Advanced Computer Graphics (Spring 2013)
CS 283, Lecture 4: Mesh Data Structures
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To Do
Assignment 1, Due Feb 22.
- Start reading and working on it now. Some parts you can do now. Some parts after next week
Any difficulties (finding partners etc.) with assignment?

Motivation
- A polygon mesh is a collection of triangles
- We want to do operations on these triangles
  - E.g. walk across the mesh for simplification
  - Display for rendering
  - Computational geometry
- Best representations (mesh data structures)?
  - Compactness
  - Generality
  - Simplicity for computations
  - Efficiency

Mesh Data Structures
Desirable Characteristics 1
- Generality – from most general to least
  - Polygon soup
  - Only triangles
  - 2-manifold: ≤ 2 triangles per edge
  - Orientable: consistent CW / CCW winding
  - Closed: no boundary
- Compact storage

Outline
- Independent faces
- Indexed face set
- Adjacency lists
- Winged-edge
- Half-edge

Overview of mesh decimation and simplification
### Independent Faces

Faces list vertex coordinates
- Redundant vertices
- No topology information

#### Face Table

- \( F_0 \): \((x_0, y_0, z_0), (x_1, y_1, z_1), (x_2, y_2, z_2)\)
- \( F_1 \): \((x_3, y_3, z_3), (x_4, y_4, z_4), (x_5, y_5, z_5)\)
- \( F_2 \): \((x_6, y_6, z_6), (x_7, y_7, z_7), (x_8, y_8, z_8)\)

### Indexed Face Set

- Faces list vertex references – “shared vertices”
- Commonly used (e.g. OFF file format itself)
- Augmented versions simple for mesh processing

#### Vertex Table

- \( v_0 \): \((x_0, y_0, z_0)\)
- \( v_1 \): \((x_1, y_1, z_1)\)
- \( v_2 \): \((x_2, y_2, z_2)\)
- \( v_3 \): \((x_3, y_3, z_3)\)
- \( v_4 \): \((x_4, y_4, z_4)\)

#### Face Table

- \( F_0 \): \(0, 1, 2\)
- \( F_1 \): \(1, 4, 2\)
- \( F_2 \): \(1, 3, 4\)

Note CCW ordering

### Efficient Algorithm Design

- Can sometimes design algorithms to compensate for operations not supported by data structures
- Example: per-vertex normals
  - Average normal of faces touching each vertex
  - With indexed face set, vertex \( \rightarrow \) face is \( O(n) \)
  - Naive algorithm for all vertices: \( O(n^2) \)
  - Can you think of an \( O(n) \) algorithm?
- Useful to augment with vertex \( \rightarrow \) face adjacency
  - For all vertices, find adjacent faces as well
  - Can be implemented while simply looping over faces

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Full Adjacency Lists

- Store all vertex, face, and edge adjacencies

**Edge Adjacency Table**
- $e_0: v_0, v_1; F_0, ø; ø, e_2, e_1, ø$
- $e_1: v_1, v_2; F_0, F_1; e_5, e_0, e_2, e_6$

**Face Adjacency Table**
- $F_0: v_0, v_1, v_2; F_1, ø, ø; e_0, e_2, e_0$
- $F_1: v_1, v_4, v_2; ø, F_0, F_2; e_6, e_1, e_5$
- $F_2: v_1, v_3, v_4; ø, F_1, ø; e_4, e_5, e_3$

**Vertex Adjacency Table**
- $v_0: v_1, v_2; F_0; e_0, e_2$
- $v_1: v_3, v_4, v_2, v_0; F_2, F_1, F_0; e_3, e_5, e_1, e_0$

Full adjacency: Issues

- Garland and Heckbert claim they do this
- Easy to find stuff
- Issue is storage
- And updating everything once you do something like an edge collapse for mesh simplification
- I recommend you implement something simpler (like indexed face set plus vertex to face adjacency)

Partial Adjacency Lists

- Store some adjacencies, use to derive others
- Many possibilities...

**Edge Adjacency Table**
- $e_0: v_0, v_1; F_0, ø; ø, e_2, e_1, ø$
- $e_1: v_1, v_2; F_0, F_1; e_5, e_0, e_2, e_6$

**Face Adjacency Table**
- $F_0: v_0, v_1, v_2; F_1, ø, ø; e_0, e_2, e_0$
- $F_1: v_1, v_4, v_2; ø, F_0, F_2; e_6, e_1, e_5$
- $F_2: v_1, v_3, v_4; ø, F_1, ø; e_4, e_5, e_3$

**Vertex Adjacency Table**
- $v_0: v_1, v_2; F_0; e_0, e_2$
- $v_1: v_3, v_4, v_2, v_0; F_2, F_1, F_0; e_3, e_5, e_1, e_0$

Partial Adjacency Lists

- Some combinations only make sense for closed manifolds

**Edge Adjacency Table**
- $e_0: v_0, v_1; F_0, ø; ø, e_2, e_1, ø$
- $e_1: v_1, v_2; F_0, F_1; e_5, e_0, e_2, e_6$

**Face Adjacency Table**
- $F_0: v_0, v_1, v_2; F_1, ø, ø; e_0, e_2, e_0$
- $F_1: v_1, v_4, v_2; ø, F_0, F_2; e_6, e_1, e_5$
- $F_2: v_1, v_3, v_4; ø, F_1, ø; e_4, e_5, e_3$

**Vertex Adjacency Table**
- $v_0: v_1, v_2; F_0; e_0, e_2$
- $v_1: v_3, v_4, v_2, v_0; F_2, F_1, F_0; e_3, e_5, e_1, e_0$

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Overview of mesh decimation and simplification

Winged, Half Edge Representations

- Idea is to associate information with edges
- Compact Storage
- Many operations efficient
- Allow one to walk around mesh
- Usually general for arbitrary polygons (not triangles)
- But implementations can be complex with special cases relative to simple indexed face set++ or partial adjacency table
### Winged Edge

- Most data stored at edges
- Vertices, faces point to one edge each

**Edge Adjacency Table**
- $e_0: v_0, v_1; F_0, ø; e_2, e_1, ø$
- $e_1: v_1, v_2; F_0, F_1; e_5, e_0, e_2, e_6$

**Face Adjacency Table**
- $F_0: v_0, v_1, v_2; F_1, ø, ø; e_0, e_2, e_0$
- $F_1: v_1, v_4, v_2; ø, F_0, F_2; e_6, e_1, e_5$

**Vertex Adjacency Table**
- $v_0: v_1, v_2; F_0; e_0, e_2$
- $v_1: v_3, v_4, v_2, v_0; F_2, F_1, F_0; e_3, e_5, e_1, e_0$

### Half Edge

- Instead of single edge, 2 directed “half edges”
- Makes some operations more efficient
- Walk around face very easily (each face needs only store one pointer)

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*Overview of mesh decimation and simplification*

### Mesh Decimation

- **Triangles**
  - 41,855
  - 27,970
  - 20,922
  - 12,939
  - 8,385
  - 4,766

*Michelangelo's St. Matthew
Original model: ~400M polygons*
**Primitive Operations**

Simplify model a bit at a time by removing a few faces
- Repeated to simplify whole mesh

**Types of operations**
- Vertex cluster
- Vertex remove
- Edge collapse (main operation used in assignment)

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**Vertex Cluster**

- **Method**
  - Merge vertices based on proximity
  - Triangles with repeated vertices can collapse to edges or points
- **Properties**
  - General and robust
  - Can be unattractive if results in topology change

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**Vertex Remove**

- **Method**
  - Remove vertex and adjacent faces
  - Fill hole with new triangles (reduction of 2)
- **Properties**
  - Requires manifold surface, preserves topology
  - Typically more attractive
  - Filling hole well not always easy

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**Edge Collapse**

- **Method**
  - Merge two edge vertices to one
  - Delete degenerate triangles
- **Properties**
  - Special case of vertex cluster
  - Allows smooth transition
  - Can change topology

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**Mesh Decimation/Simplification**

Typical: greedy algorithm
- Measure error of possible "simple" operations (primarily edge collapses)
- Place operations in queue according to error
- Perform operations in queue successively (depending on how much you want to simplify model)
- After each operation, re-evaluate error metrics

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**Geometric Error Metrics**

- **Motivation**
  - Promote accurate 3D shape preservation
  - Preserve screen-space silhouettes and pixel coverage
- **Types**
  - Vertex-Vertex Distance
  - Vertex-Plane Distance
  - Point-Surface Distance
  - Surface-Surface Distance
Vertex-Vertex Distance
- $E = \max(|v_3-v_1|, |v_3-v_2|)$
- Appropriate during topology changes
  - Rossignac and Borrel 93
  - Luebke and Erikson 97
- Loose for topology-preserving collapses

Vertex-Plane Distance
- Store set of planes with each vertex
- Error based on distance from vertex to planes
- When vertices are merged, merge sets
  - Ronfard and Rossignac 96
- Store plane sets, compute max distance
  - Error Quadrics – Garland and Heckbert 96
- Store quadric form, compute sum of squared distances

Point-Surface Distance
- For each original vertex, find closest point on simplified surface
- Compute sum of squared distances

Surface-Surface Distance
- Compute or approximate maximum distance between input and simplified surfaces
  - Tolerance Volumes - Guéziec 96
  - Simplification Envelopes - Cohen/Varshney 96
  - Hausdorff Distance - Klein 96
  - Mapping Distance - Bajaj/Schikore 96, Cohen et al. 97

Geometric Error Observations
- Vertex-vertex and vertex-plane distance
  - Fast
  - Low error in practice, but not guaranteed by metric
- Surface-surface distance
  - Required for guaranteed error bounds

Mesh Simplification
Advanced Considerations
- Type of input mesh?
- Modifies topology?
- Continuous LOD?
- Speed vs. quality?
View-Dependent Simplification

- Simplify dynamically according to viewpoint
  - Visibility
  - Silhouettes
  - Lighting

Appearance Preserving

- 7,809 tris
- 488 tris
- 975 tris
- 1,951 tris
- 3,905 tris

Summary

- Many mesh data structures
  - Compact storage vs ease, efficiency of use
  - How fast and easy are key operations
  
- Mesh simplification
  - Reduce size of mesh in efficient quality-preserving way
  - Based on edge collapses mainly

- Choose appropriate mesh data structure
  - Efficient to update, edge-collapses are local

- Fairly modern ideas (last 15-20 years)
  - Think about some of it yourself, see papers given out
  - We will cover simplification, quadric metrics next week