Meshes and Manifolds

Computer Graphics
CMU 15-462/15-662
Last time: overview of geometry

- Many types of geometry in nature
- Demand sophisticated representations
- Two major categories:
  - IMPLICIT - “tests” if a point is in shape
  - EXPLICIT - directly “lists” points
- Lots of representations for both
- Today:
  - what is a surface, anyway?
  - nuts & bolts of polygon meshes
  - geometry processing / resampling
Manifold Assumption

- Today we’re going to introduce the idea of manifold geometry
- Can be hard to understand motivation at first!
- So first, let’s revisit a more familiar example...
Bitmap Images, Revisited

To encode images, we used a regular grid of pixels:
But images are not fundamentally made of little squares:

Gōyō Hashiguchi, *Kamisuki* (ca 1920)
So why did we choose a square grid?

...rather than dozens of possible alternatives?
Regular grids make life easy

- One reason: SIMPLICITY / EFFICIENCY
  - E.g., always have four neighbors
  - Easy to index, easy to filter...
  - Storage is just a list of numbers

- Another reason: GENERALITY
  - Can encode basically any image

- Are regular grids always the best choice for bitmap images?
  - No! E.g., suffer from anisotropy, don’t capture edges, ...
  - But more often than not are a pretty good choice

- Will see a similar story with geometry...
So, how should we encode surfaces?
Smooth Surfaces

- Intuitively, a **surface** is the boundary or “shell” of an object
  (Think about the candy shell, not the chocolate.)
- Surfaces are *manifold*:
  - If you zoom in far enough, can draw a regular coordinate grid
  - E.g., the Earth from space vs. from the ground
Isn’t every shape manifold?

- No, for instance:

Can’t draw ordinary 2D grid at center, no matter how close we get.
Examples—Manifold vs. Nonmanifold

Which of these shapes are manifold?
A manifold polygon mesh has fans, not fins

- For polygonal surfaces just two easy conditions to check:
  1. Every edge is contained in only two polygons (no “fins”)
  2. The polygons containing each vertex make a single “fan”
What about boundary?

- The boundary is where the surface “ends.”
- E.g., waist & ankles on a pair of pants.
- Locally, looks like a *half* disk
- Globally, each boundary forms a loop

Polygon mesh:
- one polygon per boundary edge
- boundary vertex looks like “pacman”
Ok, but why is the manifold assumption *useful*?
Keep it Simple!

- Same motivation as for images:
  - make some assumptions about our geometry to keep data structures/algorithms simple and efficient
  - in *many common cases*, doesn’t fundamentally limit what we can do with geometry

<table>
<thead>
<tr>
<th></th>
<th>(i, j-1)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(i-1, j)</td>
<td>(i, j)</td>
<td>(i+1, j)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(i, j+1)</td>
</tr>
</tbody>
</table>

![Diagram](image-url)
How do we actually encode all this data?
Warm up: storing numbers

- Q: What data structures can we use to store a list of numbers?
  - One idea: use an array (constant time lookup, coherent access)

| 1.7 | 2.9 | 0.3 | 7.5 | 9.2 | 4.8 | 6.0 | 0.1 |

- Alternative: use a linked list (linear lookup, incoherent access)

- Q: Why bother with the linked list?
  - A: For one, we can easily insert numbers wherever we like...
Polygon Soup

- Most basic idea:
  - For each triangle, just store three coordinates
  - No other information about connectivity
  - Not much different from point cloud! (“Triangle cloud?”)

- Pros:
  - Really stupidly simple

- Cons:
  - Redundant storage
  - Hard to do much beyond simply drawing the mesh on screen
  - Need spatial data structures (later) to find neighbors
Adjacency List (Array-like)

- Store triples of coordinates \((x,y,z)\), tuples of indices
- E.g., tetrahedron:
  
  \[
  \begin{array}{ccc}
  VERTICES & \text{POLYGONS} \\
  i & j & k \\
  \hline
  0: & -1 & -1 & -1 & 0 & 2 & 1 \\
  1: & 1 & -1 & 1 & 0 & 3 & 2 \\
  2: & 1 & 1 & -1 & 3 & 0 & 1 \\
  3: & -1 & 1 & 1 & 3 & 1 & 2 \\
  \end{array}
  \]

- Q: How do we find all the polygons touching vertex 2?
- Ok, now consider a more complicated mesh:

Very expensive to find the neighboring polygons! (What’s the cost?)
Incidence Matrices

- If we want to know who our neighbors are, why not just store a list of neighbors?
- Can encode all neighbor information via *incidence matrices*
- E.g., tetrahedron:

<table>
<thead>
<tr>
<th>VERTEX ↔ EDGE</th>
<th>EDGE ↔ FACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>v0  v1  v2  v3</td>
<td>e0  e1  e2  e3  e4  e5</td>
</tr>
<tr>
<td>v0  1  1  0  0</td>
<td>e0  1  0  0  1  0  1</td>
</tr>
<tr>
<td>v1  0  1  1  0</td>
<td>e1  0  1  0  0  1  1</td>
</tr>
<tr>
<td>v2  1  0  1  0</td>
<td>e2  1  1  1  0  0  0</td>
</tr>
<tr>
<td>v3  1  0  0  1</td>
<td>e3  0  0  1  1  1  0</td>
</tr>
<tr>
<td>e0  1  1  0  0</td>
<td>e4  0  0  1  1</td>
</tr>
<tr>
<td>e1  0  1  1  0</td>
<td>e5  0  1  0  1</td>
</tr>
<tr>
<td>e2  1  0  1  0</td>
<td></td>
</tr>
<tr>
<td>e3  1  0  0  1</td>
<td></td>
</tr>
<tr>
<td>e4  0  0  1  1</td>
<td></td>
</tr>
<tr>
<td>e5  0  1  0  1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 1 means “touches”; 0 means “does not touch”
- Instead of storing lots of 0’s, use *sparse matrices*
- Still large storage cost, but finding neighbors is now $O(1)$
- Hard to change connectivity, since we used fixed indices
- Bonus feature: mesh does not have to be manifold
Aside: Sparse Matrix Data Structures

- Ok, but how do we actually store a “sparse matrix”?
- Lots of possible data structures:
  - **Associative array from** (row, column) **to value**
    - easy to lookup/set entries, fast (e.g., hash table)
    - harder to do matrix operations (e.g., multiplication)
  - **Array of linked lists** (one per row)
    - conceptually simple
    - slow access time, incoherent memory access
  - **Compressed column format**—pack entries in list
    - hard to add/modify entries
    - fast for actual matrix operations
- In practice: often build up entries using an “easier” data structure, convert to compressed format for computation
Halfedge Data Structure (Linked-list-like)

- Store *some* information about neighbors
- Don’t need an exhaustive list; just a few key pointers
- Key idea: two halfedges act as “glue” between mesh elements:

```c
struct Halfedge
{
    Halfedge* twin;
    Halfedge* next;
    Vertex* vertex;
    Edge* edge;
    Face* face;
};
```

```c
struct Vertex
{
    Halfedge* halfedge;
};
```

```c
struct Edge
{
    Halfedge* halfedge;
};
```

```c
struct Face
{
    Halfedge* halfedge;
};
```

- Each vertex, edge face points to just *one* of its halfedges.
**Halfedge makes mesh traversal easy**

- Use “twin” and “next” pointers to move around mesh
- Use “vertex”, “edge”, and “face” pointers to grab element
- Example: visit all vertices of a face:
  ```c
  Halfedge* h = f->halfedge;
  do {
    h = h->next;
    // do something w/ h->vertex
  } while( h != f->halfedge );
  ```
- Example: visit all neighbors of a vertex:
  ```c
  Halfedge* h = v->halfedge;
  do {
    h = h->twin->next;
  } while( h != v->halfedge );
  ```
- Note: only makes sense if mesh is manifold!
Halfedge connectivity is *always* manifold

- Consider simplified halfedge data structure
- Require only "common-sense" conditions

```c
struct Halfedge {
    Halfedge *next, *twin;
};
```

- Keep following `next`, and you’ll get faces.
- Keep following `twin` and you’ll get edges.
- Keep following `next->twin` and you’ll get vertices.

Q: Why, therefore, is it impossible to encode the red figures?
Connectivity vs. Geometry

- Recall manifold conditions (fans not fins):
  - every edge contained in two faces
  - every vertex contained in one fan

- These conditions say nothing about vertex positions! Just connectivity

- Hence, can have perfectly good (manifold) connectivity, even if geometry is awful

- In fact, sometimes you can have perfectly good manifold connectivity for which any vertex positions give “bad” geometry!

- Can lead to confusion when debugging: mesh looks “bad”, even though connectivity is fine
Halfedge meshes are easy to edit

- Remember key feature of linked list: insert/delete elements
- Same story with halfedge mesh ("linked list on steroids")
- E.g., for triangle meshes, several atomic operations:

  ![Diagram](image_url)

  - flip
  - split
  - collapse

- Must be careful to preserve manifoldness!
Edge Flip (Triangles)

- Triangles (a,b,c), (b,d,c) become (a,d,c), (a,b,d):

```
   a---b
   |   |
   v   v
   c---d
```

- Long list of pointer reassignments (edge->halfedge = ...)
- However, no elements created/destroyed.
- Q: What happens if we flip twice?
- Challenge: can you implement edge flip such that pointers are unchanged after two flips?
Edge Split (Triangles)

- Insert midpoint $m$ of edge $(c,b)$, connect to get four triangles:

This time, have to *add* new elements.
- Lots of pointer reassignments.
- Q: Can we “reverse” this operation?
Edge Collapse (Triangles)

- Replace edge \((b,c)\) with a single vertex \(m\):

Now have to **delete** elements.

Still lots of pointer assignments!

Q: How would we implement this with an adjacency list?

Any other good way to do it? (E.g., different data structure?)
Alternatives to Halfedge

- Many very similar data structures:
  - winged edge
  - corner table
  - quadedge
  - ...

- Each stores local neighborhood information

- Similar tradeoffs relative to simple polygon list:
  - **CONS**: additional storage, incoherent memory access
  - **PROS**: better access time for individual elements, intuitive traversal of local neighborhoods

- With some thought*, can design halfedge-type data structures with coherent data storage, support for non manifold connectivity, etc.

*see for instance http://geometry-central.net/
## Comparison of Polygon Mesh Data Structures

<table>
<thead>
<tr>
<th></th>
<th>Adjacency List</th>
<th>Incidence Matrices</th>
<th>Halfedge Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant-time neighborhood access?</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>easy to add/remove mesh elements?</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>nonmanifold geometry?</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>

**Conclusion:** pick the right data structure for the job!
Ok, but what can we actually *do* with our fancy new data structures?
Subdivision Modeling
Subdivision Modeling

- Common modeling paradigm in modern 3D tools:
  - Coarse “control cage”
  - Perform local operations to control/edit shape
  - Global subdivision process determines final surface
Subdivision Modeling—Local Operations

For general polygon meshes, we can dream up lots of local mesh operations that might be useful for modeling:

...and many, many more!
Next Time: Digital Geometry Processing

- Extend traditional digital signal processing (audio, video, etc.) to deal with *geometric* signals:
  - upsampling / downsampling / resampling / filtering ... 
  - aliasing (reconstructed surface gives “false impression”)