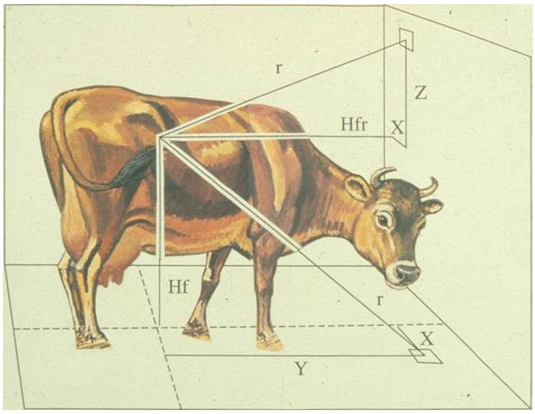
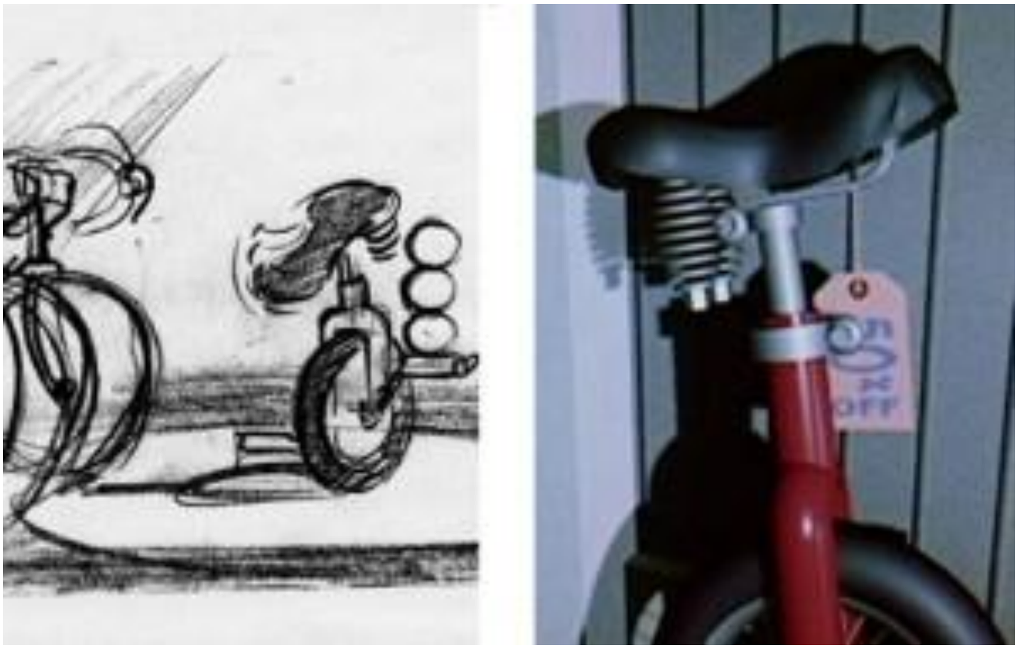
Local vs. Global Illumination & Radiosity



An early application of radiative heat transfer in stables.

Red's Dream, Pixar, 1987



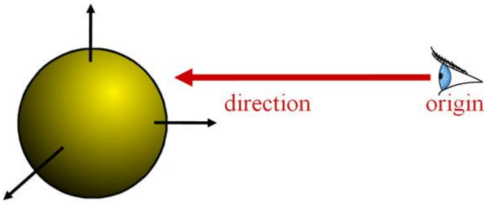
Red's Dream, Pixar, 1987

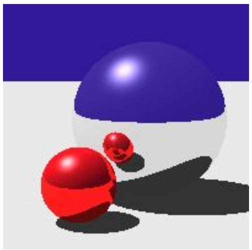
Announcement: Quiz 1

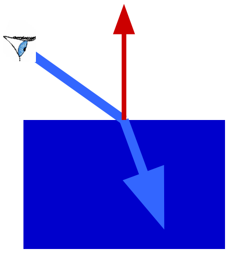
- Friday (Feb 24th), during class (2:00-3:50pm)
  - Students w/ extra time accommodations may stay late as needed
- One double-sided 8.5”x11” sheet of notes allowed
- Practice Problems (from 2014 & 2017) on the course calendar
- Coverage:
  - Lecture and assigned readings thru Lecture 10
  - When there was a choice of papers: you are responsible for having read one paper per lecture
  - Worksheets thru Lecture 10
  - Homeworks 0, 1, & 2

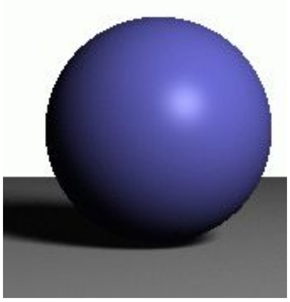
Last Time?

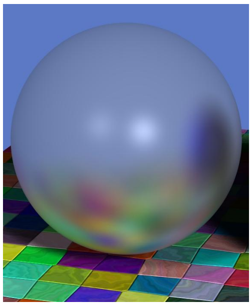
- Ray Casting & Ray-Object Intersection
- Recursive Ray Tracing
- Distributed Ray Tracing

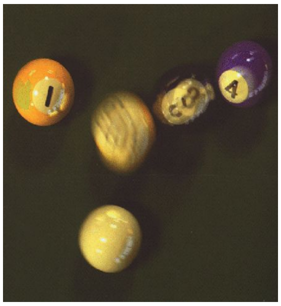


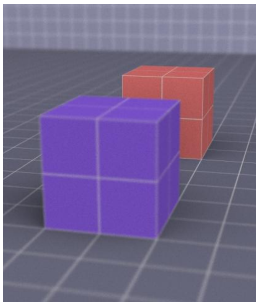












Today

- Paper for Today: Distributed Ray Tracing
- Local Illumination
- Why is Global Illumination Important?
- Radiosity Matrix
- Calculating the Form Factors
- Advanced Radiosity
- Worksheet

How to read a research paper?

- Read it multiple times, skim it first, re-read sections as necessary
- Have an open mind, question it, not everything they say is 100% correct, be skeptical
- Abstract is the high level, good place to start, its their overall goals
- Read the conclusion first (yes! Out of order reading is helpful!)
- Google things you don't understand, get another perspective, (or another attempt at explaining something complex)
- Don't ignore the complex/key words, look them up. (figure out which words are essential, its ok to ignore some words…)
- Equations… get a high level understanding on the equation. Skip the equations on the first read, only need to understand details of equation if you need to implement it.
  - Equations are necessary to replicate the work. It's a complete record of what happened, but many readers aren't going to undertake the replication step.
  - Know the authors background, prior research, to understand the context of this work. & publication year

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How to read a research paper?

(especially an advanced paper in a new area)

- Multiple readings are often necessary
- Don't necessarily read from front to back
- Lookup important terms
- Target application & claimed contributions
- Experimental procedure
- How well results & examples support the claims
- Scalability of the technique (Big O Notation)
- Limitations of technique, places for future research
- Possibilities for hybrid systems with other work

Components of a well-written research paper?

- Takes the time & effort to explain important ideas in paper
- Takes the time to explain purpose & intuition of the equation, and explain why & alternatives
- Figures with captions that describe the figure. Write lengthy descriptive captions – telling reader what they should see.
- Go into detail, but don't get sidetracked from main idea.
- Provides data, doesn't just expect you to trust that it works
- Well organized, classic standard sections (abstract, intro, related work, algorithm/method, results, limitations, future work, conclusion)
- An roadmap/overview of the method before diving into the details of step
- Put the prose talking about the figure next to the figure (historical color plates are separated, but also latex/word layout is annoying to fight)

Components of a well-written research paper?

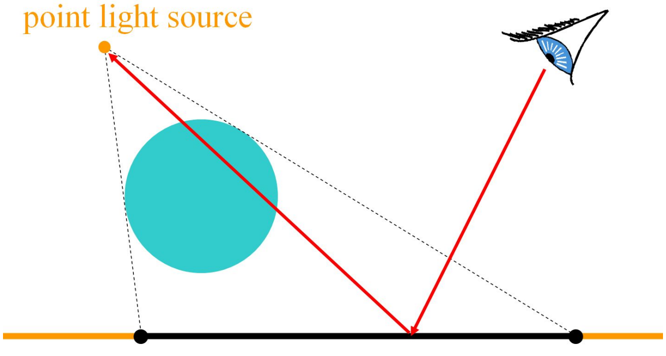
- Motivation/context/related work
- Contributions of this work
- Clear description of algorithm
  - Sufficiently-detailed to allow work to be reproduced
  - Work is theoretically sound (hacks/arbitrary constants discouraged)
- Results
  - well chosen examples
  - clear tables/illustrations/visualizations
- Conclusions
  - limitations of the method are clearly stated

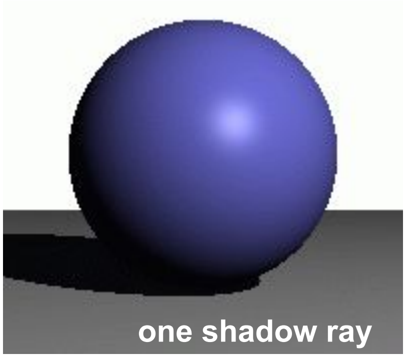
Reading for Today

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

Shadows

- one shadow ray per intersection per point light source

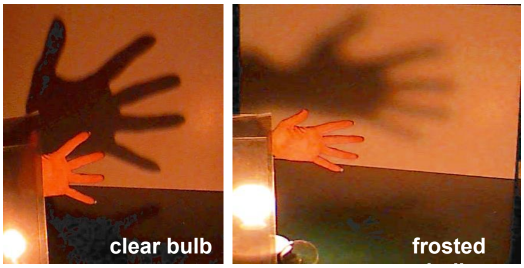




Shadows & Light Sources

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

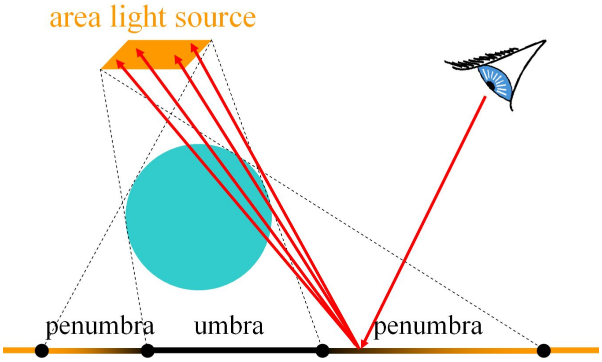
http://www.davidfay.com/index.php

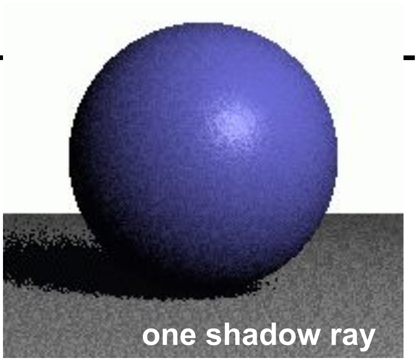


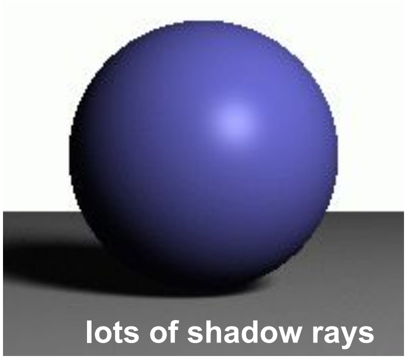
http://www.pa.uky.edu/~sciworks/light/preview/bulb2.htm

Soft Shadows

- multiple shadow rays to sample area light source

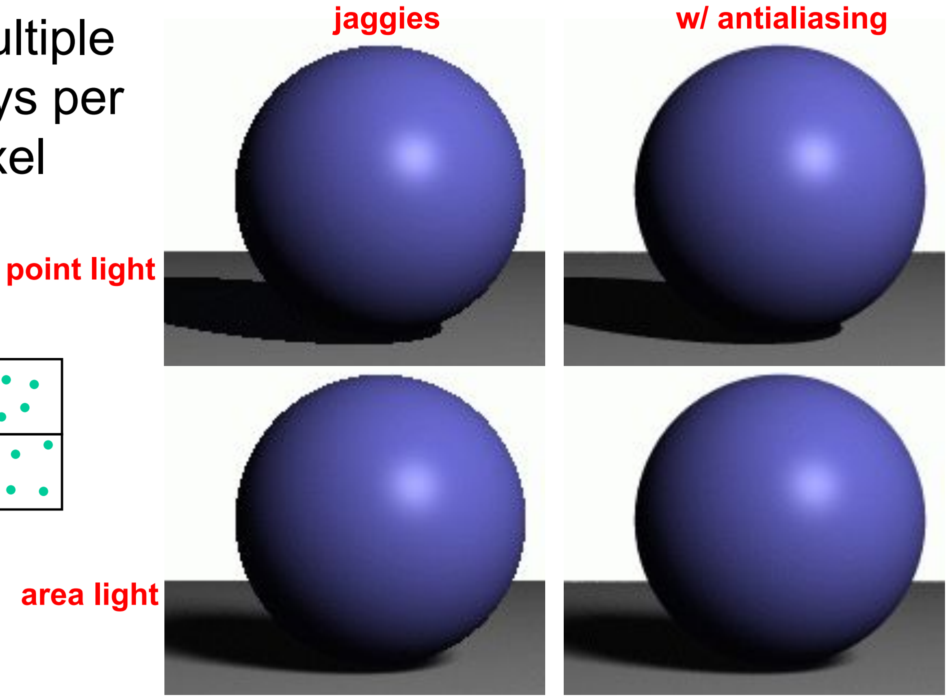


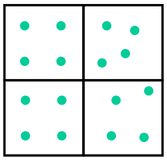




Antialiasing – Supersampling

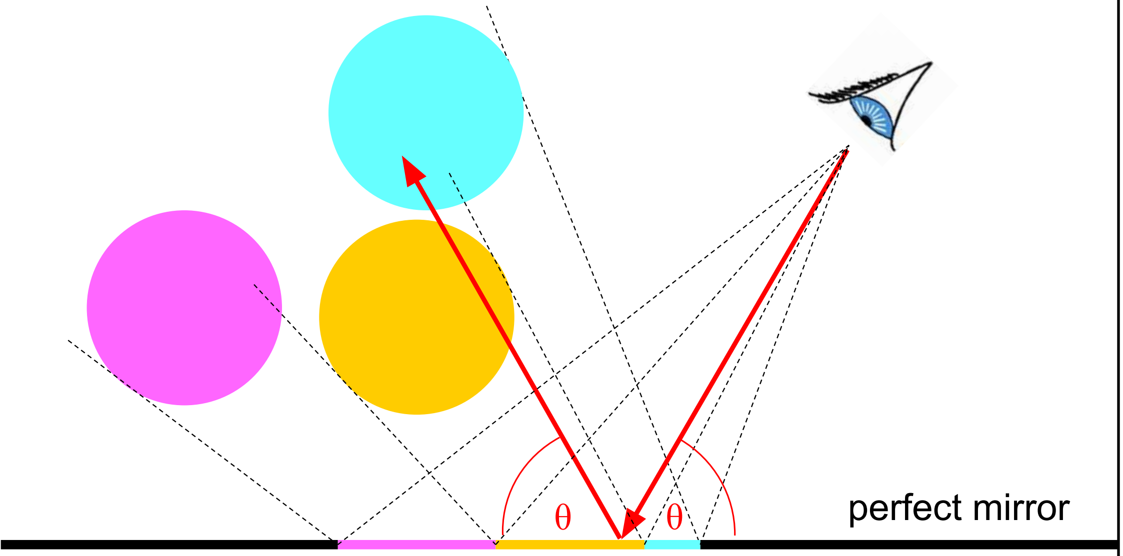
- multiple rays per pixel





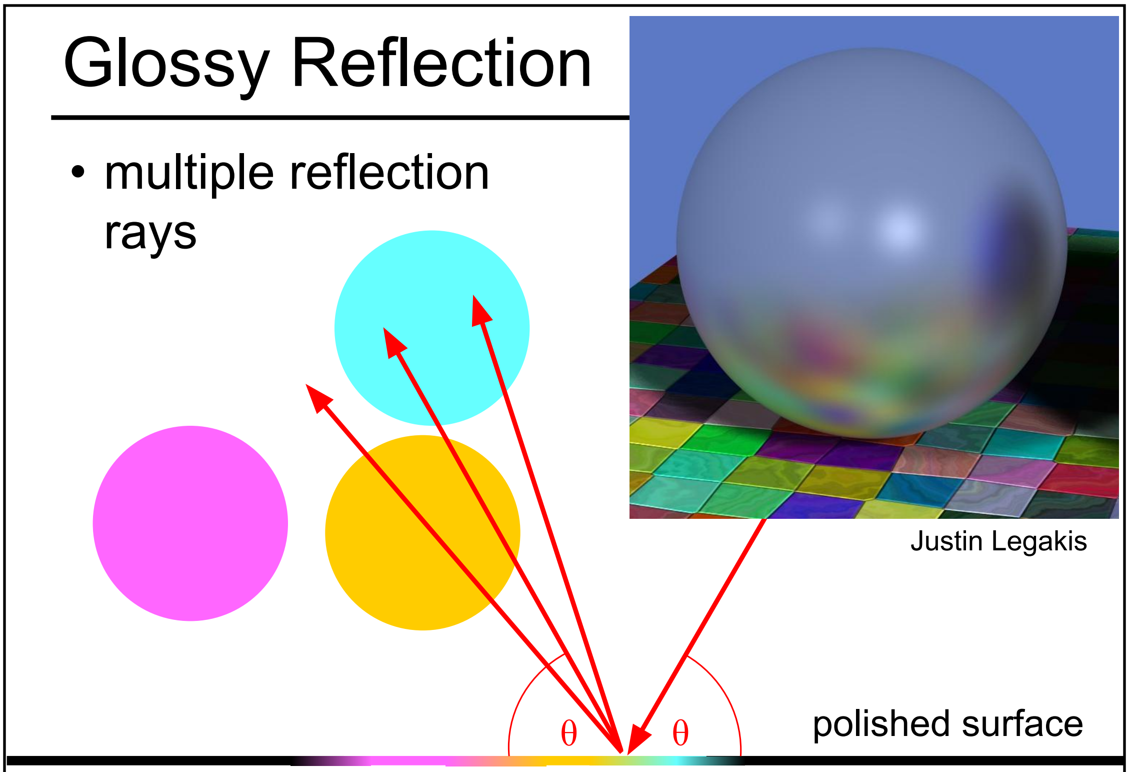
Reflection

- one reflection ray per intersection



Glossy Reflection

- multiple reflection rays

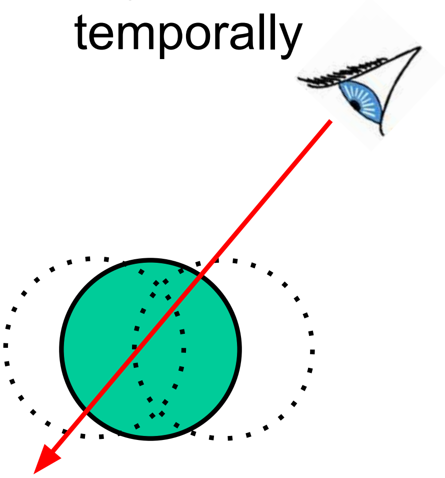


Justin Legakis

polished surface

Motion Blur

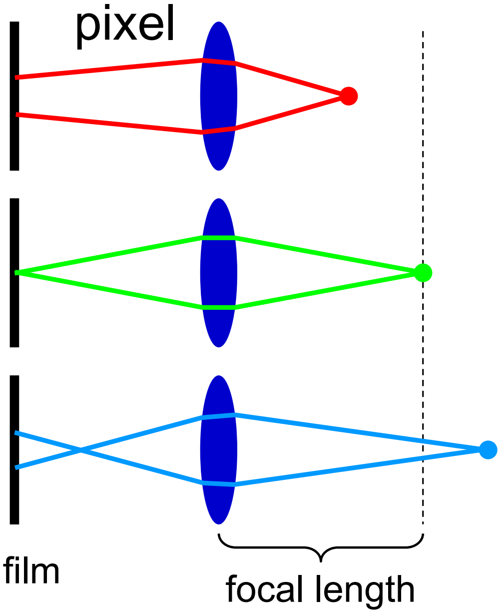
- Sample objects temporally

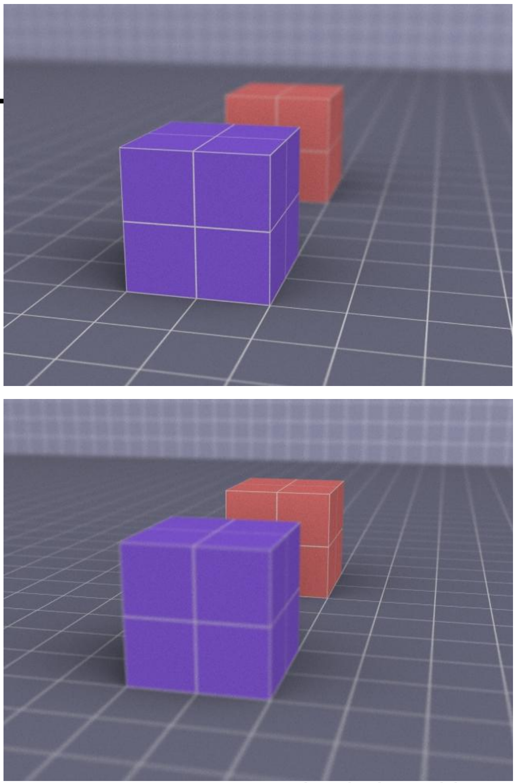


Rob Cook

Depth of Field

- multiple rays per pixel

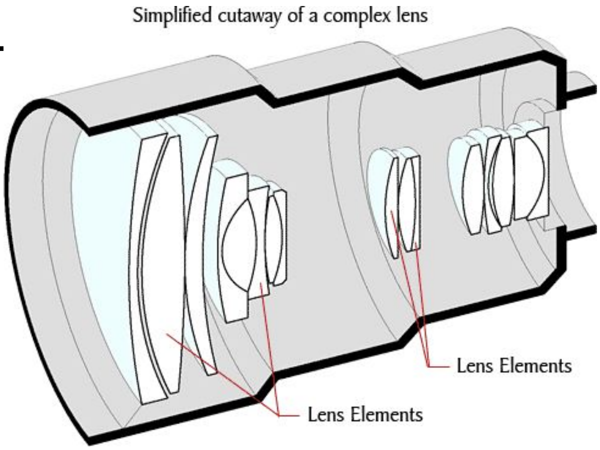




Justin Legakis

Depth of Field

- Modeling the geometry of a real-world camera lens & simulating the refraction of a cone of rays through the lens is unnecessarily complex.
- Instead, using a simple formula to determine the radius for an approximate and equivalent “circle of confusion” is sufficient.
- But we still need to trace ALOT of rays to get a satisfyingly smooth & blurry background.
- *There are cheaper hacks to mimic the background blur!*



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

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

- Paper for Today: Distributed Ray Tracing
- Local Illumination
  - BRDF
  - Ideal Diffuse Reflectance
  - Ideal Specular Reflectance
  - The Phong Model
- Why is Global Illumination Important?
- Radiosity Matrix
- Calculating the Form Factors
- Advanced Radiosity
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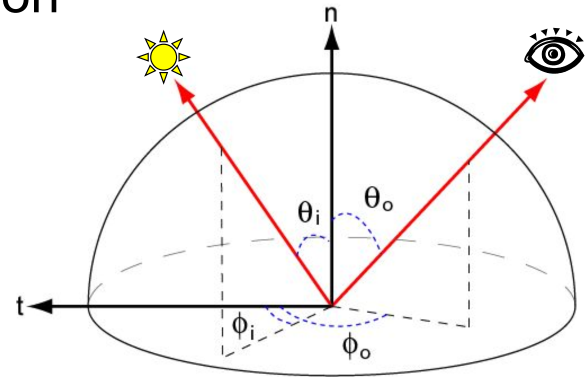
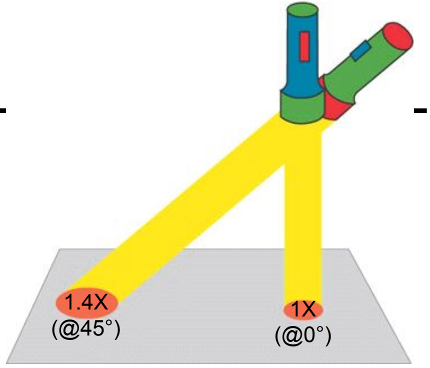
BRDF

- 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

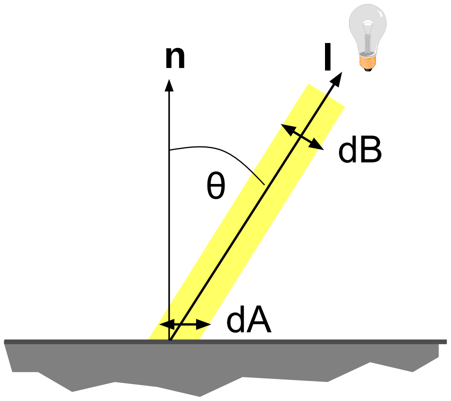


Incoming Radiance

- 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 θ
  - Same as: **l · n** (dot product with normal)

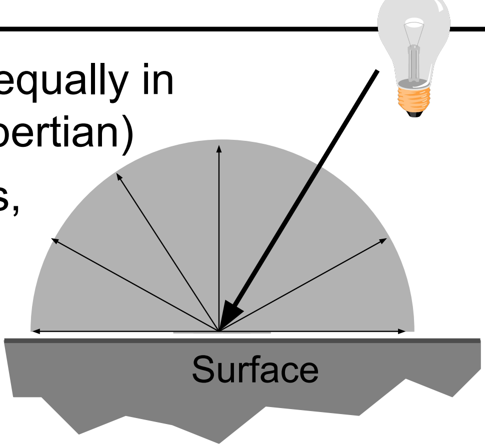


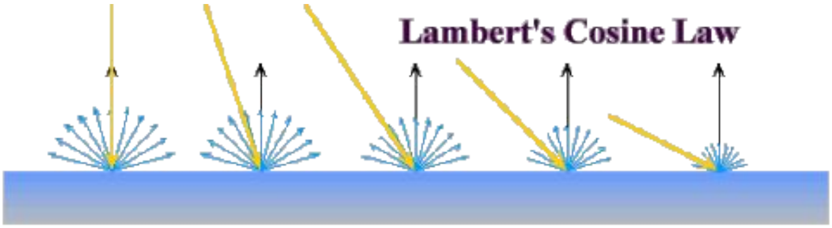
http://www.shsu.edu/~dl_www/bkonline/131online/f02latitude/02index.htm



Ideal Diffuse Reflectance

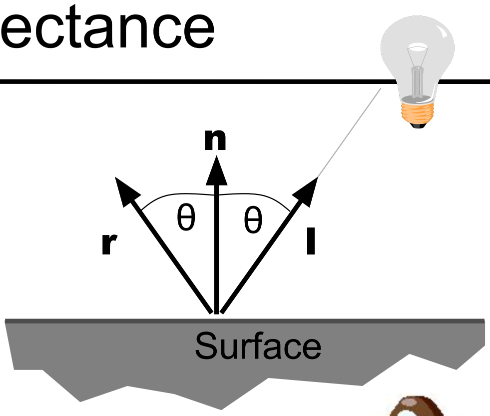
- Assume surface reflects equally in all directions (a.k.a. Lambertian)
- An ideal diffuse surface is, at the microscopic level, a very rough surface
- Examples: chalk, clay, some paints





Ideal Specular Reflectance

- Assume surface reflects only in mirror direction
  - View dependent
- Microscopic surface elements are oriented in the same direction as the surface
- Examples: mirrors, highly polished metals

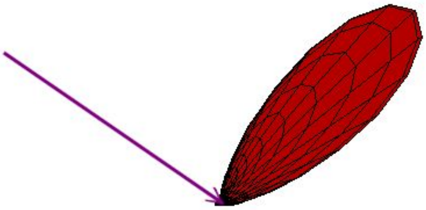


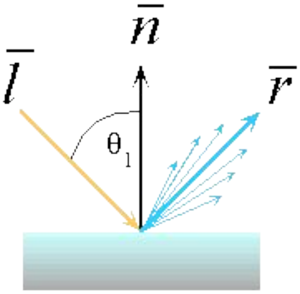
Non-Ideal Reflectors

- 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?



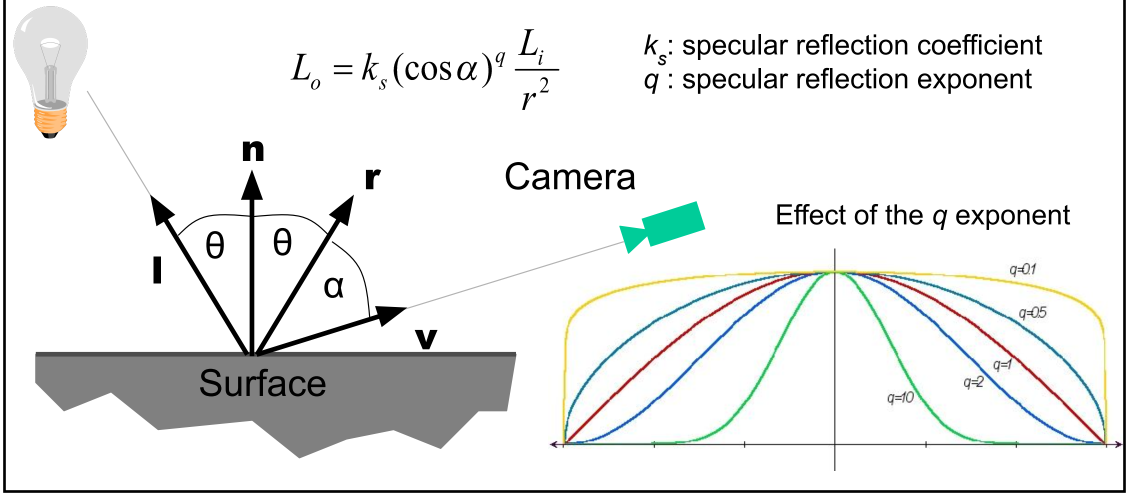


The Phong Model

- 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*

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

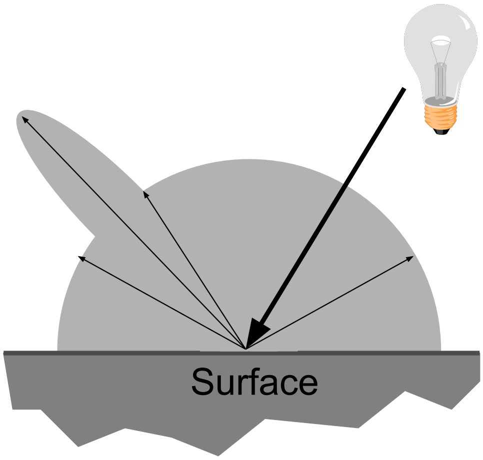
k_s: specular reflection coefficient
q : specular reflection exponent

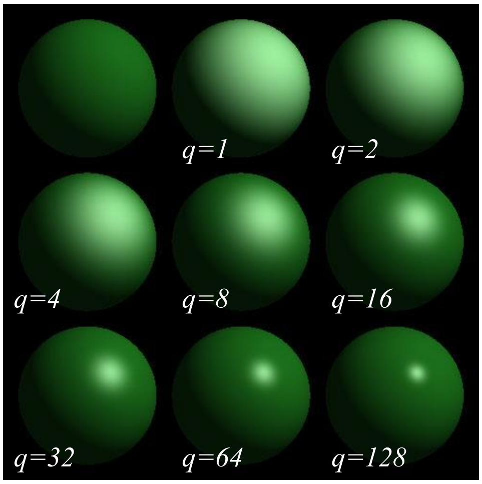


The Phong Model

- Sum of three components:

  diffuse reflection + specular reflection + "ambient".

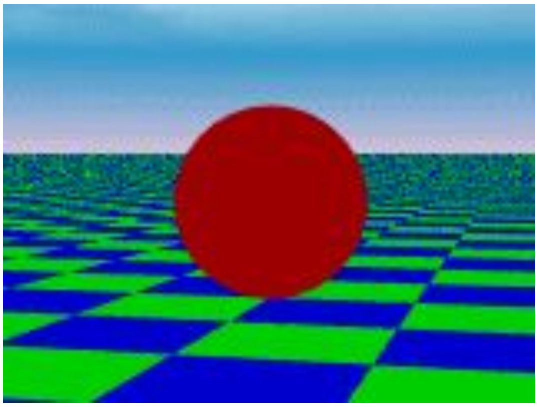




variations in Phong specular exponent

Ambient Illumination

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



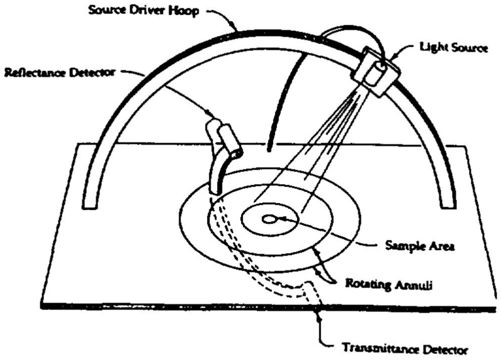
$$L(\omega_r) = k_a$$

- This is a total hack!

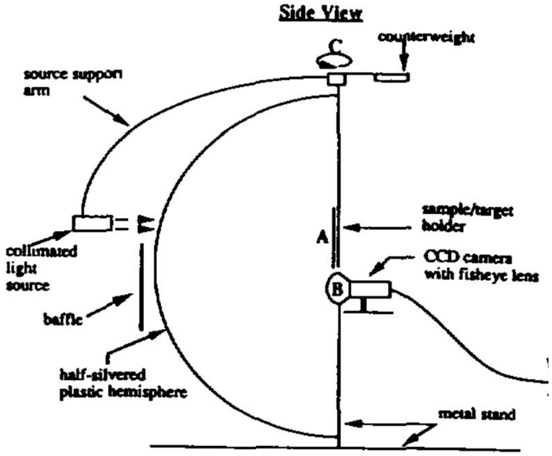
Reading for Today *(optional)*

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

Gonioreflectometers



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**

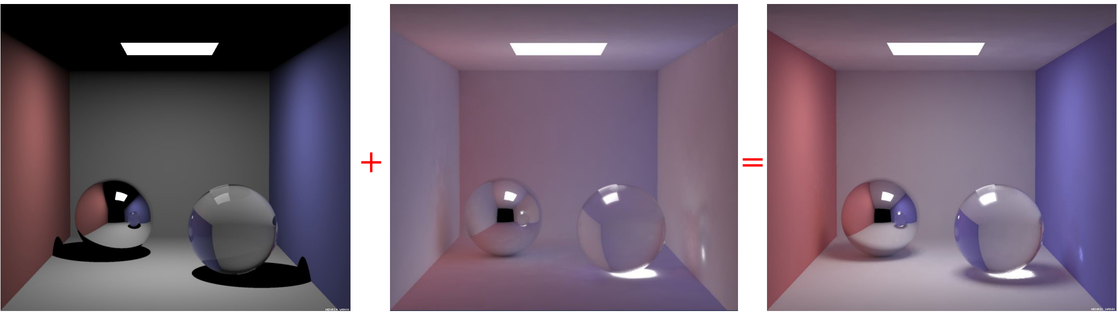
Today

- Paper for Today: Distributed Ray Tracing
- Local Illumination
- Why is Global Illumination Important?
    - The Cornell Box
    - Radiosity vs. Ray Tracing
- Radiosity Matrix
- Calculating the Form Factors
- Advanced Radiosity
- Worksheet

Why 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?
    - Ambient term to fake some uniform indirect light

ray tracing **indirect illumination** **“right” answer**



(no ambient term)

it is smooth, but not constant!

Henrik Wann Jensen

Why Radiosity?

- Sculpture by John Ferren
- *Diffuse* panels

photograph:

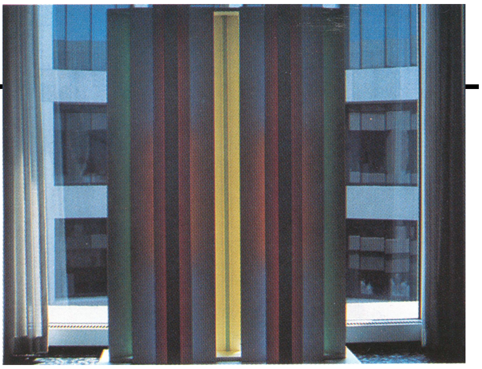
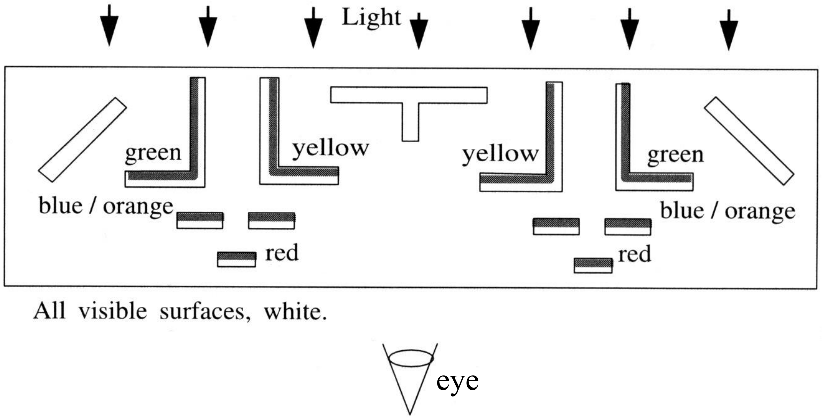
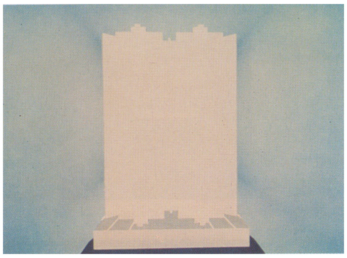


diagram
from above:



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.

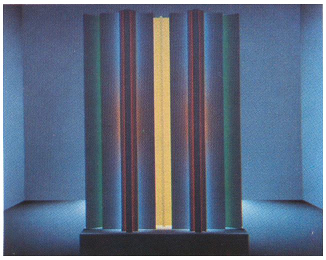
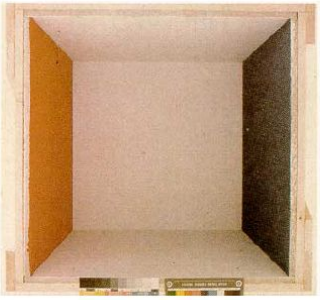
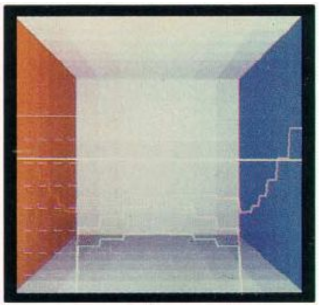


Image rendered with radiosity. Note the color bleeding effects.

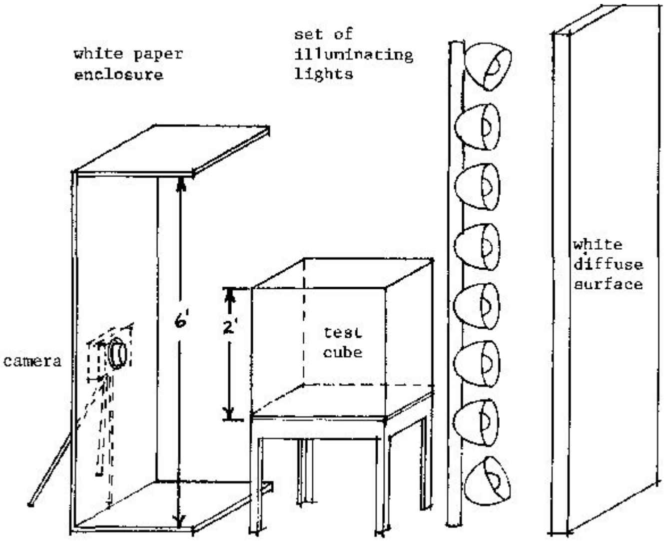
Reading for Friday - *after Quiz 1*



photograph



simulation



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

The Cornell Box

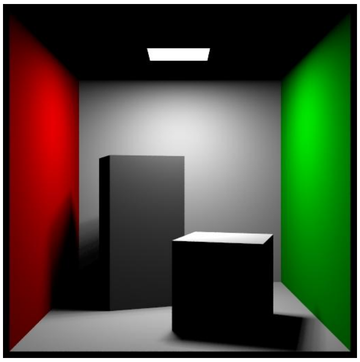
- Careful calibration and measurement allows for comparison between physical scene & simulation

photograph

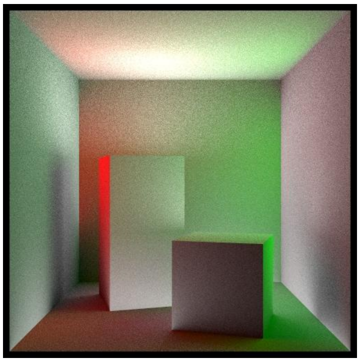
simulation

Light Measurement Laboratory
Cornell University, Program for Computer Graphics

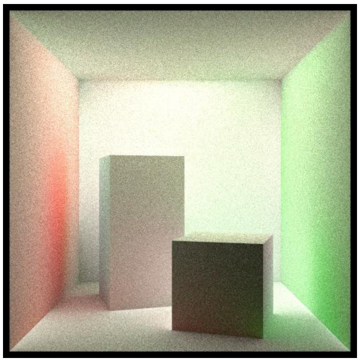
Visualizing Inter-reflections…



direct illumination
(0 bounces)



1 bounce



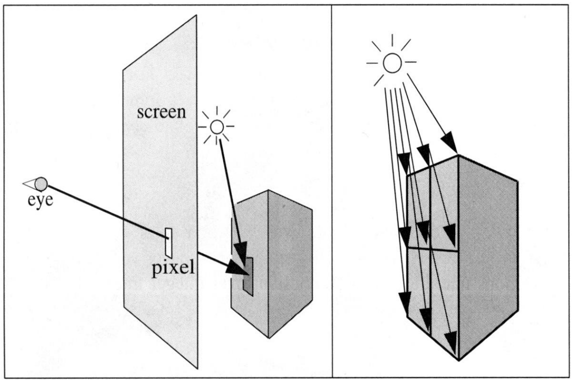
2 bounces

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 (just don't move the light)
  - Can pre-compute complex lighting to allow interactive walkthroughs



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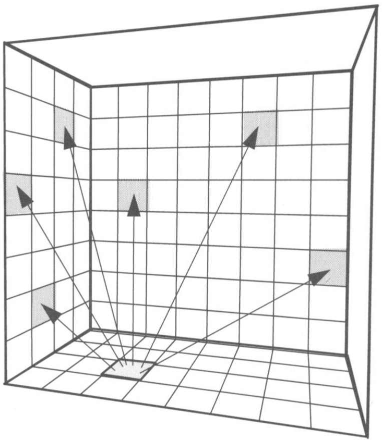
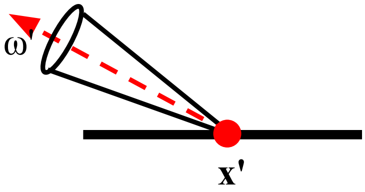
Radiosity Overview

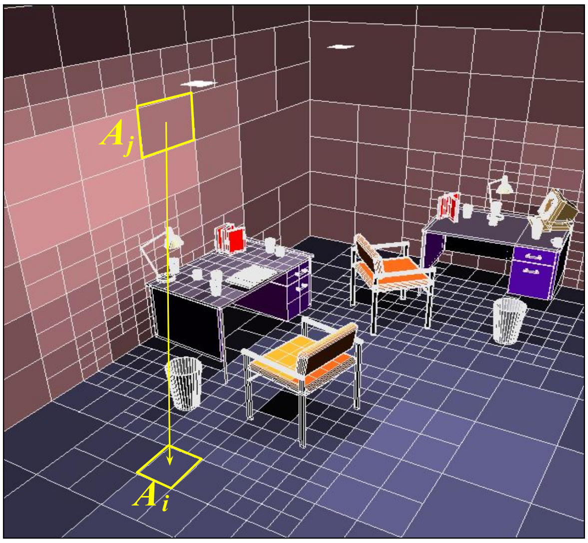


- Surfaces are assumed to be perfectly Lambertian (diffuse)
  - reflect incident light in all directions with equal intensity
- The scene is divided into a set of small areas, or patches.
- The radiosity, B_i, of patch *i* is the total rate of energy leaving a surface. The radiosity over a patch is constant.
- 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 in Matrix Form

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

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.

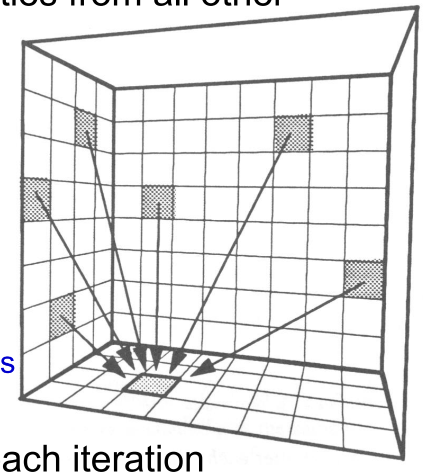
Solving the Radiosity Matrix

- Initialize all radiosity values to 0
- Each iteration, update the radiosity of each patch by *gathering* the contribution of radiosities from all other

$$\begin{bmatrix}B_1\\B_2\\\vdots\\B_i\\\vdots\\B_n\end{bmatrix}=\begin{bmatrix}E_1\\E_2\\\vdots\\E_i\\\vdots\\E_n\end{bmatrix}+\begin{bmatrix} & & & \\ & & & \\ & & & \\ \rho_i F_{i1} & \rho_i F_{i2} & \cdots & \rho_i F_{in}\\ & & & \\ & & & \end{bmatrix}\begin{bmatrix}B_1\\B_2\\\vdots\\B_i\\\vdots\\B_n\end{bmatrix}$$

Radiosity values on iteration ***t+1***

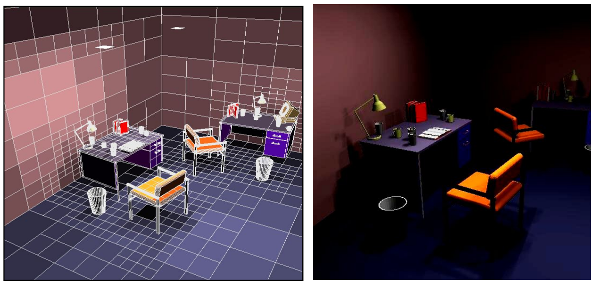
Radiosity values on iteration ***t***

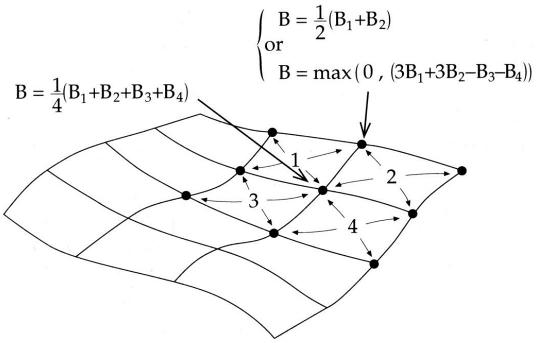


- Radiosity values only increase on each iteration
- This method is fundamentally a Gauss-Seidel relaxation

Interpolating Vertex Radiosities

- B_i radiosity values are constant over the extent of a patch.
- How are they mapped to the vertex radiosities (intensities) needed by the renderer?
  - Average the radiosities of patches that contribute to the vertex
  - Vertices on the edge of a surface are assigned values extrapolation





Questions?

Factory simulation. 30,000 patches.
Program of Computer Graphics, Cornell University.

Today

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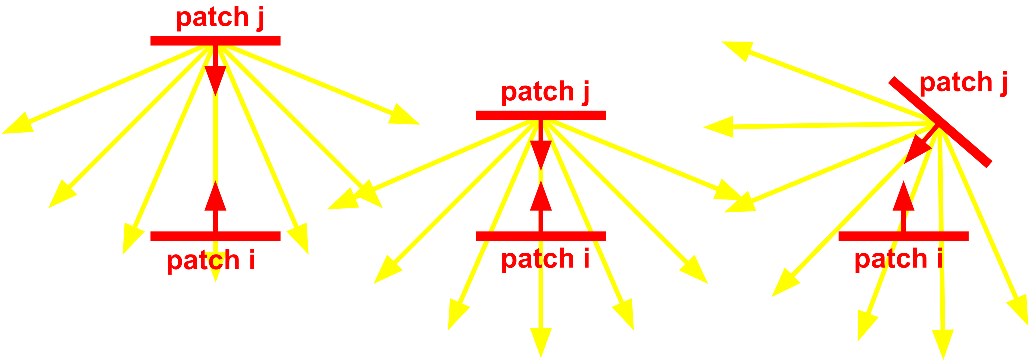
Calculating the Form Factor F_{ij}

- 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}

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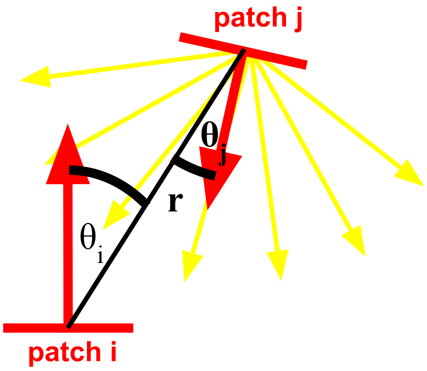
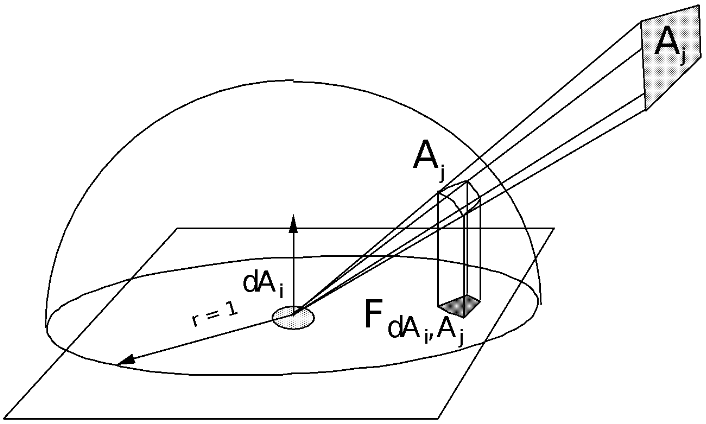


WARNING: common typo is to flip i & j

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

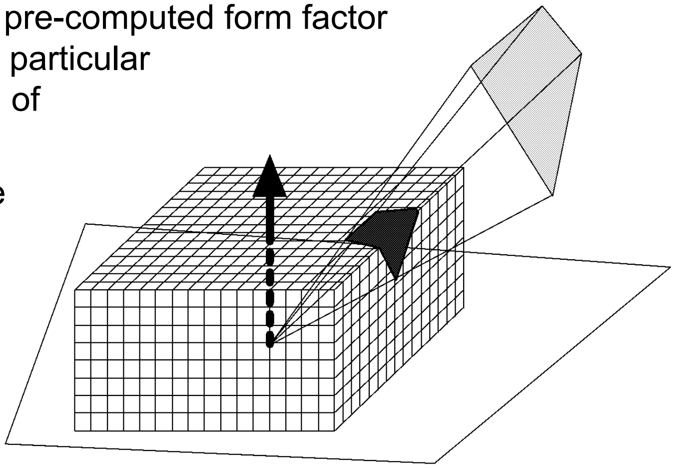
Form Factor Determination

The Nusselt analog: the form factor of a patch is equivalent to the fraction of the unit circle that is formed by taking the projection of the patch onto the hemisphere surface and projecting it down onto the circle.



Hemicube Algorithm

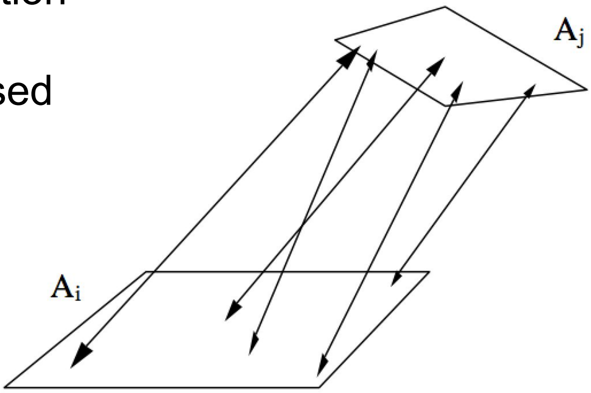
- A hemicube is constructed around the center of each patch
- Faces of the hemicube are divided into "pixels"
- Each patch is projected (rasterized) onto the faces of the hemicube
- Each pixel stores its pre-computed form factor
  The form factor for a particular patch is just the sum of the pixels it overlaps
- Patch occlusions are handled similar to z-buffer rasterization



Form Factor from Ray Casting

- 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

Use this for HW3!



Questions?

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

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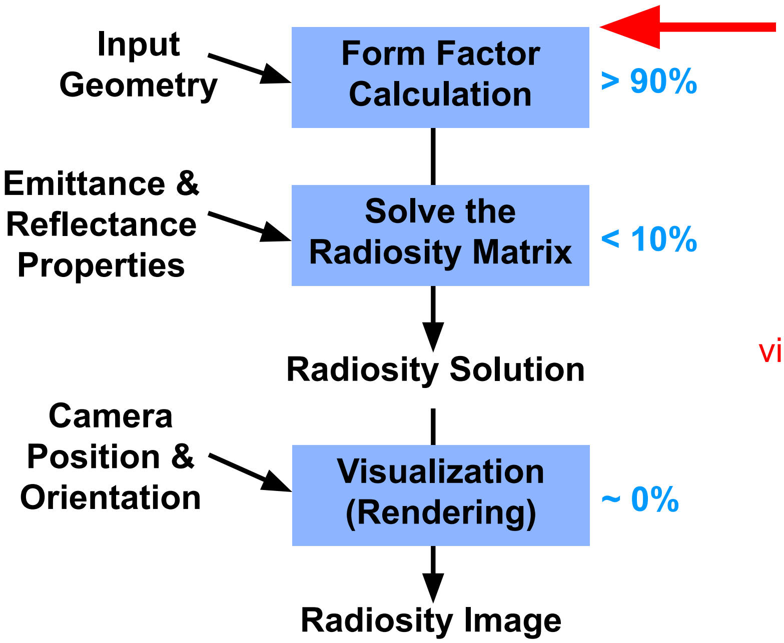
Stages in a Radiosity Solution

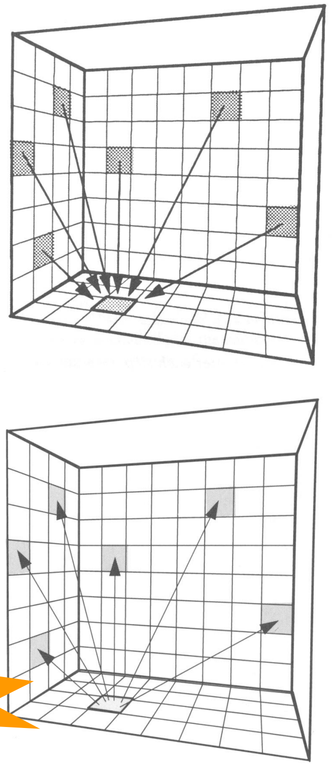


Why so costly?

Calculation & storage of n^2 form factors

(n^3 for naive visibility calculation)

Progressive Refinement



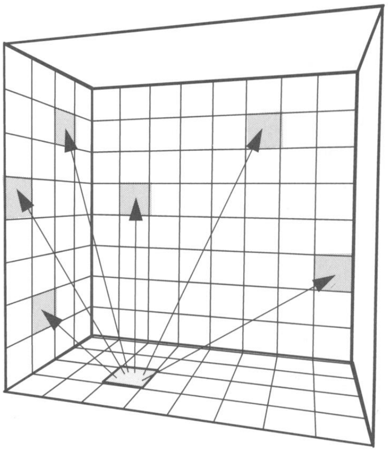
- Goal: Provide frequent and timely updates to the user during computation
- Key Idea: Update the entire image at every iteration, rather than a single patch
- How? Instead of summing the light received by one patch, distribute the radiance of the patch with the most *undistributed radiance*.

Use this for HW3!

Reordering the Solution for PR

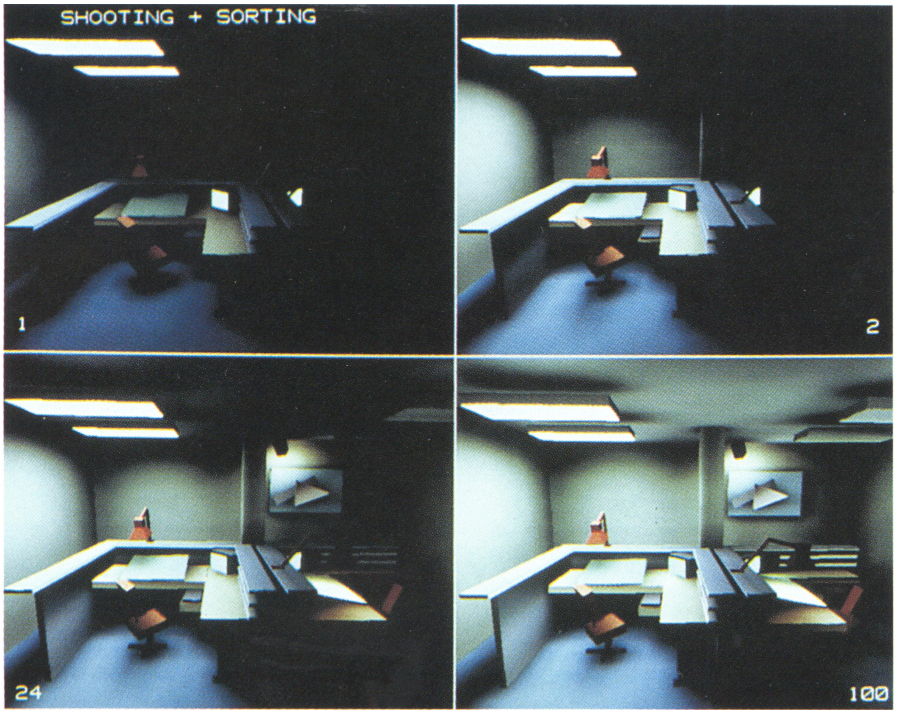
Shooting: the radiosity of all patches is updated for each iteration:

$$\begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ \vdots \\ B_n \end{bmatrix} + \begin{bmatrix} \cdots & \rho_1 F_{1i} & \cdots \\ \cdots & \rho_2 F_{2i} & \\ & & \\ & & \\ \cdots & \rho_n F_{ni} & \cdots \end{bmatrix} \begin{bmatrix} \vdots \\ B_i \\ \vdots \end{bmatrix}$$

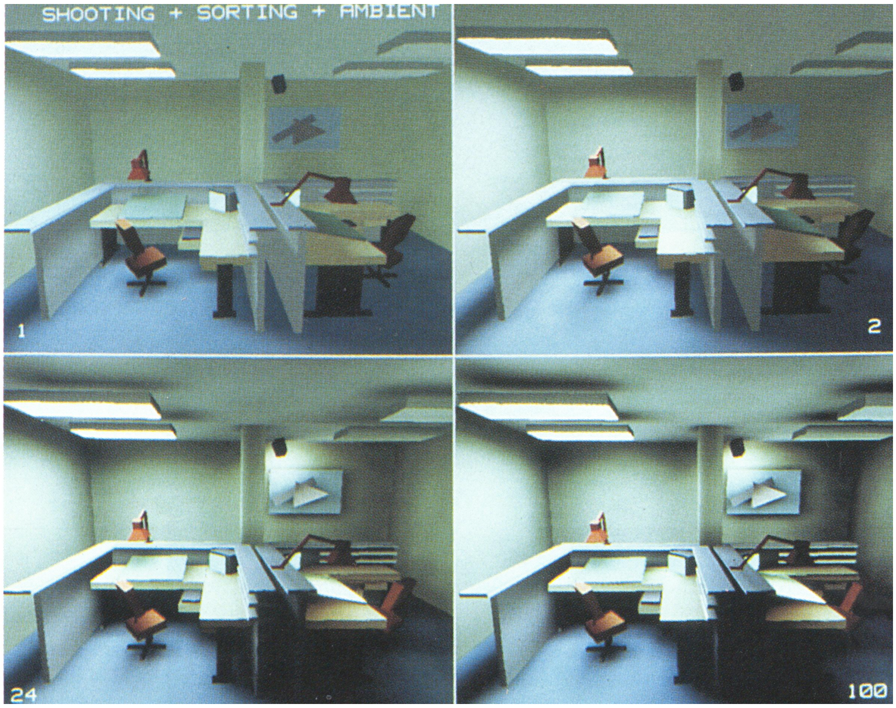


This method is fundamentally a Southwell relaxation

Progressive Refinement w/out Ambient Term



Progressive Refinement with Ambient Term

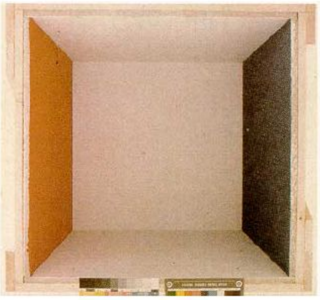


Questions?

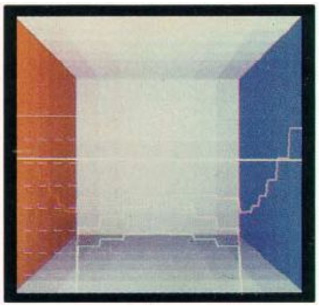
Lightscape **http://www.lightscape.com**

Reading for Next Time:

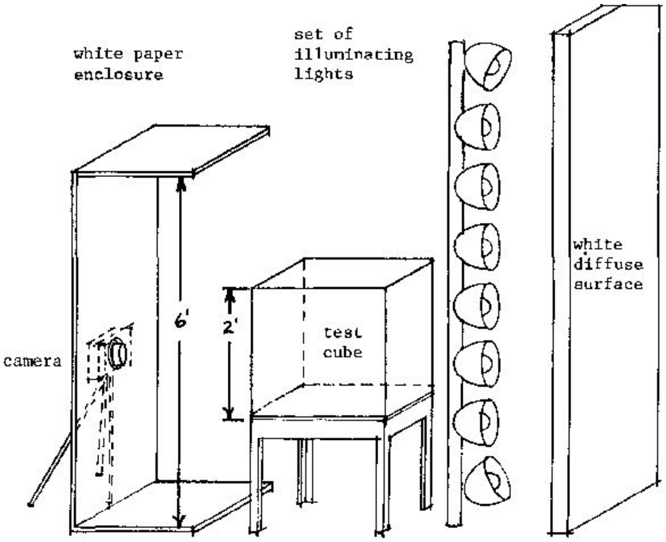
The lecture AFTER the quiz!



photograph



simulation



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

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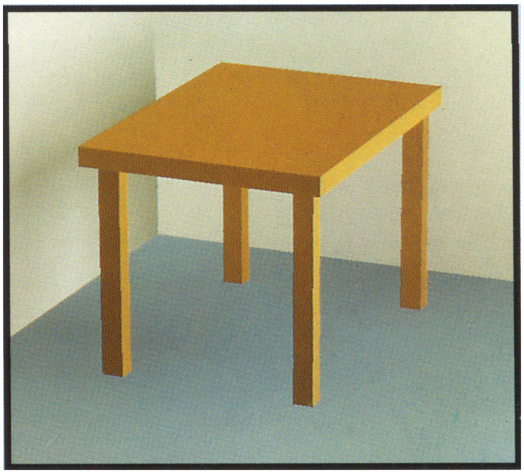
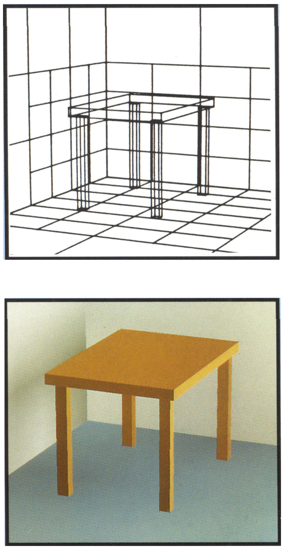
Increasing the Accuracy of the Solution

What's wrong with this picture?

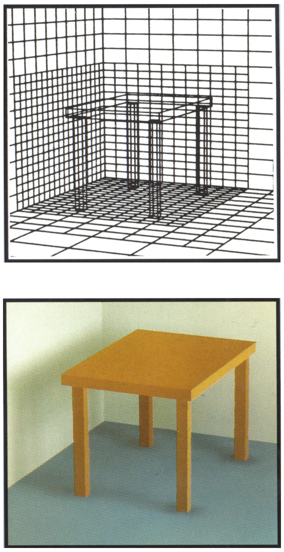


- Image quality is a function of patch size
- Compute a solution on a uniform initial mesh, then refine the mesh in areas that exceed some error tolerance:
  - shadow boundaries
  - other areas with a high radiosity gradient

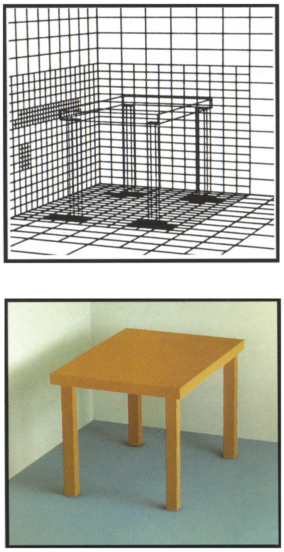
Adaptive Subdivision of Patches



Coarse patch solution
(145 patches)



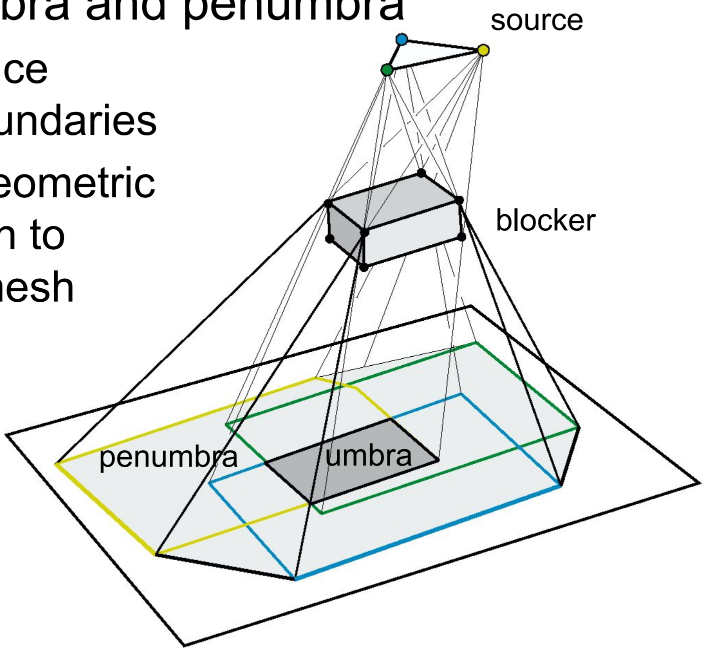
Improved solution
(1021 subpatches)



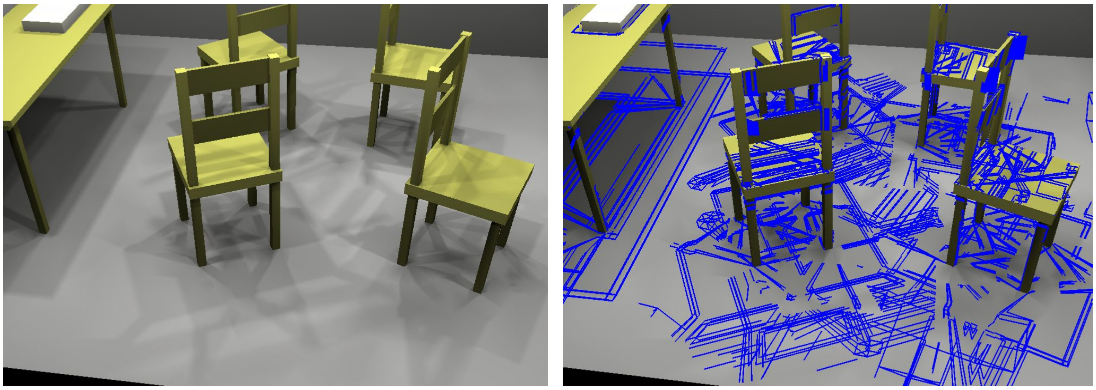
Adaptive subdivision
(1306 subpatches)

Discontinuity Meshing

- Limits of umbra and penumbra
  - Captures nice shadow boundaries
  - Complex geometric computation to construct mesh



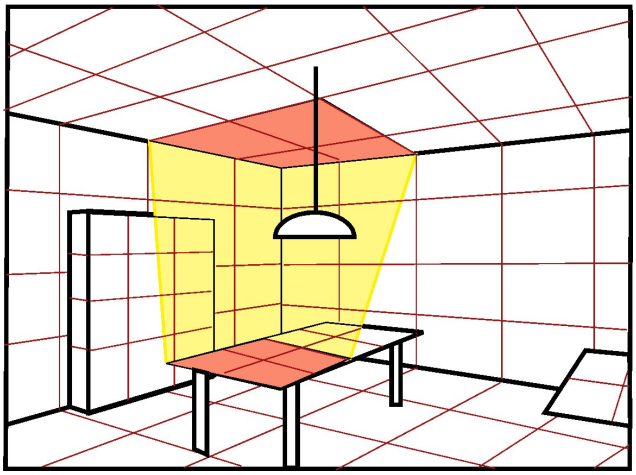
Optional Reading for Next Time:



"Fast and Accurate Hierarchical Radiosity Using Global Visibility"
Durand, Drettakis, & Puech 1999

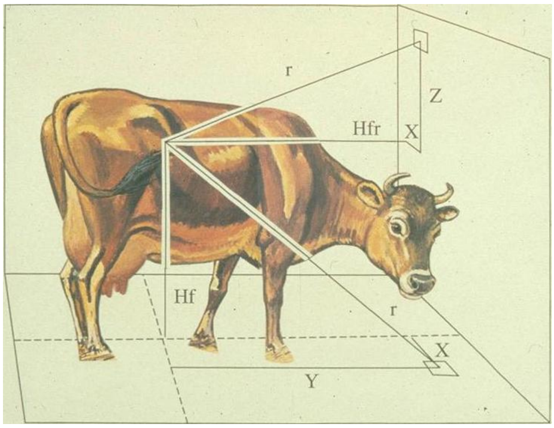
Hierarchical Radiosity

- Group elements when the light exchange is not important
  - Breaks the quadratic complexity
  - Control non trivial, memory cost



Practical Problems with Radiosity

- Meshing
  - memory
  - robustness
- Form factors
  - computation



Cow-cow form factor?

- Diffuse limitation
  - extension to specular takes too much memory

Questions?

Rendered using the Lightscape Visualization System.
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Pop Worksheet!

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