Computer Graphics (CS 543)
Lecture 3 (Part 2): Building 3D Models

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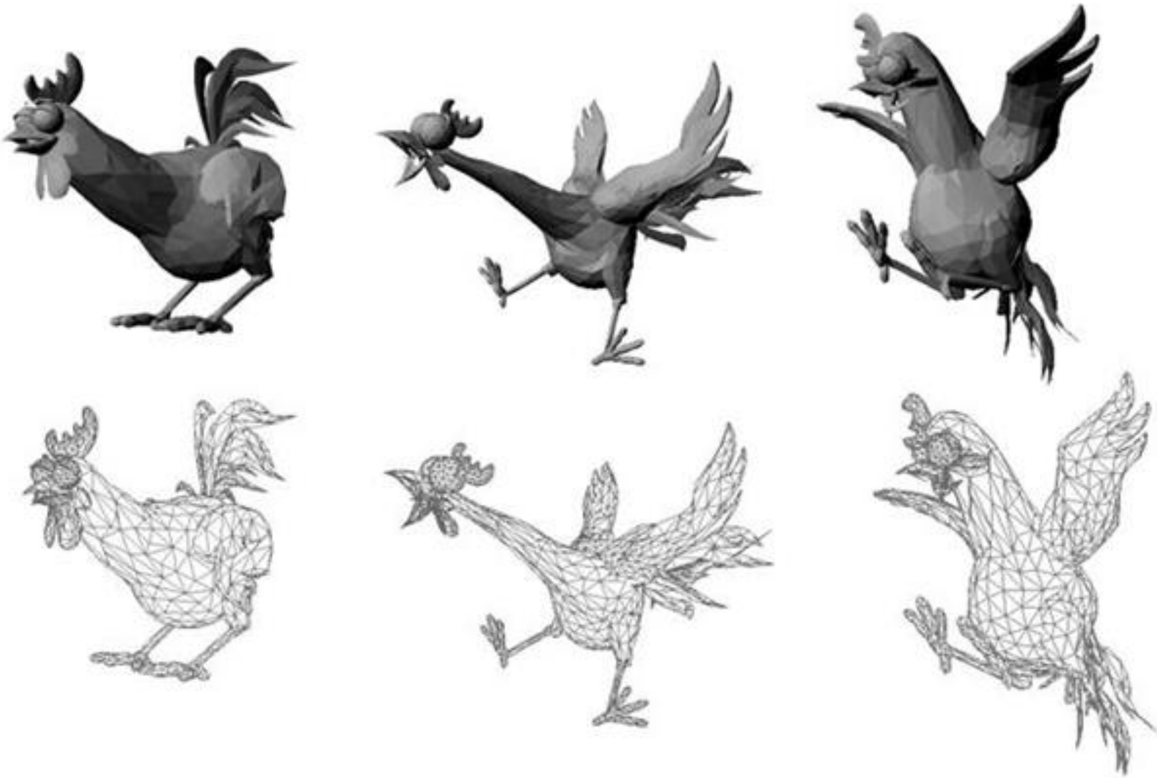
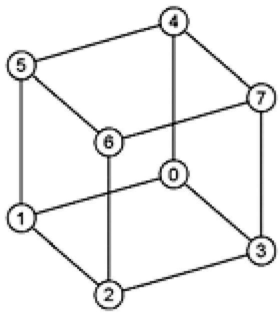
3D Applications

- **2D points:** (x,y) coordinates
- **3D points:** have (x,y,z) coordinates



Setting up 3D Applications: Main Steps

- Programming 3D similar to 2D
    1. Load representation of 3D object into data structure

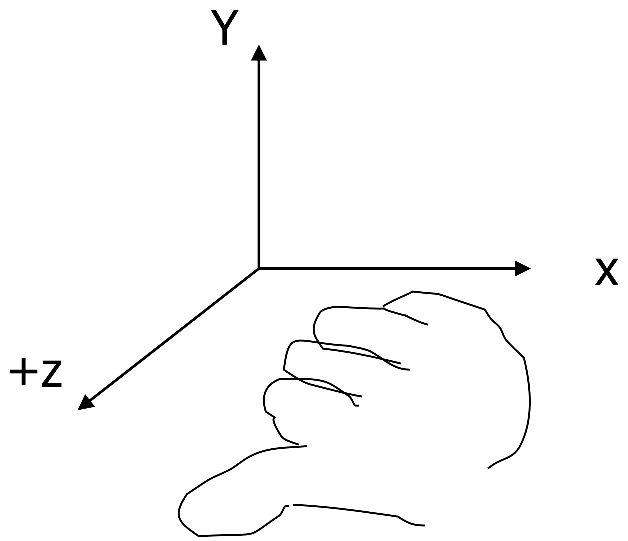


Each vertex has (x,y,z) coordinates.
Store as **vec3 NOT vec2**

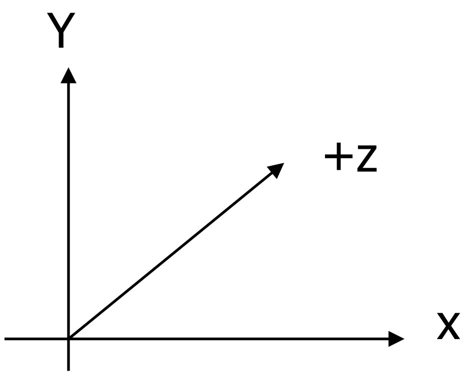
2. Draw 3D object
3. **Set up Hidden surface removal:** Correctly determine order in which primitives (triangles, faces) are rendered (e.g Blocked faces **NOT** drawn)

3D Coordinate Systems

- Vertex (x,y,z) positions specified on coordinate system
- OpenGL uses **right hand coordinate system**



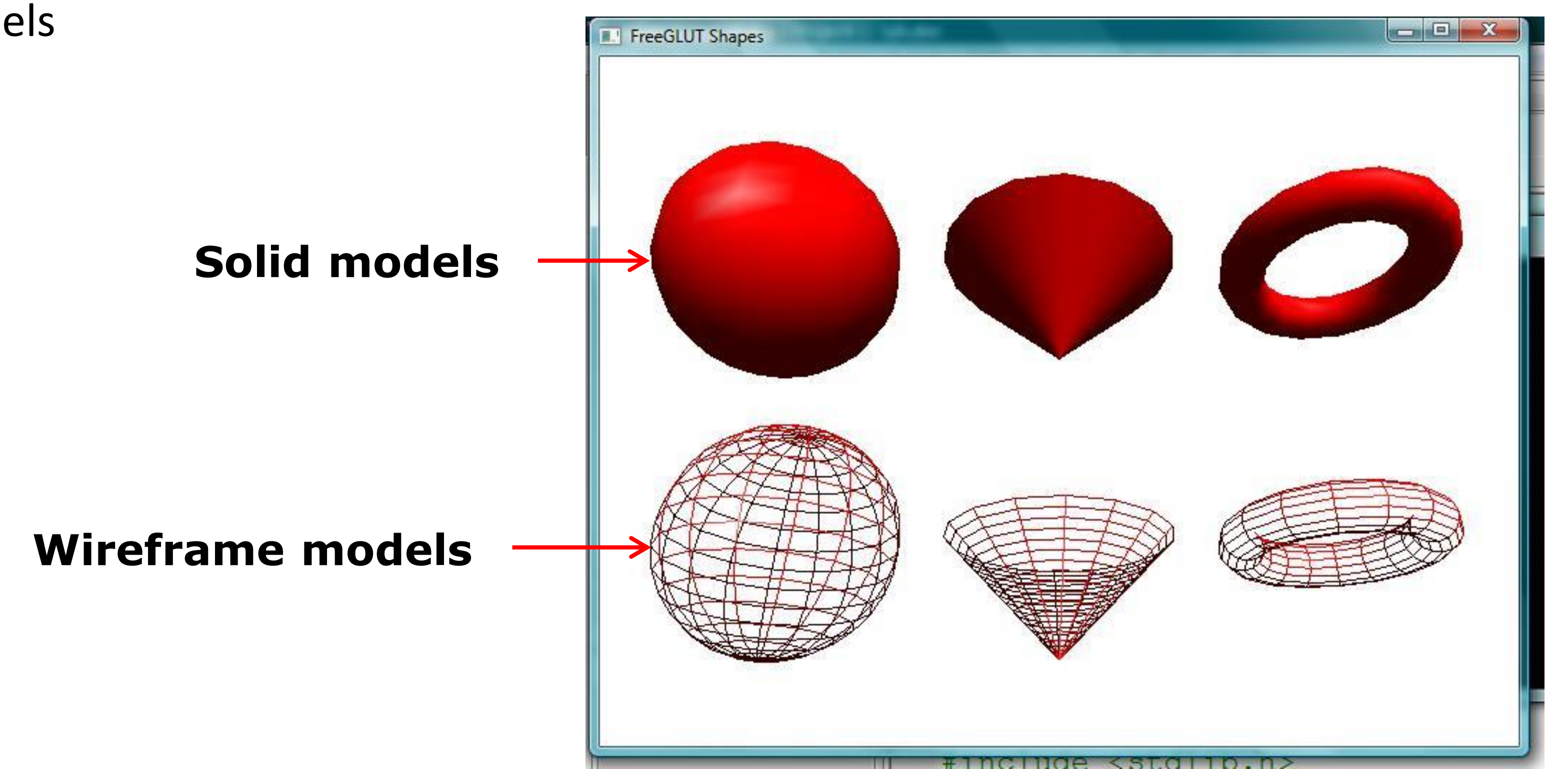
Right hand coordinate system
Tip: sweep fingers x-y: thumb is z



Left hand coordinate system
•Not used in OpenGL

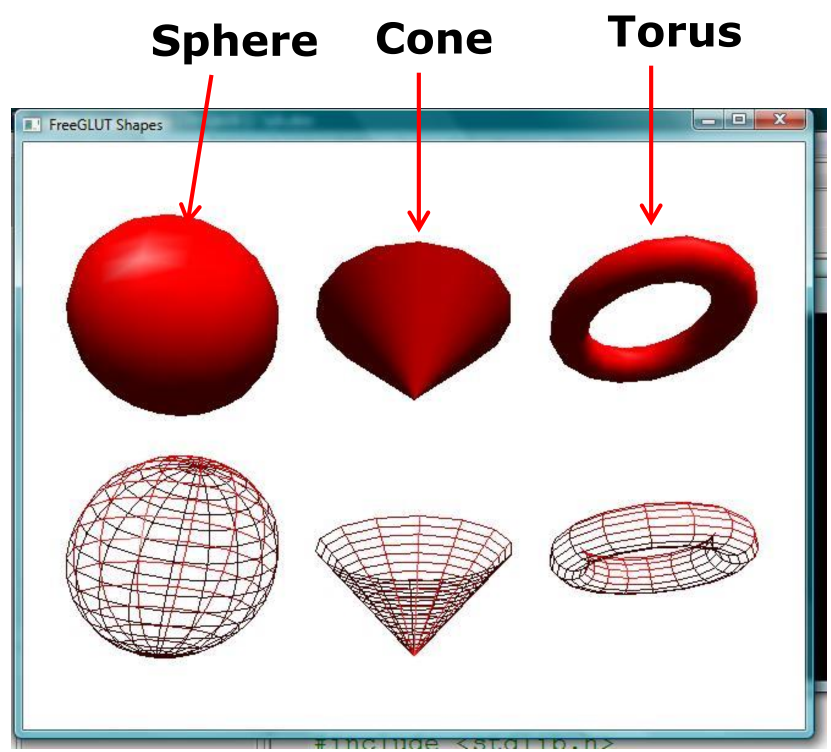
Generating 3D Models: GLUT Models

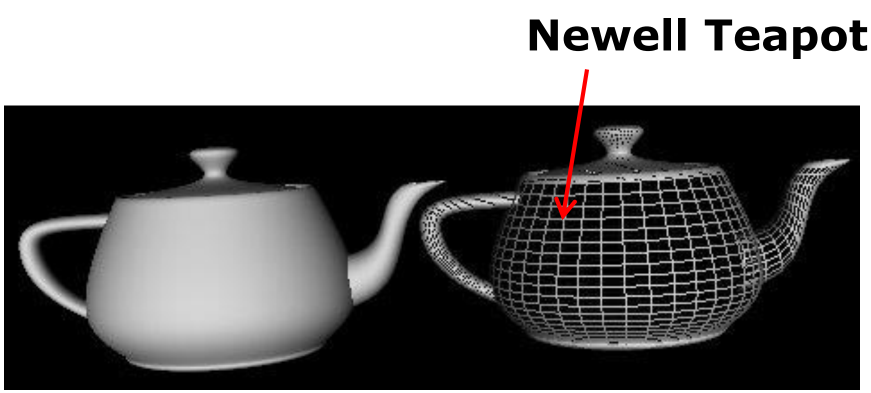
- Make GLUT 3D calls in **OpenGL program** to generate vertices describing different shapes (Restrictive?)
- Two types of GLUT models:
  - Wireframe Models
  - Solid Models



3D Modeling: GLUT Models

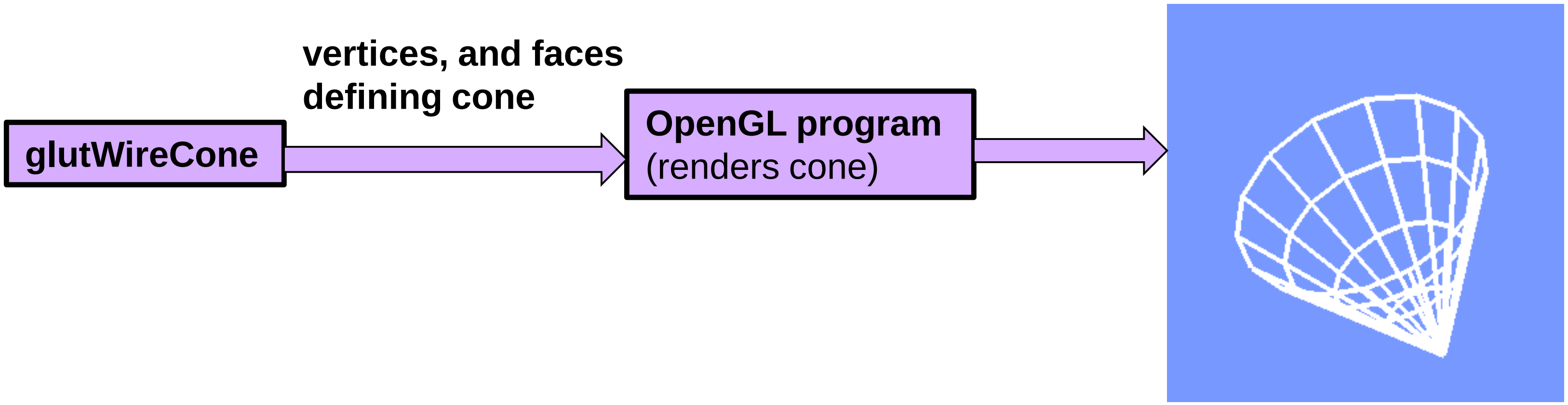
- Basic Shapes
  - **Cone:** glutWireCone( ), glutSolidCone( )
  - **Sphere:** glutWireSphere( ), glutSolidSphere( )
  - **Cube:** glutWireCube( ), glutSolidCube( )
- More advanced shapes:
  - Newell Teapot: (symbolic)
  - Dodecahedron, Torus





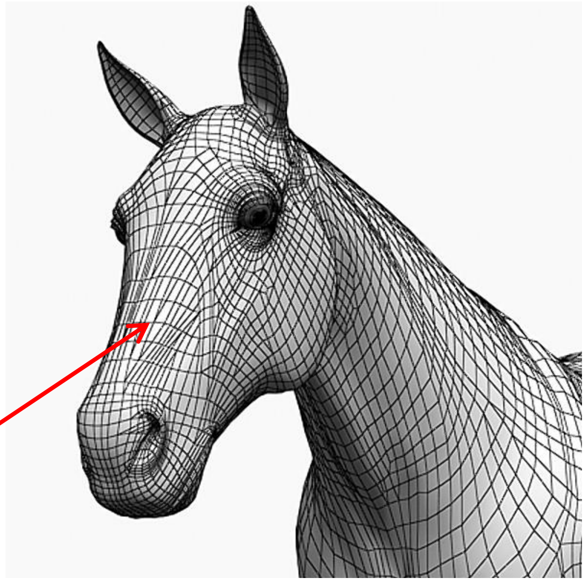
3D Modeling: GLUT Models

- Glut functions under the hood
  - generate sequence of points that define a shape
  - Generated vertices and faces passed to OpenGL for rendering
- **Example:** **glutWireCone** generates sequence of vertices, and faces defining **cone** and connectivity



Polygonal Meshes

- Modeling with GLUT shapes (cube, sphere, etc) too restrictive
- Difficult to approach realism. E.g. model a horse
- Preferred way is using polygonal meshes:
  - Collection of polygons, or faces, that form “skin” of object
  - More flexible, represents complex surfaces better
  - Examples:
    - Human face
    - Animal structures
    - Furniture, etc



Each face of mesh is a polygon

Polygonal Meshes

- Mesh = sequence of polygons forming thin skin around object
- OpenGL Good at drawing polygons, triangles
- Meshes now standard in graphics
- Simple meshes exact. (e.g barn)
- Complex meshes approximate (e.g. human face)

Same Mesh at Different Resolutions

Original: 424,000 triangles

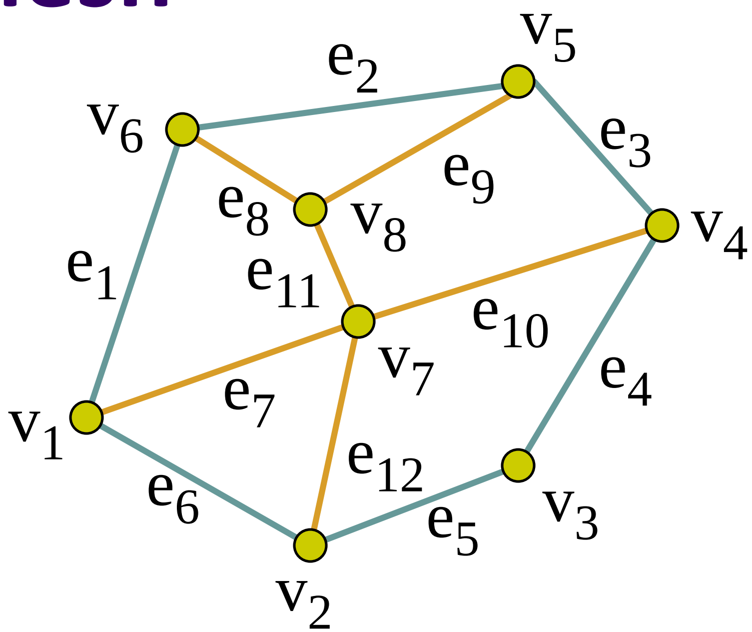
60,000 triangles (14%).

1000 triangles (0.2%)

(courtesy of Michael Garland and Data courtesy of Iris Development.)

Representing a Mesh

- Consider a mesh



- There are 8 vertices and 12 edges
  - 5 interior polygons
  - 6 interior (shared) edges (shown in orange)
- Each vertex has a location $v_i = (x_i\ y_i\ z_i)$

Simple Representation

- Define each polygon by (x,y,z) locations of its vertices
- OpenGL code

```
vertex[i]   = vec3(x1, y1, z1);
vertex[i+1] = vec3(x6, y6, z6);
vertex[i+2] = vec3(x7, y7, z7);
i+=3;
```

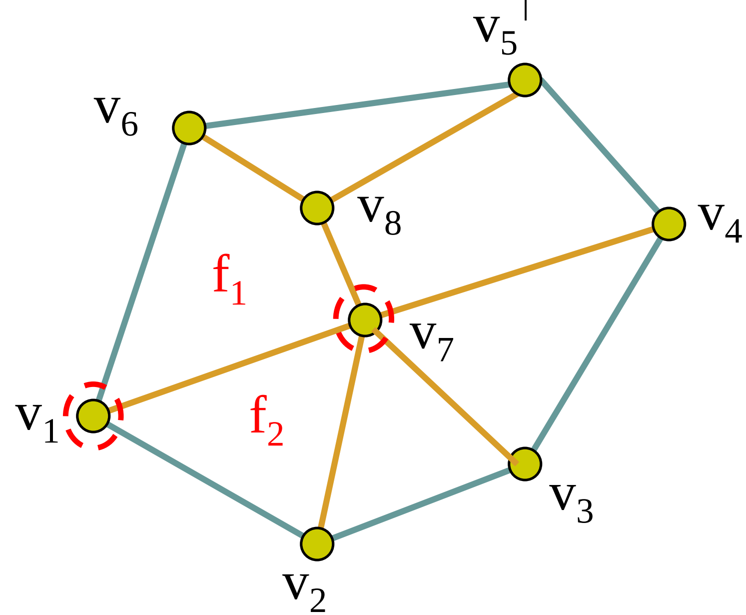
Issues with Simple Representation

- Declaring face f1

```
vertex[i]   = vec3(x1, y1, z1);
vertex[i+1] = vec3(x7, y7, z7);
vertex[i+2] = vec3(x8, y8, z8);
vertex[i+3] = vec3(x6, y6, z6);
```

- Declaring face f2

```
vertex[i]   = vec3(x1, y1, z1);
vertex[i+1] = vec3(x2, y2, z2);
vertex[i+2] = vec3(x7, y7, z7);
```



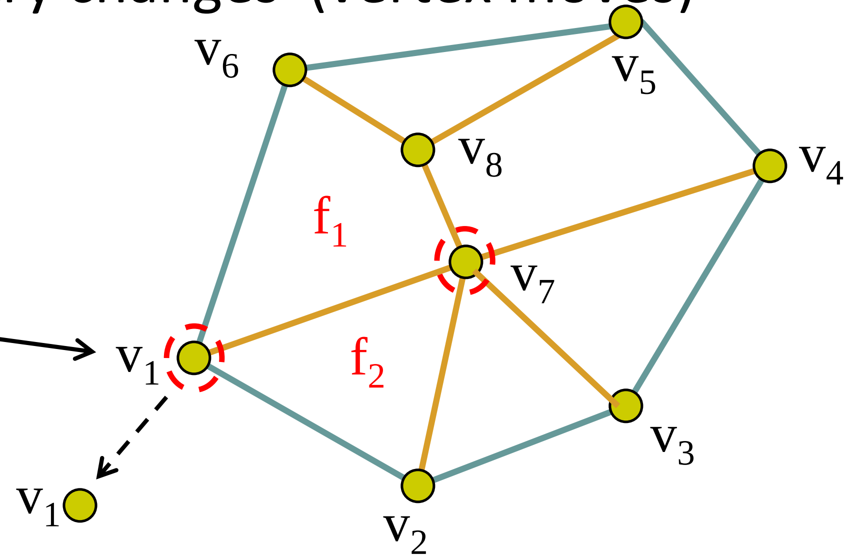
- Inefficient and unstructured
  - **Repeats:** vertices **v1 and v7 repeated** while declaring f1 and f2
  - Shared vertices shared declared multiple times
  - Delete vertex? Move vertex? Search for all occurences of vertex

Geometry vs Topology

- **Geometry:** (x,y,z) locations of the vertices
- **Topology:** How vertices and edges are connected

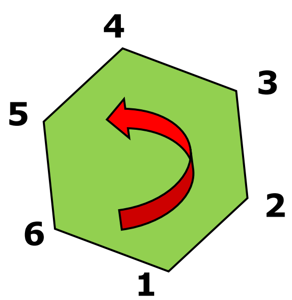
- Good data structures separate **geometry** from **topology**
  - **Example:**
    - A polygon is **ordered list** of vertices
    - An edge connects successive pairs of vertices
  - Topology holds even if geometry changes (vertex moves)

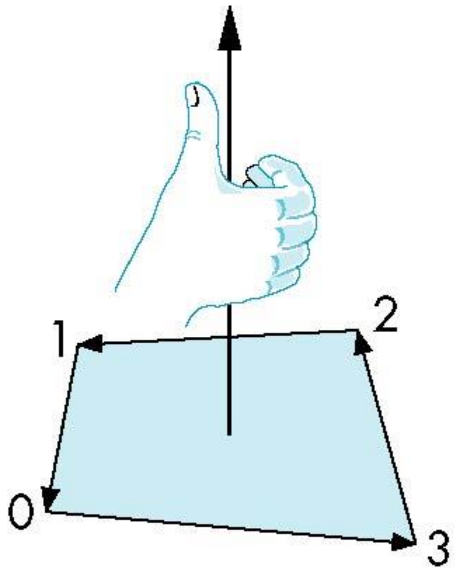
Example: even if we move (x,y,z) location of v1, v1 still connected to v6, v7 and v2

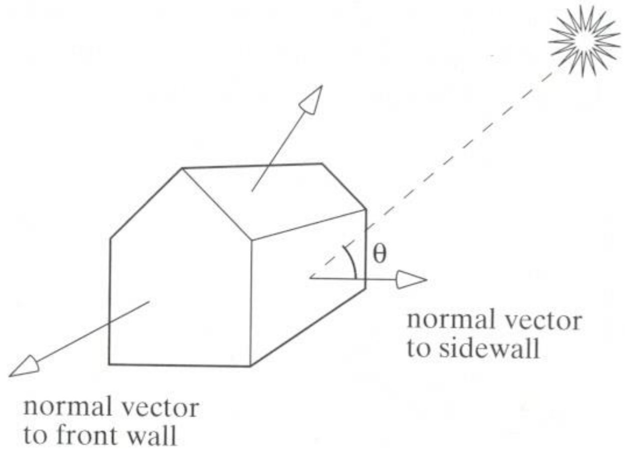


Polygon Traversal Convention

- **Convention:** traverse vertices counter-clockwise around normal
- Focus on direction of traversal
  - Orders $\{v_1, v_0, v_3\}$ and $\{v_3, v_2, v_1\}$ are same *(ccw)*
  - Order $\{v_1, v_2, v_3\}$ is different *(clockwise)*
- **Normal vector:** Direction each polygon is facing

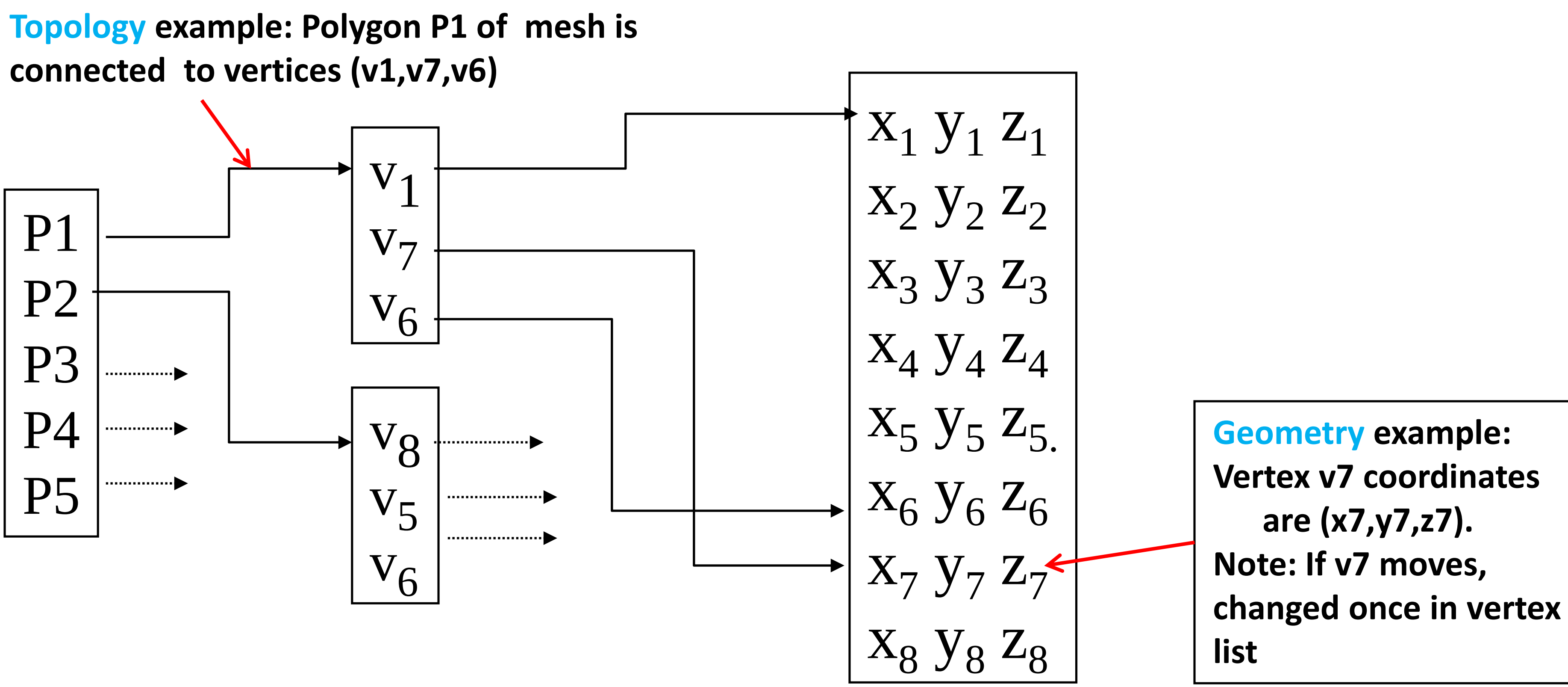






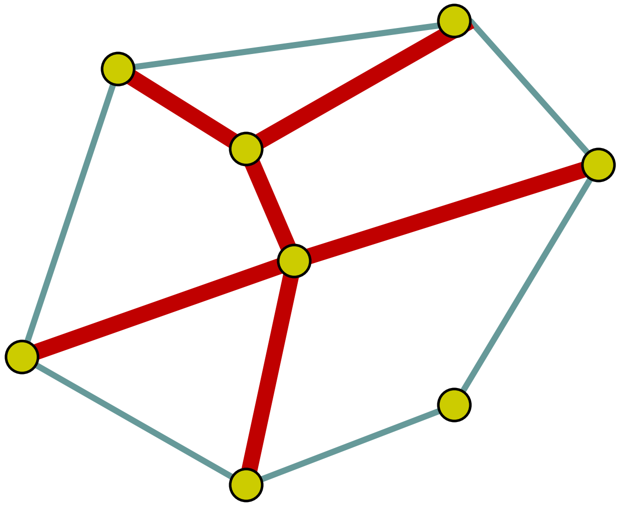
Vertex Lists

- **Vertex list:** (x,y,z) of vertices (its geometry) are put in array
- Use pointers from vertices into vertex list
- **Polygon list:** vertices connected to each polygon (face)



Vertex List Issue: Shared Edges

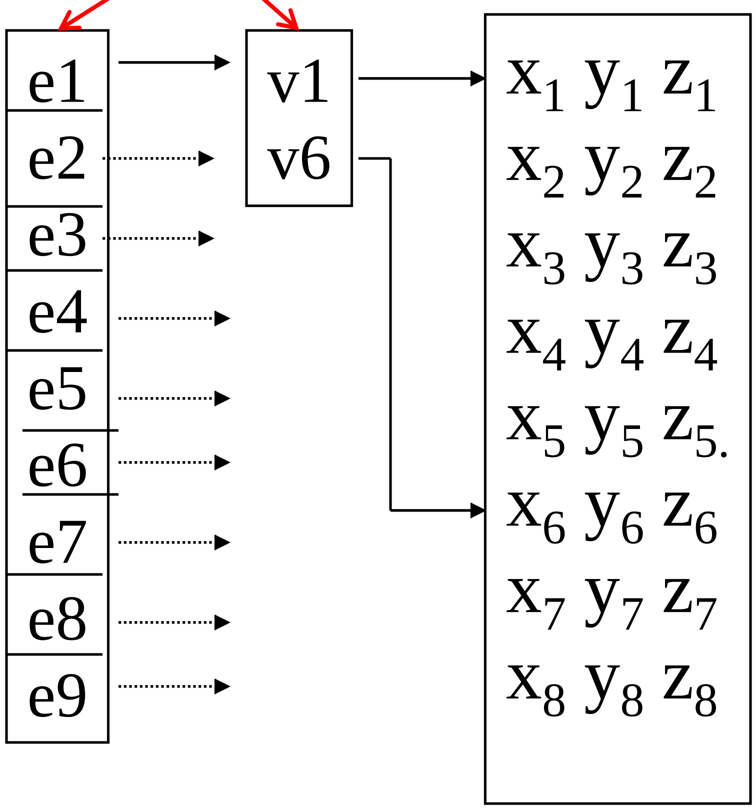
- Vertex lists draw filled polygons correctly
- If each polygon is drawn by its edges, shared edges are drawn twice

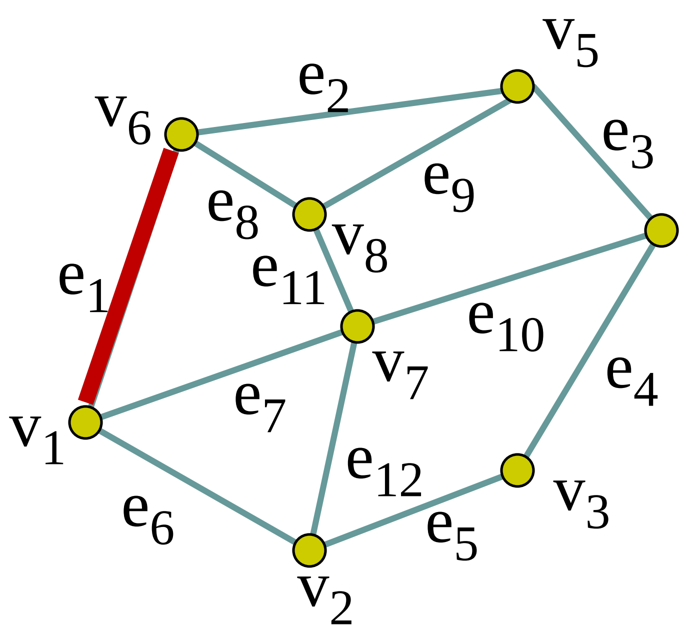


- **Alternatively:** Can store mesh by *edge list*

Edge List

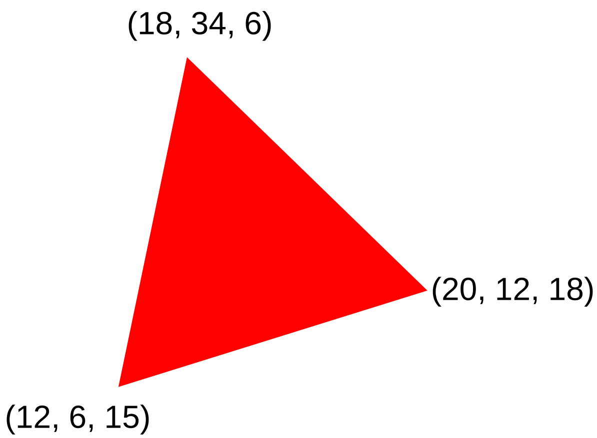
Simply draw each edges once
E.g e1 connects v1 and v6





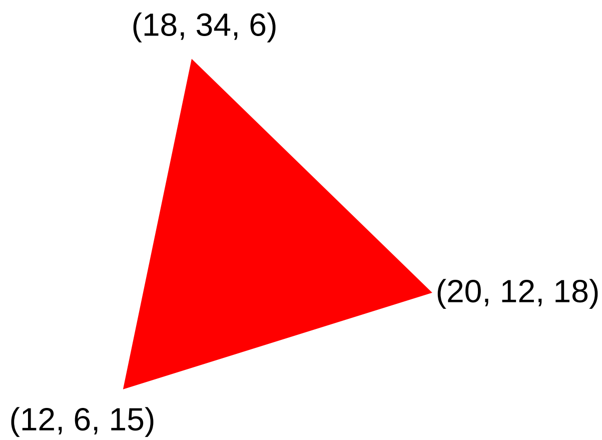
Note polygons are not represented

Vertex Attributes

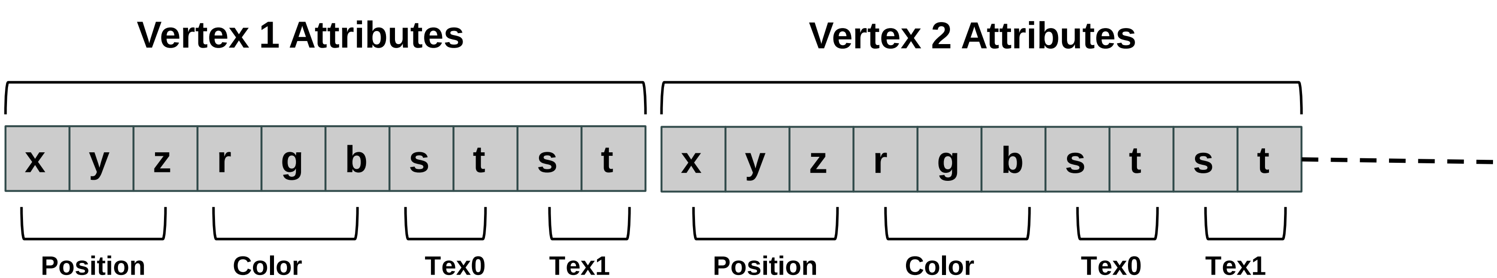


- Vertices can have attributes
  - Position (e.g 20, 12, 18)
  - Color (e.g. red)
  - Normal (x,y,z)
  - Texture coordinates

Vertex Attributes

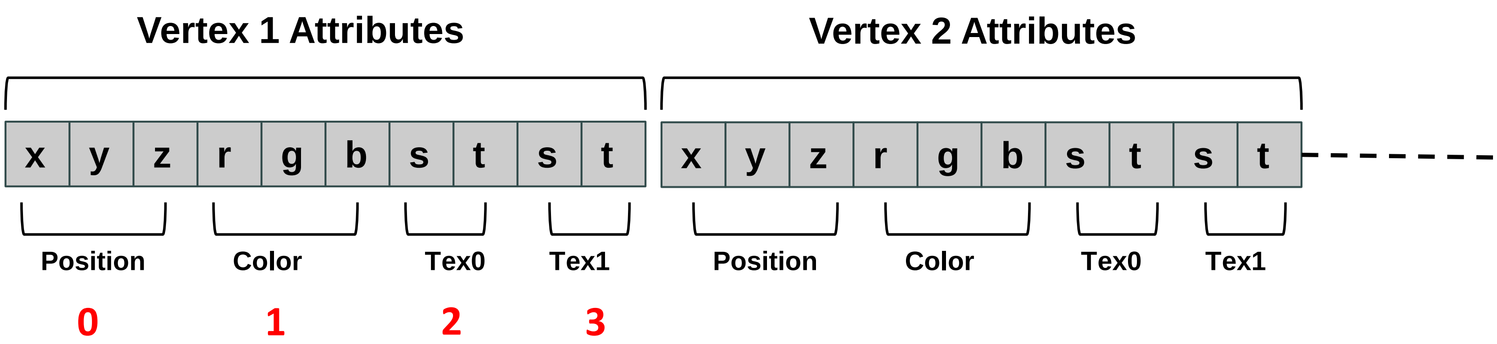


- Store vertex attributes in single Array (array of structures)
- **Later:** pass array to OpenGL, specify attributes, order, position using `glVertexAttribPointer`



Declaring Array of Vertex Attributes

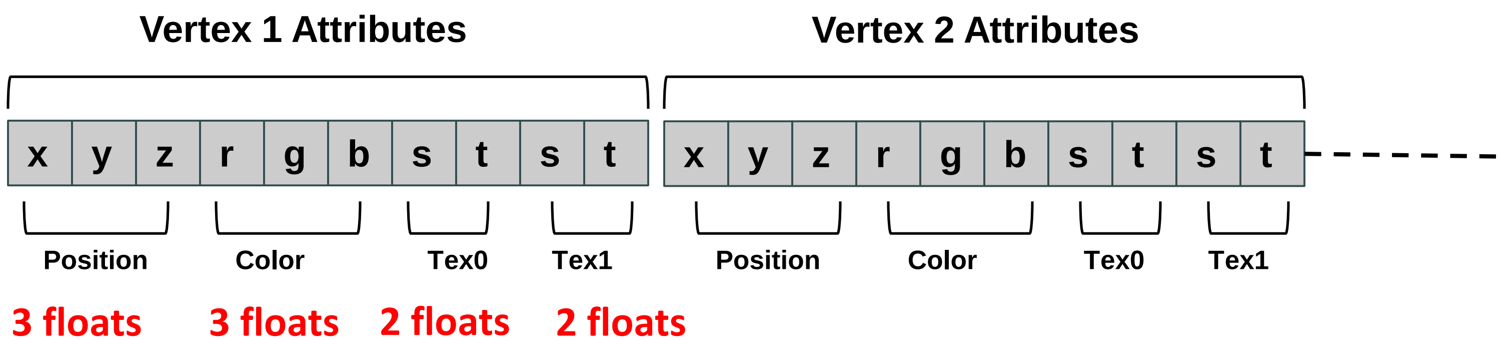
- Consider the following array of vertex attributes



- So we can define attribute positions (per vertex)

```
#define VERTEX_POS_INDEX            0
#define VERTEX_COLOR_INDEX          1
#define VERTEX_TEXCOORD0_INDX       2
#define VERTEX_TEXCOORD1_INDX       3
```

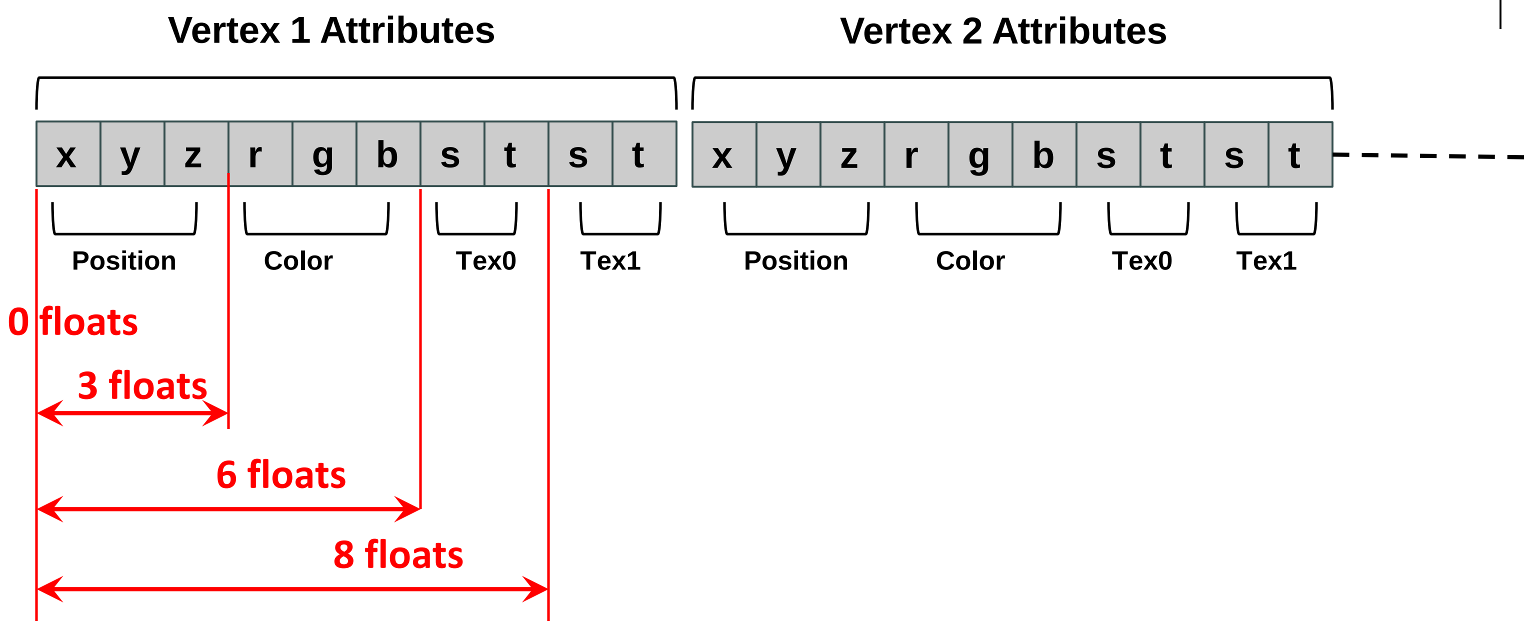
Declaring Array of Vertex Attributes



- Also define number of floats (storage) for each vertex attribute

```
#define VERTEX_POS_SIZE           3     // x, y and z
#define VERTEX_COLOR_SIZE         3     // r, g and b
#define VERTEX_TEXCOORD0_SIZE     2     // s and t
#define VERTEX_TEXCOORD1_SIZE     2     // s and t

#define VERTEX_ATTRIB_SIZE     VERTEX_POS_SIZE + VERTEX_COLOR_SIZE + \
                               VERTEX_TEXCOORD0_SIZE + \
                               VERTEX_TEXCOORD1_SIZE
```

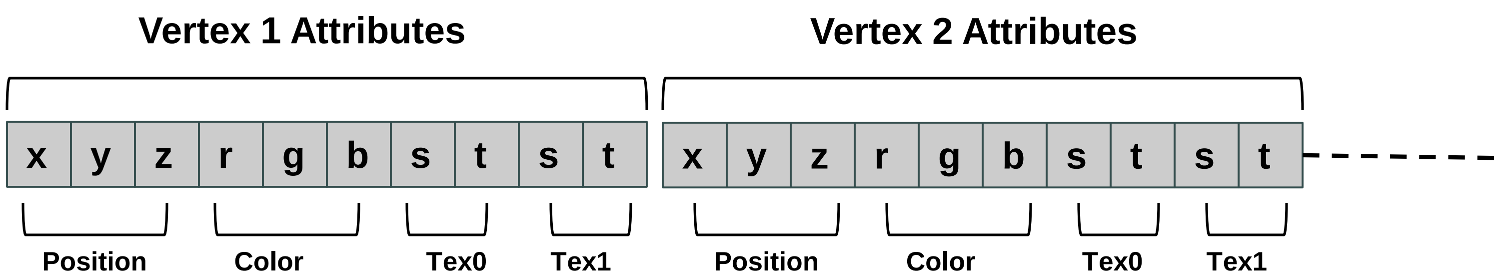
Declaring Array of Vertex Attributes



- Define offsets (# of floats) of each vertex attribute from beginning

```
#define VERTEX_POS_OFFSET             0
#define VERTEX_COLOR_OFFSET           3
#define VERTEX_TEXCOORD0_OFFSET       6
#define VERTEX_TEXCOORD1_OFFSET       8
```

Allocating Array of Vertex Attributes



- Allocate memory for entire array of vertex attributes

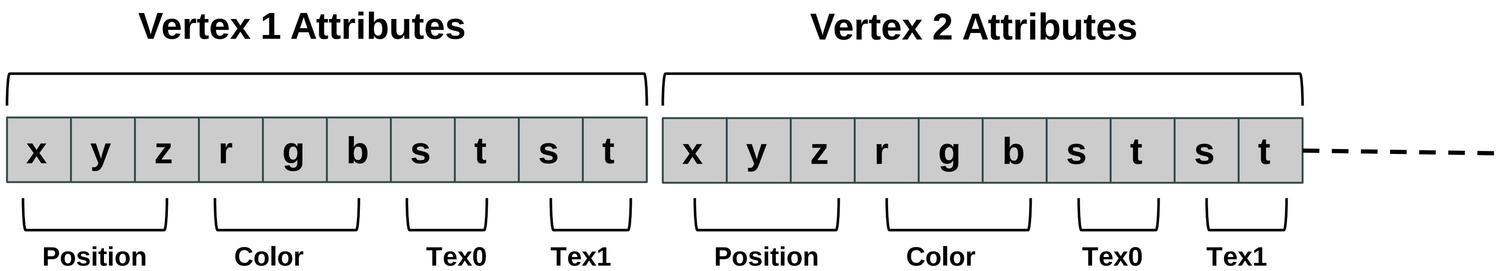
Recall

```
#define VERTEX_ATTRIB_SIZE     VERTEX_POS_SIZE + VERTEX_COLOR_SIZE + \
                               VERTEX_TEXCOORD0_SIZE + \
                               VERTEX_TEXCOORD1_SIZE
```

```
float *p = malloc(numVertices * VERTEX_ATTRIB_SIZE * sizeof(float));
```

Allocate memory for all vertices

Specifying Array of Vertex Attributes



- **glVertexAttribPointer** used to specify vertex attributes
- Example: to specify vertex position attribute

Position 0

3 values (x, y, z)

```
glVertexAttribPointer(VERTEX_POS_INDX, VERTEX_POS_SIZE,
                      GL_FLOAT, GL_FALSE,
                      VERTEX_ATTRIB_SIZE * sizeof(float), p);
```

Data should not Be normalized

Data is floats

```
glEnableVertexAttribArray(0);
```

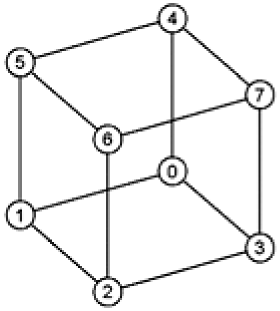
Stride: distance between consecutive vertices

Pointer to data

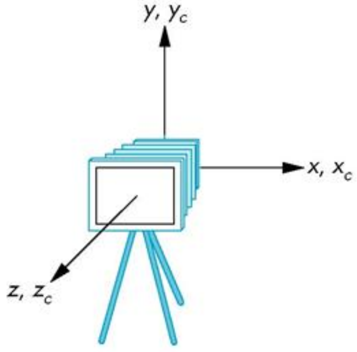
- `do same for normal, tex0 and tex1`

Full Example: Rotating Cube in 3D

- **Desired Program behaviour:**
  - Draw colored cube
  - Continuous rotation about X,Y or Z axis
    - Idle function called repeatedly when nothing to do
    - Increment angle of rotation in idle function
  - Use 3-button mouse to change direction of rotation
    - Click left button -> rotate cube around X axis
    - Click middle button -> rotate cube around Y axis
    - Click right button -> rotate cube around Z axis



- Use default camera
  - If we don't set camera, we get a default camera
  - Located at origin and points in the negative z direction

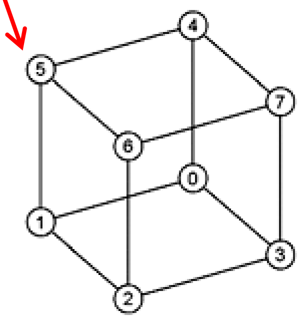


(a)

Cube Vertices

Declare array of (x,y,z,w) vertex positions
for a unit cube centered at origin
(Sides aligned with axes)

```
point4 vertices[8] = {
0  point4( -0.5, -0.5,  0.5, 1.0 ),
1  point4( -0.5,  0.5,  0.5, 1.0 ),
2  point4(  0.5,  0.5,  0.5, 1.0 ),
3  point4(  0.5, -0.5,  0.5, 1.0 ),
4  point4( -0.5, -0.5, -0.5, 1.0 ),
5  point4( -0.5,  0.5, -0.5, 1.0 ),
6  point4(  0.5,  0.5, -0.5, 1.0 ),
7  point4(  0.5, -0.5, -0.5, 1.0 )
};
              x      y      z     1
```



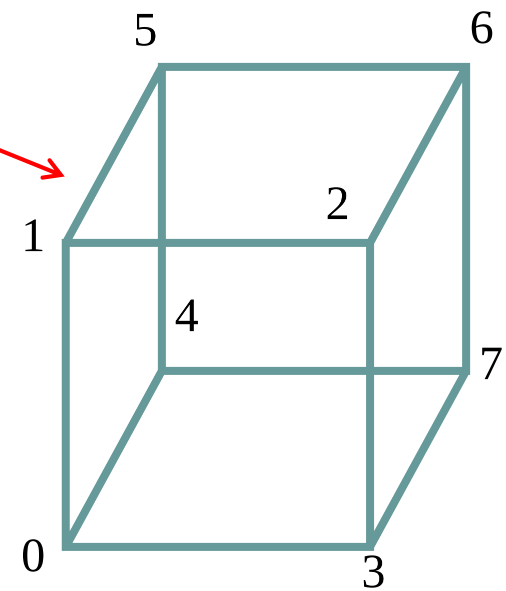

```
color4 vertex_colors[8] = {
    color4( 0.0, 0.0, 0.0, 1.0 ),  // black
    color4( 1.0, 0.0, 0.0, 1.0 ),  // red
    color4( 1.0, 1.0, 0.0, 1.0 ),  // yellow
    color4( 0.0, 1.0, 0.0, 1.0 ),  // green
    color4( 0.0, 0.0, 1.0, 1.0 ),  // blue
    color4( 1.0, 0.0, 1.0, 1.0 ),  // magenta
    color4( 1.0, 1.0, 1.0, 1.0 ),  // white
    color4( 0.0, 1.0, 1.0, 1.0 )   // cyan
};
             r    g    b    1
```

Declare array of vertex colors
(set of RGBA colors vertex can have)

Color Cube

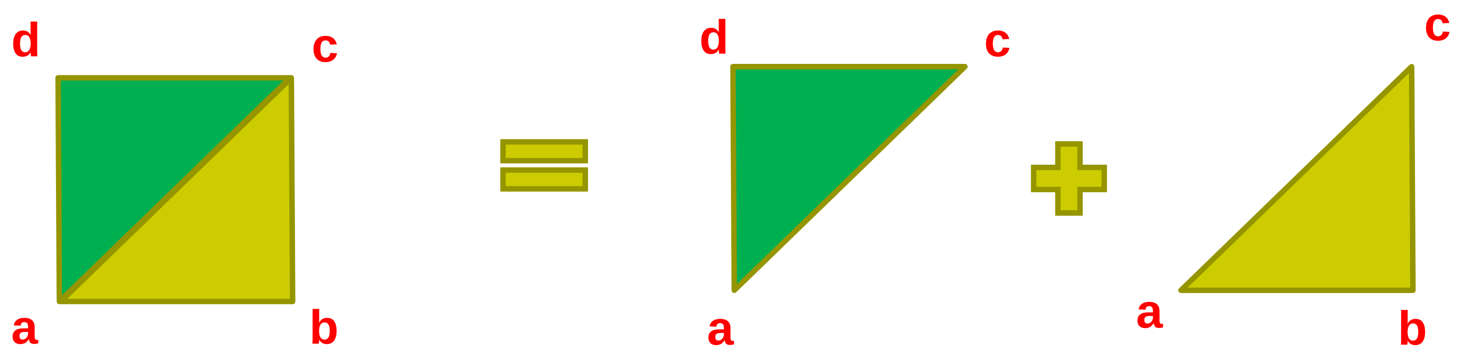
```
// generate 6 quads,
// sides of cube

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

```
point4 vertices[8] = {
  0 point4( -0.5, -0.5,  0.5, 1.0 ),
  1 point4( -0.5,  0.5,  0.5, 1.0 ),
    point4(  0.5,  0.5,  0.5, 1.0 ),
    point4(  0.5, -0.5,  0.5, 1.0 ),
  4 point4( -0.5, -0.5, -0.5, 1.0 ),
  5 point4( -0.5,  0.5, -0.5, 1.0 ),
    point4(  0.5,  0.5, -0.5, 1.0 ),
    point4(  0.5, -0.5, -0.5, 1.0 )
};
```



Function **quad** is
Passed vertex indices

Quad Function




```
// quad generates two triangles (a,b,c) and (a,c,d) for each face
// and assigns colors to the vertices

int Index = 0;  // Index goes 0 to 5, one for each vertex of face

void quad( int a, int b, int c, int d )
{
 0  colors[Index] = vertex_colors[a]; points[Index] = vertices[a]; Index++;
 1  colors[Index] = vertex_colors[b]; points[Index] = vertices[b]; Index++;
 2  colors[Index] = vertex_colors[c]; points[Index] = vertices[c]; Index++;
 3  colors[Index] = vertex_colors[a]; points[Index] = vertices[a]; Index++;
 4  colors[Index] = vertex_colors[c]; points[Index] = vertices[c]; Index++;
 5  colors[Index] = vertex_colors[d]; points[Index] = vertices[d]; Index++;
}
```

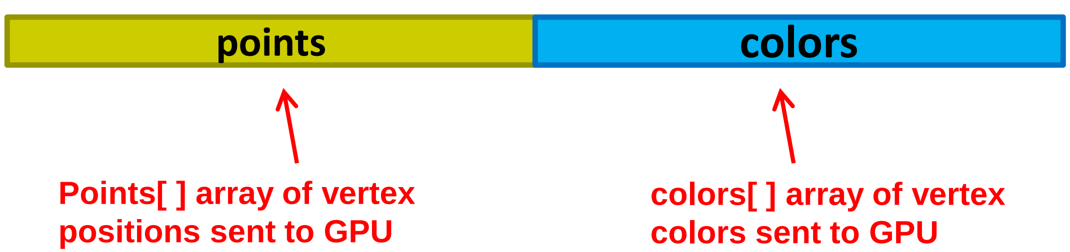
Points[ ] array to be
Sent to GPU

Read from appropriate index
of unique positions declared

quad 0 = points[0 - 5]
quad 1 = points[6 – 11]
quad 2 = points [12 – 17] …etc

Initialization I

```
void init()
{
    colorcube(); // Generates cube data in application using quads

    // Create a vertex array object
    GLuint vao;
    glGenVertexArrays ( 1, &vao );
    glBindVertexArray ( vao );

    // Create a buffer object and move data to GPU
    GLuint buffer;
    glGenBuffers( 1, &buffer );
    glBindBuffer( GL_ARRAY_BUFFER, buffer );
    glBufferData( GL_ARRAY_BUFFER, sizeof(points) +
                                   sizeof(colors), NULL, GL_STATIC_DRAW );
```



Initialization II

Send points[ ] and colors[ ] data to GPU separately using **`glBufferSubData`**

```
glBufferSubData( GL_ARRAY_BUFFER, 0, sizeof(points), points );
glBufferSubData( GL_ARRAY_BUFFER, sizeof(points), sizeof(colors), colors );
```


```
// Load vertex and fragment shaders and use the resulting shader program
GLuint program = InitShader( "vshader36.glsl", "fshader36.glsl" );
glUseProgram( program );
```

Initialization III

```
// set up vertex arrays

GLuint vPosition = glGetAttribLocation( program, "vPosition" );
glEnableVertexAttribArray( vPosition );
glVertexAttribPointer( vPosition, 4, GL_FLOAT, GL_FALSE, 0,
                                                    BUFFER_OFFSET(0) );

GLuint vColor = glGetAttribLocation( program, "vColor" );
glEnableVertexAttribArray( vColor );
glVertexAttribPointer( vColor, 4, GL_FLOAT, GL_FALSE, 0,
                                        BUFFER_OFFSET(sizeof(points)) );
```

Specify vertex data

Specify color data

points	colors

```
theta = glGetUniformLocation( program, "theta" );
```

Want to Connect rotation variable theta in program to variable in shader

Display Callback

```
void display( void )
{
    glClear( GL_COLOR_BUFFER_BIT|GL_DEPTH_BUFFER_BIT );

    glUniform3fv( theta, 1, theta );
    glDrawArrays( GL_TRIANGLES, 0, NumVertices );

    glutSwapBuffers();
}
```

Draw series of triangles forming cube

Mouse Callback

```
…
enum { Xaxis = 0, Yaxis = 1, Zaxis = 2, NumAxes = 3 };



void mouse( int button, int state, int x, int y )
{
    if ( state == GLUT_DOWN ) {
        switch( button ) {
            case GLUT_LEFT_BUTTON:    axis = Xaxis;  break;
            case GLUT_MIDDLE_BUTTON:  axis = Yaxis;  break;
            case GLUT_RIGHT_BUTTON:   axis = Zaxis;  break;
        }
    }
}
```

Select axis (x,y,z) to rotate around
Using mouse click

Idle Callback

```
void idle( void )
{
    theta[axis] += 0.01;

    if ( theta[axis] > 360.0 ) {
        theta[axis] -= 360.0;
    }

    glutPostRedisplay();
}
```

The idle( ) function is called whenever nothing to do

Use it to increment rotation angle in steps of theta = 0.01 around currently selected axis

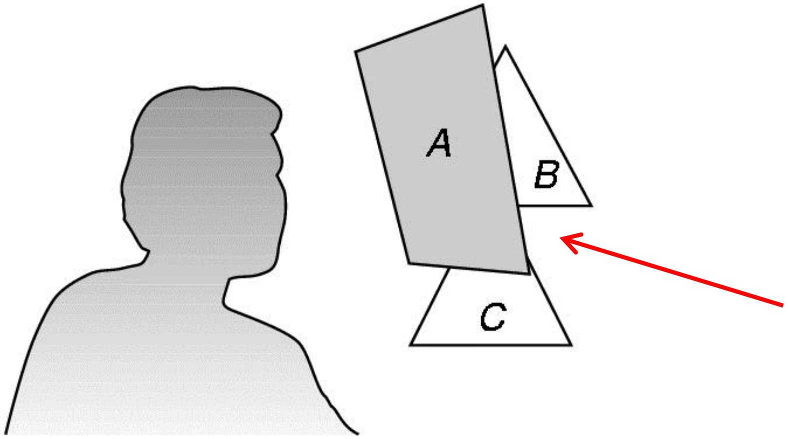
```
void main( void ){
  .........

  glutIdleFunc( idle );
  .........
}
```

Note: still need to:

- Apply rotation by (theta) in shader

Hidden-Surface Removal

- If multiple surfaces overlap, we want to see only **closest**
- OpenGL uses *hidden-surface* technique called the ***z-buffer*** algorithm
- Z-buffer compares objects distances from viewer (depth) to determine closer objects



If overlap,
Draw face **A** (front face)
Do not draw faces **B** and **C**

Using OpenGL's *z*-buffer algorithm

- Z-buffer uses an extra buffer, (the z-buffer), to store depth information, compare distance from viewer
- 3 steps to set up Z-buffer:
  1. In **`main( )`** function

     ```
     glutInitDisplayMode(GLUT_SINGLE | GLUT_RGB | GLUT_DEPTH)
     ```

  2. Enabled in **`init( )`** function

     ```
     glEnable(GL_DEPTH_TEST)
     ```

  3. Clear depth buffer whenever we clear screen

     ```
     glClear(GL_COLOR_BUFFER_BIT | DEPTH_BUFFER_BIT)
     ```

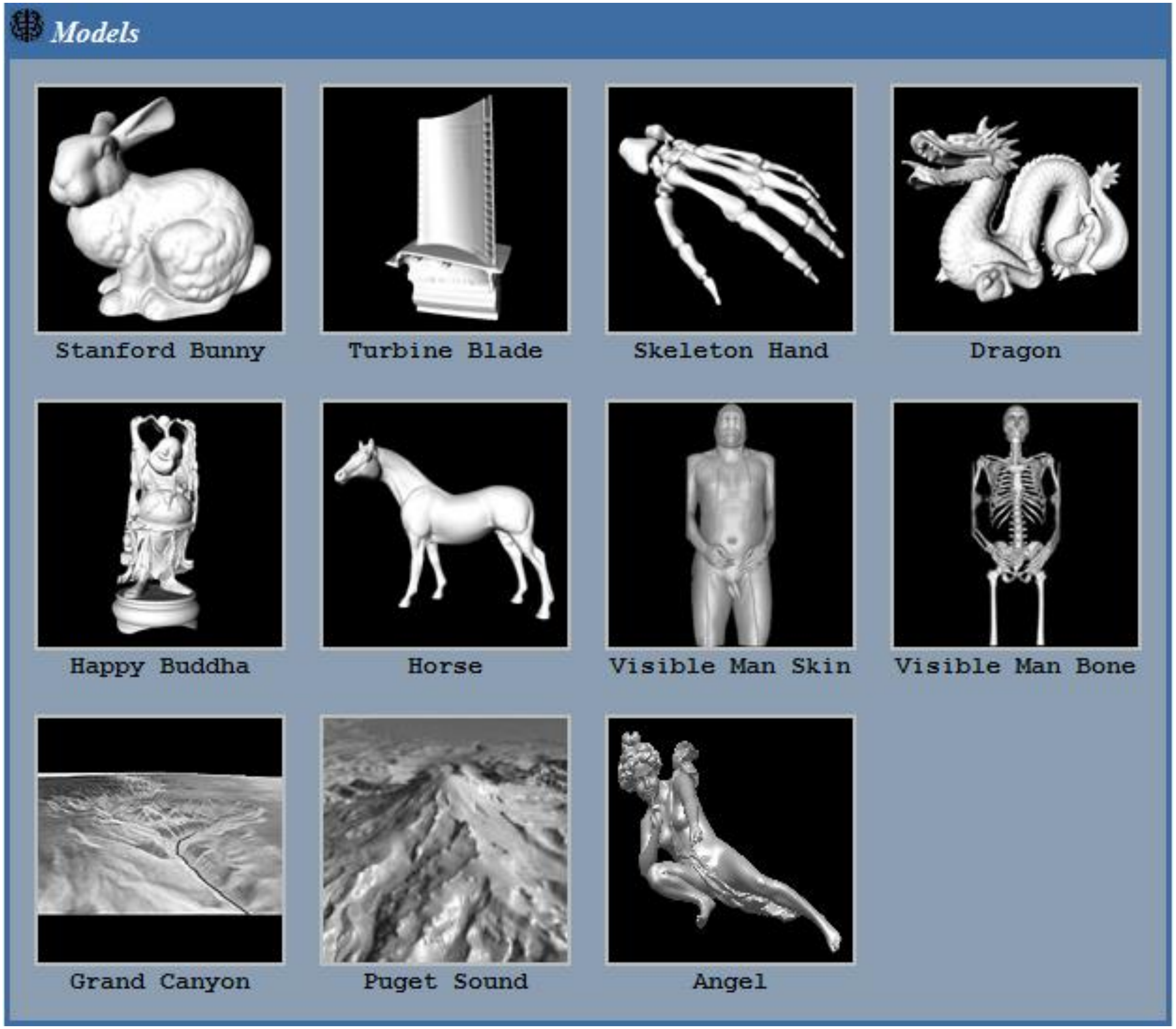
3D Mesh file formats

- 3D meshes usually stored in 3D file format
- Format defines how vertices, edges, and faces are declared
- Over 400 different file formats
- **Polygon File Format (PLY)** used a lot in graphics
- Originally PLY was used to store 3D files from 3D scanner
- We will use PLY files in this class

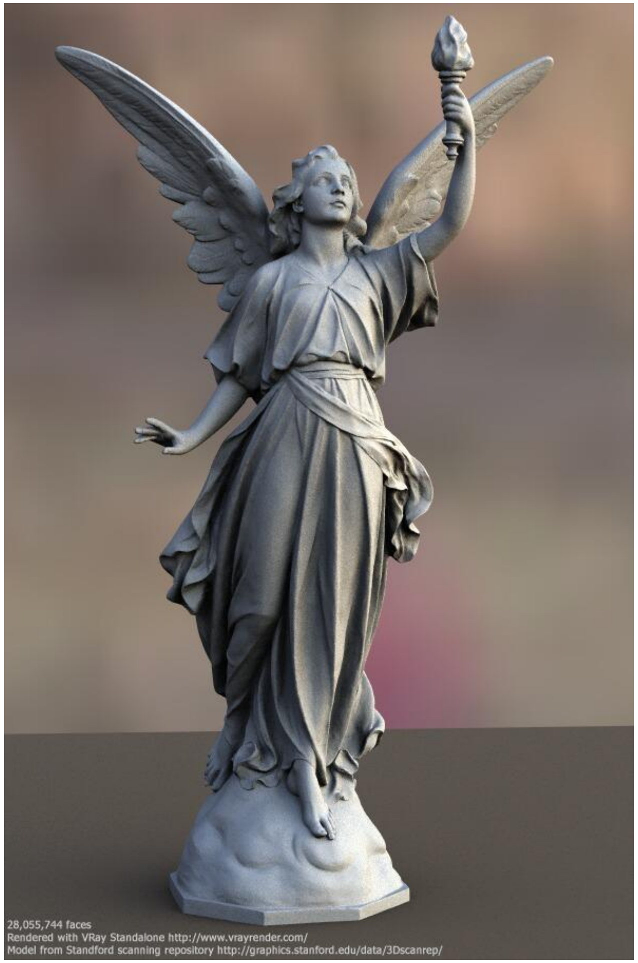
Sample PLY File

```
ply
format ascii 1.0
comment this is a simple file
obj_info any data, in one line of free form text element vertex 3
property float x
property float y
property float z
element face 1
property list uchar int vertex_indices
end_header
-1 0 0
0 1 0
1 0 0
3 0 1 2
```

Georgia Tech Large Models Archive



Stanford 3D Scanning Repository



Lucy: 28 million faces

Happy Buddha: 9 million faces

References

- Angel and Shreiner, Interactive Computer Graphics, 6^{th} edition, Chapter 3
- Hill and Kelley, Computer Graphics using OpenGL, 3^{rd} edition