Lecture 8: Geometric Queries

Computer Graphics: Rendering, Geometry, and Image Manipulation
Stanford CS248A, Winter 2023
Last time

How to perform a number of basic mesh processing operations

- Subdivision (upsampling)

- Mesh simplification (downsampling)

- Mesh resampling
Geometric queries — motivation

Intersecting rays and triangles (ray tracing)

Intersecting triangles (collisions)

Closest point on surface queries
Closest point queries

Given a point, in space (e.g., a new sample point), how do we find the closest point on a given surface?

- Q: Does implicit/explicit representation make this easier?
- Q: Does our half-edge data structure help?
- Q: What’s the cost of the naïve algorithm?
- Q: How do we find the distance to a single triangle anyway?
Many types of geometric queries

- Plenty of other things we might like to know:
  - Do two triangles intersect?
  - Are we inside or outside an object?
  - Does one object contain another?
  - ...

- Data structures we’ve seen so far not really designed for this...
- Need some new ideas!
- TODAY: come up with simple (aka: slow) algorithms
- NEXT TIME: intelligent ways to accelerate geometric queries
Warm up: closest point on point

Given a query point \((p_x, p_y)\), how do we find the closest point on the point \((a_x, a_y)\)?

Bonus question: what’s the distance?
Slightly harder: closest point on line

- Now suppose I have a line $N^T x = c$, where $N$ is the unit normal.
  - Remember: a line is all points $x$ such that $N^T x = c$

- How do I find the point on the line closest to my query point $p$?
Review: matrix form of a line (and a plane)

Line is defined by:
- Its normal: \( N \)
- A point \( x_0 \) on the line

\[
N \cdot (x - x_0) = 0
\]

\[
N^T(x - x_0) = 0
\]

\[
N^T x = N^T x_0
\]

\[
N^T x = c
\]

The line (in 2D) is all points \( x \), where \( x - x_0 \) is orthogonal to \( N \).
(N, \( x \), \( x_0 \) on this slide are 2-vectors)

(And a plane (in 3D) is all points \( x \) where \( x - x_0 \) is orthogonal to \( N \).)
(N, \( x \), \( x_0 \) are 3-vectors)
Closest point on line

- Now suppose I have a line $\mathbf{N}^T \mathbf{x} = c$, where $\mathbf{N}$ is the unit normal.
  - Remember: a line is all points $\mathbf{x}$ such that $\mathbf{N}^T \mathbf{x} = c$
- How do I find the point on line that is closest to my query point $\mathbf{p}$?

Many ways to do it:

$$\mathbf{N}^T(\mathbf{p} + t\mathbf{N}) = c$$

$$\iff \mathbf{N}^T \mathbf{p} + t\mathbf{N}^T \mathbf{N} = c$$

$$\iff t = c - \mathbf{N}^T \mathbf{p}$$

$$\Rightarrow \mathbf{p} + t\mathbf{N} = \mathbf{p} + (c - \mathbf{N}^T \mathbf{p})\mathbf{N}$$
Harder: closest point on line segment

- Two cases: endpoint or interior

- Already have basic components:
  - point-to-point
  - point-to-line

- Algorithm?
  - find closest point on line
  - check if it is between endpoints
  - if not, take closest endpoint

- How do we know if it’s between endpoints?
  - write closest point on line as $a + t(b-a)$
  - if $t$ is between 0 and 1, it’s inside the segment!
Even harder: closest point on triangle in 2D

- What are all the possibilities for the closest point?
- Almost just minimum distance to three line segments:

Q: What about a point inside the triangle?
Closest point on triangle in 3D

- Not so different from 2D case
- Algorithm:
  - Project point onto plane of triangle
  - Use three half-plane tests to classify point (vs. half plane)
  - If inside the triangle, we’re done!
  - Otherwise, find closest point on associated vertex or edge

By the way, how do we find closest point on plane?
- Same expression as closest point on a line! \[ p + (c - N^TP)p \]
Closest point on triangle mesh in 3D?

- Conceptually easy:
  - loop over all triangles
  - compute closest point to current triangle
  - keep globally closest point

- Q: What’s the cost?

- What if we have billions of faces?

- NEXT TIME: Better data structures!
Closest point to *implicit* surface?

- If we change our representation of geometry, algorithms can change completely
- E.g., how might we compute the closest point on an implicit surface described via its distance function?
- One idea:
  - start at the query point
  - compute gradient of distance (using, e.g., finite differences)
  - take a little step (decrease distance)
  - repeat until we’re at the surface (zero distance)
Different query: ray-mesh intersection

- A “ray” is an oriented line starting at a point
- Think about a ray of light traveling from the sun
- Want to know where a ray pierces a surface
  - Notice: this is a different query than finding the closest point on surface from ray’s origin.

- Applications?
  - GEOMETRY: inside-outside test
  - RENDERING: visibility, ray tracing
  - ANIMATION: collision detection

- Ray might pierce surface in many places!
Ray equation

Can express ray as...

\[ r(t) = o + td \]

- **origin**
- **unit direction**
- point along ray
- Position along ray (some students think “time”)

Stanford CS248A, Winter 2023
Intersecting a ray with an implicit surface

- Recall implicit surfaces: all points \( x \) such that \( f(x) = 0 \)
- Q: How do we find points where a ray pierces this surface?
- Well, we know all points along the ray: \( r(t) = o + td \)
- Idea: replace “\( x \)” with “\( r(t) \)” in 1st equation, and solve for \( t \)
- Example: unit sphere

\[
 f(x) = |x|^2 - 1 \\
 \Rightarrow f(r(t)) = |o + td|^2 - 1 \\
 |d|^2 t^2 + 2(o \cdot d) t + |o|^2 - 1 = 0 \\
 a t^2 + b t + c = 0
\]

Note: \( |d|^2 = 1 \) since \( d \) is a unit vector

\[
 t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]

Why two solutions?

quadratic formula:
Ray-plane intersection

- Suppose we have a plane $N^T x = c$
  - $N$ - unit normal
  - $c$ - offset
- How do we find intersection with ray $r(t) = o + td$?

- Key idea: again, replace the point $x$ with the ray equation $t$:
  $$N^T r(t) = c$$

- Now solve for $t$:
  $$N^T (o + td) = c \quad \Rightarrow t = \frac{c - N^T o}{N^T d}$$

- And plug $t$ back into ray equation:
  $$r(t) = o + \frac{c - N^T o}{N^T d} d$$
Ray-triangle intersection

- Triangle is in a plane...
- Algorithm:
  - Compute ray-plane intersection
  - Q: What do we do now?
Barycentric coordinates (as ratio of areas)

Barycentric coords are *signed* areas:

\[
\alpha = \frac{A_A}{A} \\
\beta = \frac{A_B}{A} \\
\gamma = \frac{A_C}{A}
\]

Why must coordinates sum to one? Why must coordinates be between 0 and 1?

Useful: Heron’s formula:

\[
A_C = \frac{1}{2} (\mathbf{b} - \mathbf{a}) \times (\mathbf{x} - \mathbf{a})
\]
Ray-triangle intersection

Algorithm:
- Compute ray-plane intersection
- Compute barycentric coordinates of hit point
- If barycentric coordinates are all positive, point is in triangle

Many different techniques if you care about efficiency
Ray-triangle intersection (another way)

- Parameterize triangle with vertices $\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2$ using barycentric coordinates *

  \[
  f(u, v) = (1 - u - v)\mathbf{p}_0 + u\mathbf{p}_1 + v\mathbf{p}_2
  \]

- Can think of a triangle as an affine map of the unit triangle

* I'm writing $u,v$ instead of beta, gamma to make explicit representation of triangle very clear.
Another way: ray-triangle intersection

Plug parametric ray equation directly into equation for points on triangle:

\[ p_0 + u(p_1 - p_0) + v(p_2 - p_0) = o + td \]

Solve for \( u, v, t \):

\[
\begin{bmatrix}
  p_1 - p_0 & p_2 - p_0 & -d
\end{bmatrix}
\begin{bmatrix}
  u \\
  v \\
  t
\end{bmatrix} = o - p_0
\]

\( M^{-1} \) transforms triangle back to unit triangle in \( u,v \) plane, and transforms ray’s direction to be orthogonal to plane.

It’s a point in 2D triangle test now!
One more query: mesh-mesh intersection

- GEOMETRY: How do we know if a mesh intersects itself?
- ANIMATION: How do we know if a collision occurred?
Warm up: point-point intersection

- Q: How do we know if p intersects a?
- A: ...check if they’re the same point!
Slightly harder: point-line intersection

- Q: How do we know if a point intersects a given line?
- A: ...plug it into the line equation!
Line-line intersection

- Two lines: \( ax=b \) and \( cx=d \)
- Q: How do we find the intersection?
- A: See if there is a simultaneous solution
- Leads to linear system:

\[
\begin{bmatrix}
  a_1 & a_2 \\
  c_1 & c_2 \\
\end{bmatrix}
\begin{bmatrix}
  x_1 \\
  x_2 \\
\end{bmatrix}
= 
\begin{bmatrix}
  b \\
  d \\
\end{bmatrix}
\]
Degenerate line-line intersection?

- What if lines are almost parallel?
- Small change in normal can lead to big change in intersection!
- Instability very common, very important with geometric predicates. Demands special care (e.g., analysis of matrix).

See for example Shewchuk, “Adaptive Precision Floating-Point Arithmetic and Fast Robust Geometric Predicates”
Triangle-triangle intersection?

- Lots of ways to do it
- Basic idea:
  - Q: Any ideas?
  - One way: reduce to edge-triangle intersection
  - Check if each line passes through plane (ray-triangle)
  - Then do interval test
- What if triangle is moving?
  - Important case for animation
  - Can think of triangles as prisms in time
  - Turns dynamic problem (in nD + time) into purely geometric problem in (n+1)-dimensions
Ray-scene intersection

Given a scene defined by a set of $N$ primitives and a ray $r$, find the closest point of intersection of $r$ with the scene

$t_{\text{closest}} = \infty$
for each primitive p in scene:
\[ t = p.\text{intersect}(r) \]
if $t \geq 0$ && $t < t_{\text{closest}}$:
\[ t_{\text{closest}} = t \]

// closest hit is:
// $r.o + t_{\text{closest}} \times r.d$

(Assume $p.\text{intersect}(r)$ returns value of $t$ corresponding to the point of intersection with ray $r$)

Complexity? $O(N)$

Can we do better? Of course… but you’ll have to wait until next class
Rendering via ray casting:
(one common use of ray-scene intersection tests)
Rasterization and ray casting are two algorithms for solving the same problem: determining “visibility from a camera”
Recall triangle visibility:

Question 1: what samples does the triangle overlap? ("coverage")

Question 2: what triangle is closest to the camera in each sample? ("occlusion")
The visibility problem

- What scene geometry is visible at each screen sample?
  - What scene geometry *projects* onto screen sample points? (coverage)
  - Which geometry is visible from the camera at each sample? (occlusion)
Basic rasterization algorithm

Sample = 2D point
Coverage: 2D triangle/sample tests (does projected triangle cover 2D sample point)
Occlusion: depth buffer

initialize z_closest[] to INFINITY  // store closest-surface-so-far for all samples
initialize color[]  // store scene color for all samples
for each triangle t in scene:  // loop 1: over triangles
    t_proj = project_triangle(t)
    for each 2D sample s in frame buffer:  // loop 2: over visibility samples
        if (t_proj covers s)
            compute color of triangle at sample
            if (depth of t at s is closer than z_closest[s])
                update z_closest[s] and color[s]

“Given a triangle, find the samples it covers”
(finding the samples is relatively easy since they are distributed uniformly on screen)

More efficient hierarchical rasterization:
For each TILE of image
    If triangle overlaps tile, check all samples in tile
The visibility problem (described differently)

- In terms of casting rays from the camera:
  - Is a scene primitive hit by a ray originating from a point on the virtual sensor and traveling through the aperture of the pinhole camera? (coverage)
  - What primitive is the first hit along that ray? (occlusion)
Basic ray casting algorithm

Sample = a ray in 3D

Coverage: 3D ray-triangle intersection tests (does ray “hit” triangle)

Occlusion: closest intersection along ray

initialize color[] // store scene color for all samples

for each sample s in frame buffer: // loop 1: over visibility samples (rays)
    r = ray from s on sensor through pinhole aperture
    r.min_t = INFINITY // only store closest-so-far for current ray
    r.tri = NULL;

    for each triangle tri in scene: // loop 2: over triangles
        if (intersects(r, tri)) {
            // 3D ray-triangle intersection test
            if (intersection distance along ray is closer than r.min_t)
                update r.min_t and r.tri = tri;
        }
    
    color[s] = compute surface color of triangle r.tri at hit point

Compared to rasterization approach: just a reordering of the loops!

“Given a ray, find the closest triangle it hits.”
Basic rasterization vs. ray casting

■ Rasterization:
  - Proceeds in triangle order (for all triangles)
  - Store entire depth buffer (requires access to 2D array of fixed size)
  - Do not have to store entire scene geometry in memory
    - Naturally supports unbounded size scenes

■ Ray casting:
  - Proceeds in screen sample order (for all rays)
    - Do not have to store closest depth so far for the entire screen (just the current ray)
    - This is the natural order for rendering transparent surfaces (process surfaces in the order they are encountered along the ray: front-to-back)
  - Must store entire scene geometry for fast access
In other words...

- Rasterization is an efficient implementation of ray casting where:
  - Ray-scene intersection is computed for a batch of rays
  - All rays in the batch originate from the same origin
  - Rays are distributed uniformly in the plane of projection
  
  (Note: not uniform distribution in angle... angle between rays is smaller away from the view direction)
Generality of ray-scene queries

What object is visible to the camera?
What light sources are visible from a point on a surface (is a surface in shadow?)
What reflection is visible on a surface?

In contrast, rasterization is a highly-specialized solution for computing visibility for a set of uniformly distributed rays originating from the same point (most often: the camera)
Shadows

Image credit: Grand Theft Auto V
How to compute if a surface point is in shadow?

Assume you have an algorithm for ray-scene intersection…
A simple shadow computation algorithm

- Trace ray from point $P$ to location $L_i$ of light source
- If ray hits scene object before reaching light source... then $P$ is in shadow
Direct illumination + reflection + transparency

Image credit: Henrik Wann Jensen
Global illumination solution

Image credit: Henrik Wann Jensen
Direct illumination
Sixteen-bounce global illumination
Next time: spatial acceleration data structures

- Testing every primitive in scene to find ray-scene intersection is slow!
- Consider linearly scanning through a list vs. binary search
  - can apply this same kind of thinking to geometric queries
Acknowledgements

- Thanks to Keenan Crane for presentation resources