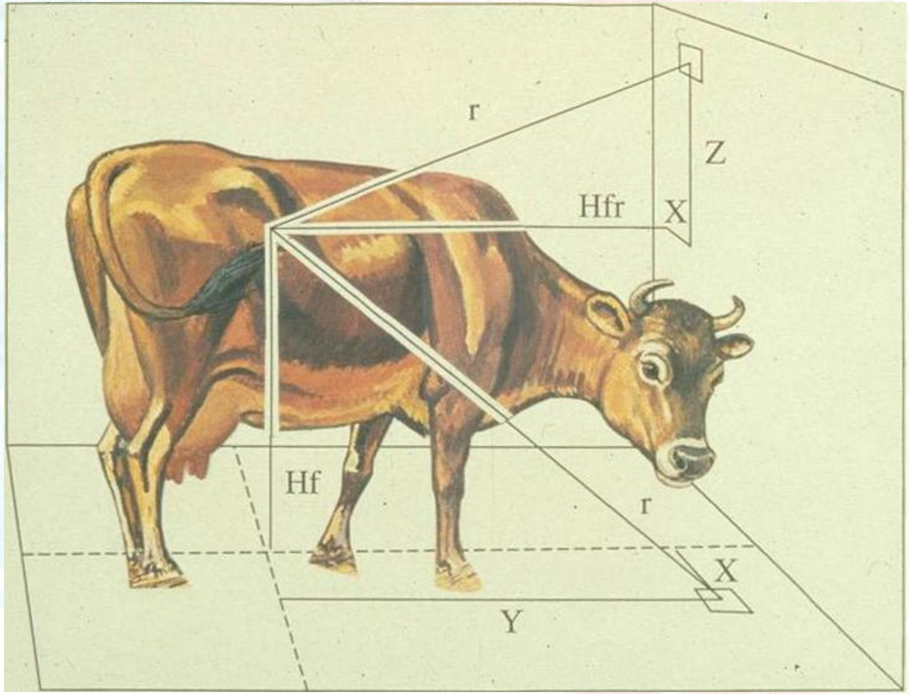
CSCI 4530/6530 Advanced Computer Graphics

https://www.cs.rpi.edu/~cutler/classes/advancedgraphics/S25/

Lecture 12: Local vs. Global Illumination & Radiosity



An early application of radiative heat transfer in stables.

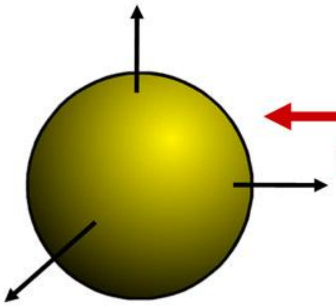
Worksheet: Ray Tracing

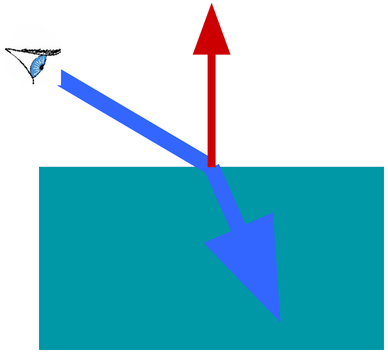
multicolored painted diffuse (matte) mural wall
function M(x,y,z) returns the RGB color at the specified location.

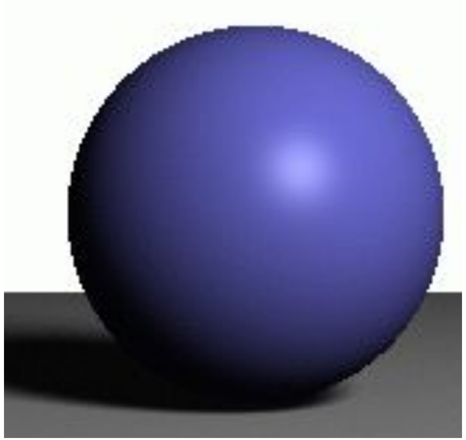
Red's Dream, Pixar, 1987

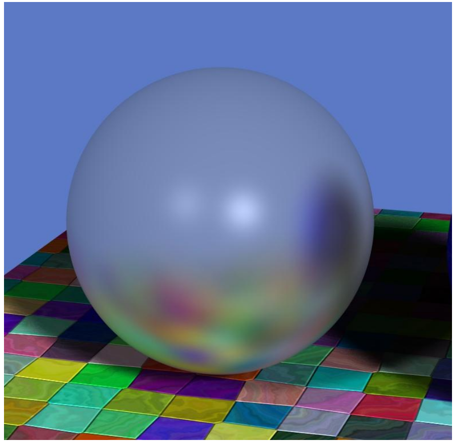
Last Time?

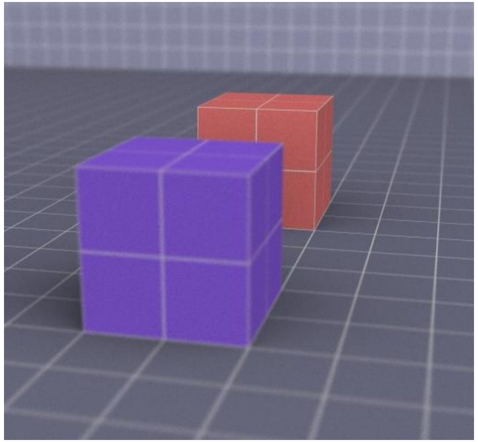
- Ray Casting & Ray-Object Intersection
- Recursive Ray Tracing
- Distributed Ray Tracing











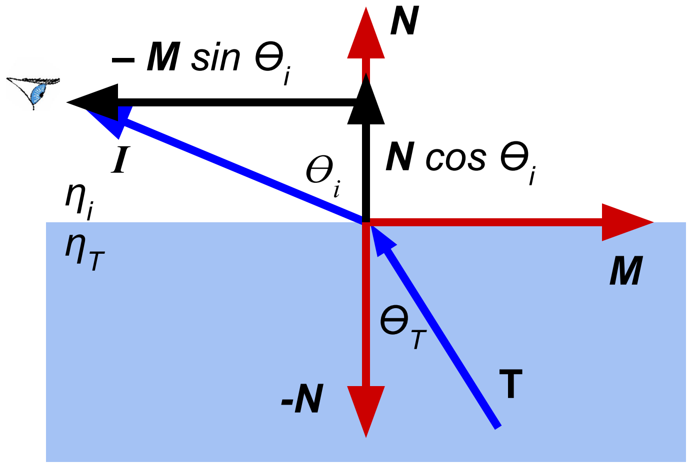
Refraction

Note: The math works the same tracing the ray either "forwards" or "backwards", but it's really easy to get confused and have a sign error in the direction.

$$\mathbf{I} = \mathbf{N}\cos\Theta_i - \mathbf{M}\sin\Theta_i$$

$$\mathbf{M} = (\mathbf{N}\cos\Theta_i - \mathbf{I}) / \sin\Theta_i$$

$$\begin{aligned}
\mathbf{T} &= -\mathbf{N}\cos\Theta_T + \mathbf{M}\sin\Theta_T \\
&= -\mathbf{N}\cos\Theta_T + (\mathbf{N}\cos\Theta_i - \mathbf{I})\sin\Theta_T / \sin\Theta_i \\
&= -\mathbf{N}\cos\Theta_T + (\mathbf{N}\cos\Theta_i - \mathbf{I})\,\eta_r \\
&= [\,\eta_r\cos\Theta_i - \cos\Theta_T\,]\,\mathbf{N} - \eta_r\,\mathbf{I} \\
&= [\,\eta_r\cos\Theta_i - \sqrt{(1 - \sin^2\Theta_T)}\,]\,\mathbf{N} - \eta_r\,\mathbf{I} \\
&= [\,\eta_r\cos\Theta_i - \sqrt{(1 - \eta_r^2\sin^2\Theta_i)}\,]\,\mathbf{N} - \eta_r\,\mathbf{I} \\
&= [\,\eta_r\cos\Theta_i - \sqrt{(1 - \eta_r^2(1 - \cos^2\Theta_i))}\,]\,\mathbf{N} - \eta_r\,\mathbf{I} \\
&= [\,\eta_r(\mathbf{N}\cdot\mathbf{I}) - \sqrt{(1 - \eta_r^2(1 - (\mathbf{N}\cdot\mathbf{I})^2))}\,]\,\mathbf{N} - \eta_r\,\mathbf{I}
\end{aligned}$$



Snell-Descartes Law:

$$\eta_i \sin\Theta_i = \eta_T \sin\Theta_T$$

$$\frac{\sin\Theta_T}{\sin\Theta_i} = \frac{\eta_i}{\eta_T} = \eta_r$$

- *Total internal reflection when the square root is imaginary*
- *Don't forget to normalize!*

Total Internal Reflection

From "Color and Light in Nature"
by Lynch and Livingston

Fig. 3.7A The optical manhole. From under water, the entire celestial hemisphere is compressed into a circle only 97.2° across. The dark boundary defining the edges of the manhole is not sharp due to surface waves. The rays are analogous to the crepuscular type seen in hazy air, Section 1.9. (Photo by D. Granger)

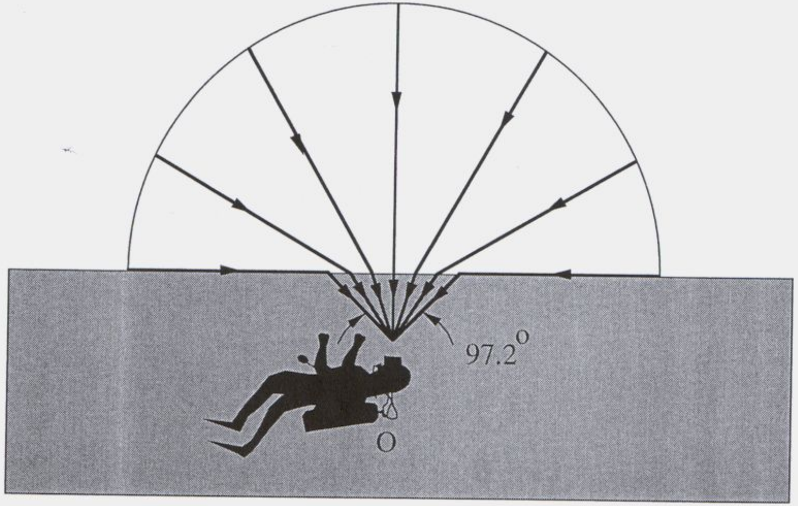
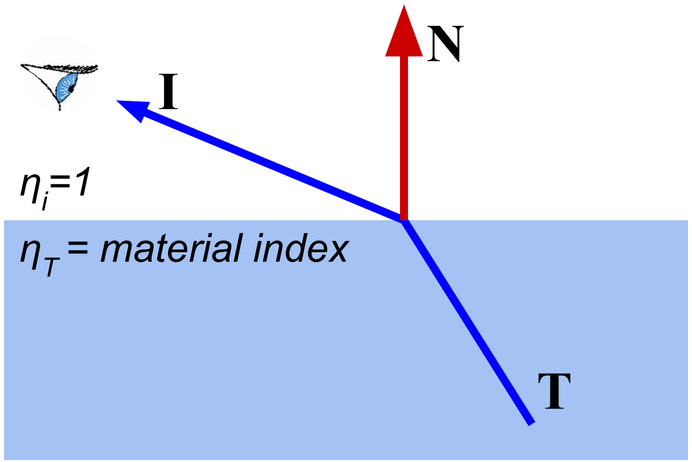
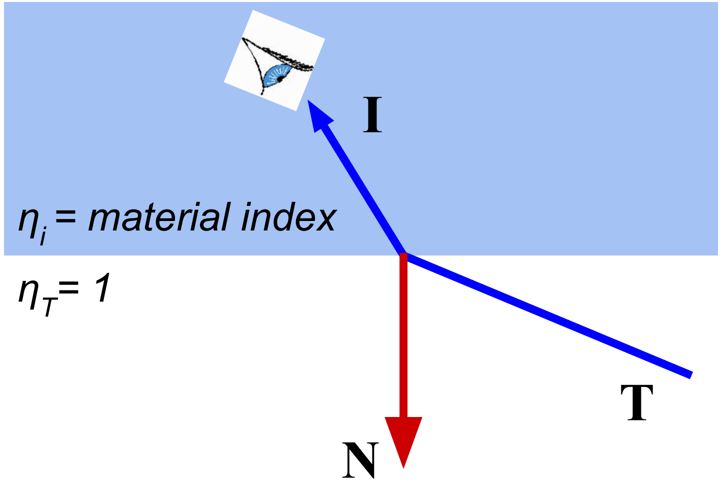


Fig. 3.7B The optical manhole. Light from the horizon (angle of incidence = 90°) is refracted downward at an angle of 48.6°. This compresses the sky into a circle with a diameter of 97.2° instead of its usual 180°.

Refraction & the Sidedness of Objects

- Make sure you know whether you are entering or leaving the transmissive material:





Light bends towards the surface normal when entering a denser material.
It bends away from the normal when leaving the denser material.

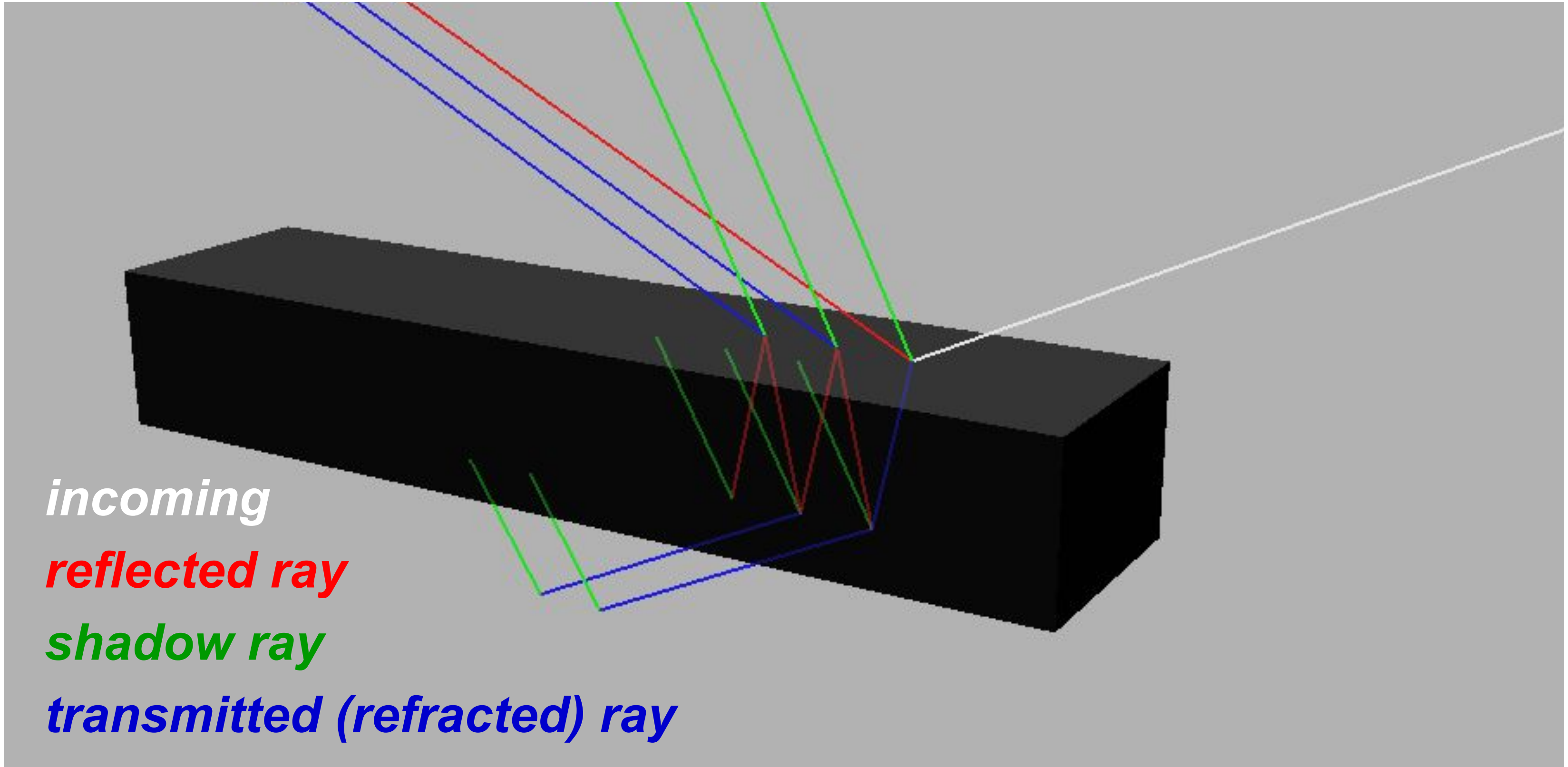
Refraction & the Sidedness of Objects

What about intersecting transparent objects?

Image by Henrik Wann Jensen

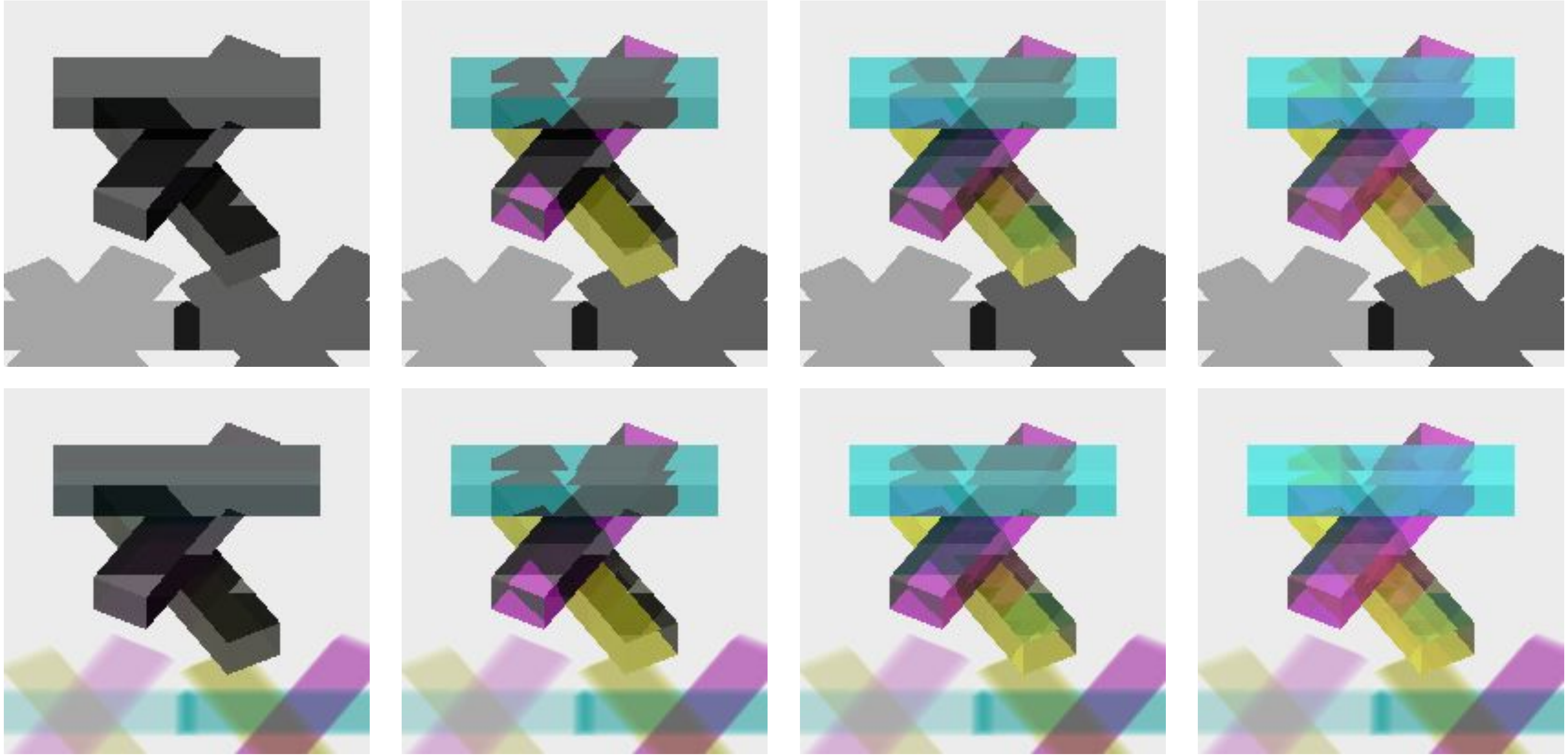
Ray Debugging

- Visualize the ray tree for single image pixel



Shadows of Transparent Objects

- Is this physically accurate?



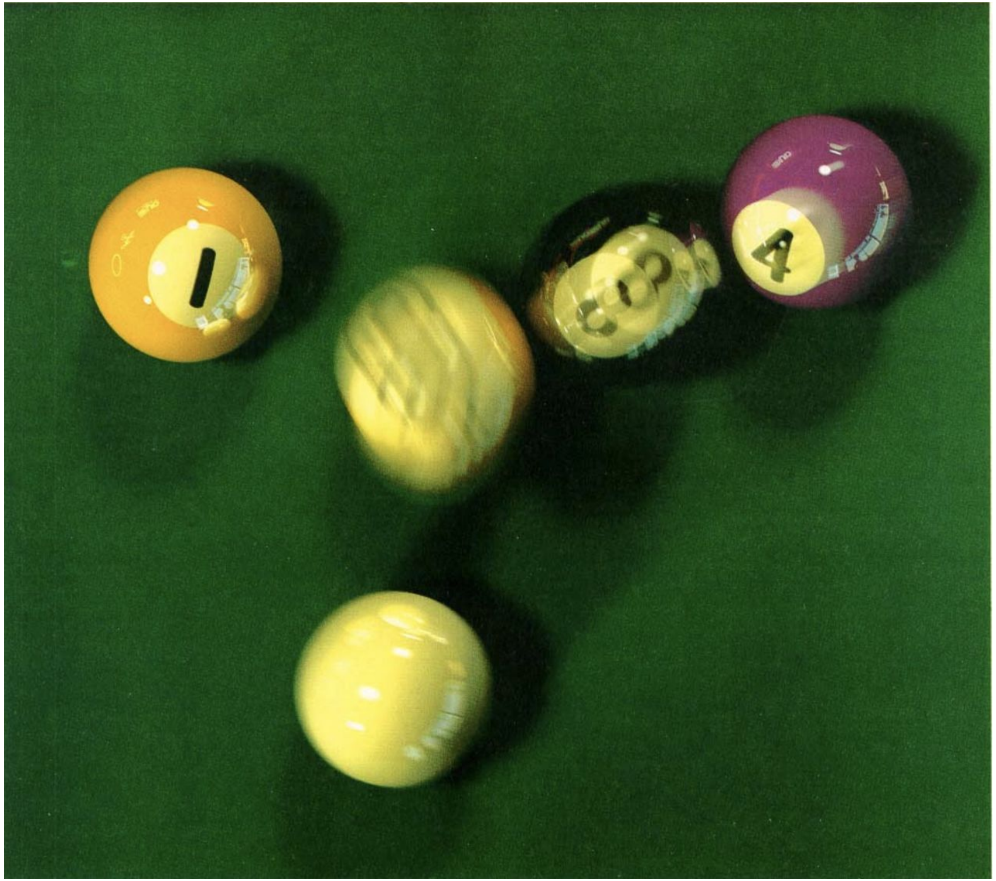
Today

- Worksheet
- Paper for Today: Distributed Ray Tracing
  - Soft shadows
  - Antialiasing (getting rid of jaggies)
  - Glossy reflection
  - Motion blur
  - Depth of field (focus)
- Local Illumination and Phong Material Model
- Optional Paper for Today: Anisotropic Reflection
- Global Illumination and Brief Introduction to Radiosity
- Paper for Next Time

Reading for Today

Everyone should read this paper for HW3

"Distributed Ray Tracing",
Cook, Porter, & Carpenter,
SIGGRAPH 1984.

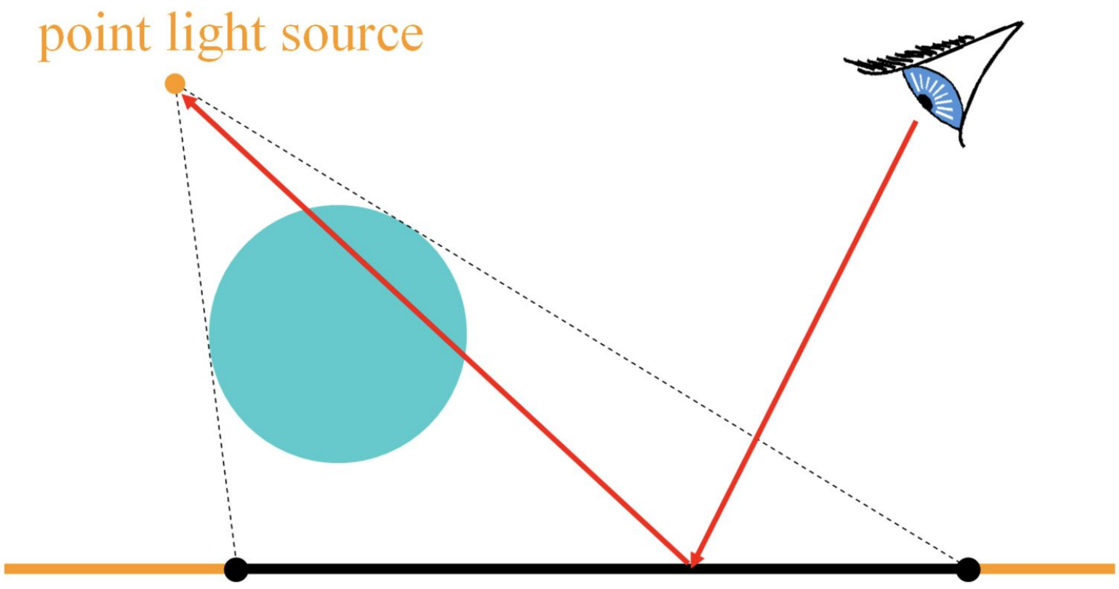


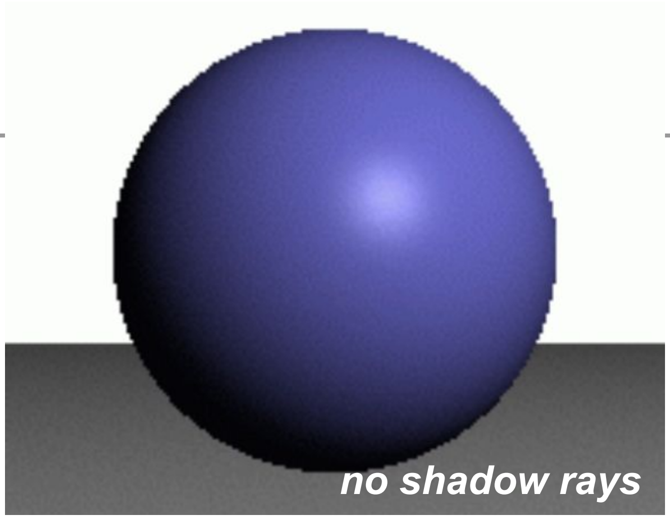
- So many effects can be re-created just by tracing more rays!
  - Unified, physically-grounded method.
  - Makes scenes more realistic. Obvious once you the improvements.
- Not distributed as in *parallel computing*. Rather about *spatial sampling*.
- Paper could benefit from more diagrams
- Paper could go into more detail about the correct way to sample distribution. How exactly are the random rays generated? How many?
  - Might be hard to reproduce results from paper alone.
- No runtimes. No discussion of performance limitations.
  - Is it really "practically no more expensive than standard ray tracing?"
- Want more detail on first equation in Section 2

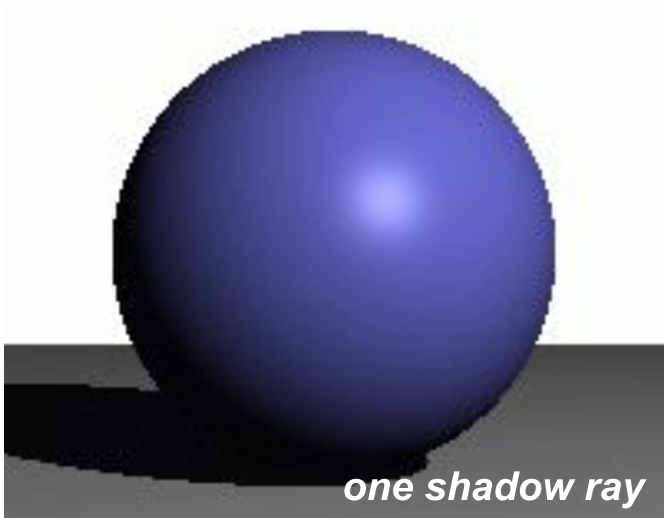
  NOTE: "The Rendering Equation" (will be published 2 years after this)
- *Multiple references to forthcoming/unpublished references*

Ray Tracing Shadows

- One shadow ray
  per intersection
  per point light source



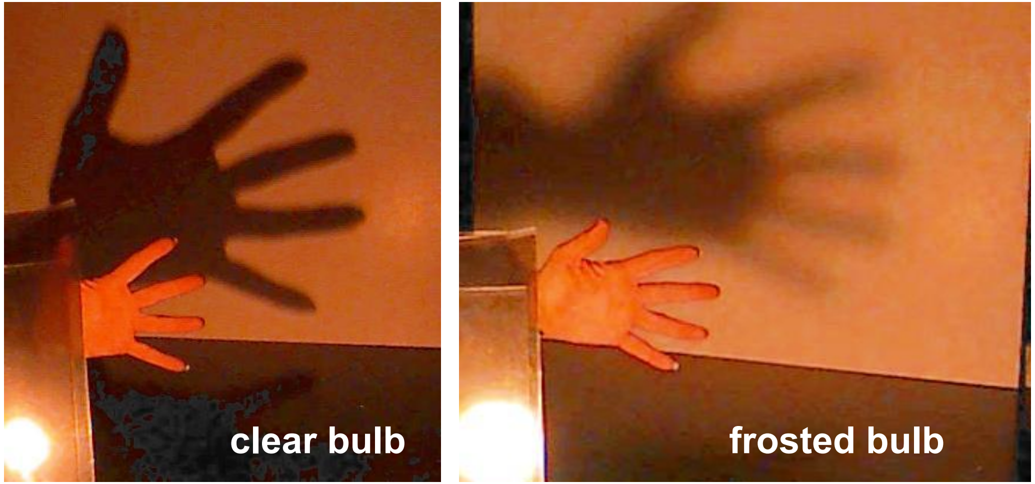




Shadows & Light Sources

http://3media.initialized.org/photos/2000-10-18/index_gall.htm

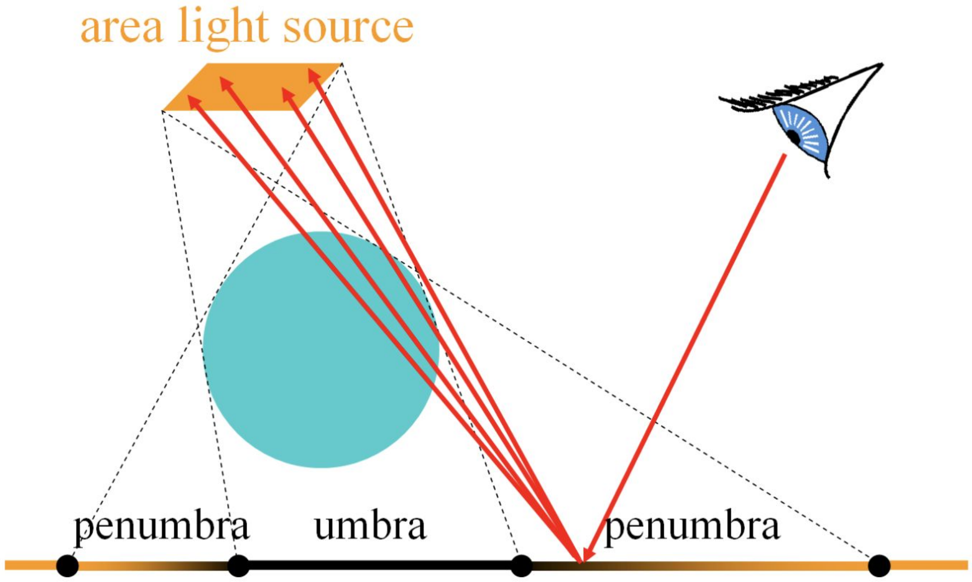
http://www.davidfay.com/index.php

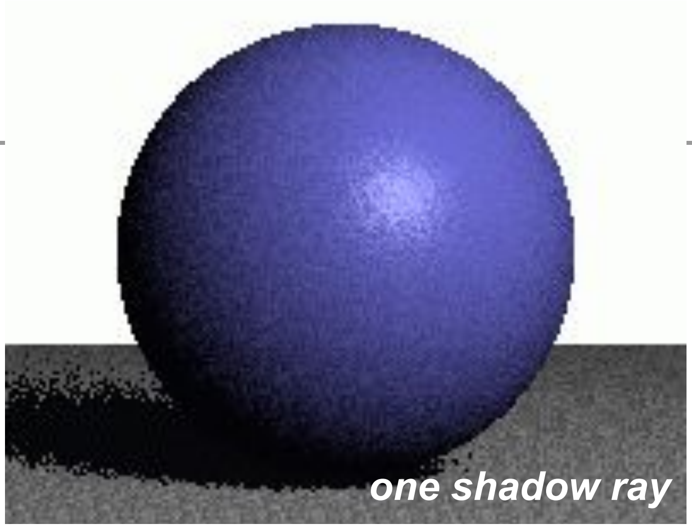


http://www.pa.uky.edu/~sciworks/light/preview/bulb2.htm

Ray Tracing Soft Shadows

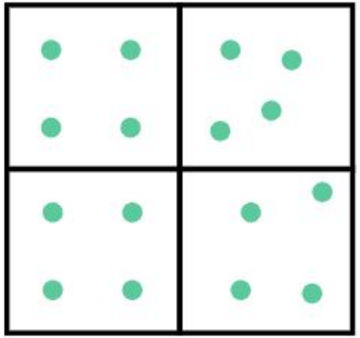
- multiple shadow rays to sample area light source

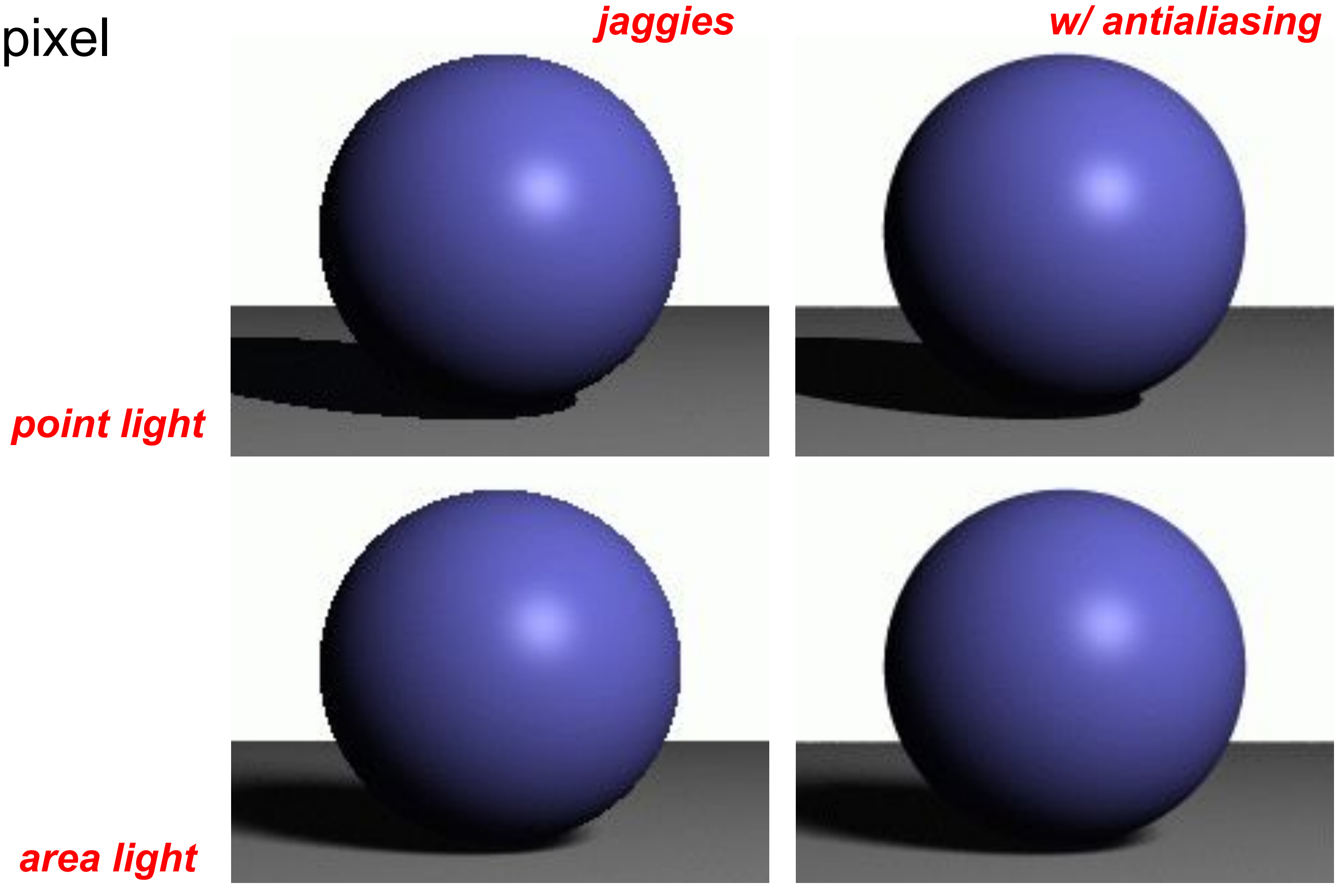




Antialiasing – Supersampling

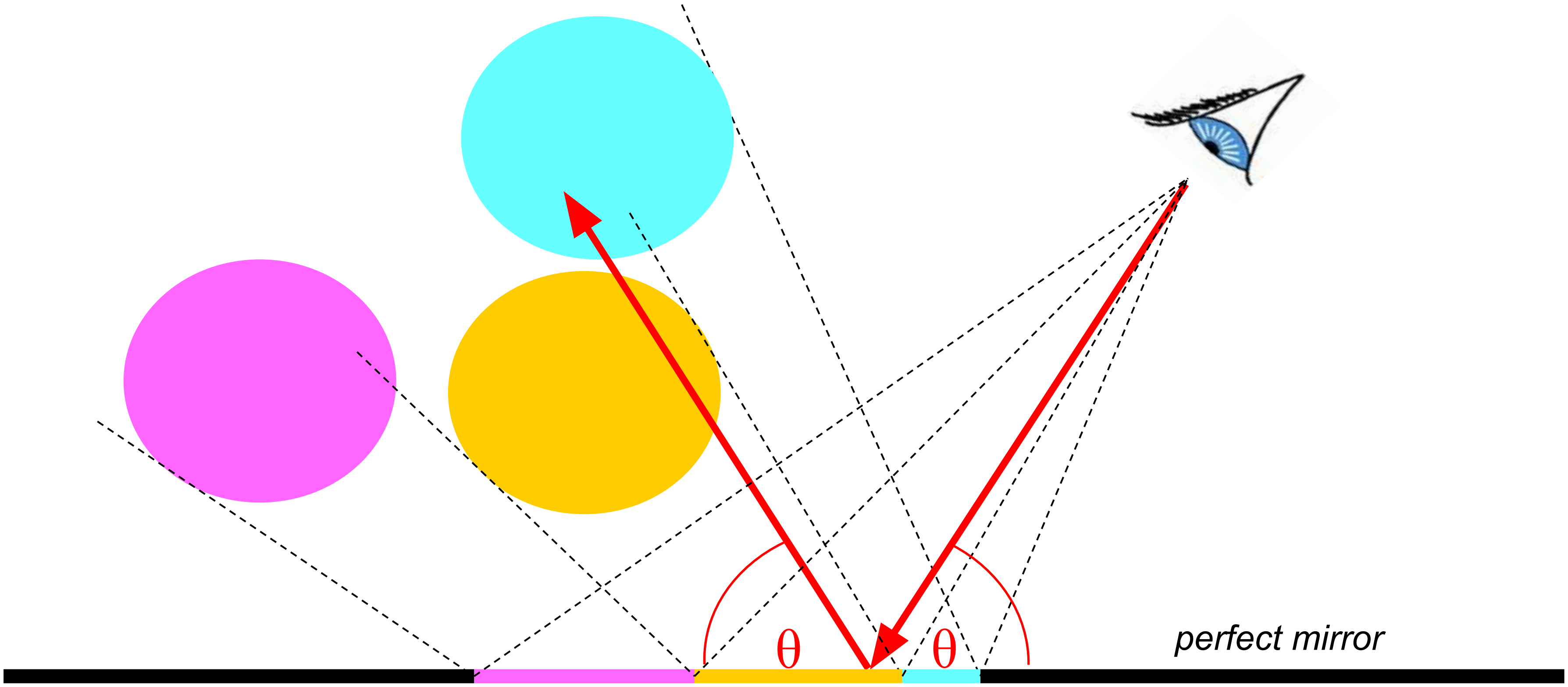
- multiple rays per pixel





Ray Tracing Perfect Mirror Reflection

- one reflection ray per intersection



Ray Tracing Glossy Reflection

- multiple reflection rays

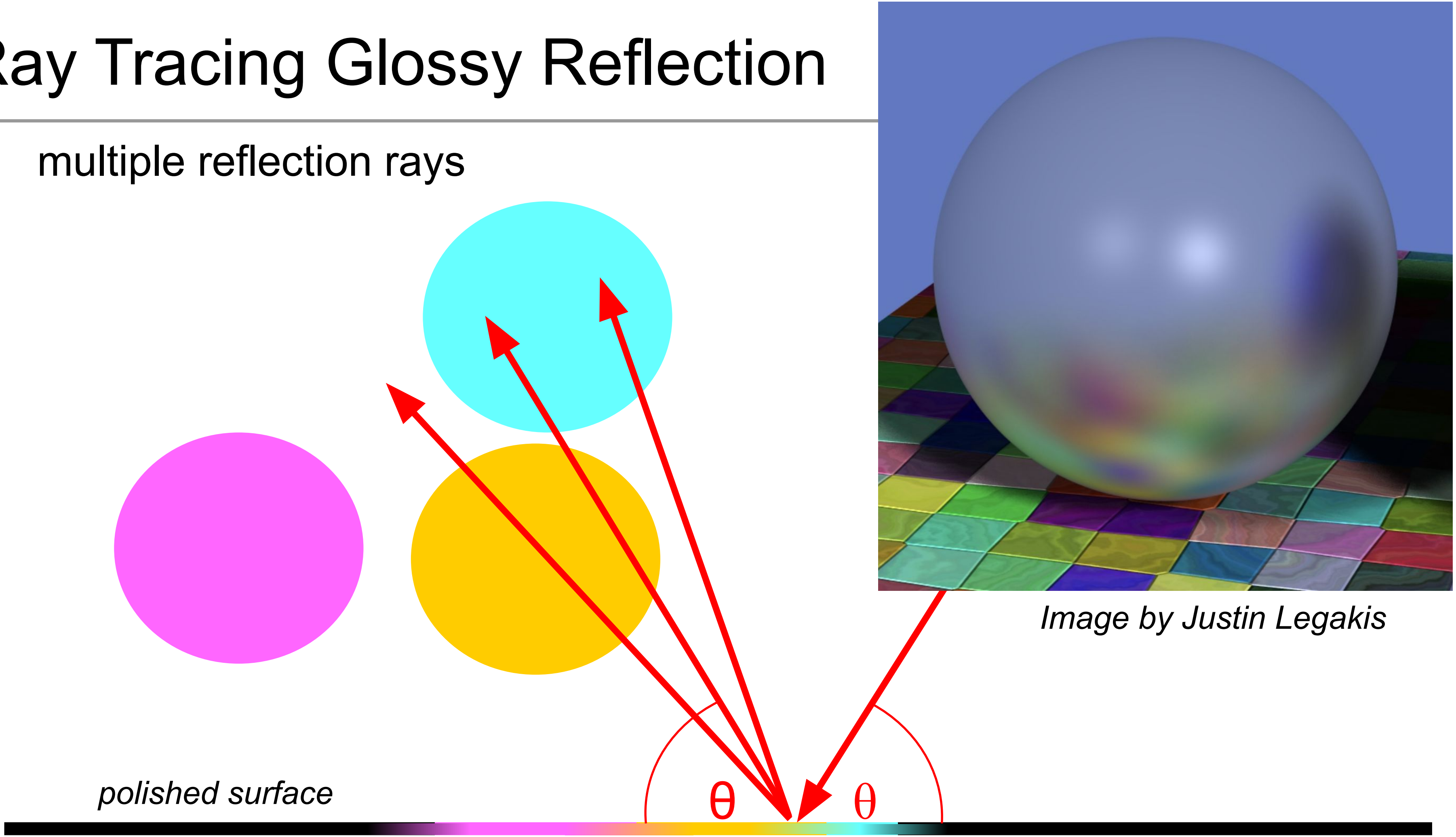
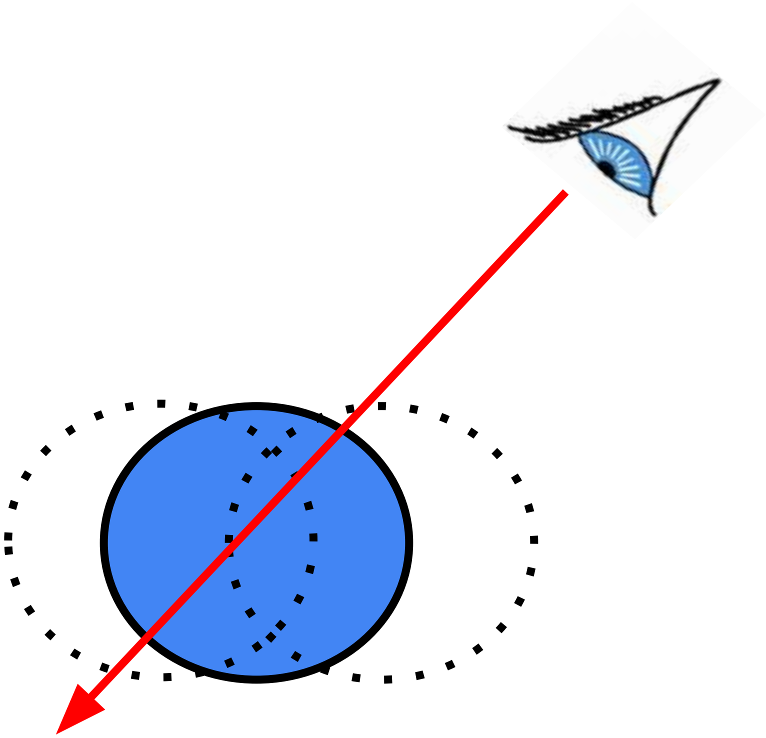


Image by Justin Legakis

Ray Tracing Motion Blur

- Sample objects temporally



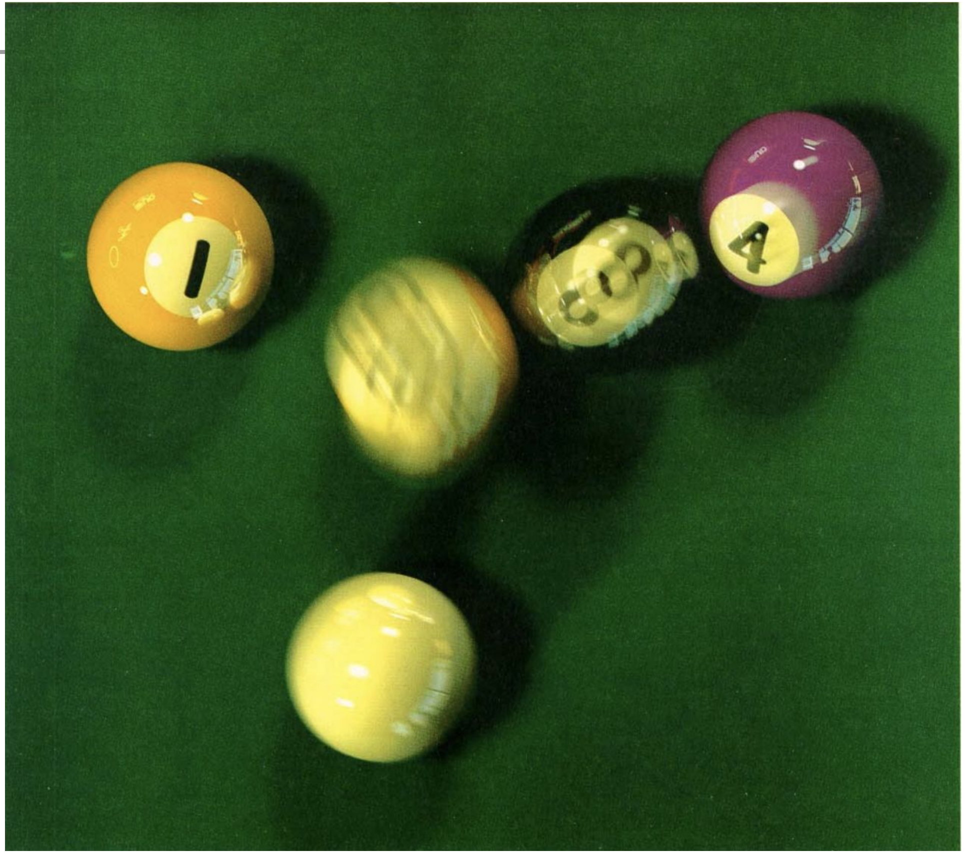
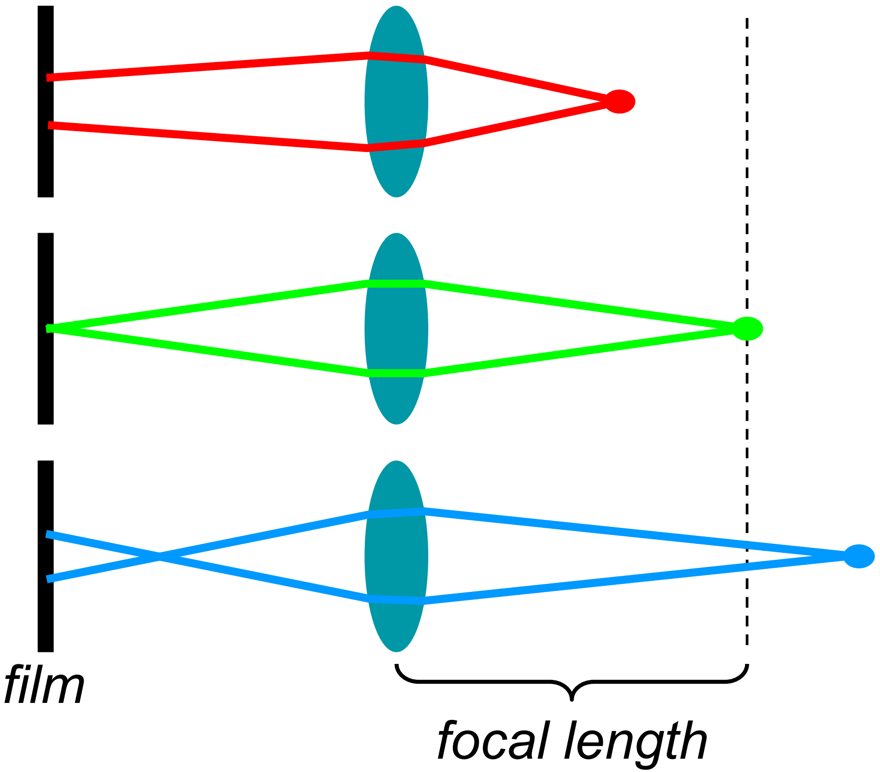


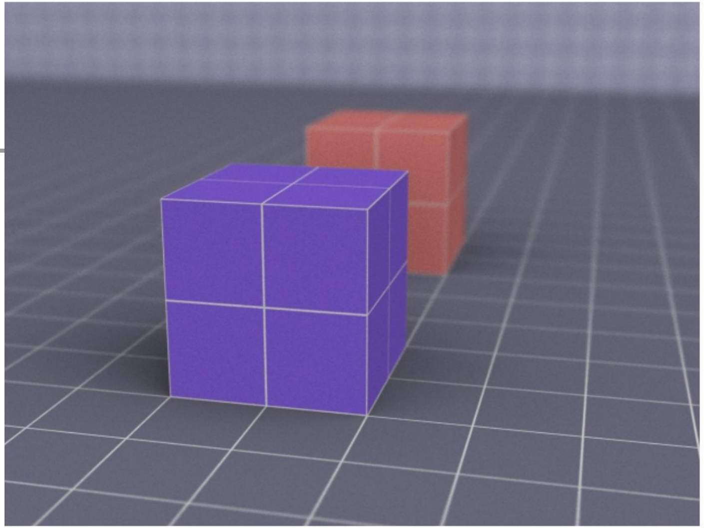
Image by Rob Cook

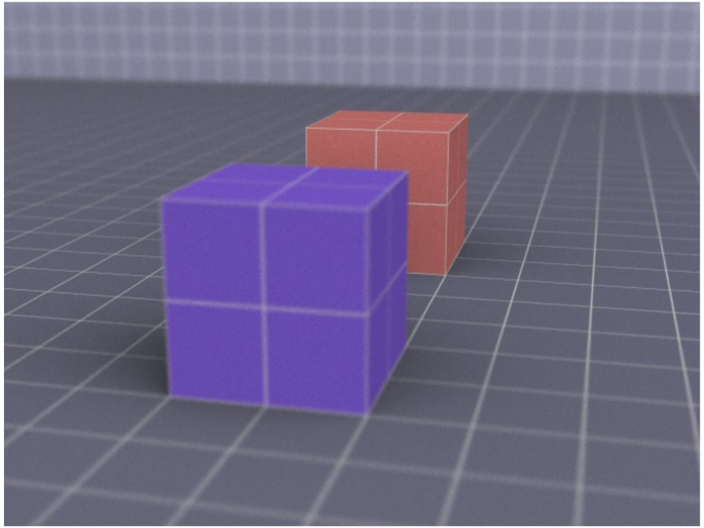
Depth of Field

Images by Justin Legakis

- multiple rays per pixel

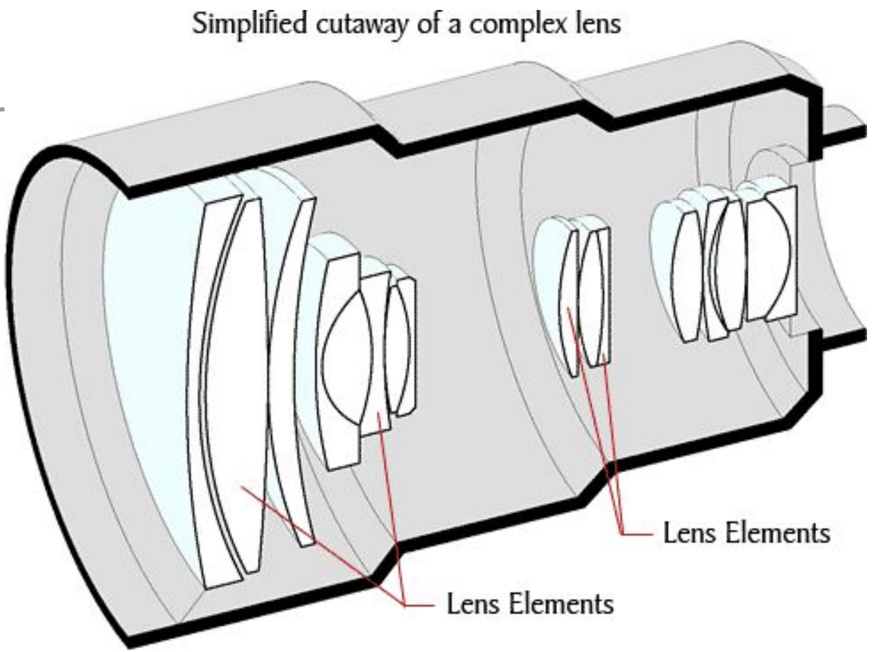






Depth of Field

- We could model the geometry of a real-world camera lens & simulate the refraction of a cone of rays through the lens….
- But a simple formula to determine the radius for an approximate and equivalent "circle of confusion" is sufficient.



https://oneslidephotography.com/facts-and-myths-about-camera-lenses/

- But we still need to trace ALOT of rays to get a satisfyingly smooth & blurry background.

- *NOTE: There are cheaper hacks to mimic the background blur!*

Ray Tracing

Does it ever end?

trace ray

Intersect all objects

color = ambient term

For every light

  cast shadow ray

  color += local shading term

If mirror

  color += $color_{refl}$ * trace reflected ray

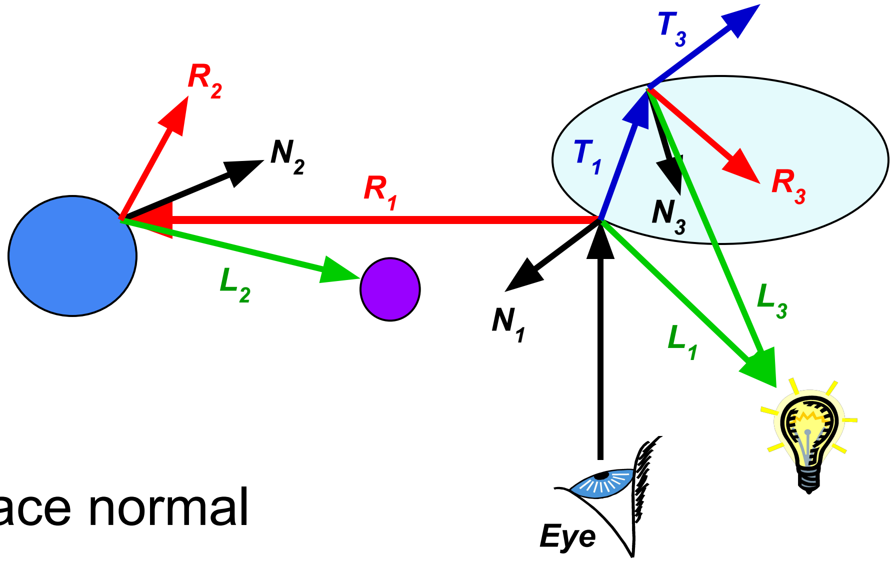
If transparent

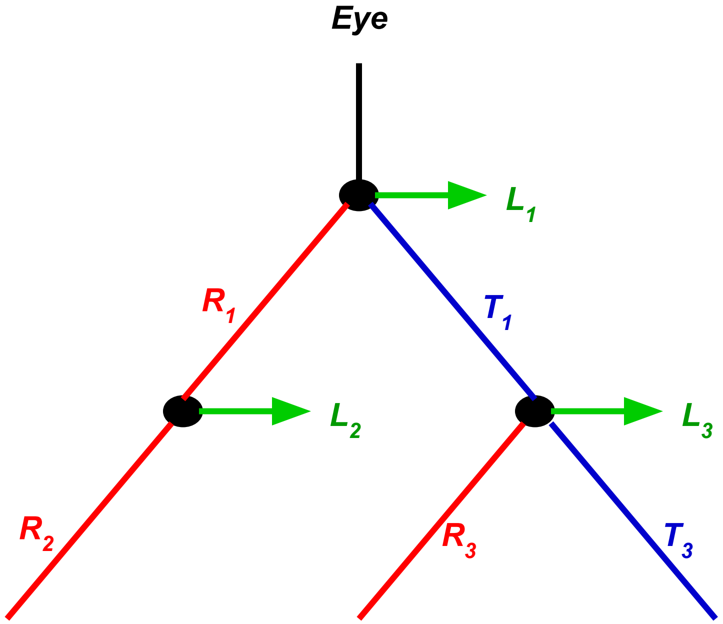
  color += $color_{trans}$ * trace transmitted ray

Stopping criteria:

- Recursion depth: Stop after a number of bounces
- Ray contribution: Stop if reflected / transmitted contribution becomes too small

The Ray Tree





N_i surface normal

R_i reflected ray

L_i shadow ray

T_i transmitted (refracted) ray

Big O Notation Complexity?

Ray Tracing Algorithm Analysis

- Ray casting
- Lots of primitives
- Recursive
- Distributed Ray Tracing Effects
  - Soft shadows
  - Anti-aliasing
  - Glossy reflection
  - Motion blur
  - Depth of field

cost ≈ height * width *
num primitives *
intersection cost *
size of recursive ray tree *
num shadow rays *
num supersamples *
num glossy rays *
num temporal samples *
num focal samples *
. . .

can we reduce this?

these can serve double duty

Today

- Worksheet
- Paper for Today: Distributed Ray Tracing
- Local Illumination and Phong Material Model
  - BRDF
  - Ideal Diffuse Reflectance
  - Ideal Specular Reflectance
  - The Phong Model
- Optional Paper for Today: Anisotropic Reflection
- Global Illumination and Brief Introduction to Radiosity
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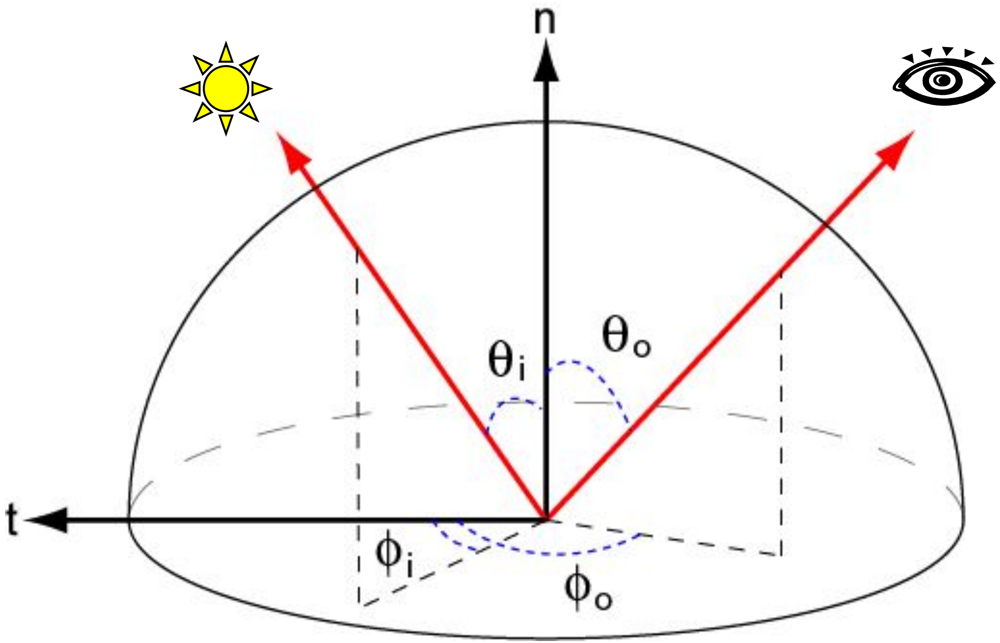
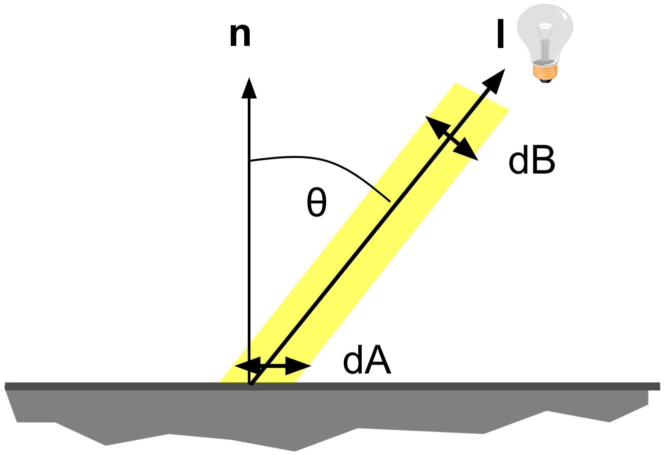
BRDF

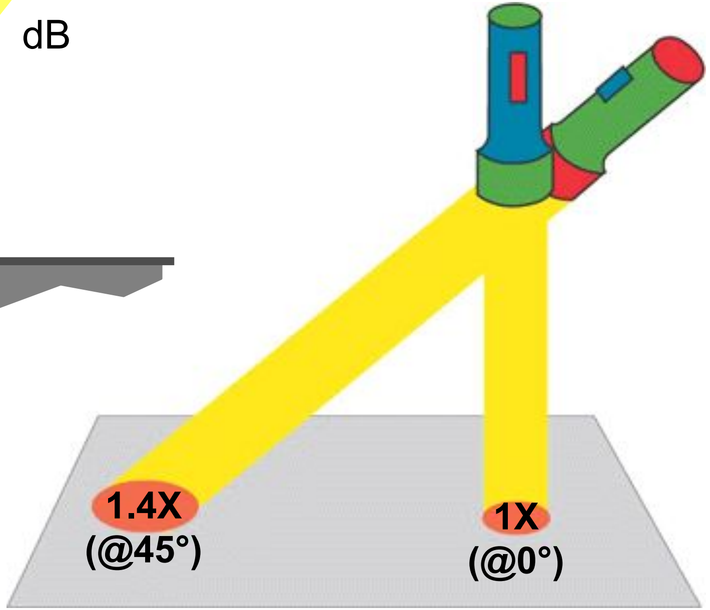
- Ratio of light coming from one direction that gets reflected in another direction
- Bidirectional Reflectance Distribution Function
  - 4D
  - $R(\theta_i, \varphi_i; \theta_o, \varphi_o)$
  - Note: BRDF for *isotropic* materials is 3D



Incoming Radiance

- The amount of light received by a surface depends on incoming angle
  - Bigger at normal incidence
  - (Winter/Summer difference)
- By how much?
  - $dB = dA \cos \theta$
  - Same as: $\mathbf{l} \cdot \mathbf{n}$ (dot product with normal)

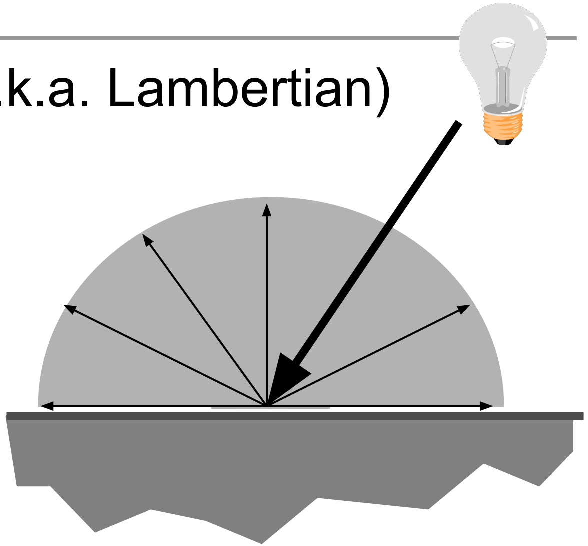


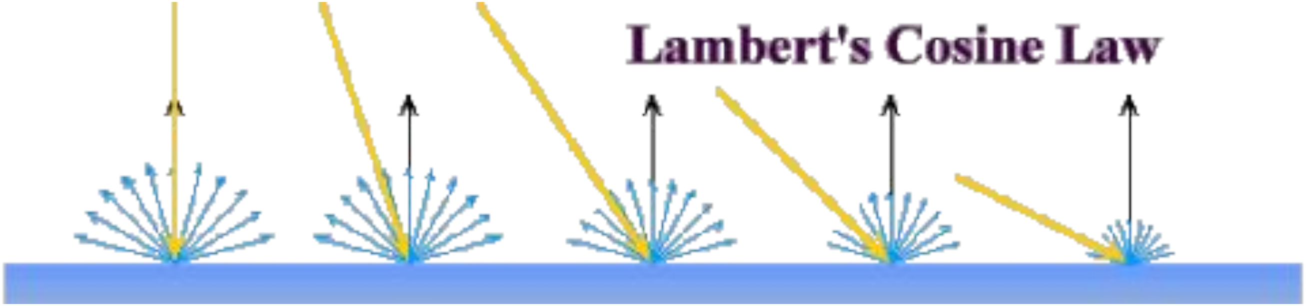


http://www.shsu.edu/~dl_www/bkonline/131online/f02latitude/02index.htm

Ideal Diffuse Reflectance

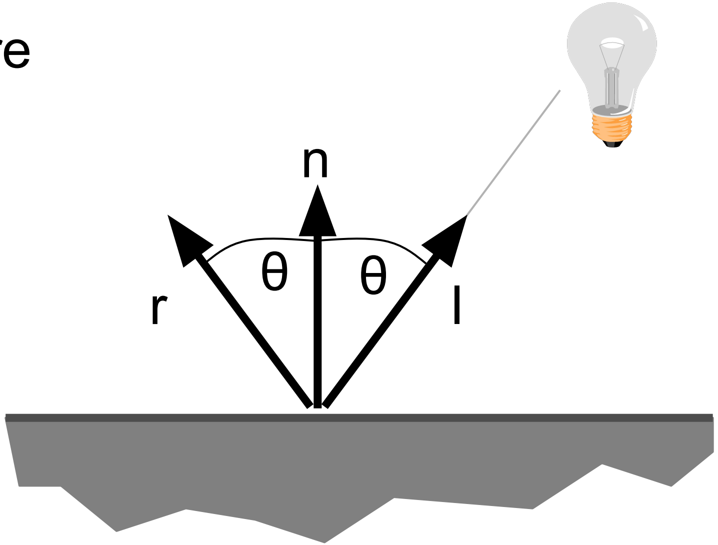
- Assume surface reflects equally in all directions (a.k.a. Lambertian)
- At a microscopic level, ideal diffuse surface is:
  - **a very rough surface**
  - normal/orientation highly variable/random
- Examples: chalk, clay, some paints





Ideal Specular Reflectance

- Assume surface reflects only in mirror direction - *view dependent*
- At a microscopic level, ideal specular surface is:
  - **a very smooth/polished surface**
  - normal/orientation is the same everywhere
- Examples:
  mirrors, highly
  polished metals



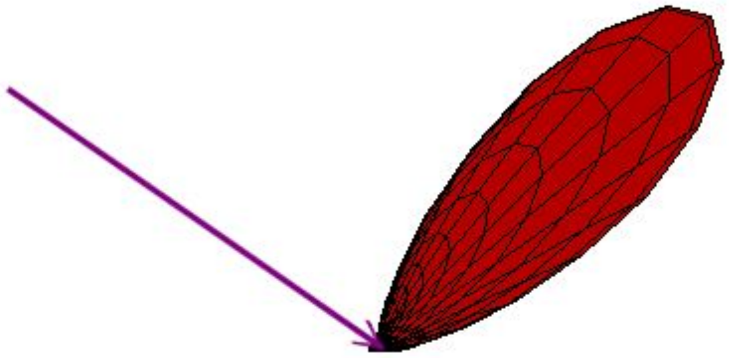
Non-Ideal Reflectors

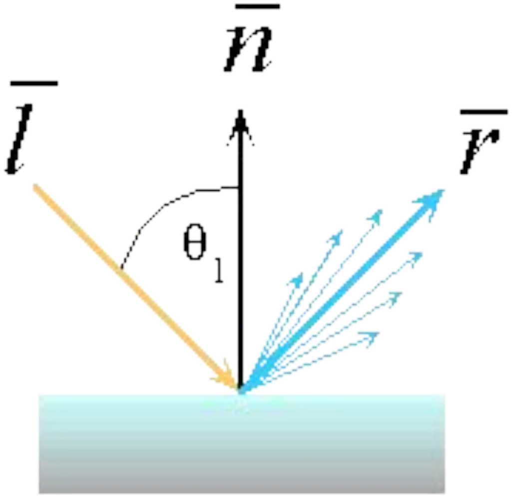
- Real materials tend to be *neither* “ideal diffuse” *nor* “ideal reflective”
- Highlight is blurry, looks glossy



Non-Ideal Reflectors

- Most light reflects in the ideal reflected direction
- Microscopic surface variations will reflect light just slightly offset
- How much light is reflected?



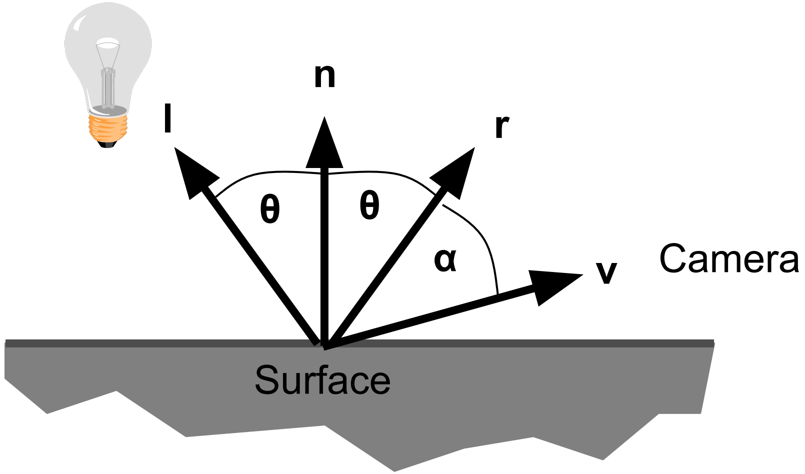


The Phong Model

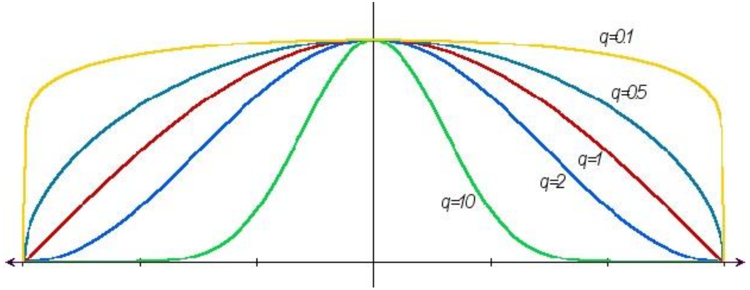
- An empirical/observational model
- How much light is reflected “specularly”?
- Depends on the angle ***α***, between the ideal reflection direction ***r*** and the viewer direction ***l***

$$L_o = k_s (\cos\alpha)^q \frac{L_i}{r^2}$$

k_s specular reflection coefficient
q specular reflection exponent
L_o light outgoing
L_i light incoming

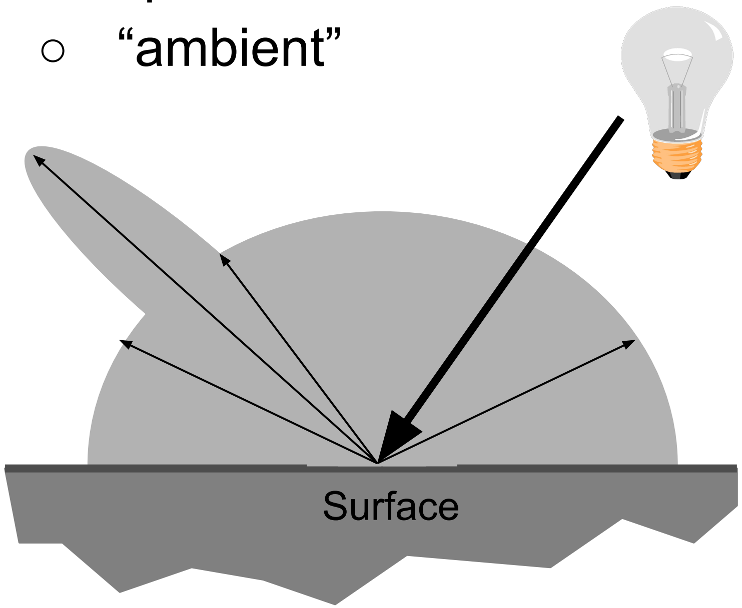


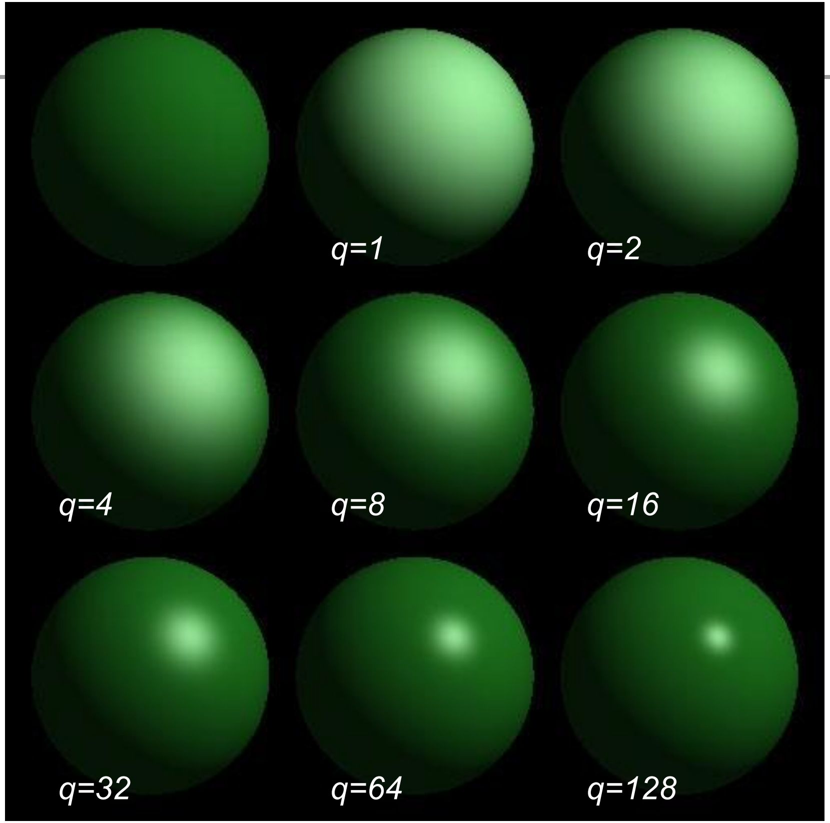
Effect of the q exponent



The Phong Model

- Sum of three components:
  - diffuse reflection +
  - specular reflection +
  - “ambient”





variations in Phong specular exponent

Ambient Illumination

- In a typical brightly-lit interior, everything receives at least a little bit of light
- Ambient illumination represents the reflection of all indirect illumination

$$L(\omega_r) = k_a$$

- This is a "hack"

dark (not black) shadows
less ambient illumination

large bounce fill lights to emulate daylight
more ambient illumination

https://indietips.com/the-key-to-creating-realistic-lighting-in-film/

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- Worksheet
- Paper for Today: Distributed Ray Tracing
- Local Illumination and Phong Material Model
- Optional Paper for Today: Anisotropic Reflection
- Global Illumination and Brief Introduction to Radiosity
- Paper for Next Time

Reading for Today *(optional)*

"Measuring and Modeling Anisotropic Reflection",
Greg Ward,
SIGGRAPH 1992

Gonioreflectometer

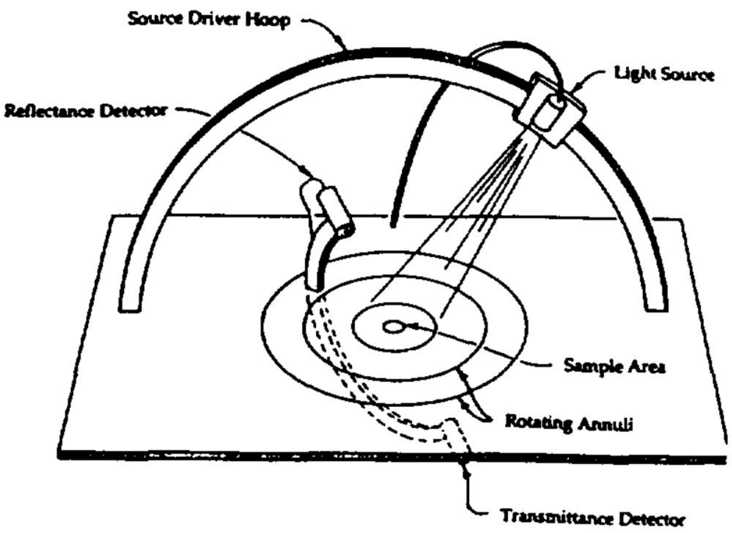
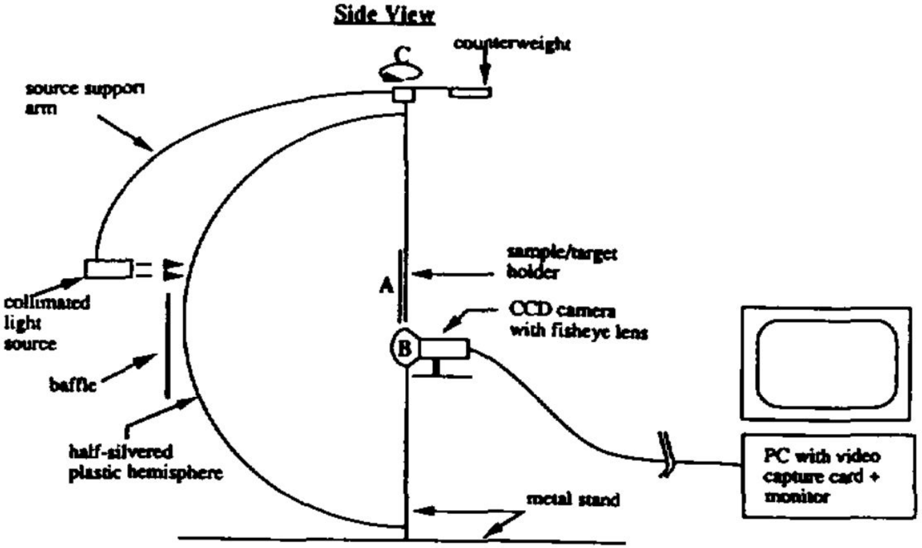


Figure 1. A conventional gonioreflectometer with movable light source and photometer.



Traditional: motorized sampling of many combinations of angles (expensive & slow)

Introduced by Ward 1992: hemi-ellipsoidal dome to capture lots (all?) angles at once (more cost effective)

Questions? *Lightscape* *http://www.lightscape.com*

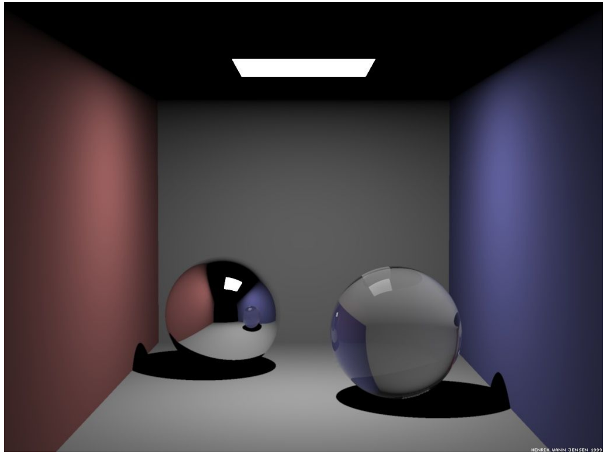
Today

- Worksheet
- Paper for Today: Distributed Ray Tracing
- Local Illumination and Phong Material Model
- Optional Paper for Today: Anisotropic Reflection
- Global Illumination and Brief Introduction to Radiosity
  - What is Global Illumination? Why is it important?
  - The Cornell Box
  - Radiosity vs. Ray Tracing
- Paper for Next Time

What is Global Illumination?

- Simulate all light inter-reflections (indirect lighting)
  - in a room, a lot of the light is indirect: it is reflected by walls.
- How have we dealt with this so far?
  - Uniform/constant ambient term to fake indirect illumination

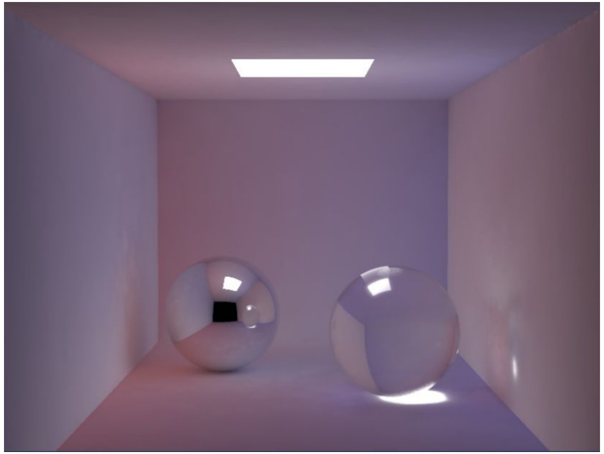
ray tracing



(no ambient term)

+

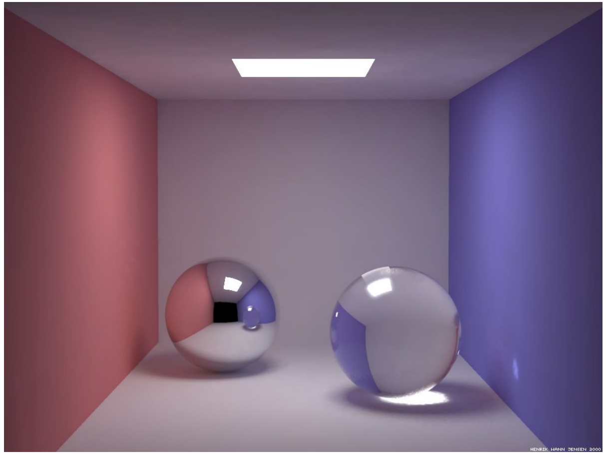
indirect illumination



it is smooth, but not constant!

=

"right" answer



Henrik Wann Jensen

Why is Global Illumination Important?

- Sculpture by John Ferren
- *Diffuse* panels

photograph:

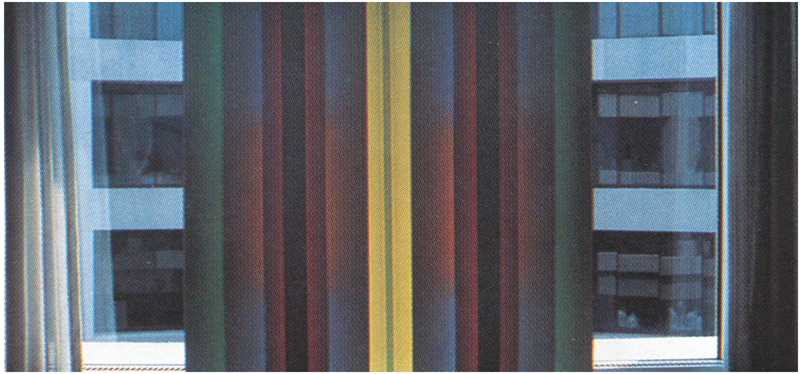
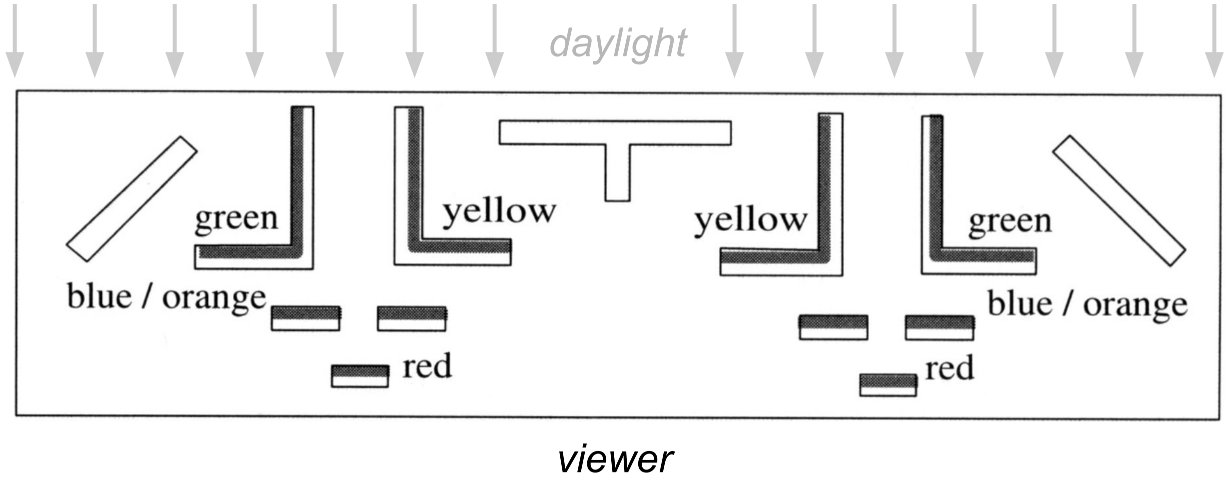


diagram from above:

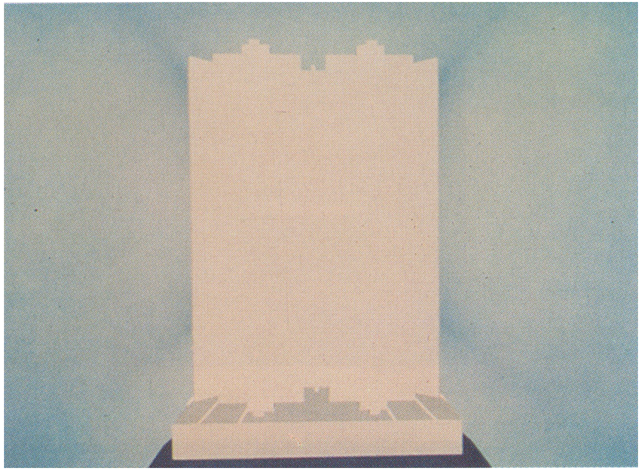


All surfaces directly visible by viewer are white!

Radiosity vs. Ray Tracing

Original sculpture by John Ferren

Lit by daylight from behind.



Ray traced image

A standard ray tracer cannot simulate the interreflection of light between diffuse surfaces.

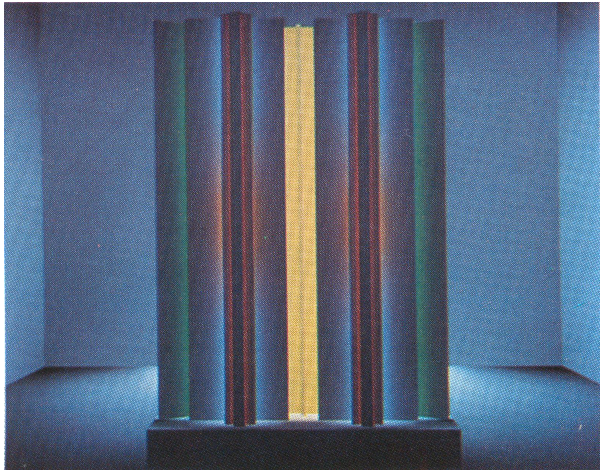
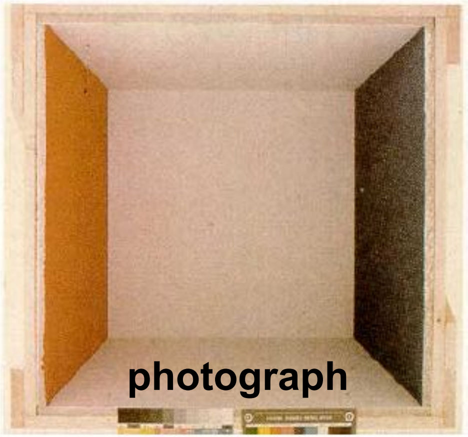
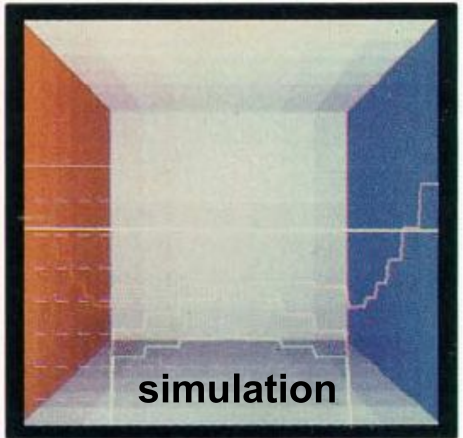


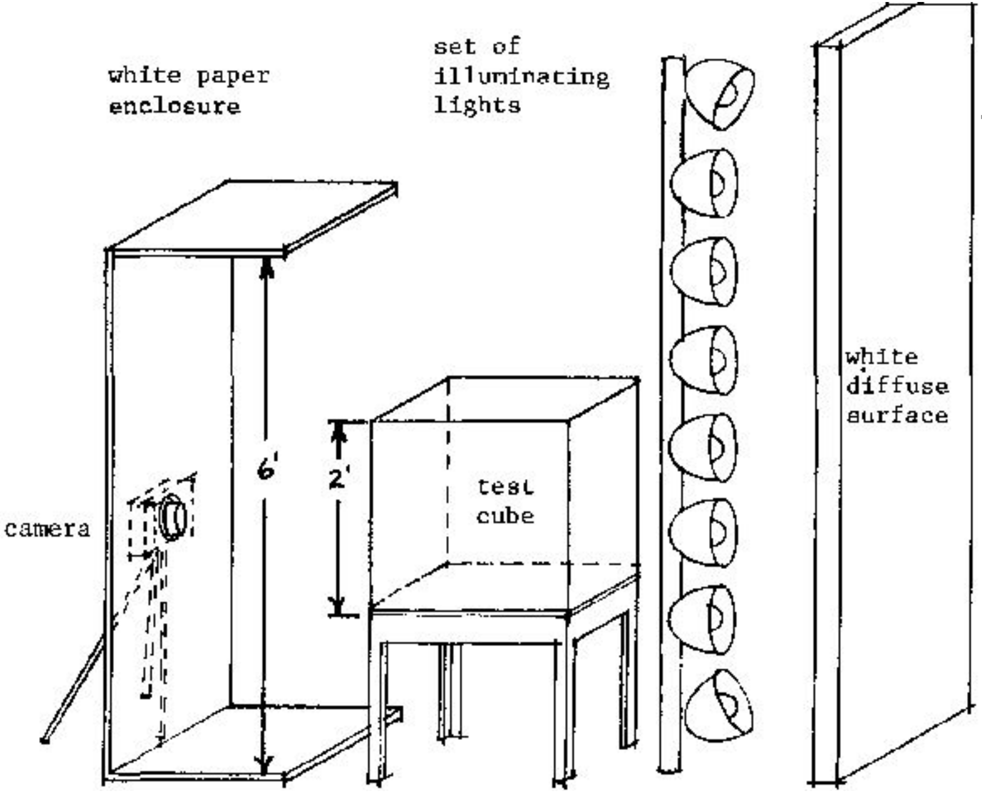
Image rendered with radiosity

Note the accurate color bleeding effects.

The Cornell Box



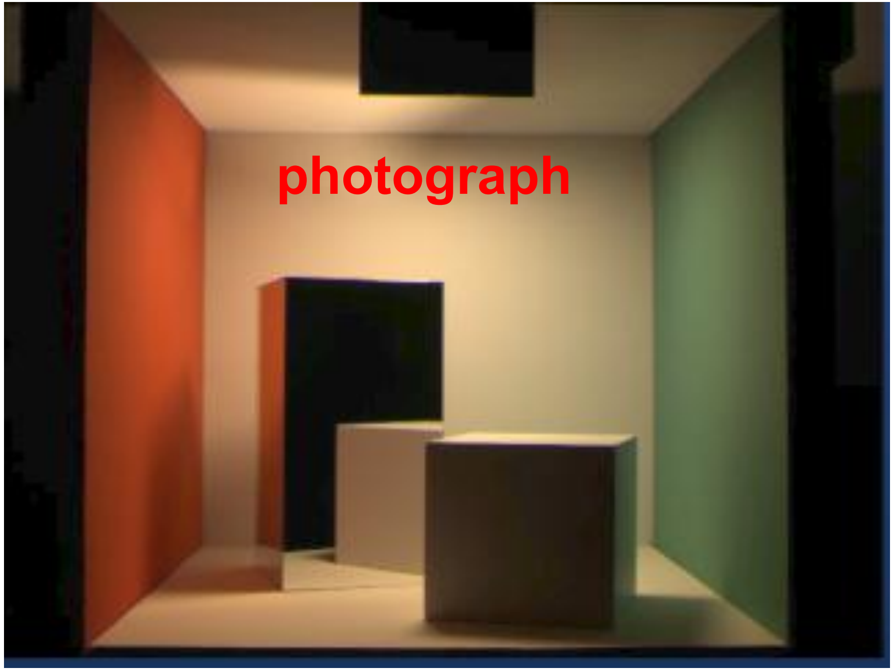


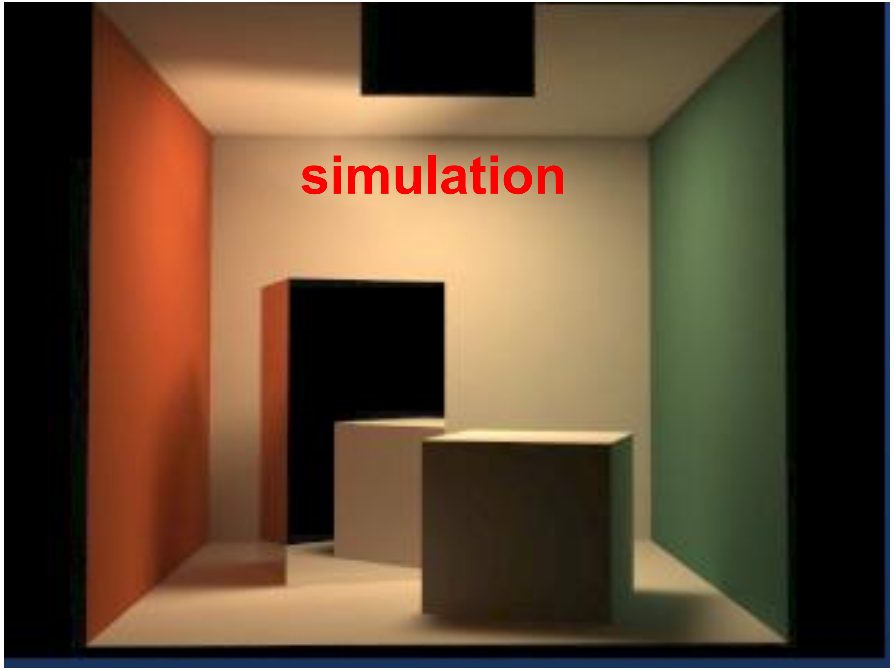


Goral, Torrance, Greenberg & Battaile
Modeling the Interaction of Light Between Diffuse Surfaces SIGGRAPH '84

The Cornell Box

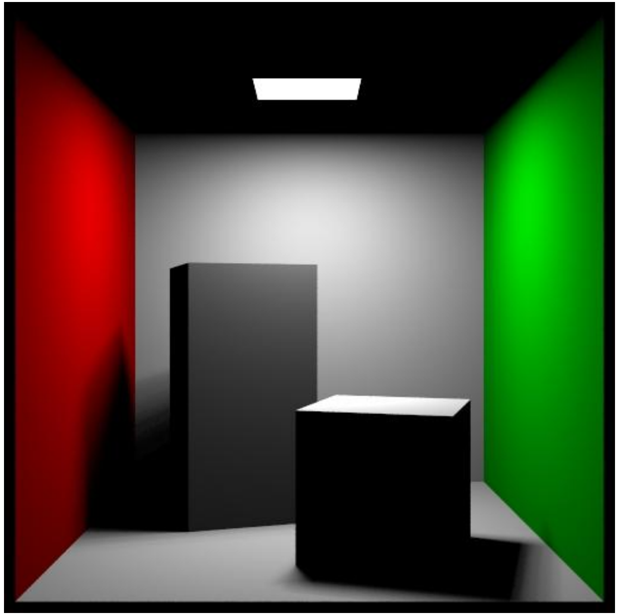
- Careful calibration and measurement allows for comparison between physical scene & simulation



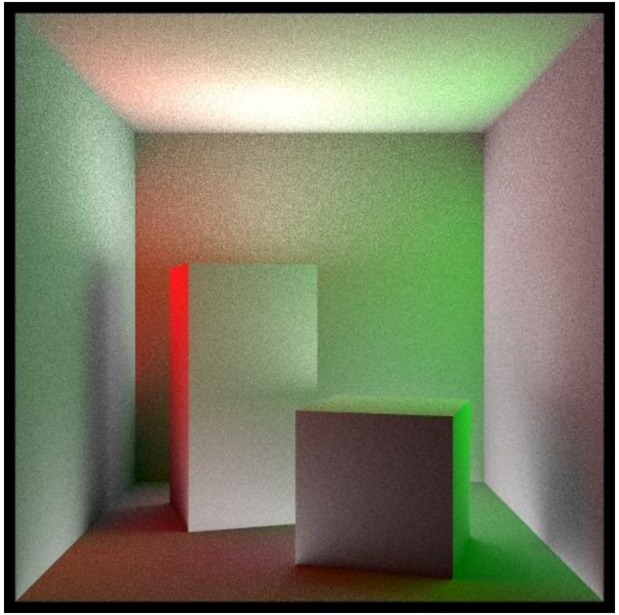


Light Measurement Laboratory Cornell University, Program for Computer Graphics

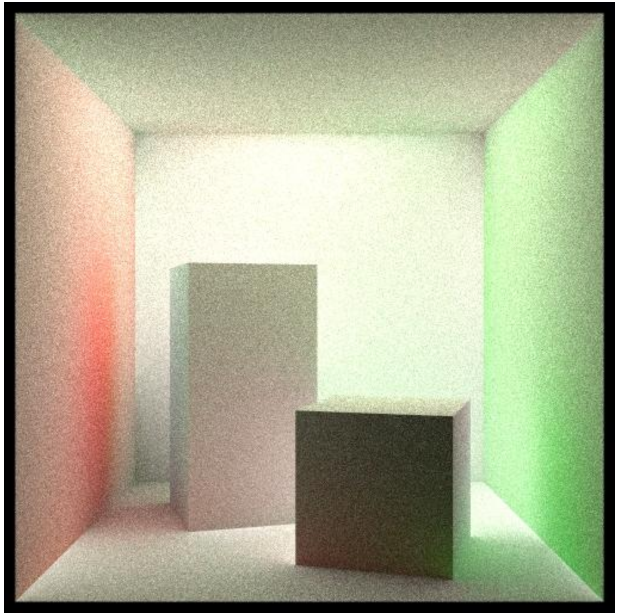
Visualizing Indirect Light / Inter-Reflections



direct illumination
(0 bounces)



1 bounce



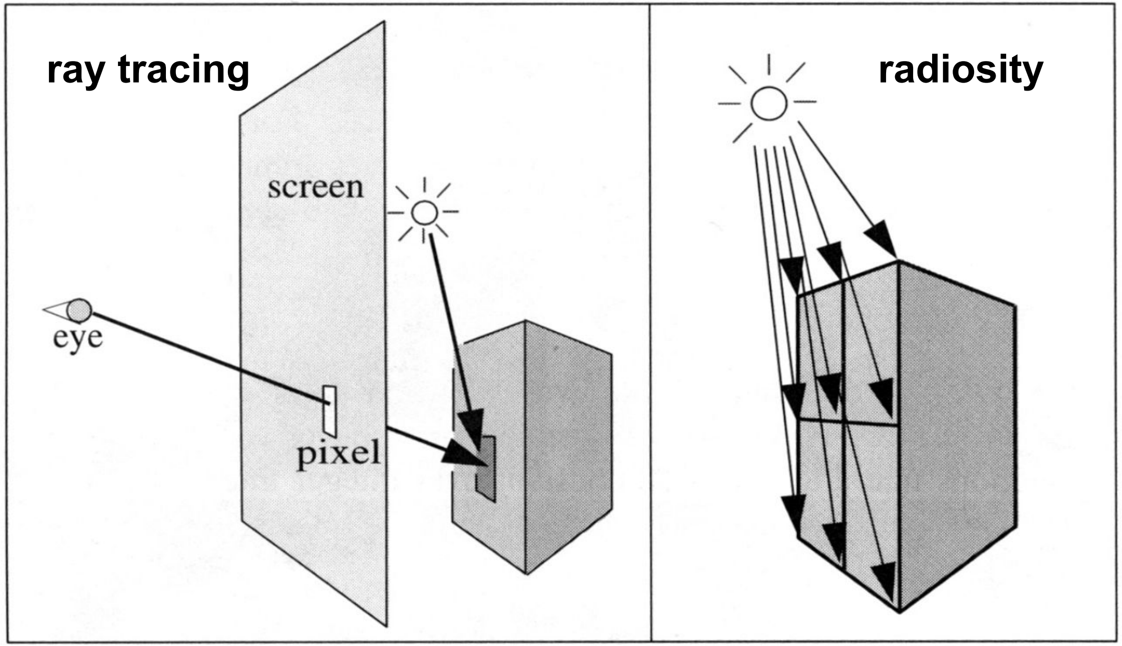
2 bounces

Note: image brightness not constant between images

images by Micheal Callahan
http://www.cs.utah.edu/~shirley/classes/cs684_98/students/callahan/bounce/

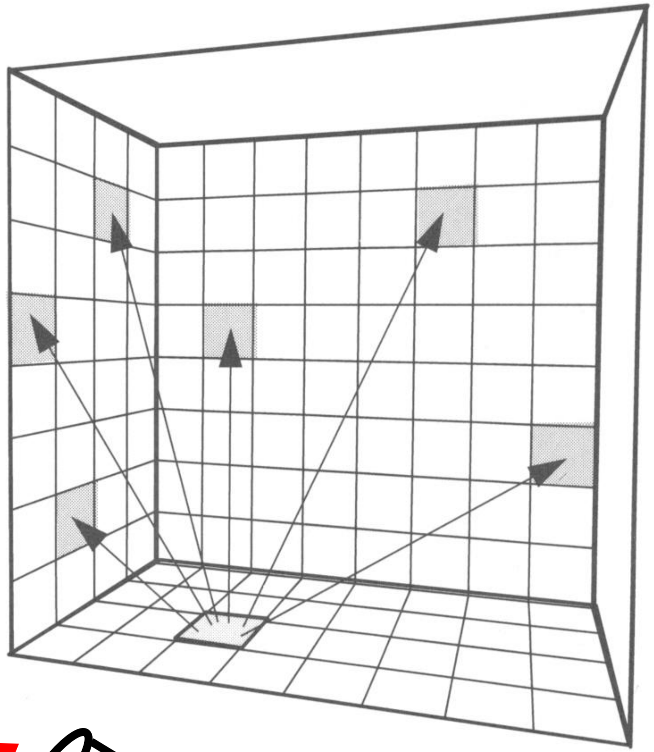
Radiosity vs. Ray Tracing

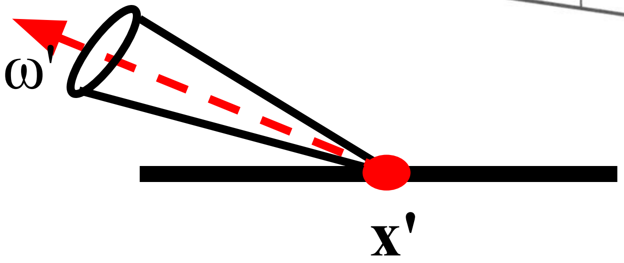
- Ray tracing is an *image-space* algorithm
  - If the camera is moved, we have to start over
- Radiosity is computed in *object-space*
  - View-independent (as long as we don't move the light)
  - Can pre-compute complex lighting to allow interactive walkthroughs



Radiosity Overview

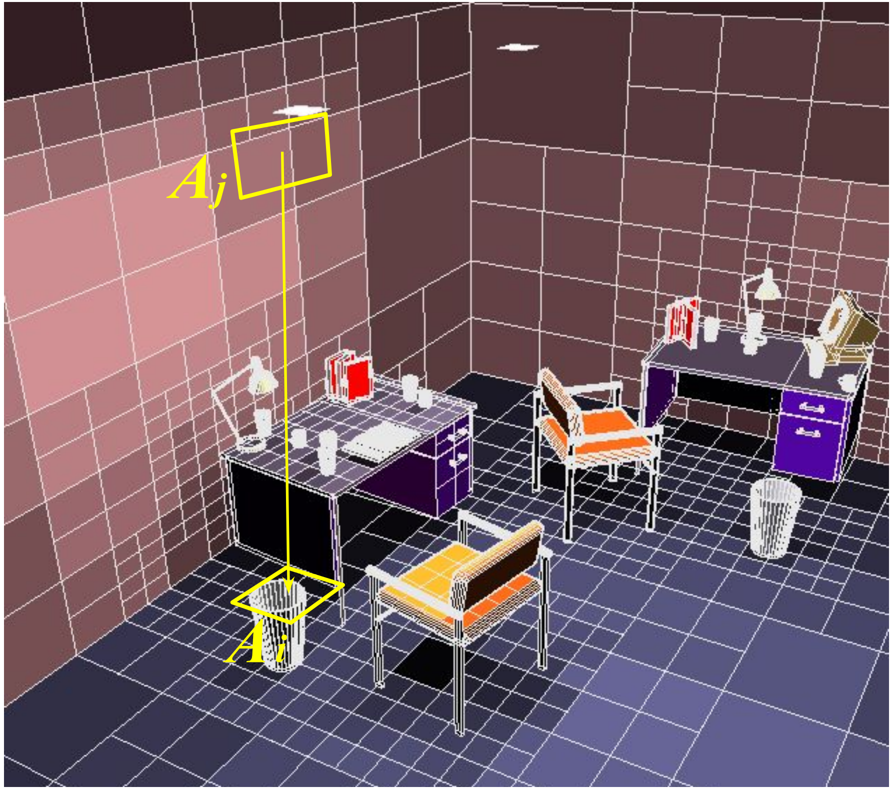
- Surfaces are assumed to be perfectly Lambertian (diffuse)
  - reflect incident light in all directions with equal intensity
- The scene is divided into a set of small areas, or patches
- The radiosity, $\mathbf{B}_i$, of patch *i* is the total rate of energy leaving a surface. The radiosity over a patch is constant.
- Units for radiosity: Watts / steradian * meter^2





Discrete Radiosity Equation

- Discretize the scene into *n* patches, over which the radiosity is constant



light leaving patch *i*

material reflectivity

$$B_i = E_i + \rho_i \sum_{j=1}^{n} F_{ij} B_j$$

light emitted from patch *i*

form factor

The equation is recursive, but it can be solved iteratively

Radiosity Equation in Matrix Form

- *n* simultaneous equations with *n* unknown B_i values can be written in matrix form:

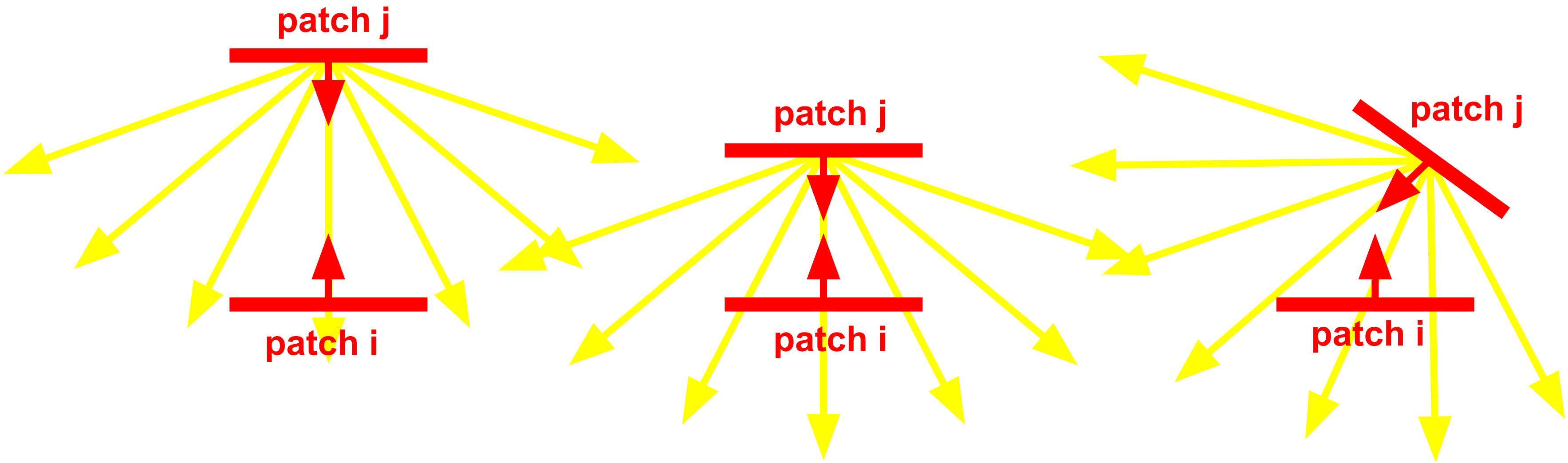
solve for B_i

$$\begin{bmatrix} 1-\rho_1 F_{11} & -\rho_1 F_{12} & \cdots & -\rho_1 F_{1n} \\ -\rho_2 F_{21} & 1-\rho_2 F_{22} & & \\ \vdots & & \ddots & \\ -\rho_n F_{n1} & \cdots & \cdots & 1-\rho_n F_{nn} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_n \end{bmatrix}$$

- A solution yields a single radiosity value B_i for each patch in the environment, a view-independent solution.

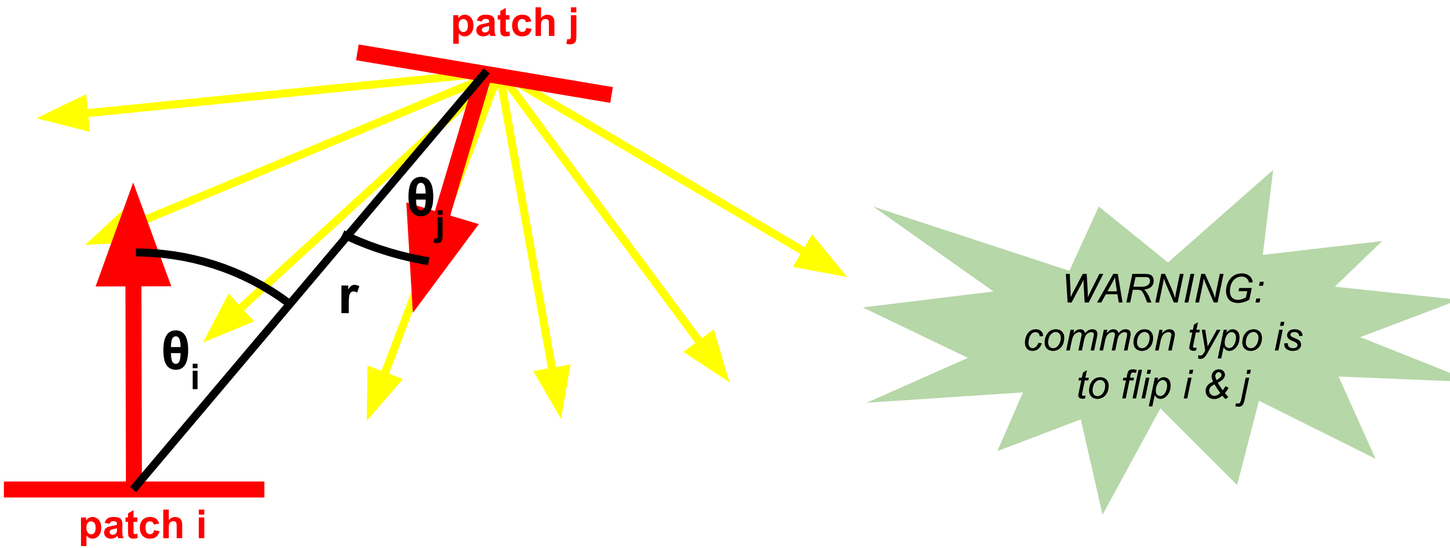
What is the Form Factor F_{ij} ?

- F_{ij} = fraction of light energy leaving patch j that arrives at patch i
- Takes account of both:
  - geometry (size, orientation & position)
  - visibility (are there any occluders?)



Calculating the Form Factor F_{ij}

- F_{ij} = fraction of light energy leaving patch j that arrives at patch i

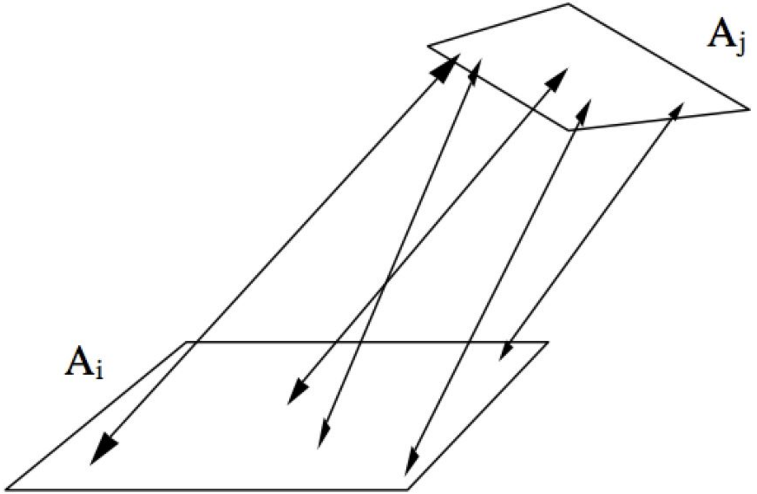


$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} V_{ij}\, dA_j\, dA_i$$

Form Factor from Ray Casting

Use this for HW3!

- Cast *n* rays between the two patches
  - Compute visibility (what fraction of rays do not hit an occluder)
  - Integrate the point-to-point form factor
- Permits the computation of the patch-to-patch form factor, as opposed to point-to-patch



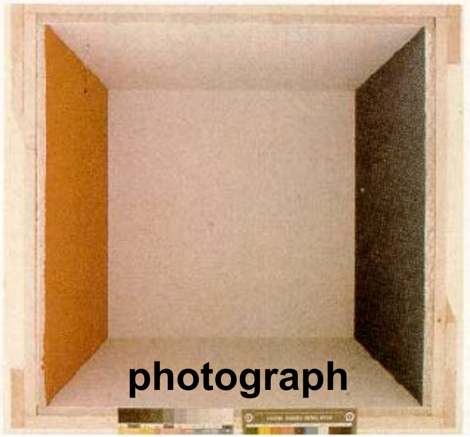
Questions?

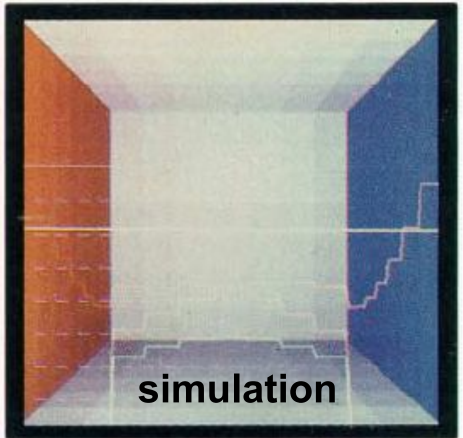
Lightscape
http://www.lightscape.com

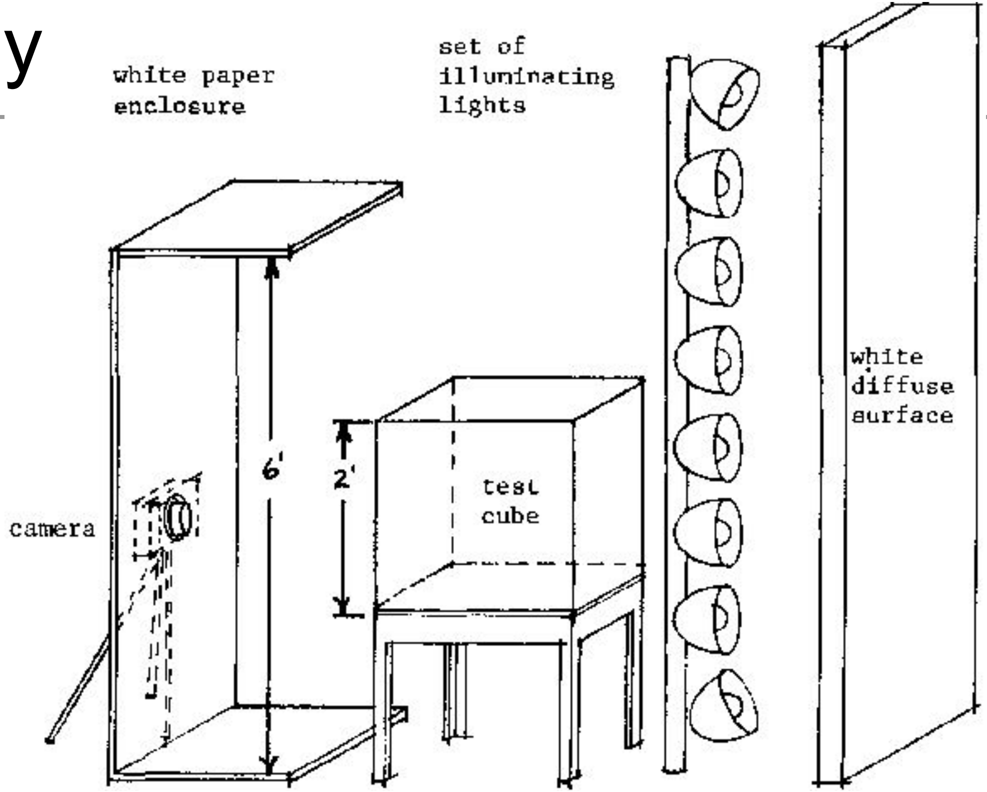
Today

- Worksheet
- Paper for Today: Distributed Ray Tracing
- Local Illumination and Phong Material Model
- Optional Paper for Today: Anisotropic Reflection
- Global Illumination and Brief Introduction to Radiosity
- Paper for Next Time

Reading for Tuesday







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