CSCI 420 Computer Graphics
Lecture 16

Geometric Queries for Ray Tracing

Ray-Surface Intersection
Barycentric Coordinates
[Angel Ch. 11]

Jernej Barbic
University of Southern California

Ray-Surface Intersections

- Necessary in ray tracing
- General implicit surfaces
- General parametric surfaces
- Specialized analysis for special surfaces
  - Spheres
  - Planes
  - Polygons
  - Quadrics

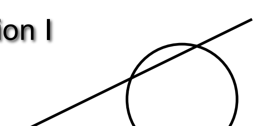
Intersection of Rays and Parametric Surfaces

- Ray in parametric form
  - Origin $\mathbf{p}_0 = [x_0\ \ y_0\ \ z_0]^T$
  - Direction $\mathbf{d} = [x_d\ \ y_d\ \ z_d]^T$
  - Assume **d** is normalized ($x_d^2 + y_d^2 + z_d^2 = 1$)
  - Ray $\mathbf{p}(t) = \mathbf{p}_0 + \mathbf{d}\, t$ for $t > 0$
- Surface in parametric form
  - Point $\mathbf{q} = g(u, v)$, possible bounds on u, v
  - Solve $\mathbf{p}_0 + \mathbf{d}\, t = g(u, v)$
  - Three equations in three unknowns (t, u, v)

Intersection of Rays and Implicit Surfaces

- Ray in parametric form
  - Origin $\mathbf{p}_0 = [x_0\ \ y_0\ \ z_0]^T$
  - Direction $\mathbf{d} = [x_d\ \ y_d\ \ z_d]^T$
  - Assume **d** normalized ($x_d^2 + y_d^2 + z_d^2 = 1$)
  - Ray $\mathbf{p}(t) = \mathbf{p}_0 + \mathbf{d}\, t$ for $t > 0$
- Implicit surface
  - Given by $f(\mathbf{q}) = 0$
  - Consists of all points **q** such that $f(\mathbf{q}) = 0$
  - Substitute ray equation for **q**: $f(\mathbf{p}_0 + \mathbf{d}\, t) = 0$
  - Solve for t (univariate root finding)
  - Closed form (if possible), otherwise numerical approximation

Ray-Sphere Intersection I



- Common and easy case
- Define sphere by
  - Center $\mathbf{c} = [x_c\ \ y_c\ \ z_c]^T$
  - Radius r
  - Surface $f(\mathbf{q}) = (x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2 - r^2 = 0$
- Plug in ray equations for x, y, z:

$$x = x_0 + x_d t, \qquad y = y_0 + y_d t, \qquad z = z_0 + z_d t$$

- And we obtain a scalar equation for *t*:

$$(x_0 + x_d t - x_c)^2 + (y_0 + y_d t - y_c)^2 + (z_0 + z_d t - z_c)^2 = r^2$$

Ray-Sphere Intersection II

- Simplify to

$$at^2 + bt + c = 0$$

where

$$a = x_d^2 + y_d^2 + z_d^2 = 1 \qquad \text{since } |d| = 1$$
$$b = 2(x_d(x_0 - x_c) + y_d(y_0 - y_c) + z_d(z_0 - z_c))$$
$$c = (x_0 - x_c)^2 + (y_0 - y_c)^2 + (z_0 - z_c)^2 - r^2$$

- Solve to obtain t_0 and t_1

$$t_{0,1} = \frac{-b \pm \sqrt{b^2 - 4c}}{2}$$

Check if $t_0, t_1 > 0$ (ray)
Return $\min(t_0, t_1)$

Ray-Sphere Intersection III

- For lighting, calculate unit normal

$$n = \frac{1}{r}[(x_i - x_c) \quad (y_i - y_c) \quad (z_i - z_c)]^T$$

- Negate if ray originates inside the sphere!
- Note possible problems with roundoff errors

7

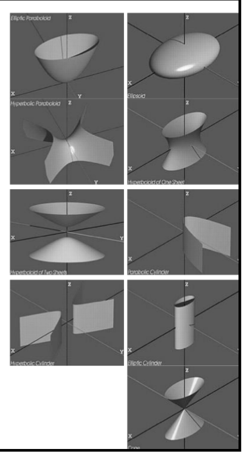
Simple Optimizations

- Factor common subexpressions

- Compute only what is necessary
  – Calculate $b^2 - 4c$, abort if negative
  – Compute normal only for closest intersection
  – Other similar optimizations

8

Ray-Quadric Intersection



- Quadric f(**p**) = f(x, y, z) = 0, where f is polynomial of order 2

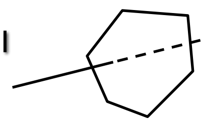
- Sphere, ellipsoid, paraboloid, hyperboloid, cone, cylinder

- Closed form solution as for sphere

- Important case for modelling in ray tracing

- Combine with CSG

Ray-Polygon Intersection I



- Assume planar polygon in 3D
  1. Intersect ray with plane containing polygon
  2. Check if intersection point is inside polygon
- Plane
  – Implicit form: ax + by + cz + d = 0
  – Unit normal: **n** = [a b c]^T with $a^2 + b^2 + c^2 = 1$
- Substitute:

$$a(x_0 + x_d t) + b(y_0 + y_d t) + c(z_0 + z_d t) + d = 0$$

- Solve:

$$t = \frac{-(ax_0 + by_0 + cz_0 + d)}{ax_d + by_d + cz_d}$$

10

Ray-Polygon Intersection II

- Substitute *t* to obtain intersection point in plane

- Rewrite using dot product

d coefficient of plane

$$t = \frac{-(ax_0 + by_0 + cz_0 + d)}{ax_d + by_d + cz_d} = \frac{-(n \cdot p_0 + d)}{n \cdot d}$$

ray direction

- If **n** • **d** = 0, no intersection (ray parallel to plane)

- If t ≤ 0, the intersection is behind ray origin

11

Test if point inside polygon

- Could use even-odd rule, or winding rule

- Easier if polygon is in 2D (project from 3D to 2D)

- Easier for triangles (tessellate polygons)

12

Point-in-triangle testing

- Critical for polygonal models
- Project the triangle, and point of plane intersection, onto one of the planes
  x = 0, y = 0, or z = 0
  (pick a plane not perpendicular to triangle)
  (such a choice always exists)
- Then, do the 2D test in the plane, by computing barycentric coordinates
  (follows next)

13

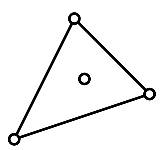
Outline

- Ray-Surface Intersections
- Special cases: sphere, polygon
- Barycentric Coordinates

14

Interpolated Shading for Ray Tracing

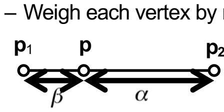
- Assume we know normals at vertices
- How do we compute normal of interior point?
- Need linear interpolation between 3 points
- Barycentric coordinates
- Yields same answer as scan conversion



15

Barycentric Coordinates in 1D

- Linear interpolation
  - $\mathbf{p}(t) = (1 - t)\mathbf{p}_1 + t\,\mathbf{p}_2$, $0 \le t \le 1$
  - $\mathbf{p}(t) = \alpha\,\mathbf{p}_1 + \beta\,\mathbf{p}_2$ where $\alpha + \beta = 1$
  - $\mathbf{p}$ is between $\mathbf{p}_1$ and $\mathbf{p}_2$ iff $0 \le \alpha, \beta \le 1$
- Geometric intuition
  - Weigh each vertex by ratio of distances from ends

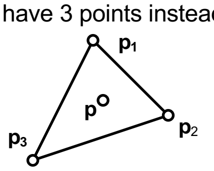


- α, β are called barycentric coordinates

16

Barycentric Coordinates in 2D

- Now, we have 3 points instead of 2

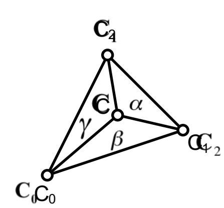


- Define 3 barycentric coordinates, α, β, γ
- $\mathbf{p} = \alpha\,\mathbf{p}_1 + \beta\,\mathbf{p}_2 + \gamma\,\mathbf{p}_3$
- $\mathbf{p}$ inside triangle iff $0 \le \alpha, \beta, \gamma \le 1$, $\alpha + \beta + \gamma = 1$
- How do we calculate α, β, γ given $\mathbf{p}$?

17

Barycentric Coordinates for Triangle

- Coordinates are ratios of triangle areas



$$\alpha = \frac{Area(\mathbf{C}\mathbf{C}_1\mathbf{C}_2)}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)}$$

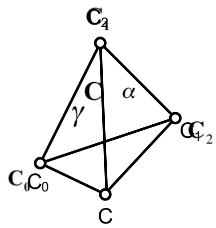
$$\beta = \frac{Area(\mathbf{C}_0\mathbf{C}\mathbf{C}_2)}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)}$$

$$\gamma = \frac{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C})}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)} = 1 - \alpha - \beta$$

- Areas in these formulas should be signed, depending on clockwise (-) or anti-clockwise orientation (+) of the triangle! Very important for point-in-triangle test.

18

Negative Area



$$\alpha = \frac{Area(\mathbf{C}\mathbf{C}_1\mathbf{C}_2)}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)} > 0$$

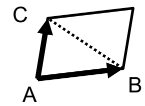
$$\beta = \frac{Area(\mathbf{C}_0\mathbf{C}\mathbf{C}_2)}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)} > 0$$

$$\gamma = \frac{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C})}{Area(\mathbf{C}_0\mathbf{C}_1\mathbf{C}_2)} \boxed{< 0}$$

Point C is outside of the triangle!

19

Computing Triangle Area in 3D



- Use cross product
- Parallelogram formula
- Area(ABC) = (1/2) |(B – A) x (C – A)|
- How to get correct sign for barycentric coordinates?
  - tricky, but possible:
    compare directions of vectors (B – A) x (C – A), for triangles CC_1C_2 vs $C_0C_1C_2$, etc.
    (either 0 (sign+) or 180 deg (sign-) angle)
  - easier alternative: project to 2D, use 2D formula
  - projection to 2D preserves barycentric coordinates

20

Computing Triangle Area in 2D

- Suppose we project the triangle to xy plane
- Area(xy-projection(ABC)) =

  $(1/2)\ ((b_x - a_x)(c_y - a_y) - (c_x - a_x)\ (b_y - a_y))$

- This formula gives correct sign
  (important for barycentric coordinates)

21

Summary

- Ray-Surface Intersections
- Special cases: sphere, polygon
- Barycentric Coordinates

22