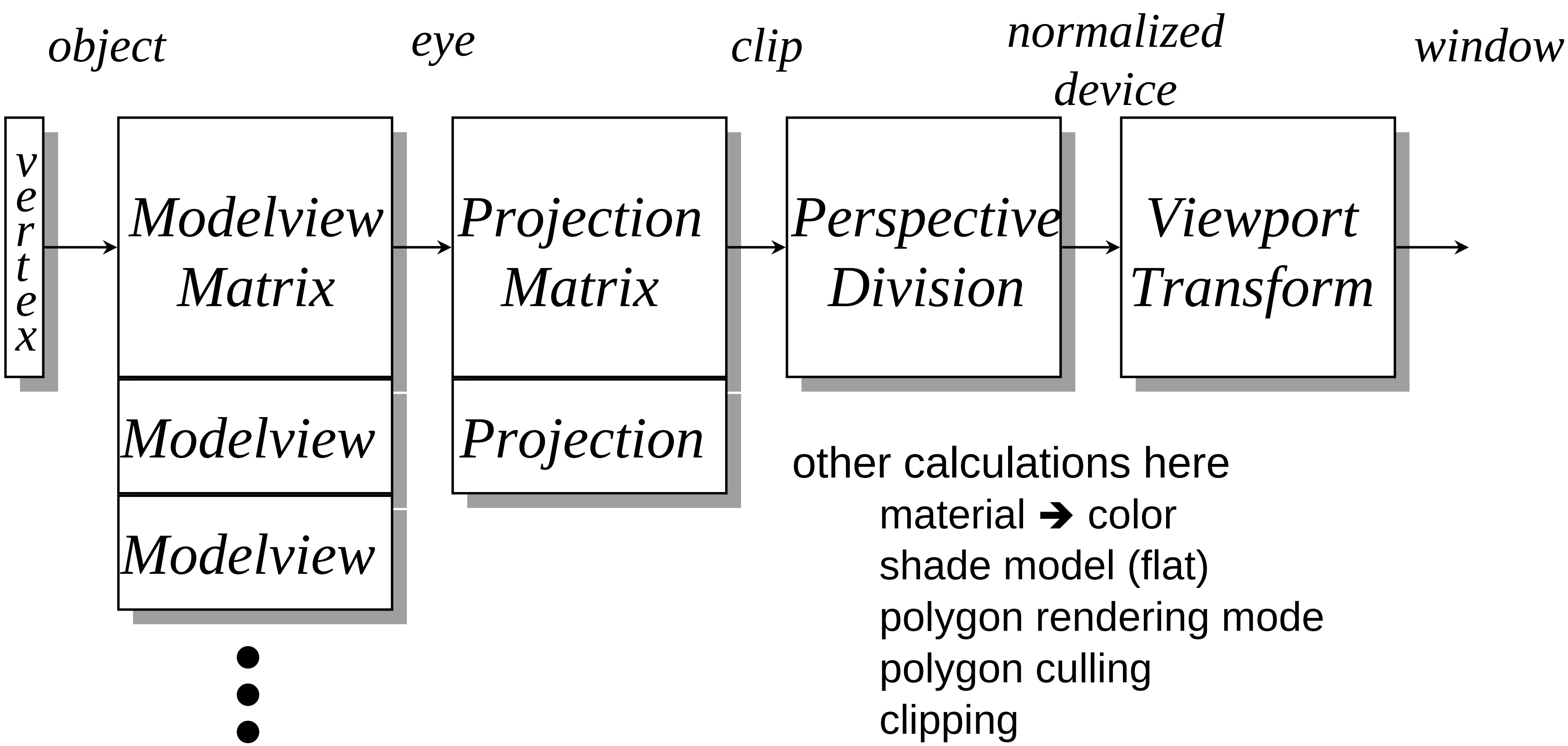
Programmer does not have to remember the exact matrices

- check appendix of Red Book (Programming Guide)

Programming Transformations

- Prior to rendering, view, locate, and orient:
  - eye/camera position
  - 3D geometry
- Manage the matrices
  - including matrix stack
- Combine (composite) transformations

Transformation Pipeline



other calculations here
- material ➔ color
- shade model (flat)
- polygon rendering mode
- polygon culling
- clipping

Matrix Operations

Specify Current Matrix Stack

```
glMatrixMode( GL_MODELVIEW or GL_PROJECTION )
```

Other Matrix or Stack Operations

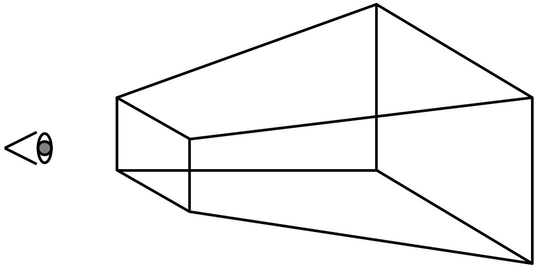
```
glLoadIdentity()      glPushMatrix()
                    glPopMatrix()
```

Viewport

- usually same as window size
- viewport aspect ratio should be same as projection transformation or resulting image may be distorted

```
glViewport( x, y, width, height )
```

Projection Transformation



Shape of viewing frustum

Perspective projection

gluPerspective(***fovy, aspect, zNear, zFar*** **)**

glFrustum(***left, right, bottom, top, zNear, zFar*** **)**

Orthographic parallel projection

glOrtho(***left, right, bottom, top, zNear, zFar*** **)**

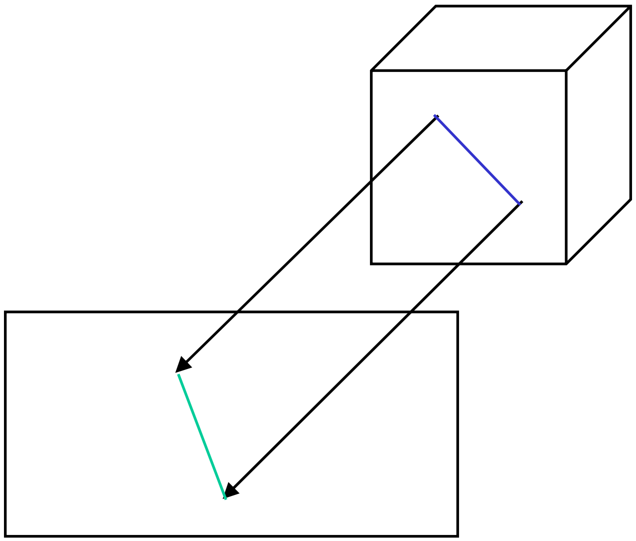
gluOrtho2D(***left, right, bottom, top*** **)**

- calls **glOrtho** with z values near zero

Applying Projection Transformations

Typical use (orthographic projection)

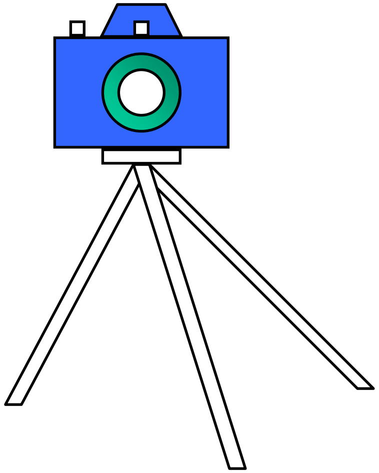
```
glMatrixMode( GL_PROJECTION );
glLoadIdentity();
glOrtho( left, right, bottom, top, zNear, zFar );
```



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

tripod

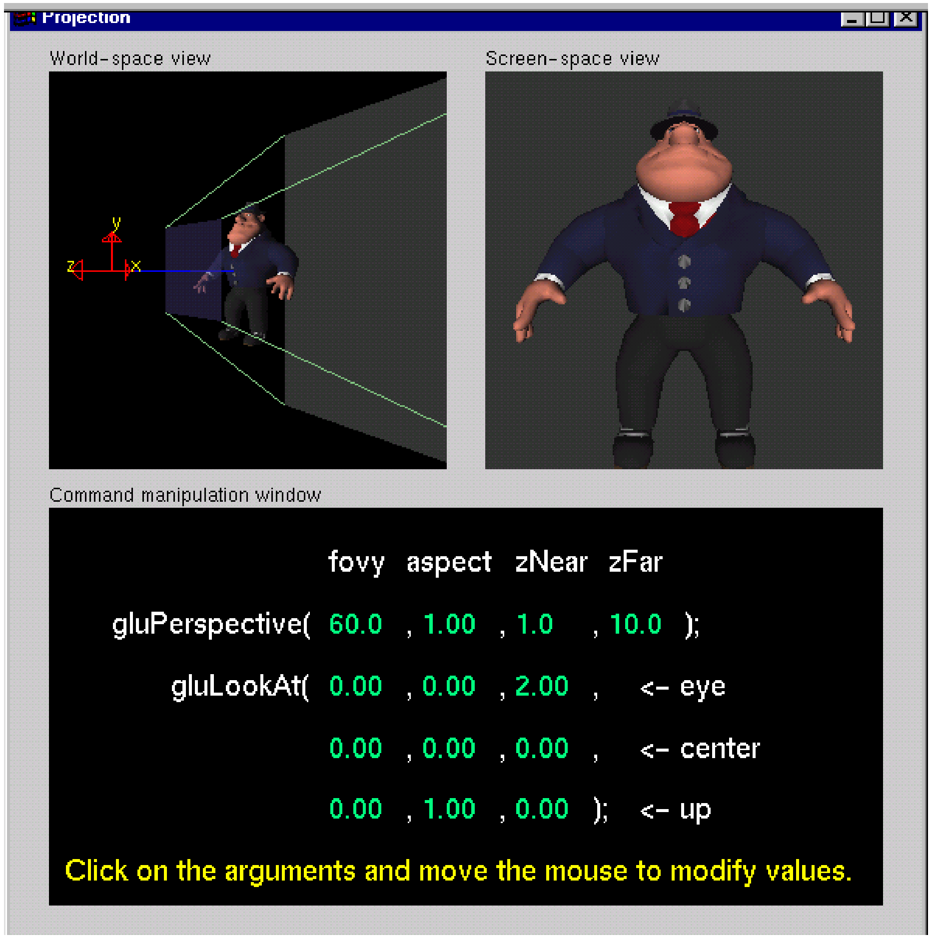


```
gluLookAt( eyex, eyey, eyez,
           aimx, aimy, aimz,
           upx, upy, upz )
```

(i.e. $eye_x, eye_y, eye_z, aim_x, aim_y, aim_z, up_x, up_y, up_z$)

  - up vector determines unique orientation
  - careful of degenerate positions

Projection Tutorial



http://www.xmission.com/~nate/tutors.html

Modeling Transformations

Move object

```
glTranslate{fd}( x, y, z )
```

Rotate object around arbitrary axis

```
glRotate{fd}( angle, x, y, z )
```

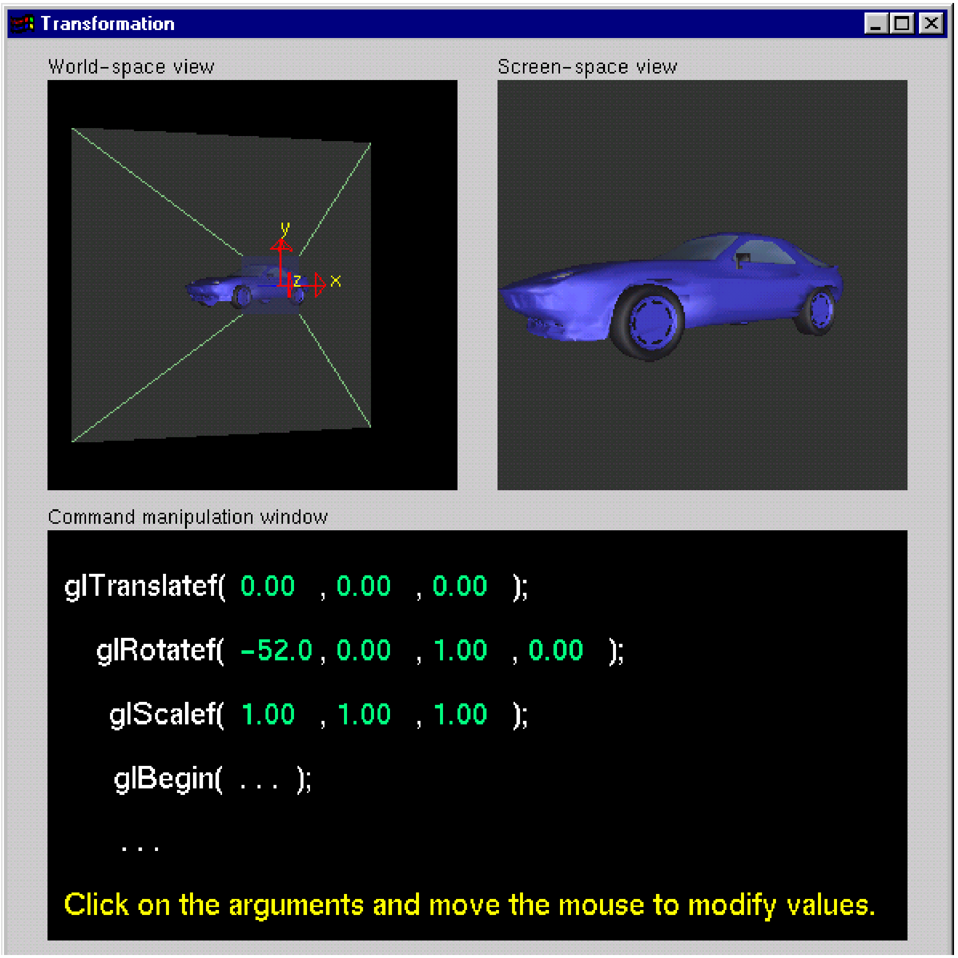
$$\begin{pmatrix} x & y & z \end{pmatrix}$$

- angle is in degrees

Dilate (stretch or shrink) or mirror object

```
glScale{fd}( x, y, z )
```

Transformation Tutorial



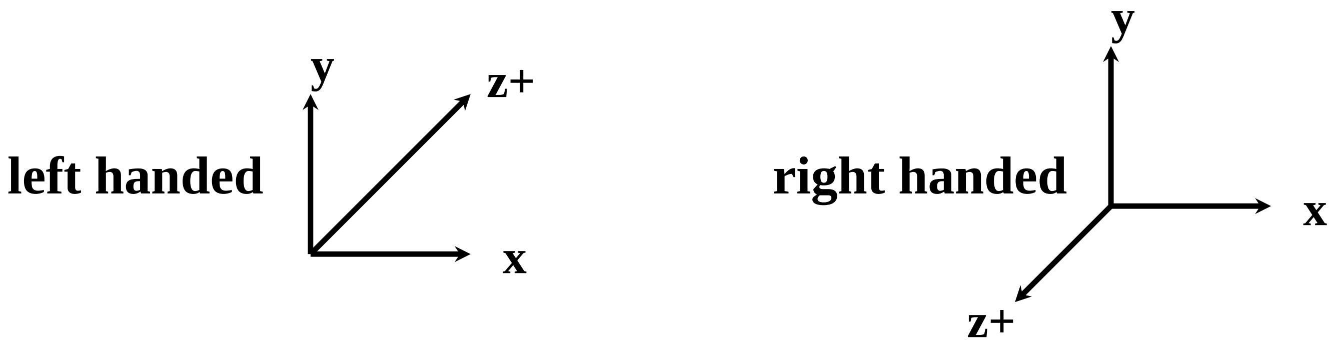
http://www.xmission.com/~nate/tutors.html

Connection: Viewing and Modeling

- Moving camera is equivalent to moving every object in the world towards a stationary camera
- Viewing transformations are equivalent to several modeling transformations
  - **`gluLookAt()`** has its own command
  - can make your own *polar view* or *pilot view*

Projection is left handed

- Projection transformations (`gluPerspective, glOrtho`) are left handed
  - think of ***zNear*** and ***zFar*** as distance from view point
- Everything else is right handed, including the vertexes to be rendered



Common Transformation Usage

- 3 examples of `resize()` routine
  - restate projection & viewing transformations
- Usually called when window resized
- Registered as callback for `glutReshapeFunc()`

resize(): Perspective & LookAt

```
void resize( int w, int h )
{
   glViewport( 0, 0, (GLsizei) w,
               (GLsizei) h );
   glMatrixMode( GL_PROJECTION );
   glLoadIdentity();
   gluPerspective( 64.0, (GLfloat) w / h,
                   1.0, 100.0 );
   glMatrixMode( GL_MODELVIEW );
   glLoadIdentity();
   gluLookAt( 0.0, 0.0, 4.0,
              0.0, 0.0, 0.0,
              0.0, 1.0, 0.0 );
}
```

`resize()`: Perspective & Translate

Same effect as previous LookAt

```
void resize( int w, int h )
{
   glViewport( 0, 0, (GLsizei) w, (GLsizei) h );
   glMatrixMode( GL_PROJECTION );
   glLoadIdentity();
   gluPerspective( 64.0, (GLfloat) w/h,
                   1.0, 100.0 );
   glMatrixMode( GL_MODELVIEW );
   glLoadIdentity();
   glTranslatef( 0.0, 0.0, -4.0 );
}
```

`resize()`: Ortho (part 1)

```
void resize( int width, int height )
{
   GLdouble aspect =
     (GLdouble) width / height;
   GLdouble left = -2.4, right = 2.4;
   GLdouble bottom = -2.4, top = 2.4;
   glViewport( 0, 0, (GLsizei) w,
                    (GLsizei) h );
   glMatrixMode( GL_PROJECTION );
   glLoadIdentity();
```

… continued …

resize(): Ortho (part 2)

```
if ( aspect < 1.0 ) {
      left /= aspect;
      right /= aspect;
  } else {
      bottom *= aspect;
      top *= aspect;
  }
  glOrtho( left, right,
           bottom, top,
           near, far );
  glMatrixMode( GL_MODELVIEW );
  glLoadIdentity();
}
```

Compositing Modeling Transformations

- Problem 1: hierarchical objects
  - one position depends upon a previous position
  - robot arm or hand; sub-assemblies
- Solution 1: moving local coordinate system
  - modeling transformations move coordinate system
  - post-multiply column-major matrices
  - OpenGL post-multiplies matrices

Compositing Modeling Transformations

- Problem 2: objects move relative to absolute world origin
  - my object rotates around the wrong origin
    - make it spin around its center or something else
- Solution 2: fixed coordinate system
  - modeling transformations move objects around fixed coordinate system
  - pre-multiply column-major matrices
  - OpenGL post-multiplies matrices
  - must <u>reverse order of operations</u> to achieve desired effect

Additional Clipping Planes

- At least 6 more clipping planes available
- Good for cross-sections
- Modelview matrix moves clipping plane
- $Ax + By + Cz + D < 0$ clipped

```
glEnable( GL_CLIP_PLANEi )
glClipPlane( GL_CLIP_PLANEi, GLdouble* coeff )
```

Reversing Coordinate Projection

Screen space back to world space

```
glGetIntegerv( GL_VIEWPORT, GLint viewport[4] )

glGetDoublev( GL_MODELVIEW_MATRIX, GLdouble mvmatrix[16] )

glGetDoublev( GL_PROJECTION_MATRIX,
              GLdouble projmatrix[16] )

gluUnProject( GLdouble winx, winy, winz,
              mvmatrix[16], projmatrix[16],
              GLint viewport[4],
              GLdouble *objx, *objy, *objz )
```

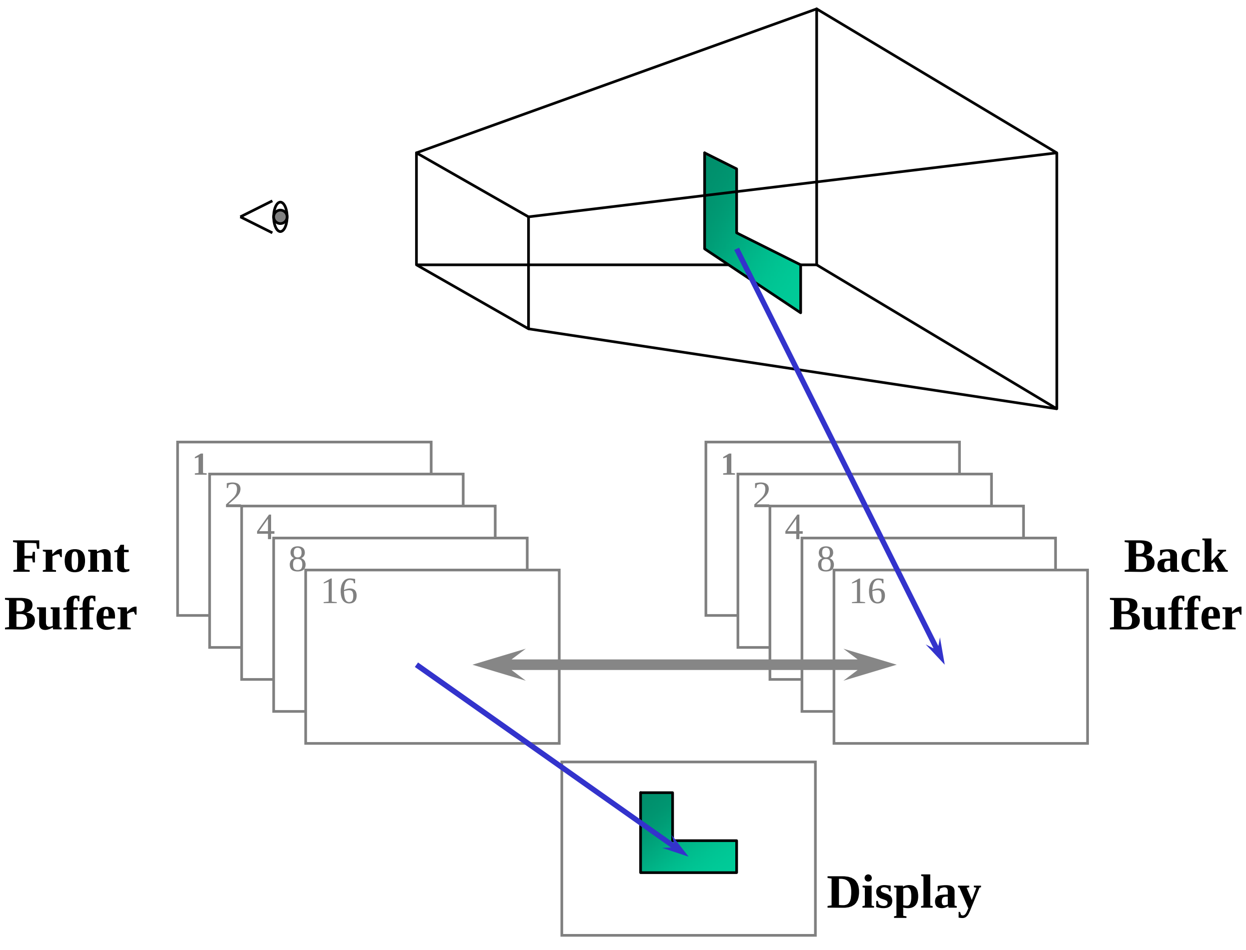
`gluProject` goes from world to screen space

Animation and Depth Buffering

Animation and Depth Buffering

- Discuss double buffering and animation
- Discuss hidden surface removal using the depth buffer

Double Buffering



Animation Using Double Buffering

① Request a double buffered color buffer

```
glutInitDisplayMode( GLUT_RGB | GLUT_DOUBLE );
```

② Clear color buffer

```
glClear( GL_COLOR_BUFFER_BIT );
```

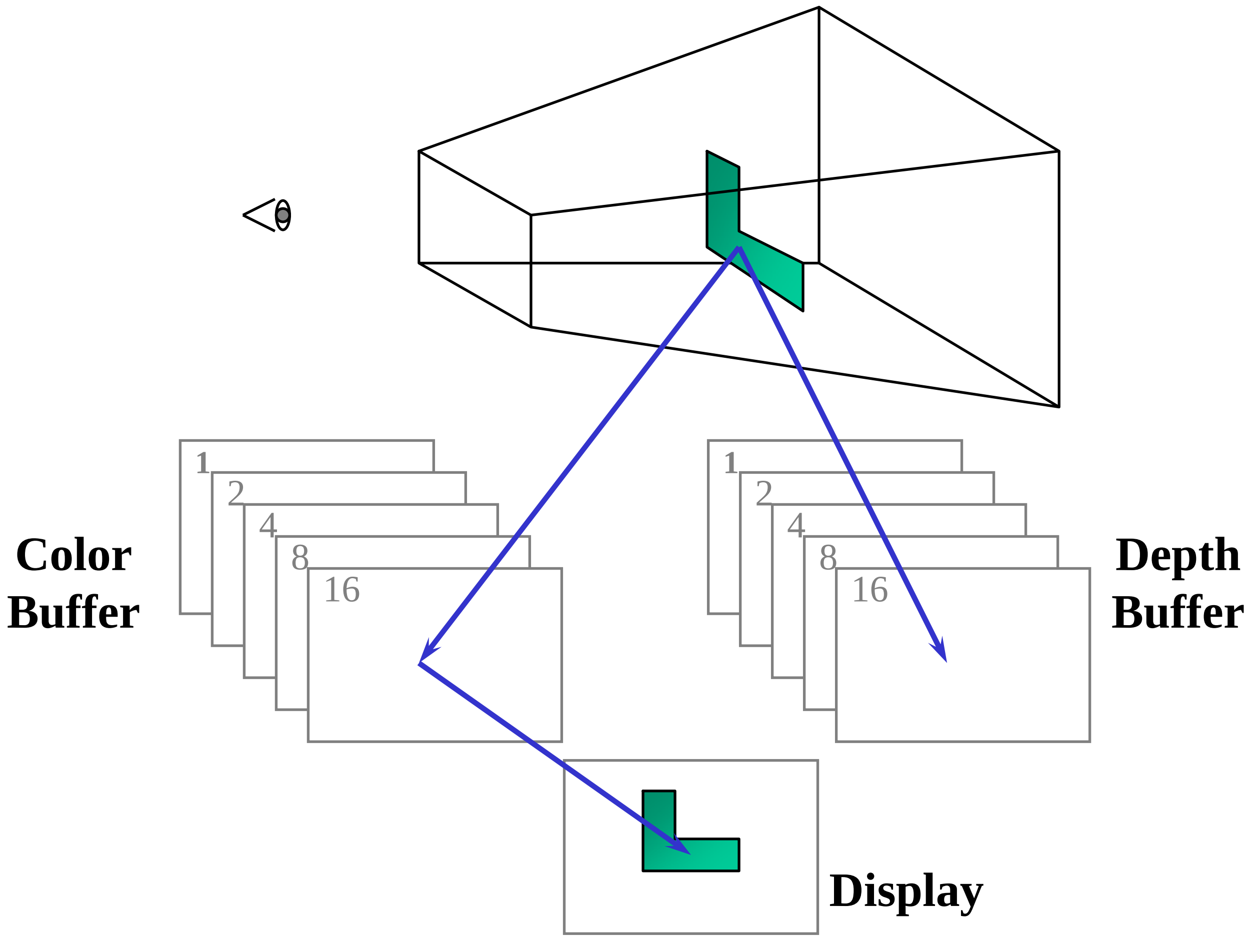
③ Render scene

④ Request swap of front and back buffers

```
glutSwapBuffers();
```

- Repeat steps 2 - 4 for animation

Depth Buffering and Hidden Surface Removal



Depth Buffering Using OpenGL

① Request a depth buffer

```
glutInitDisplayMode( GLUT_RGB | GLUT_DOUBLE |
                     GLUT_DEPTH );
```

② Enable depth buffering

```
glEnable( GL_DEPTH_TEST );
```

③ Clear color and depth buffers

```
glClear( GL_COLOR_BUFFER_BIT |
         GL_DEPTH_BUFFER_BIT );
```

④ Render scene

⑤ Swap color buffers

An Updated Program Template

```
void main( int argc, char** argv )
{
     glutInit( &argc, argv );
     glutInitDisplayMode( GLUT_RGB |
        GLUT_DOUBLE | GLUT_DEPTH );
     glutCreateWindow( "Tetrahedron" );
     init();
     glutIdleFunc( idle );
     glutDisplayFunc( display );
     glutMainLoop();
}
```

An Updated Program Template (cont.)

```
void init( void )
{
   glClearColor( 0.0, 0.0, 1.0, 1.0 );
}


void idle( void )
{
   glutPostRedisplay();
}
```

An Updated Program Template (cont.)

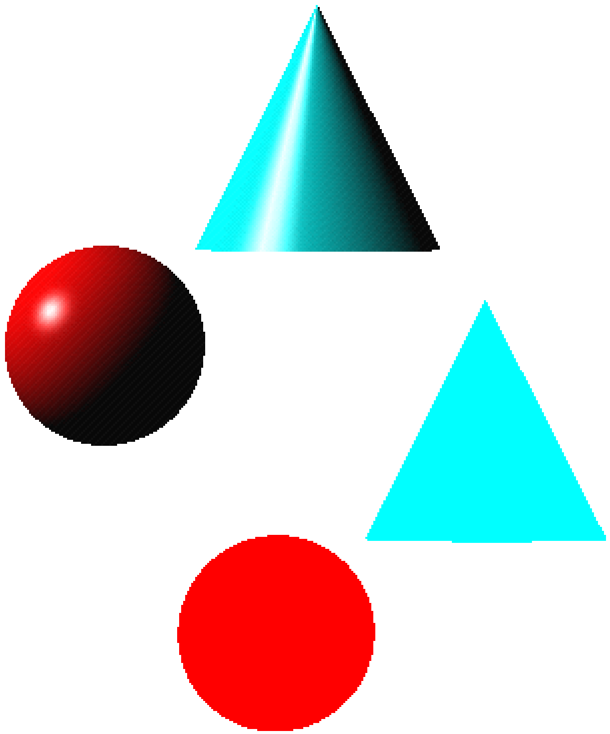
```
void drawScene( void )
{
     GLfloat vertices[] = { … };
     GLfloat colors[] = { … };
     glClear( GL_COLOR_BUFFER_BIT |
       GL_DEPTH_BUFFER_BIT );
     glBegin( GL_TRIANGLE_STRIP );
   /* calls to glColor*() and glVertex*() */
     glEnd();
     glutSwapBuffers();
}
```

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
- available in both color index and RGBA mode



How OpenGL Simulates Lights

- Phong lighting model
  - Computed at vertices
- Lighting contributors
  - Surface material properties
  - Light properties
  - Lighting model properties

Surface Normals

Normals define how a surface reflects light

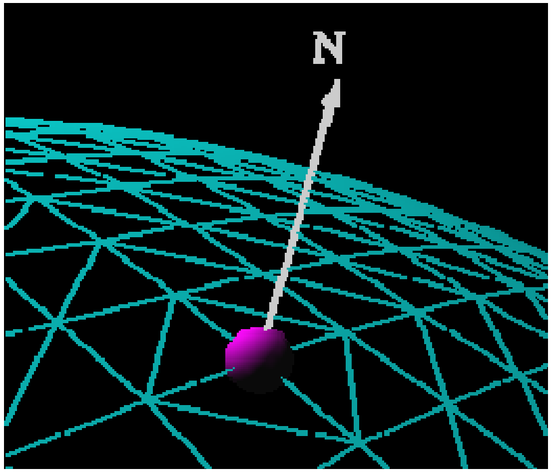
```
glNormal3f( x, y, z )
```

- Current normal is used to compute vertex's color
- Use *unit* normals for proper lighting
    - scaling affects a normal's length

glEnable(*GL_NORMALIZE*)

or

glEnable(*GL_RESCALE_NORMAL*)



Material Properties

Define the surface properties of a primitive

```
glMaterialfv( face, property, value );
```

GL_DIFFUSE	Base color
GL_SPECULAR	Highlight Color
GL_AMBIENT	Low-light Color
GL_EMISSION	Glow Color
GL_SHININESS	Surface Smoothness

separate materials for front and back

Light Properties

```
glLightfv( light, property, value );
```

- ***light*** specifies which light
  - multiple lights, starting with **GL_LIGHT0**

```
glGetIntegerv( GL_MAX_LIGHTS, &n );
```

- ***properties***
  - colors
  - position and type
  - attenuation

Light Sources (cont.)

Light color properties

- **GL_AMBIENT**
- **GL_DIFFUSE**
- **GL_SPECULAR**

Types of Lights

OpenGL supports two types of Lights

- Local (Point) light sources
- Infinite (Directional) light sources

Type of light controlled by w coordinate

$$w = 0 \quad \textbf{\textit{Infinite Light directed along}} \left(x \quad y \quad z\right)$$

$$w \neq 0 \quad \textbf{\textit{Local Light positioned at}} \left({}^{x}\!/_{w} \quad {}^{y}\!/_{w} \quad {}^{z}\!/_{w}\right)$$

Turning on the Lights

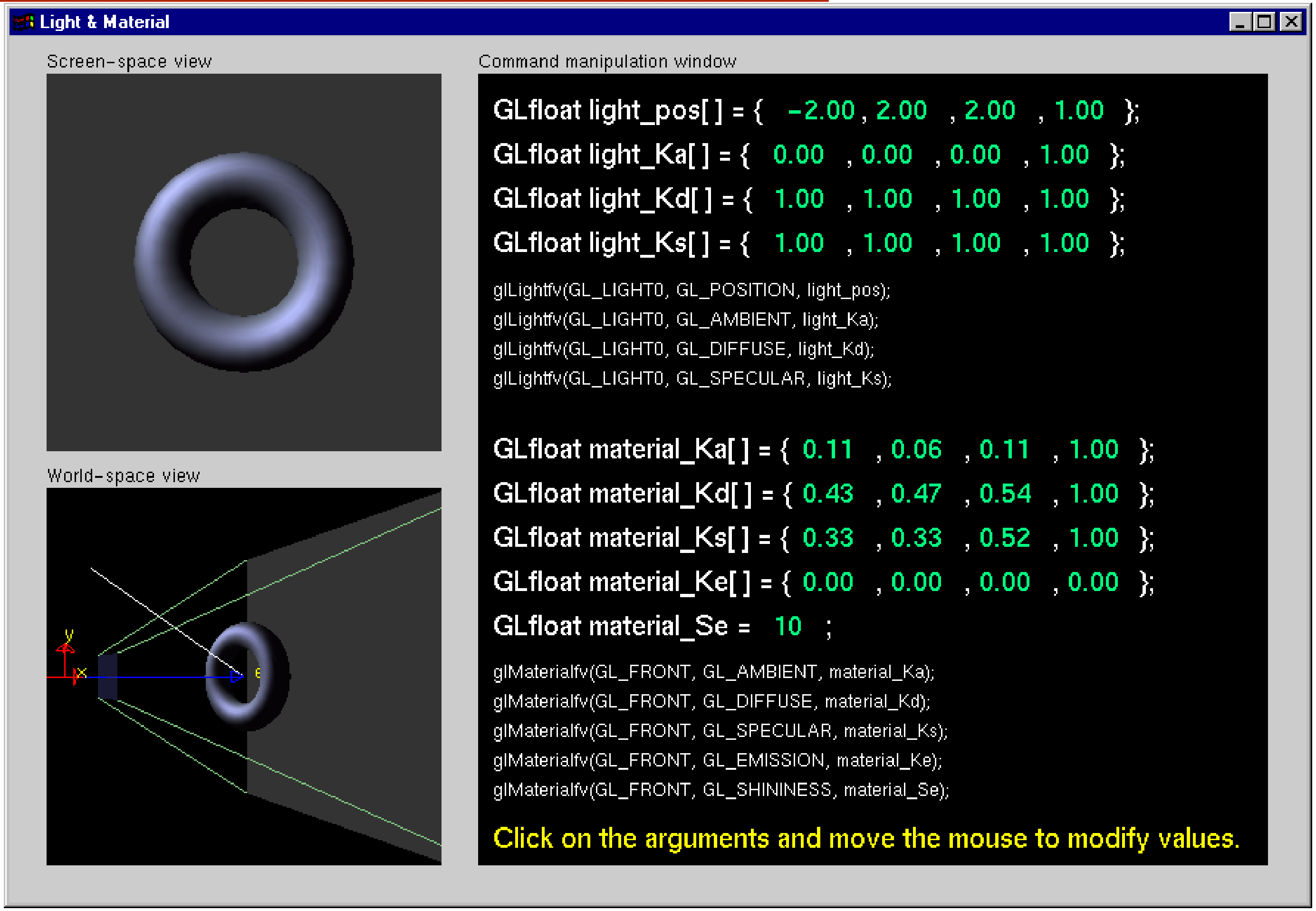
Flip each light's switch

```
glEnable( GL_LIGHTn );
```

Turn on the power

```
glEnable( GL_LIGHTING );
```

Light Material Tutorial



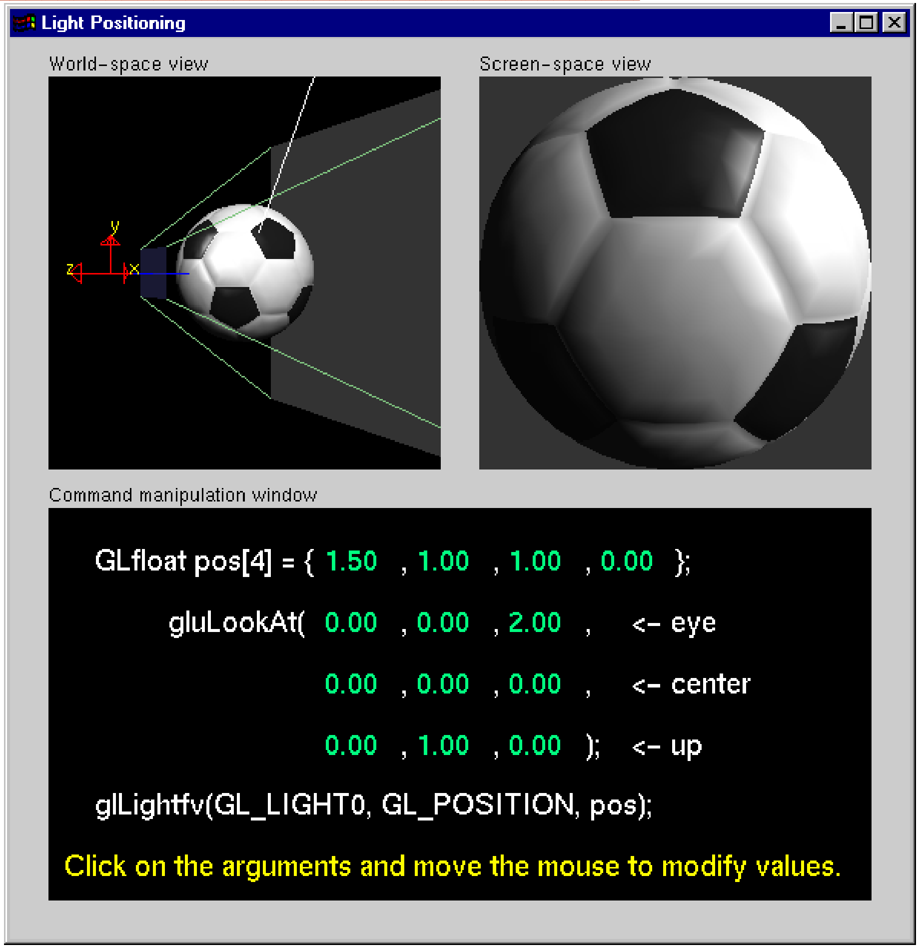
http://www.xmission.com/~nate/tutors.html

Controlling a Light's Position

Modelview matrix affects a light's position

- Different effects based on <u>when</u> position is specified
  - eye coordinates
  - world coordinates
  - model coordinates
- Push and pop matrices to uniquely control a light's position

Light Position Tutorial



http://www.xmission.com/~nate/tutors.html

Advanced Lighting Features

Spotlights

- localize lighting affects
  - ***GL_SPOT_DIRECTION***
  - ***GL_SPOT_CUTOFF***
  - ***GL_SPOT_EXPONENT***

Advanced Lighting Features

Light attenuation

- decrease light intensity with distance
  - ***GL_CONSTANT_ATTENUATION***
  - ***GL_LINEAR_ATTENUATION***
  - ***GL_QUADRATIC_ATTENUATION***

$$f_i = \frac{1}{k_c + k_l d + k_q d^2}$$

Light Model Properties

```
glLightModelfv( property, value );
```

Enabling two sided lighting

GL_LIGHT_MODEL_TWO_SIDE

Global ambient color

GL_LIGHT_MODEL_AMBIENT

Local viewer mode

GL_LIGHT_MODEL_LOCAL_VIEWER

Separate specular color

GL_LIGHT_MODEL_COLOR_CONTROL

Tips for Better Lighting

- Recall lighting computed only at vertices
  - model tessellation heavily affects lighting results
    - better results but more geometry to process
- Use a single infinite light for fastest lighting
  - minimal computation per vertex

Imaging and Raster Primitives

Imaging and Raster Primitives

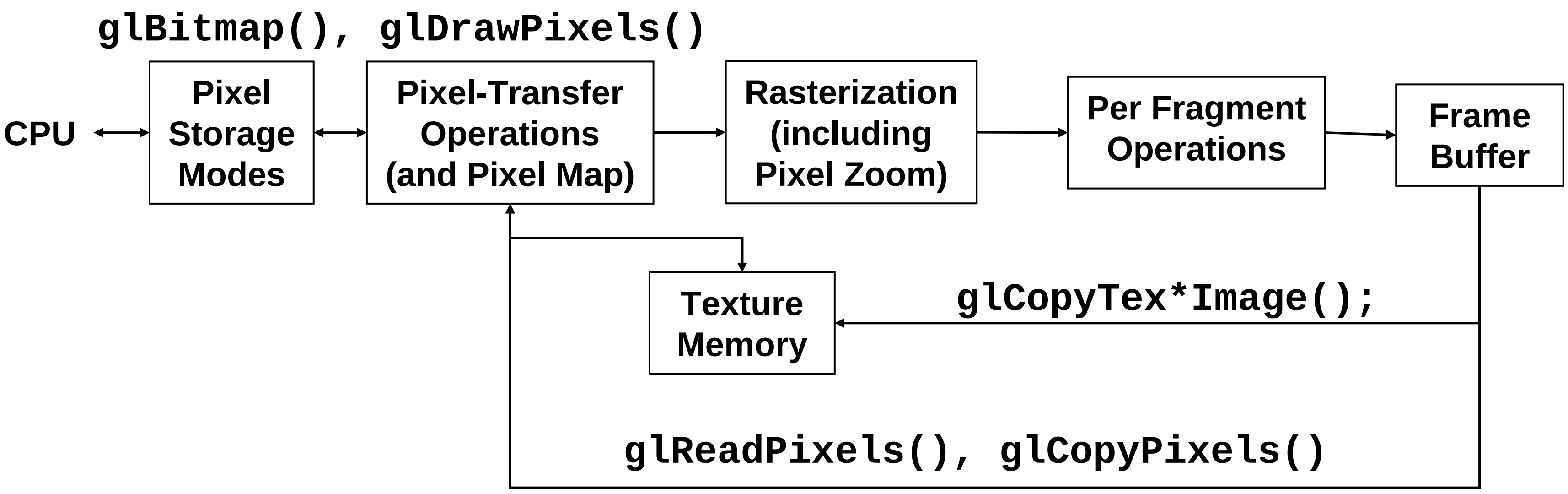
- Describe OpenGL's raster primitives: bitmaps and image rectangles
- Demonstrate how to get OpenGL to read and render pixel rectangles

Pixel-based primitives

- Bitmaps
  - 2D array of bit masks for pixels
    - update pixel color based on current color
- Images
  - 2D array of pixel color information
    - complete color information for each pixel
- OpenGL doesn’t understand image formats

Pixel Pipeline

Programmable pixel storage and transfer operations



Positioning Image Primitives

`glRasterPos3f( x, y, z )`

- raster position transformed like geometry
- discarded if raster position is outside of viewport
  - may need to fine tune viewport for desired results

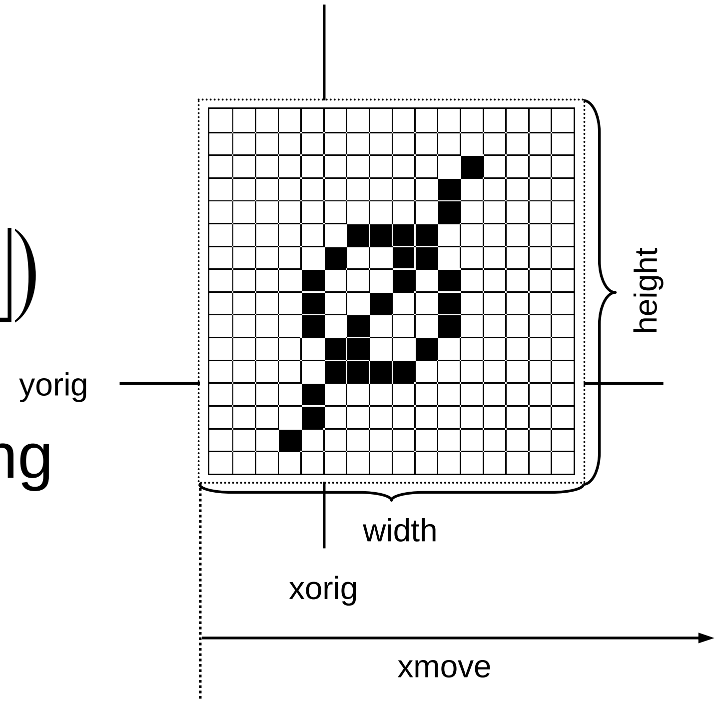
Raster Position

Rendering Bitmaps

```
glBitmap( width, height,
          xorig, yorig,
          xmove, ymove,
          bitmap )
```

– render bitmap in current color at $\left(\lfloor x - xorig \rfloor \quad \lfloor y - yorig \rfloor \right)$

– advance raster position by $\left(xmove \quad ymove \right)$ after rendering



Rendering Fonts using Bitmaps

OpenGL uses bitmaps for font rendering

- each character is stored in a display list containing a bitmap
- window system specific routines to access system fonts

```
glXUseXFont()
wglUseFontBitmaps()
```

Rendering Fonts using Bitmaps

Rendering fonts using GLUT

The GLUT library provides some functionality for simple font rendering in OpenGL. These fonts can be either drawn as bitmaps or as line segments:

- `glutBitmapCharacter`
- `glutStrokeCharacter`

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutBitmapCharacter

The function glutBitmapCharacter renders fonts using bitmaps. The syntax is:

```
glutBitmapCharacter (void *font, GLint c);
```

The following font constants are available:

- GLUT_BITMAP_8_BY_13
- GLUT_BITMAP_9_BY_14
- GLUT_BITMAP_TIMES_ROMAN_10
- GLUT_BITMAP_TIMES_ROMAN_24
- GLUT_BITMAP_HELVETICA_10
- GLUT_BITMAP_HELVETICA_12
- GLUT_BITMAP_HELVETICA_18

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutBitmapCharacter

Note: the function `glutBitmapCharacter` does not provide any means to specify the location of where the text is to be put. Instead, the current raster position is used. Hence, you can specify the location using the function `glRasterPos`.

If you need to determine the length (in pixels) that a given text would need using a specific font (for example, for centering text), you can use:

```
glutBitmapLength (void *font,
                  GLuchar *text);
```

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutBitmapCharacter

The function `glutBitmapCharacter` only renders a single character at a time, however, it advances the current raster location so that – after rendering a character – the current raster location will be exactly at the right end of the bitmap used for rendering the character. This way, text strings can be rendered by consecutively calling `glutBitmapCharacter` :

```
void bitmap_output (GLfloat x, GLfloat y,
                    char *string, void *font)
{
  int len, i;
  glRasterPos2f(x, y);
  len = (int) strlen(string);
  for (i = 0; i < len; i++) {
    glutBitmapCharacter(font, string[i]);
  }
}
```

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutStrokeCharacter

Another font rendering method provided by GLUT is `glutStrokeCharacter`:

glutStrokeCharacter (void *font, Glint c);

Since `glutStrokeCharacter` uses regular lines for rendering the character, you need to use `glTranslate` to specify the location. Similar to `glutBitmapCharacter`, `glutStrokeCharacter` automatically advances to the end of the character using `glTranslate`.

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutStrokeCharacter

Two fonts are available for `glutStrokeCharacter`:

- `GLUT_STROKE_ROMAN`
- `GLUT_STROKE_MONO_ROMAN`

To determine the length that a rendered text requires, this function can be used:

```
float glutStrokeLengthf (void *font,
                         const unsigned char *string);
```

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutStrokeCharacter

Thus, rendering text using this function could look like this:

```
void stroke_output(GLfloat x, GLfloat y, GLfloat z,
                   char *string, GLfloat scale)
{
  int len, i;
  glPushMatrix();
  glTranslatef(x, y, z);
  glScalef(scale, scale, scale);
  len = (int) strlen(string);
  for (i = 0; i < len; i++)
    glutStrokeCharacter(GLUT_STROKE_ROMAN,
                        string[i]);
  glPopMatrix();
}
```

Rendering Fonts using Bitmaps

Rendering fonts using GLUT – glutStrokeCharacter

Since regular lines (`GL_LINES`) are used for rendering the characters, we can use the usual functions to change the attributes:

Antialiasing:

```
glBlendFunc (GL_SRC_ALPHA,
             GL_ONE_MINUS_SRC_ALPHA);
glEnable (GL_BLEND);
glEnable (GL_LINE_SMOOTH);
```

Line width:

```
glLineWidth (2.0);
```

Rendering Images

`glDrawPixels(` *`width, height, format, type, pixels`* `)`

- render pixels with lower left of image at current raster position
- numerous formats and data types for specifying storage in memory
  - best performance by using format and type that matches hardware

Reading Pixels

`glReadPixels( x, y, width, height, format, type, pixels )`

- read pixels form specified *(x,y)* position in framebuffer
- pixels automatically converted from framebuffer format into requested format and type

Framebuffer pixel copy (copies pixels within framebuffer)

`glCopyPixels( x, y, width, height, type )`

Pixel Zoom

`glPixelZoom( x, y )`

- expand, shrink or reflect pixels around current raster position
- fractional zoom supported

Raster Position

`glPixelZoom(1.0, -1.0);`

Storage and Transfer Modes

Storage modes control accessing memory

- byte alignment in host memory
- extracting a subimage

Transfer modes allow modify pixel values

- scale and bias pixel component values
- replace colors using pixel maps

Texture Mapping

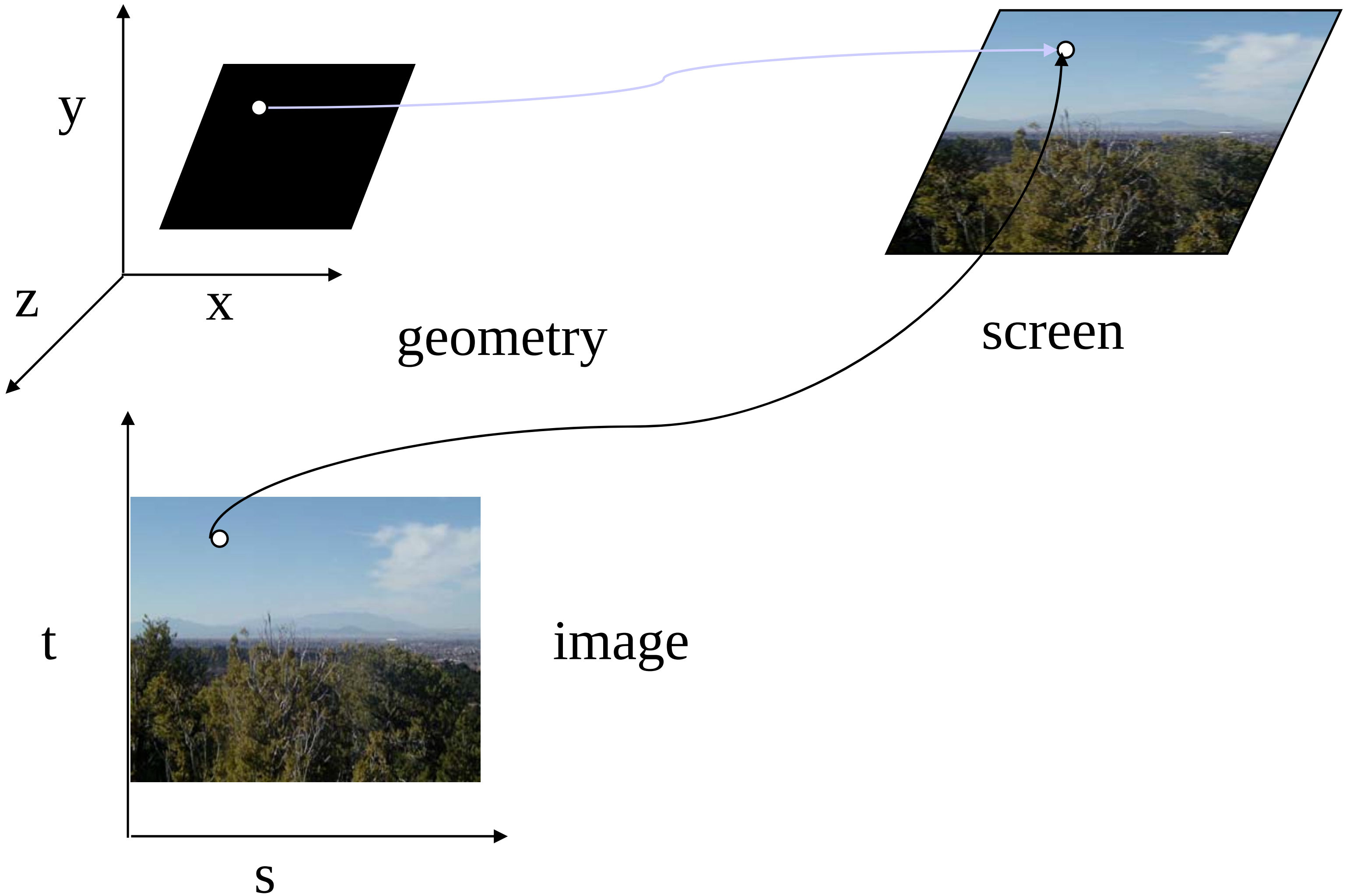
Texture Mapping

Apply a 1D, 2D, or 3D image to geometric primitives

Uses of Texturing

- simulating materials
- reducing geometric complexity
- image warping
- reflections

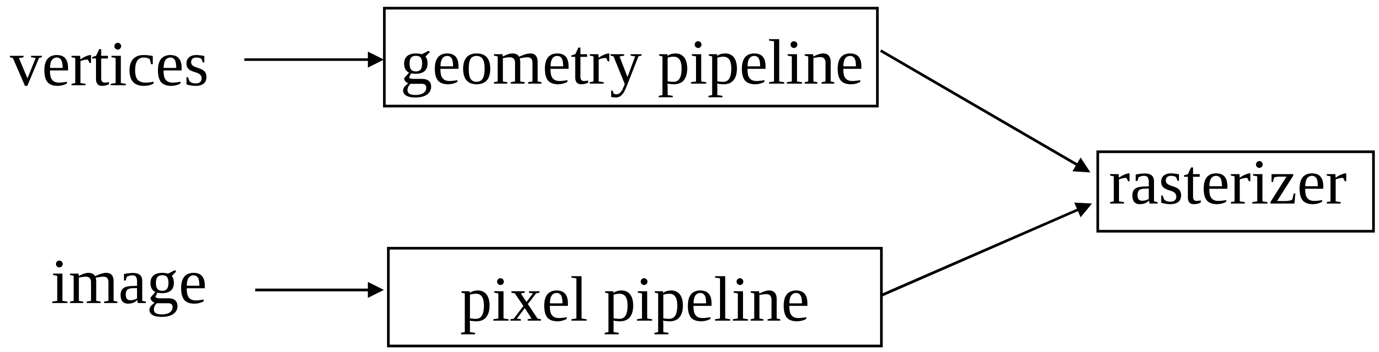
Texture Mapping



Texture Mapping and the OpenGL Pipeline

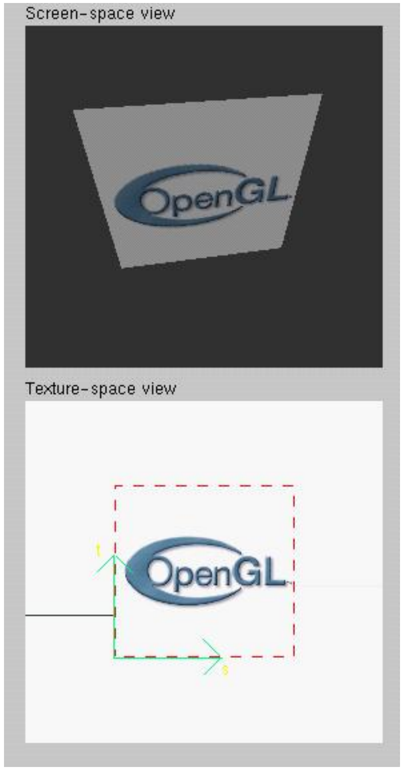
Images and geometry flow through separate pipelines that join at the rasterizer

- "complex" textures do not affect geometric complexity



Texture Example

The texture (below) is a
246 x 246 image that has been
mapped to a rectangular
polygon which is viewed in
perspective



Applying Textures I

Three steps:

① specify texture
- read or generate image
- assign to texture

② assign texture coordinates to vertices

③ specify texture parameters
- wrapping, filtering

Applying Textures II

- specify textures in texture objects
- set texture filter
- set texture function
- set texture wrap mode
- set optional perspective correction hint
- bind texture object
- enable texturing
- supply texture coordinates for vertex
  - coordinates can also be generated

Texture Objects

- Like display lists for texture images
  - one image per texture object
  - may be shared by several graphics contexts
- Generate texture names

```
glGenTextures( n, *texIds );
```

Texture Objects (cont.)

Create texture objects with texture data and state

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

Bind textures before using

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

Specify Texture Image

- Define a texture image from an array of texels in CPU memory

```
glTexImage2D( target, level, components,
    w, h, border, format, type, *texels );
```

  - dimensions of image must be powers of 2
- Texel colors are processed by pixel pipeline
  - pixel scales, biases and lookups can be done

Converting A Texture Image

If dimensions of image are not power of 2

```
gluScaleImage( format, w_in, h_in,
    type_in, *data_in, w_out, h_out,
        type_out, *data_out );
```

- *_in ***is for source image***
- *_out ***is for destination image***

Image interpolated and filtered during scaling

Specifying a Texture: Other Methods

Use frame buffer as source of texture image

uses current buffer as source image

`glCopyTexImage2D(...)`

`glCopyTexImage1D(...)`

Modify part of a defined texture

`glTexSubImage2D(...)`

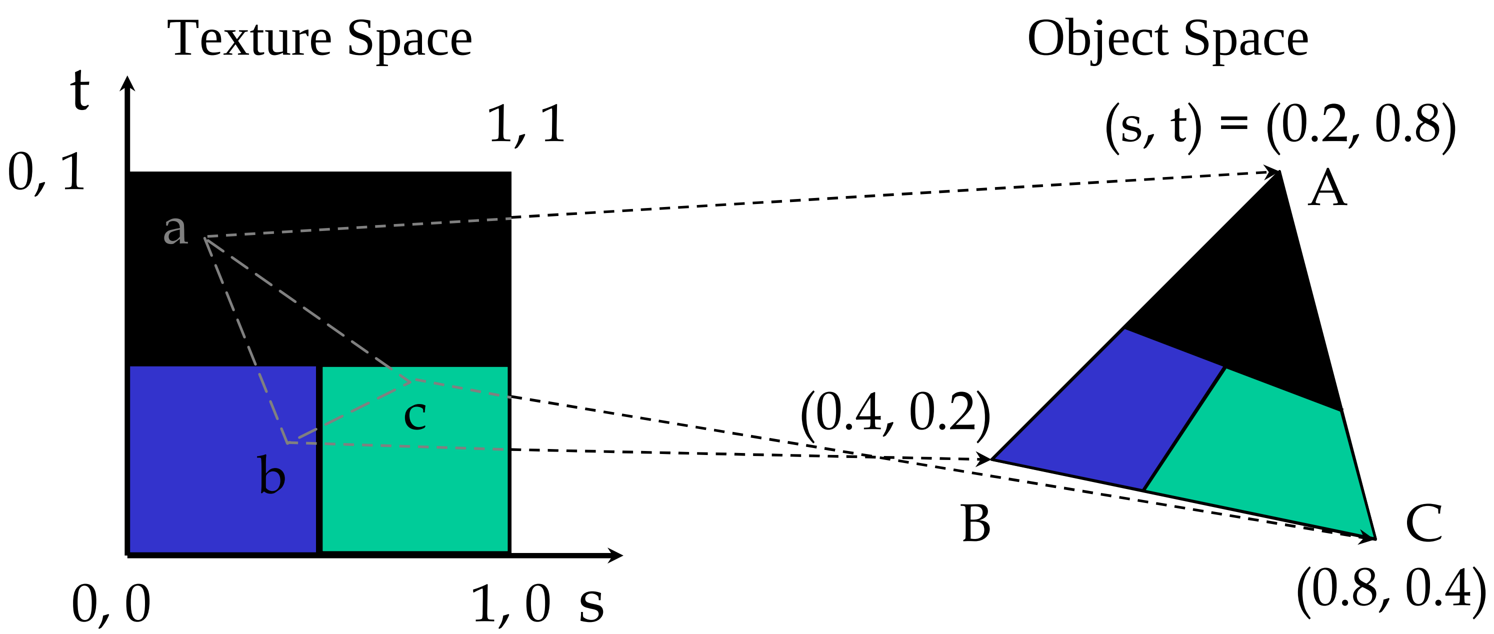
`glTexSubImage1D(...)`

Do both with *`glCopyTexSubImage2D(...)`*, etc.

Mapping a Texture

Based on parametric texture coordinates

`glTexCoord*()` specified at each vertex



Generating Texture Coordinates

Automatically generate texture coords

glTexGen{ifd}[v]()

specify a plane

- generate texture coordinates based upon distance from plane

$$Ax + By + Cz + D = 0$$

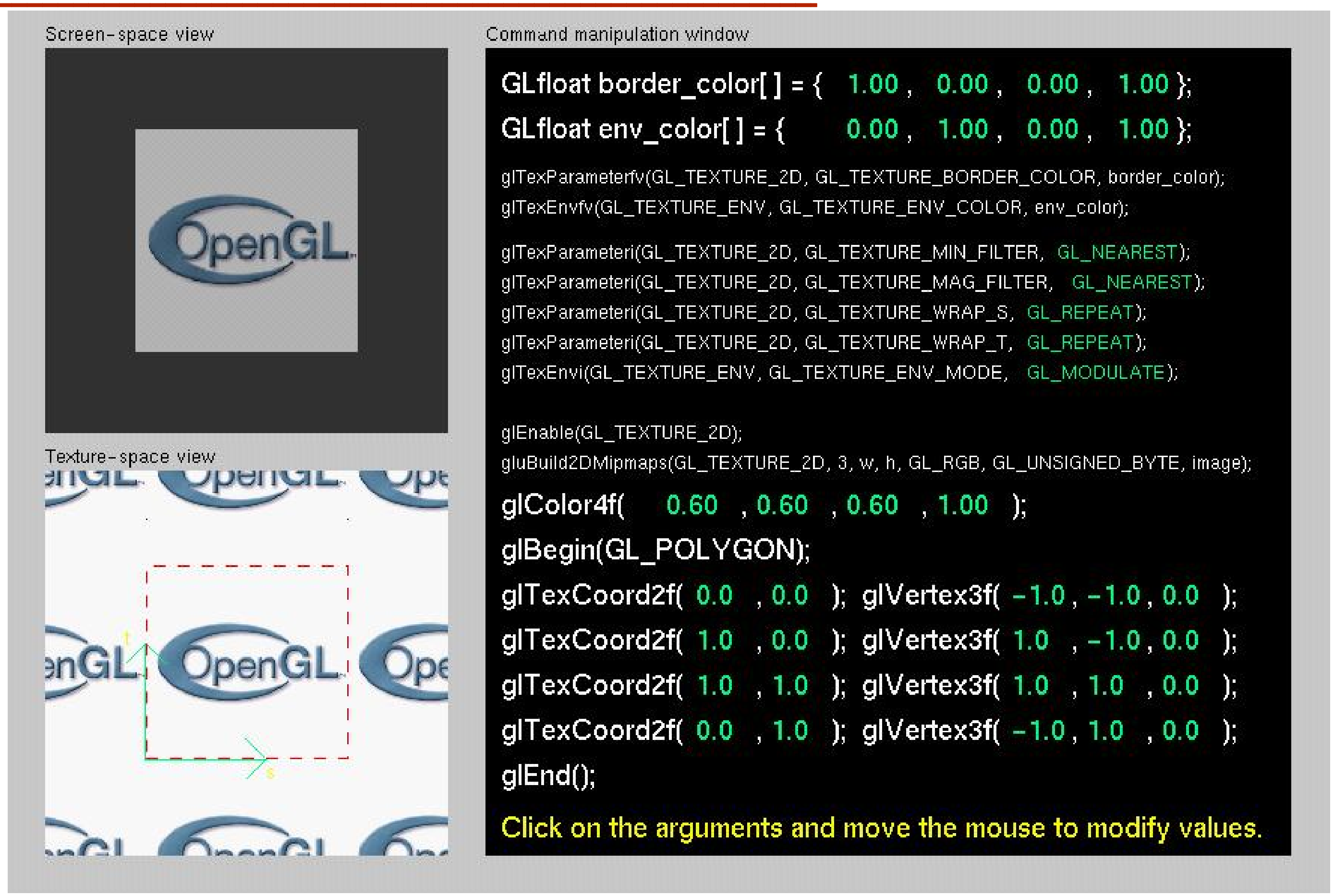
generation modes

GL_OBJECT_LINEAR (mapping w.r.t. object)

GL_EYE_LINEAR (mapping w.r.t. eye location)

GL_SPHERE_MAP (environment mapping)

Tutorial: Texture



http://www.xmission.com/~nate/tutors.html

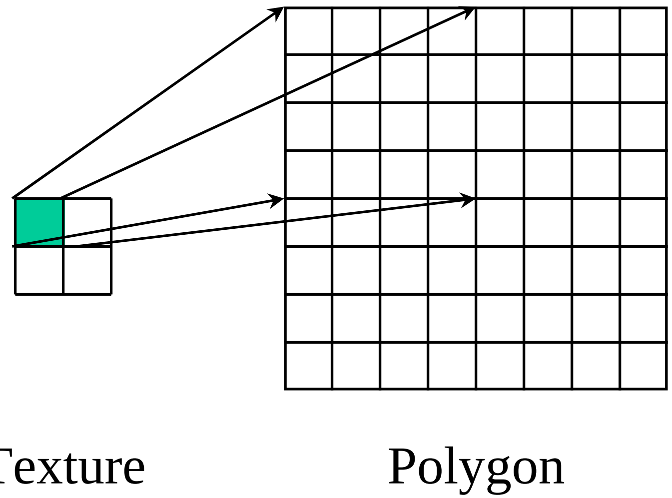
Texture Application Methods

- Filter Modes
  - minification or magnification
  - special mipmap minification filters
- Wrap Modes
  - clamping or repeating
- Texture Functions
  - how to mix primitive's color with texture's color
    - blend, modulate or replace texels

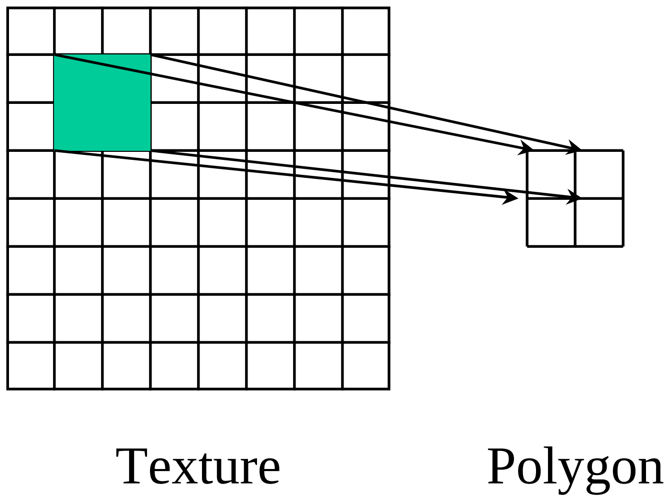
Filter Modes

Example:

```
glTexParameteri( target, type, mode );
```



Magnification



Minification

Mipmapped Textures

- Mipmap allows for prefiltered texture maps of decreasing resolutions
- Lessens interpolation errors for smaller textured objects
- Declare mipmap level during texture definition

```
glTexImage*D( GL_TEXTURE_*D, level, … )
```

- GLU mipmap builder routines

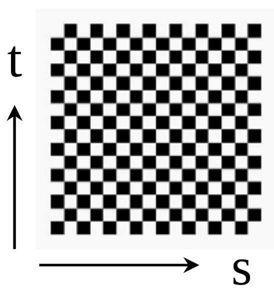
```
gluBuild*DMipmaps( … )
```

- OpenGL 1.2 introduces advanced LOD controls

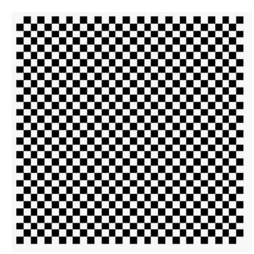
Wrapping Mode

Example:

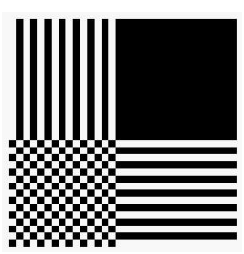
```
glTexParameteri( GL_TEXTURE_2D,
     GL_TEXTURE_WRAP_S, GL_CLAMP )
glTexParameteri( GL_TEXTURE_2D,
     GL_TEXTURE_WRAP_T, GL_REPEAT )
```



texture



GL_REPEAT wrapping



GL_CLAMP wrapping

Texture Functions

Controls how texture is applied

```
glTexEnv{fi}[v]( GL_TEXTURE_ENV, prop, param )
```

GL_TEXTURE_ENV_MODE modes

GL_MODULATE

GL_BLEND

GL_REPLACE

Set blend color with *GL_TEXTURE_ENV_COLOR*

(This can be useful for incorporating lighting and textures; otherwise lighting is overwritten by texture)

Perspective Correction Hint

- Texture coordinate and color interpolation
  - either linearly in screen space
  - or using depth/perspective values (slower)
- Noticeable for polygons "on edge"

```
glHint( GL_PERSPECTIVE_CORRECTION_HINT, hint )
```

- where ***hint*** is one of

  GL_DONT_CARE

  GL_NICEST

  GL_FASTEST

Is There Room for a Texture?

- Query largest dimension of texture image
  - typically largest square texture
  - doesn't consider internal format size

  `glGetIntegerv( GL_MAX_TEXTURE_SIZE, &size )`

- Texture proxy
  - will memory accommodate requested texture size?
  - no image specified; placeholder
  - if texture won't fit, texture state variables set to 0
    - doesn't know about other textures
    - only considers whether this one texture will fit all of memory

Texture Residency

- Working set of textures
  - high-performance, usually hardware accelerated
  - textures must be in texture objects
  - a texture in the *working set* is *resident*
  - for residency of current texture, check **`GL_TEXTURE_RESIDENT`** state
- If too many textures, not all are resident
  - can set priority to have some kicked out first
  - establish 0.0 to 1.0 priorities for texture objects

Advanced OpenGL Topics

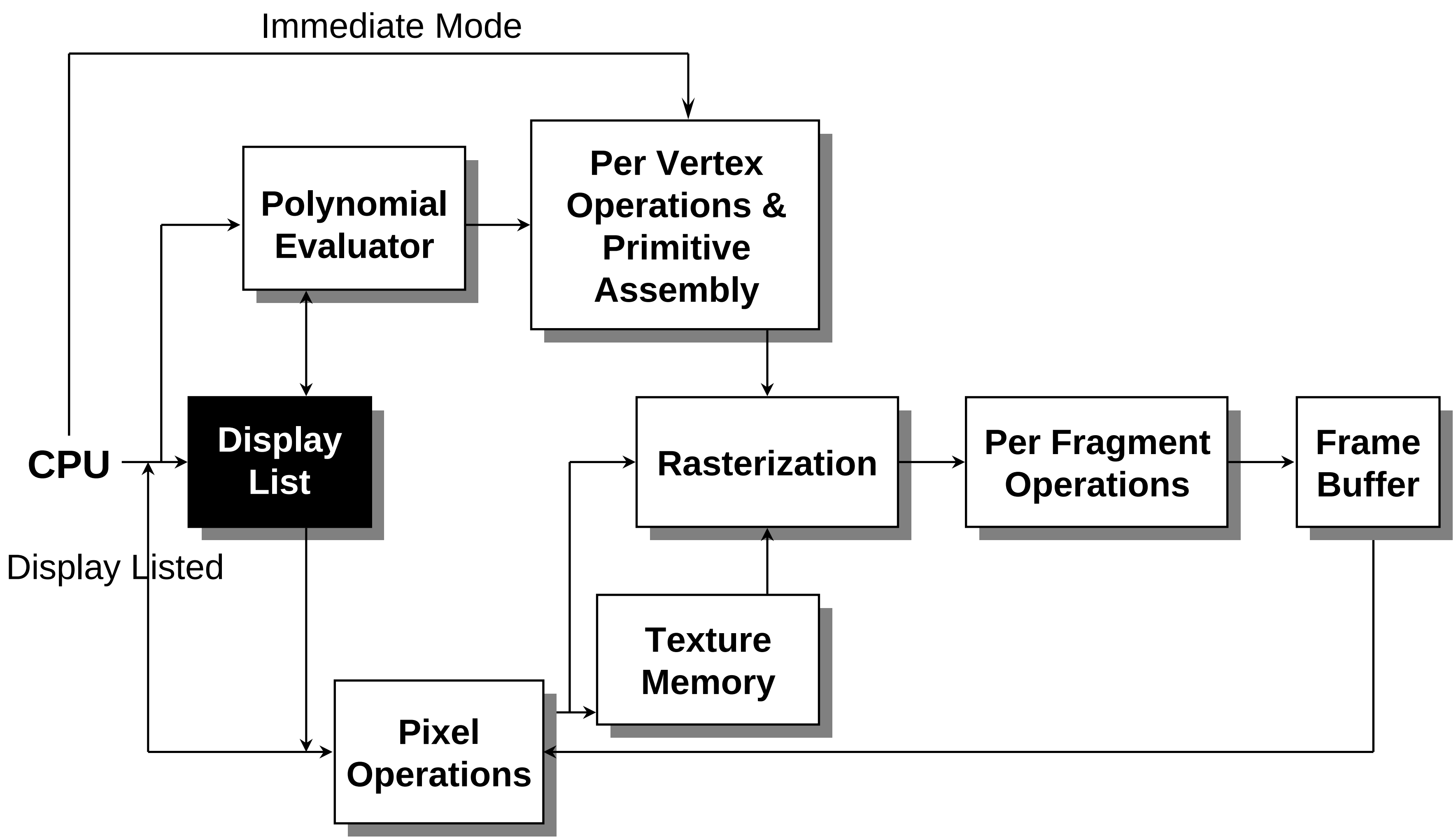
Advanced OpenGL Topics

- Display Lists and Vertex Arrays
- Alpha Blending and Antialiasing
- Using the Accumulation Buffer
- Fog
- Feedback & Selection
- Fragment Tests and Operations
- Using the Stencil Buffer

Immediate Mode versus Display Listed Rendering

- Immediate Mode Graphics
  - Primitives are sent to pipeline and display right away
  - No memory of graphical entities
- Display Listed Graphics
  - Primitives placed in display lists
  - Display lists kept on graphics server
  - Can be redisplayed with different state
  - Can be shared among OpenGL graphics contexts

Immediate Mode versus Display Lists



Display Lists

Creating a display list

```
GLuint id;
void init( void )
{
    id = glGenLists( 1 );
    glNewList( id, GL_COMPILE );
    /* other OpenGL routines */
    glEndList();
}
```

Call a created list

```
void display( void )
{
    glCallList( id );
}
```

Display Lists

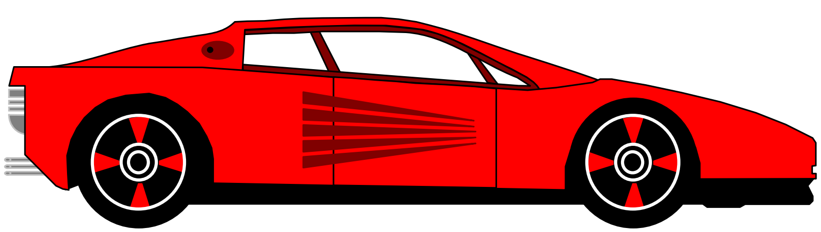
- Not all OpenGL routines can be stored in display lists
- State changes persist, even after a display list is finished
- Display lists can call other display lists
- Display lists are not editable, but you can fake it
  - make a list (A) which calls other lists (B, C, and D)
  - delete and replace B, C, and D, as needed

Display Lists and Hierarchy

Consider model of a car

- Create display list for chassis
- Create display list for wheel

```
glNewList( CAR, GL_COMPILE );
    glCallList( CHASSIS );
    glTranslatef( … );
    glCallList( WHEEL );
    glTranslatef( … );
    glCallList( WHEEL );
        …
glEndList();
```



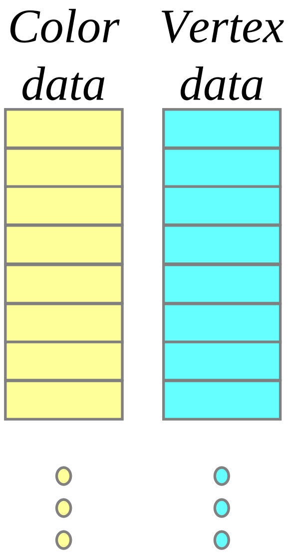
Advanced Primitives

- Vertex Arrays
- Bernstein Polynomial Evaluators
  - basis for GLU NURBS
    - NURBS (Non-Uniform Rational B-Splines)
- GLU Quadric Objects
  - sphere
  - cylinder (or cone)
  - disk (circle)

Vertex Arrays

Pass arrays of vertices, colors, etc. to OpenGL in a large chunk

```
glVertexPointer( 3, GL_FLOAT, 0, coords )
glColorPointer( 4, GL_FLOAT, 0, colors )
glEnableClientState( GL_VERTEX_ARRAY )
glEnableClientState( GL_COLOR_ARRAY )
glDrawArrays( GL_TRIANGLE_STRIP, 0,
              numVerts );
```



All active arrays are used in rendering

Why use Display Lists or Vertex Arrays?

- May provide better performance than immediate mode rendering
- Display lists can be shared between multiple OpenGL context
  - reduce memory usage for multi-context applications
- Vertex arrays may format data for better memory access

Alpha: the 4th Color Component

- Measure of Opacity
  - simulate translucent objects
    - glass, water, etc.
  - composite images
  - antialiasing
  - ignored if blending is not enabled

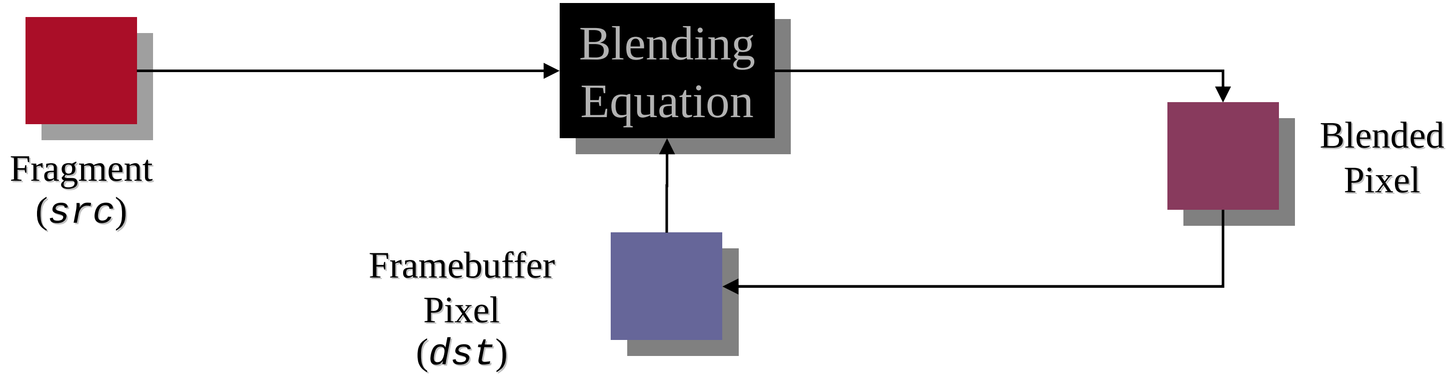
```
glEnable( GL_BLEND )
```

Blending

Combine pixels with what's in already
in the framebuffer

```
glBlendFunc( src, dst )
```

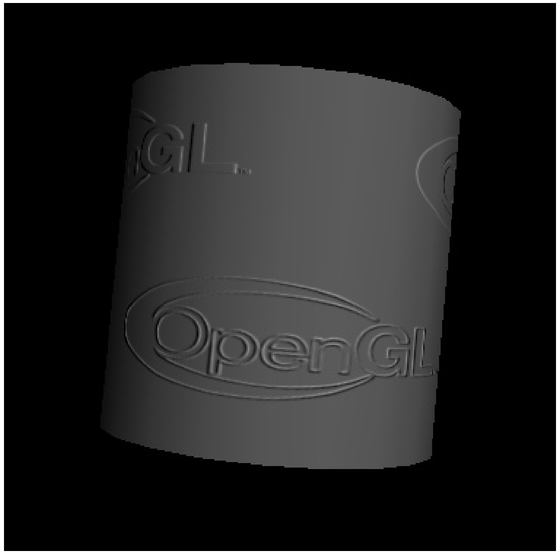
$$\vec{C}_r = src\ \vec{C}_f + dst\ \vec{C}_p$$



Multi-pass Rendering

Blending allows results from multiple drawing passes to be combined together

- enables more complex rendering algorithms



Example of bump-mapping done with a multi-pass OpenGL algorithm

Antialiasing

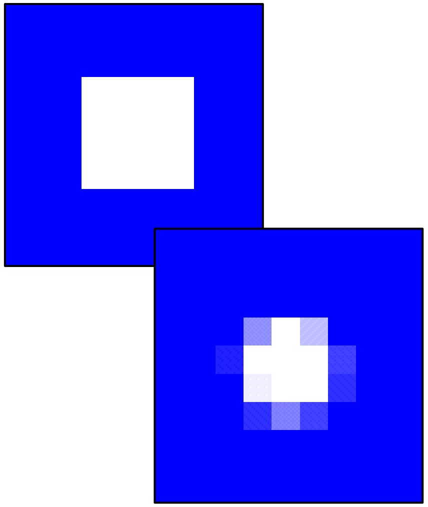
Removing the Jaggies

`glEnable( mode )`

- **GL_POINT_SMOOTH**
- **GL_LINE_SMOOTH**
- **GL_POLYGON_SMOOTH**

– alpha value computed by computing sub-pixel coverage

– available in both RGBA and colormap modes



Accumulation Buffer

Problems of compositing into color buffers

- limited color resolution
  - clamping
  - loss of accuracy
- Accumulation buffer acts as a “floating point” color buffer
  - accumulate into accumulation buffer
  - transfer results to frame buffer

Accessing Accumulation Buffer

`glAccum( op, value )`

- operations
  - within the accumulation buffer: ***GL_ADD, GL_MULT***
  - from read buffer: ***GL_ACCUM, GL_LOAD***
  - transfer back to write buffer: ***GL_RETURN***
- **glAccum(*GL_ACCUM, 0.4*)** multiplies each value in write buffer by 0.4 and adds to accumulation buffer

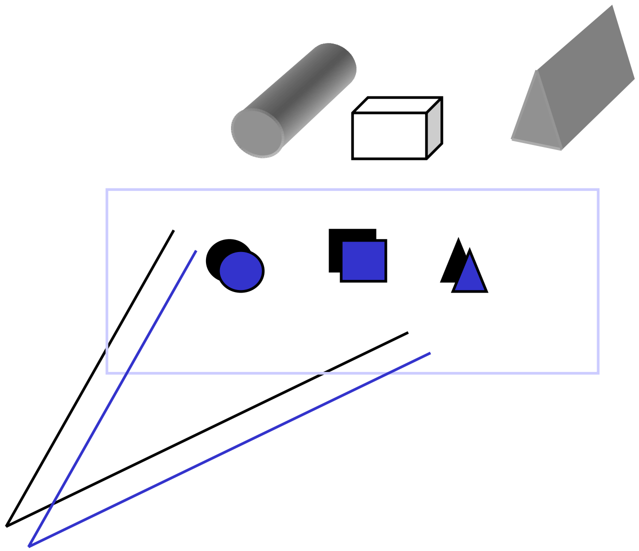
Accumulation Buffer Applications

- Compositing
- Full Scene Antialiasing
- Depth of Field
- Filtering
- Motion Blur

Full Scene Antialiasing : *Jittering the view*

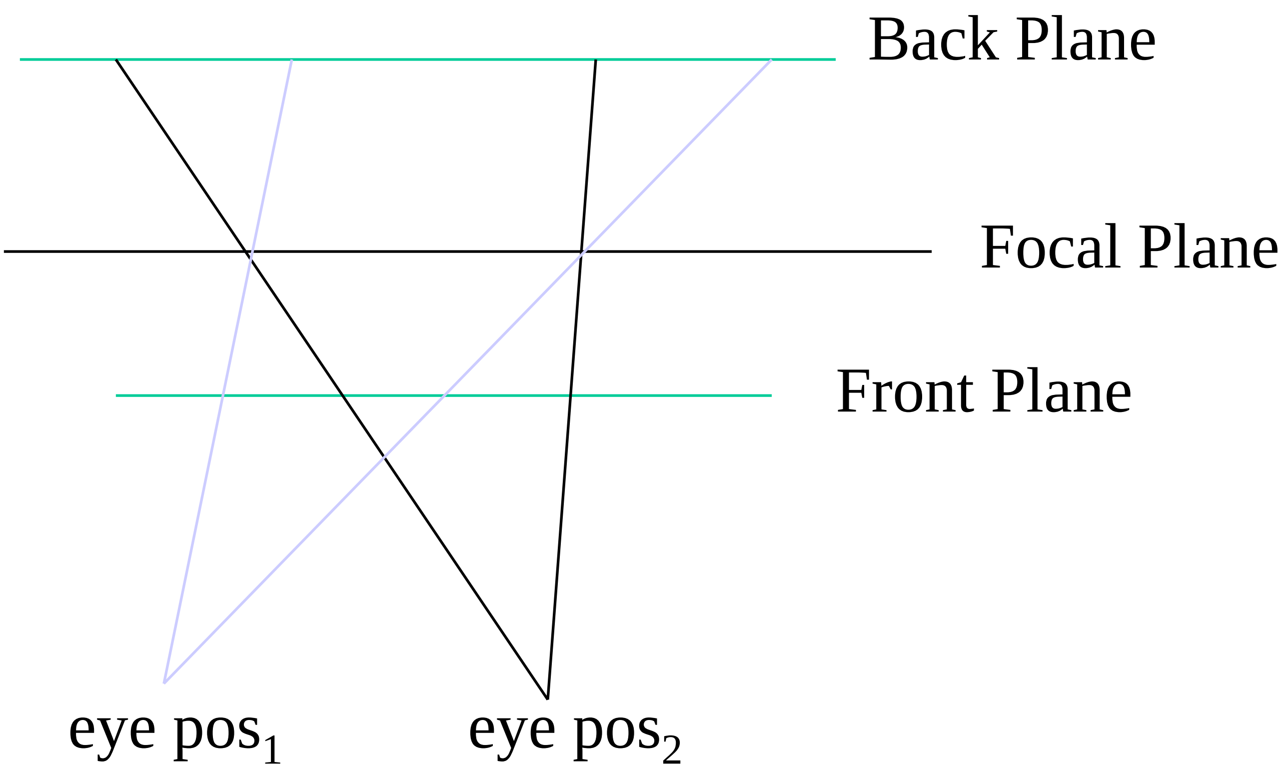
Each time we move the viewer, the image shifts

- Different aliasing artifacts in each image
- Averaging images using accumulation buffer averages out these artifacts



Depth of Focus : *Keeping a Plane in Focus*

Jitter the viewer to keep one plane unchanged



Fog

`glFog( property, value )`

- Depth Cueing

  Specify a range for a linear fog ramp

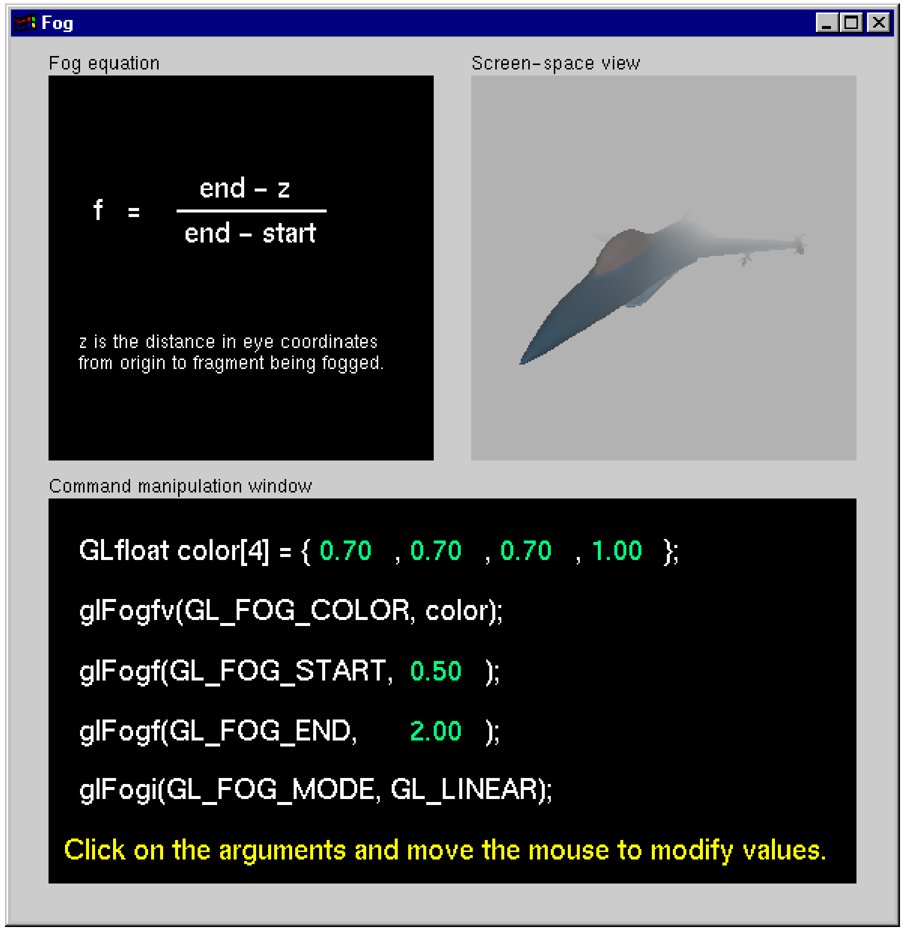
  GL_FOG_LINEAR

- Environmental effects
  - Simulate more realistic fog

  GL_FOG_EXP

  GL_FOG_EXP2

Fog Tutorial



http://www.xmission.com/~nate/tutors.html

Feedback Mode

- Transformed vertex data is returned to the application, not rendered
  - useful to determine which primitives will make it to the screen
- Need to specify a feedback buffer

```
glFeedbackBuffer( size, type, buffer )
```

- Select feedback mode for rendering

```
glRenderMode( GL_FEEDBACK )
```

Selection Mode

- Method to determine which primitives are inside the viewing volume
- Need to set up a buffer to have results returned to you

glSelectBuffer(*size*, *buffer*)

- Select selection mode for rendering

glRenderMode(*GL_SELECT*)

Selection Mode (cont.)

- To identify a primitive, give it a name
  - “names” are just integer values, not strings
- Names are stack based
  - allows for hierarchies of primitives
- Selection Name Routines

```
glLoadName( name )  glPushName( name )
glInitNames()
```

Picking

- Picking is a special case of selection
- Programming steps
  - restrict “drawing” to small region near pointer
    - use **`gluPickMatrix()`** on projection matrix
  - enter selection mode; re-render scene
  - primitives drawn near cursor cause hits
  - exit selection; analyze hit records

Picking Template

```
glutMouseFunc( pickMe );

void pickMe( int button, int state, int x,
int y )
{
   GLuint nameBuffer[246];
   GLint hits;
   GLint myViewport[4];
   if (button != GLUT_LEFT_BUTTON ||
       state != GLUT_DOWN) return;
   glGetIntegerv( GL_VIEWPORT, myViewport );
   glSelectBuffer( 246, nameBuffer );
   (void) glRenderMode( GL_SELECT );
   glInitNames();
```

Picking Template (cont.)

```
   glMatrixMode( GL_PROJECTION );
   glPushMatrix();
   glLoadIdentity();
   gluPickMatrix( (GLdouble) x, (GLdouble)
      (myViewport[3]-y), 4.0, 4.0,
       myViewport );
/*   gluPerspective or glOrtho or other
   projection  */
   glPushName( 1 );
/*   draw something  */
   glLoadName( 2 );
/*   draw something else … continue …  */
```

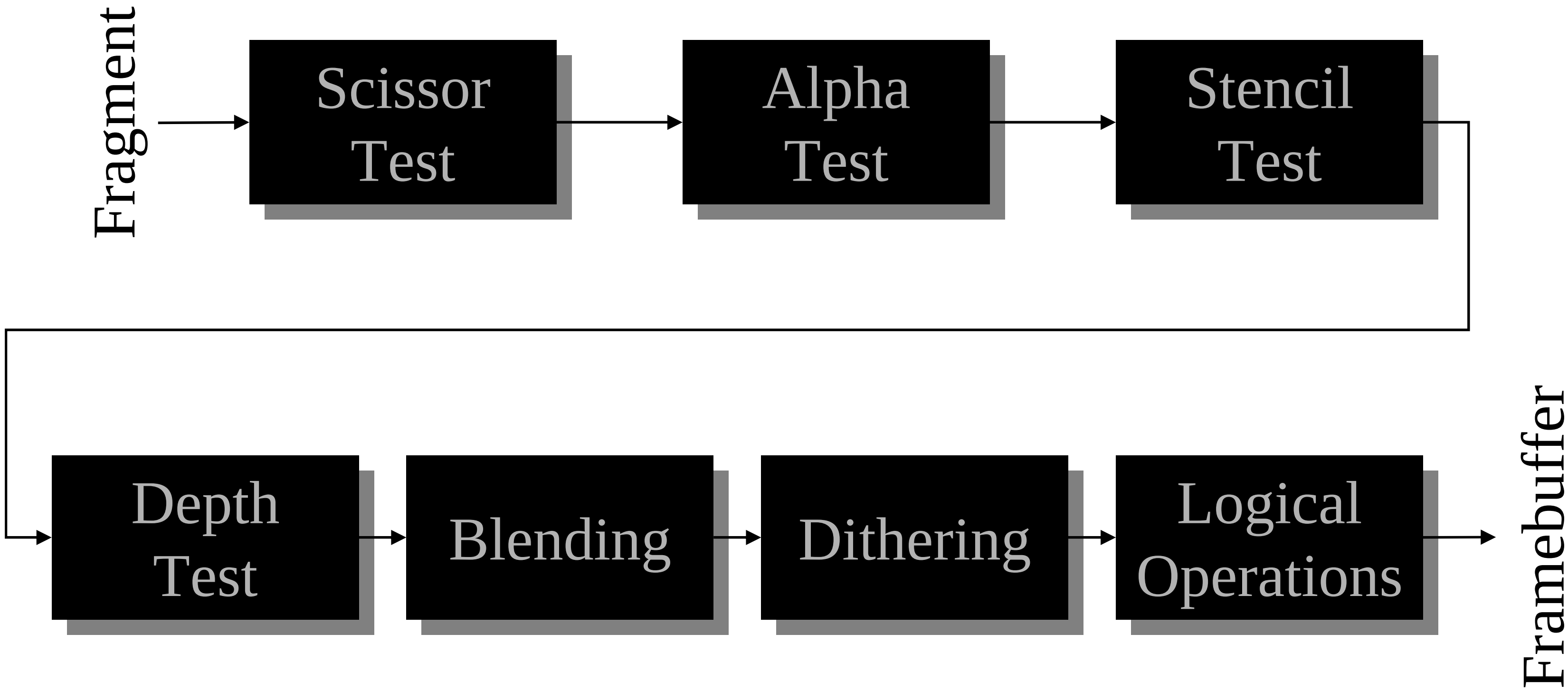
Picking Template (cont.)

```
    glMatrixMode( GL_PROJECTION );
    glPopMatrix();
    hits = glRenderMode( GL_RENDER );
/*   process nameBuffer  */
}
```

Picking Ideas

- For OpenGL Picking Mechanism
  - only render what is pickable (e.g., don't clear screen!)
  - use an "invisible" filled rectangle, instead of text
  - if several primitives drawn in picking region, hard to use z values to distinguish which primitive is "on top"
- Alternatives to Standard Mechanism
  - color or stencil tricks (for example, use **`glReadPixels()`** to obtain pixel value from back buffer)

Getting to the Framebuffer



Scissor Box

- Additional Clipping Test

```
glScissor( x, y, w, h )
```

  – any fragments outside of box are clipped
  – useful for updating a small section of a viewport
    - affects **glClear()** operations

Alpha Test

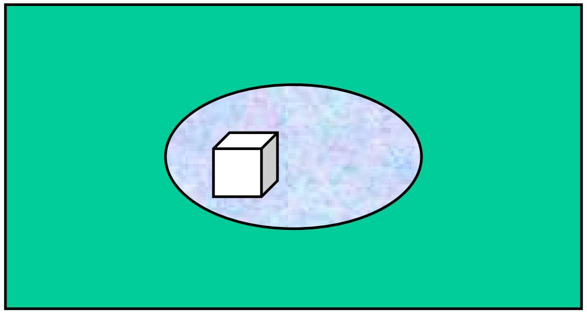
Reject pixels based on their alpha value

```
glAlphaFunc( func, value )
glEnable( GL_ALPHA_TEST )
```

use alpha as a mask in textures

Stencil Buffer

- Used to control drawing based on values in the stencil buffer
  - Fragments that fail the stencil test are not drawn
  - Example: create a mask in stencil buffer and draw only objects not in mask area



Controlling Stencil Buffer

`glStencilFunc( func, ref, mask )`

- compare value in buffer with **ref** using **func**
- only applied for bits in **mask** which are 1
- **func** is one of standard comparison functions

`glStencilOp( fail, zfail, zpass )`

- Allows changes in stencil buffer based on passing or failing stencil and depth tests: **GL_KEEP, GL_INCR**

Creating a Mask

```
glInitDisplayMode( …|GLUT_STENCIL|… );
glEnable( GL_STENCIL_TEST );
glClearStencil( 0x1 );

glStencilFunc( GL_ALWAYS, 0x1, 0x1 );
glStencilOp( GL_REPLACE, GL_REPLACE,
             GL_REPLACE );
```

- *draw mask*

Using Stencil Mask

`glStencilFunc( GL_EQUAL, 0x1, 0x1 )`

- draw objects where stencil = 1

```
glStencilFunc( GL_NOT_EQUAL, 0x1, 0x1 );
glStencilOp( GL_KEEP, GL_KEEP, GL_KEEP );
```

- draw objects where stencil != 1

Dithering

```
glEnable( GL_DITHER )
```

- Dither colors for better looking results
  - Used to simulate more available colors

Logical Operations on Pixels

Combine pixels using bitwise logical operations

`glLogicOp( mode )`

- Common modes
  - **`GL_XOR`**
  - **`GL_AND`**

Advanced Imaging

Imaging Subset

- Only available if **`GL_ARB_imaging`** defined
  - Color matrix
  - Convolutions
  - Color tables
  - Histogram
  - MinMax
  - Advanced Blending

On-Line Resources

- **`http://www.opengl.org`**
  - start here; up to date specification and lots of sample code
- **`news:comp.graphics.api.opengl`**
- **`http://www.sgi.com/software/opengl`**
- **`http://www.mesa3d.org/`**
  - Brian Paul's Mesa 3D
- **`http://www.xmission.com/~nate/tutors.html`**
  - very special thanks to Nate Robins for the OpenGL Tutors
  - source code for tutors available here!

Books

OpenGL Programming Guide, 3rd Edition

OpenGL Reference Manual, 3rd Edition

OpenGL Programming for the X Window System

- includes many GLUT examples

Interactive Computer Graphics: A top-down approach with OpenGL, 2nd Edition

http://www.cs.unm.edu/~angel/BOOK/