CS-184: Computer Graphics
Lecture #6: Raytracing

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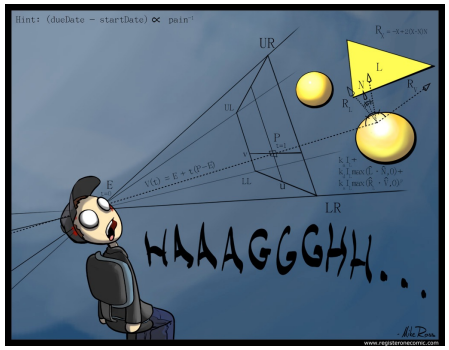
Today

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

Raytracing Assignment



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Light in an Environment

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

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Global Illumination Effects

PCKTWTCH
Kevin Odhner
POV-Ray

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Global Illumination Effects

A Philco 6Z4 Vacuum Tube
Steve Anger
POV-Ray

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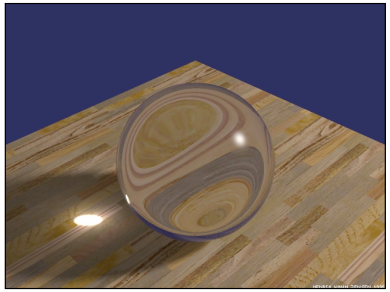
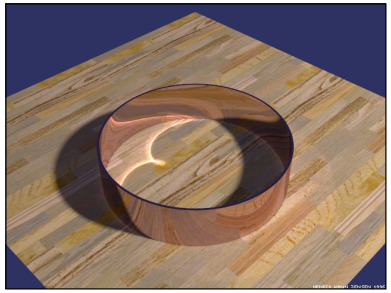
Global Illumination Effects



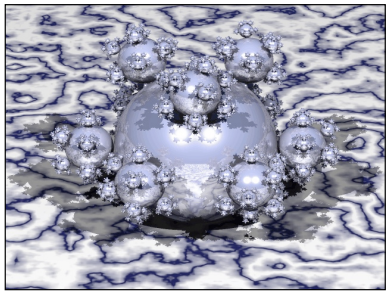
Caustic Sphere
Henrik Jensen
(refraction caustic)

Global Illumination Effects



Caustic Ring
Henrik Jensen
(reflection caustic)

Global Illumination Effects



Sphere Flake
Henrik Jensen

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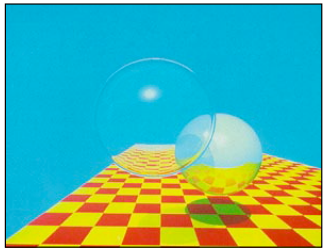
Early Raytracing



Turner Whitted

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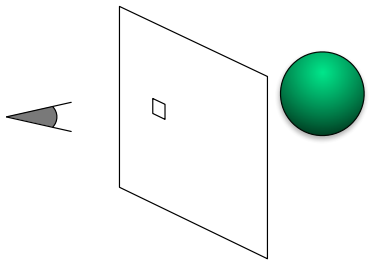
Raytracing

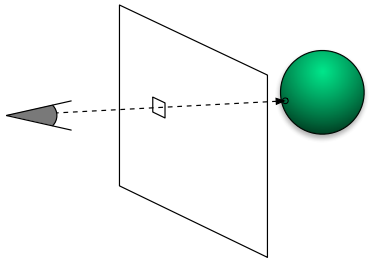
- Scan conversion
  - 3D → 2D → Image
  - Based on transforming geometry
- Raytracing
  - 3D → Image
  - Geometric reasoning about light rays

Raytracing



Eye, view plane section, and scene

Raytracing



Launch ray from eye through pixel, see what it hits

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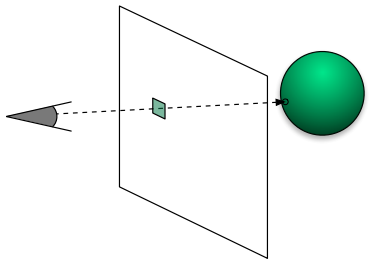
Raytracing



Compute color and fill-in the pixel

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Raytracing

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

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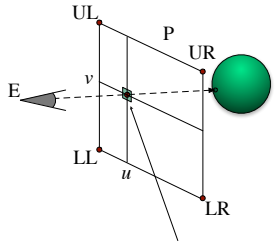
Building Eye Rays

- Rectilinear image plane build from four points



$$P = u\,(vLL + (1-v)UL) + (1-u)(vLR + (1-v)UR)$$

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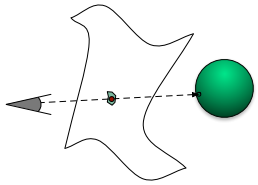
Building Eye Rays

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



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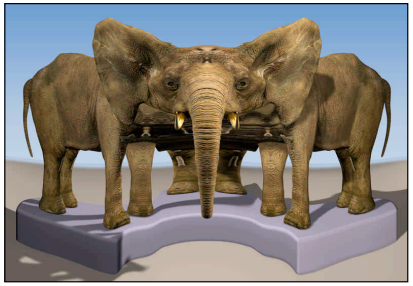
Examples



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

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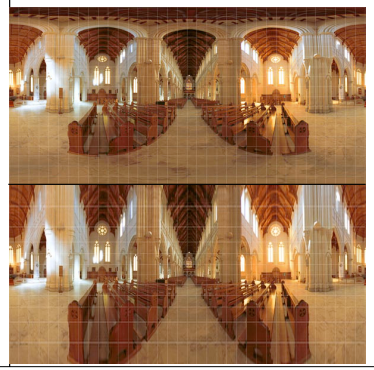
Examples



Spherical and Cylindrical Projections
Ben Kreunen
From *Big Ben's Panorama Tutorials*

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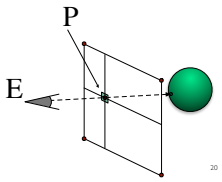
Building Eye Rays

- Ray equation

$$\mathrm{R}(t) = \mathrm{E} + t(\mathrm{P} - \mathrm{E})$$

$$t \in [1 \ldots + \infty]$$

- Through eye at $t = 0$
- At pixel center at $t = 1$



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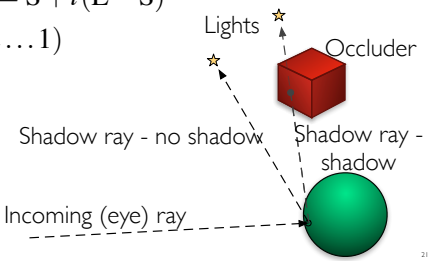
Shadow Rays

- Detect shadow by rays to light source

$$\mathrm{R}(t) = \mathrm{S} + t(\mathrm{L} - \mathrm{S})$$
$$t \in [\varepsilon \ldots 1)$$



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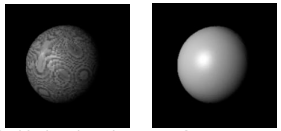
Shadow Rays

- 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



Self-shadowing Correct

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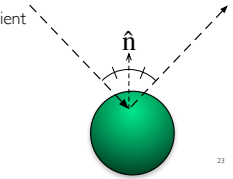
Reflection Rays

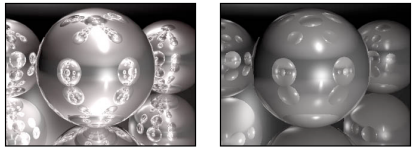
- Recursive shading
  - Ray bounces off object
  - Treat bounce rays (mostly) like eye rays
  - Shade bounce ray and return color
    - Shadow rays
    - Recursive reflections
  - Add color to shading at original point
    - Specular or separate reflection coefficient

$$\mathrm{R}(t) = \mathrm{S} + t\,\mathrm{B}$$
$$t \in [\varepsilon \ldots + \infty)$$



Reflection Rays

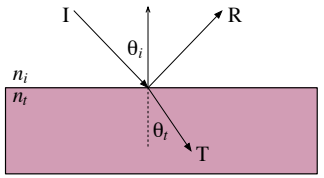
- Recursion Depth
  - Truncate at fixed number of bounces
  - Multiplier less than J.N.D.



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...)

$\sin\theta_t > 1$ Total (internal) reflection



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Refracted Rays

- Coefficient on transmitted ray depends on θ
  - 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

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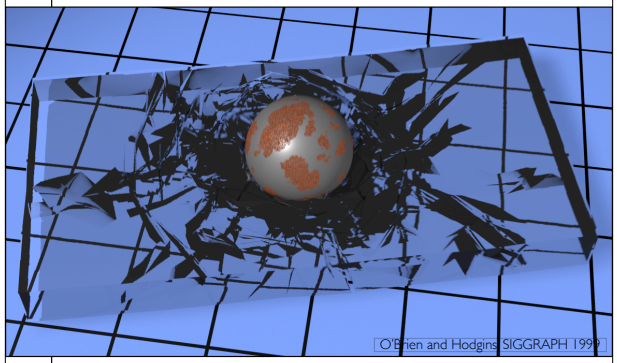
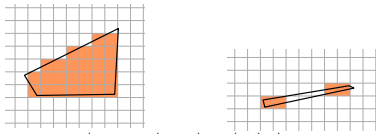
Refracted Rays



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 ≥ twice highest frequency*

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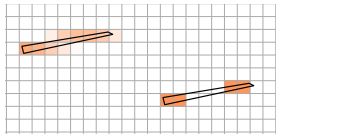
Anti-Aliasing

- Desired solution of an integral over pixel



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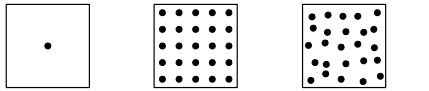
"Distributed" Raytracing

- Send multiple rays through each pixel



One Sample 5x5 Grid 5x5 Jittered Grid

- Average results together
- Jittering trades aliasing for noise

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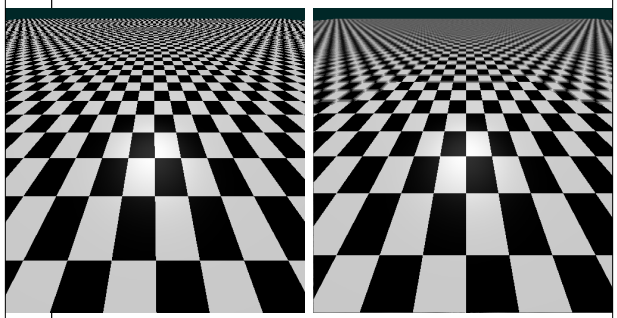
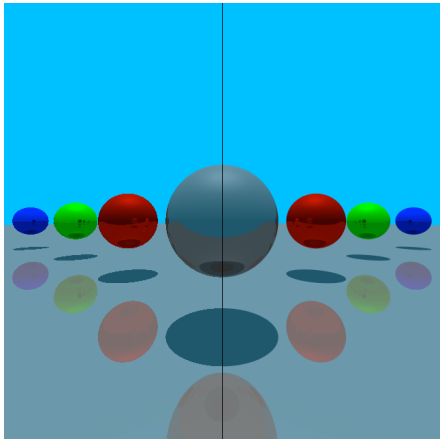
"Distributed" Raytracing

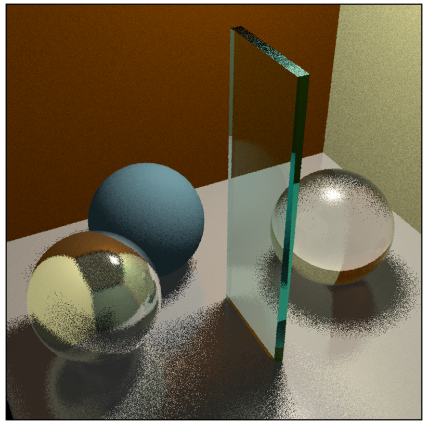


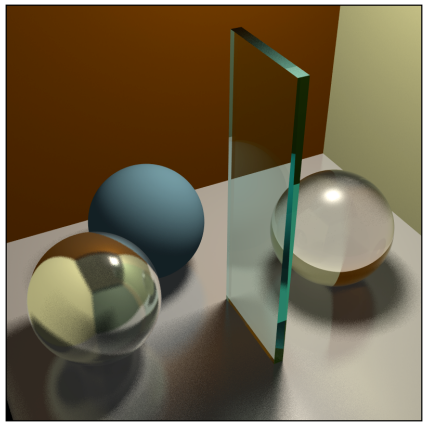


Beverly Chiu and Max Delgadillo
CS 184 2007

"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?





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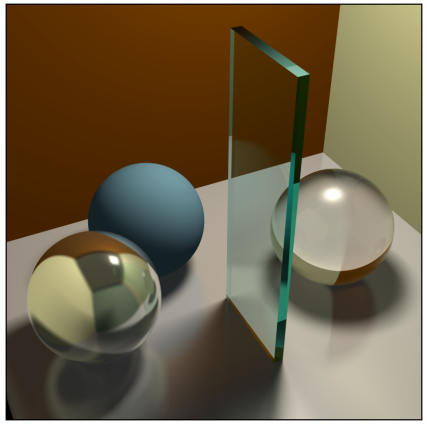

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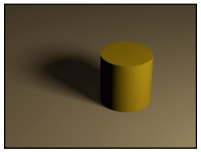
Soft Shadows



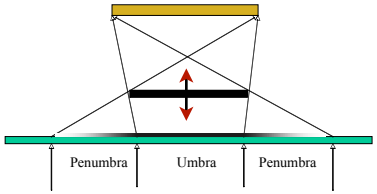


Figure from S. Chenney

Soft Shadows

- Distribute shadow rays over light surface

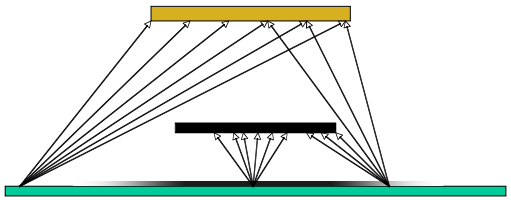
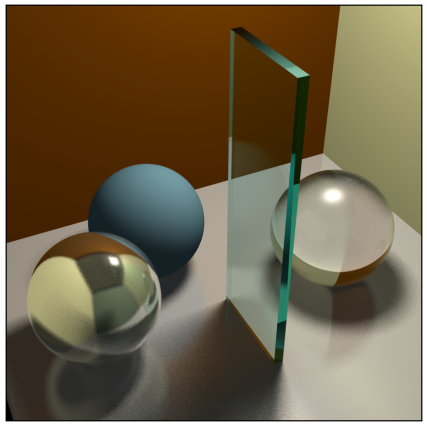


Figure from S. Chenney



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Motion Blur

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

Pool Balls
Tom Porter
RenderMan

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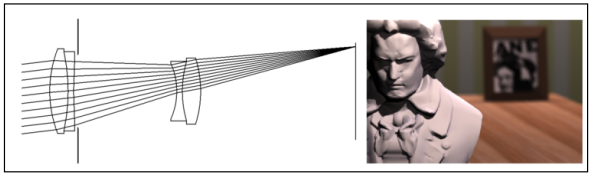
Depth of Field



Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

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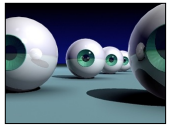
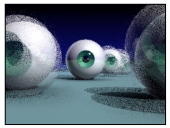
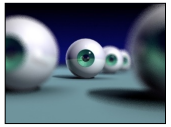
Depth of Field



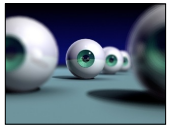
No DoF



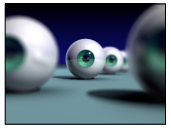
Jittered rays for DoF



More rays



Multiple images for DoF



Even more rays

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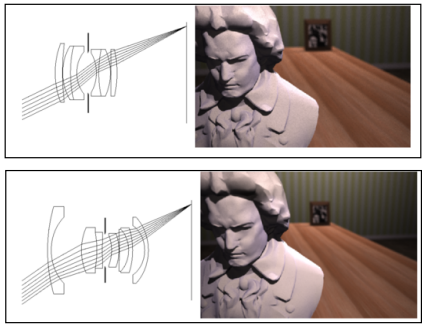
Other Lens Effects



Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

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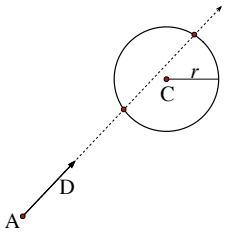
Ray -vs- Sphere Test

- Ray equation: $\mathrm{R}(t) = \mathrm{A} + t\,\mathrm{D}$
- Implicit equation for sphere: $|\mathrm{X} - \mathrm{C}|^2 - r^2 = 0$
- Combine:

$$|\mathrm{R}(t) - \mathrm{C}|^2 - r^2 = 0$$

$$|\mathrm{A} + t\,\mathrm{D} - \mathrm{C}|^2 - r^2 = 0$$

- Quadratic equation in t



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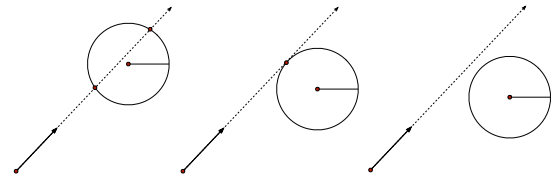
Ray -vs- Sphere Test



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Ray -vs- Triangle

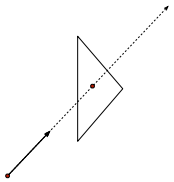
- Ray equation: $\mathrm{R}(t) = \mathrm{A} + t\,\mathrm{D}$
- Triangle in barycentric coordinates:

$$\mathrm{X}(\beta,\gamma) = \mathrm{V}_1 + \beta(\mathrm{V}_2 - \mathrm{V}_1) + \gamma(\mathrm{V}_3 - \mathrm{V}_1)$$

- Combine:

$$\mathrm{V}_1 + \beta(\mathrm{V}_2 - \mathrm{V}_1) + \gamma(\mathrm{V}_3 - \mathrm{V}_1) = \mathrm{A} + t\,\mathrm{D}$$

- Solve for β, γ, and t
  - 3 equations 3 unknowns
  - Beware divide by near-zero
  - Check ranges



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