An Interactive Introduction to OpenGL Programming

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What You'll See Today

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

Goals for Today

- Demonstrate enough OpenGL to write an interactive graphics program with
  - custom modeled 3D objects or imagery
  - lighting
  - texture mapping
- Introduce advanced topics for future investigation

OpenGL and GLUT Overview

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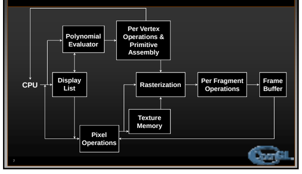
OpenGL and GLUT Overview

- 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



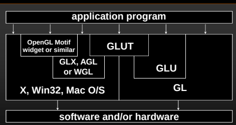
OpenGL as a Renderer

- 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
- 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

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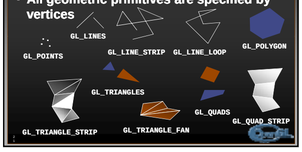
Elementary Rendering

- 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( 1.5, 1.118 );
   glVertex2f( 0.5, 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)

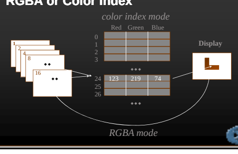
Specifying Geometric Primitives

- Primitives are specified using
  `glBegin( primType );`
  `glEnd();`
  - *primType* determines how vertices are combined

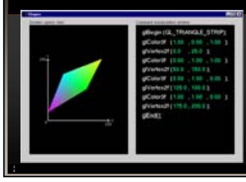
```
GLfloat red, greed, blue;
Glfloat coords[3];
glBegin( primType );
for ( i = 0; i < nVerts; ++i ) {
  glColor3f( red, green, blue );
  glVertex3fv( coords );
}
glEnd();
```


OpenGL Color Models

- RGBA or Color Index

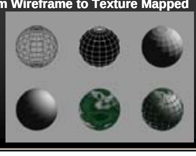


Shapes Tutorial



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
    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

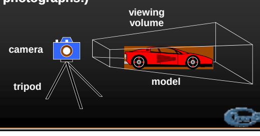
Ed Angel

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 $\mathbf{M}\vec{v}$

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

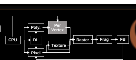
Specifying Transformations

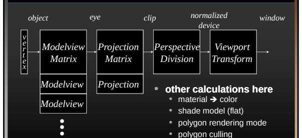
- **Programmer has two styles of specifying transformations**
  - specify matrices (`glLoadMatrix, glMultMatrix`)
  - specify operation (`glRotate, glOrtho`)
- **Programmer does not have to remember the exact matrices**
  - check appendix of Red Book (Programming Guide)

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

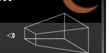
Matrix Operations

- **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**

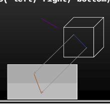


- **Perspective projection**
  `gluPerspective( fovy, aspect, zNear, zFar )`
  `glFrustum( left, right, bottom, top, zNear, zFar )`
- **Orthographic parallel projection**
  `glOrtho( left, right, bottom, top, zNear, zFar )`
  `gluOrtho2D( left, right, bottom, top )`
  - calls `glOrtho` with z values 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

- `gluLookAt(` 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

Modeling Transformations

- **Move object**
  `glTranslate{fd}( x, y, z )`
- **Rotate object around arbitrary axis** $(x\ y\ z)$
  `glRotate{fd}( angle, x, y, z )`
  - angle is in degrees
- **Dilate (stretch or shrink) or mirror object**
  `glScale{fd}( x, y, z )`

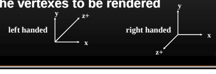
Transformation Tutorial

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( 65.0, (GLfloat) w / h,
                   1.0, 100.0 );
   glMatrixMode( GL_MODELVIEW );
   glLoadIdentity();
   gluLookAt( 0.0, 0.0, 5.0,
              0.0, 0.0, 0.0,
              0.0, 1.0, 0.0 );
}
```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`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( 65.0, (GLfloat) w/h,
                   1.0, 100.0 );
   glMatrixMode( GL_MODELVIEW );
   glLoadIdentity();
   glTranslatef( 0.0, 0.0, -5.0 );
}
```

`resize()`: Ortho (part 1)

```
void resize( int width, int height )
{
   GLdouble aspect = (GLdouble) width / height;
   GLdouble left = -2.5, right = 2.5;
   GLdouble bottom = -2.5, top = 2.5;
   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

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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 reverse order of operations 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

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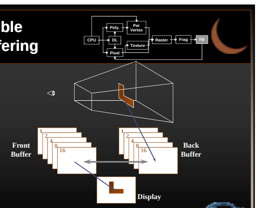
Animation and Depth Buffering

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

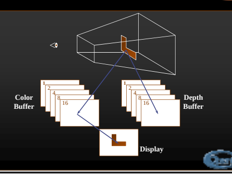
Double Buffering

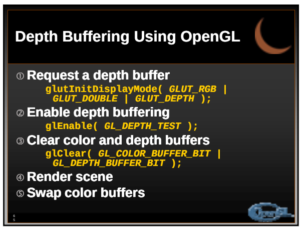


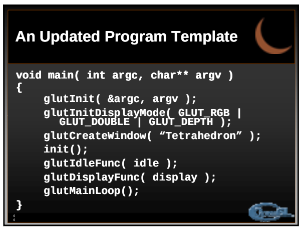
Animation Using Double Buffering

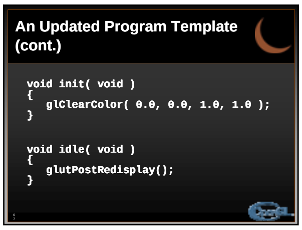
① **Request a double buffered color buffer**
`glutInitDisplayMode( GLUT_RGB | GLUT_DOUBLE );`
② **Clear color buffer**
`glClear( GL_COLOR_BUFFER_BIT );`
③ **Render scene**
④ **Request swap of front and back buffers**
`glutSwapBuffers();`
- **Repeat steps 2 - 4 for animation**

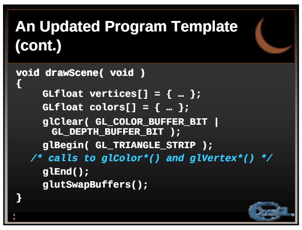
Depth Buffering and Hidden Surface Removal











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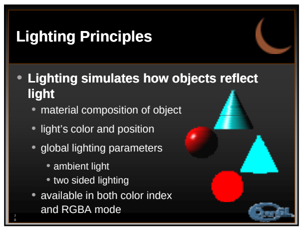

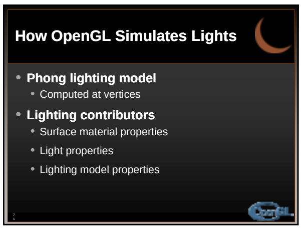

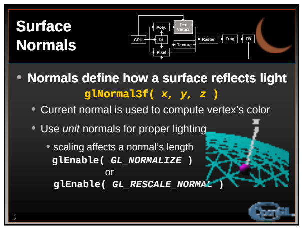

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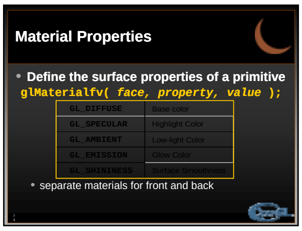

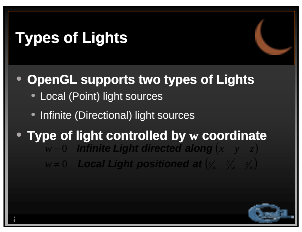

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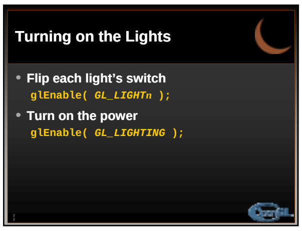
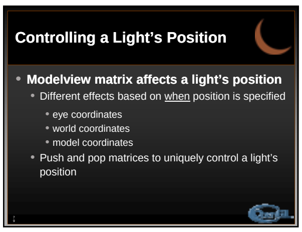




Advanced Lighting Features

- **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

Vicki Shreiner

Imaging and Raster Primitives

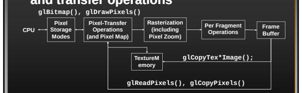
- **Describe OpenGL's raster primitives: bitmaps and image rectangles**
- **Demonstrate how to get OpenGL to read and render pixel rectangles**

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

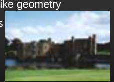
- **Programmable pixel storage and transfer operations**



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

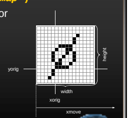


Raster Position

Rendering Bitmaps

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

- render bitmap in current color at $(\lfloor x - xorig \rfloor \quad \lfloor y - yorig \rfloor)$
- advance raster position by $(xmove \quad ymove)$ 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 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**
  `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

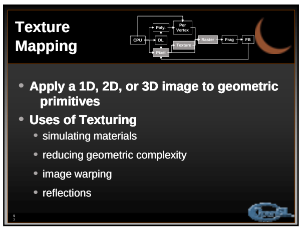
`glPixelZoom(1.0, -1.0);`

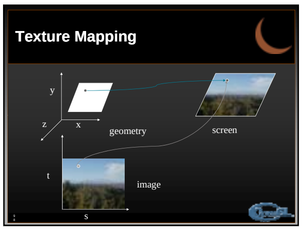
Storage and Transfer Modes

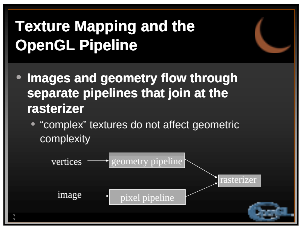
- **Storage modes control accessing memory**
  - byte alignment in host memory
  - extracting a subimage
- **Transfer modes allow modify pixel values**
  - scale and bias pixel component values
  - replace colors using pixel maps

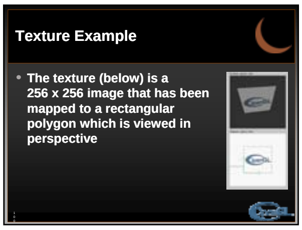
Texture Mapping

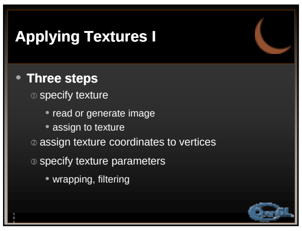
Ed Angel

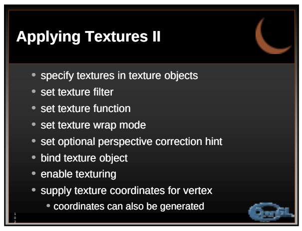

Texture Mapping
CPU
DL
Poly.
Per Vertex
Texture
Pixel
Raster
Frag
FB
Apply a 1D, 2D, or 3D image to geometric primitives
Uses of Texturing
simulating materials
reducing geometric complexity
image warping
reflections

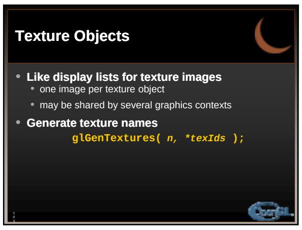

Texture Mapping
y
z
x
geometry
screen
t
image
s

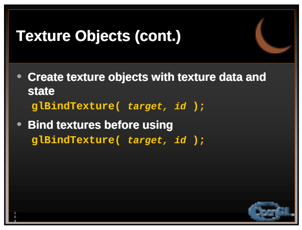

Texture Mapping and the OpenGL Pipeline
Images and geometry flow through separate pipelines that join at the rasterizer
"complex" textures do not affect geometric complexity
vertices
geometry pipeline
rasterizer
image
pixel pipeline

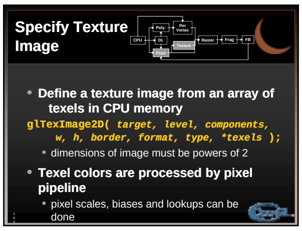

Texture Example
The texture (below) is a 256 x 256 image that has been mapped to a rectangular polygon which is viewed in perspective

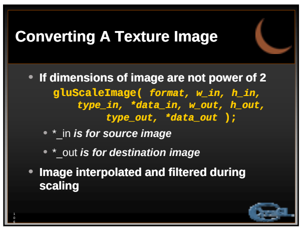

Applying Textures I
Three steps
① specify texture
read or generate image
assign to texture
② assign texture coordinates to vertices
③ specify texture parameters
wrapping, filtering

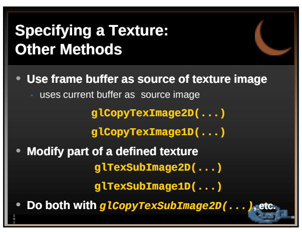

Applying Textures II
specify textures in texture objects
set texture filter
set texture function
set texture wrap mode
set optional perspective correction hint
bind texture object
enable texturing
supply texture coordinates for vertex
coordinates can also be generated

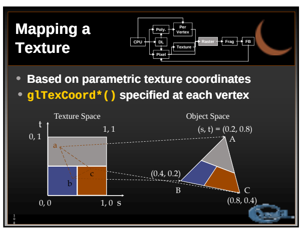

Texture Objects
Like display lists for texture images
one image per texture object
may be shared by several graphics contexts
Generate texture names
glGenTextures(n, *texIds);

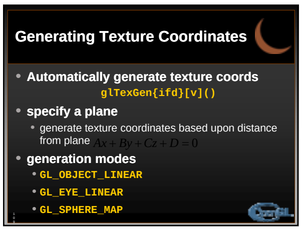

Texture Objects (cont.)
Create texture objects with texture data and state
glBindTexture(target, id);
Bind textures before using
glBindTexture(target, id);


Specify Texture Image
CPU
DL
Poly.
Per Vertex
Texture
Pixel
Raster
Frag
FB
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

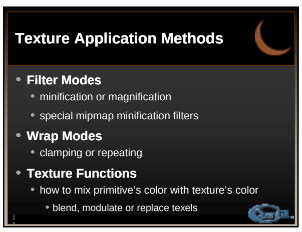

Converting A Texture Image
If dimensions of image are not power of 2
gluScaleImage(format, w_in, h_in, type_in, *data_in, w_out, h_out, type_out, *data_out);
*_in is for source image
*_out is for destination image
Image interpolated and filtered during scaling

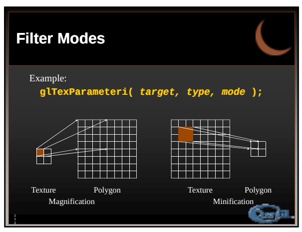

Specifying a Texture: Other Methods
Use frame buffer as source of texture image
uses current buffer as source image
glCopyTexImage2D(...)
glCopyTexImage1D(...)
Modify part of a defined texture
glTexSubImage2D(...)
glTexSubImage1D(...)
Do both with glCopyTexSubImage2D(...), etc.

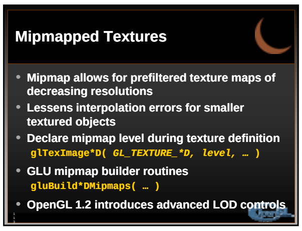

Mapping a Texture
CPU
DL
Poly.
Per Vertex
Texture
Pixel
Raster
Frag
FB
Based on parametric texture coordinates
glTexCoord*() specified at each vertex
Texture Space
Object Space
t
0, 1
1, 1
a
b
c
0, 0
1, 0
s
(s, t) = (0.2, 0.8)
A
(0.4, 0.2)
B
C
(0.8, 0.4)

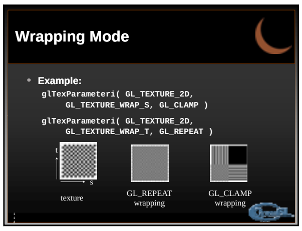

Generating Texture Coordinates
Automatically generate texture coords
glTexGen{ifd}[v]()
specify a plane
generate texture coordinates based upon distance from plane Ax + By + Cz + D = 0
generation modes
GL_OBJECT_LINEAR
GL_EYE_LINEAR
GL_SPHERE_MAP

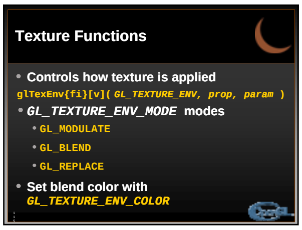

Tutorial: Texture

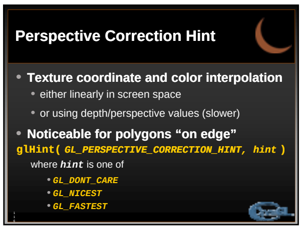

Texture Application Methods
Filter Modes
minification or magnification
special mipmap minification filters
Wrap Modes
clamping or repeating
Texture Functions
how to mix primitive's color with texture's color
blend, modulate or replace texels

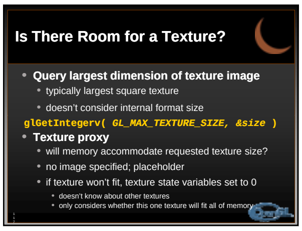

Filter Modes
Example:
glTexParameteri(target, type, mode);
Texture
Polygon
Magnification
Texture
Polygon
Minification

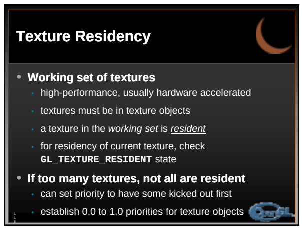

Mipmapped Textures
Mipmap allows for prefiltered texture maps of decreasing resolutions
Lessens interpolation errors for smaller textured objects
Declare mipmap level during texture definition
glTexImage*D(GL_TEXTURE_*D, level, …)
GLU mipmap builder routines
gluBuild*DMipmaps(…)
OpenGL 1.2 introduces 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

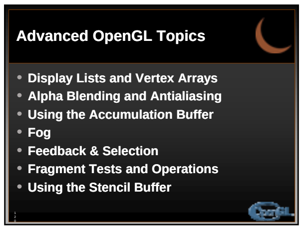

Texture Functions
Controls how texture is applied
glTexEnv{fi}[v](GL_TEXTURE_ENV, prop, param)
GL_TEXTURE_ENV_MODE modes
GL_MODULATE
GL_BLEND
GL_REPLACE
Set blend color with GL_TEXTURE_ENV_COLOR

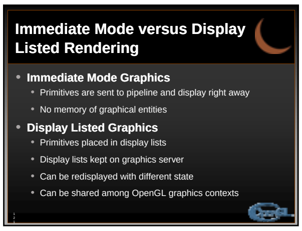

Perspective Correction Hint
Texture coordinate and color interpolation
either linearly in screen space
or using depth/perspective values (slower)
Noticeable for polygons "on edge"
glHint(GL_PERSPECTIVE_CORRECTION_HINT, hint)
where hint is one of
GL_DONT_CARE
GL_NICEST
GL_FASTEST

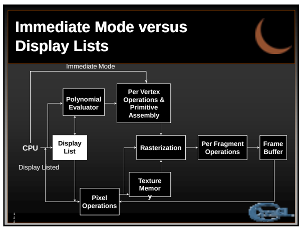

Is There Room for a Texture?
Query largest dimension of texture image
typically largest square texture
doesn't consider internal format size
glGetIntegerv(GL_MAX_TEXTURE_SIZE, &size)
Texture proxy
will memory accommodate requested texture size?
no image specified; placeholder
if texture won't fit, texture state variables set to 0
doesn't know about other textures
only considers whether this one texture will fit all of memory

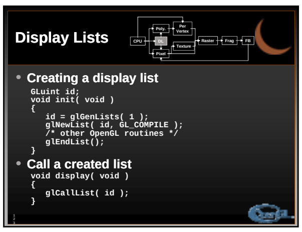

Texture Residency
Working set of textures
high-performance, usually hardware accelerated
textures must be in texture objects
a texture in the working set is resident
for residency of current texture, check GL_TEXTURE_RESIDENT state
If too many textures, not all are resident
can set priority to have some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

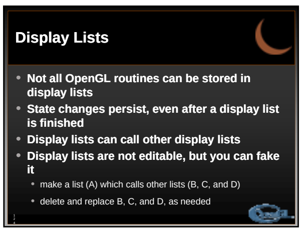

Advanced OpenGL Topics
Dave Shreiner

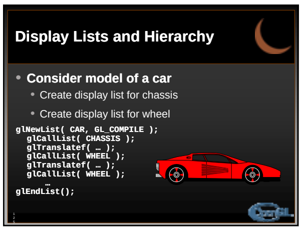

Advanced OpenGL Topics
Display Lists and Vertex Arrays
Alpha Blending and Antialiasing
Using the Accumulation Buffer
Fog
Feedback & Selection
Fragment Tests and Operations
Using the Stencil Buffer

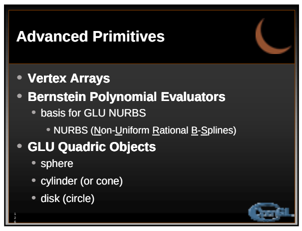

Immediate Mode versus Display Listed Rendering
Immediate Mode Graphics
Primitives are sent to pipeline and display right away
No memory of graphical entities
Display Listed Graphics
Primitives placed in display lists
Display lists kept on graphics server
Can be redisplayed with different state
Can be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

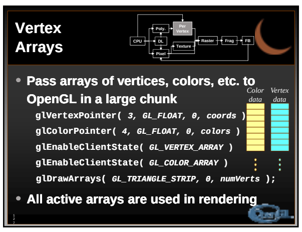

Immediate Mode versus Display Lists
Immediate Mode
Polynomial Evaluator
Per Vertex Operations & Primitive Assembly
CPU
Display List
Display Listed
Rasterization
Per Fragment Operations
Frame Buffer
Texture Memor
Pixel Operations

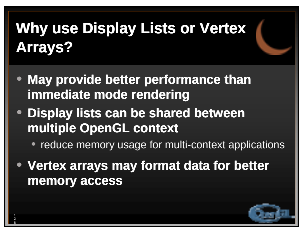

Display Lists
Creating a display list
GLuint id;
void init(void)
{
id = glGenLists(1);
glNewList(id, GL_COMPILE);
/* other OpenGL routines */
glEndList();
}
Call a created list
void display(void)
{
glCallList(id);
}


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);
Color data
Vertex data
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

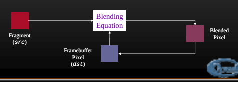
`glEnable( GL_BLEND )`

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

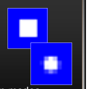
Example of bump-mapping done with a multi-pass OpenGL algorithm

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 )`

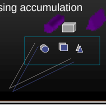
- operations
  - within the accumulation buffer: `GL_ADD, GL_MULT`
  - from read buffer: `GL_ACCUM, GL_LOAD`
  - transfer back to write buffer: `GL_RETURN`
- `glAccum(GL_ACCUM, 0.5)` multiplies each value in write buffer by 0.5 and adds to accumulation buffer

Accumulation Buffer Applications

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

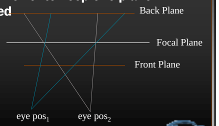
Full Scene Antialiasing : *Jittering the view*

- **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

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 )`

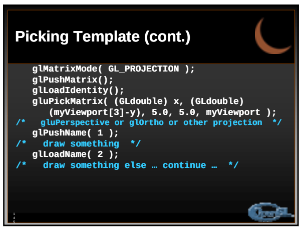
`glInitNames()`

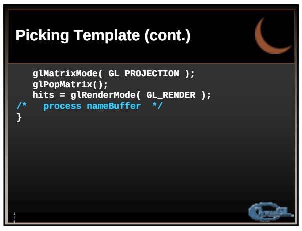
Picking

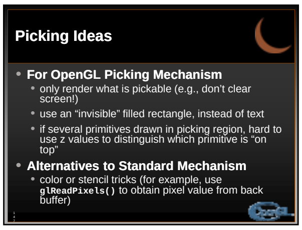
- **Picking is a special case of selection**
- **Programming steps**
  - restrict "drawing" to small region near pointer
    use `gluPickMatrix()` on projection matrix
  - enter selection mode; re-render scene
  - primitives drawn near cursor cause hits
  - exit selection; analyze hit records

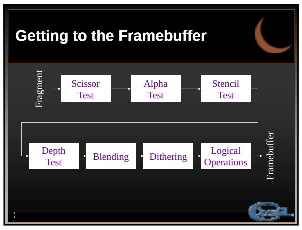
Picking Template

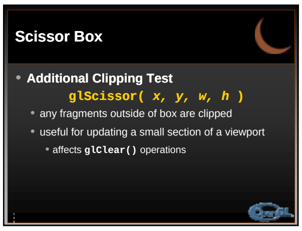
```
glutMouseFunc( pickMe );

void pickMe( int button, int state, int x, int y )
  {
   GLuint nameBuffer[256];
   GLint hits;
   GLint myViewport[4];
   if (button != GLUT_LEFT_BUTTON ||
       state != GLUT_DOWN) return;
   glGetIntegerv( GL_VIEWPORT, myViewport );
   glSelectBuffer( 256, nameBuffer );
   (void) glRenderMode( GL_SELECT );
   glInitNames();
```

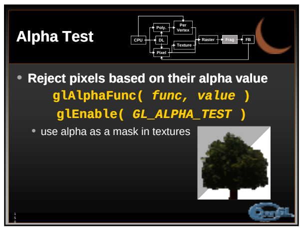

Picking Template (cont.)
glMatrixMode(GL_PROJECTION);
glPushMatrix();
glLoadIdentity();
gluPickMatrix((GLdouble) x, (GLdouble)
(myViewport[3]-y), 5.0, 5.0, myViewport);
/* gluPerspective or glOrtho or other projection */
glPushName(1);
/* draw something */
glLoadName(2);
/* draw something else … continue … */

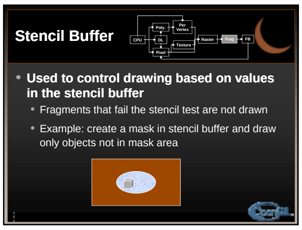

Picking Template (cont.)
glMatrixMode(GL_PROJECTION);
glPopMatrix();
hits = glRenderMode(GL_RENDER);
/* process nameBuffer */
}

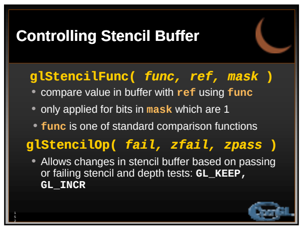

Picking Ideas
For OpenGL Picking Mechanism
only render what is pickable (e.g., don't clear screen!)
use an "invisible" filled rectangle, instead of text
if several primitives drawn in picking region, hard to use z values to distinguish which primitive is "on top"
Alternatives to Standard Mechanism
color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

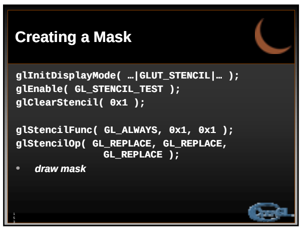

Getting to the Framebuffer
Fragment
Scissor Test
Alpha Test
Stencil Test
Depth Test
Blending
Dithering
Logical Operations
Framebuffer

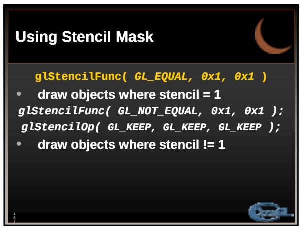

Scissor Box
Additional Clipping Test
glScissor(x, y, w, h)
any fragments outside of box are clipped
useful for updating a small section of a viewport
affects glClear() operations


Alpha Test
CPU
DL
Poly.
Per Vertex
Texture
Pixel
Raster
Frag
FB
Reject pixels based on their alpha value
glAlphaFunc(func, value)
glEnable(GL_ALPHA_TEST)
use alpha as a mask in textures

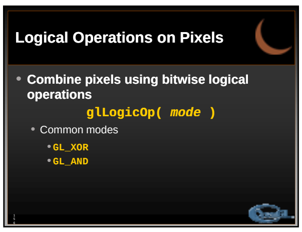

Stencil Buffer
CPU
DL
Poly.
Per Vertex
Texture
Pixel
Raster
Frag
FB
Used to control drawing based on values in the stencil buffer
Fragments that fail the stencil test are not drawn
Example: create a mask in stencil buffer and draw only objects not in mask area

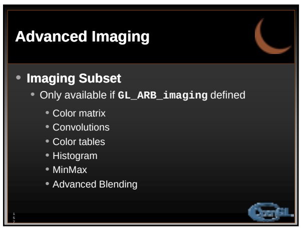

Controlling Stencil Buffer
glStencilFunc(func, ref, mask)
compare value in buffer with ref using func
only applied for bits in mask which are 1
func is one of standard comparison functions
glStencilOp(fail, zfail, zpass)
Allows changes in stencil buffer based on passing or failing stencil and depth tests: GL_KEEP, GL_INCR

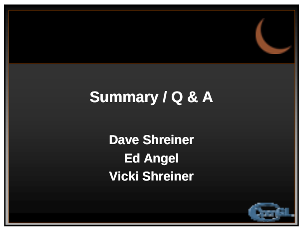

Creating a Mask
glInitDisplayMode(…|GLUT_STENCIL|…);
glEnable(GL_STENCIL_TEST);
glClearStencil(0x1);
glStencilFunc(GL_ALWAYS, 0x1, 0x1);
glStencilOp(GL_REPLACE, GL_REPLACE,
GL_REPLACE);
draw mask

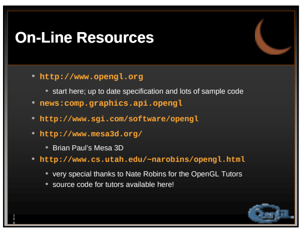

Using Stencil Mask
glStencilFunc(GL_EQUAL, 0x1, 0x1)
draw objects where stencil = 1
glStencilFunc(GL_NOT_EQUAL, 0x1, 0x1);
glStencilOp(GL_KEEP, GL_KEEP, GL_KEEP);
draw objects where stencil != 1


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


Summary / Q & A
Dave Shreiner
Ed Angel
Vicki Shreiner


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.cs.utah.edu/~narobins/opengl.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


Thanks for Coming
Questions and Answers
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Ed Angel angel@cs.unm.edu
Vicki Shreiner vshreiner@sgi.com