An Introduction to OpenGL Programming

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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?

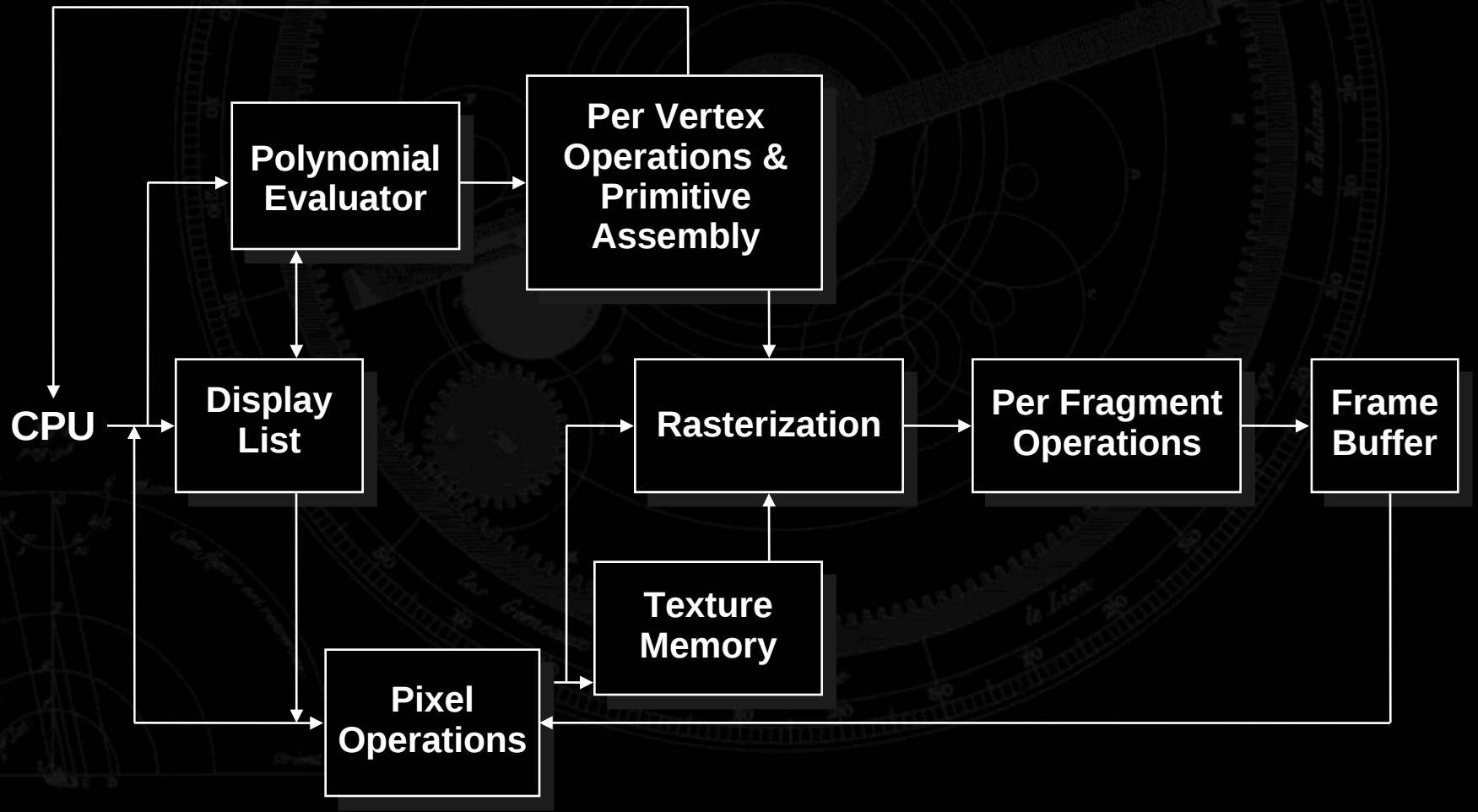
Graphics rendering API

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

Good tutorial: http://nehe.gamedev.net

Docs: http://www.opengl.org/sdk/docs/man/

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

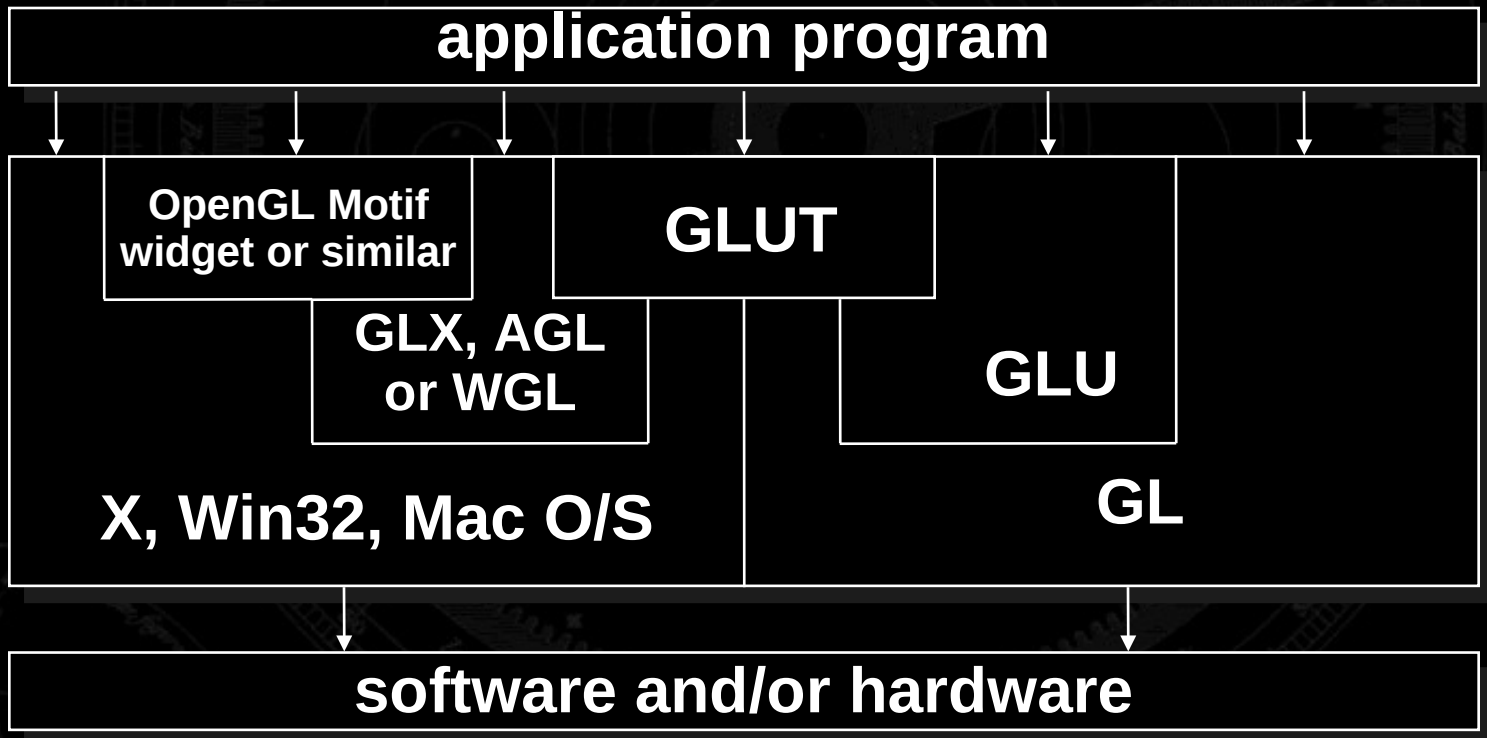
GLU (OpenGL Utility Library)

- 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( unsigned char key, int x, int y )
{
  switch( key ) {
    case ‘q’ : case ‘Q’ :
      exit( EXIT_SUCCESS );
      break;
    case ‘r’ : case ‘R’ :
      rotate = GL_TRUE;
      glutPostRedisplay();
      break;
  }
}
```

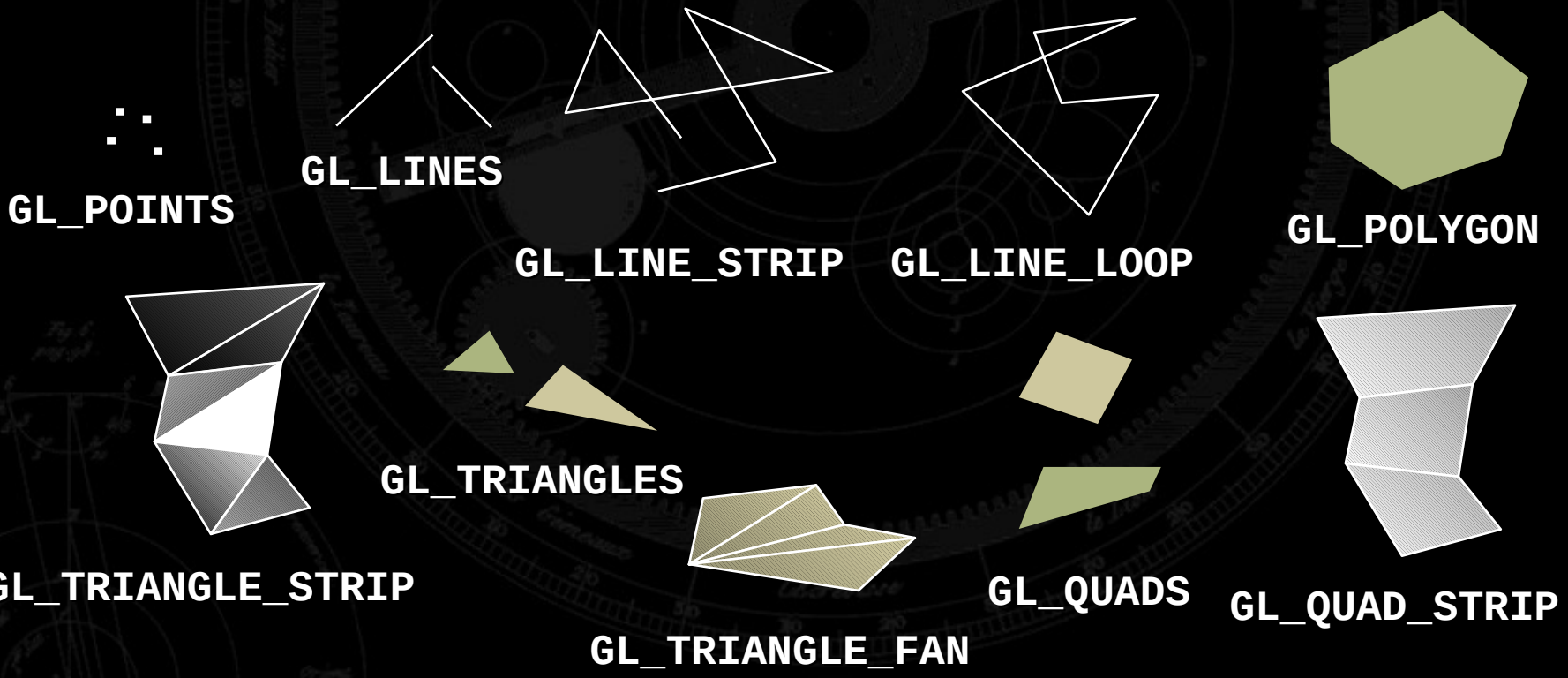
Elementary Rendering

Elementary Rendering

Geometric Primitives
Managing OpenGL State
OpenGL Buffers

OpenGL Geometric Primitives

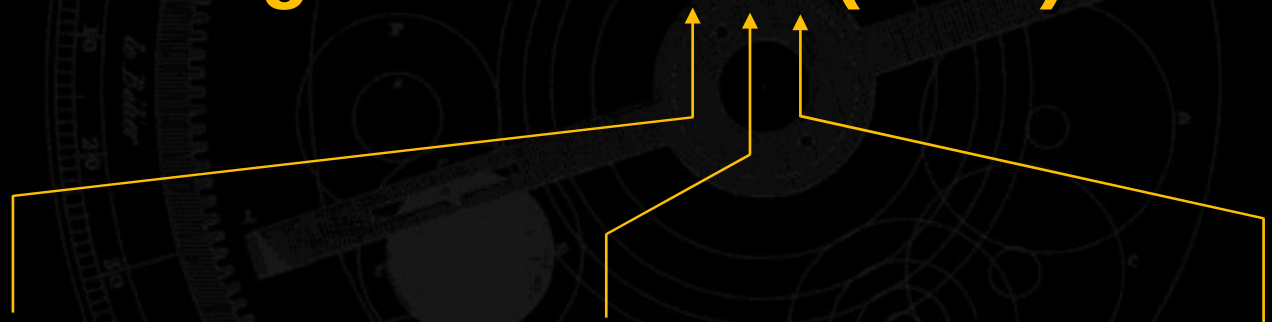
All geometric primitives are specified by vertices



Simple Example

```
void drawRhombus( GLfloat color[] )
{
    glBegin( GL_QUADS );
    glColor3fv( color );
    glVertex2f( 0.0, 0.0 );
    glVertex2f( 1.0, 0.0 );
    glVertex2f( 1.5, 1.118 );
    glVertex2f( 0.5, 1.118 );
    glEnd();
}
```

OpenGL Command Formats



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

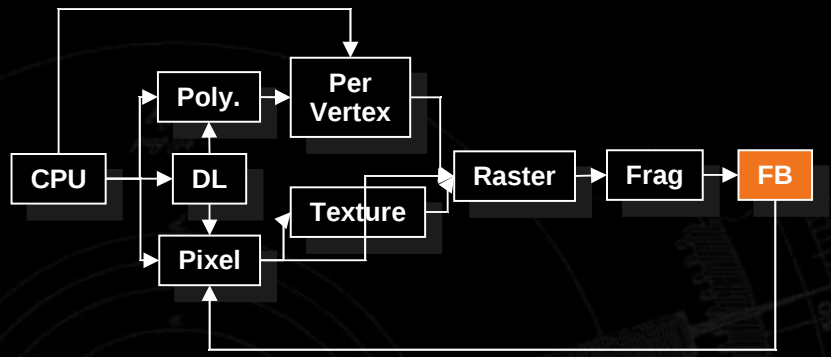
Primitives are specified using

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

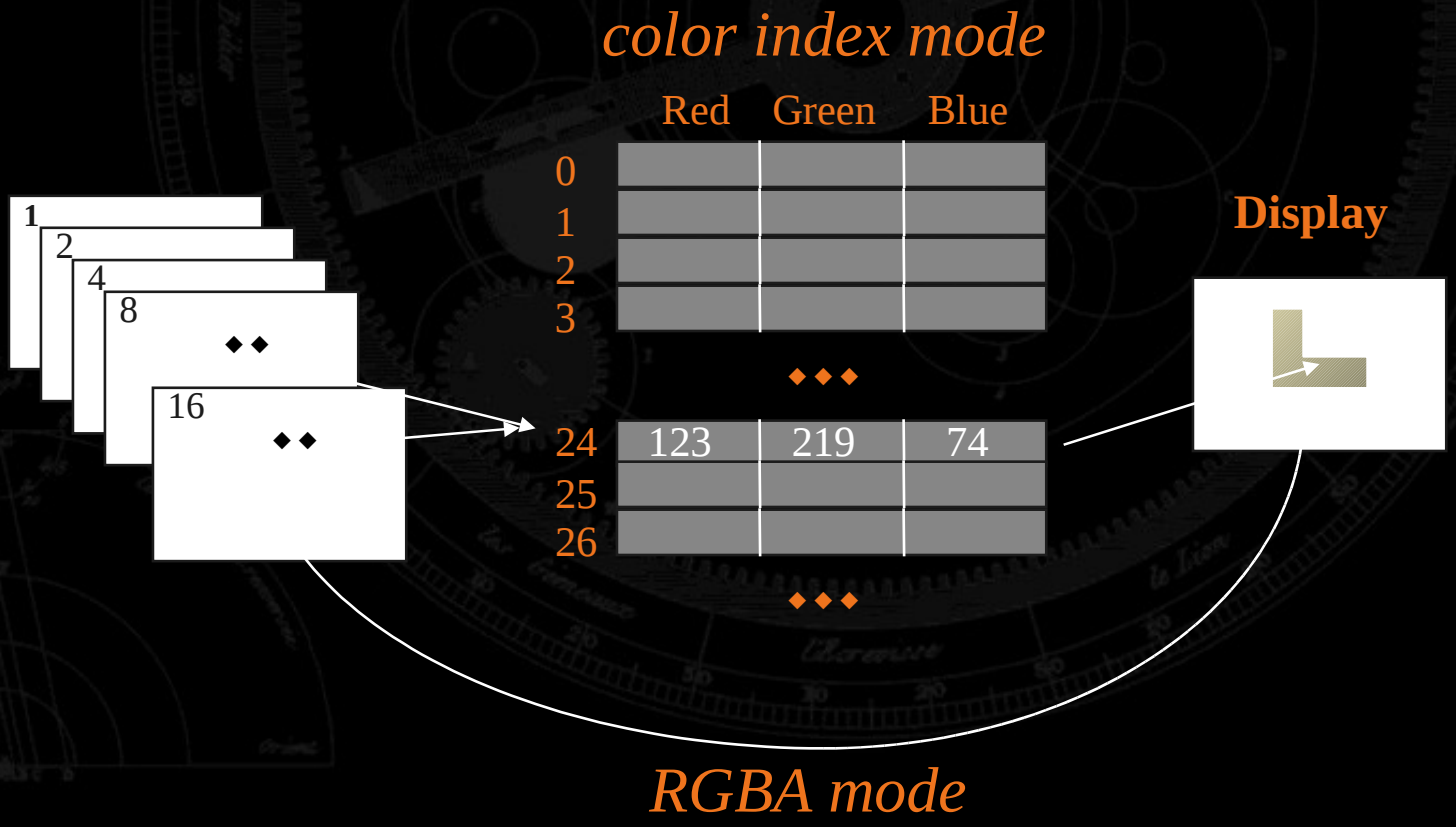
- *primType* determines how vertices are combined

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

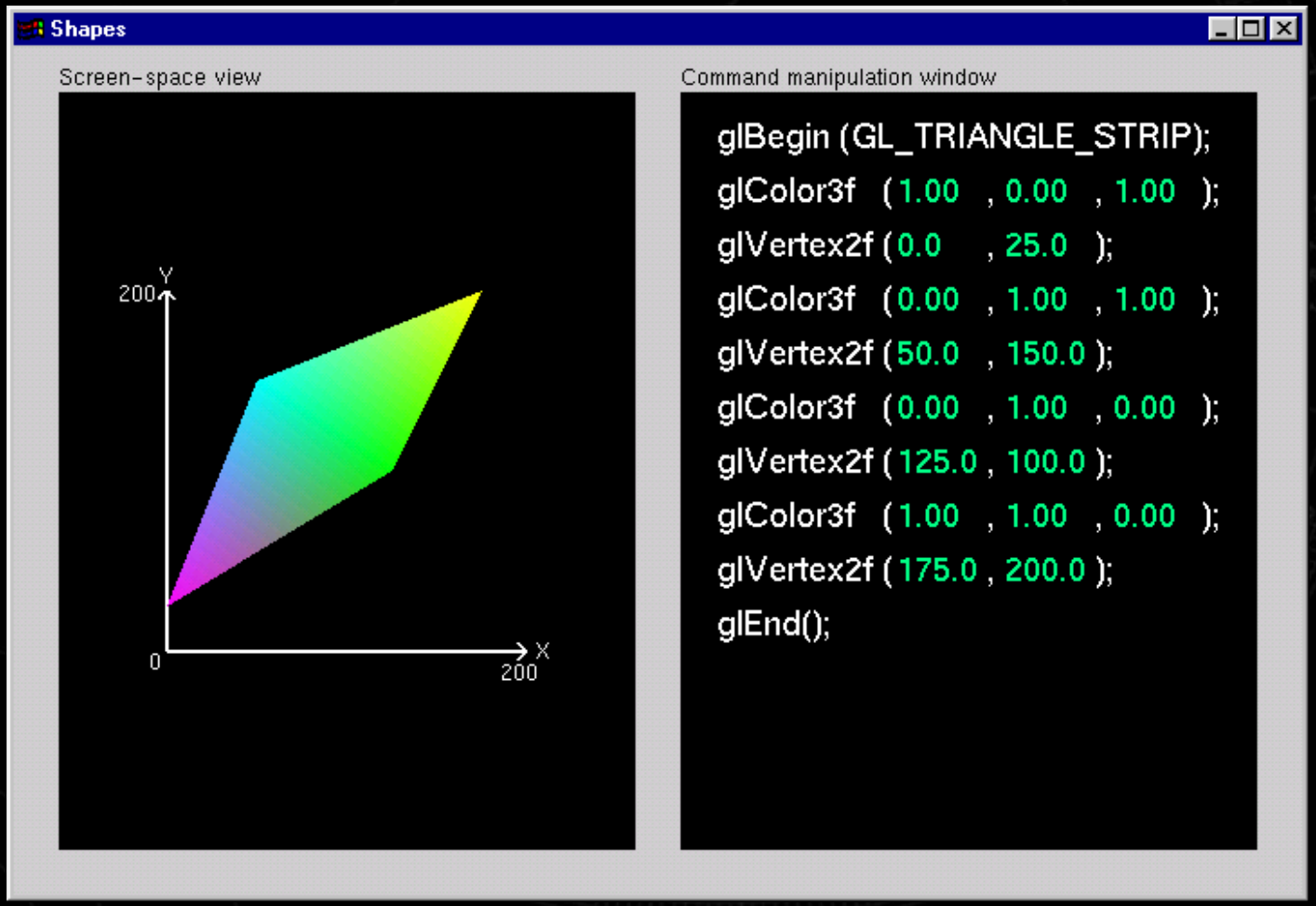
OpenGL Color Models



RGBA or Color Index

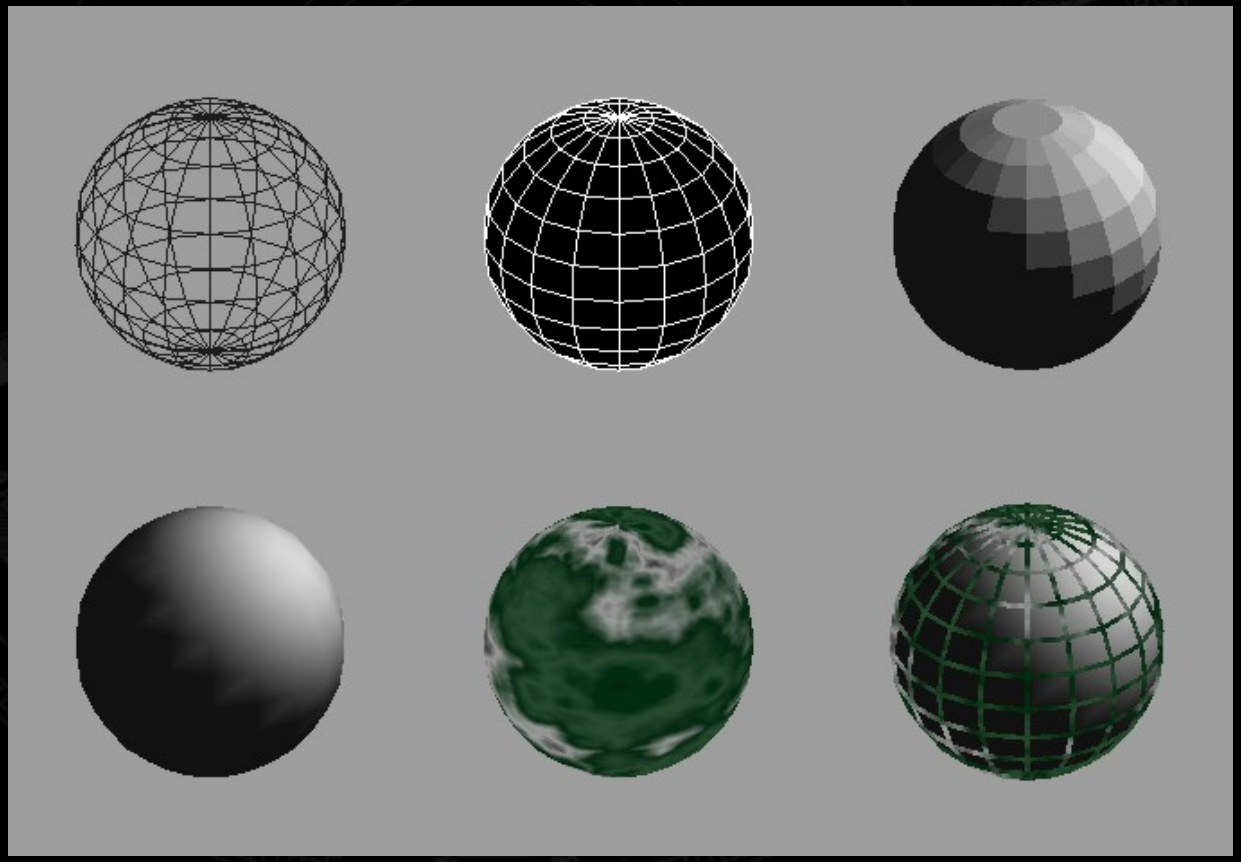


Shapes


Shapes
Screen-space view
Command manipulation window
glBegin (GL_TRIANGLE_STRIP);
glColor3f (1.00 , 0.00 , 1.00);
glVertex2f (0.0 , 25.0);
glColor3f (0.00 , 1.00 , 1.00);
glVertex2f (50.0 , 150.0);
glColor3f (0.00 , 1.00 , 0.00);
glVertex2f (125.0 , 100.0);
glColor3f (1.00 , 1.00 , 0.00);
glVertex2f (175.0 , 200.0);
glEnd();
Y
200
0
X
200

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 in OpenGL

Modeling

Viewing

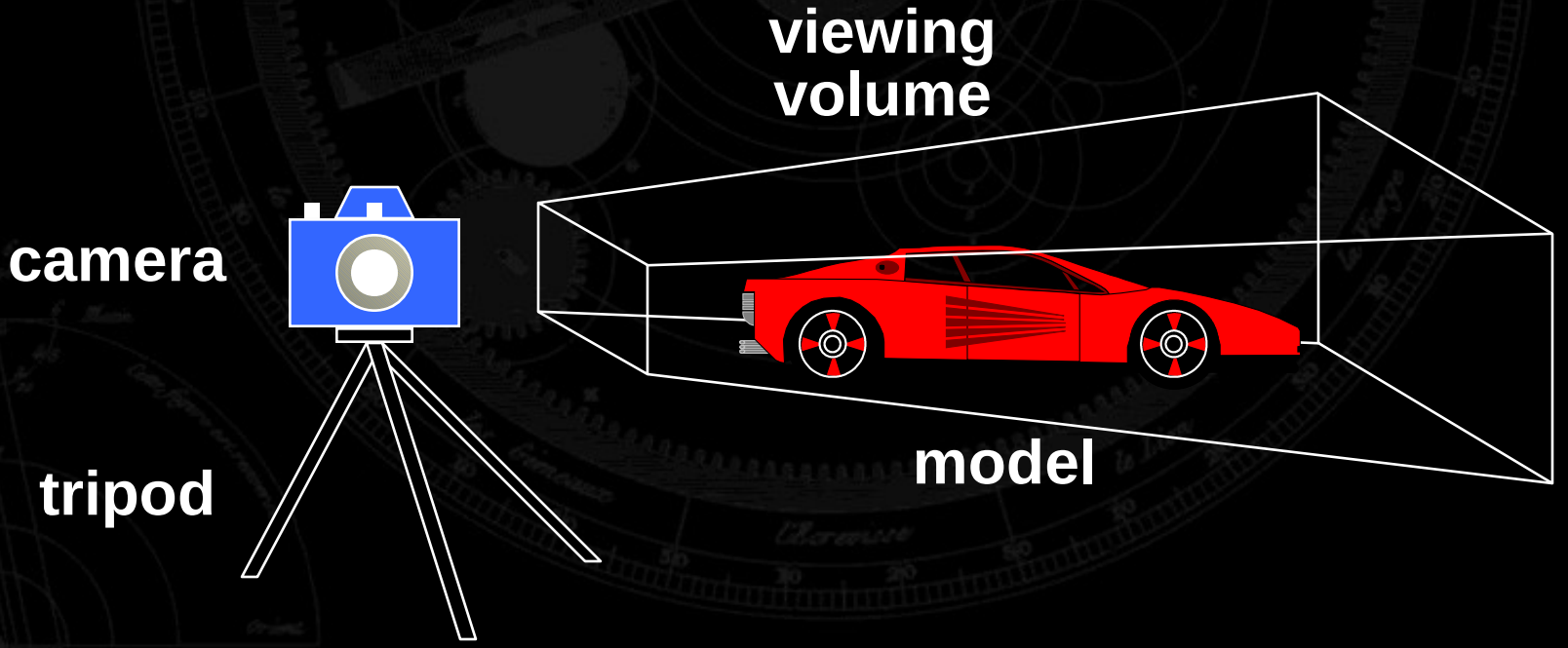
- orient camera
- projection

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

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

- 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

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

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:

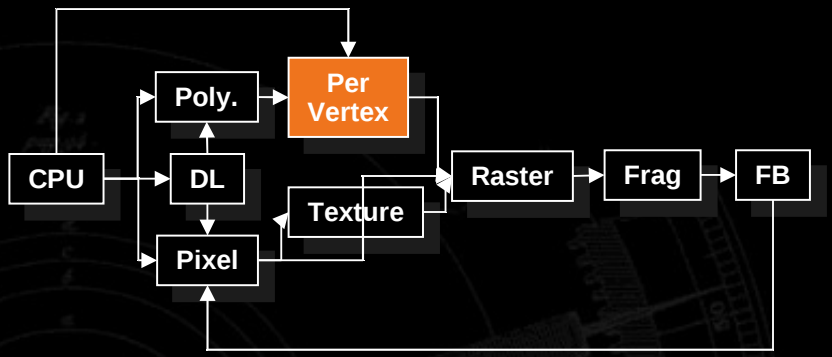
- eye/camera position
- 3D geometry

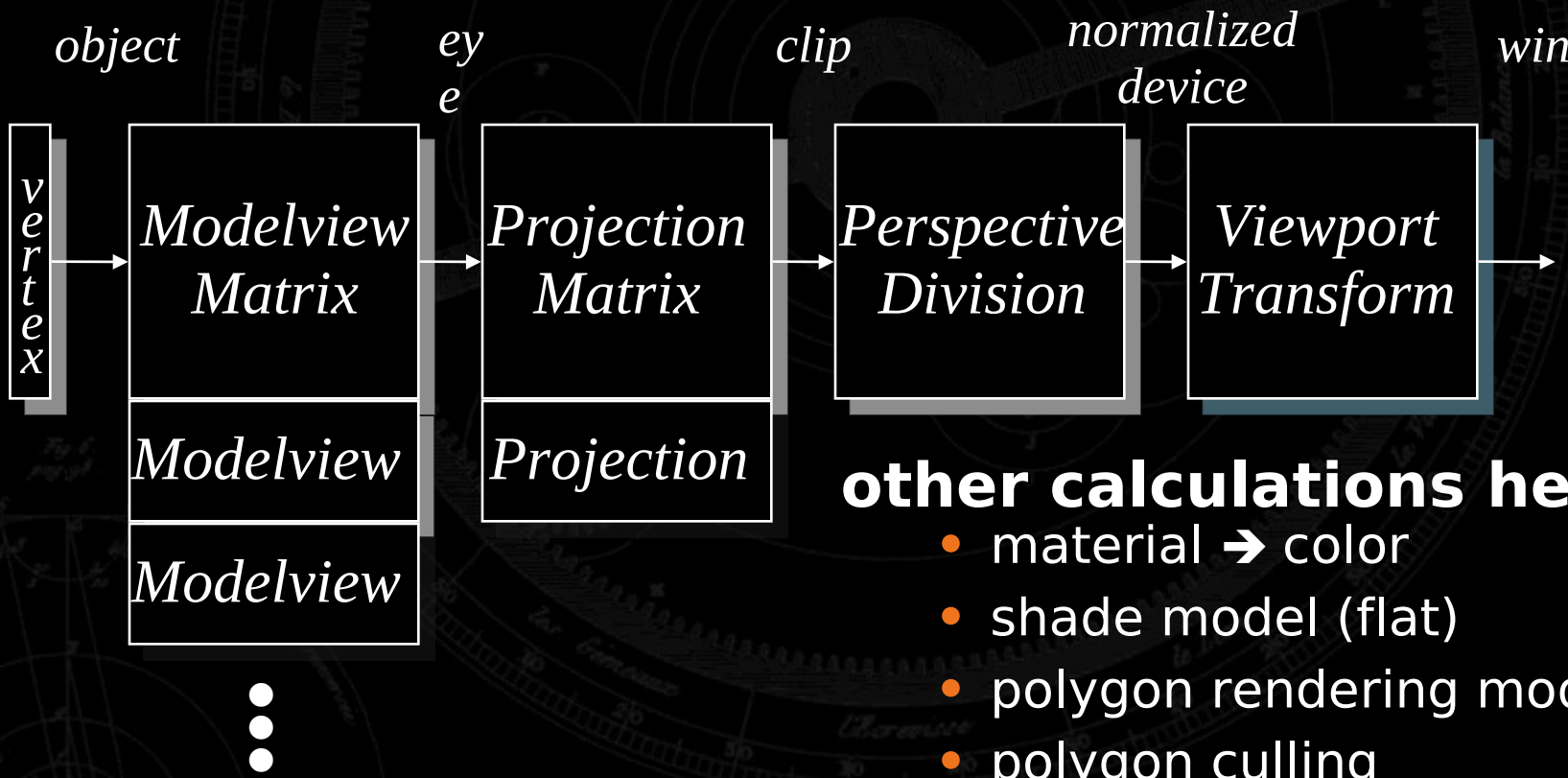
Manage the matrices

- 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

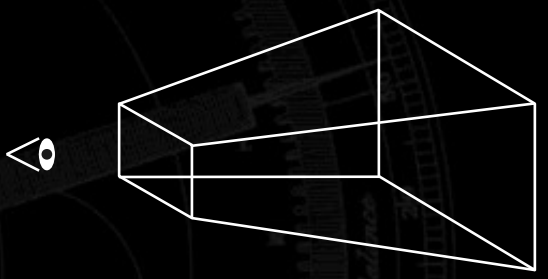
```
glLoadIdentity()  glPushMatrix()  glPopMatrix()
```

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 )`

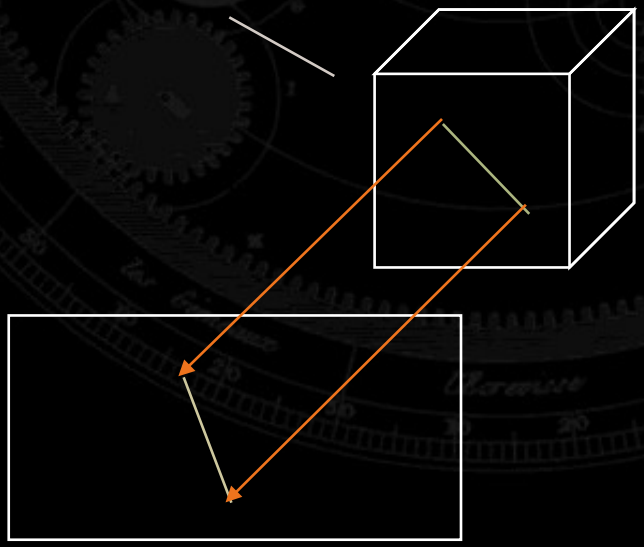
`gluOrtho2D( left, right, bottom, top )`

- 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

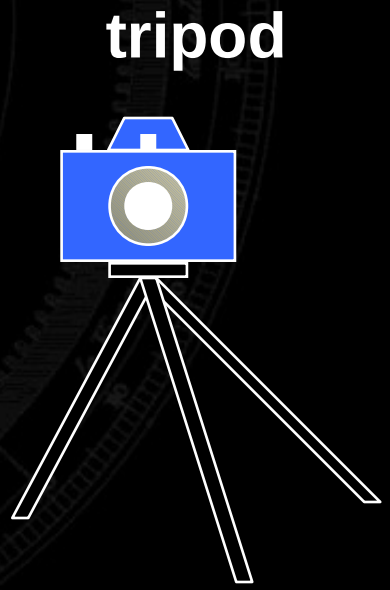
- place the tripod down; aim camera

To "fly through" a scene

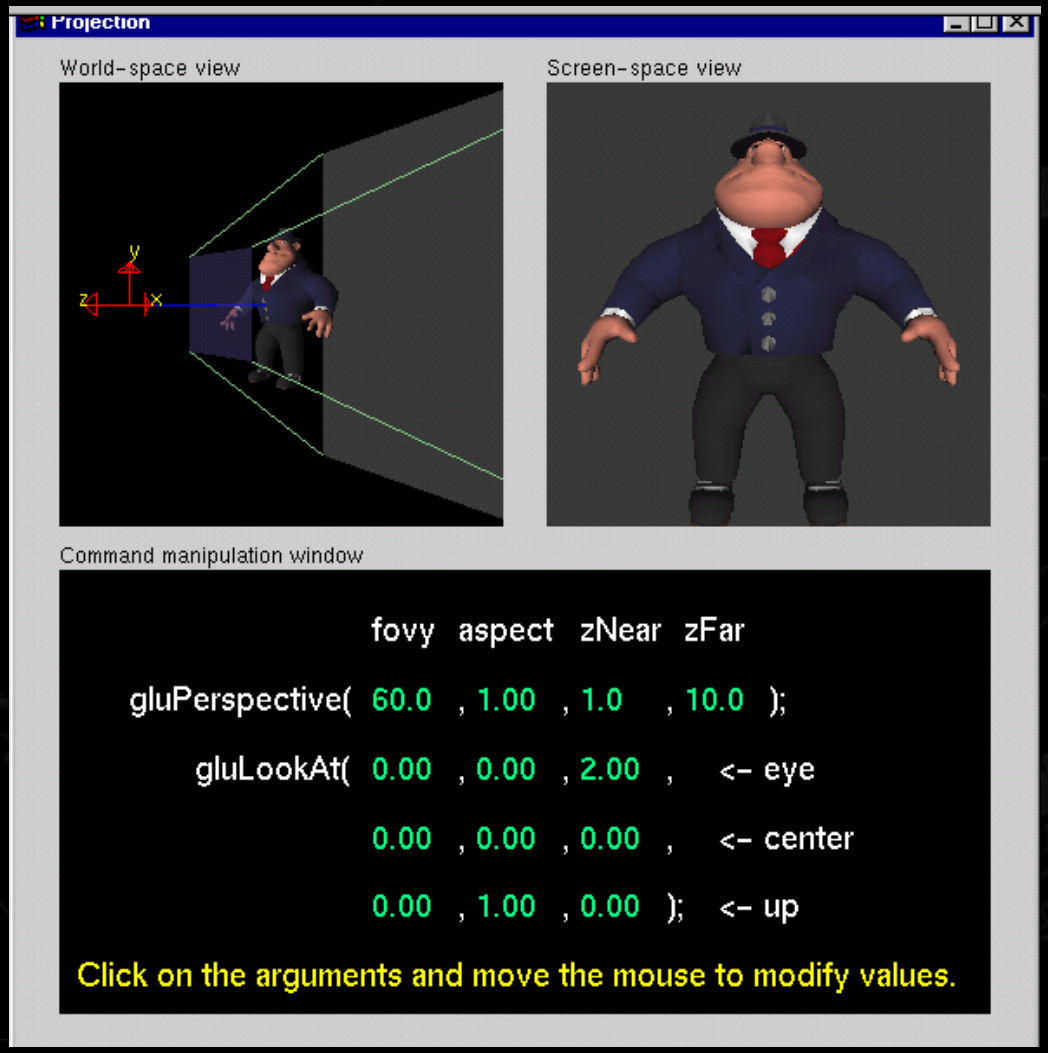
- change viewing transformation and redraw scene

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

- 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)

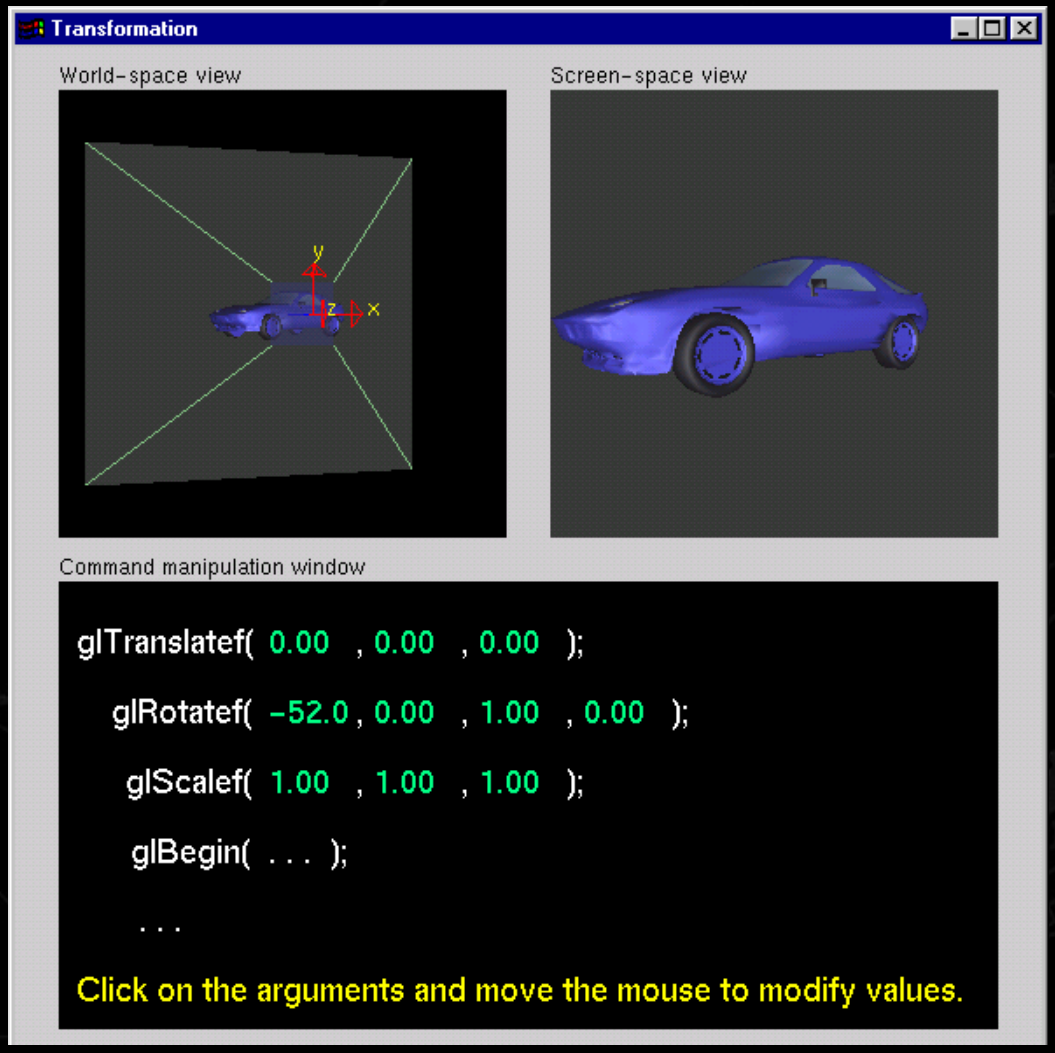
```
glRotate{fd}( angle, x, y, z )
```

- 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

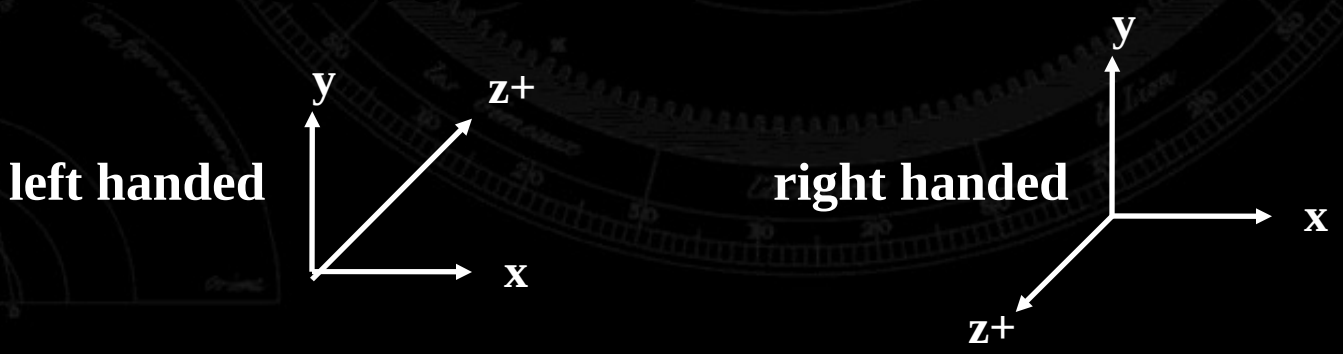
- `gluLookAt()` has its own command
- can make your own *polar view* or *pilot view*

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, (GLdouble) 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, (GLdouble) 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

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 )
```

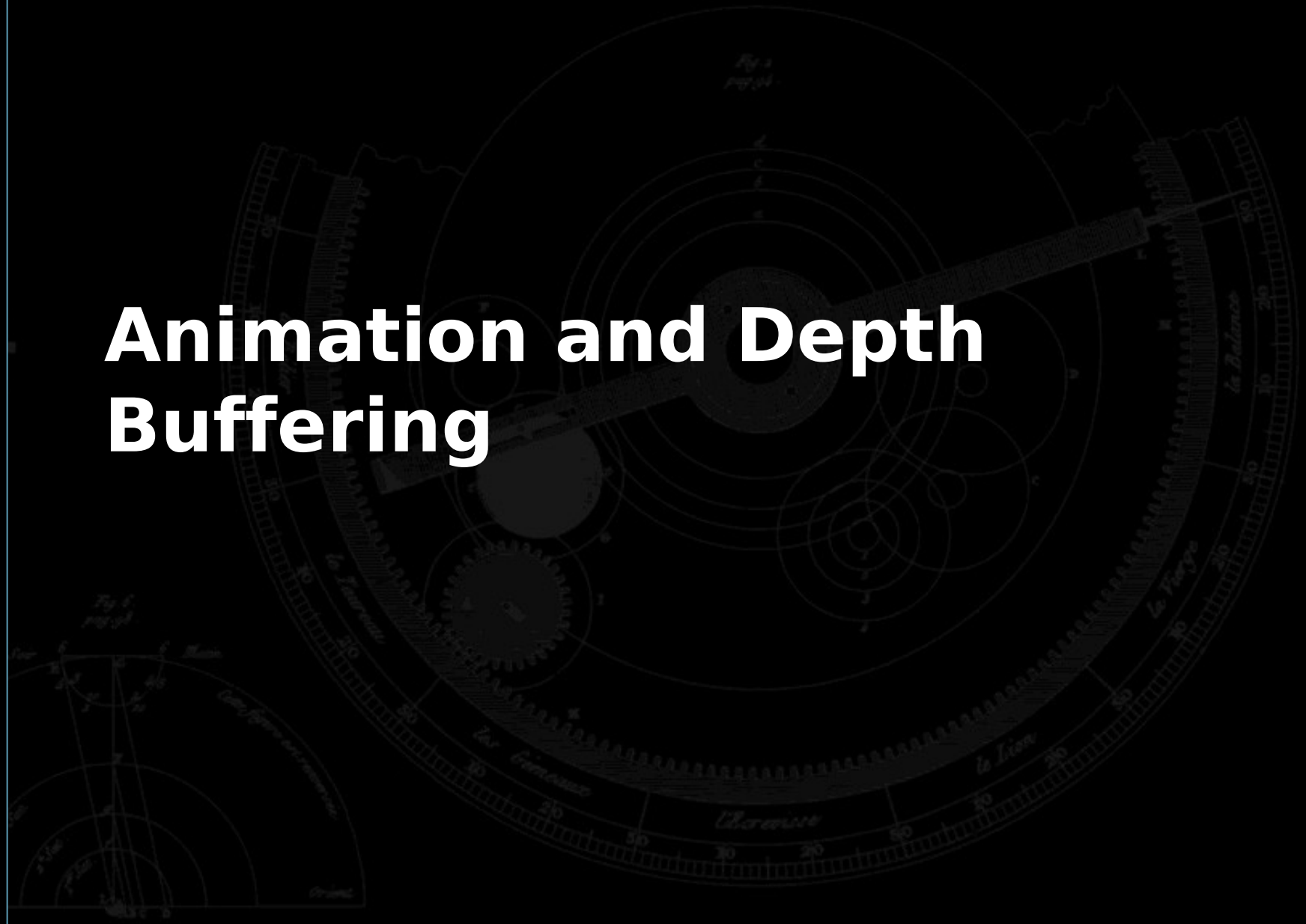
Reversing Coordinate Projection

- 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

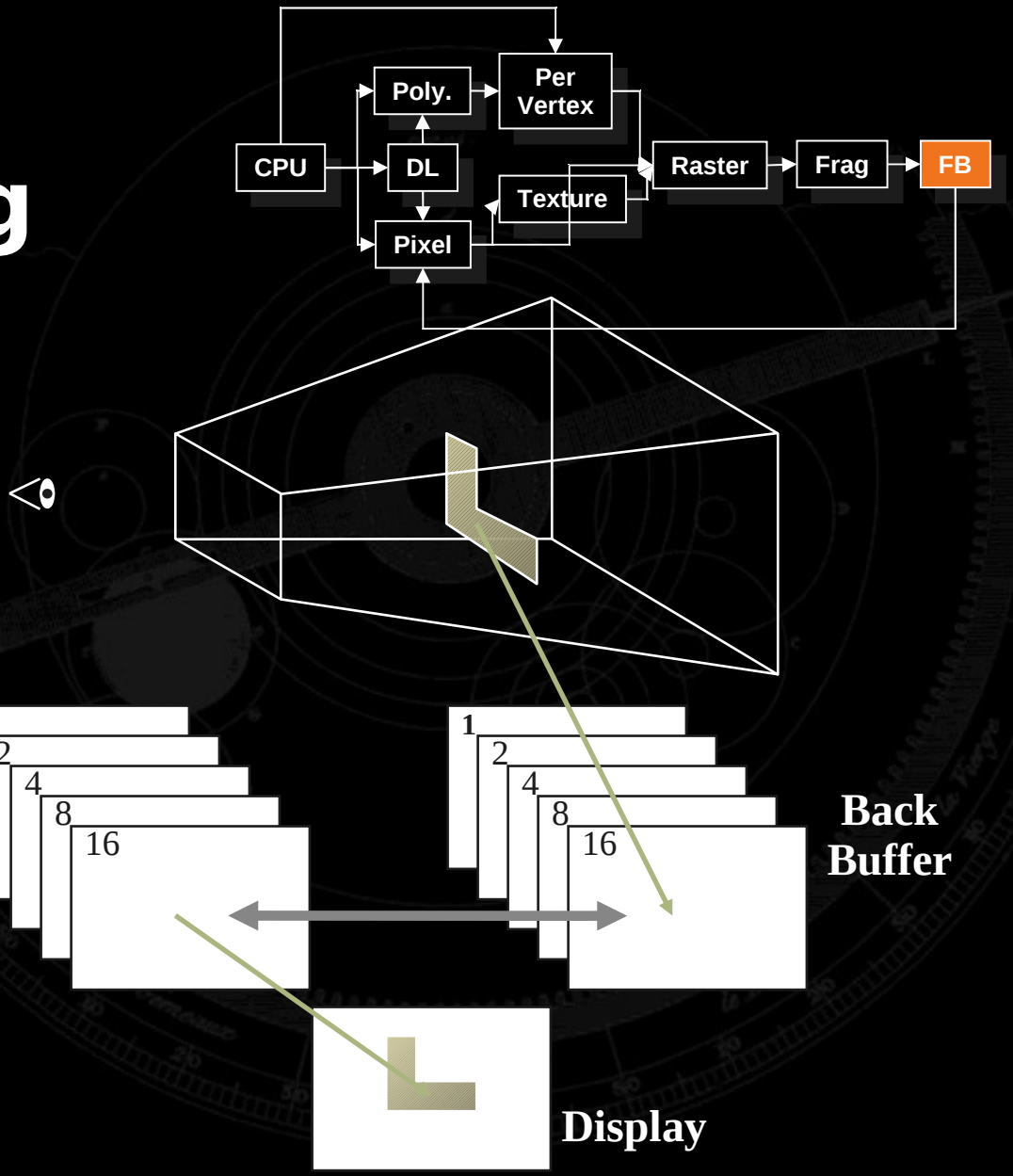
Animation and Depth Buffering



Animation and Depth Buffering

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

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 );
```

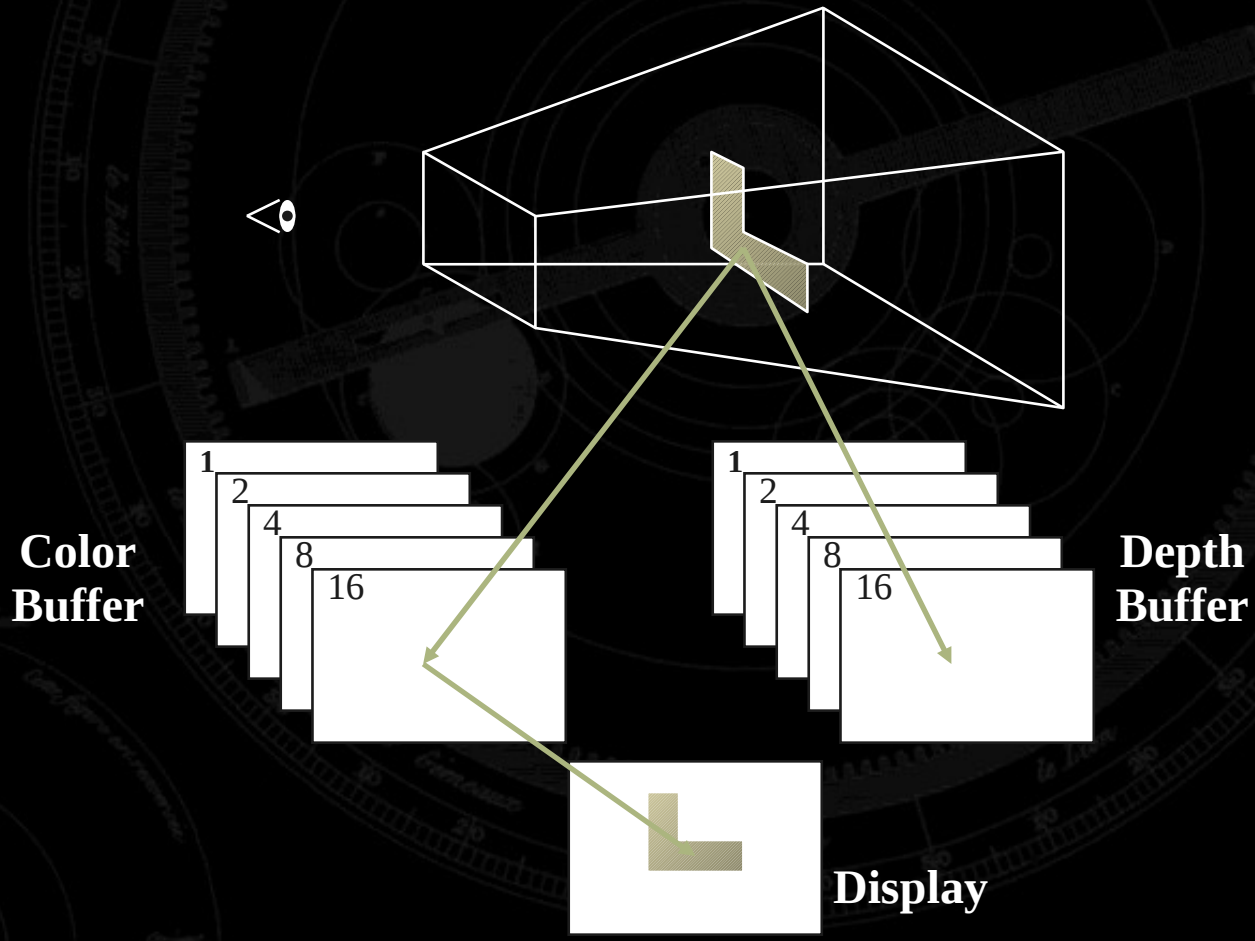
Render scene

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.)

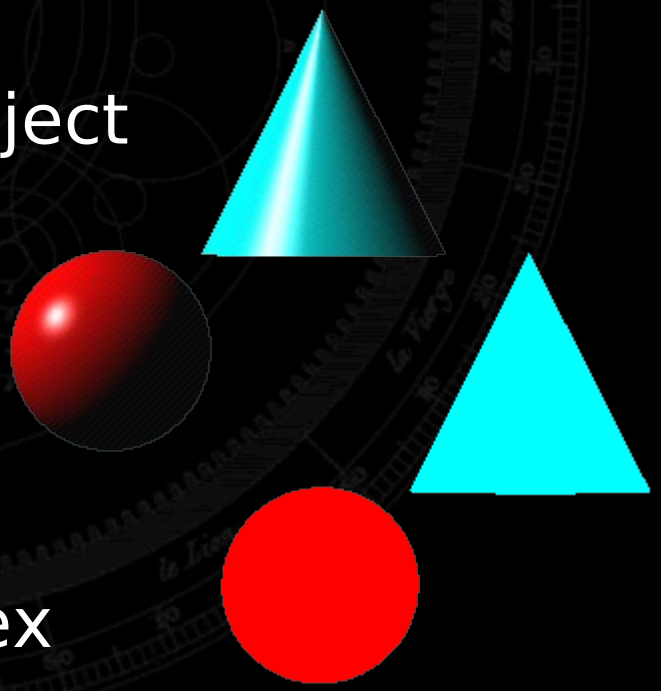
```
void drawScene( void )
{
     GLfloat vertices[] = { … };
     GLfloat colors[] = { … };
     glClear( GL_COLOR_BUFFER_BIT |
       GL_DEPTH_BUFFER_BIT );
     glBegin( GL_TRIANGLE_STRIP );
   /* calls to glColor*() and glVertex*() */
     glEnd();
     glutSwapBuffers();
}
```

Lighting

Lighting Principles

Lighting simulates how objects reflect light

- material composition of object
- light's color and position
- global lighting parameters
  - ambient light
  - two sided lighting
- available in both color index and RGBA mode



How OpenGL Simulates Lights

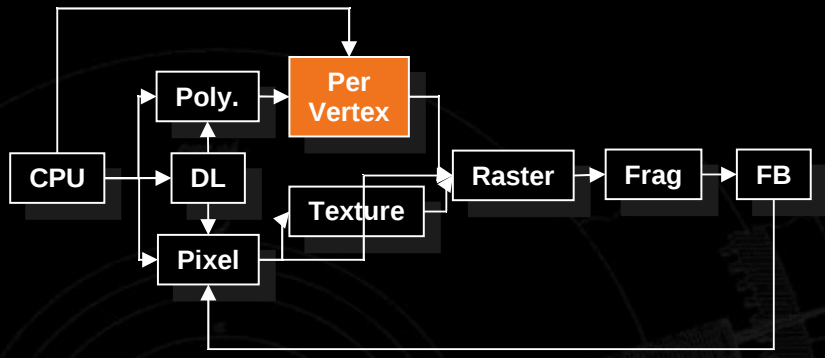
Phong lighting model

- Computed at vertices

Lighting contributors

- Surface material properties
- Light properties
- Lighting model properties

Surface Normals



Normals define how a surface reflects light

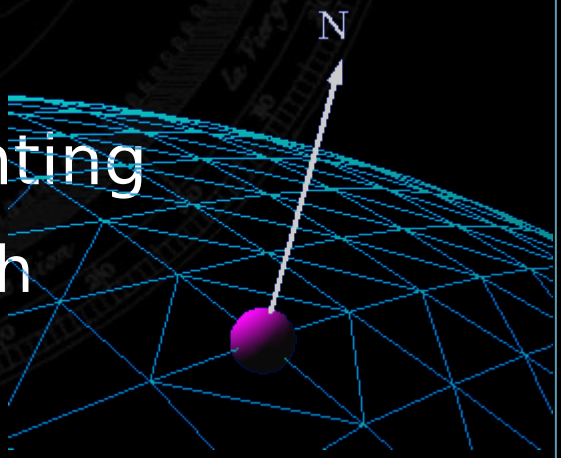
`glNormal3f( x, y, z )`

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

`glEnable( GL_NORMALIZE )`

or

`glEnable( GL_RESCALE_NORMAL )`



Material Properties

Define the surface properties of a primitive

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

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

- separate materials for front and back

Light Properties

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

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

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

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

Light Sources (cont.)

Light color properties

- `GL_AMBIENT`
- `GL_DIFFUSE`
- `GL_SPECULAR`

Types of Lights

OpenGL supports two types of Lights

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

Type of light controlled by w coordinate

$w = 0$ ***Infinite Light directed along*** $\begin{pmatrix} x & y & z \end{pmatrix}$

$w \neq 0$ ***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 );
```

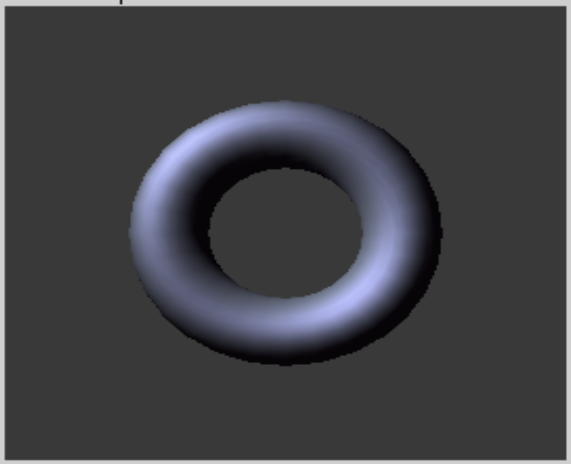
Turn on the power

```
glEnable( GL_LIGHTING );
```

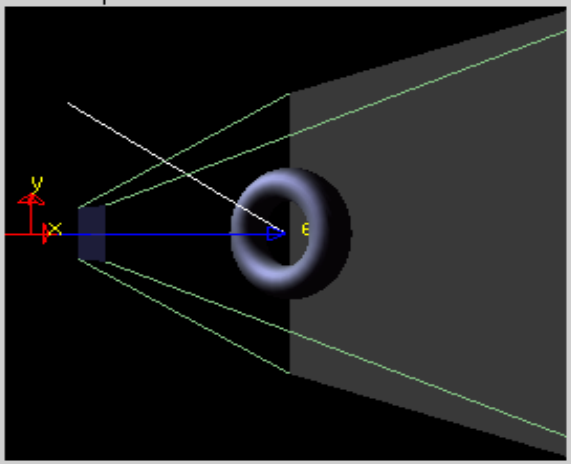
Light Material Tutorial

Light & Material

Screen-space view



World-space view



Command manipulation window

```
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  };

glLightfv(GL_LIGHT0, GL_POSITION, light_pos);
glLightfv(GL_LIGHT0, GL_AMBIENT, light_Ka);
glLightfv(GL_LIGHT0, GL_DIFFUSE, light_Kd);
glLightfv(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  ;

glMaterialfv(GL_FRONT, GL_AMBIENT, material_Ka);
glMaterialfv(GL_FRONT, GL_DIFFUSE, material_Kd);
glMaterialfv(GL_FRONT, GL_SPECULAR, material_Ks);
glMaterialfv(GL_FRONT, GL_EMISSION, material_Ke);
glMaterialfv(GL_FRONT, GL_SHININESS, material_Se);
```

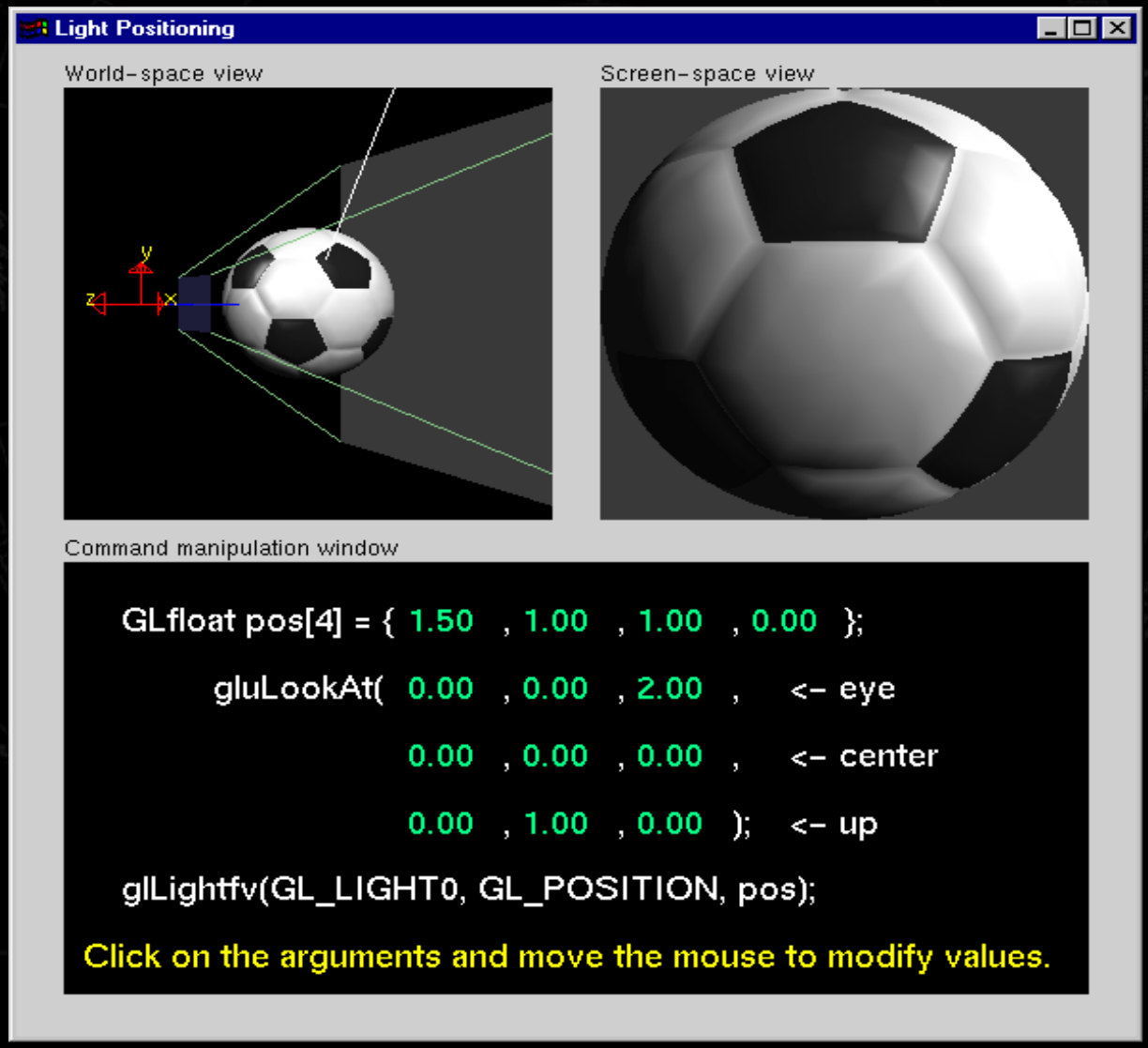
Click on the arguments and move the mouse to modify values.

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



Advanced Lighting Features

Spotlights

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

Advanced Lighting Features

Light attenuation

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

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

Light Model Properties

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

Enabling two sided lighting

`GL_LIGHT_MODEL_TWO_SIDE`

Global ambient color

`GL_LIGHT_MODEL_AMBIENT`

Local viewer mode

`GL_LIGHT_MODEL_LOCAL_VIEWER`

Separate specular color

`GL_LIGHT_MODEL_COLOR_CONTROL`

Tips for Better Lighting

Recall lighting computed only at vertices

- model tessellation heavily affects lighting results
- better results but more geometry to process

Use a single infinite light for fastest lighting

- minimal computation per vertex

Imaging and Raster Primitives

Imaging and Raster Primitives

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

Pixel-based primitives

Bitmaps

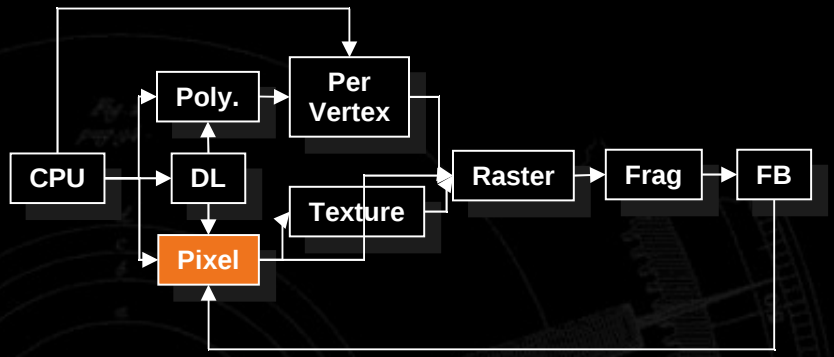
- 2D array of bit masks for pixels
  - update pixel color based on current color

Images

- 2D array of pixel color information
  - complete color information for each pixel

OpenGL doesn’t understand image formats

Pixel Pipeline



Programmable pixel storage and transfer operations

`glBitmap(), glDrawPixels()`

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

Texture Memory

`glCopyTex*Image();`

`glReadPixels(), glCopyPixels()`

Positioning Image Primitives

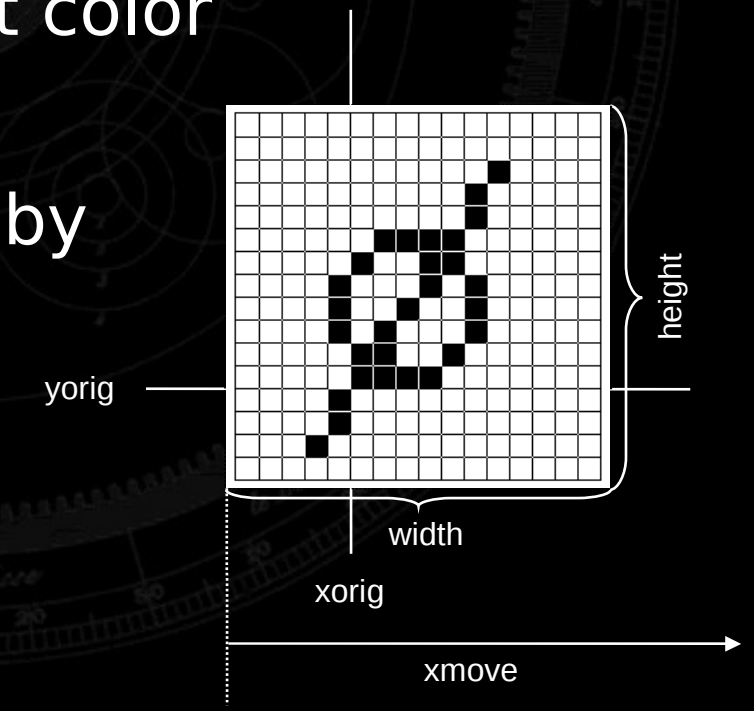
`glRasterPos3f( x, y, z )`

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

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 from 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

Storage and Transfer Modes

Storage modes control accessing memory

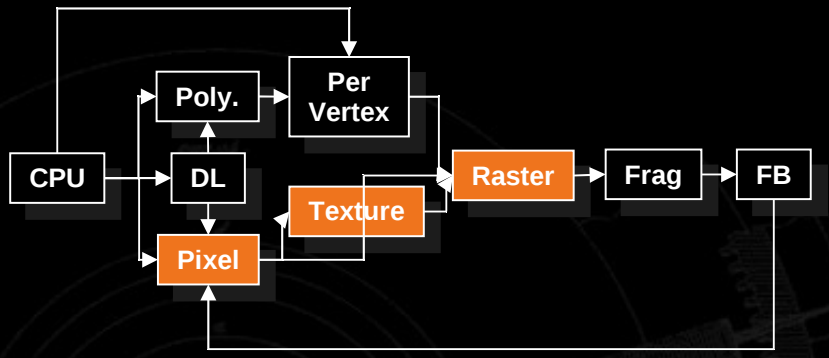
- byte alignment in host memory
- extracting a subimage

Transfer modes allow modify pixel values

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

Texture Mapping

Texture Mapping

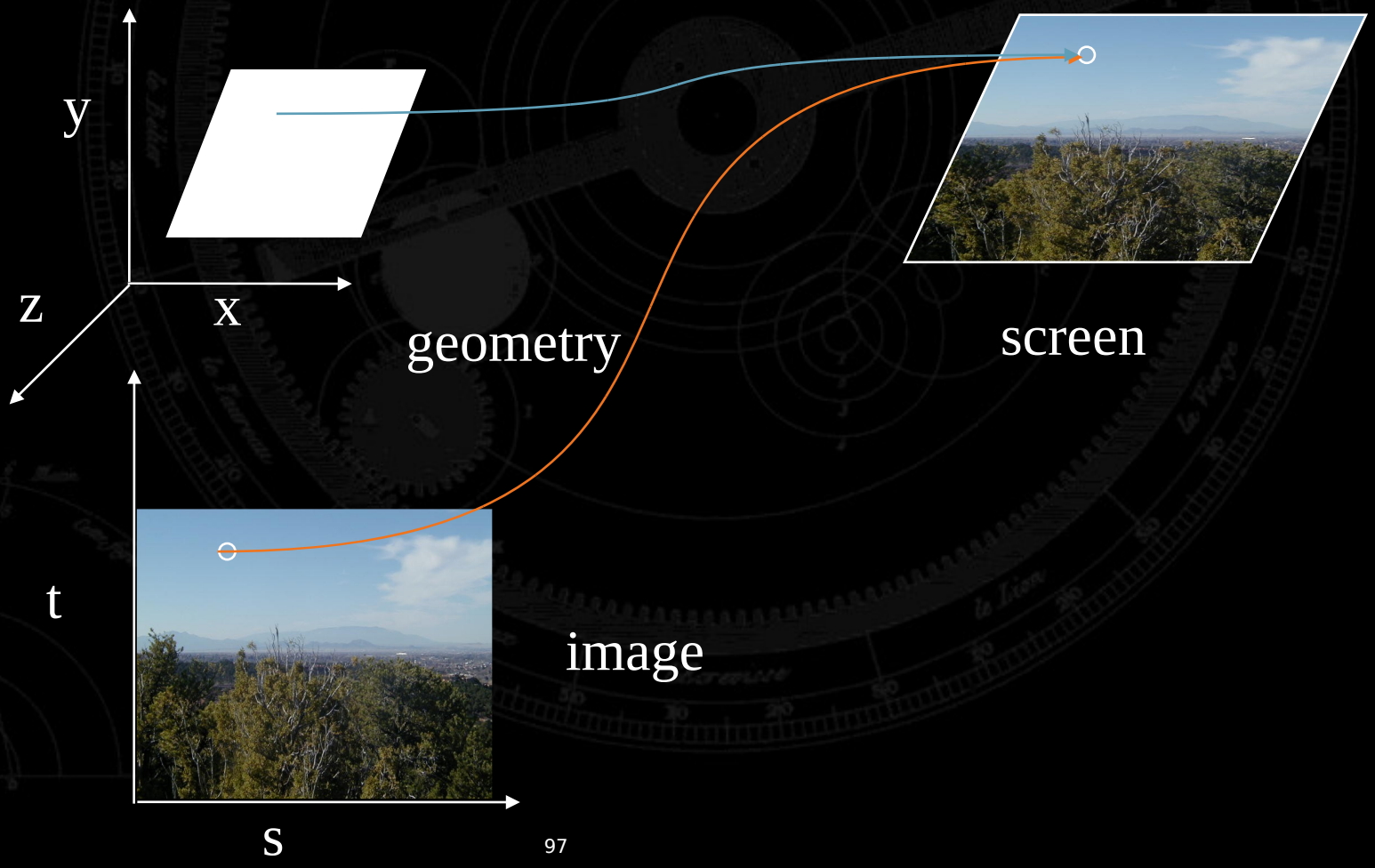


Apply a 1D, 2D, or 3D image to geometric primitives

Uses of Texturing

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

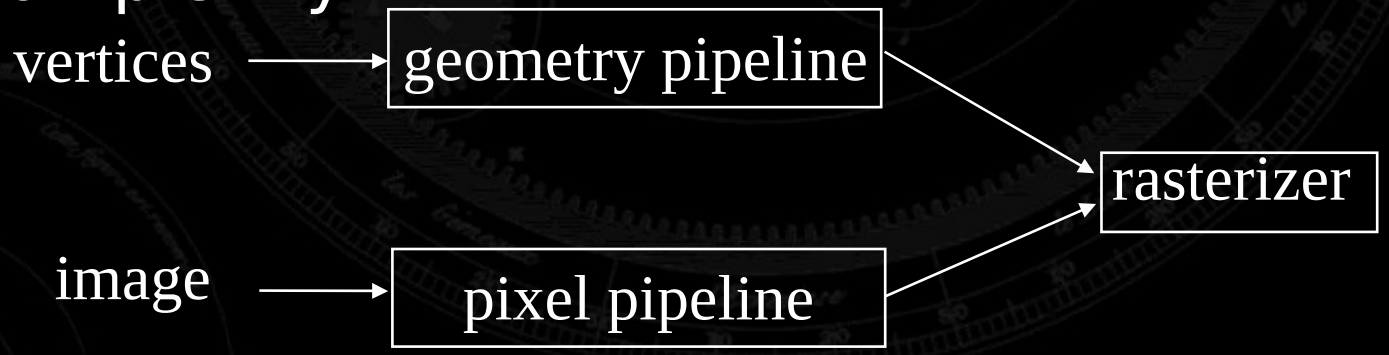
Texture Mapping



Texture Mapping and the OpenGL Pipeline

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

- "complex" textures do not affect geometric complexity



Texture Example

The texture (below) is a 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
- enable texturing

② assign texture coordinates to vertices

③ specify texture parameters
- wrapping, filtering

Applying Textures II

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

Texture Objects

Like display lists for texture images

- one image per texture object
- may be shared by several graphics contexts

Generate texture names

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

Texture Objects (cont.)

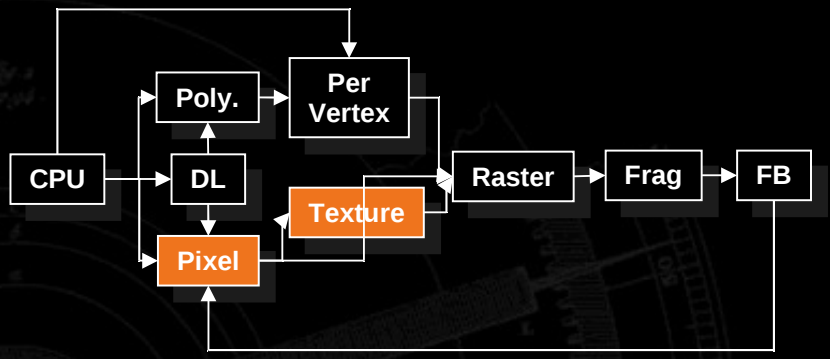
Create texture objects with texture data and state

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

Bind textures before using

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

Specify Texture Image



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

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

- dimensions of image must be powers of 2

Texel colors are processed by pixel pipeline

- pixel scales, biases and lookups can be done

Converting A Texture Image

If dimensions of image are not power of 2

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

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

Image interpolated and filtered during scaling

Specifying a Texture: Other Methods

Use frame buffer as source of texture image

- uses current buffer as source image

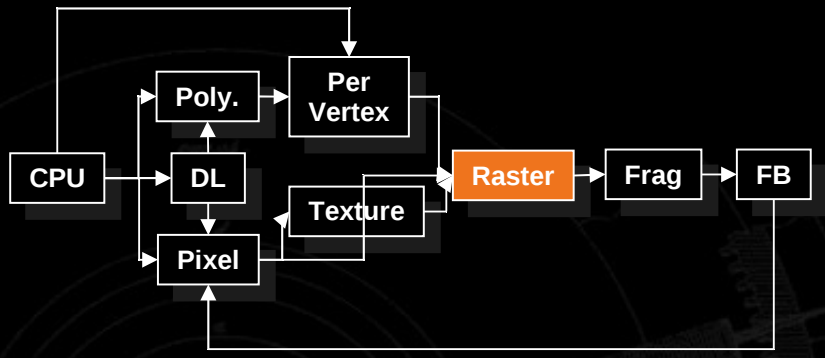
```
glCopyTexImage1D(...)
glCopyTexImage2D(...)
```

Modify part of a defined texture

```
glTexSubImage1D(...)
glTexSubImage2D(...)
glTexSubImage3D(...)
```

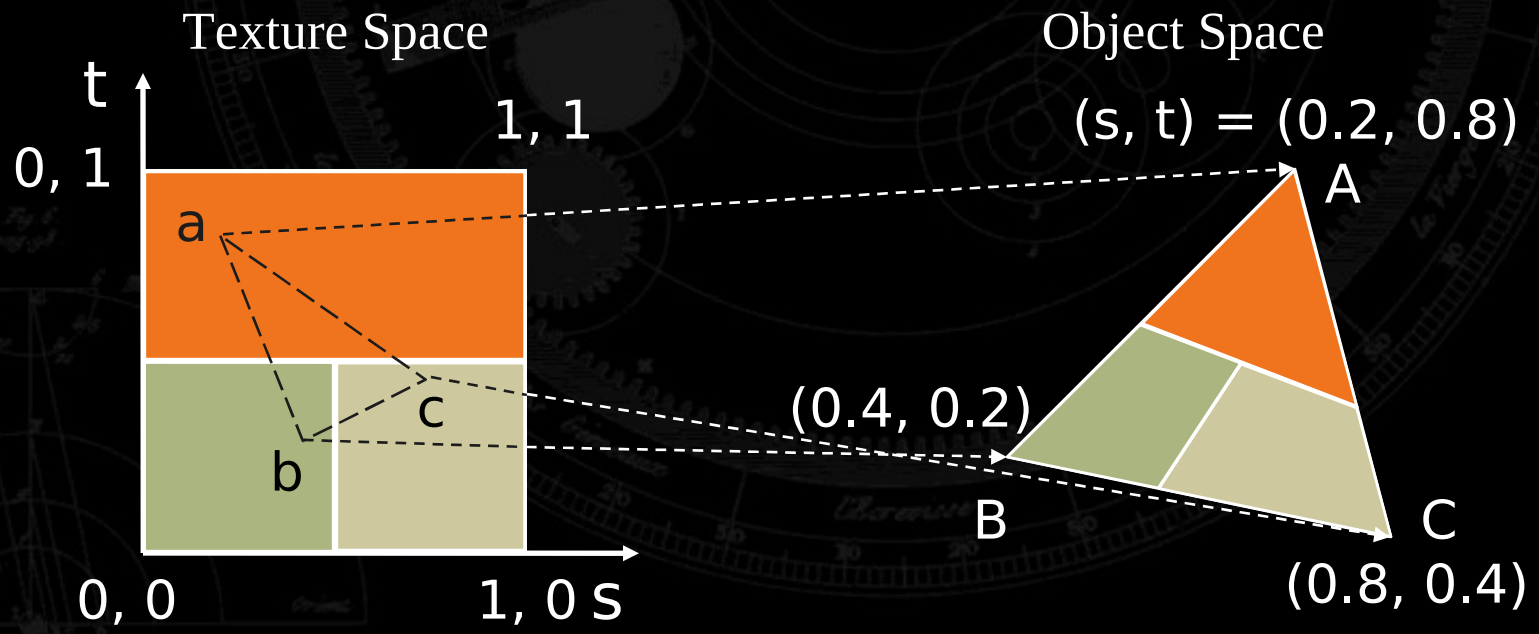
Do both with *`glCopyTexSubImage2D(...)`*, etc.

Mapping a Texture



Based on parametric texture coordinates

`glTexCoord*()` specified at each vertex



Generating Texture Coordinates

Automatically generate texture coords

`glTexGen{ifd}[v]()`

specify a plane

- generate texture coordinates based upon distance from plane $Ax + By + Cz + D = 0$

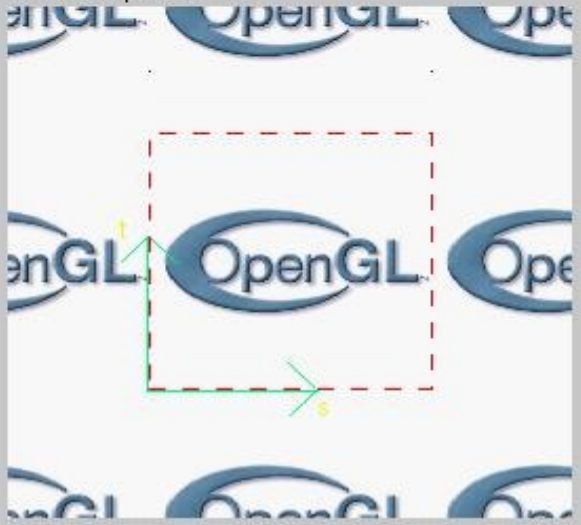
generation modes

- `GL_OBJECT_LINEAR`
- `GL_EYE_LINEAR`
- `GL_SPHERE_MAP`

Tutorial: Texture

Screen-space view

Texture-space view



Command manipulation window

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

glTexParameterfv(GL_TEXTURE_2D, GL_TEXTURE_BORDER_COLOR, border_color);
glTexEnvfv(GL_TEXTURE_ENV, GL_TEXTURE_ENV_COLOR, env_color);

glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER,  GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER,  GL_NEAREST);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S,  GL_REPEAT);
glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T,  GL_REPEAT);
glTexEnvi(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE,  GL_MODULATE);

glEnable(GL_TEXTURE_2D);
gluBuild2DMipmaps(GL_TEXTURE_2D, 3, w, h, GL_RGB, GL_UNSIGNED_BYTE, image);
glColor4f(  0.60  , 0.60  , 0.60  , 1.00  );
glBegin(GL_POLYGON);
glTexCoord2f( 0.0  , 0.0  ); glVertex3f( -1.0 , -1.0 , 0.0  );
glTexCoord2f( 1.0  , 0.0  ); glVertex3f( 1.0  , -1.0 , 0.0  );
glTexCoord2f( 1.0  , 1.0  ); glVertex3f( 1.0  , 1.0  , 0.0  );
glTexCoord2f( 0.0  , 1.0  ); glVertex3f( -1.0 , 1.0  , 0.0  );
glEnd();
```

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

Texture Application Methods

Filter Modes

- minification or magnification
- special mipmap minification filters

Wrap Modes

- clamping or repeating

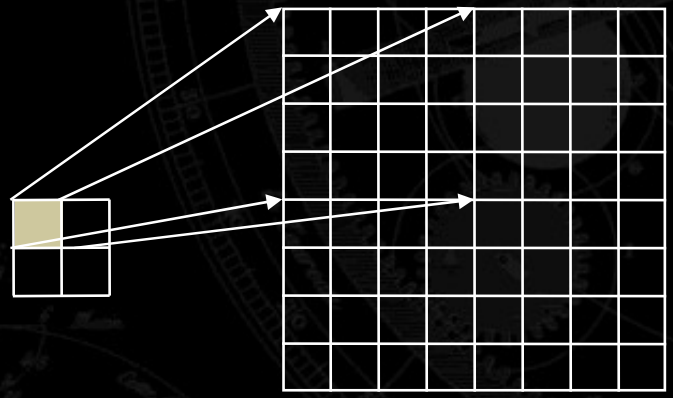
Texture Functions

- how to mix primitive’s color with texture’s color
- blend, modulate or replace texels

Filter Modes

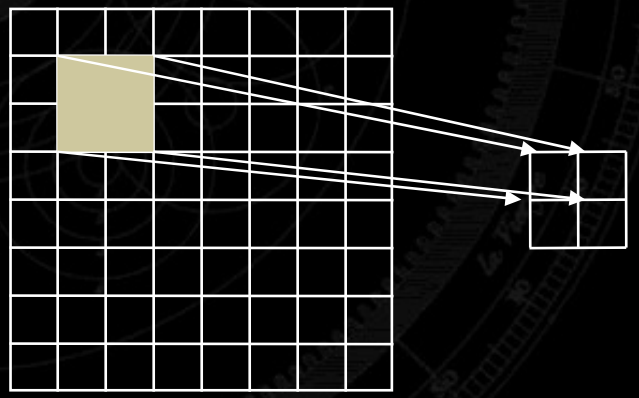
Example:

```
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 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

Advanced OpenGL Topics

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

Immediate Mode versus Display Listed Rendering

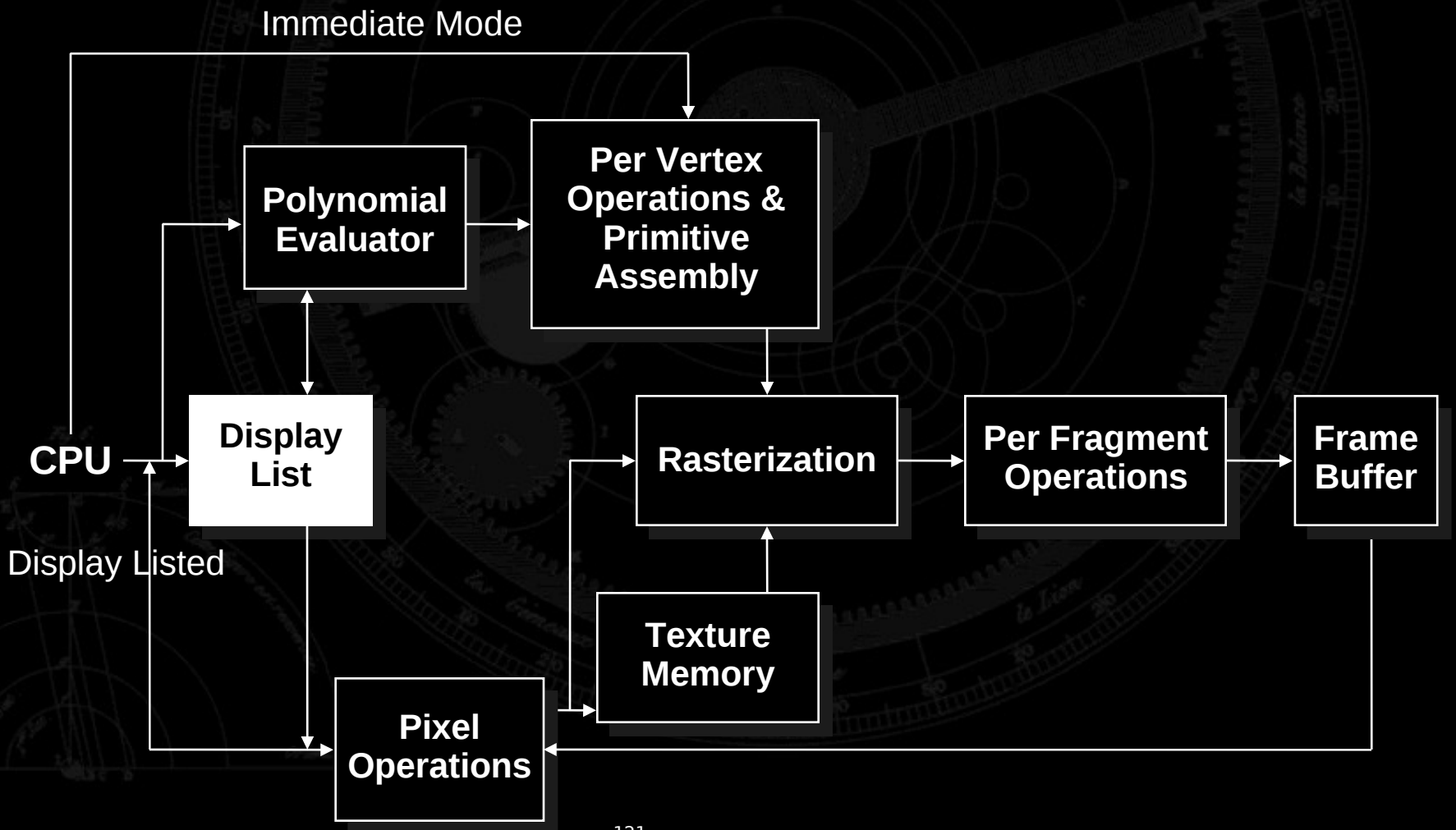
Immediate Mode Graphics

- Primitives are sent to pipeline and display right away
- No memory of graphical entities

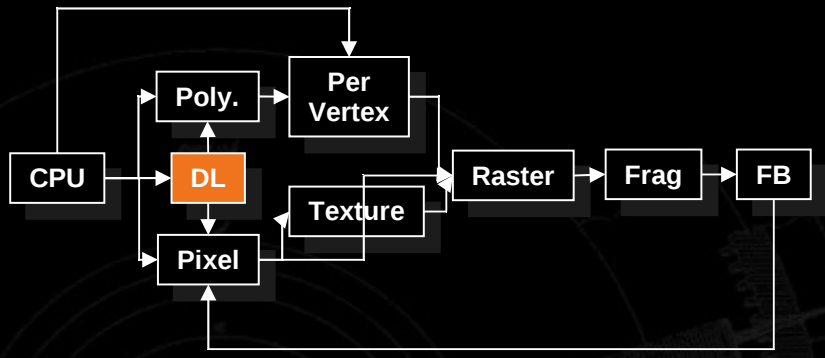
Display Listed Graphics

- Primitives placed in display lists
- Display lists kept on graphics server
- Can be redisplayed with different state
- Can be shared among OpenGL graphics contexts

Immediate Mode versus Display Lists



Display Lists



Creating a display list

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

Call a created list

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

Display Lists

Not all OpenGL routines can be stored in display lists

State changes persist, even after a display list is finished

Display lists can call other display lists

Display lists are not editable, but you can fake it

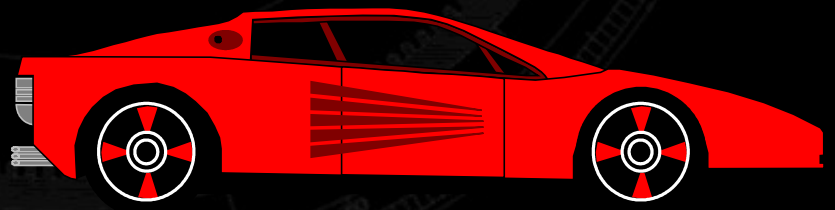
- make a list (A) which calls other lists (B, C, and D)
- delete and replace B, C, and D, as needed

Display Lists and Hierarchy

Consider model of a car

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

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



Advanced Primitives

Vertex Arrays

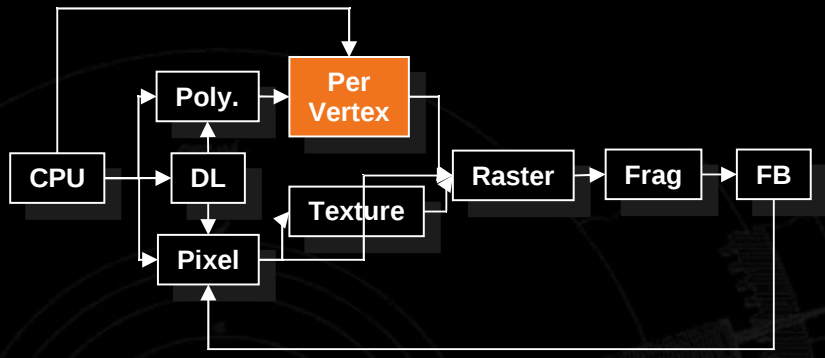
Bernstein Polynomial Evaluators

- basis for GLU NURBS
  - NURBS (Non-Uniform Rational B-Splines)

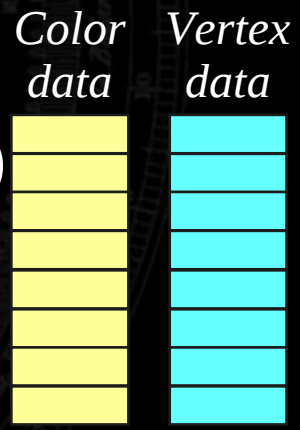
GLU Quadric Objects

- sphere
- cylinder (or cone)
- disk (circle)

Vertex Arrays



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




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

All active arrays are used in rendering

Why use Display Lists or Vertex Arrays?

May provide better performance than immediate mode rendering

Display lists can be shared between multiple OpenGL context

- reduce memory usage for multi-context applications

Vertex arrays may format data for better memory access

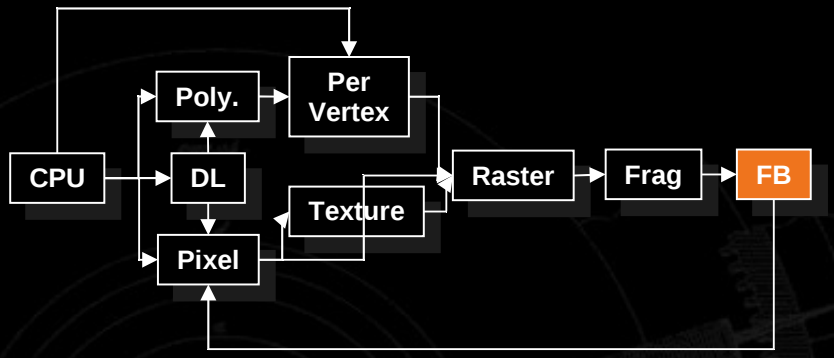
Alpha: the 4th Color Component

Measure of Opacity

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

```
glEnable( GL_BLEND )
```

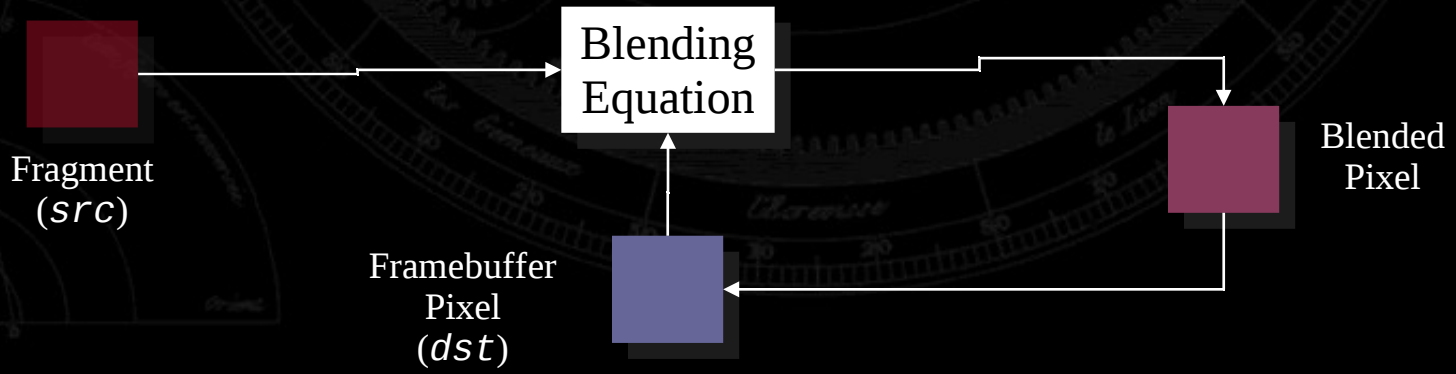
Blending



Combine pixels with what's in already in the framebuffer

`glBlendFunc( src, dst )`

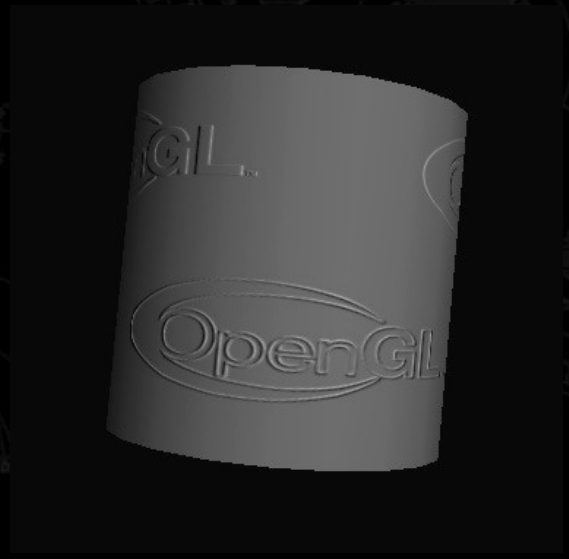
$$C_r = src\ C_f + dst\ C_p$$



Multi-pass Rendering

Blending allows results from multiple drawing passes to be combined together

- enables more complex rendering algorithms



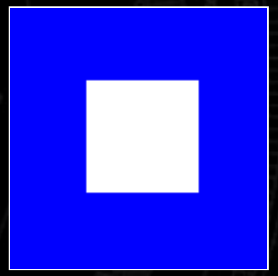
Example of bump-mapping done with a multi-pass OpenGL algorithm

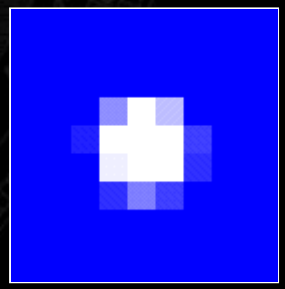
Antialiasing

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

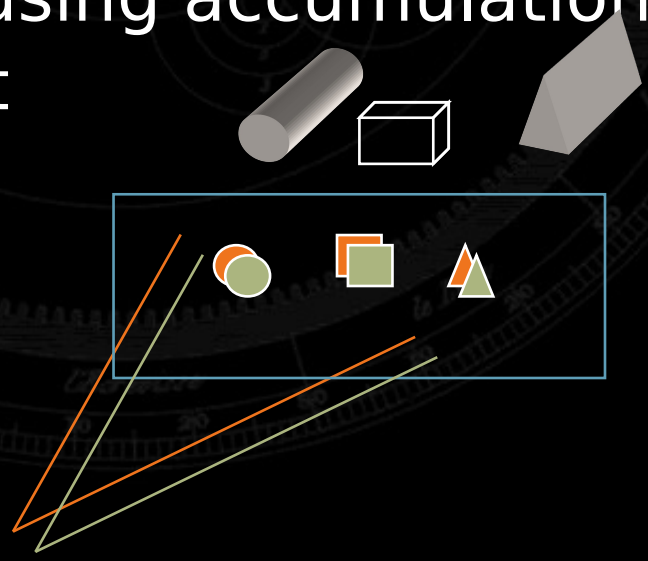
Accumulation Buffer Applications

Compositing
Full Scene Antialiasing
Depth of Field
Filtering
Motion Blur

Full Scene Antialiasing : *Jittering the view*

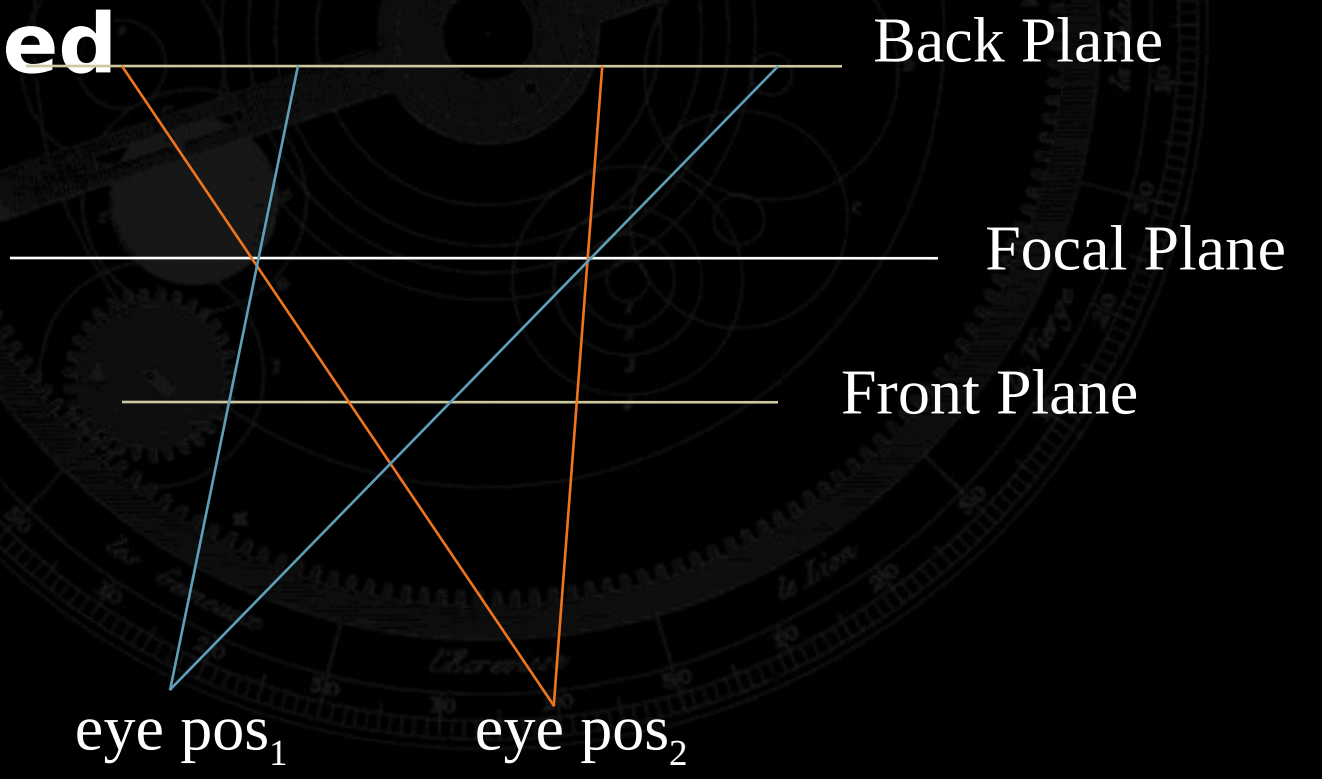
Each time we move the viewer, the image shifts

- 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{if}(` ***`property, value`*** `)`

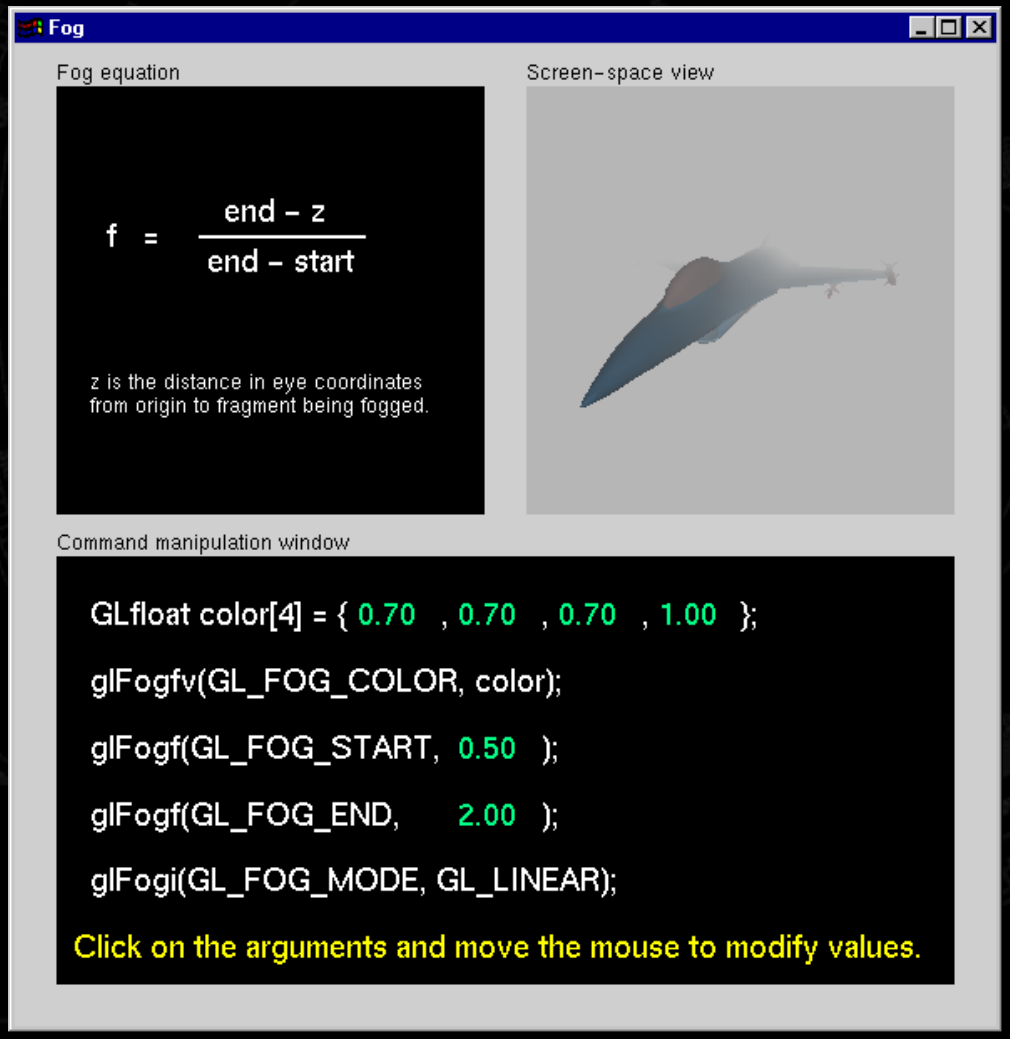
Depth Cueing

- 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

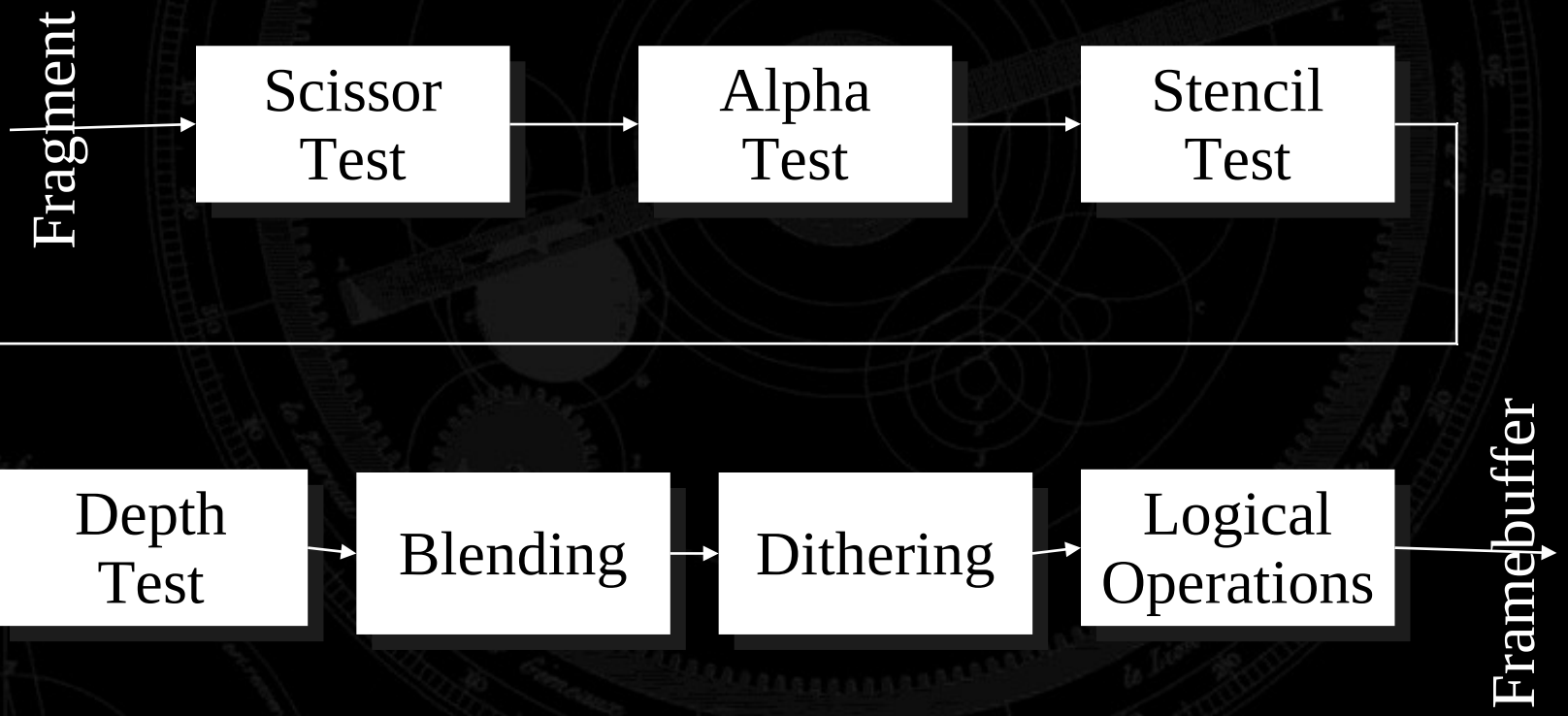
For OpenGL Picking Mechanism

- 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



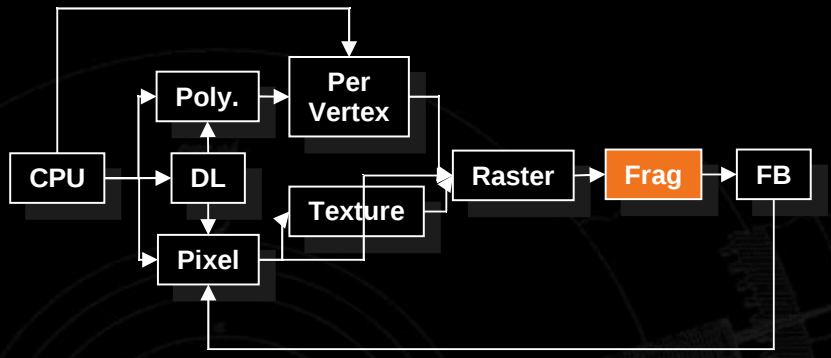
Scissor Box

Additional Clipping Test

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

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

Alpha Test

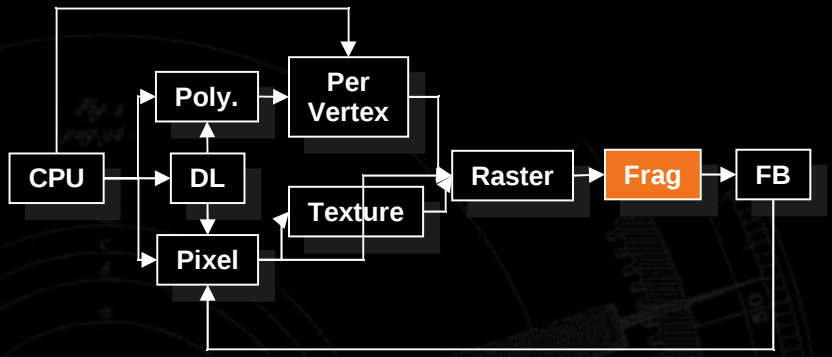


Reject pixels based on their alpha value

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

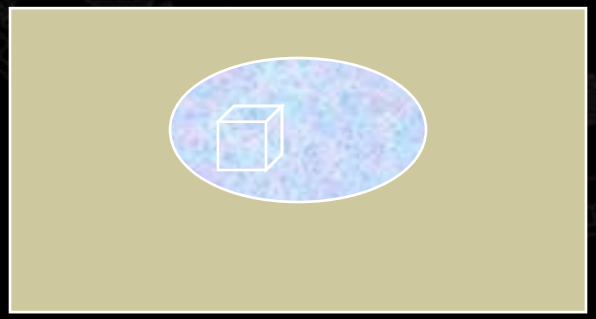
- use alpha as a mask in textures

Stencil Buffer



Used to control drawing based on values in the stencil buffer

- Fragments that fail the stencil test are not drawn
- Example: create a mask in stencil buffer and draw only objects not in mask area



Controlling Stencil Buffer

glStencilFunc(*func, ref, mask*)

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

glStencilOp(*fail, zfail, zpass*)

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

Creating a Mask

```
glInitDisplayMode( …|GLUT_STENCIL|… );
glEnable( GL_STENCIL_TEST );
glClearStencil( 0x0 );

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

draw mask

Using Stencil Mask

Draw objects where stencil = 1

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

Draw objects where stencil != 1

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

Dithering

```
glEnable( GL_DITHER )
```

Dither colors for better looking results

- Used to simulate more available colors

Logical Operations on Pixels

Combine pixels using bitwise logical operations

`glLogicOp( mode )`

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

Advanced Imaging

Imaging Subset

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

On-Line Resources

- **http://www.opengl.org**
  - start here; up to date specification and lots of sample code
- **news:comp.graphics.api.opengl**
- **http://www.sgi.com/software/opengl**
- **http://www.mesa3d.org/**
  - Brian Paul’s Mesa 3D

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