CS-184: Computer Graphics

Lecture #10: Raytracing

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Today

- Raytracing
  - Shadows and direct lighting
  - Reflection and refraction
  - Antialiasing, motion blur, soft shadows, and depth of field

- Intersection Tests
  - Ray-primitive
  - Sub-linear tests
Light in an Environment

Lady writing a Letter with her Maid
National Gallery of Ireland, Dublin
Johannes Vermeer, 1670

Global Illumination Effects

PCKTWTCH
Kevin Odhner
POV-Ray
Global Illumination Effects

A Philco 6Z4 Vacuum Tube
Steve Anger
POV-Ray

Caustic Sphere
Henrik Jensen
(refraction caustic)
Global Illumination Effects

Caustic Ring
Henrik Jensen
(reflection caustic)

Global Illumination Effects

Sphere Flake
Henrik Jensen
Early Raytracing

Raytracing

- **Scan conversion**
  - $3D \rightarrow 2D \rightarrow Image$
  - Based on transforming geometry
- **Raytracing**
  - $3D \rightarrow Image$
  - Geometric reasoning about light rays
Raytracing

Eye, view plane section, and scene

Launch ray from eye through pixel, see what it hits
Raytracing

Basic tasks

- Build a ray
- Figure out what a ray hits
- Compute shading

Compute color and fill-in the pixel
Building Eye Rays

- Rectilinear image plane build from four points

\[ P = u (v_{LL} + (1 - v)U_L) + (1 - u)(v_{LR} + (1 - v)U_R) \]

Building Eye Rays

- Nonlinear projections
  - Non-planar projection surface
  - Variable eye location
Examples

Multiple-Center-of-Projection Images
P. Rademacher and G. Bishop
SIGGRAPH 1998

Examples

Spherical and Cylindrical Projections
Ben Kreunen
From Big Ben’s Panorama Tutorials
Building Eye Rays

- Ray equation
  \[ R(t) = E + t(P - E) \]
  \[ t \in [1 \ldots +\infty] \]
  - Through eye at \( t = 0 \)
  - At pixel center at \( t = 1 \)

Shadow Rays

- Detect shadow by rays to light source
  \[ R(t) = S + t(L - S) \]
  \[ t \in [\varepsilon \ldots 1) \]
Shadow Rays

- Test for occluder
  - No occluder, shade normally (e.g. Phong model)
  - Yes occluder, skip light (don’t skip ambient)
- Self shadowing
  - Add shadow bias
  - Test object ID

Reflection Rays

- Recursive shading
  \[ R(t) = S + tB \]
  - Ray bounces off object
  - Treat bounce rays (mostly) like eye rays
  - Shade bounce ray and return color
    - Shadow rays
    - Recursive reflections
  - Add color to shading at original point
    - Specular or separate reflection coefficient
Reflection Rays

- Recursion Depth
  - Truncate at fixed number of bounces
  - Multiplier less than J.N.D.

Refracted Rays

- Transparent materials bend light
  - Snell’s Law \( \frac{n_i}{n_t} = \frac{\sin \theta_t}{\sin \theta_i} \) (see clever formula in text...)

\( \sin \theta_t > 1 \iff \text{Total (internal) reflection} \)
Refracted Rays

- Coefficient on transmitted ray depends on $\theta$
  - Schlick approximation to Fresnel Equations
    \[
    k_t(\theta_i) = k_0 + (1 - k_0)(1 - \cos \theta_i)^5
    \]
    \[
    k_0 = \left( \frac{n_t - 1}{n_t + 1} \right)^2
    \]
  - Attenuation
    - Wavelength (color) dependant
    - Exponential with distance

O’Brien and Hodgins, SIGGRAPH 1999
Anti-Aliasing

- Boolean on/off for pixels causes problems
  - Consider scan conversion algorithm:
    - Compare to casting a ray through each pixel center
  - Recall Nyquist Theorem
    - $Sampling \ rate \geq twice \ highest \ frequency$

Anti-Aliasing

- Desired solution of an integral over pixel
“Distributed” Raytracing

- Send multiple rays through each pixel
- Average results together
- Jittering trades aliasing for noise

One Sample  
5x5 Grid  
5x5 Jittered Grid

“Distributed” Raytracing

- Use multiple rays for reflection and refraction
  - At each bounce send out many extra rays
  - Quasi-random directions
  - Use BRDF (or Phong approximation) for weights

- How many rays?
Soft Shadows

- Soft shadows result from non-point lights
  - Some part of light visible, some other part occluded
Soft Shadows

- Distribute shadow rays over light surface

Figure from S. Chenney
Motion Blur

- Distribute rays over time
  - More when we talk about animation...

Depth of Field

- Distribute rays over a lens assembly
Depth of Field

No DoF

Multiple images for DoF

Jittered rays for DoF

More rays

Even more rays

Other Lens Effects

Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995
Ray -vs- Sphere Test

- Ray equation: $R(t) = A + tD$
- Implicit equation for sphere: $|X - C|^2 - r^2 = 0$
- Combine:
  $|R(t) - C|^2 - r^2 = 0$
  $|A + tD - C|^2 - r^2 = 0$
- Quadratic equation in $t$

Two solutions
One solution
Imaginary
Ray -vs- Triangle

- Ray equation: \( R(t) = A + tD \)
- Triangle in barycentric coordinates:
  \[
  X(\beta, \gamma) = V_1 + \beta(V_2 - V_1) + \gamma(V_3 - V_1)
  \]
- Combine:
  \[
  V_1 + \beta(V_2 - V_1) + \gamma(V_3 - V_1) = A + tD
  \]
- Solve for \( \beta, \gamma, \) and \( t \)
  - 3 equations 3 unknowns
  - Beware divide by near-zero
  - Check ranges