3D Graphics with OpenGL:
Hierarchical Models, Interaction, Animation

Z-Buffer Hidden Surface Removal

Illumination and Shading

3D Graphics Using OpenGL

- OpenGL 3D Coordinate System
- Building Polygon Models
- ModelView & Projection Transformations
- Quadric Surfaces
- User Interaction
- Hierarchical Modeling
- Animation
OpenGL 3D Coordinate System

- A Right-handed coordinate system
  - Viewpoint is centered at origin initially

![3D Coordinate System Diagram](image)

Defining 3D Polygons in OpenGL

- e.g., front face of a cube centered at origin

```c
glBegin(GL_POLYGON)
glVertex3f(-0.5f, 0.5f, 0.5f);
glVertex3f(-0.5f, -0.5f, 0.5f);
glVertex3f(0.5f, -0.5f, 0.5f);
glVertex3f(0.5f, 0.5f, 0.5f);
glEnd();
```

- need to define the other faces
Model-View and Projection Transformations

- Each vertex in model passes through two transformations
  - Defined by two 4X4 matrices
    - Model-view and projection matrices
  - Model-view matrix
    - Position objects relative to camera
  - Projection matrix
    - Forms the image through projection to a projection plane and helps with clipping

Projection Transformation

- First tell OpenGL you’re using the projection matrix
  glMatrixMode(GL_PROJECTION);;
- Then Initialize it to the Identity matrix
  glLoadIdentity();;
- Then define the viewing volume, for example:
  glFrustum(-1.0, 1.0, -1.0, 1.0, 2.0, 7.0);
  - (left, right, bottom, top, near, far)
    - near & far are positive distances, near < far
  - Viewing volume is the frustum of a pyramid
  - Used for perspective projection
  or glOrtho(-1.0, 1.0, -1.0, 1.0, 2.0, 7.0);
  - Viewing volume is a rectangular solid
  - for parallel projection
- For both the viewpoint (eye) is at (0,0,0)
The Viewing Volume
- Everything outside viewing volume is clipped
- Think of near plane as being window’s client area

Modelview Transformation
Our cube as specified is not visible
It lies in front of near clipping plane
Positioning the Camera

- By default it’s at (0,0,0), pointing in –z direction, up direction is y-axis
- Can set the camera point
- And the “lookat” point
- And the up direction
  \[ \text{gluLookAt}(x_c,y_c,z_c,x_a,y_a,z_a,x_u,y_u,z_u); \]
  \( (x_c,y_c,z_c) \) coordinates of virtual camera
  \( (x_a,y_a,z_a) \) coordinates of lookat point
  \( (x_u,y_u,z_u) \) up direction vector
- Example:
  \[ \text{gluLookAt}(2.0,2.0,2.0,0.0,0.0,0.0,0.0,0.0,1.0); \]
  camera at (2,2,2), looking at origin, z-axis is up

Modelview Transformation

- Used to perform geometric translations, rotations, scalings
- Also implements the viewing transformation
- If we don’t position the camera, we need to move our cube into the viewing volume
  \[ \text{glMatrixMode} \text{(GL}_\text{MODELVIEW}); \]
  \[ \text{glLoadIdentity}(); \]
  \[ \text{glTranslatef}(0.0f, 0.0f, -3.5f); \]
  – Translates cube down z-axis by 3.5 units
OpenGL performs transformations on all vertices
- First modelview transformation
- Then projection transformation
- The two matrices are concatenated
- Resulting matrix multiplies all points in the model

OpenGL Geometric Transformations
- "Modeling" Transformations

```
glScalef(2.0f, 2.0f, 2.0f); // twice as big
   parameters: sx, sy, sz

glTranslatef(2.0f, 3.5f, 1.8f); // move object
   parameters: tx, ty, tz

glRotatef(30.0f, 0.0f, 0.0f, 1.0f); // 30 degrees about z-axis
   parameters:
   - angle
   - (x,y,z) -> coordinates of vector about which to rotate
```
OpenGL Composite Transformations

- Combine transformation matrices
- Example: Rotate by 45 degrees about a line parallel to the z axis that goes through the point (xf,yf,zf) – the fixed point
  
  ```
  glMatrixMode(GL_MODELVIEW);
  glLoadIdentity();
  glTranslate(xf,yf,zf);
  glRotate(45, 0.0,0.0,1.0);
  glTranslate(-xf,-yf,-zf);
  ```

  - Note last transformation specified is first applied
    - Because each transformations in OpenGL is applied to present matrix by postmultiplication

Typical code for a polygon mesh model

```
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
glFrustum(-1.0, 1.0, -1.0, 1.0, 2.0, 7.0);
glMatrixMode(GL_MODELVIEW);
gLoadIdentity();
glTranslatef(0.0f, 0.0f, -3.5f);               // translate into viewing frustum
glRotatef(30.0f, 0.0f, 0.0f, 1.0f);           // rotate about z axis by 30
glClearColor(1.0f, 1.0f, 1.0f, 1.0f);       // set background color
glClear(GL_COLOR_BUFFER_BIT);  // clear window
glColor3f(0.0f, 0.0f, 0.0f);                     // drawing color

//define polygon vertices here
```

- See 3dxform example program
The OpenGL Utility Library (GLU) and Quadric Surfaces

- Provides many modeling features
  - Quadric surfaces
    - described by quadratic equations in x,y,z
    - spheres, cylinders, disks
    - Polygon Tessellation
      - Approximating curved surfaces with polygon facets
  - Non-Uniform Rational B-Spline Curves & Surfaces (NURBS)
- Routines to facilitate setting up matrices for specific viewing orientations & projections

Modeling & Rendering a Quadric with the GLU

1. Get a pointer to a quadric object
2. Make a new quadric object
3. Set the rendering style
4. Draw the object
5. When finished, delete the object
OpenGL GLU Code to Render a Sphere

```c
GLUquadricObj *mySphere
mySphere=gluNewQuadric();
    // create the new sphere object
gluQuadricDrawStyle(mySphere,GLU_FILL);
    // some other styles: GLU_POINT, GLU_LINE
gluSphere(mySphere,1.0,12,12);
    // radius, # longitude lines, # latitude lines
```

The GLUT and Quadric Surfaces

- An alternative to GLU Quadrics with many more predefined quadric surface objects
  - `glutWire***()`
  - `glutSolid***()`
  - Some examples:
    - `glutWireCube(size); glutSolidCube(size);`
    - `glutWireSphere(radius,nlongitudes,nlatitudes);`
    - `glutWireCone(rbase,height,nlongitudes,nlatitudes);`
    - `glutWireTeapot(size);`
    - Lots of others
  - See `cone_perspective` example program

Interaction in OpenGL

- OpenGL GLUT Callback Functions
  - GLUT’s version of event/message handling
  - Programmer specifies function to be called by OS in response to different events
  - Specify the function by using glut***Func(ftn)
    - We’ve already seen glutDisplayFunc(disp_ftn)
    - disp_ftn called when client area needs to be repainted
      - Like Windows response to WM_PAINT messages
    - All GLUT callback functions work like MFC On***() event handler functions

Some Other GLUT Callbacks

- glutReshapeFunc(ftn(width,height))
  - Identifies function ftn() invoked when user changes size of window
    - height & width of new window returned to ftn()

- glutKeyboardFunc(ftn(key,x,y))
  - Identifies function ftn() invoked when user presses a keyboard key
  - Character code (key) and position of mouse cursor (x,y) returned to ftn()

- glutSpecialFunction(ftn(key,x,y))
  - For special keys such as function & arrow keys
Mouse Callbacks

- glutMouseFunc(ftn(button, state, x, y))
  - Identifies function ftn() called when mouse events occur
  - Button presses or releases
    - Position (x,y) of mouse cursor returned
    - Also the state (GLUT_UP or GLUT_DOWN)
    - Also which button
      - GLUT_LEFT_BUTTON, GLUT_RIGHT_BUTTON, or GLUT_MIDDLE_BUTTON

Mouse Motion

- Move event: when mouse moves with a button pressed –
  - glutMotionFunctionFunc(ftn(x,y))
    - ftn(x,y) called when there’s a move event
    - Position (x,y) of mouse cursor returned
- Passive motion event: when mouse moves with no button pressed
  - glutPassiveMotionFunctionFunc(ftn(x,y))
    - ftn(x,y) called when there’s a passive motion event
    - Position (x,y) of mouse cursor returned
GLUT Menus

- Can create popup menus and add menu items with:
  - `glutCreateMenu (menu-ftn(ID))`
    - `menu-ftn(ID)` is callback function called when user selects an item from the menu
    - `ID` identifies which item was chosen
  - `glutAddMenuEntry(name, ID_value)`
    - Adds an entry with name displayed to current menu
    - `ID_value` returned to `menu_ftn()` callback
  - `glutAttachMenu(button)`
    - Attaches current menu to specified mouse button
    - When that button is pressed, menu pops up

Hierarchical Models

- In many applications the parts of a model depend on each other
- Often the parts are arranged in a hierarchy
  - Represent as a tree data structure
  - Transformations applied to parts in parent nodes are also applied to parts in child nodes
  - Simple example: a robot arm
    - Base, lower arm, and upper arm
    - Base rotates ➔ lower and upper arm also rotate
    - Lower arm rotates ➔ upper arm also rotates
Simple Robot Arm Hierarchical Model

Use of Matrix Stacks in OpenGL to Implement Hierarchies

- Matrix stacks store projection & model-view matrices
- Push and pop matrices with:
  - glPushMatrix();
  - glPopMatrix();
- Can use to position entire object while also preserving it for drawing other objects
- Use in conjunction with geometrical transformations
- Example: Robot program
OpenGL Hierarchical Models

- Set up a hierarchical representation of scene (a tree)
- Each object is specified in its own modeling coordinate system
- Traverse tree and apply transformations to bring objects into world coordinate system
- Traversal rule:
  - Every time we go to the left at a node with another unvisited right child, do a push
  - Every time we return to that node, do a pop
  - Do a pop at the end so number of pushes & pops are the same

GLUT Animation

- Simple method is to use an “idle” callback
  - Called whenever window’s event queue is empty
  - Could be used to update display with the next frame of the animation
  - Identify the idle function with:
    - glutIdleFunc(idle_ftn())
  - Simple Example:
    ```c
    void idle_ftn()
    {
      glutPostRedisplay();
    }
    ```
  - Posts message to event queue that client area needs to be repainted
  - Causes display callback function to be invoked
  - Effectively displays next frame of animation
Double Buffering

- Use two display buffers
- Front buffer is displayed by display hardware
- Application draws into back buffer
- Buffers are swapped after new frame is drawn into back buffer
- Implies only one access to display hardware per frame
- Eliminates flicker
- In OpenGL, implement by replacing glFlush() with glutSwapBuffers() in display callback
- In initialization function, must use:
  ```c
  glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB);
  ```
- See anim_square & cone_Anim examples

General Hidden Surface Removal

Z-Buffer Hidden Surface Removal Algorithm
Hidden Surface Removal

• Determination of surfaces not visible to the viewer
• Many different techniques
  – Back face culling, for single objects only
  – Z-Buffer
  – Depth Sort

Z-Buffer Hidden Surface Removal Algorithm

• Basic Idea:
  – At a given pixel we want to plot color of closest surface that projects to that pixel
  – We’re looking for minimum zv
  – Use a buffer (array) parallel to the frame buffer
    • Store minimum values of zv
    • One for every pixel
    • Called the Z-Buffer
Z-Buffer Technique Applied to a Polygon Mesh

- Initialize Z-Buffer and Frame Buffer
- Look at each polygon
  - Look at each point (xs,ys) projected to by the polygon
  - Compute zv of the point on the polygon
    - If zv is closer than value stored at [x,y] in Z-Buffer
      - Replace value in Z-Buffer with zv
      - Update corresponding element in frame buffer with color of the polygon

Z-Buffer Hidden Surface Removal

Initialize all Z[x,y], FB[x,y]
For each polygon P
  For each pixel (x,y) covered by P
    if (z < Z[x,y])
      Z[x,y] = z
      FB[x,y] = color of P

Frame Buffer

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When completed, each position (pixel) in the frame buffer will contain the color of the closest polygon, and each position in the Z-buffer will contain the distance to the intersection with that polygon.
Z-Buffer Algorithm Applied to Convex Polygons

Data Structures:
- For each polygon
  - Polygon color
  - Polygon vertex coordinates: xs, ys, and zv
    - Note mixed coordinates
  - Edge table (xmin, ymin, zmin, xmax, ymax, zmax)
  - Active edge list (AEL) with active edges intersected by current scanline sorted on xs
    - (See scanline polygon fill notes)

Other Data Structures
- Frame Buffer FBuf[x][y]
  - Will store the color of each pixel (x,y)
- Z-Buffer ZBuf[x][y]
  - Will store the zv distance of point on closest polygon that projects to pixel (x,y) on screen
- Initialize each element of FBuf[][] to background color
- Initialize each element of ZBuf[][] to infinity (largest possible value)
The Algorithm
For each polygon
For each scanline y spanning the polygon
Get left & right active edges from AEL
Get x,z coordinates of endpoints from edge table
Compute scanline/edge intersection pts \((x_L, z_L, x_R, z_R)\)
(Use x-y & z-y interpolation)
For \((x=x_L\) to \(x_R)\)
Compute z by z-x interpol.
If \((z < ZBuf[x,y])\)
\(ZBuf[x,y] = z\)
\(FBuf[x,y] = \text{polygon color}\)

Double Interpolation
- We know (from Edge Table):
  lower/upper vertices of left active edge:
  \((x_0, y_0, z_0)\) and \((x_1, y_1, z_1)\)
  lower/upper vertices of right active edge:
  \((x_2, y_2, z_2)\) and \((x_3, y_3, z_3)\)
- We also know y of current scanline
**x-y Interpolation:**
- Find x coords of intersection pts (xL,xR)
- Left Edge:
  \[
  \frac{xL-x0}{x1-x0} = \frac{y-y0}{y1-y0}
  \]
- Solving for xL:
  \[
  xL = (x1-x0) \frac{(y-y0)}{(y1-y0)} + x0
  \]
- Similarly for xR on right edge:
  \[
  xR = (x3-x2) \frac{(y-y2)}{(y3-y2)} + x2
  \]

**z-y Interpolation**
- Find z coordinates of intersection points of scan line (y) with left and right edges
- Done the same way as x-y interpolation
- x coordinates replaced by z coordinates
- Results:
  - zL = (z1-z0) \frac{(y-y0)}{(y1-y0)} + z0
  - zR = (z3-z2) \frac{(y-y2)}{(y3-y2)} + z2
**z-x Interpolation**

- Find z value on polygon at pixel x on current scanline (y)
- Interpolate between the left and right edge intersection points:
  \[
  \frac{z-z_L}{z_R-z_L} = \frac{x-x_L}{x_R-x_L}
  \]
  Solving for z:
  \[
  z = (z_R-z_L)\frac{(x-x_L)}{(x_R-x_L)} + z_L
  \]

**Speeding up the Algorithm**

- Do interpolations incrementally
  - Get new values from old values by adding correct increments
  - \(x_L, x_R, z_L, z_R\) (in the outer loop)
  - \(z\) (in the inner loop)
  - Avoids multiplications and divisions inside algorithm loops
Z-Buffer Performance

- Outer loop repeats for each polygon
- Complex scenes have more polygons
  - So complex scenes should be slower
- But:-- More polygons usually means smaller polygons
  - So inner loops (y and x) are faster
- For most real scenes, performance is approximately independent of scene complexity

Disadvantage of Z-Buffer

- Memory requirements
- Z-Buffer is at least as big as the frame buffer
- For best results, need floating point or doubles for z values
- Example 1000 X 1000 resolution screen
  - Assume 8 bytes to store a double
  - 8 Megabytes required for Z-Buffer
- But memory has become cheap
- Z-Buffer used very commonly now
- Often implemented in hardware