Interactive Computer Graphics

OpenGL and the Graphics Pipeline

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

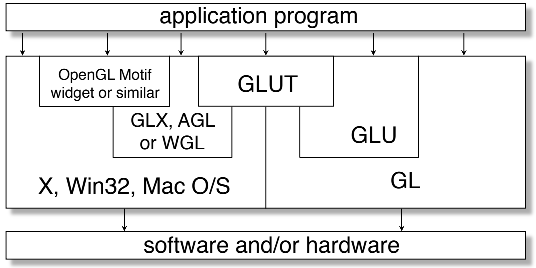
OpenGL as a Renderer

- 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

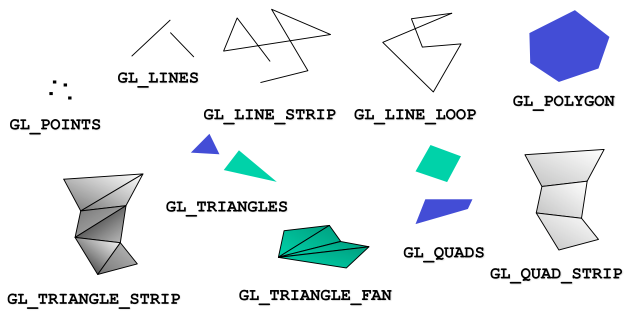
```
glutKeyboardFunc( keyboard );
```

```
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

- Geometric Primitives
- Managing OpenGL State
- OpenGL Buffers

OpenGL Geometric Primitives



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

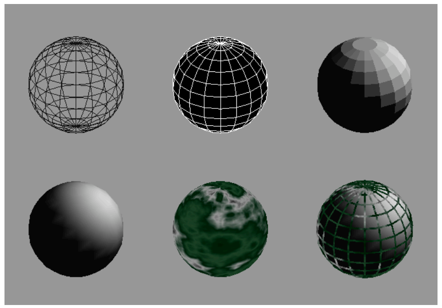
```
glBegin( primType );
glEnd();
```

  - *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();
```

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

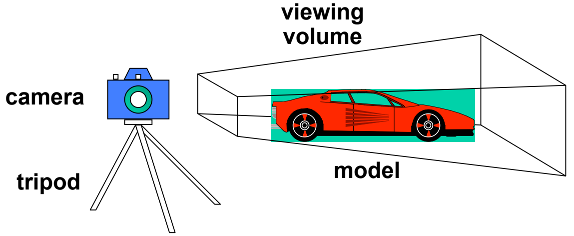
```
glEnable( GL_LIGHTING );
glDisable( GL_TEXTURE_2D );
```

Transformations 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

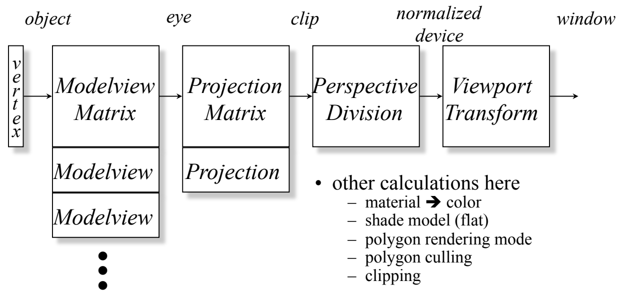
- A vertex is transformed by 4 x 4 matrices
  - all affine operations are matrix multiplications
  - all matrices are stored column-major in OpenGL
  - matrices are always post-multiplied
  - product of matrix and vector is $\mathbf{M}\vec{v}$

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

Specifying Transformations

- Programmer has two styles of specifying transformations
  - specify matrices (`glLoadMatrix, glMultMatrix`)
  - specify operation (`glRotate, glOrtho`)
- Prior to rendering, view, locate, and orient:
  - eye/camera position
  - 3D geometry
- Manage the matrices
  - including matrix stack
- Combine (composite) transformations

Transformation Pipeline



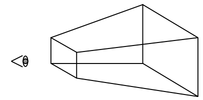
- other calculations here
  - material → color
  - shade model (flat)
  - polygon rendering mode
  - polygon culling
  - clipping

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

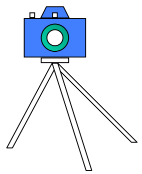


- Shape of viewing frustum
- Perspective projection
  ```
  gluPerspective( fovy, aspect, zNear, zFar )
  glFrustum( left, right, bottom, top, zNear, zFar )
  ```
- Orthographic parallel projection
  ```
  glOrtho( left, right, bottom, top, zNear, zFar )
  gluOrtho2D( left, right, bottom, top )
  ```
  - calls `glOrtho` with z values near zero
- 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

tripod



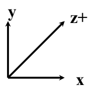
Modeling Transformations

- Moving camera is equivalent to moving every object in the world towards a stationary camera
- Move object
  `glTranslate{fd}( x, y, z )`
- Rotate object around arbitrary axis
  `glRotate{fd}( angle, x, y, z )`
  - angle is in degrees
- Dilate (stretch or shrink) or mirror object
  `glScale{fd}( x, y, z )`

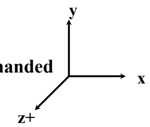
Projection is left handed

- 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

left handed



right handed



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 );
}
```

`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 …

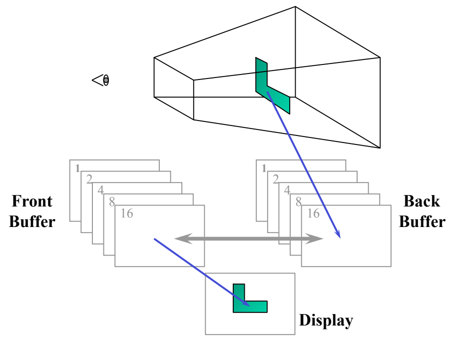
`resize():` *Ortho (part 2)*

```
   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

Double Buffering



Animation Using Double Buffering

- Request a double buffered color buffer

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

- Clear color buffer

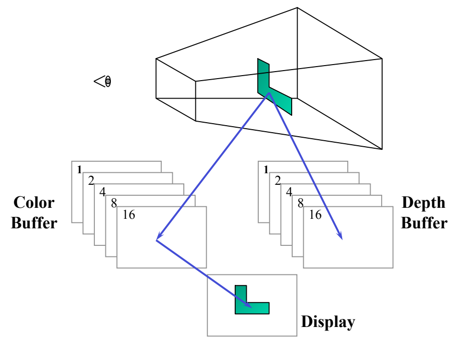
```
glClear( GL_COLOR_BUFFER_BIT );
```

- Render scene
- Request swap of front and back buffers

```
glutSwapBuffers();
```

- Repeat steps 2 - 4 for animation

Depth Buffering and Hidden Surface Removal



Depth Buffering Using OpenGL

- Request a depth buffer

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

- Enable depth buffering

```
glEnable( GL_DEPTH_TEST );
```

- Clear color and depth buffers

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

- Render scene
- 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.)

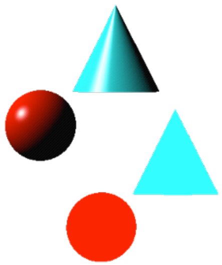
```
void drawScene( void )
{
     GLfloat vertices[] = { … };
     GLfloat colors[] = { … };
     glClear( GL_COLOR_BUFFER_BIT |
       GL_DEPTH_BUFFER_BIT );
     glBegin( GL_TRIANGLE_STRIP );

     /* calls to glColor*() and glVertex*() */

     glEnd();
     glutSwapBuffers();
}
```

Lighting 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

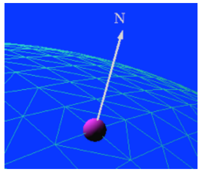
```
glNormal3f( x, y, z )
```

  – 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 );
```

  – separate materials for front and back

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

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

$$w = 0 \quad \text{Infinite Light directed along } \begin{pmatrix} x & y & z \end{pmatrix}$$
$$w \neq 0 \quad \text{Local Light positioned at } \begin{pmatrix} x/w & y/w & z/w \end{pmatrix}$$

Turning on the Lights

- Flip each light's switch

```
glEnable( GL_LIGHTn );
```

- Turn on the power

```
glEnable( GL_LIGHTING );
```

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

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

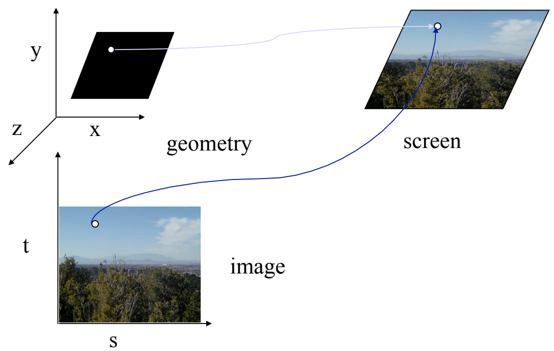
Tips for Better Lighting

- 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

Texture Mapping

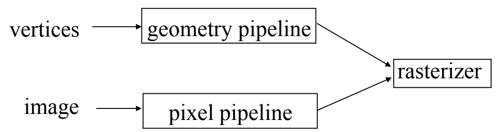
- Apply a 1D, 2D, or 3D image to geometric primitives
- Uses of Texturing
  - simulating materials
  - reducing geometric complexity
  - image warping
  - reflections

Texture Mapping



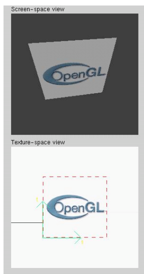
Texture Mapping and the OpenGL Pipeline

- 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 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

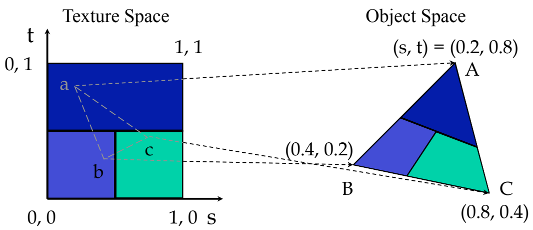
- Define a texture image from an array of texels in CPU memory

```
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

Mapping a Texture

- Based on parametric texture coordinates
- `glTexCoord*()` specified at each vertex



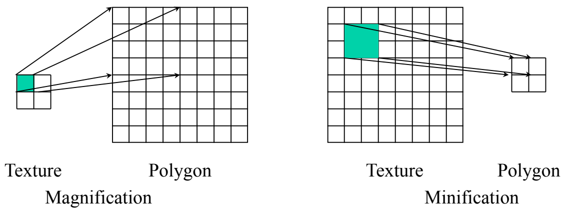
Texture Application Methods

- 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 );
```



Mipmapped Textures

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

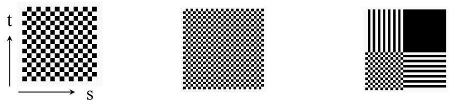
  `glTexImage*D( GL_TEXTURE_*D, level, … )`
- GLU mipmap builder routines

  `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***

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

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