Ray Tracing

Today

- Basic algorithms
- Ray-surface intersection for single surface

Next lecture

- Acceleration techniques for large numbers of objects

Classic Ray Tracing

Greeks: Do light rays proceed from the eye to the light, or from the light to the eye?

Gauss: Rays through lenses

Three ideas about light

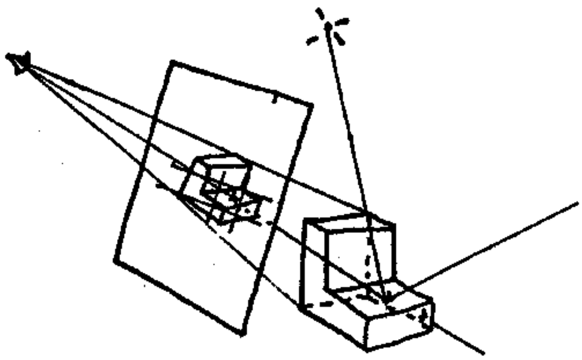
1. Light rays travel in straight lines
2. Light rays do not interfere with each other if they cross
3. Light rays travel from the light sources to the eye, but the physics is invariant under path reversal (reciprocity).

Ray Tracing in Computer Graphics

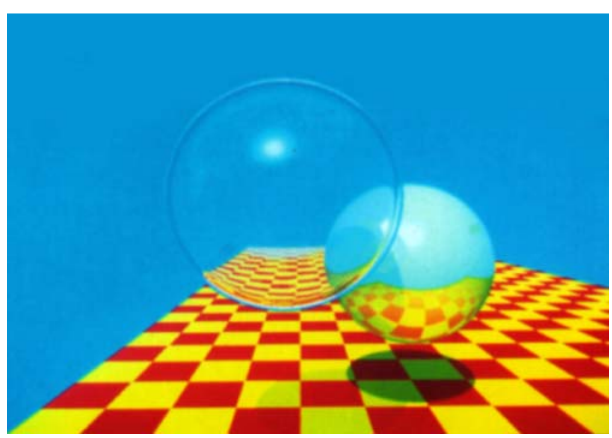
Appel 1968 - Ray casting

1. Generate an image by sending one ray per pixel

2. Check for shadows by sending a ray to the light



Ray Tracing in Computer Graphics

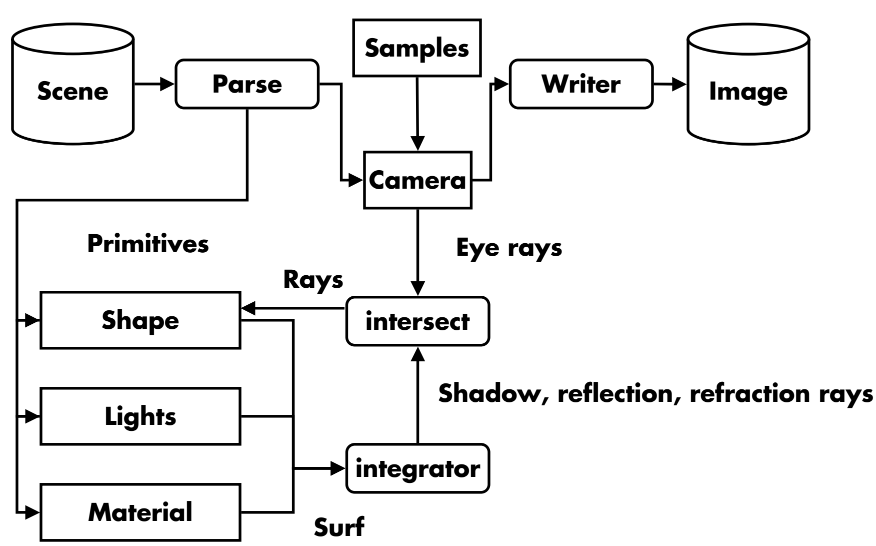


Whitted 1979

Recursive ray tracing (reflection and refraction)

Ray Tracing Demo

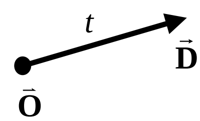
Ray Tracing Architecture



Ray-Plane Intersection

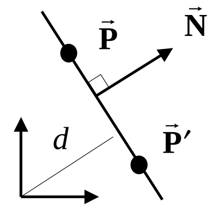
Ray: $\vec{\mathbf{P}} = \vec{\mathbf{O}} + t\,\vec{\mathbf{D}}$

$0 \le t < \infty$



Plane: $(\vec{\mathbf{P}} - \vec{\mathbf{P}}') \bullet \vec{\mathbf{N}} = 0$

$ax + by + cz + d = 0$



Solve for intersection

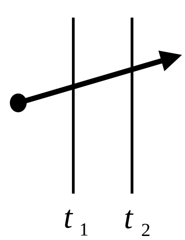
- **Substitute ray eqn into plane equation**

$$(\vec{\mathbf{P}} - \vec{\mathbf{P}}') \bullet \vec{\mathbf{N}} = (\vec{\mathbf{O}} + t\vec{\mathbf{D}} - \vec{\mathbf{P}}') \bullet \vec{\mathbf{N}} = 0$$

$$t = -\frac{(\vec{\mathbf{O}} - \vec{\mathbf{P}}') \bullet \vec{\mathbf{N}}}{\vec{\mathbf{D}} \bullet \vec{\mathbf{N}}}$$

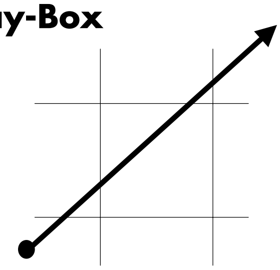
Ray-Polyhedra

Ray-Slab

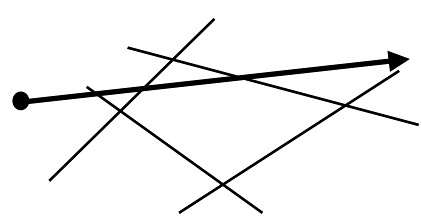


Note: Procedural geometry

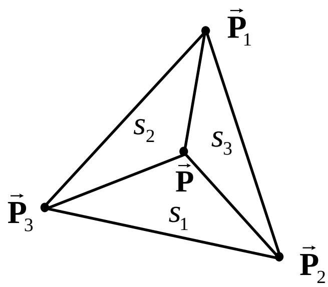
Ray-Box



Ray-Convex Polyhedra



Ray-Triangle Intersection



$$s_1 = \text{area}(\Delta \mathbf{P}\mathbf{P}_2\mathbf{P}_3)$$

$$s_2 = \text{area}(\Delta \mathbf{P}\mathbf{P}_3\mathbf{P}_1)$$

$$s_3 = \text{area}(\Delta \mathbf{P}\mathbf{P}_1\mathbf{P}_2)$$

Barycentric coordinates

$$\vec{\mathbf{P}} = s_1\vec{\mathbf{P}}_1 + s_2\vec{\mathbf{P}}_2 + s_3\vec{\mathbf{P}}_3$$

Inside criteria

$$0 \le s_1 \le 1$$

$$0 \le s_2 \le 1$$

$$0 \le s_3 \le 1$$

$$s_1 + s_2 + s_3 = 1$$

Ray-Triangle Intersection

$$\vec{\mathbf{P}} = s_1\vec{\mathbf{P}}_1 + s_2\vec{\mathbf{P}}_2 + s_3\vec{\mathbf{P}}_3 \Rightarrow \begin{bmatrix} \mathbf{P}_1 & \mathbf{P}_2 & \mathbf{P}_3 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \mathbf{P} \end{bmatrix}$$

$$s_1 = \frac{\begin{vmatrix} \mathbf{P} & \mathbf{P}_2 & \mathbf{P}_3 \end{vmatrix}}{\begin{vmatrix} \mathbf{P}_1 & \mathbf{P}_2 & \mathbf{P}_3 \end{vmatrix}} = \mathbf{P} \bullet \frac{\mathbf{P}_2 \times \mathbf{P}_3}{\Delta}$$

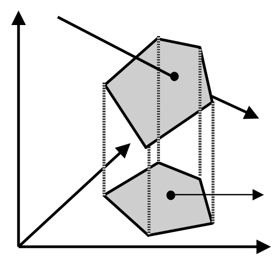
$$s_2 = \frac{\begin{vmatrix} \mathbf{P}_1 & \mathbf{P} & \mathbf{P}_3 \end{vmatrix}}{\begin{vmatrix} \mathbf{P}_1 & \mathbf{P}_2 & \mathbf{P}_3 \end{vmatrix}} = \mathbf{P} \bullet \frac{\mathbf{P}_3 \times \mathbf{P}_1}{\Delta}$$

$$s_3 = \frac{\begin{vmatrix} \mathbf{P}_1 & \mathbf{P}_2 & \mathbf{P} \end{vmatrix}}{\begin{vmatrix} \mathbf{P}_1 & \mathbf{P}_2 & \mathbf{P}_3 \end{vmatrix}} = \mathbf{P} \bullet \frac{\mathbf{P}_1 \times \mathbf{P}_2}{\Delta}$$

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \mathbf{P}_2 \times \mathbf{P}_3 \\ \mathbf{P}_3 \times \mathbf{P}_1 \\ \mathbf{P}_1 \times \mathbf{P}_2 \end{bmatrix} \begin{bmatrix} \mathbf{P} \end{bmatrix}$$

Ray-Polygon Intersection

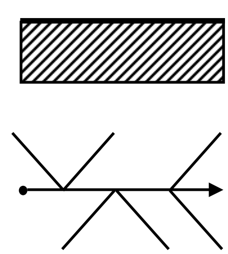
1. Find intersection with plane of support
2. Test whether point is inside 3D polygon
   a. Project onto *xy* plane
   b. Test whether point is inside 2D polygon



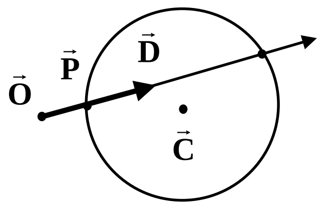
Point in Polygon

```
inside(vert v[], int n, float x, float y)
{
  int cross=0; float x0, y0, x1, y1;

  x0 = v[n-1].x - x;
  y0 = v[n-1].y - y;
  while( n-- ) {
    x1 = v->x - x;
    y1 = v->y - y;
    if( y0 > 0 ) {
      if( y1 <= 0 )
        if( x1*y0 > y1*x0 ) cross++;
    }
    else {
      if( y1 > 0 )
        if( x0*y1 > y0*x1 ) cross++;
    }
    x0 = x1; y0 = y1; v++;
  }
  return cross & 1;
}
```



Ray-Sphere Intersection



Ray: $\vec{\mathbf{P}} = \vec{\mathbf{O}} + t\vec{\mathbf{D}}$

Sphere: $\left(\vec{\mathbf{P}} - \vec{\mathbf{C}}\right)^2 - R^2 = 0$

$$\left(\vec{\mathbf{O}} + t\,\vec{\mathbf{D}} - \vec{\mathbf{C}}\right)^2 - R^2 = 0$$

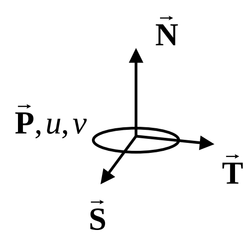
$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$at^2 + bt + c = 0$$
$$a = \vec{\mathbf{D}}^2$$
$$b = 2(\vec{\mathbf{O}} - \vec{\mathbf{C}}) \bullet \vec{\mathbf{D}}$$
$$c = (\vec{\mathbf{O}} - \vec{\mathbf{C}})^2 - R^2$$

Geometric Methods

Methods

- **Find normal and tangents**
- **Find surface parameters**



E.g. Sphere

Normal $\vec{\mathbf{N}} = \vec{\mathbf{P}} - \vec{\mathbf{C}}$

Parameters

$$x = \sin\theta\cos\phi \qquad \phi = \tan^{-1}(x, y)$$
$$y = \sin\theta\sin\phi \qquad \theta = \cos^{-1} z$$
$$z = \cos\theta$$

Ray-Implicit Surface Intersection

$$f(x,y,z)=0$$

$$x = x_0 + x_1\,t$$
$$y = y_0 + y_1\,t$$
$$z = z_0 + z_1\,t$$

$$f^*(t)=0$$

1. Substitute ray equation

2. Find *positive, real* roots

Univariate root finding

- **Newton's method**
- ***Regula-falsi***
- **Interval methods**
- **Heuristics**

Ray-Algebraic Surface Intersection

$$p_n(x,y,z)=0$$

$$x = x_0 + x_1\,t$$
$$y = y_0 + y_1\,t$$
$$z = z_0 + z_1\,t$$

$$p_n^*(t)=0$$

Degree *n*

***Linear*: Plane**

***Quadric*: Spheres, ...**

***Quartic*: Tori**

Polynomial root finding

- **Quadratic, cubic, quartic**
- **Bezier/Bernoulli basis**
- **Descartes' rule of signs**
- **Sturm sequences**

History

Polygons	Appel '68
Quadrics, CSG	Goldstein & Nagel '71
Tori	Roth '82
Bicubic patches	Whitted '80, Kajiya '82
Superquadrics	Edwards & Barr '83
Algebraic surfaces	Hanrahan '82
Swept surfaces	Kajiya '83, van Wijk '84
Fractals	Kajiya '83
Height fields	Coquillart & Gangnet '84, Musgrave '88
Deformations	Barr '86
Subdivision surfs.	Kobbelt, Daubert, Siedel, '98

P. Hanrahan, A survey of ray-surface intersection algorithms