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

CPU → Display List → Polynomial Evaluator → Per Vertex Operations & Primitive Assembly → Rasterization → Per Fragment Operations → Frame Buffer

- Display List
- Polynomial Evaluator
- Per Vertex Operations & Primitive Assembly
- Rasterization
- Per Fragment Operations
- Frame Buffer

- Pixel Operations
- Texture Memory
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

application program

OpenGL Motif widget or similar

GLUT

GLX, AGL or WGL

GLU

X, Win32, Mac O/S

GL

software and/or hardware
Preliminaries

Headers Files

```c
#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

```c
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

```c
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

```c
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

```c
glutIdleFunc( idle );

void idle( void )
{
    t += dt;
    glutPostRedisplay();
}
```
**User Input Callbacks**

Process user input

```c
int keyboardFunc( 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.

- **GL_LINES**
- **GL_POINTS**
- **GL_LINE_STRIP**
- **GL_LINE_LOOP**
- **GL_TRIANGLES**
- **GL_QUADS**
- **GL_TRIANGLE_STRIP**
- **GL_TRIANGLE_FAN**
- **GL_POLYGON**
- **GL_QUAD_STRIP**
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 )

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Specifying Geometric Primitives

Primitives are specified using

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

`primType` determines how vertices are combined

```c
GLfloat red, greed, blue;
GLfloat coords[3];

for ( i = 0; i < nVerts; ++i ) {
    glColor3f( red, green, blue );
    glVertex3fv( coords );
}

glEnd();
```
OpenGL Color Models

RGBA or Color Index

color index mode

RGBA mode

Display

Department of Computer Science and Engineering
Shapes Tutorial

```
gBegin (GL_TRIANGLES_STRIP);
gColor3f (1.00, 0.00, 1.00);
gVertex2f (0.0, 25.0);
gColor3f (0.00, 1.00, 1.00);
gVertex2f (50.0, 150.0);
gColor3f (0.00, 1.00, 0.00);
gVertex2f (125.0, 100.0);
gColor3f (1.00, 1.00, 0.00);
gVertex2f (175.0, 200.0);
gEnd();
```

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

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

Enabling Features

```c
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 $M\vec{v}$

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

Programmer has two styles of specifying transformations

- specify matrices (\texttt{glLoadMatrix}, \texttt{glMultMatrix})
- specify operation (\texttt{glRotate}, \texttt{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

- object
- eye
- clip
- normalized device
- window

Modelview Matrix → Projection Matrix → Perspective Division → Viewport Transform

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

Specify Current Matrix Stack

\[
\text{glMatrixMode( } \text{GL_MODELVIEW or GL_PROJECTION } \text{ )}
\]

Other Matrix or Stack Operations

\[
\text{glLoadIdentity()} \quad \text{glPushMatrix()}
\]

\[
\text{glPopMatrix()} \quad \text{glPopMatrix()}
\]

Viewport

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

\[
\text{glViewport( x, y, width, height )}
\]
Projection Transformation

Shape of viewing frustum

Perspective projection

\[
\text{gluPerspective}( \text{fovy, aspect, zNear, zFar} )
\]

\[
\text{glFrustum}( \text{left, right, bottom, top, zNear, zFar} )
\]

Orthographic parallel projection

\[
\text{glOrtho}( \text{left, right, bottom, top, zNear, zFar} )
\]

\[
\text{gluOrtho2D}( \text{left, right, bottom, top} )
\]

- calls \text{glOrtho} with z values near zero
Applying Projection Transformations

Typical use (orthographic projection)

```c
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

\[
\text{gluLookAt}( \text{eye}_x, \text{eye}_y, \text{eye}_z, \\
\quad \text{aim}_x, \text{aim}_y, \text{aim}_z, \\
\quad \text{up}_x, \text{up}_y, \text{up}_z )
\]
  – up vector determines unique orientation
  – careful of degenerate positions
Projection Tutorial

```
gluPerspective( 60.0, 1.00, 1.0, 100.0 );
gluLookAt( 0.00, 0.00, 2.00, <- eye
           0.00, 0.00, 0.00, <- center
           0.00, 1.00, 0.00 ); <- up
```

Click on the arguments and move the mouse to modify values.

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

Move object

\[
gl\text{Translate}\{fd\}( x, y, z )
\]

Rotate object around arbitrary axis

\[
gl\text{Rotate}\{fd\}( \text{angle}, x, y, z )
\]
  \[\text{angle is in degrees}\]

Dilate (stretch or shrink) or mirror object

\[
gl\text{Scale}\{fd\}( x, y, z )
\]
Transformation Tutorial

```c
glTranslatef( 0.00, 0.00, 0.00 );

glRotatef( -52.0, 0.00, 1.00, 0.00 );

glScalef( 1.00, 1.00, 1.00 );

glBegin( ... );
...
```

Click on the arguments and move the mouse to modify values.

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 $z_{Near}$ and $z_{Far}$ 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

```c
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

```c
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)**

```c
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();
    glMatrixMode( GL_PROJECTION );
    glLoadIdentity();

    ... continued ...
```
```c
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-multiples 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

```c
glEnable( GL_CLIP_PLANEi )
glClipPlane( GL_CLIP_PLANEi, GLdouble* coeff )
```
Reversing Coordinate Projection

Screen space back to world space

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

Front Buffer

Back Buffer

Display
Animation Using Double Buffering

1. Request a double buffered color buffer
   ```c
   glutInitDisplayMode( GLUT_RGB | GLUT_DOUBLE );
   ```
2. Clear color buffer
   ```c
   glClear( GL_COLOR_BUFFER_BIT );
   ```
3. Render scene
4. Request swap of front and back buffers
   ```c
   glutSwapBuffers();
   ```
• Repeat steps 2 - 4 for animation
Depth Buffering and Hidden Surface Removal
Depth Buffering Using OpenGL

① Request a depth buffer
   ```c
   glutInitDisplayMode( GLUT_RGB | GLUT_DOUBLE | GLUT_DEPTH );
   ```

② Enable depth buffering
   ```c
   glEnable( GL_DEPTH_TEST );
   ```

③ Clear color and depth buffers
   ```c
   glClear( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );
   ```

④ Render scene

⑤ Swap color buffers
An Updated Program Template

```c
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.)

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

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

\[ \text{glNormal3f}( x, y, z ) \]

- Current normal is used to compute vertex’s color
- Use *unit* normals for proper lighting
  - scaling affects a normal’s length
    \[ \text{glEnable}( \text{GL_NORMALIZE} ) \]
    or
    \[ \text{glEnable}( \text{GL_RESCALE_NORMAL} ) \]
Material Properties

Define the surface properties of a primitive

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL.Diffuse</td>
<td>Base color</td>
</tr>
<tr>
<td>GL.Specular</td>
<td>Highlight Color</td>
</tr>
<tr>
<td>GL.Ambient</td>
<td>Low-light Color</td>
</tr>
<tr>
<td>GL.Emission</td>
<td>Glow Color</td>
</tr>
<tr>
<td>GL.Shininess</td>
<td>Surface Smoothness</td>
</tr>
</tbody>
</table>

separate materials for front and back
Light Properties

\[ \text{glLightfv( light, property, value );} \]

- **light** specifies which light
  - multiple lights, starting with GL_LIGHT0
    \[ \text{glGetIntegerv( GL_MAX_LIGHTS, \&n );} \]
  
- **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

\[
\begin{align*}
w &= 0 & \text{Infinite Light directed along } (x, y, z) \\
w &\neq 0 & \text{Local Light positioned at } \left(\frac{x}{w}, \frac{y}{w}, \frac{z}{w}\right)
\end{align*}
\]
Turning on the Lights

Flip each light’s switch

\[ \text{glEnable}( \text{GL\_LIGHTn} ); \]

Turn on the power

\[ \text{glEnable}( \text{GL\_LIGHTING} ); \]
Light Material Tutorial

GLfloat light_pos[] = { -2.00, 2.00, 2.00, 1.00};
GLfloat light_Ka[] = { 0.00, 0.00, 0.00, 1.00};
GLfloat light_Kd[] = { 1.00, 1.00, 1.00, 1.00};
GLfloat light_Ks[] = { 1.00, 1.00, 1.00, 1.00};
gLightfv(GL_LIGHT0, GL_POSITION, light_pos);
gLightfv(GL_LIGHT0, GL_AMBIENT, light_Ka);
gLightfv(GL_LIGHT0, GL_DIFFUSE, light_Kd);
gLightfv(GL_LIGHT0, GL_SPECULAR, light_Ks);  

GLfloat material_Ka[] = { 0.11, 0.06, 0.11, 1.00};
GLfloat material_Kd[] = { 0.43, 0.47, 0.54, 1.00};
GLfloat material_Ks[] = { 0.33, 0.33, 0.52, 1.00};
GLfloat material_Ke[] = { 0.00, 0.00, 0.00, 0.00};
GLfloat material_Se = 10;
mMaterialfv(GL_FRONT, GL_AMBIENT, material_Ka);
mMaterialfv(GL_FRONT, GL_DIFFUSE, material_Kd);
mMaterialfv(GL_FRONT, GL_SPECULAR, material_Ks);
mMaterialfv(GL_FRONT, GL_EMISSION, material_Ke);
mMaterialfv(GL_FRONT, GL_SHININESS, material_Se);

Click on the arguments and move the mouse to modify values.

http://www.xmission.com/~nate/tutors.html
Controlling a Light’s Position

Modelview matrix affects a light’s position

- Different effects based on when position is specified
  - eye coordinates
  - world coordinates
  - model coordinates
- Push and pop matrices to uniquely control a light’s position
Light Position Tutorial

GLfloat pos[4] = { 1.50, 1.00, 1.00, 0.00 };  
gluLookAt( 0.00, 0.00, 2.00,  <- eye  
  0.00, 0.00, 0.00,  <- center  
  0.00, 1.00, 0.00 );  <- up  
gllightfv(GL_LIGHT0, GL_POSITION, pos);  

Click on the arguments and move the mouse to modify values.

http://www.xmission.com/~nate/tutors.html
Advanced Lighting Features

Spotlights

- localize lighting affects
  - \texttt{GL\_SPOT\_DIRECTION}
  - \texttt{GL\_SPOT\_CUTOFF}
  - \texttt{GL\_SPOT\_EXPONENT}
Advanced Lighting Features

Light attenuation

- decrease light intensity with distance
  - \texttt{GL\_CONSTANT\_ATTENUATION}
  - \texttt{GL\_LINEAR\_ATTENUATION}
  - \texttt{GL\_QUADRATIC\_ATTENUATION}

\[
f_i = \frac{1}{k_c + k_l d + k_q d^2}
\]
Light Model Properties

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

Enabling two sided lighting

```c
GL_LIGHT_MODEL_TWO_SIDE
```

Global ambient color

```c
GL_LIGHT_MODEL_AMBIENT
```

Local viewer mode

```c
GL_LIGHT_MODEL_LOCAL_VIEWER
```

Separate specular color

```c
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

```
glBitmap(), glDrawPixels()

CPU → Pixel Storage Modes → Pixel-Transfer Operations (and Pixel Map) → Rasterization (including Pixel Zoom) → Per Fragment Operations → Frame Buffer

Texture Memory

glCopyTexImage();
glReadPixels(), glCopyPixels()
```
Positioning Image Primitives

\texttt{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
Rendering Bitmaps

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

- render bitmap in current color at \( \left( x - xorig \right) \), \( y - yorig \)
- 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
  
  \texttt{glXUseXFont()}
  
  \texttt{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:

```c
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:

```c
    glutBitmapLength (void *font,
                      GLchar *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:

```c
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:

```c
    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:

```c
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:

```c
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 (\texttt{GL_LINES}) are used for rendering the characters, we can use the usual functions to change the attributes:

Antialiasing:

\begin{verbatim}
    glEnable (GL_BLEND);
    glEnable (GL_LINE_SMOOTH);

    glBlendFunc (GL_SRC_ALPHA,
                GL_ONE_MINUS_SRC_ALPHA);
\end{verbatim}

Line width:

\begin{verbatim}
    glLineWidth (2.0);
\end{verbatim}
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

\texttt{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)

\texttt{glCopyPixels}( x, y, width, height, type )
Pixel Zoom

\texttt{glPixelZoom(x, y)}

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

Geometry

Screen

Image

Department of Computer Science and Engineering
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

```c
glGenTextures( n, *texIds );
```
Texture Objects (cont.)

Create texture objects with texture data and state

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

Bind textures before using

```c
glBindTexture( target, id );
```
Specify Texture Image

• Define a texture image from an array of texels in CPU memory
  
  \texttt{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

```c
void gluScaleImage(GLenum format, GLint w_in, GLint h_in,
                   GLenum type_in, void* data_in, GLint w_out, GLint h_out,
                   GLenum type_out, void* 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

\texttt{glCopyTexImage2D(...)}
\texttt{glCopyTexImage1D(...)}

Modify part of a defined texture

\texttt{glTexSubImage2D(...)}
\texttt{glTexSubImage1D(...)}

Do both with \texttt{glCopyTexSubImage2D(...)}, etc.
Mapping a Texture

Based on parametric texture coordinates

`glTexCoord*()` specified at each vertex

Texture Space

Object Space

```
(0.2, 0.8)
(0.4, 0.2)
(0.8, 0.4)
```
Generating Texture Coordinates

Automatically generate texture coords

\[ \text{glTexGen} \{ \text{ifd} \} [v]() \]

specify a plane

- generate texture coordinates based upon distance from plane

\[ Ax + By + Cz + D = 0 \]

generation modes

- \text{GL\_OBJECT\_LINEAR} (mapping w.r.t. object)
- \text{GL\_EYE\_LINEAR} (mapping w.r.t. eye location)
- \text{GL\_SPHERE\_MAP} (environment mapping)
Tutorial: Texture

GLfloat border_color[] = { 1.00 , 0.00 , 0.00 , 1.00 };  
GLfloat env_color[] = { 0.00 , 1.00 , 0.00 , 1.00 };  

gTexImage2D(GL_TEXTURE_2D, 0, GL_RGB, w, h, GL_RGB, GL_UNSIGNED_BYTE, image);  

gColor4f( 0.60 , 0.60 , 0.60 , 1.00 );  

gBegin(GL_POLYGON);  

gTexCoord2f( 0.0 , 0.0 ); glVertex3f( -1.0 , -1.0 , 0.0 );  

gTexCoord2f( 1.0 , 0.0 ); glVertex3f( 1.0 , -1.0 , 0.0 );  

gTexCoord2f( 1.0 , 1.0 ); glVertex3f( 1.0 , 1.0 , 0.0 );  

gTexCoord2f( 0.0 , 1.0 ); glVertex3f( -1.0 , 1.0 , 0.0 );  

gEnd();

Click on the arguments and move the mouse to modify values.

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:

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

![Diagram showing texture and polygon magnification and minification](image)
Mipmapped Textures

• Mipmap allows for prefiltered texture maps of decreasing resolutions
• Lessens interpolation errors for smaller textured objects
• Declare mipmap level during texture definition
  \texttt{glTexImage*D( GL\_TEXTURE\_*D, level, ... )}
• GLU mipmap builder routines
  \texttt{gluBuild*DMipmaps( ... )}
• OpenGL 1.2 introduces advanced LOD controls
Wrapping Mode

Example:

```c
glTexParameteri( GL_TEXTURE_2D,
               GL_TEXTURE_WRAP_S, GL_CLAMP )

glTexParameteri( GL_TEXTURE_2D,
               GL_TEXTURE_WRAP_T, GL_REPEAT )
```

The images illustrate the difference between GL_REPEAT and GL_CLAMP wrapping modes for a 2D texture.
Texture Functions

Controls how texture is applied

\[ \text{glTexEnv}\{fi\}[v]( \text{GL\_TEXTURE\_ENV}, \text{prop}, \text{param} ) \]

**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”

```c
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
    
    ```c
    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 Anti-aliasing
- 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 Memory

Pixel Operations

Department of Computer Science and Engineering
Display Lists

Creating a display list

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

Call a created list

```c
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

```c
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

```c
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 4\textsuperscript{th} Color Component

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

\texttt{glEnable( GL\_BLEND )}
Blending

Combine pixels with what’s in already in the framebuffer

\[ \tilde{C}_r = \text{src} \, \tilde{C}_f + \text{dst} \, \tilde{C}_p \]

\begin{align*}
\text{glBlendFunc( src, dst )}
\end{align*}
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

```c
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

\texttt{glAccum( op, value )}

- operations
  - within the accumulation buffer: \texttt{GL_ADD, GL_MULT}
  - from read buffer: \texttt{GL_ACCUM, GL_LOAD}
  - transfer back to write buffer: \texttt{GL_RETURN}
- \texttt{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

\[ f = \frac{\text{end} - z}{\text{end} - \text{start}} \]

\( z \) is the distance in eye coordinates from origin to fragment being fogged.

Command manipulation window:

```c
GLfloat color[4] = { 0.70, 0.70, 0.70, 1.00 };
glFogf(GL_FOG_COLOR, color);
glFogf(GL_FOG_START, 0.50);
glFogf(GL_FOG_END, 2.00);
glFogi(GL_FOG_MODE, GL_LINEAR);
```

Click on the arguments and move the mouse to modify values.

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
  \[
  \text{glFeedbackBuffer}( \text{size}, \text{type}, \text{buffer} )
  \]
- Select feedback mode for rendering
  \[
  \text{glRenderMode}( \text{GL_FEEDBACK} )
  \]
Selection Mode

- Method to determine which primitives are inside the viewing volume
- Need to set up a buffer to have results returned to you
  \[ \text{glSelectBuffer( size, buffer )} \]
- Select selection mode for rendering
  \[ \text{glRenderMode( GL_SELECT )} \]
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

```c
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.)

```c
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.)

```c
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

  \[ \text{glScissor}(x, y, w, h) \]

  - any fragments outside of box are clipped
  - useful for updating a small section of a viewport
    - affects `glClearColor()` operations
Alpha Test

Reject pixels based on their alpha value

```c
.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

\texttt{glStencilFunc( \textit{func}, \textit{ref}, \textit{mask} )}

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

\texttt{glStencilOp( \textit{fail}, \textit{zfail}, \textit{zpass} )}

- Allows changes in stencil buffer based on passing or failing stencil and depth tests: \texttt{GL\_KEEP, GL\_INCR}
Creating a Mask

```c
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

\[ \text{glLogicOp}( \text{mode} ) \]

- 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 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/