CSCI 420 Computer Graphics
Lecture 4

Interaction

Client/Server Model
Callbacks
Double Buffering
Hidden Surface Removal
Simple Transformations
[Angel Ch. 2]

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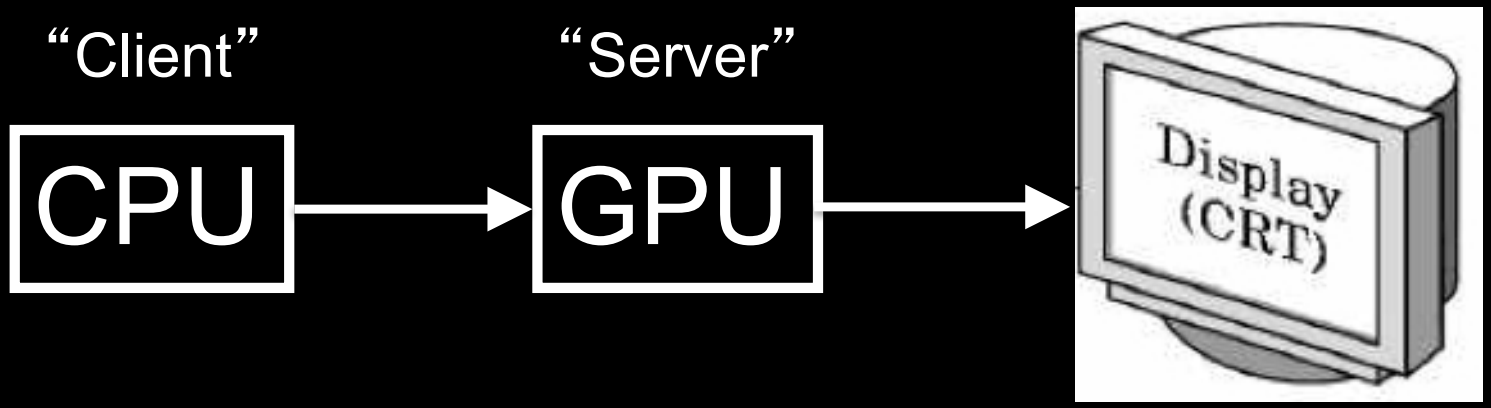
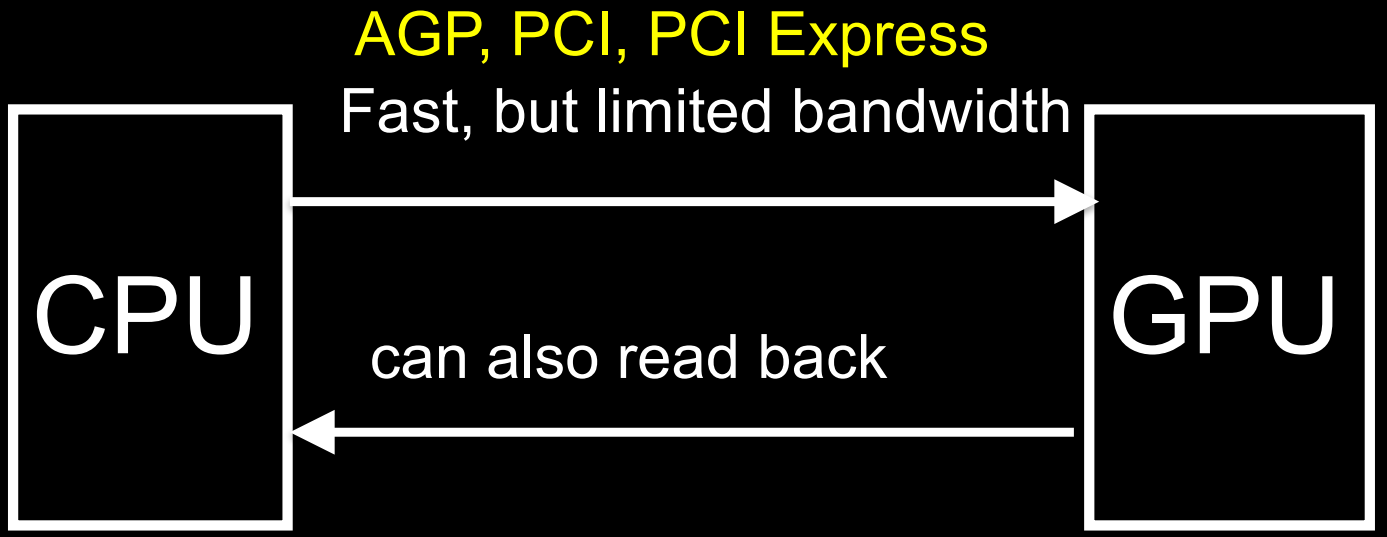
Client/Server Model

- Graphics hardware and caching



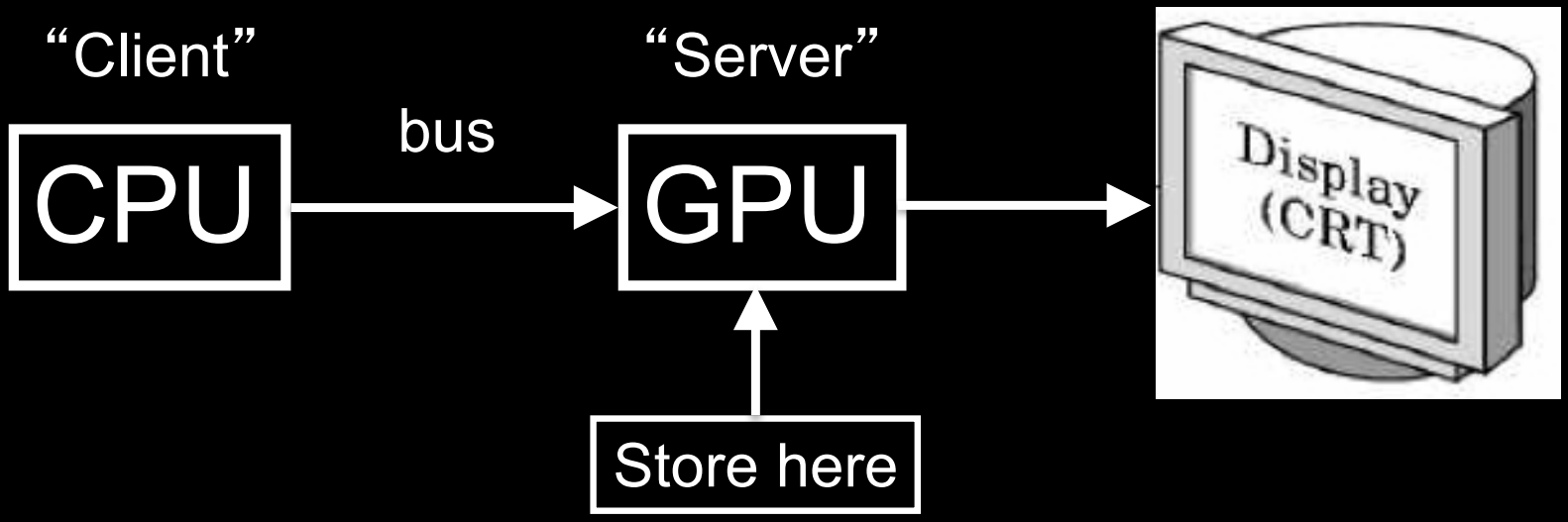
- Important for efficiency
- Need to be aware where data are stored
- Graphics driver code is on the CPU
- Rendering resources (buffers, shaders, textures, etc.) are on the GPU

The CPU-GPU bus



Buffer Objects

- Store rendering data: vertex positions, normals, texture coordinates, colors, vertex indices, etc.
- Optimize and store on server (GPU)



Vertex Buffer Objects

- Caches vertex geometric data:
  positions, normals, texture coordinates, colors
- Optimize and store on server (GPU)
- Required for core OpenGL profile

```
/* vertices of the quad (will form two triangles;
   rendered via GL_TRIANGLES) */
float positions[6][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}};

/* colors to be assigned to vertices (4th value is the alpha channel)
*/
float colors[6][4] =
  {{0.0, 0.0, 0.0, 1.0}, {1.0, 0.0, 0.0, 1.0}, {0.0, 1.0, 0.0, 1.0},
   {0.0, 0.0, 1.0, 1.0}, {1.0, 1.0, 0.0, 1.0}, {1.0, 0.0, 1.0, 1.0}};
```

Vertex Buffer Object: Initialization

```
GLuint buffer;

void initVBO()
{
  glGenBuffers(1, &buffer);
  glBindBuffer(GL_ARRAY_BUFFER, buffer);
  glBufferData(GL_ARRAY_BUFFER, sizeof(positions) + sizeof(colors),
    NULL, GL_STATIC_DRAW);   // init buffer's size, but don't assign any data to it

  // upload position data
  glBufferSubData(GL_ARRAY_BUFFER, 0, sizeof(positions), positions);

  // upload color data
  glBufferSubData(GL_ARRAY_BUFFER, sizeof(positions), sizeof(colors), colors);
}
```

Old technology: Display Lists (compatibility profile only)

- Cache a sequence of drawing commands
- Very useful with complex objects that are redrawn often (e.g., with transformations)
- Another example: fonts (2D or 3D)
- Display lists can call other display lists
- Display lists cannot be changed
- Display lists can be erased / replaced

- Display lists are now deprecated in OpenGL
- Replaced with VBOs

Display Lists

- Cache a sequence of drawing commands
- Optimize and store on server (GPU)

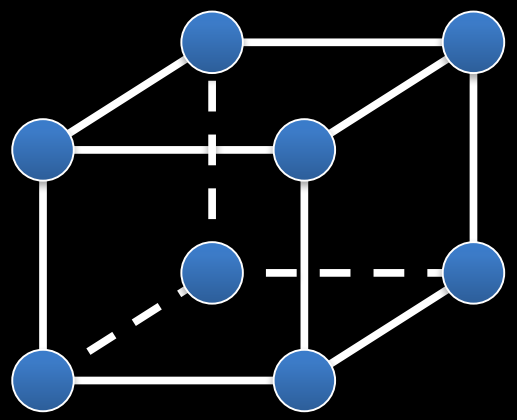
```
GLuint listName = glGenLists(1);    /* new list name */
glNewList (listName, GL_COMPILE); /* new list */
    glColor3f(1.0, 0.0, 1.0);
    glBegin(GL_TRIANGLES);
        glVertex3f(0.0, 0.0, 0.0);
        ...
    glEnd();
glEndList(); /* at this point, OpenGL compiles the list */
glCallList(listName);     /* draw the object */
```

Element Arrays

- Draw cube with 6*2*3=36 or with 8 vertices?
- Expense in drawing and transformation
- Triangle strips help to some extent
- Element arrays provide general solution
- Define (transmit) array of vertices, colors, normals
- Draw using index into array(s) :

```
// (must first set up the GL_ELEMENT_ARRAY_BUFFER) …
glDrawElements(GL_TRIANGLES, 36, GL_UNSIGNED_INT, 0);
```

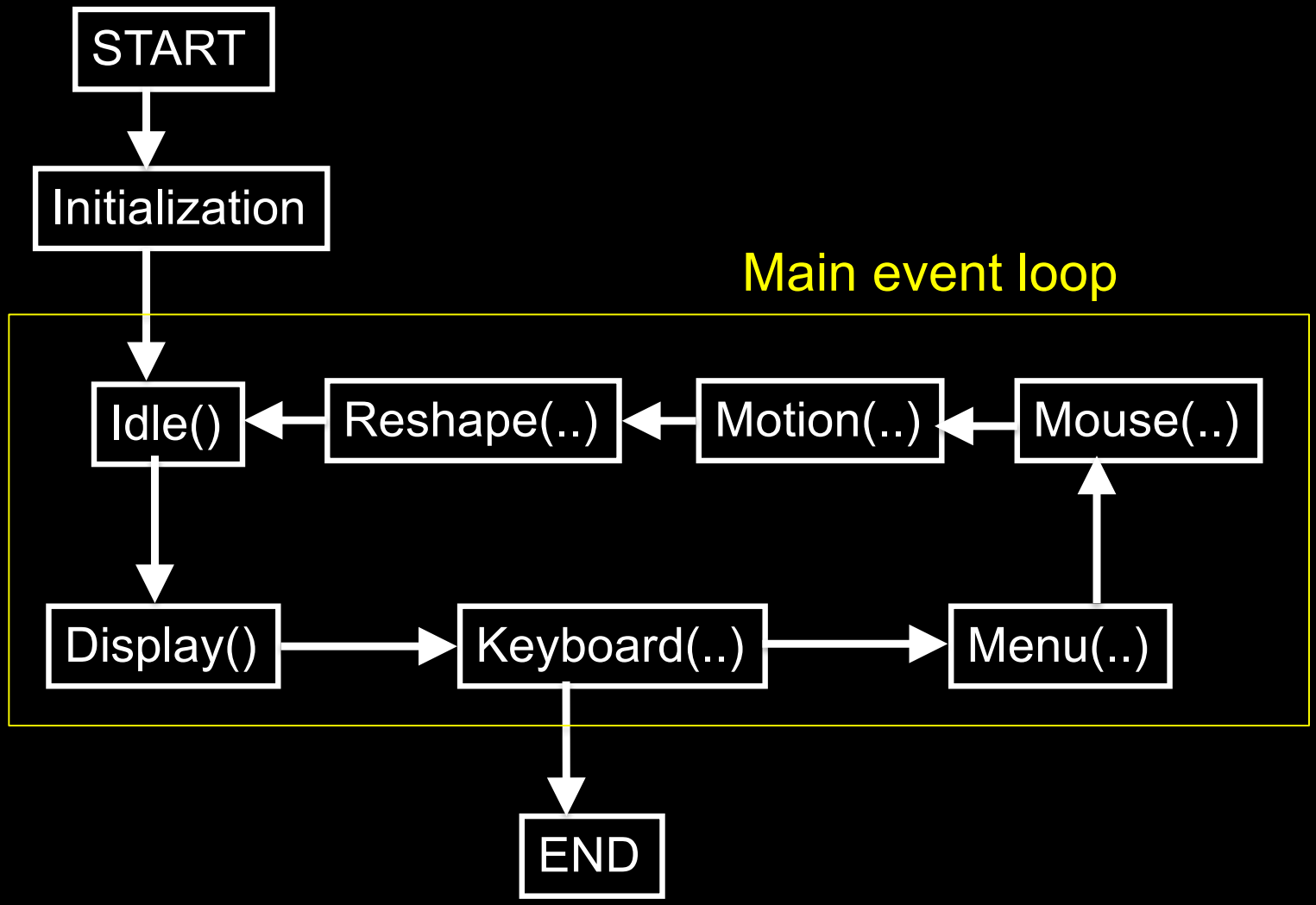
- Vertex sharing for efficient operations
- Extra credit for first assignment



Outline

- Client/Server Model
- Callbacks
- Double Buffering
- Hidden Surface Removal
- Simple Transformations
- Example

GLUT Program with Callbacks



Main Event Loop

- Standard technique for interaction
  (GLUT, Qt, wxWidgets, ...)
- Main loop processes events
- Dispatch to functions specified by client
- Callbacks also common in operating systems
- “Poor man’s functional programming”

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 pressed
- Menu (...) : after selection from menu
- Mouse (int button, int state, int x, int y) : mouse button
- Motion (...) : mouse movement
- Reshape (int w, int h) : window resize
- Any callback can be NULL

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Screen Refresh

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

Enabling Single/Double Buffering

- glutInitDisplayMode(GLUT_SINGLE);
- glutInitDisplayMode(GLUT_DOUBLE);

- Single buffering:
  Must call glFinish() at the end of Display()
- Double buffering:
  Must call glutSwapBuffers() at the end of Display()

- Must call glutPostRedisplay() at the end of Idle()

- If something in OpenGL has no effect or does not work, check the modes in glutInitDisplayMode

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Hidden Surface Removal

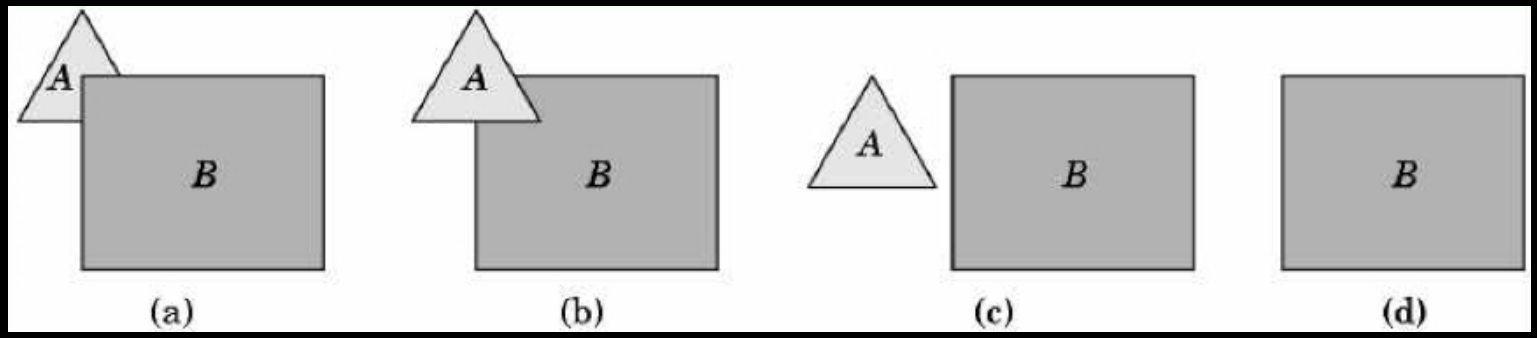
- Classic problem of computer graphics
- What is visible after clipping and projection?

- Object-space vs image-space approaches
- Object space: depth sort (Painter's algorithm)
- Image space: *z-buffer* algorithm

- Related: back-face culling

Object-Space Approach

- Consider objects pairwise

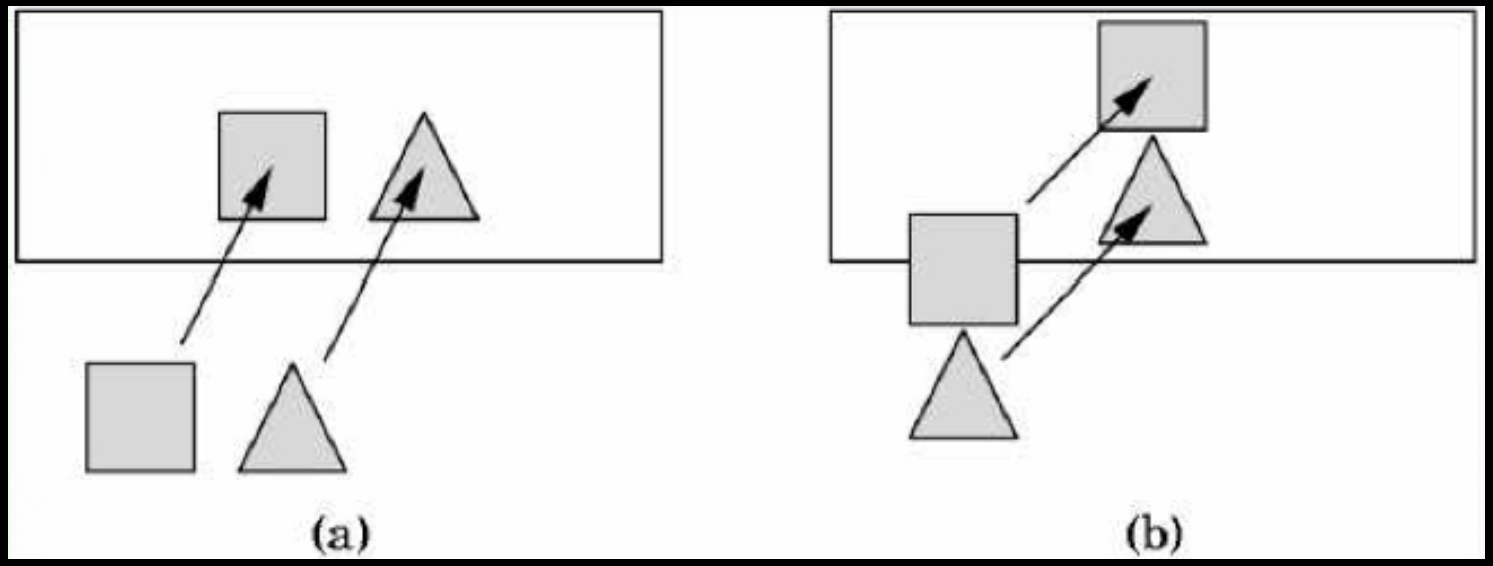


- Number of cases is $O(k^2)$ where k = # of objects
- Painter's algorithm: render back-to-front
- "Paint" over invisible polygons
- How to sort and how to test overlap?

Depth Sorting

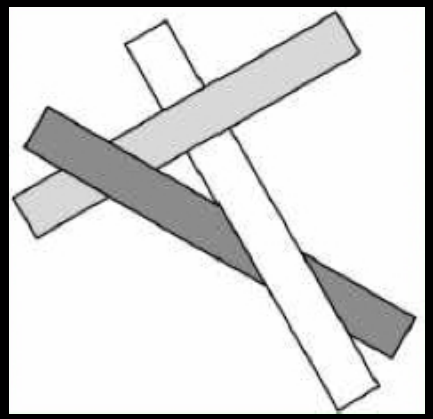
- First, sort by furthest distance z from viewer
- If minimum depth of A is greater than maximum depth of B, A can be drawn before B

- If either x or y extents do not overlap, A and B can be drawn independently

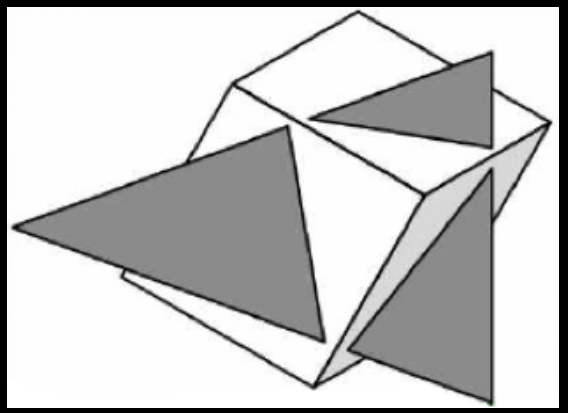


Some Difficult Cases

- Sometimes cannot sort polygons!



Cyclic overlap



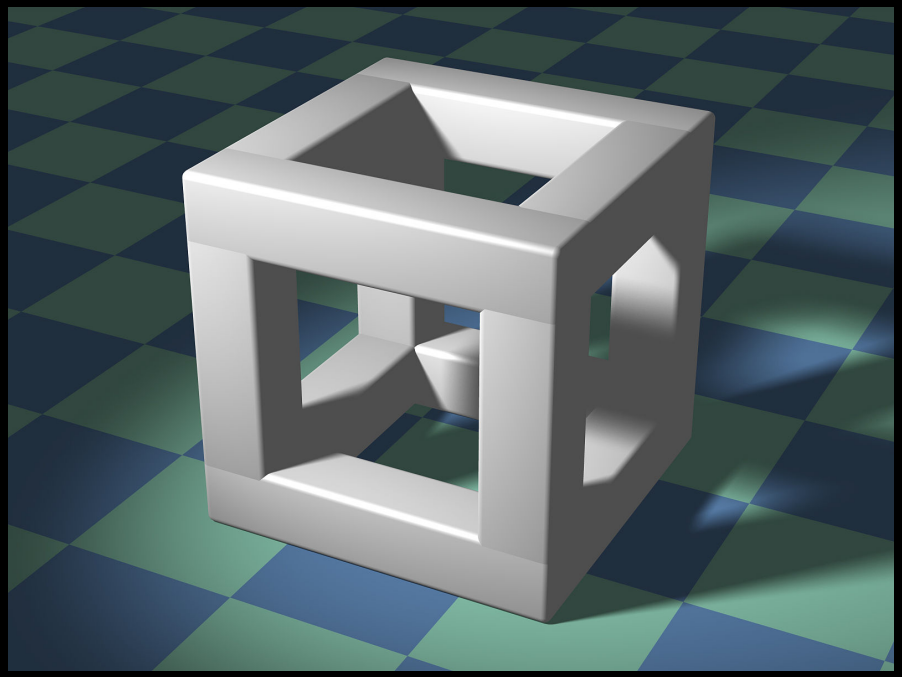
Piercing Polygons

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

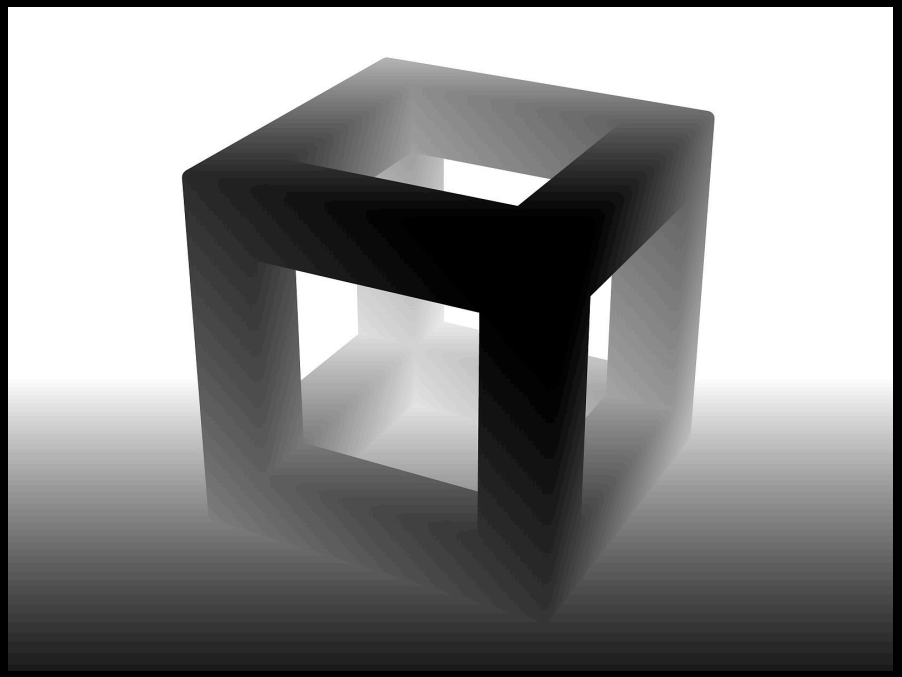
Painter's Algorithm Assessment

- 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
  - PostScript interpreters
  - OpenGL: not supported
    (must implement Painter's Algorithm manually)

Image-space approach



3D geometry



Depth image

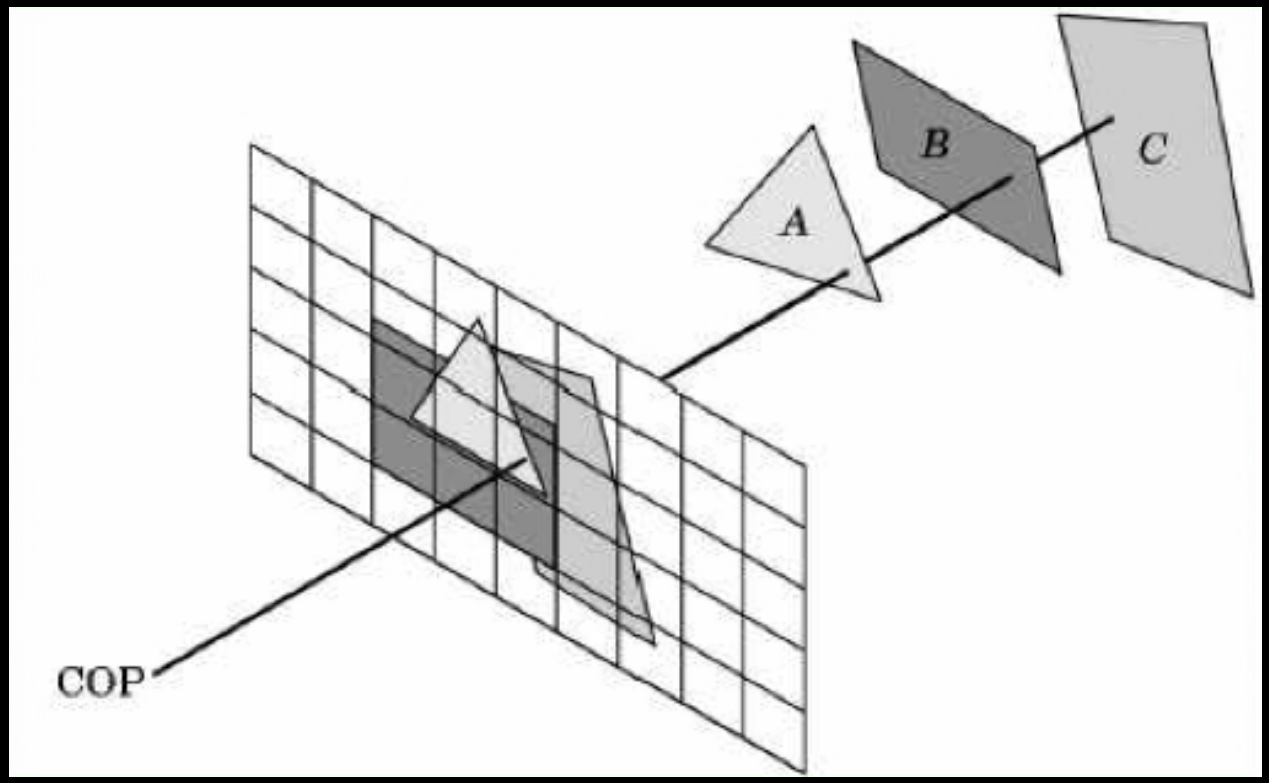
darker color is closer

Source: Wikipedia

Depth sensor camera

Image-Space Approach

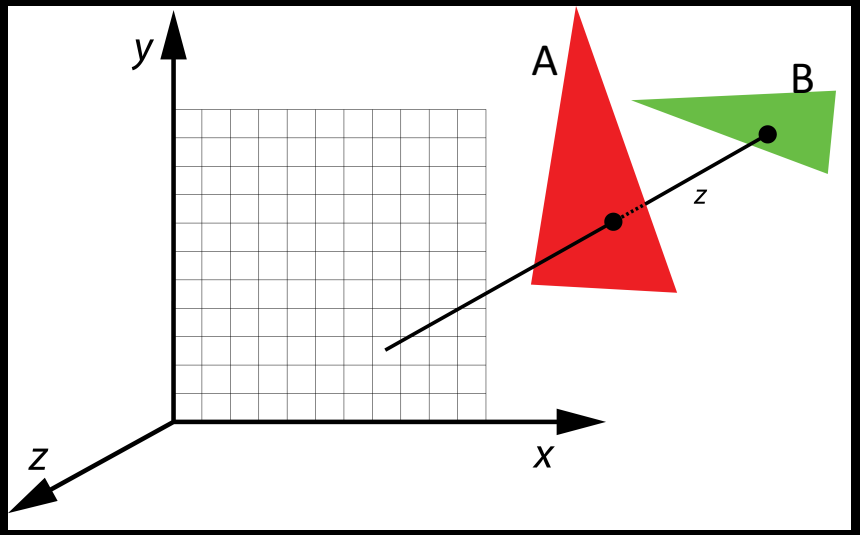
- Raycasting: intersect ray with polygons



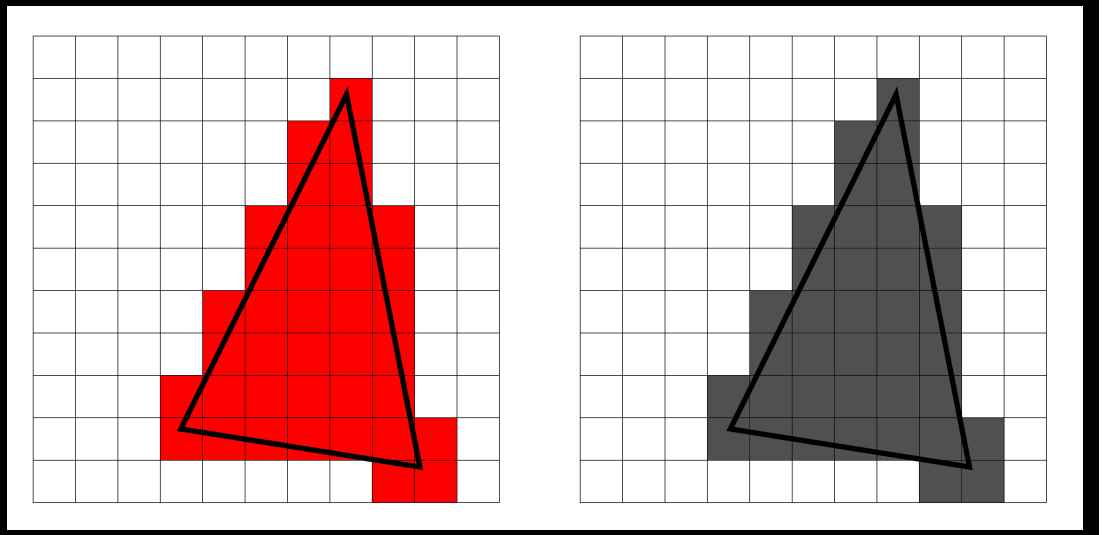
- O(k) worst case (often better)
- Images can be more jagged (need anti-aliasing)

The z-Buffer Algorithm

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



After rendering A:



color

depth

The z-Buffer Algorithm

- z-buffer stores depth values z for each pixel
- Before writing a pixel into framebuffer:
  - Compute distance z of pixel from viewer
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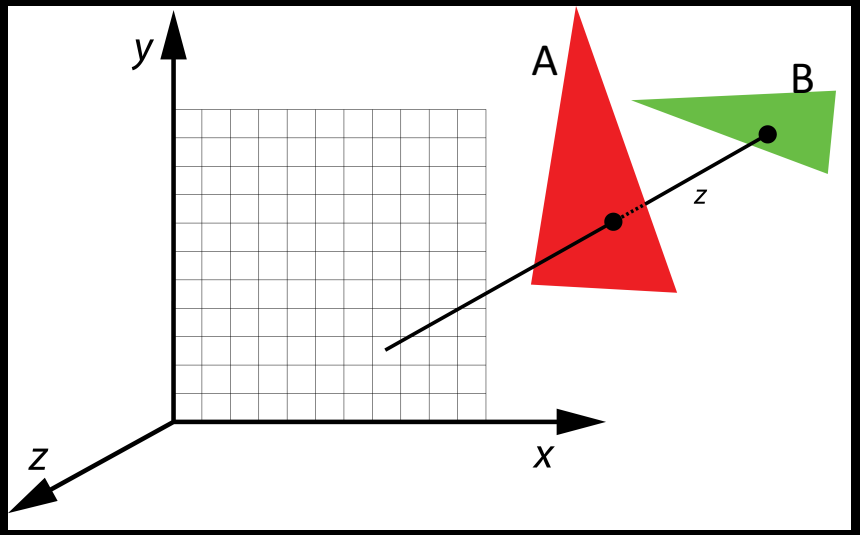
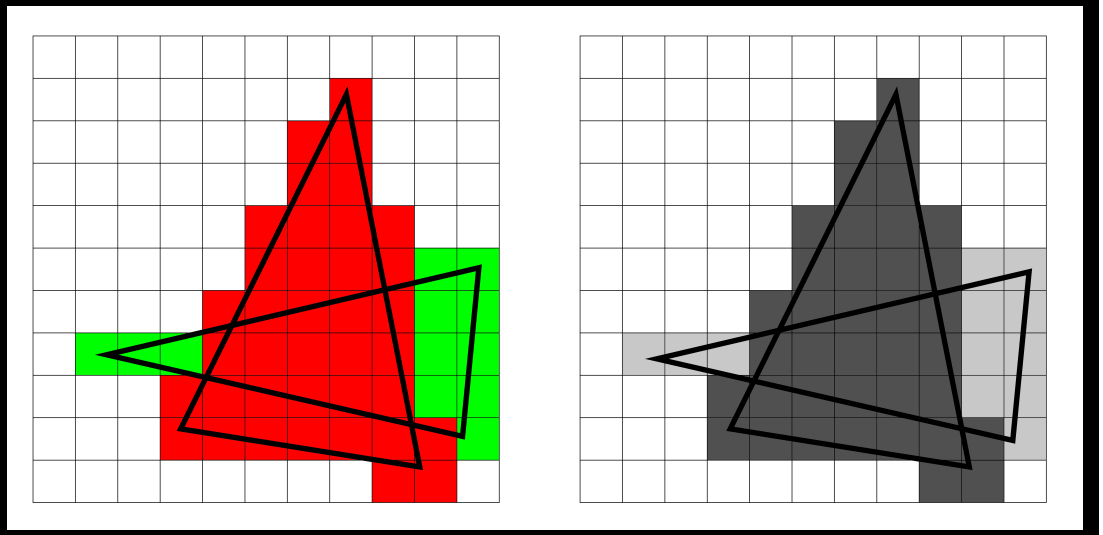


After rendering A and B:



color

depth

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
- Usage
  - z-Buffering comes standard with OpenGL; disabled by default; must be enabled

Depth Buffer in OpenGL

- glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGBA | GLUT_DEPTH);
- glEnable (GL_DEPTH_TEST);

- Inside Display():

  glClear (GL_DEPTH_BUFFER_BIT);

- Remember all of these!
- Some “tricks” use z-buffer in read-only mode

Note for Mac computers

Must use the GLUT_3_2_CORE_PROFILE flag to use the core profile:

```
glutInitDisplayMode(GLUT_3_2_CORE_PROFILE  |
   GLUT_DOUBLE  | GLUT_RGBA | GLUT_DEPTH);
```

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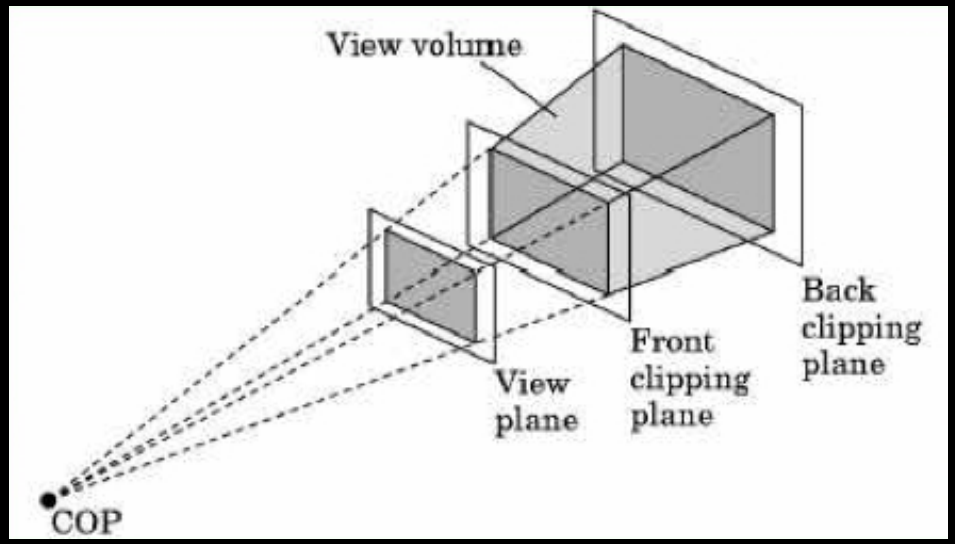
Specifying the Viewing Volume: Compatibility Mode

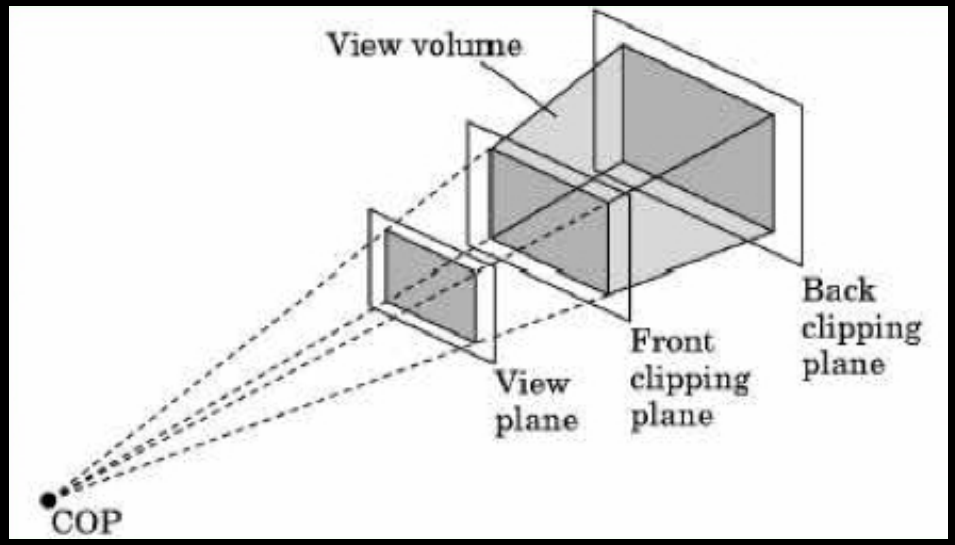
- Clip everything not in viewing volume
- Separate matrices for transformation and projection

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



Specifying the Viewing Volume: Core Profile

- Clip everything not in viewing volume
- Set the 4x4 projection matrix manually
  (or via our provided “openGLMatrix” library)
  (Lecture: “Viewing”)



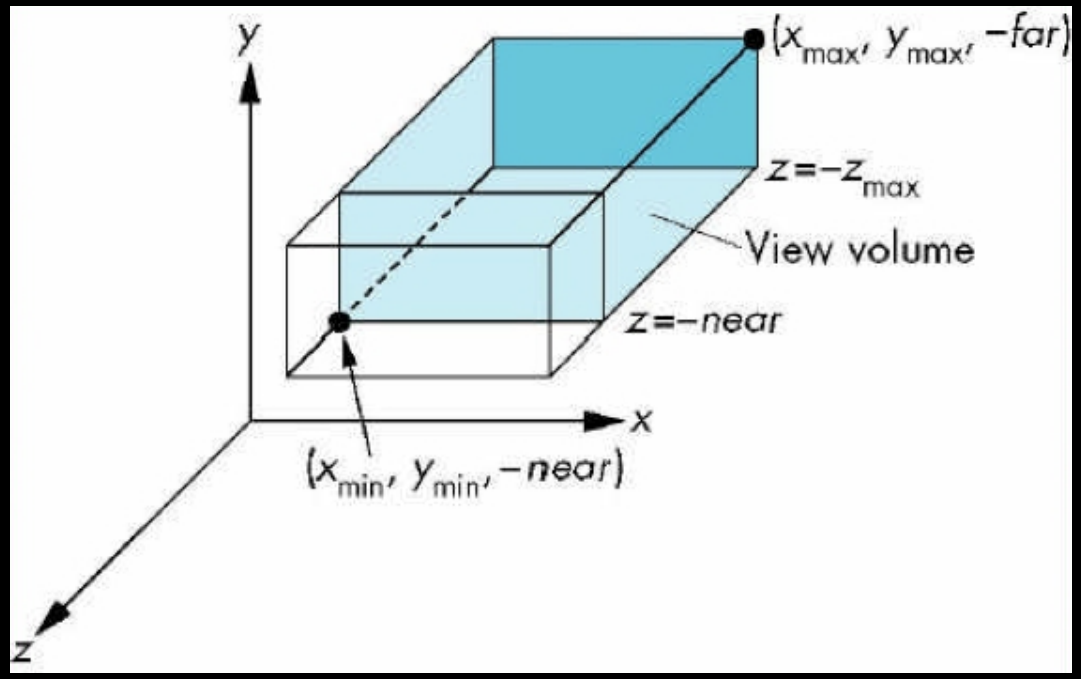
Parallel Viewing

- Orthographic projection
- Camera points in negative z direction
- Compatibility profile:

  glOrtho(xmin, xmax, ymin, ymax, near, far)
- Core profile: set the 4x4 matrix manually

  (or via our provided

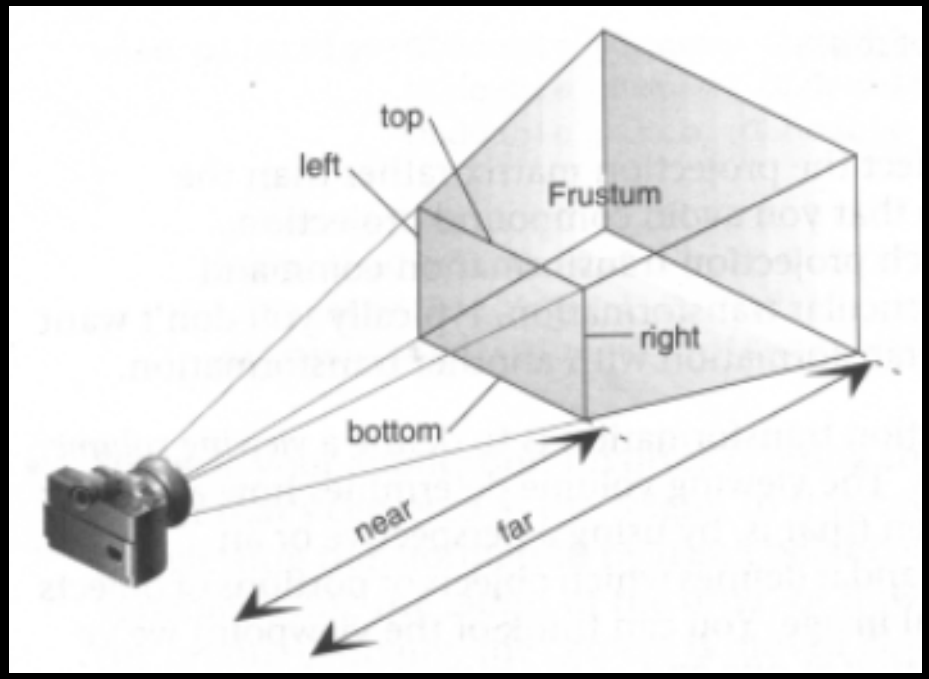
  “openGLMatrix” library)



Perspective Viewing

- Slightly more complex
- Compatibility profile:

  glFrustum(left, right, bottom, top, near, far)
- Core profile: set the 4x4 matrix manually (or via our provided "openGLMatrix" library)



Simple Transformations: Compatibility Profile

- Rotate by given angle (in degrees) about axis given by (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);
```

Simple Transformations: Core Profile

- Rotate by given angle (in degrees) about axis given by (x, y, z)
- Translate by the given x, y, and z values
- Scale with a factor in the x, y, and z direction

Create these 4x4 matrices manually
(or via our provided “openGLMatrix” library)
(Lecture: “Transformations”)

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Example: Rotating Colored Quad

- Draw a colored quad (two triangles)
- Rotate it about x, y, or z axis, depending on left, middle or right mouse click
- Stop when the space bar is pressed
- Quit when q or Q is pressed

Step 1: Defining the Vertices

Use separate arrays for vertices and colors:

```
/* vertices of the quad (will form two triangles;
   rendered via GL_TRIANGLES) */
float positions[6][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}};

/* colors to be assigned to vertices (4th value is the alpha channel) */
float colors[6][4] =
  {{0.0, 0.0, 0.0, 1.0}, {1.0, 0.0, 0.0, 1.0}, {0.0, 1.0, 0.0, 1.0},
   {0.0, 0.0, 1.0, 1.0}, {1.0, 1.0, 0.0, 1.0}, {1.0, 0.0, 1.0, 1.0}};
 // black, red, green, blue, yellow, magenta
```

Step 2: Set Up z-buffer and Double Buffering

```
int main(int argc, char **argv)
{
    glutInit(&argc, argv);
    // double buffering for smooth animation
    glutInitDisplayMode(GLUT_DOUBLE |
                        GLUT_DEPTH |
                        GLUT_RGBA);
    ...     // window creation and callbacks here (next slide)
    init(); // our custom initialization
    glutMainLoop();
    return(0);
}
```

Step 3: Install Callbacks

- Create window and set callbacks

```
glutInitWindowSize(800, 800);
glutCreateWindow(”quad");
glutReshapeFunc(myReshape);
glutDisplayFunc(display);
glutIdleFunc(spinQuad);
glutMouseFunc(mouse);
glutKeyboardFunc(keyboard);
```

Step 4: Our Initialization Function

```
#include “openGLMatrix.h” // our own (cs420) helper library


OpenGLMatrix * matrix;


void init()
{
    glClearColor (0.0, 0.0, 0.0, 0.0);
    glEnable(GL_DEPTH_TEST);
    matrix = new OpenGLMatrix();
    initVBO();
    initPipelineProgram();
}
```

Step 5: Init Vertex Buffer Object (VBO)

```
GLuint buffer;

void initVBO()
{
  glGenBuffers(1, &buffer);
  glBindBuffer(GL_ARRAY_BUFFER, buffer);
  glBufferData(GL_ARRAY_BUFFER, sizeof(positions) + sizeof(colors),
    NULL, GL_STATIC_DRAW);   // init buffer's size, but don't assign any
                             // data to it
  // upload position data
  glBufferSubData(GL_ARRAY_BUFFER, 0,
     sizeof(positions), positions);

  // upload color data
  glBufferSubData(GL_ARRAY_BUFFER, sizeof(positions),
     sizeof(colors), colors);
}
```

Step 6: Init Pipeline Program

```
void initPipelineProgram()
{
  // initialize shader pipeline program (shader lecture)
  // …
}
```

Step 7: Reshape Callback

Set projection and viewport, preserve aspect ratio

```
void myReshape(int w, int h)
{
  GLfloat aspect = (GLfloat) w / (GLfloat) h;
  glViewport(0, 0, w, h);
  matrix->SetMatrixMode(OpenGLMatrix::Projection);
  matrix->LoadIdentity();
  matrix->Ortho(-2.0, 2.0, -2.0/aspect, 2.0/aspect, 0.0, 10.0);
  matrix->SetMatrixMode(OpenGLMatrix::ModelView);
}
```

Step 8: Display Callback

Clear, rotate, draw, swap

```
GLfloat theta[3] = {0.0, 0.0, 0.0};

void display()
{
  glClear(GL_COLOR_BUFFER_BIT |
            GL_DEPTH_BUFFER_BIT);
  matrix->LoadIdentity();
  matrix->LookAt(0, 0, 0, 0, 0, -1, 0, 1, 0); // default camera
  matrix->Rotate(theta[0], 1.0, 0.0, 0.0);
  matrix->Rotate(theta[1], 0.0, 1.0, 0.0);
  matrix->Rotate(theta[2], 0.0, 0.0, 1.0);
  bindProgram();
  renderQuad();
  glutSwapBuffers();
}
```

Step 9: Bind Program

```
void bindProgram()
{
  // bind our buffer, so that glVertexAttribPointer refers
  // to the correct buffer
  glBindBuffer(GL_ARRAY_BUFFER, buffer);
  GLuint loc = glGetAttribLocation(program, “position”);
  glEnableVertexAttribArray(loc);
  const void * offset = (const void*) 0;
  glVertexAttribPointer(loc, 3, GL_FLOAT, GL_FALSE, 0, offset);

  GLuint loc2 = glGetAttribLocation(program, “color”);
  glEnableVertexAttribArray(loc2);
  const void * offset = (const void*) sizeof(positions);
  glVertexAttribPointer(loc2, 4, GL_FLOAT, GL_FALSE, 0, offset);

  // write projection and modelview matrix to shader
  // next lexture…
}
```

Step 10: Drawing the Quad

- Use GL_TRIANGLES

```
void renderQuad()
{
  GLint first = 0;
  GLsizei numberOfVertices = 6;
  glDrawArrays(GL_TRIANGLES, first, numberOfVertices);
}
```

Step 11: Animation

- Set idle callback

```
GLfloat delta = 2.0;
GLint axis = 2;
GLint spin = 1;
void spinQuad()
{
  // spin the quad delta degrees around the selected axis
  if (spin)
     theta[axis] += delta;
  if (theta[axis] > 360.0)
     theta[axis] -= 360.0;

  // display result (do not forget this!)
  glutPostRedisplay();
}
```

Step 12: 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 13: Toggle Rotation or Exit

- Keyboard callback

```
void keyboard(unsigned char key, int x, int y)
{
  if (key == 'q' || key == 'Q')
    exit(0);
  if (key == ' ') // spacebar
    spin= !spin;
}
```

Summary

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- Simple Transformations
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