Adjacency Data Structures

includes material from Justin Legakis

Last Time?

• Simple Transformations
  
  
<table>
<thead>
<tr>
<th>Identity</th>
<th>Translation</th>
<th>Rotation</th>
<th>Isotropic (Uniform) Scaling</th>
<th>Scaling</th>
<th>Reflection</th>
<th>Shear</th>
</tr>
</thead>
</table>

• Classes of Transformations
• Representation
  – homogeneous coordinates
• Composition
  – not commutative
• Orthographic & Perspective Projections

\[
\begin{bmatrix}
  x' \\
  y' \\
  z'
\end{bmatrix} = \begin{bmatrix}
  a & b & c & d \\
  e & f & g & h \\
  i & j & k & l \\
  0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
  x \\
  y \\
  z \\
  1
\end{bmatrix}
\]
Assignment 0: OpenGL Warmup

• Get familiar with:
  – C++ environment
  – OpenGL
  – Transformations
  – simple Vector & Matrix classes
  – CMake

• Have Fun!
• Due ASAP…

Today

• Surface Definitions
• Simple Data Structures
• Fixed Storage Data Structures
• Fixed Computation Data Structures
• Mesh Simplification
Today

- **Surface Definitions**
  - Well-Formed Surfaces
  - Orientable Surfaces
  - Computational Complexity
- **Simple Data Structures**
- **Fixed Storage Data Structures**
- **Fixed Computation Data Structures**
- **Mesh Simplification**

Well-Formed Surfaces

- Components Intersect "Properly"
  - Any pair of Faces are: disjoint, share single Vertex, or share 2 Vertices and the Edge joining them
  - Every edge is incident to exactly 2 vertices
  - Every edge is incident to exactly 2 faces
- Local Topology is "Proper"
  - Neighborhood of a vertex is homeomorphic to a disk (permits stretching and bending, but not tearing)
  - Also called a 2-manifold
  - If boundaries are allowed, points on the boundary are homeomorphic to a half-disk, called a "manifold with boundaries"
- Global Topology is "Proper"
  - Connected, Closed, & Bounded
Orientable Surfaces?

Closed Surfaces and Refraction

- Original Teapot model is not "watertight":
  intersecting surfaces at spout & handle, no bottom,
  a hole at the spout tip, a gap between lid & base
- Requires repair before ray tracing with refraction
Computational Complexity

- Adjacent Element Access Time
  - linear, constant time average case, or constant time?
  - requires loops/recursion/if?
- Memory
  - variable size arrays or constant size?
- Maintenance
  - ease of editing
  - ensuring consistency

Questions?
Today

• Surface Definitions
• **Simple Data Structures**
  – List of Polygons
  – List of Edges
  – List of Unique Vertices & Indexed Faces:
  – Simple Adjacency Data Structure
• Fixed Storage Data Structures
• Fixed Computation Data Structures
• Mesh Simplification

**List of Polygons:**

(3, -2, 5), (3, 6, 2), (-6, 2, 4)
(2, 2, 4), (0, -1, -2), (9, 4, 0), (4, 2, 9)
(1, 2, -2), (8, 8, 7), (-4, -5, 1)
(-8, 2, 7), (-2, 3, 9), (1, 2, -7)
List of Edges:

(3,6,2), (-6,2,4)
(2,2,4), (0,-1,-2)
(9,4,0), (4,2,9)
(8,8,7), (-4,-5,1)
(-8,2,7), (1,2,-7)
(3,0,-3), (-7,4,-3)
(9,4,0), (4,2,9)
(3,6,2), (-6,2,4)
(-3,0,-4), (7,-3,-4)

List of Unique Vertices & Indexed Faces:

Vertices:  
(-1, -1, -1)  
(-1, -1, 1)  
(-1, 1, -1)  
(-1, 1, 1)  
(1, -1, -1)  
(1, -1, 1)  
(1, 1, -1)  
(1, 1, 1)  

Faces:  
1 2 4 3  
5 7 8 6  
1 5 6 2  
3 4 8 7  
1 3 7 5  
2 6 8 4
Problems with Simple Data Structures

- No Adjacency Information
- Linear-time Searches

- Adjacency is implicit for structured meshes, but what do we do for unstructured meshes?

Mesh Data

- So, in addition to:
  - Geometric Information (position)
  - Attribute Information (color, texture, temperature, population density, etc.)

- Let’s store:
  - Topological Information (adjacency, connectivity)
Simple Adjacency

- Each element (vertex, edge, and face) has a list of pointers to all incident elements
- Queries depend only on local complexity of mesh
- Data structures do not have fixed size
- Slow! Big! Too much work to maintain!

Questions?
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- Surface Definitions
- Simple Data Structures
- **Fixed Storage Data Structures**
  - Winged Edge (Baumgart, 1975)
- Fixed Computation Data Structures
- Mesh Simplification

**Winged Edge (Baumgart, 1975)**

- Each edge stores pointers to 4 Adjacent Edges, 2 Face & 2 Vertex neighbors
- Vertices and Faces have a single pointer to one incident Edge
- Data Structure Size? **Fixed**
- How do we gather all faces surrounding one vertex? **Messy**, because there is no consistent way to order pointers
Today

- Surface Definitions
- Simple Data Structures
- Fixed Storage Data Structures
- Fixed Computation Data Structures
  - HalfEdge (Eastman, 1982)
  - SplitEdge
  - Corner
  - QuadEdge (Guibas and Stolfi, 1985)
  - FacetEdge (Dobkin and Laszlo, 1987)

HalfEdge (Eastman, 1982)

- Every edge is represented by two directed HalfEdge structures
- Each HalfEdge stores:
  - vertex at end of directed edge
  - symmetric half edge
  - face to left of edge
  - next points to the HalfEdge counterclockwise around face on left
- Orientation is essential, but can be done consistently!
HalfEdge (Eastman, 1982)

• Starting at a half edge, how do we find:
  
  the other vertex of the edge?
  the other face of the edge?
  the clockwise edge around the face at the left?
  all the edges surrounding the face at the left?
  all the faces surrounding the vertex?

HalfEdge (Eastman, 1982)

• Loop around a Face:

  HalfEdgeMesh::FaceLoop(HalfEdge *HE) {
    HalfEdge *loop = HE;
    do {
      loop = loop->Next;
    } while (loop != HE);
  }

• Loop around a Vertex:

  HalfEdgeMesh::VertexLoop(HalfEdge *HE) {
    HalfEdge *loop = HE;
    do {
      loop = loop->Next->Sym;
    } while (loop != HE);
  }
HalfEdge (Eastman, 1982)

- Data Structure Size?
  Fixed
- Data:
  - geometric information stored at Vertices
  - attribute information in Vertices, HalfEdges, and/or Faces
  - topological information in HalfEdges only!
- Orientable surfaces only (no Mobius Strips!)
- Local consistency everywhere implies global consistency
- Time Complexity?
  linear in the amount of information gathered

SplitEdge Data Structure:

- HalfEdge and SplitEdge are dual structures!

  \[
  \text{SplitEdgeMesh::FaceLoop()} = \text{HalfEdgeMesh::VertexLoop()}
  \]

  \[
  \text{SplitEdgeMesh::VertexLoop()} = \text{HalfEdgeMesh::FaceLoop()}
  \]
Corner Data Structure:

- The Corner data structure is its own dual!

Questions?
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QuadEdge (Guibas and Stolfi, 1985)

- Consider the Mesh and its Dual simultaneously
  - Vertices and Faces switch roles, we just re-label them
  - Edges remain Edges
- Now there are eight ways to look at each edge
  - Four ways to look at primal edge
  - Four ways to look at dual edge
QuadEdge (Guibas and Stolfi, 1985)

- Relations Between Edges: Edge Algebra
- Elements in Edge Algebra:
  - Each of 8 ways to look at each edge

- Operators in Edge Algebra:
  - Rot: Bug rotates 90 degrees to its left (switches to/from dual graph)
  - Sym: Bug turns around 180 degrees
  - Flip: Bug flips up-side down
  - Onext: Bug rotates CCW to next edge with same origin (either Vertex or Face)

QuadEdge (Guibas and Stolfi, 1985)

- Some Properties of Flip, Sym, Rot, and Onext:
  - $e \text{ Rot}^4 = e$
  - $e \text{ Rot}^2 \neq e$
  - $e \text{ Flip}^2 = e$
  - $e \text{ Flip} \text{ Rot} \text{ Flip} \text{ Rot} = e$
  - $e \text{ Rot} \text{ Flip} \text{ Rot} \text{ Flip} = e$
  - $e \text{ Rot} \text{ Onext} \text{ Rot} \text{ Onext} = e$
  - $e \text{ Flip} \text{ Onext} \text{ Flip} \text{ Onext} = e$
  - $e \text{ Flip}^{-1} = e \text{ Flip}$
  - $e \text{ Sym} = e \text{ Rot}^2$
  - $e \text{ Rot}^{-1} = e \text{ Rot}^3$
  - $e \text{ Rot}^{-1} = e \text{ Flip} \text{ Rot} \text{ Flip}$
  - $e \text{ Onext}^{-1} = e \text{ Rot} \text{ Onext} \text{ Rot}$
  - $e \text{ Onext}^{-1} = e \text{ Flip} \text{ Onext} \text{ Flip}$
QuadEdge (Guibas and Stolfi, 1985)

- Other Useful Definitions:
  - \( e \text{ Lnext} = e \text{ Rot}^{-1} \text{ Onext Rot} \)
  - \( e \text{ Rnext} = e \text{ Rot} \text{ Onext Rot}^{-1} \)
  - \( e \text{ Dnext} = e \text{ Sym} \text{ Onext Sym}^{-1} \)
  - \( e \text{ Oprev} = e \text{ Onext}^{-1} = e \text{ Rot} \text{ Onext Rot} \)
  - \( e \text{ Lprev} = e \text{ Lnext}^{-1} = e \text{ Onext Sym} \)
  - \( e \text{ Rprev} = e \text{ Rnext}^{-1} = e \text{ Sym Onext} \)
  - \( e \text{ Dprev} = e \text{ Dnext}^{-1} = e \text{ Rot}^{-1} \text{ Onext Rot} \)

- All of these functions can be expressed as a constant number of Rot, Sym, Flip, and Onext operations independent of the local topology and the global size and complexity of the mesh.

FacetEdge (Dobkin and Laszlo, 1987)

- QuadEdge (2D, surface) → FacetEdge (3D, volume)
- Faces → Polyhedra / Cells
- Edge → Polygon & Edge pair
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Hugues Hoppe “Progressive Meshes” SIGGRAPH 1996
Perform a sequence of 3 edge collapses, one-at-a-time
Always collapse the shortest edge that does not result in a zero area or “flipped”/upside-down triangle
Replacement vertex should be at the midpoint of the edge

Progressive Meshes

- Mesh Simplification
  - vertex split / edge collapse
  - geometry & discrete/scalar attributes
  - priority queue
- Level of Detail
  - geomorphs
- Progressive Transmission
- Mesh Compression
- Selective Refinement
  - view dependent
Selective Refinement

Figure 10: Selective refinement of a terrain mesh taking into account view frustum, silhouette regions, and projected screen size of faces (7,438 faces).

Preserving Discontinuity Curves

Figure 12: Approximations of a mesh $\hat{M}$ using (b–c) the PM representation, and (d–f) the MRA scheme of Eck et al. [7]. As demonstrated, MRA cannot recover $\hat{M}$ exactly, cannot deal effectively with surface creases, and produces approximating meshes of inferior quality.
Other Simplification Strategies

• Remove a vertex & surrounding triangles, re-triangulate the hole

• Merge Nearby Vertices
  – will likely change the topology…


When to Preserve Topology?

Figure 3: On the left is a regular grid of 100 closely spaced cubes. In the middle, an approximation built using only edge contractions demonstrates unacceptable fragmentation. On the right, the result of using more general pair contractions to achieve aggregation is an approximation much closer to the original.

Quadric Error Simplification

- Contract (merge) vertices $v_i$ and $v_j$ if:
  - $(v_i, v_j)$ is an edge, or
  - $\|v_i - v_j\| < t$, where $t$ is a threshold parameter
- Track cumulative error by summing 4x4 quadric error matrices after each operation:

$$\Delta(v) = \sum_{p \in plane(v)} (v^T p)(p^T v)$$
$$= \sum_{p \in plane(v)} v^T (pp^T)v$$
$$= v^T \left( \sum_{p \in plane(v)} K_p \right) v$$

$K_p = pp^T = \begin{bmatrix} a^2 & ab & ac & ad & \cdots \\ ab & b^2 & bc & bd & \cdots \\ ac & bc & c^2 & cd & \cdots \\ ad & bd & cd & d^2 & \cdots \end{bmatrix}$


Judging Element Quality

- How “equilateral” are the elements?
- For Triangles?
  - Ratio of shortest to longest edge
  - Ratio of area to perimeter^2
  - Smallest angle
  - Ratio of area to area of smallest circumscribed circle
- For Tetrahedra?
  - Ratio of volume^2 to surface area^3
  - Smallest solid angle
  - Ratio of volume to volume of smallest circumscribed sphere
Reading for Tuesday (option A)

• "Teddy: A Sketching Interface for 3D Freeform Design", Igarashi et al., SIGGRAPH 1999

• How do we represent objects that don’t have flat polygonal faces & sharp corners? What are the right tools to design/construct digital models of blobby, round, or soft things? What makes a user interface intuitive, quick, and easy-to-use for beginners?

Reading for Tuesday (option B)

• "Geometry Images", Gu, Gortler, & Hoppe, SIGGRAPH 2002

• Can we leverage existing image formats and image compression methods to store geometry? How do we take a complex 3D shape an unroll/flatten/stretch it to a square image? File size? Quality?