CMSC 498M: Chapter 3
Overview of OpenGL

Reading:
- See the **OpenGL Programming Guide**, (also known as "The Red Book") by the OpenGL Arch. Rev. Board, Shreiner, Woo, Neider, and Davis.

Overview:
- Introduction to OpenGL
- GLUT and user interaction
- OpenGL transformations and 3D viewing
- Lighting and texturing

OpenGL

Standard: Most **widely-used/supported** 2D/3D graphics API
- Windows NT/95/98/00, UNIX, Linux, MacOS, OS/2, Python, …
- Bindings for C, C++, Java, Fortran, Ada
- ATI, HP/Compaq, E&S,IBM, Intel, Intergraph, NVIDIA, Microsoft, SGI

Independent: of hardware, OS, window system.

Windowing not included: Does not include commands for windowing tasks or user interaction.

OpenGL Resources

Online Documentation:
- http://www.opengl.org/documentation/
- http://msdn.microsoft.com/library/

Tricks/Tips/Examples/Tutorials:
- http://nehe.gamedev.net/
- http://www.gamedev.net/

Sample Code:
- http://www.opengl.org/code/

GLUT: (GL toolkit)
- http://www.opengl.org/resources/libraries/glut/
- http://www.xmission.com/~nate/glut.html

OpenGL Pipeline Architecture (Simplified)

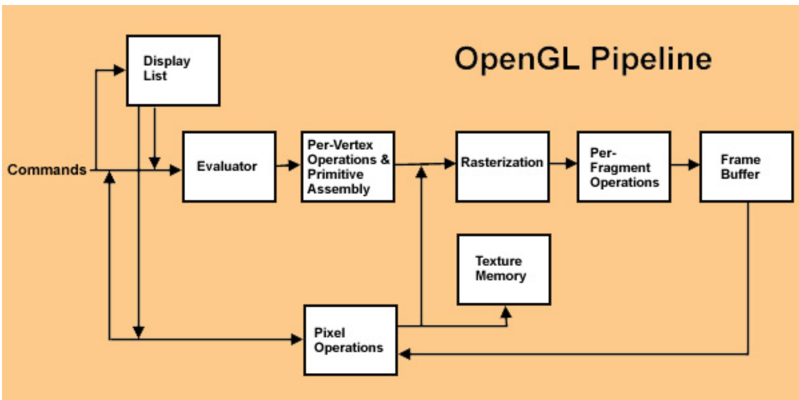
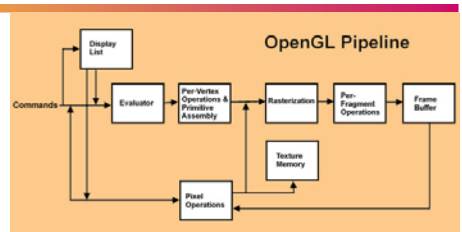


Image source: Matthew Ward

OpenGL Pipeline Architecture (Simplified)



Display List:
OpenGL drawing commands, pre-compiled for efficiency.

Evaluator:
Vertex preprocessing.

Per-Vertex Operations:
Geometric transformations applied to each vertex.

Primitive Assembly:
Vertices are grouped together to form triangles, polygons, etc.

Rasterization:
Primitives converted into pixels, called **fragments**, and colored.

Per-Fragment Operations:
Tests (e.g. depth/stencil test) to determine fragment visibility.

Pixel Operations and **Texture Memory**:
Pixels can be copied, texture mapped, or saved.

OpenGL Rendering Process

OpenGL Buffers

Color Buffers: The buffers that are normally drawn into.

- **Double-buffered system**: front and back buffers. (The front buffer is visible, and drawing take place into the back buffer.)
- **Other examples**: stereoscopic buffers (for left and right images).

Depth Buffer:

- Used for **hidden surface removal** by storing a depth value for each pixel. Only the **closest** pixel is drawn.

Stencil Buffer:

- This allows drawing to be **restricted** to certain portions of the screen.

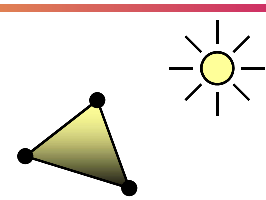
Accumulation Buffer:

- Used for accumulating a **series of images** into a final, composite image. In particular it can be used for **antialiasing** and effects like **motion blur**.

Lighting and Clipping

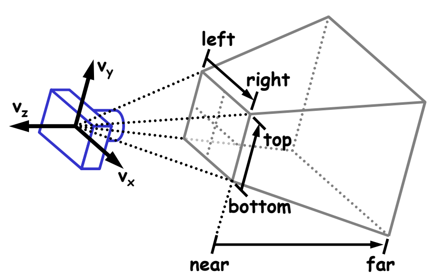
Lighting:

- The color of each vertex is determined base on the object's **material properties** and the relationship to **light sources**.



Clipping:

- Once a primitive has been assembled, it is **clipped** so that it lies within a 3-dimensional region, called the **view frustum**.
- When a polygon is **partially inside**, **new vertices** are created as needed and vertex attributes are interpolated.



Projection and Rasterization

Projection:

Vertices are projected (either **perspective** or **orthogonal**).

Viewport:

The projected vertices are mapped to the visible portion of the screen (**viewport**).

Rasterization:

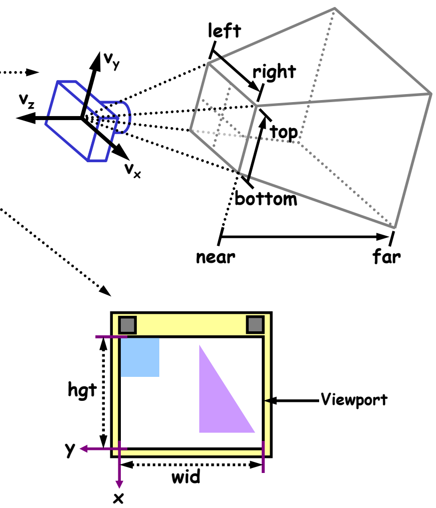
Primitives are converted into pixels (**fragments**).

Per-Fragment Operations:

Determine fragment visibility.

Depth Test: Hidden by a closer fragment?

Stencil Test: Used to restrict drawing to selected portions of the window.



Chapter 2, Slide 9

Texturing and Fog

Texture:

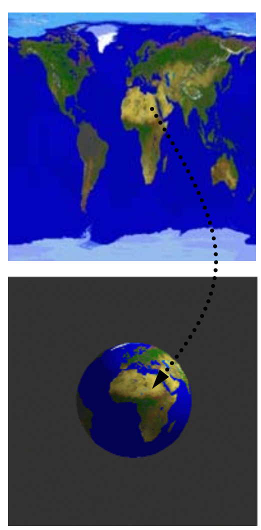
When enabled, a fragment's **texture coordinates** are used to index into a texture image, generating a **texel**.

The texel **modifies the fragment's color** based on the current texture environment, which may involve blending with the existing color.

Maxification/Minification: Different rules can be applied to interpolate values when the texel is **smaller** (requiring maxification) or **larger** (requiring minification).

Fog:

After texturing, a **fog** function may be applied to the fragments. This blends a fog color is based on the **distance** of the viewer from the fragment.



Chapter 2, Slide 10

Immediate Mode and Display Lists

Immediate Mode:

- By default, OpenGL operates in **immediate mode**, where the drawing commands are **executed immediately**.

Display Lists:

- Frequently executed commands that are **stored** for **later execution**.
- Display lists reside on the **server** (the GPU.)
- Once created they **cannot be modified**, but they **can be transformed** geometrically.
- They store both **geometric information** (vertices) and other **attributes** (color, texture coordinates, surface normals).
- Display lists can **reference other display lists**. This is useful for the display of **composite objects** (e.g., the wheels of a car).

OpenGL Drawing Primitives

OpenGL Naming Conventions (for C/C++)

Functions: begin with **gl** (example: **glBegin** – draw an object)
Constants: begin with **GL_** (example: **GL_POLYGON** – a polygon)
Types: begin with **GL** (example: **GLfloat** – single-precision float)

OpenGL Data Types

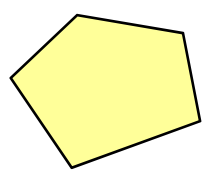
Suffix	OpenGL Datatype	C/C++ Datatype
b	GLbyte	signed char
s	GLshort	short
i	GLint	int
ub	GLubyte	unsigned char
us	GLushort	unsigned short
ui	GLuint	unsigned int
f	GLfloat	float
d	GLdouble	double

OpenGL Vertices and Primitives

OpenGL supports a number of different drawing primitives. Each primitive is specified by enumerating the vertices that define it.

General Form:

```
glBegin ( ⟨object type⟩ );
    glVertex… ( … );
    glVertex… ( … );
    glVertex… ( … );
glEnd ( );
```



Note: There are a number of other **attributes** that can be placed within the glBegin…glEnd pair. These affect things like **color**, **texture**, and **surface normals**. We will discuss these later.

Vertices: May be 2D (x,y), 3D (x,y,z), or 4D (x,y,z,w), where the w coordinate is usually 1. Called **homogeneous coordinates**.

Specifying Vertices

Vertex Arguments: All objects in OpenGL are constructed from **convex polygons**, which are represented by their **vertex coordinates**. The **argument type** is specified by the **suffix** to the OpenGL function name:

⟨**func_name**⟩ ⟨**dim**⟩ ⟨**type**⟩ **(** ⟨**argument list**⟩ **)**

Examples:

2D point in GLint (int) coordinates:

```
glVertex2i (200, -150);
```

3D point in GLfloat (float) coordinates:

```
glVertex3f (200.3f, -150f, 40.75f);
```

Vector (array) Arguments: Add suffix "v" to the function name

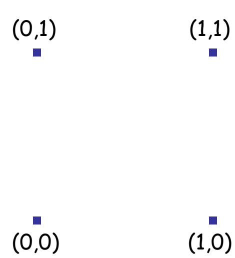
3D point in GLdouble (double) coordinates given as a vector:

```
GLdouble pt[3] = { 200.3, -150, 40.75 };
glVertex3dv (pt);
```


Object Types - Isolated Points

GL_POINTS: Draws a set of isolated points.

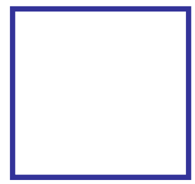
```
glBegin ( GL_POINTS );
    glVertex2i ( 0, 0 );
    glVertex2i ( 0, 1 );
    glVertex2i ( 1, 0 );
    glVertex2i ( 1, 1 );
glEnd ( );
```



Object Types - Line Loop (Polyline)

GL_LINE_LOOP: Draws a closed polygonal line (segments joined end to end).

```
glBegin ( GL_LINE_LOOP );
    glVertex2i ( 0, 0 );
    glVertex2i ( 0, 1 );
    glVertex2i ( 1, 1 );
    glVertex2i ( 1, 0 );
glEnd ( );
```



Variants:

- **GL_LINE_STRIP**: Polygonal line, but not closed off to form a loop.
- **GL_LINES**: A sequence of line segments, not connected to each other.

Object Types - Polygon

GL_POLYGON: Draws a filled convex polygon.

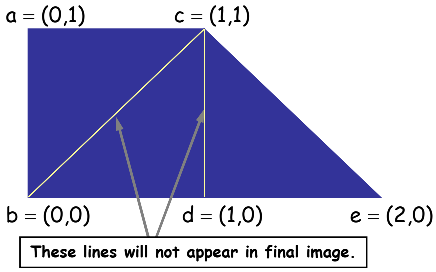
```
glBegin ( GL_POLYGON );
    glVertex2i ( 0, 0 );
    glVertex2i ( 0, 1 );
    glVertex2i ( 1, 1 );
    glVertex2i ( 1, 0 );
glEnd( );
```

Note: OpenGL assumes that all polygons are **convex**, meaning that all interior angles are at most 180 degrees. OpenGL is largely "**silent**" about errors, so be careful.

Object Types - Triangles

GL_TRIANGLES: Draws a series of filled triangles. Each sequence of three vertices defines a separate triangle.

```
glBegin ( GL_TRIANGLES );
    glVertex2i ( 0, 1 );
    glVertex2i ( 0, 0 );
    glVertex2i ( 1, 1 ); // abc
    glVertex2i ( 1, 1 );
    glVertex2i ( 0, 0 );
    glVertex2i ( 1, 0 ); // cbd
    glVertex2i ( 1, 1 );
    glVertex2i ( 1, 0 );
    glVertex2i ( 2, 0 ); // cde
glEnd ( );
```

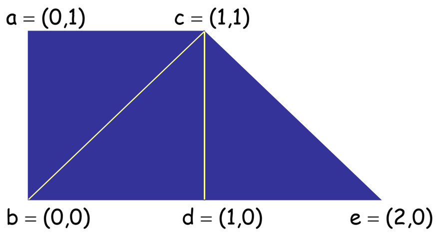


Note: List vertices in a consistent order, say, **counterclockwise**. This is used to distinguish **front** (CCW) and **back** (CW) sides.

Object Types - Triangle Strip

GL_TRIANGLE_STRIP: Draws a series of triangles by joining the next vertex to the previous two.

```
glBegin ( GL_TRIANGLE_STRIP );
    glVertex2i ( 0, 1 ); // a
    glVertex2i ( 0, 0 ); // b
    glVertex2i ( 1, 1 ); // c→abc
    glVertex2i ( 1, 0 ); // d→bcd
    glVertex2i ( 2, 0 ); // e→cde
glEnd ( );
```



Orientation: The first triangle is oriented **counterclockwise**. OpenGL will orient all remaining triangles in the strip in the same way.

Drawing Attributes

Attributes: affect the **manner** in which objects are drawn.

- These can be placed **within each glBegin…glEnd pair**.
- Once set, they **affect subsequent objects**, until changed again.

Points:

- Point size: **glPointSize** (2.0);
- Point color: **glColor3f** (0.0, 0.0, 1.0);
  (Sets RGB color components: Red, Green, Blue.)

Lines:

- Line width: **glLineWidth** (2.0);
- Line color: **glColor3f** (0.0, 0.0, 1.0);

Polygons:

- Front and/or back: **GL_FRONT**, **GL_BACK**, **GL_FRONT_AND_BACK**.
  - The **front** is the side where vertices appear in **counter-clockwise order**.
- Face color: **glColor3f** (0.0, 0.0, 1.0);
- Lighting material properties: **glMaterialf** (…)

GLUT:
Window Manipulation and User Interaction

Event-Driven Computing

Typical (noninteractive) Program:
- Read Data.
- Process Data.
- Output Results.

Event-Driven Computing: (**System's** perspective)
- Check whether an **event** has occurred.
- if (an event has occurred)
  - call **eventHandler**(eventInfo).
- Repeat.

Event-Driven Computing: (**Programmer's** perspective)
- Register "**event-handler**" pairs. (For each "event" call a function, called a **callback**, that performs "handles" this event and returns.)
- Pass control to the operating system.

Event Queue

Operating System/Window Management System: copies all **handled events** to an **Event Queue**.

Let **EQ** be the event queue (first-in, first-out queue).

New event(e):

```
if (e is handled) { append e to the end of EQ }
```

Processing Events:

Event Handlers are functions that your program provides.

```
while (true) {
    if (EQ is not empty) {
        call eventHandler( EQ.front( ) );
        remove front event from EQ;
    }
}
```

OpenGL and GLUT

OpenGL is window-system independent:

- Makes it **portable**.
- Can be targeted for **different platforms**: PCs, game consoles, interactive TV set-top boxes.
- Independent of:
  - **operating system**
  - **windows system**
  - **display size and display properties** (only assumes a raster-device).

But: OpenGL still needs to **interface** with windowing system.

For instance: X-windows, Microsoft's windows system

GLUT (to the rescue): GLUT (GL Utility Toolkit) is a window-system independent programming **interface** for OpenGL.

GLUT: OpenGL Utility Toolkit

GLUT:

- is a **simple programming interface** to the windows system.
- is largely **window-system independent**.
- supports only **pop-up menus** (no pull-down menus).
- maintains its own **event loop**.
- accepts **registration of callback functions** from user programs.
- has its own (limited) set of **fonts**.

Some useful sites for GLUT:

- **Mark Kilgard's GLUT page**: Full online documentation.
  http://www.opengl.org/documentation/specs/glut/spec3/spec3.html
- **Nate Robins GLUT for Win32**: Has precompiled binaries for Microsoft Windows and installation instructions.
  http://www.xmission.com/~nate/glut.html

GLUT Initialization

glutInit (int* **argc**, char** **argv**)
- Initialize GLUT library. Must be called first.
- Recognizes and processes GLUT-specific command-line arguments.

glutInitWindowSize (int **width**, int **height**)
- Specifies the desired window size. (No guarantees that you will get this.)

glutInitWindowPosition (int **x**, int **y**)
- Requests location (in pixels) of the upper left corner of the window. Note that (0,0) is the upper left corner of the display.

glutInitDisplayMode (unsigned int **mode**)
- Specifies a number of options affecting general operation connected by "boolean or": E.g. **GLUT_RGBA | GLUT_DEPTH | GLUT_DOUBLE**, etc…

glutCreateWindow (char* **window_name**)
- Request that the window be created. (This only issues the request and returns. The window is **not created immediately**.)

GLUT Main Event Loop

glutMainLoop ( )
- Starts the GLUT **event processing loop**.
- **Never returns** (except through callbacks).
- Calls **registered function callbacks** (user-defined event handlers) as appropriate.
- Should be called **at most once**.
- **Before** calling this, be sure to **register your events** (or this will be a very uninteresting program). ☺

Sample Program (Part I)

```
int main ( int argc, char** argv ) {         // program arguments
  glutInit( &argc, argv );                   // initialize glut and gl
                                             // double buffering and RGB
  glutInitDisplayMode ( GLUT_DOUBLE | GLUT_RGB );
  glutInitWindowSize ( 400, 300 );           // window size
  glutInitWindowPosition ( 0, 0 );           // window position in upper left
  glutCreateWindow ( argv[0] );              // create window

  … initialize callbacks here (described below) …

  myInit ( );                                // your own initializations
  glutMainLoop ( );                          // turn control over to glut
  return 0;                                  // (make the compiler happy)
}
```


GLUT Window Management

glutSwapBuffers ( )
- Swaps front and back buffers.
- This is part of a process called **double-buffering**, and is used to produce smooth, flicker-free animations.

glutPostRedisplay ( )
- Mark the current window as "**needing to be redrawn**".
- GLUT only redraws the window **when you request it**.
- Next iteration of the **glutMainLoop** will refresh the window using the **display-function callback**.
- To achieve a **continuous animation**, call this function inside a **timer loop** that wakes up every 1/30 second, say, or in an **idle loop**.

glutFullScreen ( )
- Resize window to **full screen**. (See also **glutEnterGameMode** ( )).

glutReshapeWindow (int **width**, int **height**)
- Resize the display window using the parameters.

GLUT Callback Registration

glutDisplayFunc (void (*func) ( ))

- Call the given function whenever the **window needs to be redrawn**.
  - When window is **first created**.
  - When the window is revealed because an **overlapping window is removed**.
  - When the program called **glutPostRedisplay**( ).

glutReshapeFunc (void (*func) (int **width**, int **height**))

- Call the given function whenever the **window is resized**.
- Called when the window is **first created**. (This is useful for some graphics **initializations**, such as **texture mapping**, which can only be done with an extant graphics window.)
- May involve updating the **projection** (gluPerspective) and **viewport** (glViewport) since they depend on the **window's shape**.

GLUT Callback Registration

glutKeyboardFunc (void (*func) (unsigned char **key**, int **x**, int **y**))

- Call the given function when a **keyboard key is hit**.
- The (x, y) arguments indicate where the **mouse** was when key was pressed.

glutSpecialFunc (void (*func)(int **key**, int **x**, int **y**))

- Call the given function when a special key is hit (function keys, arrows, page-up, page-down, etc.)

glutMouseFunc (void (*func) (int **button**, int **state**, int **x**, int **y**))

- Call the given function when a **mouse button is hit or released**.
- **Button argument**: GLUT_LEFT_BUTTON, GLUT_MIDDLE_BUTTON, GLUT_RIGHT_BUTTON.
- **State**: GLUT_UP, GLUT_DOWN.
- **Position** (**x, y**): Relative to upper left corner.

GLUT Callback Registration (cont)

glutMotionFunc (void (*func) (int x, int y))

- Mouse motion while button pressed. (x, y) is current mouse position.

glutPassiveMotionFunc (void (*func) (int width, int height))

- Mouse motion without button press. (**Warning**: This can generate lots of events!)

glutIdleFunc (void (*func) ( ))

- Called whenever **no other events** are on the event queue.
- Passing **NULL** disables this.

glutTimerFunc (unsigned int **msecs**, void (*func) (int value), value))

- Callback every **msecs milliseconds** (or more): Best effort.
- The **value** parameter is used for setting multiple alarms.
- Function **func** called with the specified **value** parameter.

Sample Program (Part II)

```
int main ( int argc, char** argv ) {      // program arguments
   … (given in Part I) …
  glutDisplayFunc ( myDraw );             // set up callbacks
  glutReshapeFunc ( myReshape );
  glutMouseFunc ( myMouse );
  glutKeyboardFunc ( myKeyboard );
  glutTimerFunc (20, myTimeOut, 0 );      // (see below)
  … (given in Part I) …
}
```

Sample Program (Part III)

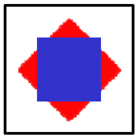
```
void myDraw ( ) {                          // called to display window
  // ...insert your drawing code here ...
}
void myReshape ( int w, int h ) {          // called if reshaped
   windowWidth = w;                        // save new window size
   windowHeight = h;
   // ...may need to update the projection ...
   glutPostRedisplay ( );                  // request window redisplay
}
void myTimeOut ( int id ) {                // called if timer event
   // ...advance the state of animation incrementally...
   glutPostRedisplay ( );                  // request redisplay
   glutTimerFunc (20, myTimeOut, 0);       // request next timer event
}
```


Sample Program (Part IV)

```
void myMouse ( int b, int s, int x, int y ) { // called if mouse click
   switch (b) {                            // b indicates button
      case GLUT_LEFT_BUTTON:
         if ( s == GLUT_DOWN ) ...         // left button pressed
         else if ( s == GLUT_UP ) ...      // left button released
         break;
      // ...                               // other button events
   }
}
void myKeyboard ( unsigned char c, int x, int y ) { // keyboard key hit
  switch (c) {                             // c is the key that is hit
    case 'q':                              // 'q' means quit
      exit(0);  break;
    // ...                                 // other keyboard events
  }
}
```

Sample Program (Part V)

```
void myDisplay ( ) {                          // display function
   glClear ( GL_COLOR_BUFFER_BIT );           // clear the window

   glColor3f ( 1.0, 0.0, 0.0 );               // set color to red
   glBegin ( GL_POLYGON );                    // draw a diamond
      glVertex2f ( 0.90, 0.50 );
      glVertex2f ( 0.50, 0.90 );
      glVertex2f ( 0.10, 0.50 );
      glVertex2f ( 0.50, 0.10 );
   glEnd ( );

   glColor3f ( 0.0, 0.0, 1.0 );               // set color to blue
   glRectf ( 0.25, 0.25, 0.75, 0.75 );        // draw a rectangle

   glutSwapBuffers ( );                       // swap buffers (make visible)
}
```



DEMO

OpenGL Transformations

Transformations in OpenGL

OpenGL provides support for transformations. There are a number of contexts in which transformations are used.

Modelview Mode (**GL_MODELVIEW**): Used for

- **transforming objects** in the scene and
- **changing the coordinates** into a form that is easier for OpenGL to deal with.

Projection Mode (**GL_PROJECTION**): Used for **projecting** objects onto the 2d image plane.

Texture Mode (**GL_TEXTURE**): Used for transforming (wrapping) **textures** onto surfaces of your objects.

Transformations in OpenGL

OpenGL has three **matrix stacks**. Matrix operations apply to the current stack.

To specify which stack you want to manipulate, use:

glMatrixMode (⟨**mode**⟩);

where ⟨**mode**⟩ is either:

- **GL_MODELVIEW**
- **GL_PROJECTION**
- **GL_TEXTURE**.

Modelview mode is the most common (and the default), so it is common to switch back to Modelview mode.

```
glMatrixMode ( GL_PROJECTION );
// … do something in Projection mode …
glMatrixMode ( GL_MODELVIEW );
```


OpenGL Matrix Stack Operations

Matrix Stack: Each matrix mode has a stack of matrices. All operations apply to the **active matrix** at the top of the stack.

glLoadIdentity ( )

- Set the active matrix to identity.

glLoadMatrixf (**GLfloat*** **m**)
glLoadMatrixd (**GLdouble*** **m**)

- Set the 16 values of the active matrix to those specified by **m**.

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

glMultMatrixf (**GLfloat*** **m**)
glMultMatrixd (**GLdouble*** **m**)

- Post-multiplies the active matrix by **m**.

WARNING! → OpenGL assumes **column-major order**, whereas C/C++ assume **row-major order**.

OpenGL Matrix Stack Operations

Stack Operations: It is possible to save the current matrix state by pushing and popping.

glPushMatrix ( )

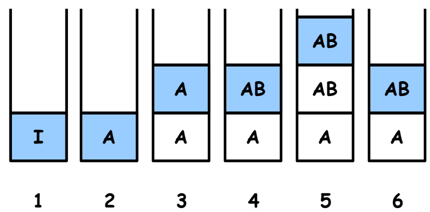
- Make a copy of the active matrix and push it on the stack.

glPopMatrix ( )

- Pop the active matrix off the stack.

Example:

1. **glLoadIdentity** ( );
2. **glLoadMatrixf** (A);
3. **glPushMatrix** ( );
4. **glMultMatrixf** (B);
5. **glPushMatrix** ( );
6. **glPopMatrix** ( );



Chapter 2, Slide 43

OpenGL Transformation Operations

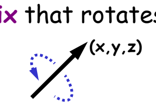
Standard Transformations: Rather than specifying your own matrix, it is more common to use one of the standard transformations. Below "**GLtype**" is either "**GLfloat**" or "**GLdouble**".

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

- Post-multiply the active matrix by a **translation matrix** that translates by (x, y, z).

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

- Post-multiply the active matrix by a **rotation matrix** that rotates CCW by **angle** degrees about the vector (x, y, z).



glScale{fd} (GLtype s_x, GLtype s_y, GLtype s_z)

- Post-multiply the active matrix by a **scale matrix** that scales x by s_x, y by s_y and z by s_z.

Chapter 2, Slide 44

Composing Transformations

Transformations can be composed through **matrix multiplication**.

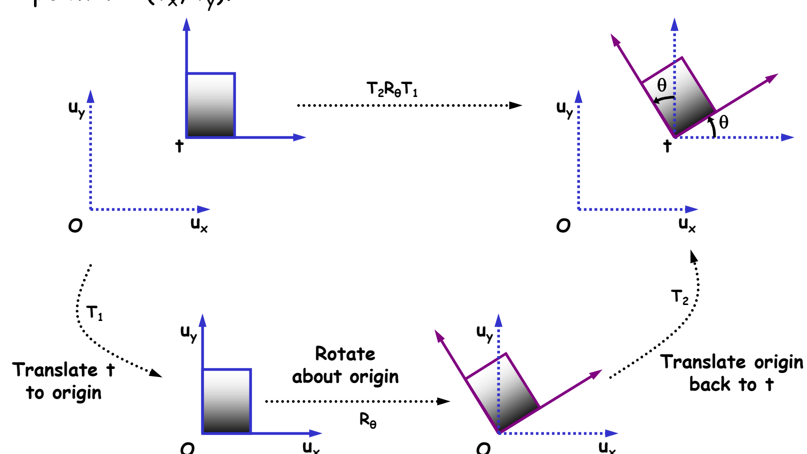
- **Efficient**: allows us to perform a **series** of transformations with a **single** matrix/vector multiplication.
- **Order**: Because we **post-multiply**, the order of evaluation is from **right to left**:

$$M_3 \cdot M_2 \cdot M_1 \cdot \mathbf{p} \quad \rightarrow \quad (M_3 \cdot (M_2 \cdot (M_1 \cdot \mathbf{p})))$$

  Note: The order in which you request transformations is the **reverse** of the order in which they are conceptually applied.
- **Remember**: Matrix multiplication is **associative** ($(AB)C = A(BC)$), but **not commutative** ($AB \neq BA$). So the order in which matrices are listed does matter.

Composing Transformations

Example: Rotate the plane counterclockwise by angle θ about the point $\mathbf{t} = (t_x, t_y)$.

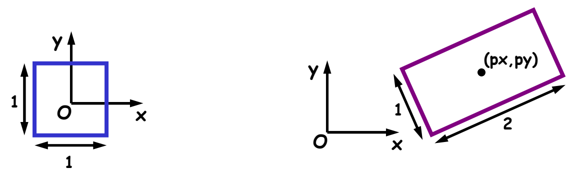


Transformations and Drawing

The active transformation matrix is **automatically** applied to **all drawing**. The **typical order** is:

- **save** the current matrix state (push)
- **apply** the desired transformation matrix to active matrix
- **draw** your object(s)
- **restore** the matrix state (pop)

Example: Suppose that **myRect**( ) draws a 1×1 rectangle centered at the origin. We want to draw a 2×1 rectangle centered at (p_x,p_y) and rotated (about the z-axis) by 20 degrees CCW.



Chapter 2, Slide 47

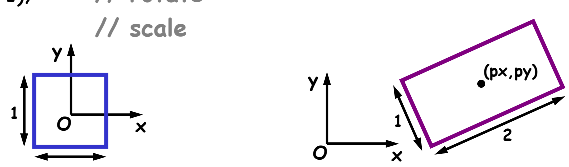
Transformations and Drawing

Conceptual Solution:

- Call myRect( ) to draw original rectangle.
- Scale it to 2x1.
- Rotate it 20 degrees CCW about z-axis.
- Translate it to (p_x,p_y).

OpenGL Order: Is the **reverse** of this. ← **WARNING!**

```
glPushMatrix ( );          // save the state
  glTranslatef (px, py, 0);  // translate
  glRotatef (20, 0, 0, 1);   // rotate
  glScalef (2, 1, 1);        // scale
  myRect ( );
glPopMatrix ( );
```



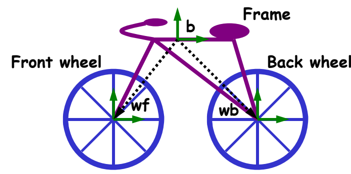
Chapter 2, Slide 48

Composite Objects and Compound Motion

Composite Object: is formed from **multiple parts** that are linked together (e.g., the arms, legs, head, torso of a person).

Compound Motion: involves coordinating the movement of the individual parts to form a motion of the composite object.

Example: Consider a bicycle consisting of three parts: frame, front wheel, and back wheel. The wheels are identical.

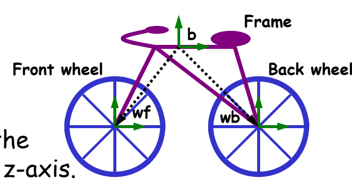


- **drawFrame( )** : Draws the frame with its center at the origin.
- **drawWheel( )** : Draws one wheel centered at the origin.
- **Other variables**:
  - b = location of bike origin relative to world origin.
  - wf/wb = vector offset of front/back wheel relative to bike origin.
  - rf/rb = rotation (in degrees) of the front and back wheel.

Composite Objects and Compound Motion

Drawing the Bike: Conceptual order:
- Draw **front wheel** at the origin.
- **Rotate** front wheel by rf degrees.
- **Translate** it to wf.
- Draw the **back wheel** at the origin.
- **Rotate** it by rb degrees.
- **Translate** it to wb.
- Draw **frame**.
- **Translate** everything to b.

For simplicity we assume the bike is in the x,y-plane so rotations are about the z-axis.

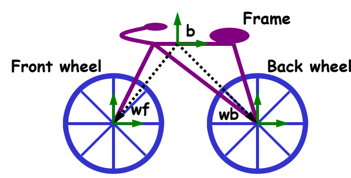


OpenGL order: We **reverse** this process by setting up the transformations first and then drawing.

Composite Objects and Compound Motion

OpenGL order:

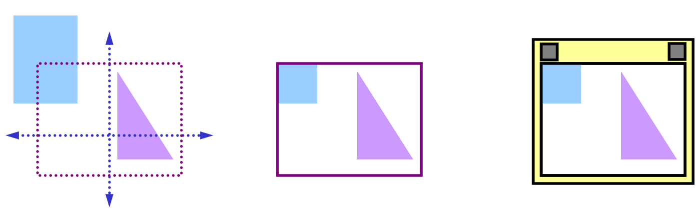
- **glPushMatrix** ( );
  - **glTranslatef** (b_x, b_y, b_z);
  - **drawFrame** ( );
  - Draw back wheel
  - **glPushMatrix** ( );
    - **glTranslatef** (wb_x, wb_y, wb_z);
    - **glRotatef** (rb, 0, 0, 1);
    - **drawWheel** ( );
  - **glPopMatrix** ( );
  - **glPushMatrix** ( );
    - **glTranslatef** (wf_x, wf_y, wf_z);
    - **glRotatef** (rf, 0, 0, 1);
    - **drawWheel** ( );
  - **glPopMatrix** ( );
  - Draw front wheel
- **glPopMatrix** ( );



2D Projection and Viewport Transformation

Projection Transformation: Maps points from your idealized drawing area to a rectangular **viewport**.

Viewport Transformation: Maps points from the viewport a region of your graphics window. (Usually all of it, but you can specify any portion you like.)

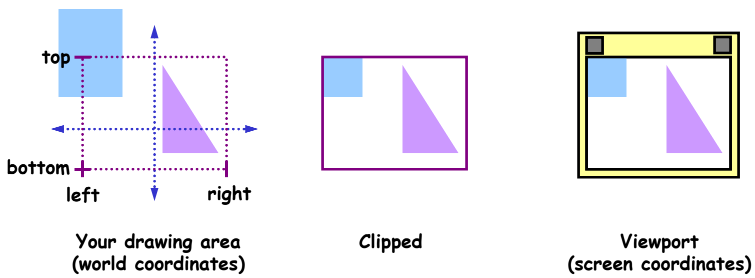


Your drawing area (world coordinates) | Clipped | Viewport (screen coordinates)

2D Projection Transformation

Projection Transformation: is set up in Projection mode.

```
glMatrixMode ( GL_PROJECTION );
glLoadIdentity ( );
gluOrtho2D ( left, right, bottom, top );
glMatrixMode ( GL_MODELVIEW );
```



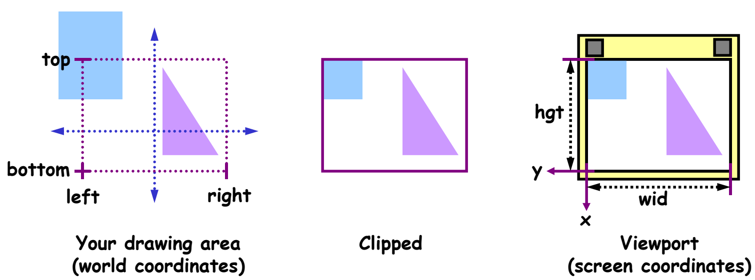
Chapter 2, Slide 53

Viewport Transformation

Viewport Transformation: is set up using glViewport.

glViewport (x, y, wid, hgt);

- (x, y) are the lower left corner of the viewport (in pixels.)
- (wid, hgt) are the width and height of the viewport (in pixels).
- Use **glViewport**(0, 0, winWid, winHgt) to use full window.
- A good place to put this is in your **reshape callback**.



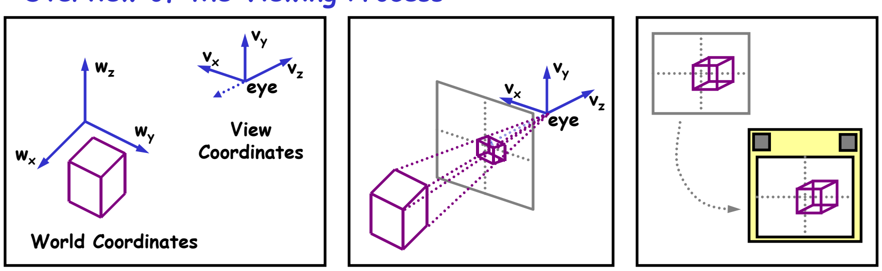
Chapter 2, Slide 54

3D Viewing in OpenGL

Transformations for 3D Viewing

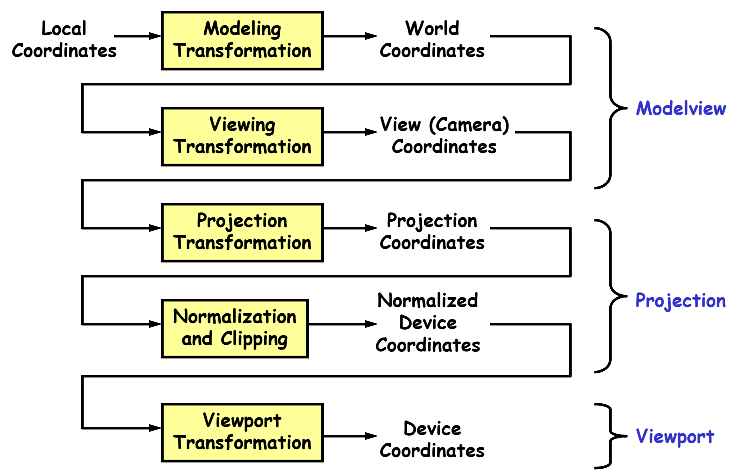
Modelview: Map 3D **world coordinates** to 3D **view coordinates**.
Projection: Projects 3D **objects** onto the 2D **view plane**.
Viewport: Map the **view plane** to the **graphics viewport**.

Overview of the Viewing Process:



Convert to View Coordinates | Project to View Plane | Map to viewport

3D Viewing Pipeline: An Expanded View

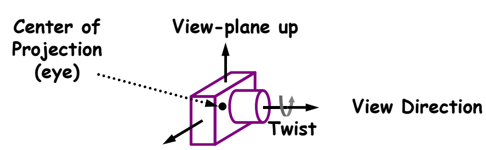


Specifying the Camera Position

World frame: The frame in which you represent your points.

View Frame: (also called **camera** or **eye frame**) Is specified by the following quantities, relative to world coordinates:

- **Eye Location**: The **center of projection**.
- **Viewing Direction**: A unit vector that is normal to the view plane, called the **view-plane normal**.
- **Camera twist**: The camera's rotation about the viewing axis, specified by indicating the **"up" direction for the camera**.



Specifying the View Frame: gluLookAt( )

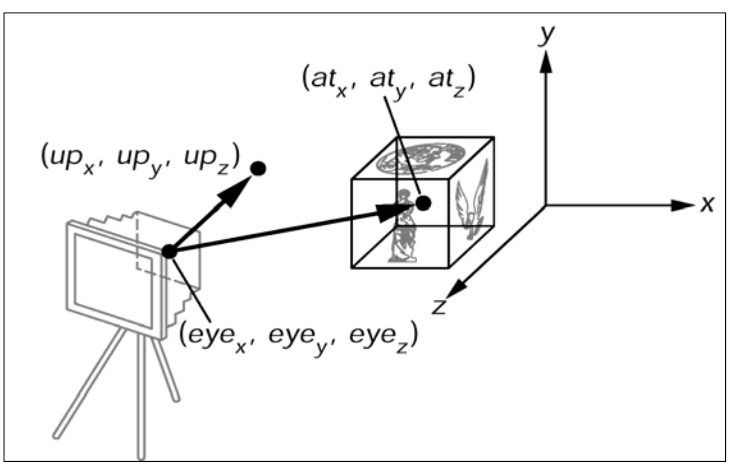
In OpenGL the view frame is specified by calling:

gluLookAt (eye_x , eye_y , eye_z , at_x , at_y , at_z , up_x , up_y , up_z)

All arguments are of type **GLdouble**. Where the following are given in world coordinates:

- **eye** = (eye_x , eye_y , eye_z) is the **location of the eye**.
- **at** = (at_x , at_y , at_z) is a point that the viewer is **looking at**. The vector **at** - **eye** is the **viewing direction**.
- **up** = (up_x , up_y , up_z) is a vector indicating which direction is **up relative to the camera**. It is used to encode the camera's twist about the viewing direction. (It need **not** be orthogonal to the view direction, but it cannot be parallel to the view direction vector.)

Specifying the View Frame: gluLookAt( )

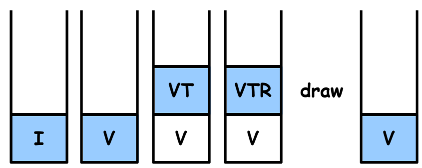


Interactive Computer Graphics by Ed Angel

Specifying the View Frame: gluLookAt( )

- **gluLookAt( )** constructs a **matrix** that converts from world coordinates to view coordinates and **multiplies** it times the top of the **modelview** matrix stack.
- Normally this is the **first matrix** on the modelview stack.

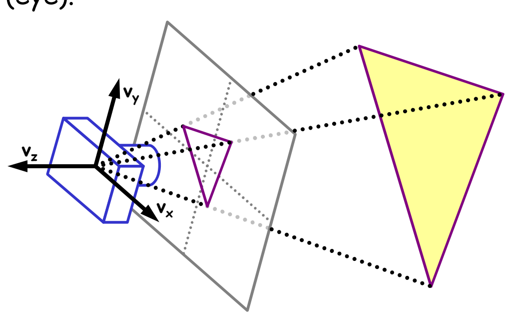
```
glLoadIdentity ( );
gluLookAt ( … );        // V
glPushMatrix ( );
    glTranslatef ( … ); // T
    glRotatef ( … );    // R
    // … do some drawing …
glPopMatrix ( );
```



- Each vertex given in the drawing process will be rotated, then translated, and finally converted into view coordinates by V.

Perspective Projection

Perspective Projection: Points are projected towards the center of projection (eye).

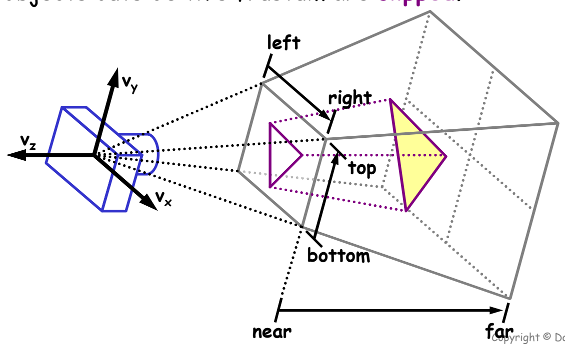


Perspective Projection in OpenGL

glFrustum: To specify the projection, you give a frustum (truncated pyramid) centered at the camera location.

glFrustum (left, right, bottom, top, near, far)

- All arguments are of type **GLdouble**.
- This is typically done in **GL_PROJECTION** mode.
- All objects outside this frustum are **clipped**.



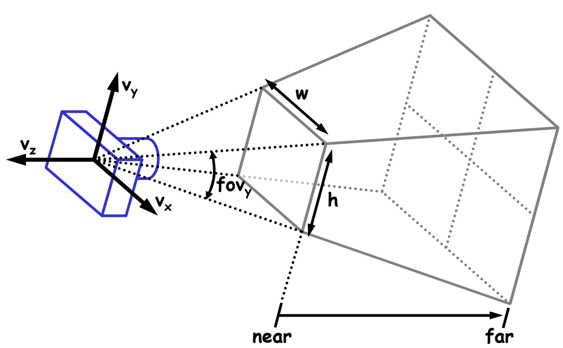
Chapter 2, Slide 63

Perspective Projection in OpenGL

Symmetric Viewing: There is a simpler form of glFrustum( ) for when the viewing situation is symmetric about the z-axis:

gluPerspective (fov_y, aspect, near, far), where

- fov_y: **y-field of view** (angle given in degrees)
- aspect: **window's aspect ratio** w/h = (right-left)/(top-bottom).



Chapter 2, Slide 64

gluPerspective( ) Operation

glFrustum( ) and **gluPerspective**( ): Generate a **transformation matrix** and multiply it times the top of the current **matrix stack** (usually the **projection** stack).

Example:

Assuming depth buffering is used.

```
void myDisplay ( ) {
  glClear ( GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT );
  glLoadIdentity ( );
  gluLookAt ( … );                              // set up view frame
  glMatrixMode ( GL_PROJECTION );               // set up projection
    glLoadIdentity ( );
    gluPerspective ( fovy, aspect, near, far );  // or glFrustum( )
  glMatrixMode ( GL_MODELVIEW );
  myWorld.draw ( );                             // draw everything
  glutSwapBuffers ( );
}
```


Lighting in OpenGL

Illumination

Illumination Models:

- Light is a very **complex physical phenomenon**.
- Most illumination models in graphics are based on **simple geometric optics**, as opposed to more complex (but realistic) **wave optics**.

Local Illumination Models: (OpenGL does this)

- **Point light sources** and **direct interactions** with light.
- **No shadows**, no **indirect reflection**
- Easy to implement and very **efficient**.

Shading:

- Involves determining the **intensity of illumination** (and its color) incident at a surface point.
- Can be **computationally intensive**, so it is common to compute it accurately at a few points (e.g., vertices) and **interpolate** in between.

Chapter 2, Slide 67

Light/Surface Interaction

Light Reflection:

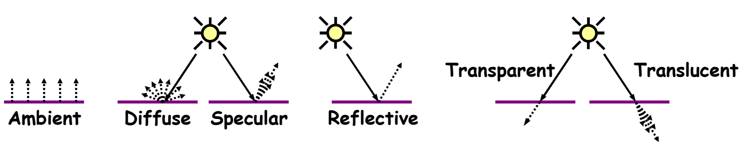
Ambient: A **background glow** that illuminates all objects, irrespective of light source location.

Diffuse: A **uniform scattering** of light, characterized by **matte** (non-shiny) objects, like cloth or foam rubber.

Specular: **Shiny** (metallic-like) reflection, like a polished wood table.

Reflective (**Pure**): No light scattering, like a **mirror**.

Transparent/Translucent: Light passes through material.



Chapter 2, Slide 68

Lighting in OpenGL

Lighting in OpenGL:

- **Ambient**, **diffuse**, **specular** illuminations are supported.
- **Attenuation** is supported: illumination grows **dimmer** as the distance from the light source **increases**.
- Users define **light sources**: position, type, color.
- **Front and back sides** of polygons may be given **different colors**.

Lighting in OpenGL

There is a bewildering a number of options and parameters that need to be set up in OpenGL in order to use lighting:

Lighting/Shading model: Global parameters that affect how **illumination** and **shading** are computed.

Light properties: Options that define the **location**, **colors**, and **intensities** of the lights.

Object material properties: The **color** of the object and degree of **ambient**, **diffuse**, **specular** reflection.

Enabling: Lighting can be enabled or disabled.

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

Lights

Lights and Lighting:

- At least **8 light sources**: **GL_LIGHT0**, …, **GL_LIGHT7**.
- **glLight*( )**: used to define individual **light properties**.
- **glLightModel*( )**: used to define **global lighting properties**.
- To determine the **maximum number of lights** supported in your implementation use:

  glGetIntegerv (GL_MAX_LIGHTS, GLint* num_lights)
- You need to **enable** (turn on) each light that you plan to use.

  glEnable (GL_LIGHT0);

  glEnable (GL_LIGHT1); …

glLight* ( )

For **scalar-valued** parameters:

glLight{if} (GLenum ⟨light⟩, GLenum ⟨pname⟩, ⟨TYPE⟩ ⟨param⟩)

For **vector-valued** parameters:

glLight{if}v (GLenum ⟨light⟩, GLenum ⟨pname⟩, ⟨TYPE⟩* ⟨param⟩)

where:

⟨**light**⟩ can be: **GL_LIGHT0**, …, **GL_LIGHT7**.

⟨**pname**⟩ can be:

- **GL_POSITION**:
  Light position.
- **GL_AMBIENT, GL_DIFFUSE, GL_SPECULAR**:
  Light colors. (RGBA vector)
- **GL_SPOT_DIRECTION, GL_SPOT_EXPONENT, GL_SPOT_CUTOFF**:
  Spotlight parameters.
- **GL_CONSTANT_ATTENUATION, GL_LINEAR_ATTENUATION, GL_QUADRATIC_ATTENUATION**:
  Parameters for attenuation. (scalar)

Light Position

Lights at infinity:

- The light position is given as a homogenous [x, y, z, w] vector. When w = 0, this defines a **light source at infinity**.
- Provides additional efficiency, since light vector is the **same** for all points in the scene.

When to set light position:

- The [x, y, z, w] vector is given in **world coordinates**. OpenGL needs to **convert** these into **view-frame coordinates**. This is done by multiplying this vector times the Modelview transformation.
- But, with each redraw cycle, the viewer typically moves and we alter the Modelview transformation (by calling gluLookAt( )).
- The upshot is that light positions need to be set **after** issuing the **gluLookAt**( ) call.
- Other lighting settings can be done only once.

Chapter 2, Slide 73

Sample Lighting Setup

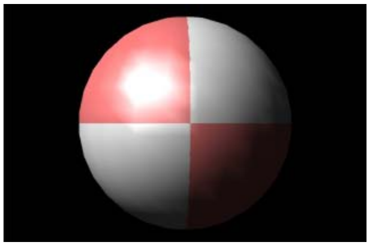
```
void setUpMyLighting ( ) {
                                                 // light intensity and location
     GLfloat ambientIntensity [4] = { 0.9, 0.0, 0.0, 1.0 };      // red
     GLfloat diffSpecIntensity [4] = { 1.2, 1.2, 1.2, 1.0 };     // white
     GLfloat position [4] = { 2.0, 4.0, 5.0, 1.0 };
                                                 // global lighting options
     glShadeModel ( GL_SMOOTH );                 // (or GL_FLAT)
     glEnable ( GL_LIGHTING );                   // enable lighting

     glEnable ( GL_LIGHT0 );                     // enable light 0
                                                 // set up light 0 properties
     glLightfv ( GL_LIGHT0,  GL_AMBIENT,  ambientIntensity );
     glLightfv ( GL_LIGHT0,  GL_DIFFUSE,  diffSpecIntensity );
     glLightfv ( GL_LIGHT0,  GL_SPECULAR, diffSpecIntensity );
     glLightfv ( GL_LIGHT0,  GL_POSITION, position );
}
```

Chapter 2, Slide 74

Drawing Objects with Lighting

glMaterial*( ): with lighting use **glMaterial***( ) to specify colors:

- Object colors under illumination are computed as a **component-wise multiplication** of the light colors and material colors
- Material properties can be specified differently for **ambient**, **diffuse**, and **specular** reflection.
- In addition to this **emission** (glowing) can be defined:
  - Lights **do not** influence emission.
  - Emissive objects **do not** illuminate other objects.



glNormal*( ):

- Used to specify vertex **surface normals** for shading.

glMaterial*( )

For **scalar-valued** parameters:

glMaterial{if} (GLenum ⟨face⟩, GLenum ⟨pname⟩, ⟨TYPE⟩ ⟨param⟩)

For **vector-valued** parameters:

glMaterial{if}v (GLenum ⟨face⟩, GLenum ⟨pname⟩, ⟨TYPE⟩* ⟨param⟩)

where:

⟨**face**⟩ can be:

GL_FRONT, **GL_BACK**, **GL_FRONT_AND_BACK**:

Indicates which **side** of the polygon is being colored. (Recall that front face is the side from which vertices are listed in CCW order.)

⟨**pname**⟩ can be:

GL_AMBIENT, **GL_DIFFUSE**, **GL_SPECULAR**, **GL_EMISSION**:

Material colors (RGBA vectors). (You can set both ambient and diffuse at once using **GL_AMBIENT_AND_DIFFUSE**.)

GL_SHININESS:

Specular illumination exponent (called α above).

Sample Drawing with Lighting

```
void doMyDrawing ( ) {
    GLfloat red[4] = {1.0, 0.0, 0.0, 1.0};// RGBA object color (red)
                                          // set material color
    glMaterialfv ( GL_FRONT_AND_BACK,
      GL_AMBIENT_AND_DIFFUSE, red );
    glBegin ( GL_POLYGON );               // draw polygon
        glNormal3f ( … );  glVertex3f ( … );
        glNormal3f ( … );  glVertex3f ( … );
        glNormal3f ( … );  glVertex3f ( … );
    glEnd ( );
}
```

You can assign different colors to different vertices. OpenGL blends.

In flat shading only one normal is needed.

glColorMaterial*( )

glColorMaterial: Allows a **simpler** but more limited way to specify material properties using glColor*( ).

To use glColorMaterial, it must be enabled (and can be disabled):

```
glEnable ( GL_COLOR_MATERIAL );
…
glDisable ( GL_COLOR_MATERIAL );
```

Example:

```
glEnable ( GL_COLOR_MATERIAL );
glColorMaterial ( GL_FRONT,  GL_DIFFUSE );
glColor3f ( 0.2, 0.5, 0.8 ); // changes the diffuse material color
  ⟨Draw objects here⟩
glColorMaterial ( GL_FRONT, GL_SPECULAR );
glColor3f ( 0.9, 0.0, 0.2 ); // changes the specular material color
  ⟨Draw objects here⟩
glDisable ( GL_COLOR_MATERIAL );
```

Texture Maping in OpenGL

Texture and Surface Detail

We have seen how to provide **color** to objects using:

- **Solid colors**: through rasterization.
- **Lighting and shading**: through various lighting and shading models.

Next we consider how to add realism through **surface detail**.

Examples:

- **Natural surfaces**: stone, wood, gravel, grass.
- **Printing and painting**: printed labels, billboards, newspapers.
- **Clothing and fabric**: woven and printed patterns, upholstery.

Image Texturing

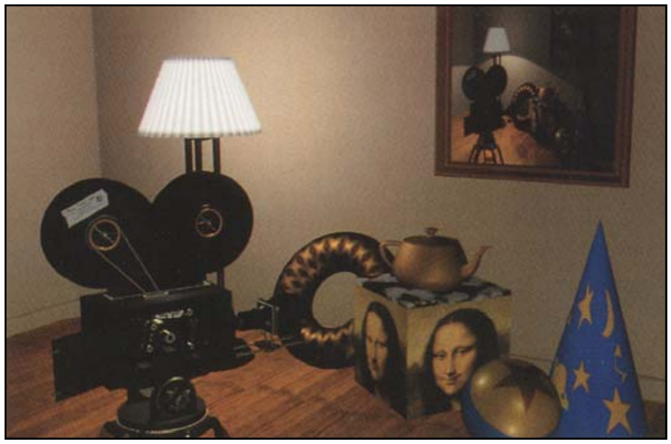
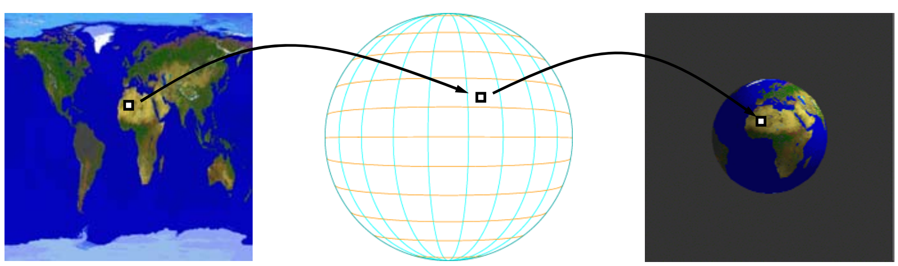


Image courtesy, Foley, van Dam, Feiner, Hughes

Texture Mapping Process



Texture Space (s, t)	Object Space (x, y, z)	Screen Space (+depth) (x_s, y_s, z_s)

Texture mapping function: Maps from **texture** to **object** space.

Inverse mapping function: Maps the other way. This is actually what we **need** in texture mapping—which **texel** corresponds to a given **surface point**.

Texturing in OpenGL: Basic Steps

One-Time Initialization: (After window is created.)
- **Create and specify a texture object**:
  - Create a new **texture object**. (OpenGL provides identifier.)
  - Provide the associated **texture image** to OpenGL.

For each Redrawing:
- **Enable texture mapping**.
- **Draw the textured polygons**:
  - Identify **which texture** is to be used.
  - Specify **texture coordinates** with vertices.
- **Disable texture mapping**:
  - when returning to normal drawing mode.

Creating Texture Object(s)

glGenTextures (**GLsizei** ⟨n⟩, **GLuint*** ⟨textureIDs⟩);
- Returns ⟨n⟩ currently unused texture IDs in ⟨textureIDs⟩.
- Each texture ID is an integer greater than 0.

glBindTexture (**GLenum** ⟨target⟩, **GLuint** ⟨textureID⟩);

where ⟨target⟩ is **GL_TEXTURE_1D**, **GL_TEXTURE_2D**, or **GL_TEXTURE_3D**.
- if ⟨textureID⟩ is being used for the **first time** a **new texture object** is created and assigned the ID = ⟨textureID⟩. This is now the **active texture**.
- if ⟨textureID⟩ has been **used before**, the texture object with ID = ⟨textureID⟩ **becomes active**.

Specifying a 2-d Texture Object

glTexImage2D (**GLenum** ⟨target⟩, **GLint** ⟨level⟩,
GLint ⟨**internalF**ormat⟩, **GLsizei** ⟨width⟩, **GLsizei** ⟨**height**⟩,
GLint ⟨border⟩, **GLenum** ⟨format⟩, **GLenum** ⟨type⟩,
const **GLVoid*** ⟨texels⟩);

Example:

```
glTexImage2D ( GL_TEXTURE_2D, 0, GL_RGBA, 128, 128, 0,
   GL_RGBA, GL_UNSIGNED_BYTE, myImage);
```

- ⟨format⟩ and ⟨type⟩ are used to specify the way in which the texels are stored in **your image array**.
- ⟨**internalF**ormat⟩ specifies how OpenGL should store the data **internally**.
- ⟨width⟩ and ⟨height⟩ give the **image size**.
- ⟨level⟩ and ⟨border⟩ **have other uses (see documentation).**

Specifying How Texture is Applied

How is the color of the texture pixel combined with the existing pixel?

The main one issue to do with whether the texture color is **combined with existing object color** after lighting (modulation) or is just **painted on** (replacement).

glTexEnv{if} (**GLenum** ⟨target⟩, **GLenum** ⟨pname⟩, ⟨TYPE⟩ ⟨value⟩);
where ⟨target⟩ is: **GL_TEXTURE_ENV**.

⟨pname⟩	⟨value⟩ **(some common choices)**
GL_TEXTURE_ENV_MODE	**GL_MODULATE** (mix with lighting) or, **GL_REPLACE** (just paint this color).

Specifying how Texture is Applied

There are also parameters that specify how the texture is to be mapped. These involve issues such whether the texture should **wrap around** (repeat) and how to **magnify/shrink** it.

glTexParameter{if} (**GLenum** ⟨target⟩, **GLenum** ⟨pname⟩, ⟨TYPE⟩ ⟨value⟩);

where ⟨target⟩ can be: **GL_TEXTURE_1D**, **GL_TEXTURE_2D**, …

⟨pname⟩	⟨value⟩
GL_TEXTURE_WRAP_S	GL_CLAMP, GL_REPEAT
GL_TEXTURE_WRAP_T	GL_CLAMP, GL_REPEAT
GL_TEXTURE_MAG_FILTER	GL_NEAREST, GL_LINEAR, …
GL_TEXTURE_MIN_FILTER	GL_NEAREST, GL_LINEAR, …

OpenGL's default value for GL_TEXTURE_MIN_FILTER is very strange. Always specify a value for this parameter.

WARNING!

Chapter 2, Slide 87

Enable the Texture and Draw

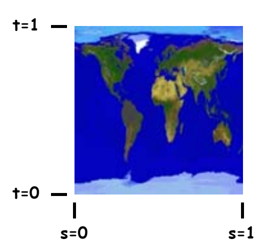
glEnable (**GL_TEXTURE_2D**);

- Enable 2-d texturing.

glTexCoord2f (**GL_FLOAT** s, **GL_FLOAT** t);

- Specify **texture coordinates** for the next vertex. (As with glNormal( ) and glColor( ), this applies to all subsequent vertices until changed.)

- Irrespective of the image size, texture coordinates s,t always vary from 0 to 1.



glDisable (**GL_TEXTURE_2D**);

- Disable 2-d texturing, to return to simple coloring.

Chapter 2, Slide 88

Example

Texture Initialization:

```
glGenTextures (…);              // create new texture objects
glBindTexture ( … );            // make this texture active
glTexParameteri ( … ); …        // define texture properties
// … input texture array from file or generate …
glTexImage2D ( … );             // provide the texture to OpenGL
```

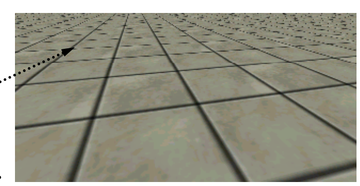
Displaying a Textured Object:

```
glEnable ( GL_TEXTURE_2D ); // enable texturing
glBindTexture ( … );            // activate the desired texture
glBegin ( GL_TRIANGLES );   // draw the object
    glTexCoord2f ( … );     glNormal3f( … );     glVertex3f ( … );
    // … (draw other vertices in the same way)
glEnd ( );
glDisable ( GL_TEXTURE_2D ); // done
```


Minimization Filtering and MIP-mapping

What if **one screen-space pixel** overlaps **many texture pixels**?

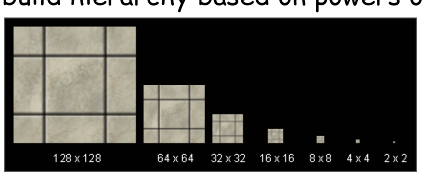
Ideally we should **average** these pixels, but this takes time. So OpenGL just takes one.

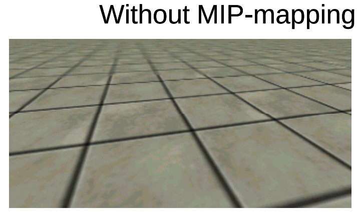


Without MIP-mapping

Result: A jagged appearance, **aliasing**.

MIP-mapping: Precompute **averages** and build hierarchy based on powers of 2.





With MIP-mapping

To render: OpenGL gets appropriate level in the MIP-map, and use this pixel. This **smooths out** the jagged lines.

MIP-mapping in OpenGL

How to Set Up a MIP Mapped Texture:

```
                      // request MIP-map for min filter
glTexParameteri ( GL_TEXTURE_2D,
                  GL_TEXTURE_MIN_FILTER,
                  GL_NEAREST_MIPMAP_LINEAR );
                      // present image to OpenGL
glTexImage2D ( /* …as before… */, myImage );
                      // compute MIP-maps
gluBuild2DMipmaps ( GL_TEXTURE_2D,      // (always the same)
                    GL_RGB,             // internal format
                    imgWidth, imgHeight, // image size
                    GL_RGB,             // image format
                    GL_UNSIGNED_BYTE,   // image type
                    myImage );          // the image
```


Pixel Buffers and Operations

Pixel Buffers and Operations

Pixel Buffers: OpenGL maintains from one to many pixel buffers. These buffers store different types of information and have different functions. We will discuss:

Buffer concepts: bitmaps, pixmaps, depth.

OpenGL Buffers: color-, depth-, accumulation-, and stencil buffers.

Transfer: reading and writing pixel buffers.

Imaging Operations: user operations, bitblt, blend.

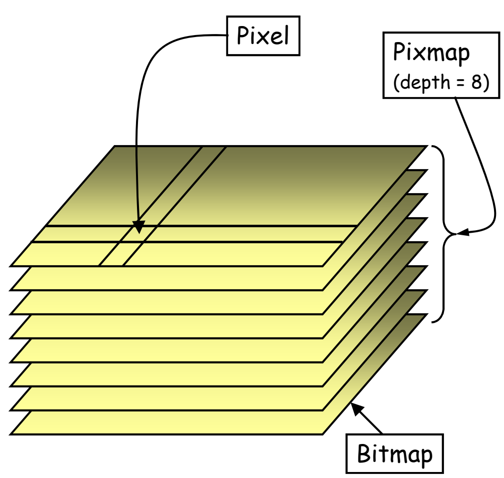
Bitmaps and Pixmaps

Pixel: A **picture element**.

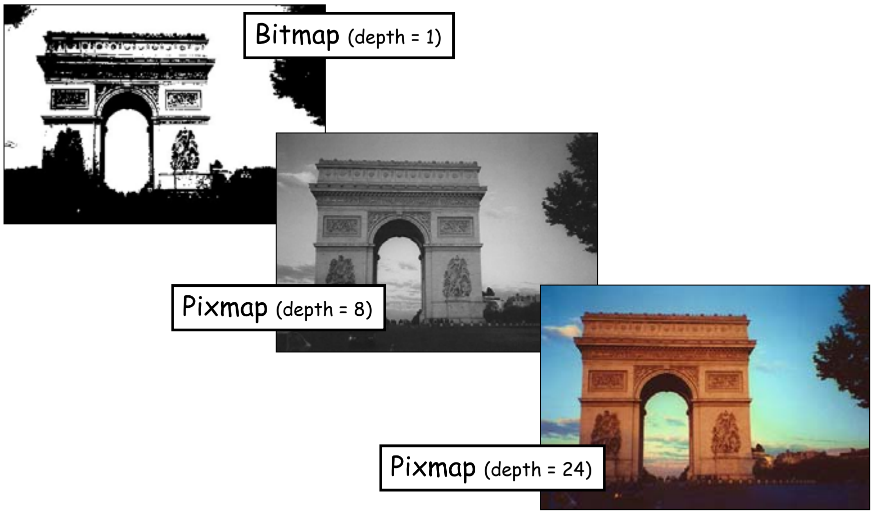
Bitmap: A 2D array of **single-bit pixels** (0/1 or black/white).

Pixmap: **Stack of bitmaps**. The number of bits per pixel is called its **depth**.

To represent full RGB color, it is sufficient to have **24-bit depth**, 8 bits each for red, green, and blue.



Bitmaps and Pixmaps



OpenGL Buffers

Color Buffer: Stores image color information.
- **RGB**: Red, green, blue
- **RGBα or RGBA**: Alpha-channel used for blending operations, such as transparency.

Depth Buffer: Stores **distance** to object pixel.
- Used for **hidden surface removal** – the closest pixel survives.
- Also called the **Z-buffer** (z-coordinate stores distance).

Accumulation Buffer: Used for **composing** and **blending** images.
- Useful for achieving affects such as **motion blur**.

Stencil Buffer:
- Useful for **masking operations**.

Buffer Creation/Specification in GLUT

void **glutInitDisplayMode** (unsigned int **mode**): where **mode** is the bitwise OR of GLUT display mode bit masks:

- **GLUT_RGBA**: Select an RGBA (direct) color. (Default)
- **GLUT_RGB**: (Same as GLUT_RGBA).
- **GLUT_INDEX**: Select indexed color.

- **GLUT_SINGLE**: Use single buffering. (Default)
- **GLUT_DOUBLE**: Use double buffering.

- **GLUT_ACCUM**: Allocate space for accumulation buffer.
- **GLUT_ALPHA**: Allocate space for α color blending.
- **GLUT_DEPTH**: Allocate space for depth buffer.
- **GLUT_STENCIL**: Allocate space for stencil buffer.

Example:

glutInitDisplayMode (**GLUT_RGBA** | **GLUT_DOUBLE** | **GLUT_DEPTH**);

Reading and Writing Buffers

glReadPixels (x, y, width, height, format, type, *pixels)
glRasterPos2i (x, y)
glDrawPixels (width, height, format, type, *pixels)
glCopyPixels (x, y, width, height, format, type, buffer)
where:

format:
GL_RGB, GL_RGBA, GL_RED, GL_GREEN, GL_BLUE, GL_ALPHA, GL_COLOR_INDEX, GL_DEPTH_COMPONENT, …

type:
GL_UNSIGNED_BYTE, GL_UNSIGNED_SHORT, GL_FLOAT, …
GL_UNSIGNED_BYTE_3_3_2, GL_UNSIGNED_SHORT_5_6_5, …

buffer:
GL_COLOR, GL_DEPTH, GL_STENCIL

Summary

Topics Covered:

- Introduction to OpenGL
- GLUT and user interaction
- OpenGL transformations and 3D viewing
- Lighting and texturing
- Buffers