Announcements

Accounts and ID's should work in Wean 5336 unless you're one of the six folks I sent email to yesterday. Send email to me or to the TA's if they don't.

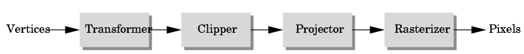
Assignment is up (with starter code).

Today more on OpenGL and a bit on transformations. Tuesday more on transformations.

More on OpenGL

Kinds of Graphics Functions

- Primitive functions
- Attribute functions
- Transformation functions
- Viewing functions
- Input functions
- Control functions

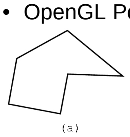


Outline

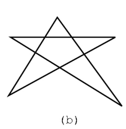
- A bit more on primitives
- Color, a more complicated example
- Client/Server Model
- Callbacks
- Double Buffering
- Hidden Surface Removal
- Another example

Note from last time: Polygon Restrictions

- OpenGL Polygons must be simple
- OpenGL Polygons must be convex

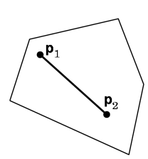


(a) simple, but not convex



(b) non-simple

convex



Why Polygon Restrictions?

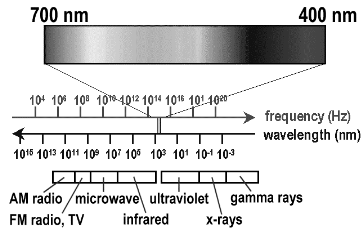
- Non-convex and non-simple polygons are expensive to process and render
- Convexity and simplicity is expensive to test
- Better to fix polygons as a pre-processing step
- Some tools in GLU for decomposing complex polygons (tessellations)
- Behavior of OpenGL implementation on disallowed polygons is "undefined"
- Triangles are most efficient in hardware

Attributes

- Part of the state of the graphics pipeline
- Set BEFORE primitives are drawn
- Remain in effect!
- Examples:
  - Color, including transparency
  - Reflection properties
  - Shading properties

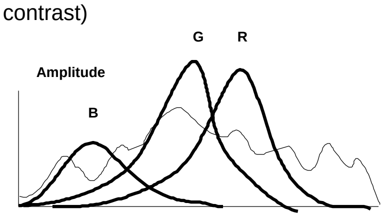
Physics of Color

- Can see only tiny piece of the spectrum
- Screens can show even less



Color Filters

- Eye can perceive only 3 basic colors
- Computer screens designed accordingly
- Many visible colors still not reproducible (high contrast)



Color Spaces

- RGB (Red, Green, Blue)
  - Convenient for display
  - Can be unintuitive (3 floats in OpenGL)
- HSV (Hue, Saturation, Value)
  - Hue: what color
  - Saturation: how far away from gray
  - Value: how bright
- Others for film, video, and printing
- Getting the colors right is a time consuming problem in the industry

Example: Drawing a shaded polygon

- More complicated example than last time
- Initialization: the “main” function

```
int main(int argc, char** argv)
{
  glutInit(&argc, argv);
  glutInitDisplayMode (GLUT_SINGLE | GLUT_RGB);
  glutInitWindowSize (500, 500);
  glutInitWindowPosition (100, 100);
  glutCreateWindow (argv[0]);
  init ();
...
```


GLUT Callbacks

- Window system independent interaction
- glutMainLoop processes events

```
...
  glutDisplayFunc(display);
  glutReshapeFunc(reshape);
  glutKeyboardFunc (keyboard);
  glutMainLoop();
  return 0;
}
```

Initializing Attributes

- Separate in “init” function

```
void init(void)
{
  glClearColor (0.0, 0.0, 0.0, 0.0);

  /* glShadeModel (GL_FLAT); */
  glShadeModel (GL_SMOOTH);
}
```


The Display Callback

- Handles display events
- Install with glutDisplayFunc(display)

```
void display(void)
{
  glClear (GL_COLOR_BUFFER_BIT); /* clear buffer */
  triangle ();                   /* draw triangle */
  glFlush ();                    /* force display */
}
```


Drawing

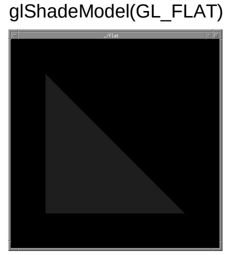
- In world coordinates; remember state!

```
void triangle(void)
{
  glBegin (GL_TRIANGLES);
    glColor3f (1.0, 0.0, 0.0); /* red */
    glVertex2f (5.0, 5.0);
    glColor3f (0.0, 1.0, 0.0); /* green */
    glVertex2f (25.0, 5.0);
    glColor3f (0.0, 0.0, 1.0); /* blue */
    glVertex2f (5.0, 25.0);
  glEnd();
}
```

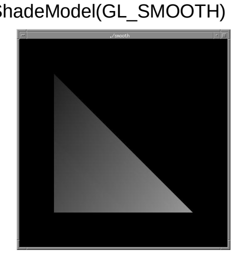

The Image

- Color of last vertex with flat shading

glShadeModel(GL_FLAT)

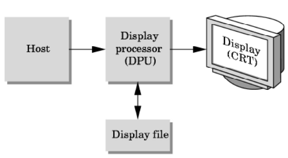


glShadeModel(GL_SMOOTH)



Client/Server Model

- Graphics hardware and caching



- Important for efficiency
- Need to be aware where data are stored
- Examples: vertex arrays, display lists

Display Lists

- Encapsulate a sequence of drawing commands
- Optimize and store on server

```
GLuint listName = glGenLists(1);   /* new name */
glNewList (listName, GL_COMPILE); /* new list */
  glColor3f(1.0, 0.0, 1.0);
  glBegin(GL_TRIANGLES);
    glVertex3f(0.0, 0.0, 0.0);
    ...
  glEnd();
  glTranslatef(1.5, 0.0, 0.0);  /* offset next object */
glEndList();
glCallList(listName);    /* draw one */
```

Display Lists Details

- Useful for sequences of transformations
- Important for complex surfaces
- Hierarchical display lists supported
- Display lists cannot be changed
- Display lists can be replaced
- Not necessary in first assignment

Main Event Loop

- Standard technique for interaction
- Mediates between client and window system
- Main loop processes events
- Dispatch to functions specified by client
- Callbacks also common in operating systems

Types of Callbacks

- Display ( ): when window must be drawn
- Idle ( ): when no other events to be handled
- Keyboard (unsigned char key, int x, int y): key
- Menu (...): after selection from menu
- Mouse (int button, int state, int x, int y): mouse
- Motion (...): mouse movement
- Reshape (int w, int h): window resize
- Any callback can be NULL

Double Buffering: Screen Refresh

- Common: 60-100 Hz
- Flicker if drawing overlaps screen refresh
- Problem during animation
- Example (cube_single.c)
- Solution two frame buffers:
  - Draw into one buffer
  - Swap and display, while drawing into other buffer
- Desirable frame rate >= 30 fps (frames/second)

Enabling Modes

- One example of many
- glutInitDisplayMode (GLUT_SINGLE);
- glutInitDisplayMode (GLUT_DOUBLE);
- glutSwapBuffers ();

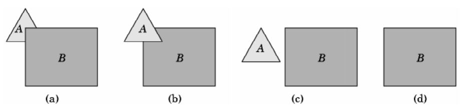
Hidden Surface Removal

- What is visible after clipping and projection?
- Object-space vs image-space approaches
- Object space: depth sort (Painter's algorithm)
- Image space: ray cast (z-buffer algorithm)
- Related: back-face culling

We'll get back to this later in the semester in much more detail!

Object-Space Approach

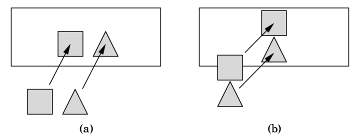
- Consider pairs of objects



- Complexity $O(k^2)$ where k = # of objects
- Painter's algorithm: render back-to-front
- "Paint" over invisible polygons
- How to sort and how to test overlap?

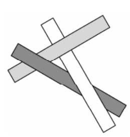
Depth Sorting

- First, sort by furthest distance z from viewer
- If minimum depth of A is greater than maximum depth of B, A can be drawn before B
- If either x or y extents do not overlap, A and B can be drawn independently

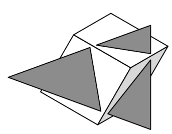


Some Difficult Cases

- Sometimes cannot sort polygons!



Cyclic overlap



Piercing Polygons

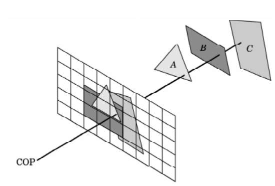
- One solution: compute intersections and subdivide
- Do while rasterizing (difficult in object space)

Painter's Algorithm Assessment

- Strengths
  - Simple (most of the time)
  - Handles transparency well
  - Sometimes, no need to sort (e.g., heightfield)
- Weaknesses
  - Clumsy when geometry is complex
  - Sorting can be expensive
- Usage
  - OpenGL (by default)
  - PostScript interpreters

Image-Space Approach

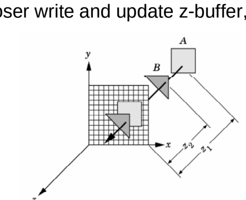
- Raycasting: intersect ray with polygons



- O(k) worst case (often better) where k=# of objects

The z-Buffer Algorithm

- z-buffer with depth value z for each pixel
- Before writing a pixel into framebuffer
  - Compute distance z of pixel origin from viewer
  - If closer write and update z-buffer, otherwise discard



z-Buffer Algorithm Assessment

- Strengths
  - Simple (no sorting or splitting)
  - Independent of geometric primitives
- Weaknesses
  - Memory intensive (but memory is cheap now)
  - Tricky to handle transparency and blending
  - Depth-ordering artifacts for near values
  - Render some wasted polygons
- Usage
  - OpenGL when enabled

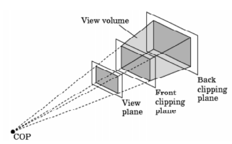
Depth Buffer in OpenGL

- glutInitDisplayMode(GLUT_DEPTH);
- glEnable (GL_DEPTH_TEST);
- glClear (GL_DEPTH_BUFFER_BIT);
- Remember all of these!

Specifying the Viewing Volume

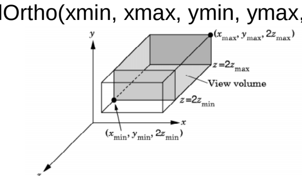
- Clip everything not in viewing volume
- Separate matrices for transformation and projection

```
glMatrixMode (GL_PROJECTION)
glLoadIdentity();
... Set viewing volume ...
glMatrixMode(GL_MODELVIEW)
```



Parallel Viewing

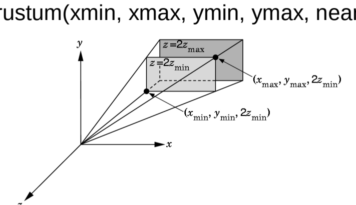
- Orthographic projection
- Camera points in negative z direction
- glOrtho(xmin, xmax, ymin, ymax, near, far)



- $2z_{min}$=-near, $2z_{max}$=-far [diagram correction]

Perspective Viewing

- Slightly more complex
- glFrustum(xmin, xmax, ymin, ymax, near, far)



- $2z_{min}$=-near, $2z_{max}$=-far [diagram correction]

Simple Transformations

- Rotate by given angle (in degrees) about ray from origin through (x, y, z)

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

- Translate by the given x, y, and z values

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

- Scale with a factor in the x, y, and z direction

  glScale{fd}(x, y, z);

Example: Rotating Color Cube

- Draw a color cube
- Rotate it about x, y, or z axis, depending on left, middle or right mouse click
- Stop when space bar is pressed
- Quit when q or Q is pressed

Step 1: Defining the Vertices

- Use parallel arrays for vertices and colors

```
/* vertices of cube about the origin */
GLfloat vertices[8][3] =
 {{-1.0, -1.0, -1.0}, {1.0, -1.0, -1.0},
  {1.0, 1.0, -1.0}, {-1.0, 1.0, -1.0}, {-1.0, -1.0, 1.0},
  {1.0, -1.0, 1.0}, {1.0, 1.0, 1.0}, {-1.0, 1.0, 1.0}};

/* colors to be assigned to edges */
GLfloat colors[8][3] =
 {{0.0, 0.0, 0.0}, {1.0, 0.0, 0.0},
  {1.0, 1.0, 0.0}, {0.0, 1.0, 0.0}, {0.0, 0.0, 1.0},
  {1.0, 0.0, 1.0}, {1.0, 1.0, 1.0}, {0.0, 1.0, 1.0}};
```


Step 2: Set Up

- Enable depth testing and double buffering

```
int main(int argc, char **argv)
{
   glutInit(&argc, argv);
   /* double buffering for smooth animation */
   glutInitDisplayMode
    (GLUT_DOUBLE | GLUT_DEPTH | GLUT_RGB);
   ...   /* window creation and callbacks here */
   glEnable(GL_DEPTH_TEST);
   glutMainLoop();
   return(0);
}
```


Step 3: Install Callbacks

- Create window and set callbacks

```
glutInitWindowSize(500, 500);
glutCreateWindow("cube");
glutReshapeFunc(myReshape);
glutDisplayFunc(display);
glutIdleFunc(spinCube);
glutMouseFunc(mouse);
glutKeyboardFunc(keyboard);
```


Step 4: Reshape Callback

- Enclose cube, preserve aspect ratio

```
void myReshape(int w, int h)
{
   GLfloat aspect = (GLfloat) w / (GLfloat) h;
   glViewport(0, 0, w, h);
   glMatrixMode(GL_PROJECTION);
   glLoadIdentity();
   if (w <= h) /* aspect <= 1 */
     glOrtho(-2.0, 2.0, -2.0/aspect, 2.0/aspect, -10.0, 10.0);
   else /* aspect > 1 */
     glOrtho(-2.0*aspect, 2.0*aspect, -2.0, 2.0, -10.0, 10.0);
   glMatrixMode(GL_MODELVIEW);
}
```


Step 5: Display Callback

- Clear, rotate, draw, flush, swap

```
GLfloat theta[3] = {0.0, 0.0, 0.0};
void display(void)
{ glClear(GL_COLOR_BUFFER_BIT
          | GL_DEPTH_BUFFER_BIT);
  glLoadIdentity();
  glRotatef(theta[0], 1.0, 0.0, 0.0);
  glRotatef(theta[1], 0.0, 1.0, 0.0);
  glRotatef(theta[2], 0.0, 0.0, 1.0);
  colorcube(); glFlush();
  glutSwapBuffers(); }
```

Step 6: Drawing Faces

- Call face(a, b, c, d) with vertex index
- Orient consistently

```
void colorcube(void)
{
  face(0,3,2,1);
  face(2,3,7,6);
  face(0,4,7,3);
  face(1,2,6,5);
  face(4,5,6,7);
  face(0,1,5,4);
}
```


Step 7: Drawing a Face

- Use vector form of primitives and attributes

```
void face(int a, int b, int c, int d)
{glBegin(GL_POLYGON);
   glColor3fv(colors[a]);
   glVertex3fv(vertices[a]);
   glColor3fv(colors[b]);
   glVertex3fv(vertices[b]);
   glColor3fv(colors[c]);
   glVertex3fv(vertices[c]);
   glColor3fv(colors[d]);
   glVertex3fv(vertices[d]);
 glEnd(); }
```


Step 8: Animation

- Set idle callback

```
GLfloat delta = 2.0;
GLint axis = 2;
void spinCube()
{
  /* spin cube delta degrees about selected axis */
  theta[axis] += delta;
  if (theta[axis] > 360.0) theta[axis] -= 360.0;

  /* display result */
  glutPostRedisplay();
}
```


Step 9: Change Axis of Rotation

- Mouse callback

```
void mouse(int btn, int state, int x, int y)
{
  if (btn==GLUT_LEFT_BUTTON
      && state == GLUT_DOWN) axis = 0;
  if (btn==GLUT_MIDDLE_BUTTON
      && state == GLUT_DOWN) axis = 1;
  if (btn==GLUT_RIGHT_BUTTON
      && state == GLUT_DOWN) axis = 2;
}
```


Step 10: Toggle Rotation or Exit

- Keyboard callback

```
void keyboard(unsigned char key, int x, int y)
{
  if (key=='q' || key == 'Q') exit(0);
  if (key==' ') {stop = !stop;};
  if (stop)
    glutIdleFunc(NULL);
  else
    glutIdleFunc(spinCube);
}
```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