Computer Graphics (CS 4731)
Lecture 7: 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

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

Each vertex has (x,y,z) coordinates. Store as `vec3`, `glUniform3f` **NOT** `vec2`
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 Mesh Example

Smoothed Out with Shading (later)

Mesh (wireframe)
Polygonal Meshes

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

```cpp
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**
  
  \[
  \begin{align*}
  \text{vertex}[i] & = \text{vec3}(x_1, y_1, z_1); \\
  \text{vertex}[i+1] & = \text{vec3}(x_7, y_7, z_7); \\
  \text{vertex}[i+2] & = \text{vec3}(x_8, y_8, z_8); \\
  \text{vertex}[i+3] & = \text{vec3}(x_6, y_6, z_6);
  \end{align*}
  \]

- **Declaring face f2**
  
  \[
  \begin{align*}
  \text{vertex}[i] & = \text{vec3}(x_1, y_1, z_1); \\
  \text{vertex}[i+1] & = \text{vec3}(x_2, y_2, z_2); \\
  \text{vertex}[i+2] & = \text{vec3}(x_7, y_7, z_7);
  \end{align*}
  \]

- **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 occurrences of vertex
Geometry vs Topology

- Better data structures separate **geometry** from **topology**
  - **Geometry**: \((x,y,z)\) locations of the vertices
  - **Topology**: How vertices and edges are connected
  - **Example**: A polygon is **ordered list** of vertices
    - An edge connecting successive pairs of vertices
  - Topology holds even if geometry changes (vertex moves)

Example: even if we move \((x,y,z)\) location of \(v_1\), \(v_1\) still connected to \(v_6\), \(v_7\) and \(v_2\)
## Polygon Traversal Convention

- Use the *right-hand rule* = counter-clockwise encirclement of outward-pointing 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)
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)

**Topology example:** Polygon P1 of mesh is connected to vertices \((v1,v7,v6)\)

**Geometry example:** Vertex \(v7\) coordinates are \((x7,y7,z7)\).

Note: If \(v7\) moves, changed once in vertex list
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

\[
\begin{align*}
\text{e1} & \rightarrow v1 \\
\text{e2} & \rightarrow v6 \\
\text{e3} & \\
\text{e4} & \\
\text{e5} & \\
\text{e6} & \\
\text{e7} & \\
\text{e8} & \\
\text{e9} & \\
\end{align*}
\]

\[
\begin{align*}
x_1 & \quad y_1 & \quad z_1 \\
x_2 & \quad y_2 & \quad z_2 \\
x_3 & \quad y_3 & \quad z_3 \\
x_4 & \quad y_4 & \quad z_4 \\
x_5 & \quad y_5 & \quad z_5 \\
x_6 & \quad y_6 & \quad z_6 \\
x_7 & \quad y_7 & \quad z_7 \\
x_8 & \quad y_8 & \quad z_8 \\
\end{align*}
\]

Note polygons are not represented
Modeling a Cube

- In 3D, declare vertices as (x,y,z) using **point3 v[3]**
- Define **global arrays** for vertices and colors

```c
typedef vec3 point3;
point3 vertices[] = {point3(-1.0,-1.0,-1.0),
                    point3(1.0,-1.0,-1.0),
                    point3(1.0,1.0,-1.0),
                    point3(-1.0,1.0,-1.0),
                    point3(-1.0,-1.0,1.0),
                    point3(1.0,-1.0,1.0),
                    point3(1.0,1.0,1.0),
                    point3(-1.0,1.0,1.0)};

typedef vec3 color3;
color3 colors[] = {color3(0.0,0.0,0.0),
                  color3(1.0,0.0,0.0),
                  color3(1.0,1.0,0.0),
                  color3(0.0,1.0,0.0),
                  color3(0.0,0.0,1.0),
                  color3(1.0,0.0,1.0),
                  color3(1.0,1.0,1.0),
                  color3(0.0,1.0,1.0)};
```
Drawing a triangle from list of indices

Draw a triangle from a list of indices into the array `vertices` and assign a color to each index

```c
void triangle(int a, int b, int c, int d)
{
    vcolors[i] = colors[d];
    position[i] = vertices[a];
    vcolors[i+1] = colors[d]);
    position[i+1] = vertices[b];
    vcolors[i+2] = colors[d];
    position[i+2] = vertices[c];
    i+=3;
}
```

Variables `a`, `b`, `c` are indices into vertex array
Variable `d` is index into color array
Note: Same face, so all three vertices have same color
Normal Vector

- **Normal vector**: Direction each polygon is facing
- Each mesh polygon has a **normal vector**
- Normal vector used in shading
- **Normal vector • light vector** determines shading (Later)
void colorcube( )
{
    quad(0,3,2,1);
    quad(2,3,7,6);
    quad(0,4,7,3);
    quad(1,2,6,5);
    quad(4,5,6,7);
    quad(0,1,5,4);
}

**Note:** vertices ordered *(counterclockwise)*
so that we obtain correct outward facing normals
Old Way for Storing Vertices: Inefficient

- Previously drew cube by its 6 faces using
  - 6 `glBegin`, 6 `glEnd`
  - 6 `glColor`
  - 24 `glVertex`
  - More commands if we use texture and lighting
  - E.g: to draw each face

```c
glBegin(GL_QUAD)
    glVertex(x1, y1, z1);
    glVertex(x2, y2, z2);
    glVertex(x3, y3, z3);
    glVertex(x4, y4, z4);
glEnd();
```
New Way: Vertex Representation and Storage

- We have declare vertex lists, edge lists and arrays
- But OpenGL expects meshes passed to have a specific structure
- We now study that structure....
Vertex Arrays

- **Previously**: OpenGL provided a facility called *vertex arrays* for storing rendering data

- Six types of arrays were supported initially
  - Vertices
  - Colors
  - Color indices
  - Normals
  - Texture coordinates
  - Edge flags

- Now vertex arrays can be used for *any attributes*
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)
Declaring Array of Vertex Attributes

- Consider the following array of vertex attributes

```
<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
<td>r</td>
<td>g</td>
<td>b</td>
<td>s</td>
<td>t</td>
<td>s</td>
<td>t</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

- Position Tex0 Color Tex1

```
0 1 2 3
```

- So we can define attribute positions (per vertex)

```c
#define VERTEX_POS_INDEX 0
#define VERTEX_COLOR_INDEX 1
#define VERTEX_TEXCOORD0_INDEX 2
#define VERTEX_TEXCOORD1_INDEX 3
```
Declaring Array of Vertex Attributes

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

```c
#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

```c
#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

```c
#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

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

```
1. glEnableVertexAttribArray(0);

2. do same for normal, tex0 and tex1
```
References