CS-184: Computer Graphics

Lecture 6: Raytracing

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University of California, Berkeley

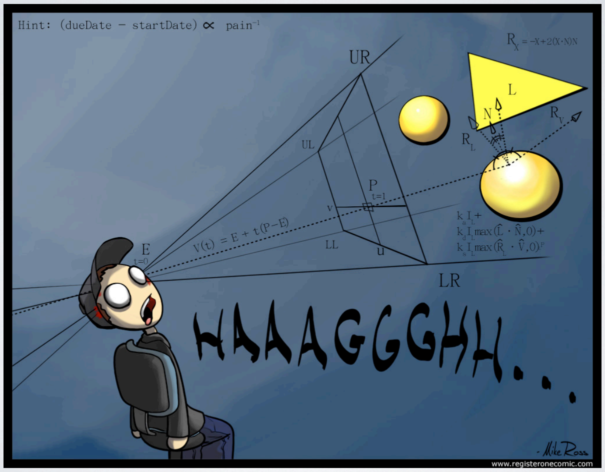
Slides based on those of James O'Brien and Adrien Treuille

Announcements

~~Assignment 3: due Fri Sep 17 by 11pm~~

Assignment 4: due Fri Oct 8 by 11pm

Raytracing Assignment



Today

Raytracing

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

Intersection Tests

- Ray-primitive

Light in an Environment

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

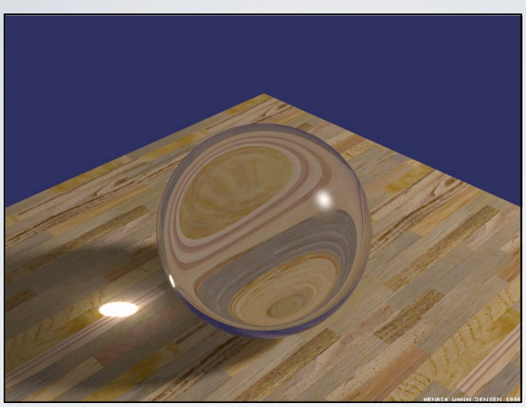
Global Illumination Effects

PCKTWTCH
Kevin Odhner
POV-Ray

Global Illumination Effects

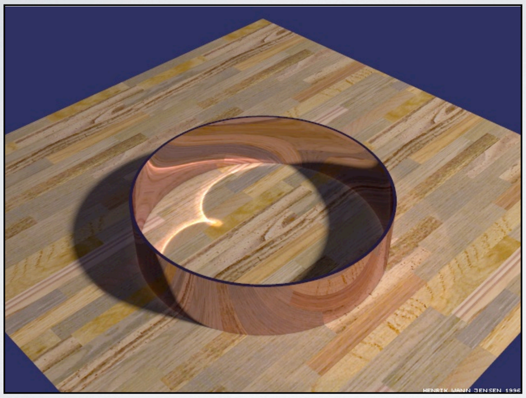
A Philco 6Z4 Vacuum Tube
Steve Anger
POV-Ray

Global Illumination Effects



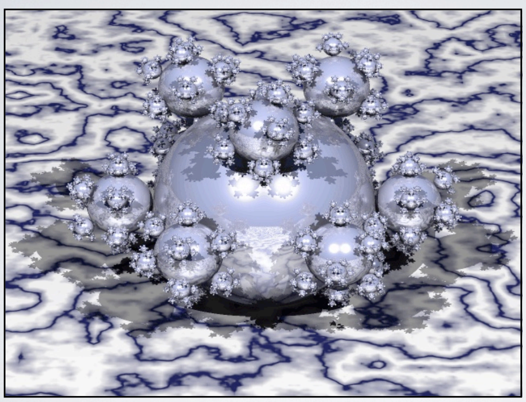
Caustic Sphere
Henrik Jensen
(refraction caustic)

Global Illumination Effects



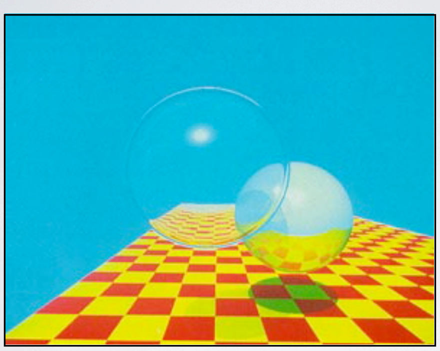
Caustic Ring
Henrik Jensen
(reflection caustic)

Global Illumination Effects



Sphere Flake
Henrik Jensen

Early Raytracing



Turner Whitted

Raytracing

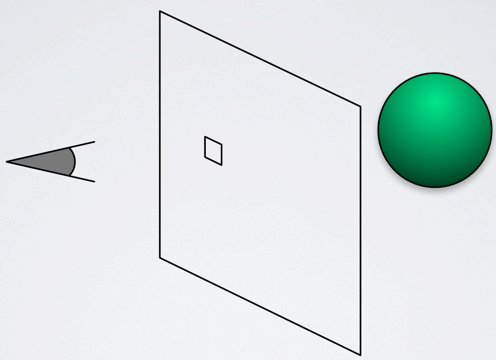
Scan conversion

- 3D → 2D → Image
- Based on transforming geometry
- Details coming in a few lectures

Raytracing

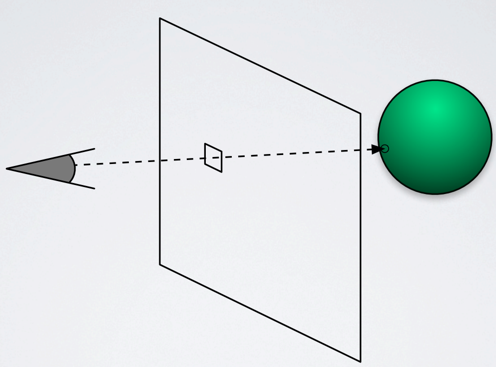
- 3D → Image
- Geometric reasoning about light rays

Raytracing



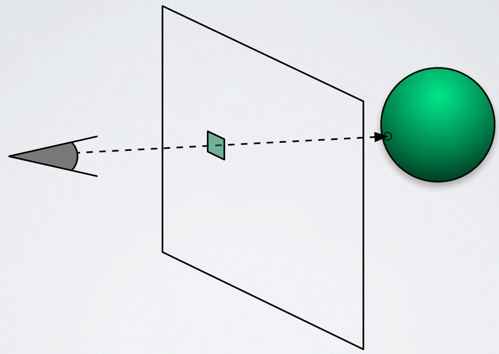
Eye, view plane section, and scene

Raytracing



Launch ray from eye through pixel, see what it hits

Raytracing



Compute color and fill-in the pixel

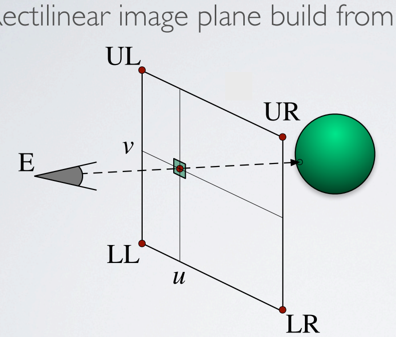
Raytracing

Basic tasks

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

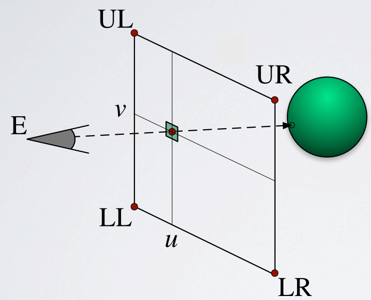
Building Eye Rays

Rectilinear image plane build from four points



Building Eye Rays

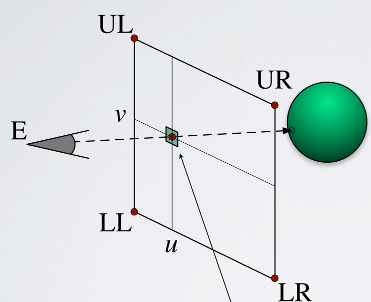
Rectilinear image plane build from four points



E = (0,0,0)
LL = (-1, -1, -1)
LR = (1, -1, -1)
UL = (-1, 1, -1)
UR = (1, 1, -1)

Building Eye Rays

Rectilinear image plane build from four points

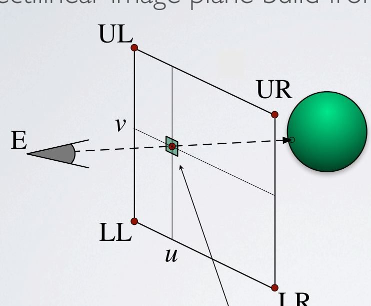


E = (0,0,0)
LL = (-1, -1, -1)
LR = (1, -1, -1)
UL = (-1, 1, -1)
UR = (1, 1, -1)

Compute 3D screen point P given window coordinates u, v between 0 and 1

Building Eye Rays

Rectilinear image plane build from four points



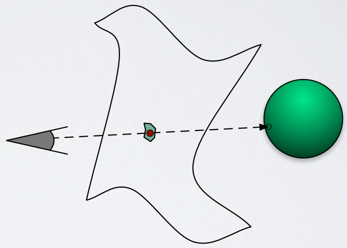
E = (0,0,0)
LL = (-1, -1, -1)
LR = (1, -1, -1)
UL = (-1, 1, -1)
UR = (1, 1, -1)

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

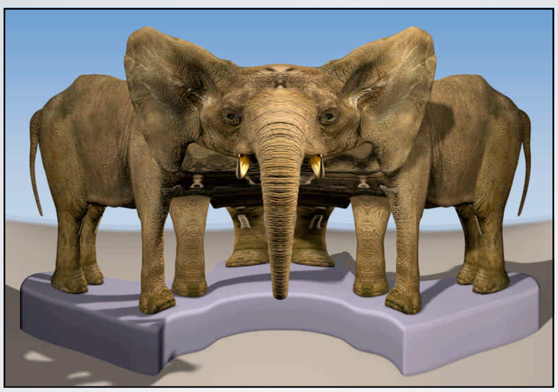
Building Eye Rays

Nonlinear projections

- Non-planar projection surface
- Variable eye location

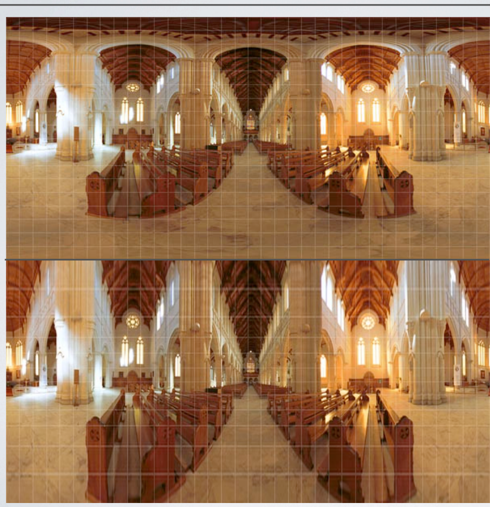


Examples



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*

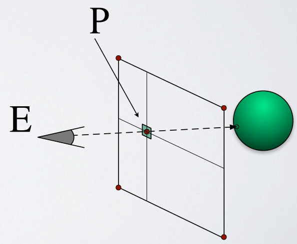
Building Eye Rays

Ray equation

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

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

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

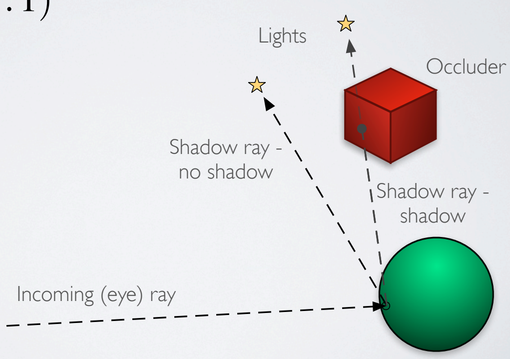


Shadow Rays

Detect shadow by rays to light source

$$R(t) = S + t(L - S)$$

$$t \in [\varepsilon \ldots 1)$$



Shadow Rays

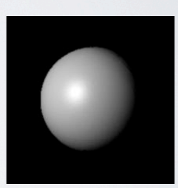
Test for occluder

- 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



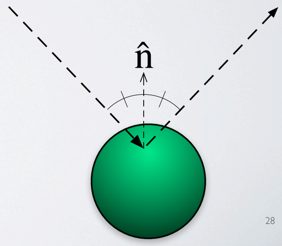
Correct

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

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



Reflection Rays

Recursion Depth

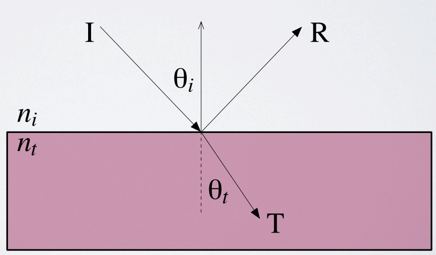
- Truncate at fixed number of bounces
- Multiplier less than J.N.D.

Refracted Rays

Transparent materials bend light

- Snell's Law $\frac{n_i}{n_t} = \frac{\sin\theta_t}{\sin\theta_i}$ where n_i, n_t are indices of refraction

$$\sin\theta_t = \frac{n_i}{n_t}\sin\theta_i$$ (see book for clever alternative formula)



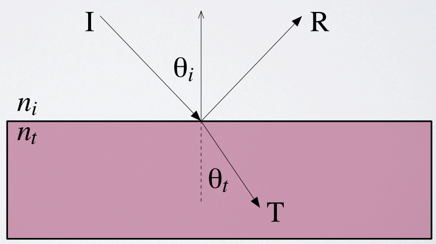
Refracted Rays

Transparent materials bend light

- Snell's Law $\frac{n_i}{n_t} = \frac{\sin\theta_t}{\sin\theta_i}$

$$\sin\theta_t = \frac{n_i}{n_t}\sin\theta_i$$

$\sin\theta_t > 1$ Total (internal) reflection light trapped in material



Total Internal Reflection

Transparent materials bend light

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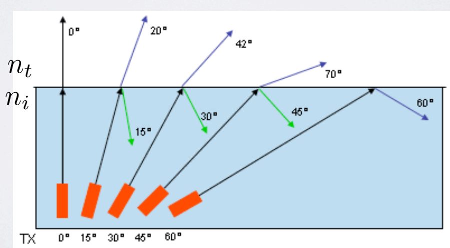
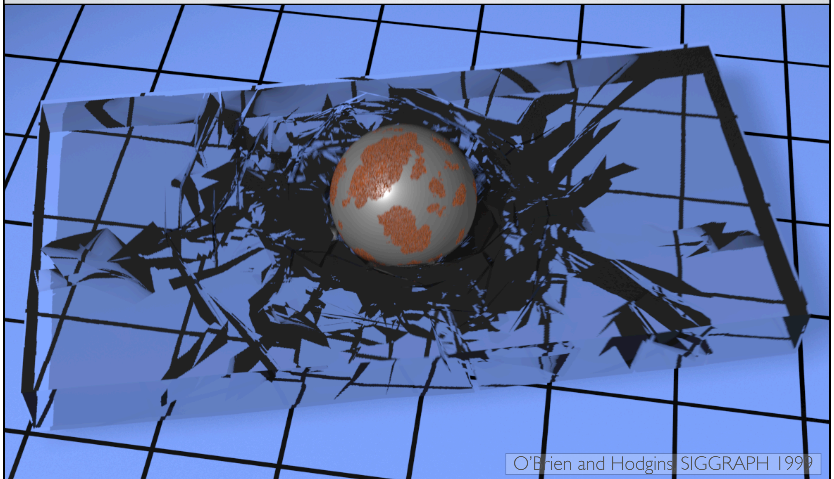


Total Internal Reflection

Refracted Rays



Refracted Rays

For dielectric materials reflectivity varies with incident angle θ

- Schlick approximation to **Fresnel Equations**

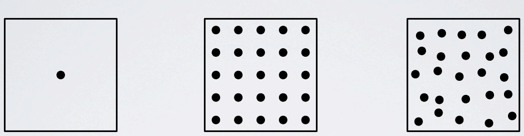
$$k_t(\theta_i) = k_0 + (1 - k_0)(1 - \cos\theta_i)^5$$

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

- Attenuation (due to impurities)
  - Wavelength (color) dependent
  - Exponential with distance

"Distribution" Raytracing

Send multiple rays through each pixel

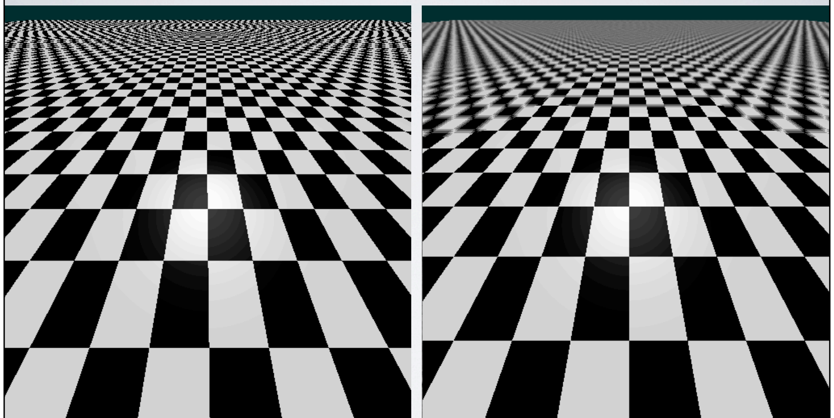


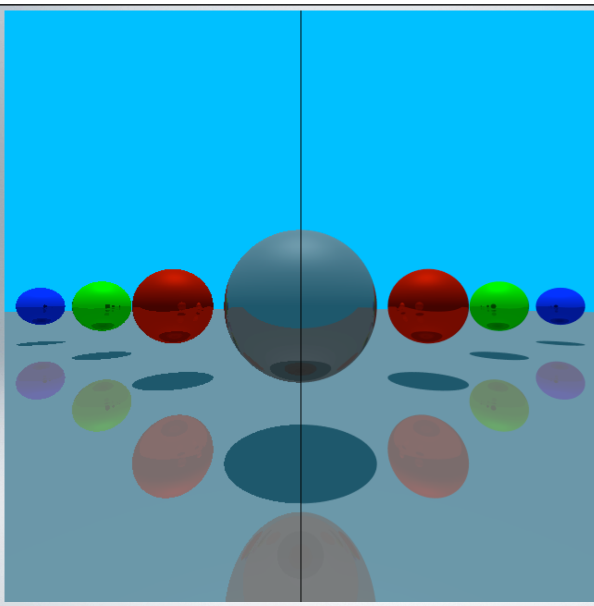
One Sample   5x5 Grid   5x5 Jittered Grid

Average results together

Jittering trades aliasing for noise

"Distribution" Raytracing





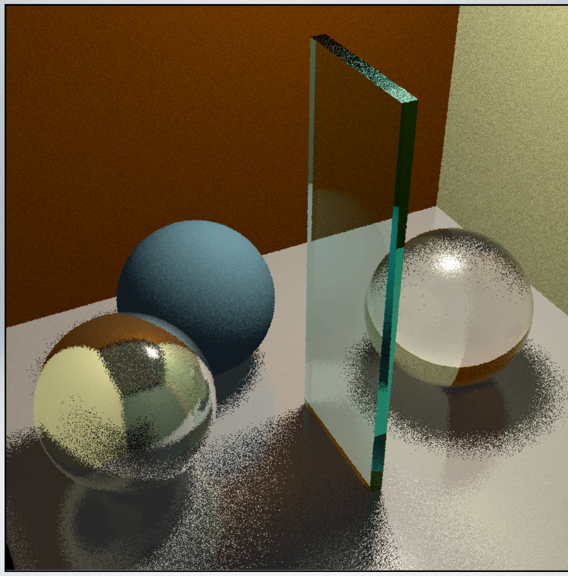
Beverly Chiu and Max Delgadillo
CS 184 2007

"Distribution" Raytracing

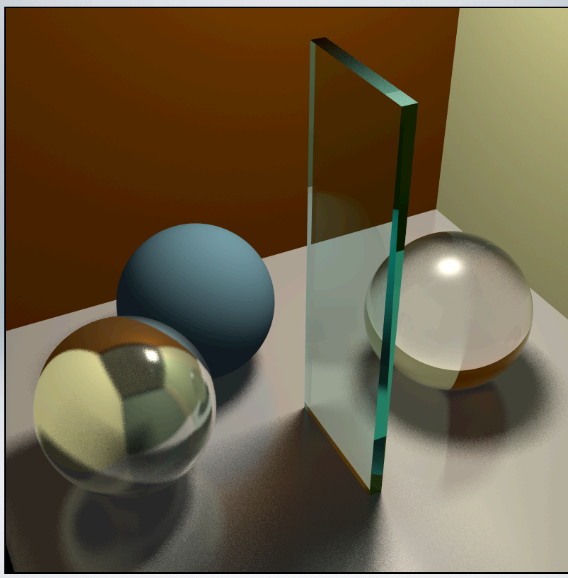
Use multiple rays for reflection and refraction

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

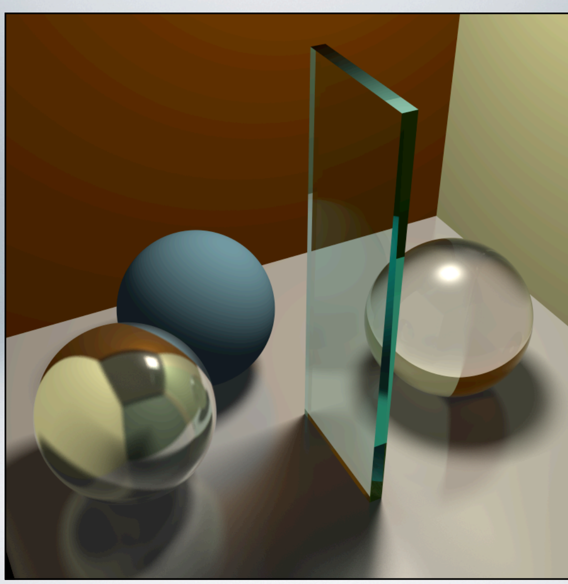
How many rays?



1



16

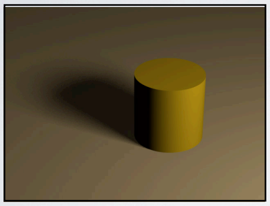


256

Soft Shadows

Soft shadows result from non-point lights

- Some part of light visible, some other part occluded



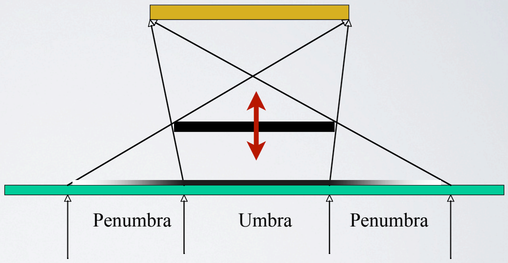


Figure from S. Chenney

Soft Shadows

Distribute shadow rays over light surface

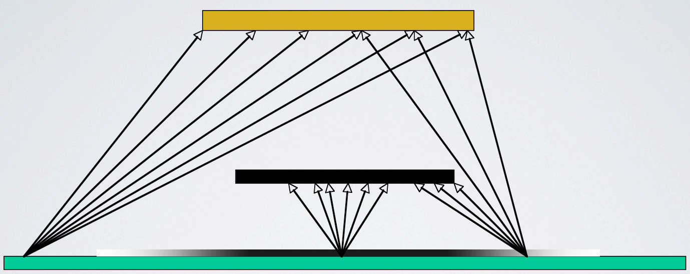
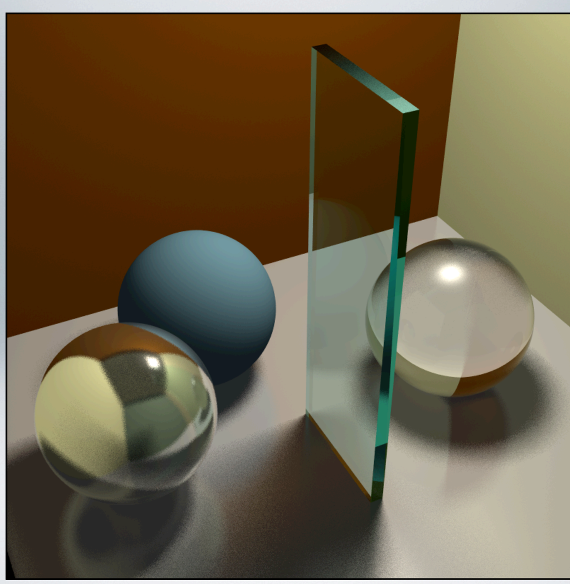


Figure from S. Chenney



Motion Blur

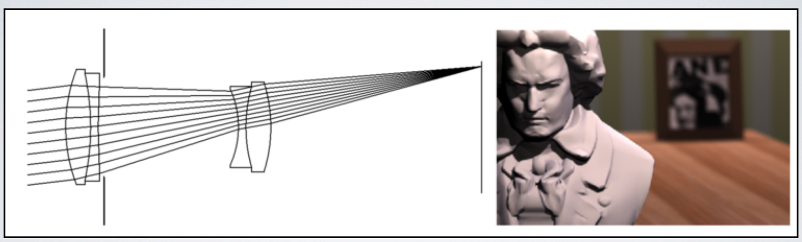
Distribute rays over *time*

- More when we talk about animation...

Pool Balls
Tom Porter
RenderMan

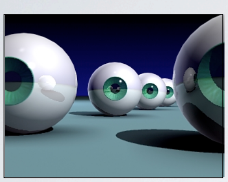
Depth of Field

Distribute rays over a lens assembly

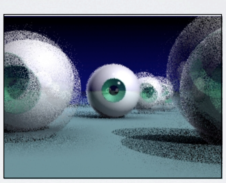


Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

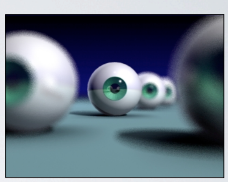
Depth of Field



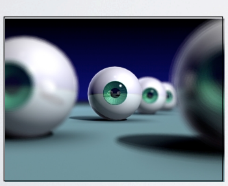
No DoF



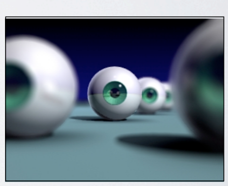
Jittered rays for DoF



More rays

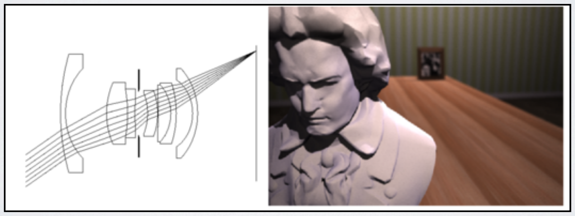


Multiple images for DoF



Even more rays

Other Lens Effects

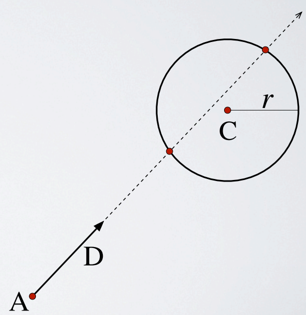


Kolb, Mitchell, and Hanrahan
SIGGRAPH 1995

Ray -vs- Sphere Test

Ray equation: $\mathrm{R}(t) = \mathrm{A} + t\,\mathrm{D}$

Implicit equation for sphere: $|\mathrm{X} - \mathrm{C}|^2 - r^2 = 0$



Ray -vs- Sphere Test

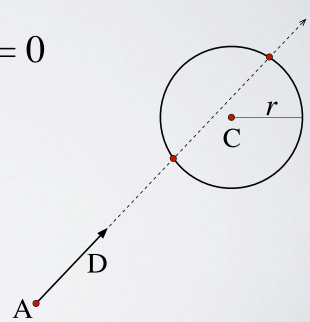
Ray equation: $\mathrm{R}(t) = \mathrm{A} + t\,\mathrm{D}$

Implicit equation for sphere: $|\mathrm{X} - \mathrm{C}|^2 - r^2 = 0$

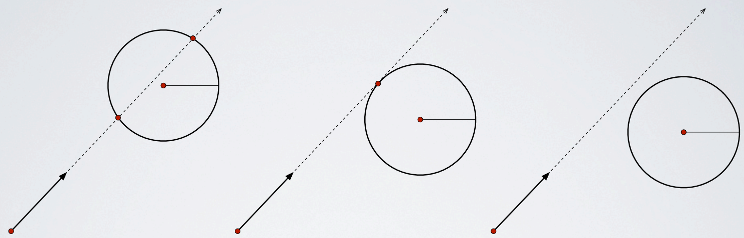
Combine: $|\mathrm{R}(t) - \mathrm{C}|^2 - r^2 = 0$

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

Quadratic equation in t



Ray -vs- Sphere Test

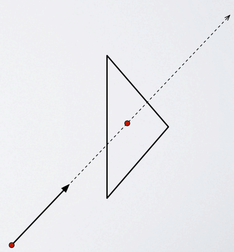


Ray -vs- Triangle

Ray equation: $\mathrm{R}(t) = \mathrm{A} + t\,\mathrm{D}$

Triangle in barycentric coordinates:

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



Ray -vs- Triangle

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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