CS-184: Computer Graphics

Lecture #7: 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

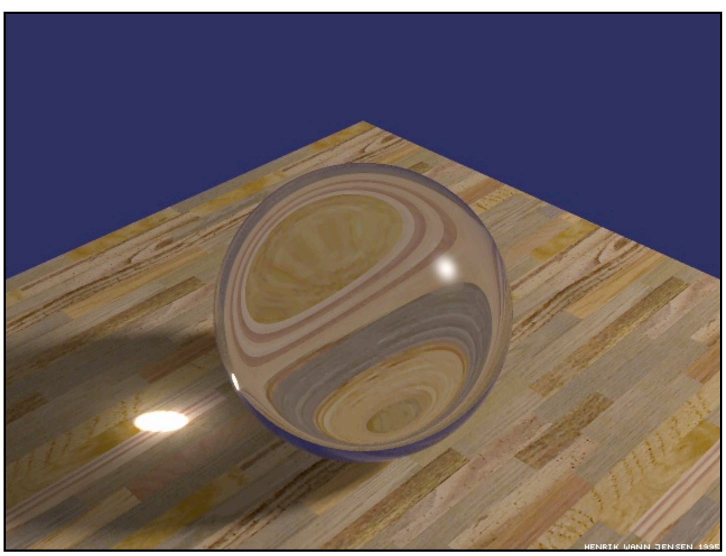
Global Illumination Effects

PCKTWTCH
Kevin Odhner
POV-Ray

Global Illumination Effects

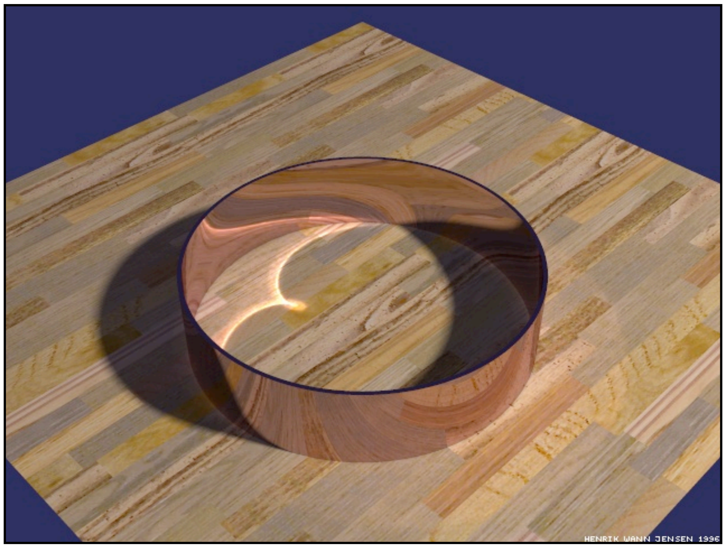
A Philco 6Z4 Vacuum Tube
Steve Anger
POV-Ray

Global Illumination Effects



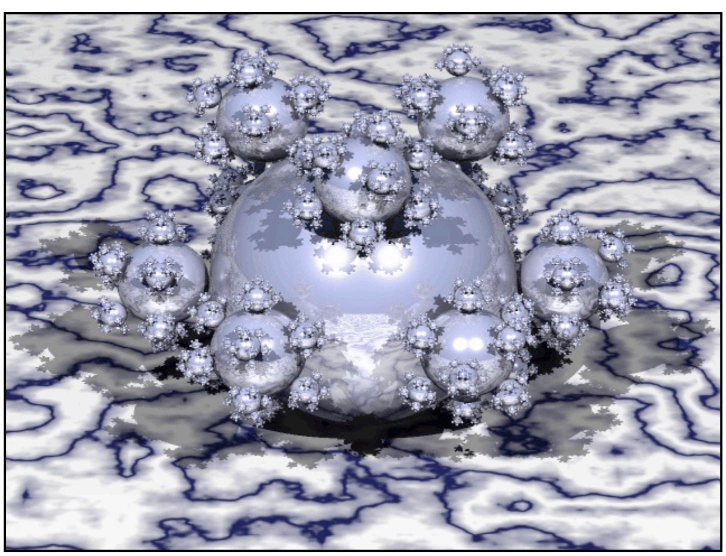
Caustic Sphere
Henrik Jensen
(refraction caustic)

Global Illumination Effects



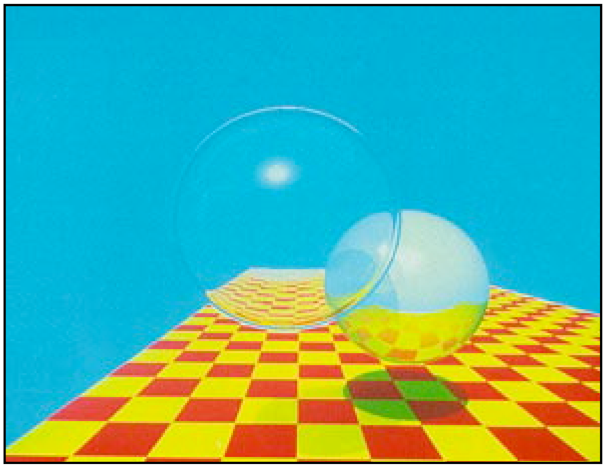
Caustic Ring
Henrik Jensen
(reflection caustic)

Global Illumination Effects



Sphere Flake
Henrik Jensen

Early Raytracing

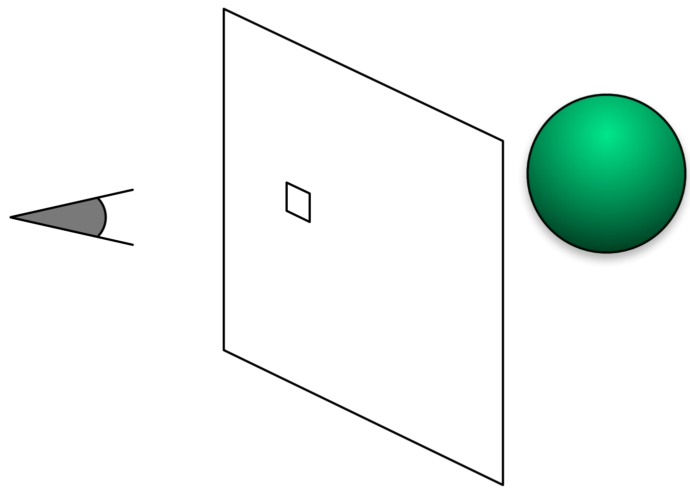


Turner Whitted

Raytracing

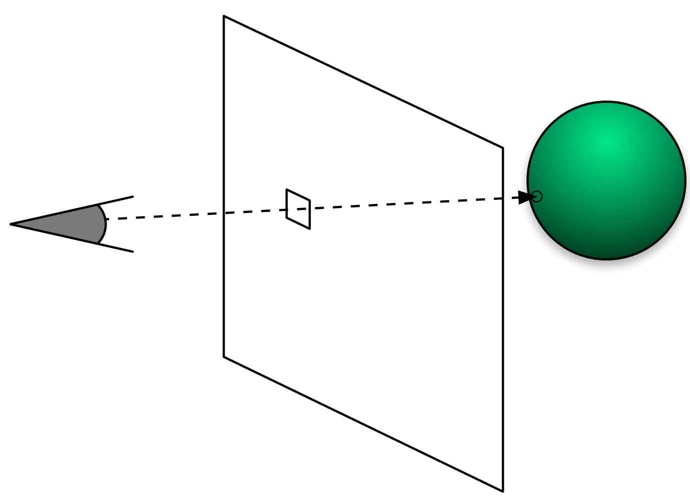
- Scan conversion
  - 3D → 2D → Image
  - Based on transforming geometry
- Raytracing
  - 3D → Image
  - Geometric reasoning about light rays

Raytracing



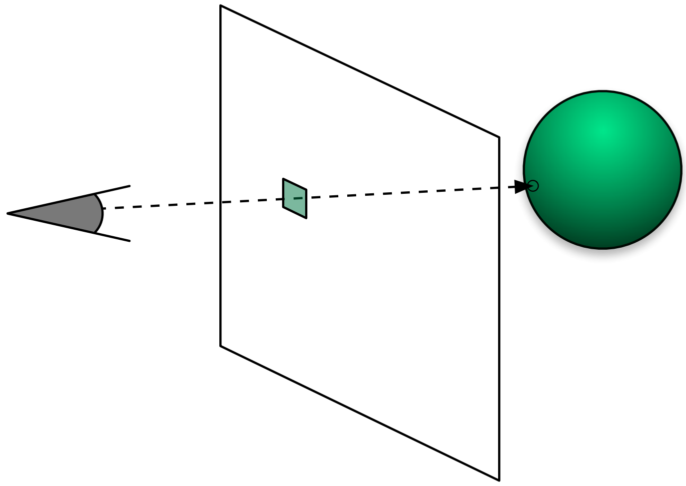
Eye, view plane section, and scene

Raytracing



Launch ray from eye through pixel, see what it hits

Raytracing



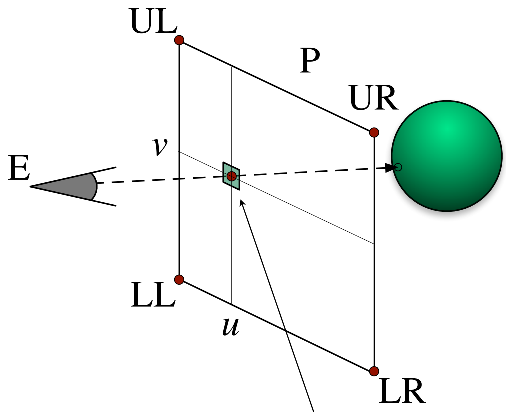
Compute color and fill-in the pixel

Raytracing

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

Building Eye Rays

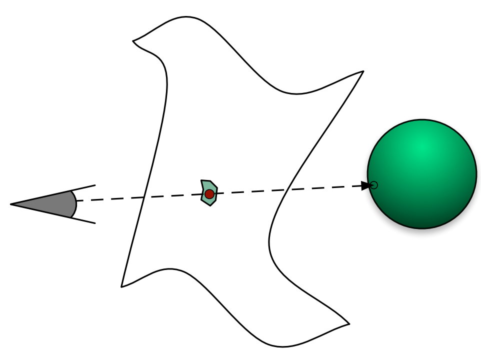
- Rectilinear image plane build from four points



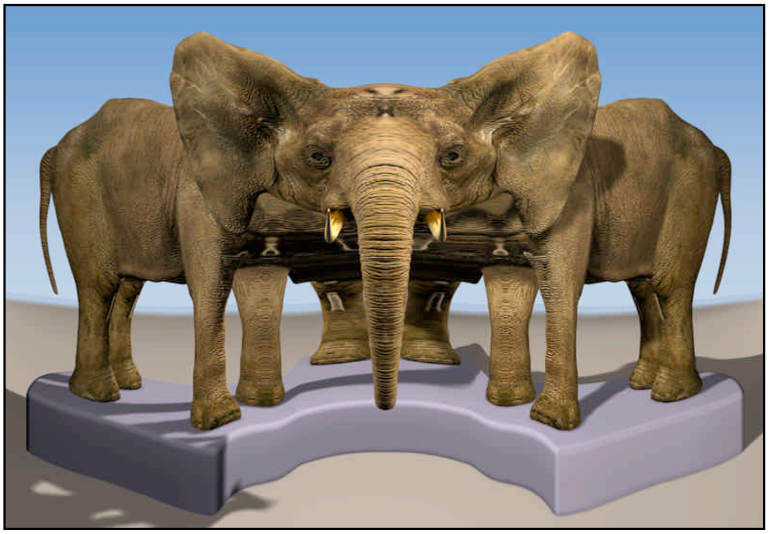
$$P = u\,(v\mathrm{LL} + (1-v)\mathrm{UL}) + (1-u)(v\mathrm{LR} + (1-v)\mathrm{UR})$$

Building Eye Rays

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

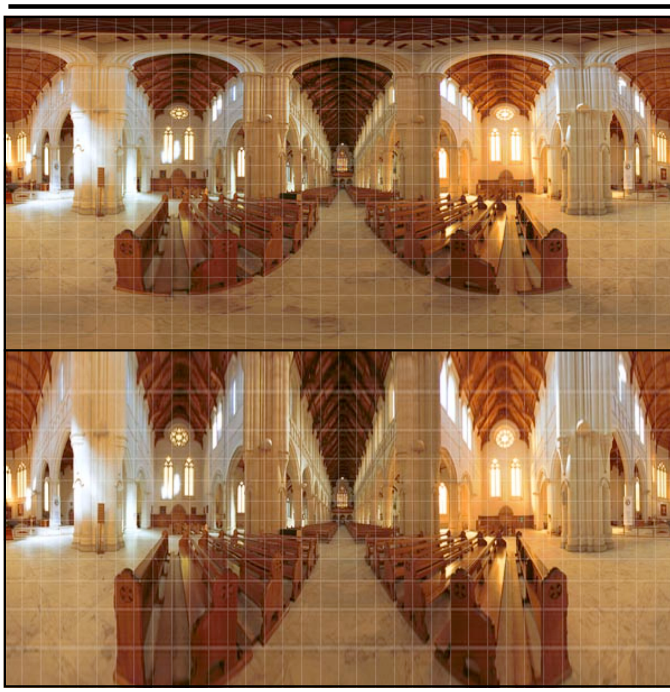


Examples



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*

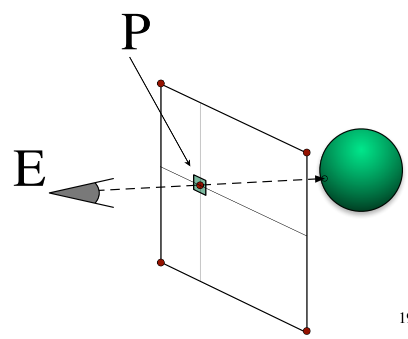
Building Eye Rays

- Ray equation

$$R(t) = E + t(P - E)$$

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

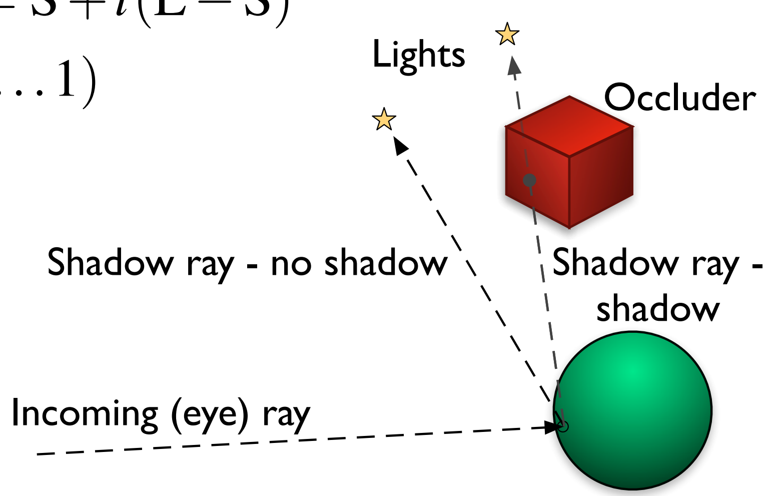
  - Through eye at $t = 0$
  - At pixel center at $t = 1$



Shadow Rays

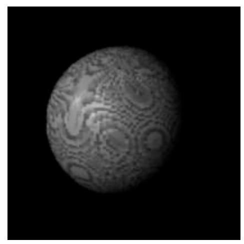
- Detect shadow by rays to light source

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

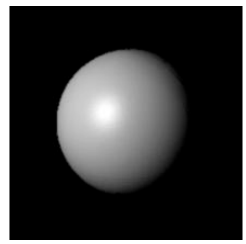


Shadow Rays

- 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



Self-shadowing



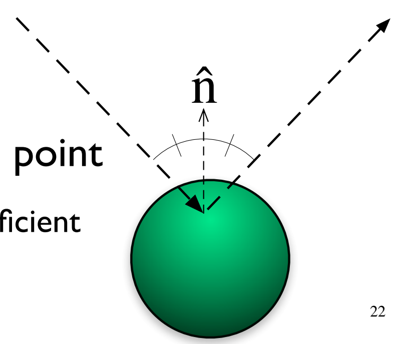
Correct

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

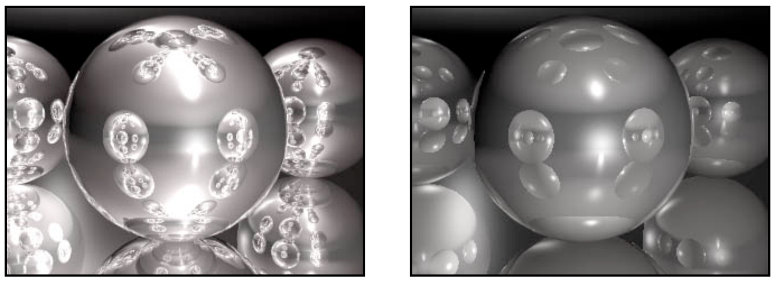
$$\mathrm{R}(t) = \mathrm{S} + t\,\mathrm{B}$$

$$t \in [\varepsilon \ldots +\infty)$$



Reflection Rays

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



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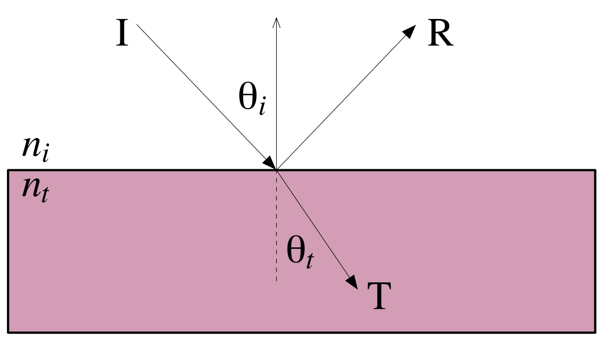
Refracted Rays

- 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

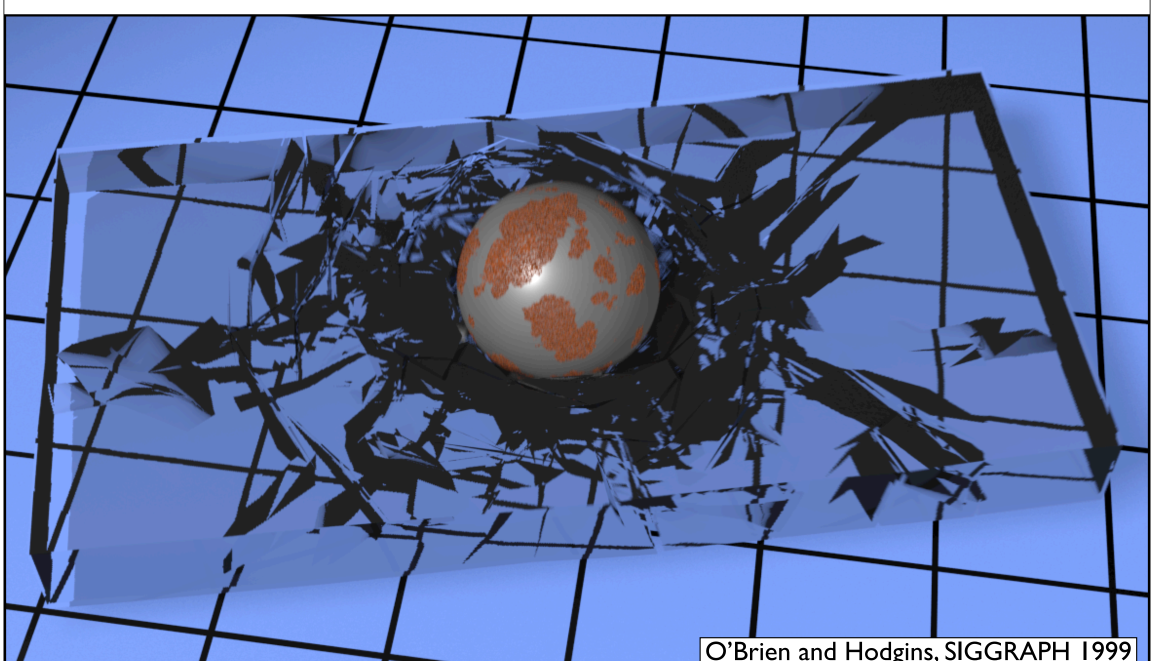
- Coefficient on transmitted ray depends on θ
  - Schlick approximation to Fresnel Equations

$$k_t(\theta_i) = k_0 + (1 - k_0)(1 - \cos\theta_i)^5$$

$$k_0 = \left(\frac{n_t - 1}{n_t + 1}\right)^2$$

  - Attenuation
    - Wavelength (color) dependant
    - Exponential with distance

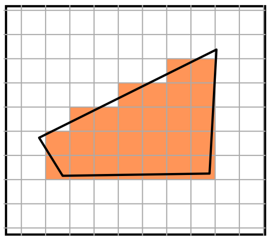
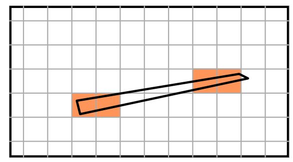
Refracted Rays



O'Brien and Hodgins, SIGGRAPH 1999

Anti-Aliasing

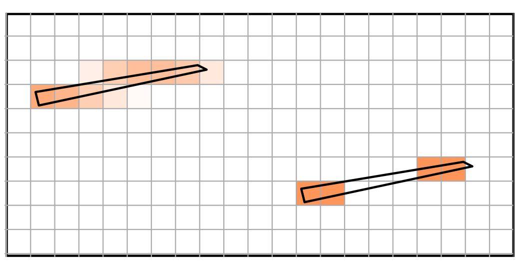
- Boolean on/off for pixels causes problems
  - Consider scan conversion algorithm:

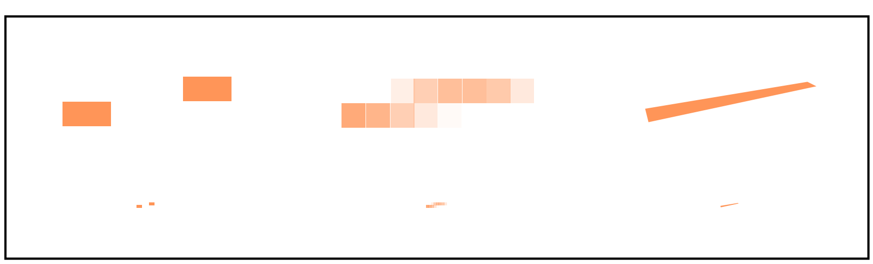



  - Compare to casting a ray through each pixel center
- Recall Nyquist Theorem
  - *Sampling rate ≥ twice highest frequency*

Anti-Aliasing

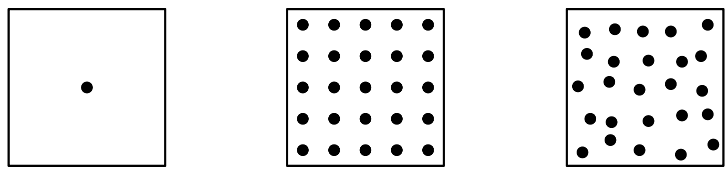
- Desired solution of an integral over pixel





"Distributed" Raytracing

- Send multiple rays through each pixel

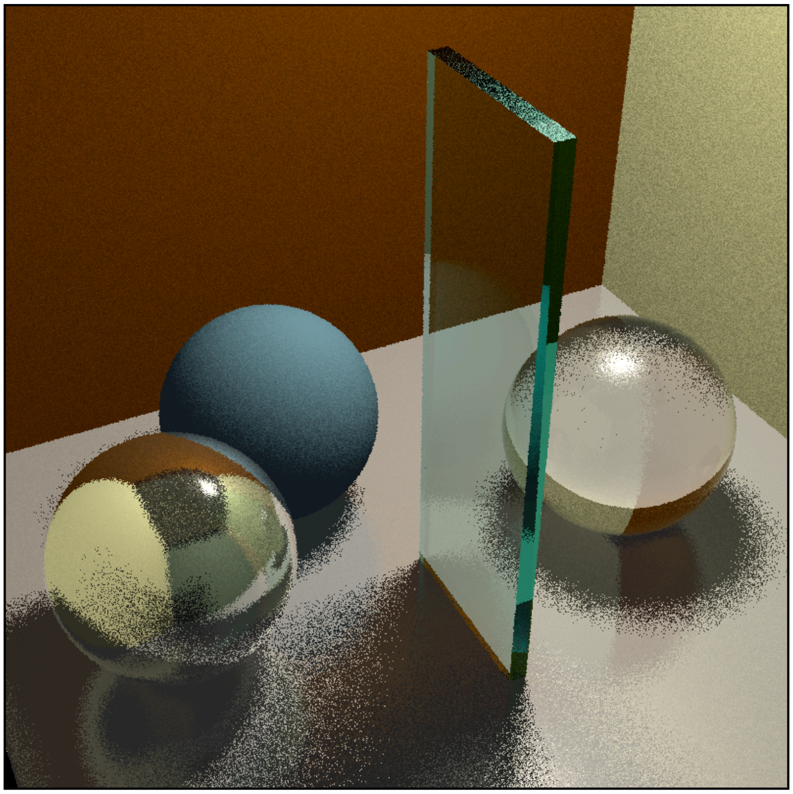


One Sample 5x5 Grid 5x5 Jittered Grid

- Average results together
- Jittering trades aliasing for noise

"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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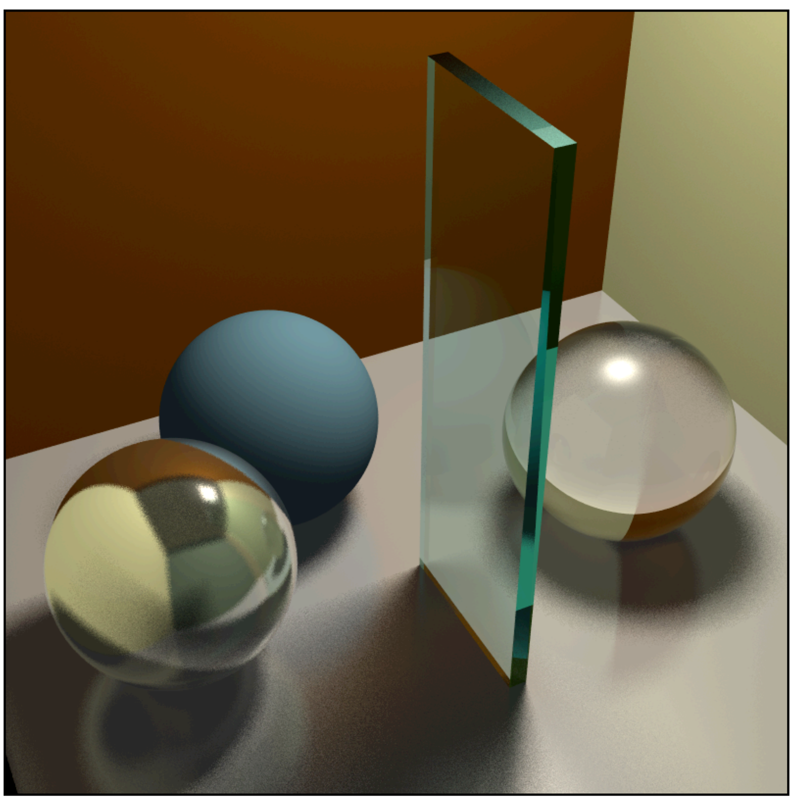

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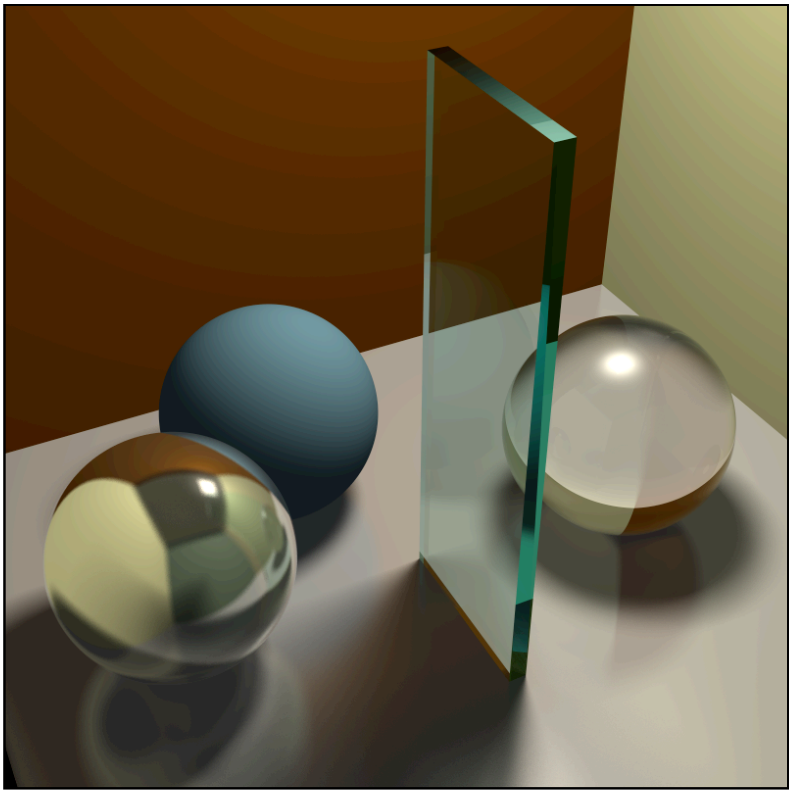

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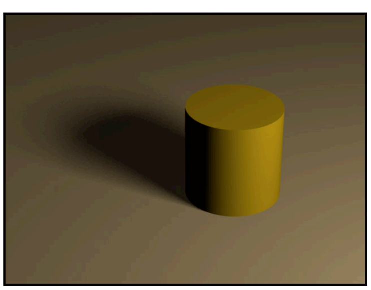
Soft Shadows

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



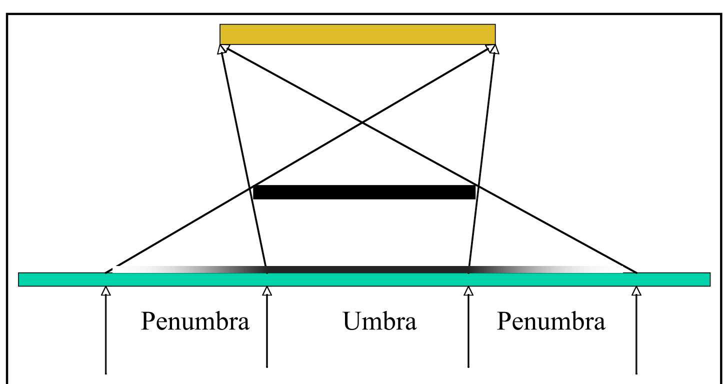


Figure from S. Chenney

Soft Shadows

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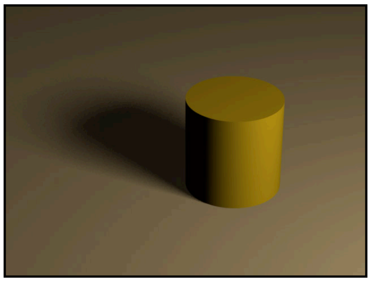


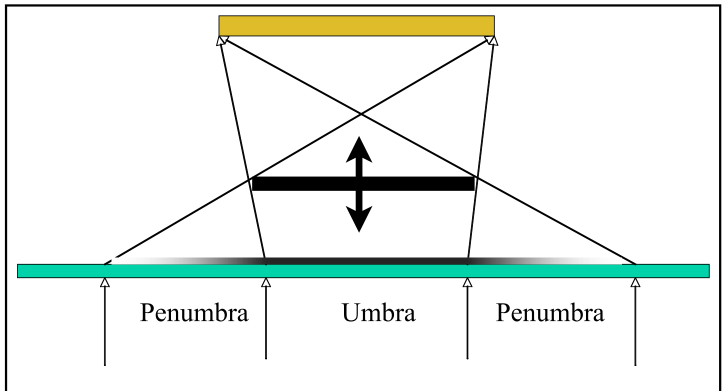


Figure from S. Chenney

Soft Shadows

- Distribute shadow rays over light surface

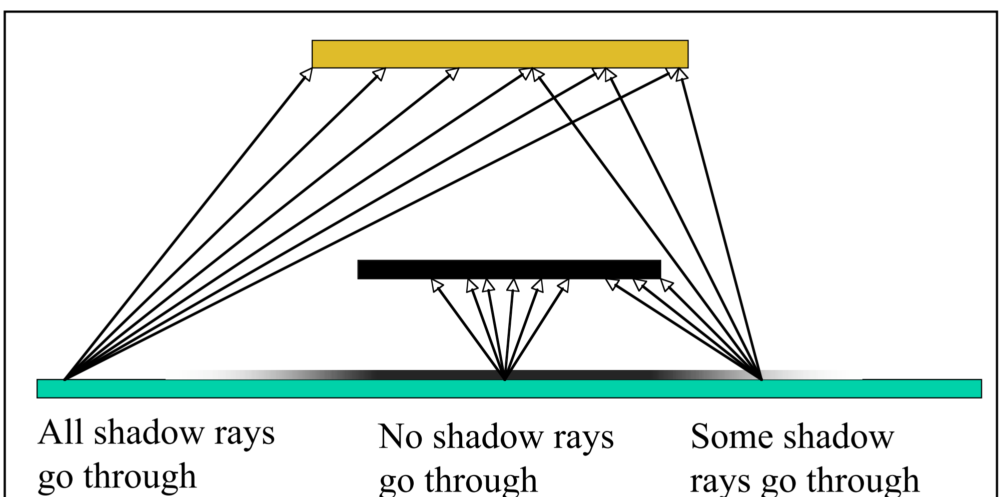
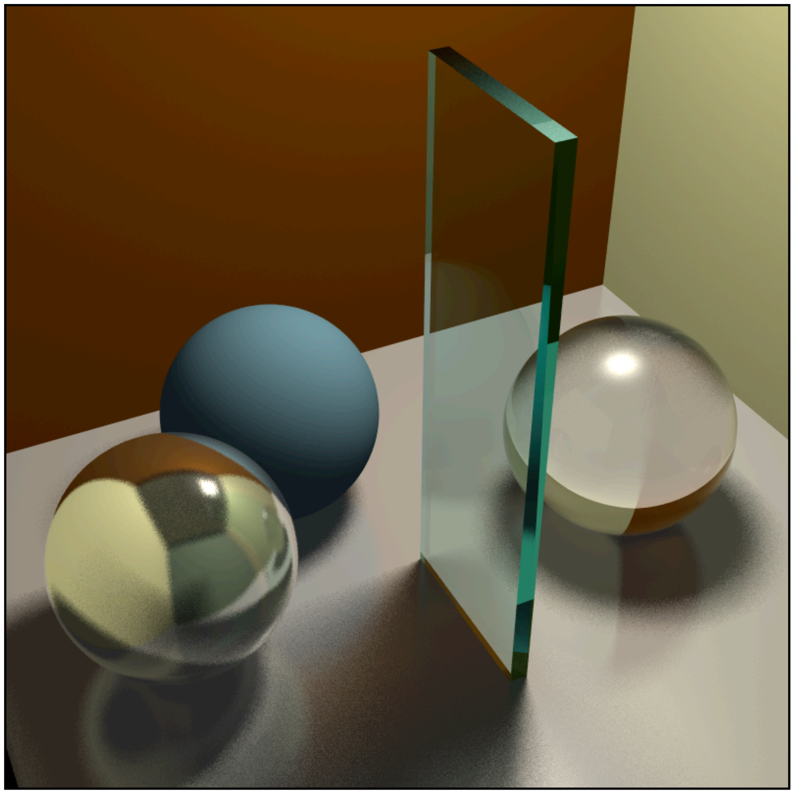


Figure from S. Chenney



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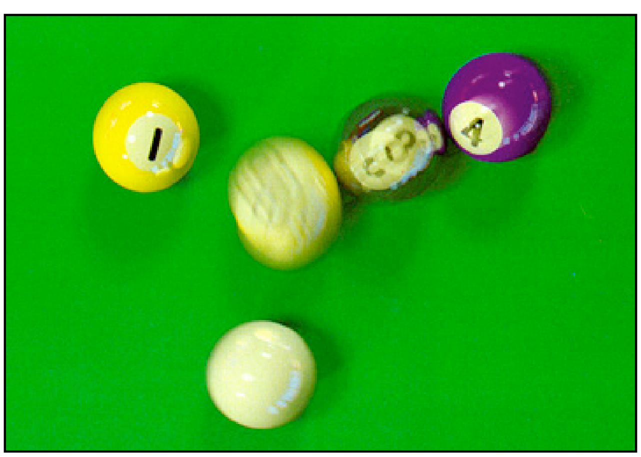
Motion Blur

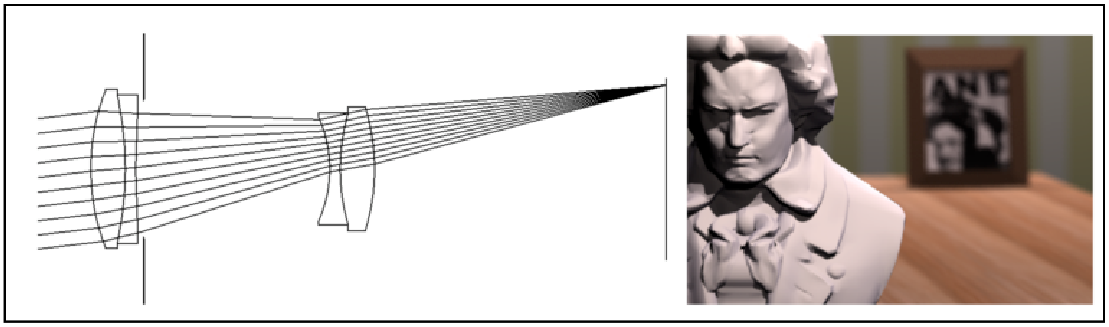
- Distribute rays over *time*
  - More when we talk about animation...



Pool Balls
Tom Porter
RenderMan

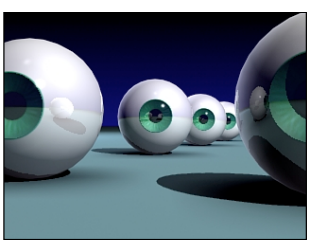
Depth of Field

- Distribute rays over a lens assembly

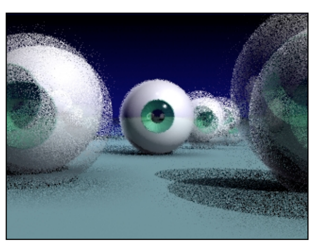


Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

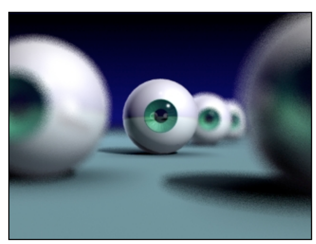
Depth of Field



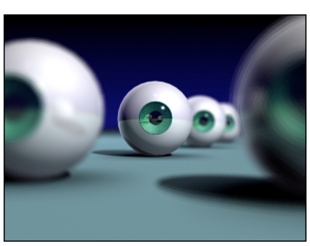
No DoF



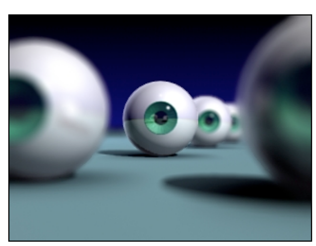
Jittered rays for DoF



More rays

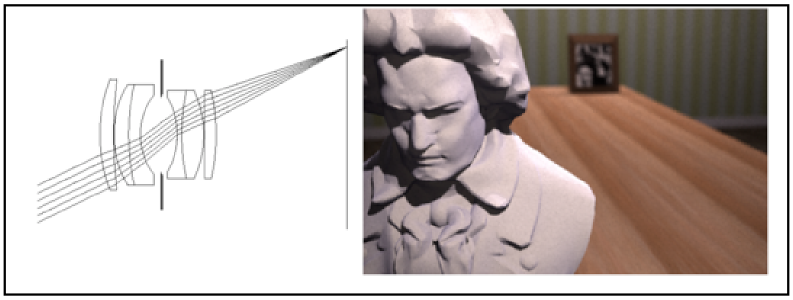


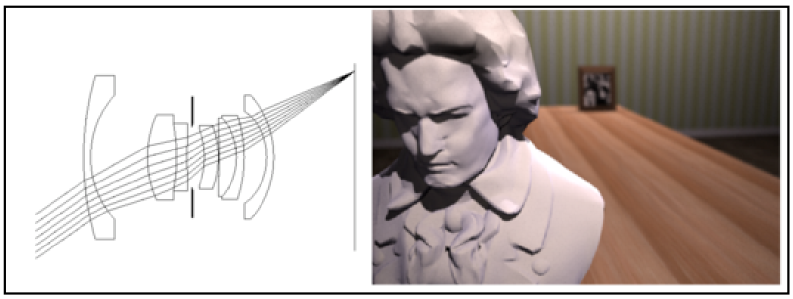
Multiple images for DoF



Even more rays

Other Lens Effects





Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

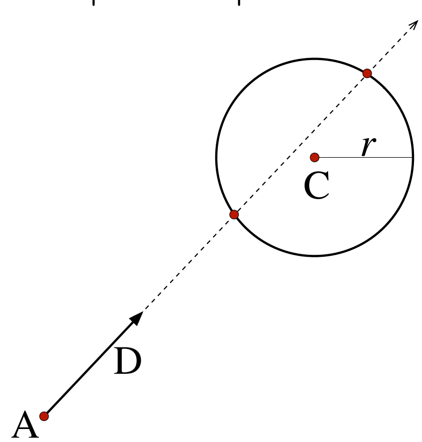
Ray -vs- Sphere Test

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

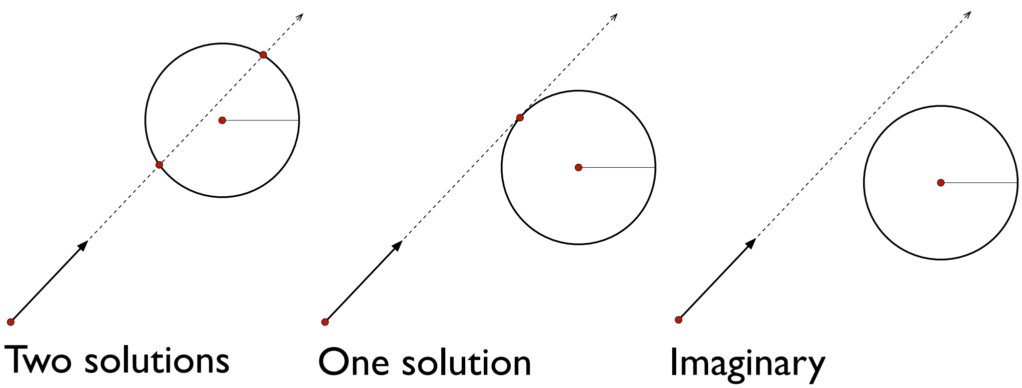
$$|\mathrm{R}(t) - \mathrm{C}|^2 - r^2 = 0$$

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

- Quadratic equation in t



Ray -vs- Sphere Test



Ray -vs- Triangle

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