CSCI 420 Computer Graphics
Lecture 18

Global Illumination

BRDFs
Raytracing and Radiosity
Subsurface Scattering
Photon Mapping
[Angel Ch. 11]

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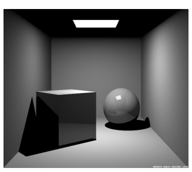
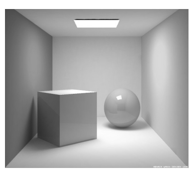
Global Illumination

- Lighting based on the full scene
- Lighting based on physics (optics)
- Traditionally represented by two algorithms
  - Raytracing – 1980
  - Radiosity – 1984
- More modern techniques include *photon mapping* and many variations of raytracing and radiosity ideas

Source: Dianne Hansford,
Arizona State Univ.

Direct Illumination vs. Global Illumination





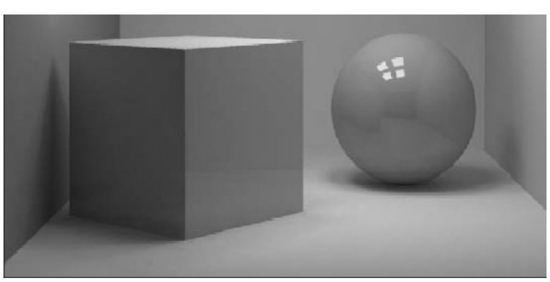
- single (or few) bounces of the light only
- for example, ray casting
- no recursion (or shallow recursion only)
- fast lighting calculations based on light and normal vectors

- reflected, scattered and transmitted light
- many (infinite) number of bounces
- physically based light transport

Indirect Illumination

Color Bleeding

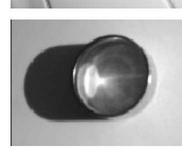
Soft Shadows



Shadows are much darker where the direct and indirect illuminations are occluded. Such shadows are important for "sitting" the sphere in the scene. They are difficult to fake without global illumination.

Caustics

- Transmitted light that refocuses on a surface, usually in a pretty pattern
- Not present with direct illumination



Light Transport and Global Illumination

- Diffuse to diffuse
- Diffuse to specular
- Specular to diffuse
- Specular to specular
- Ray tracing (viewer dependent)
  - Light to diffuse
  - Specular to specular
- Radiosity (viewer independent)
  - Diffuse to diffuse

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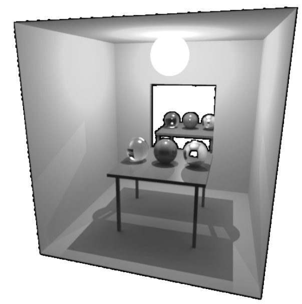
Path Types

- OpenGL
  - L(D|S)E
- Ray Tracing
  - LDS*E
- Radiosity
  - LD*E
- Path Tracing
  - attempts to trace "all rays" in a scene



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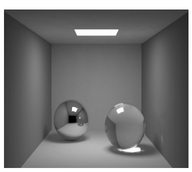
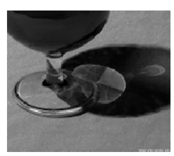
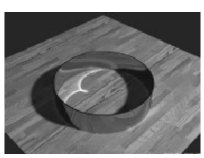
Images Rendered With Global Illumination







- Caustics
- Color bleeding
- Area light sources and soft shadows

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Outline

- Direct and Indirect Illumination
- Bidirectional Reflectance Distribution Function
- Raytracing and Radiosity
- Subsurface Scattering
- Photon Mapping

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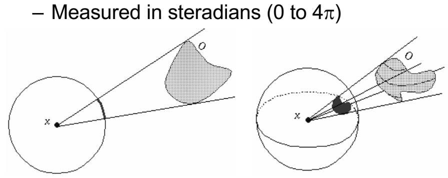
Solid Angle

- 2D angle subtended by object O from point x:
  - Length of projection onto unit circle at x
  - Measured in radians (0 to 2π)
- 3D solid angle subtended by O from point x:
  - Area of of projection onto unit sphere at x
  - Measured in steradians (0 to 4π)



J. Stewart

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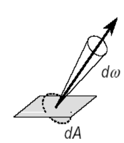
Light Emitted from a Surface

- Radiance (L): Power (ϕ) per unit area per unit solid angle
  - Measured in W / m^2str
  - *dA is projected area* (perpendicular to given direction)
- Radiosity (B): Radiance integrated over all directions
  - Power from per unit area, measured in W / m^2



$$L = \frac{d\Phi}{dA\,d\omega}$$

$$B = \int_{\Omega} L(\theta,\phi)\cos\theta\, d\omega$$

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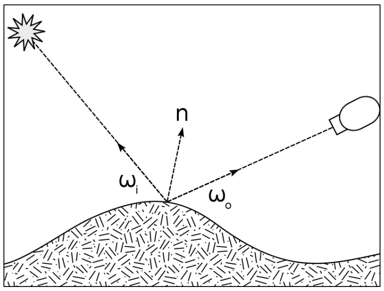
Bidirectional Reflectance Distribution Function (BRDF)

If a ray hits a surface point at angle ω_i, how much light bounces into the direction given by angle ω_o?

It depends on the type of material.



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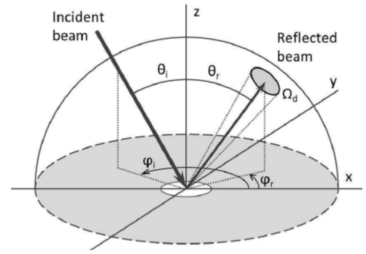
Bidirectional Reflectance Distribution

- General model of light reflection
- Hemispherical function
- 7-dimensional (location, 4 angles, wavelength)



N. Matsapey

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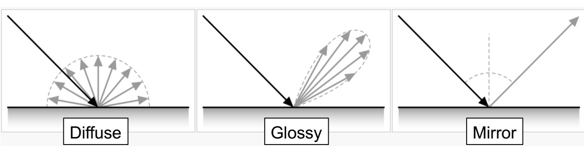
BRDF Examples

- BRDF is a property of the material
- There is no formula for most materials
- Measure BRDFs for different materials (and store in a table)



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Material Examples

Marschner et al. 2000

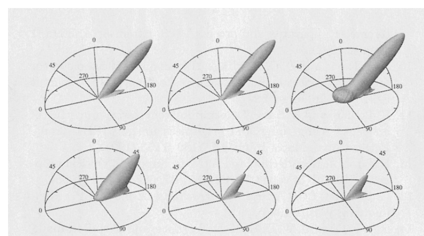

Fig. 16. Resampled scattering diagrams of the BRDF measurements of two paints: a blue enamel (top row) and a red automotive lacquer (bottom row). The RGB color measurements are shown from left to right.

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BRDF Isotropy

- Rotation invariance of BRDF
- Reduces 4 angles to 2
- Holds for a wide variety of surfaces
- Anisotropic materials
  - Brushed metal
  - Others?

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Raytracing

From: http://jedi.ks.uiuc.edu/~johns/raytracer/raygallery/stills.html

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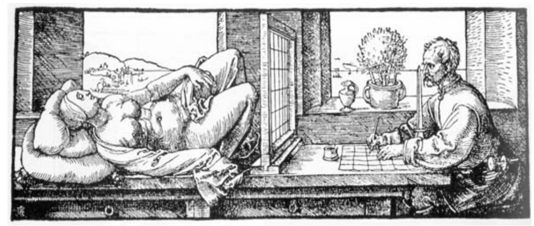
Raytracing



Albrecht Duerer,
Underweysung der Messung mit dem Zirkel und Richtscheyt
(Nurenberg, 1525), Book 3, figure 67.

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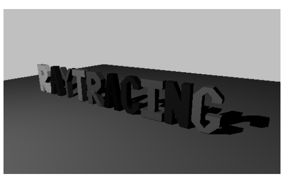
Raycasting vs. Raytracing



Raycasting

Raytracing

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Raytracing: Pros

- Simple idea and nice results
- Inter-object interaction possible
  - Shadows
  - Reflections
  - Refractions (light through glass, etc.)
- Based on real-world lighting

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Raytracing: Cons

- Slow
- Speed often highly scene-dependent
- Lighting effects tend to be abnormally sharp, without soft edges, unless more advanced techniques are used
- Hard to put into hardware

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Supersampling I

- Problem: Each pixel of the display represents one single ray
  - Aliasing
  - Unnaturally sharp images
- Solution: Send multiple rays through each "pixel" and average the returned colors together

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Supersampling II

- Direct supersampling
  - Split each pixel into a grid and send rays through each grid point
- Adaptive supersampling
  - Split each pixel only if it' s significantly different from its neighbors
- Jittering
  - Send rays through randomly selected points within the pixel

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The Radiosity Method

Cornell University

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Radiosity Example

Museum simulation. Program of Computer Graphics, Cornell University. 50,000 patches. Note indirect lighting from ceiling.

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The Radiosity Method

- Divide surfaces into patches
  (e.g., each triangle is one patch)
- Model light transfer between patches as system of linear equations
- Important assumptions:
  - **Diffuse reflection only**
  - No specular reflection
  - No participating media (no fog)
  - No transmission (only opaque surfaces)
  - Radiosity is constant across each patch
  - Solve for R, G, B separately

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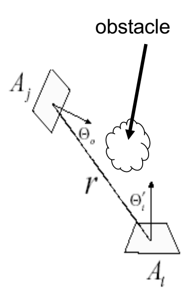
The Radiosity Form Factor

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



F_{ij} is dimensionless

V_{ij} = 0 if occluded
1 if not occluded
(visibility factor)

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Radiosity Equation

- For each patch i: $\underbrace{B_i}_{\text{outgoing radiosity}} = E_i + \rho_i \underbrace{\sum_j (F_{ji} A_j / A_i) B_j}_{\text{incoming radiosity}}$
- Variables
  - B_i = radiosity (unknown)
  - E_i = emittance of light sources (given; some patches are light sources)
  - ρ_i = reflectance (given)
  - F_{ij} = form factor from i to j (computed)
    fraction of light emitted from patch i arriving at patch j
  - A_i = area of patch i (computed)

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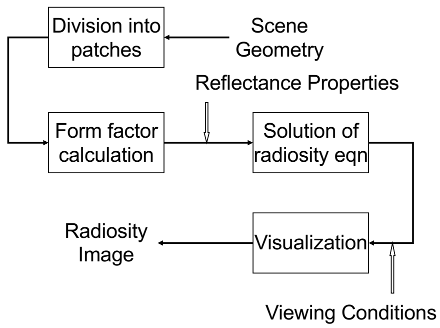
(Idealized) Radiosity Computation



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Radiosity: Pros

- Can change camera position and re-render with minimal re-computation
- Inter-object interaction possible
  - Soft shadows
  - Indirect lighting
  - Color bleeding
- Accurate simulation of energy transfer

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Radiosity: Cons

- Precomputation must be re-done if *anything* moves
- Large computational and storage costs
- Non-diffuse light not represented
  - Mirrors and shiny objects hard to include
- Lighting effects tend to be "blurry" (not sharp)
- Not applicable to procedurally defined surfaces

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Rendering Equation

$$L(\mathbf{x},\omega) = E(\mathbf{x},\omega) + \int f_r(\mathbf{x},\omega,\omega')G(\mathbf{x},\mathbf{x}')V(\mathbf{x},\mathbf{x}')L(\mathbf{x}',\omega')dA'$$

- L is the radiance from a point x on a surface in a given direction ω
- E is the emitted radiance from a point: E is non-zero only if x is emissive
- V is the visibility term: 1 when the surfaces are unobstructed along the direction ω, 0 otherwise
- G is the geometry term, which depends on the geometric relationship (such as distance) between the two surfaces x and x'
- It includes contributions from light bounced many times off surfaces
- f_r is the BRDF

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Subsurface Scattering

- Translucent objects: skin, marble, milk
- Light penetrates the object, scatters and exits
- Important and popular in computer graphics

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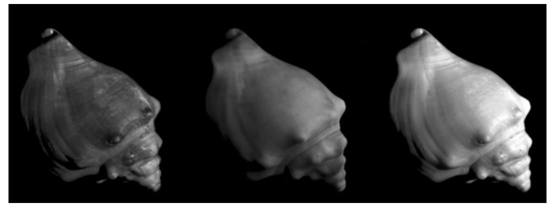
Subsurface Scattering

- Jensen et al. 2001

Using only BRDF | With subsurface light transport

Subsurface Scattering



direct only | subsurface scattered only | combined

Source: Wikipedia

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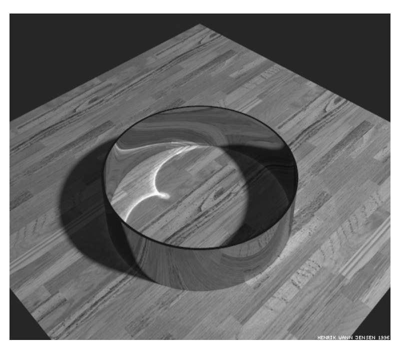
Photon Mapping

From http://graphics.ucsd.edu/~henrik/images/global.html

Photon Mapping Example

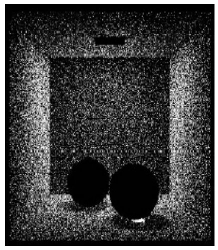
224,316 caustic photons, 3095 global photons

Photon Mapping Example



Photon Map

- “Photons” are emitted (raytraced) from light sources
- Photons either bounce or are absorbed
- Photons are stored in a *photon map,* with both position and incoming direction
- Photon map is decoupled from the geometry (often stored in a kd-tree)



Photon Map

Rendering with the Photon Map

- Raytracing step uses the closest *N* photons to each ray intersection and estimates the outgoing radiance
- Specular reflections can be done using “usual” raytracing to reduce the number of photons needed
- Numerous extensions to the idea to add more complex effects

Photon Mapping Assessment

- Enhancement to raytracing
- Can simulate caustics
- Can simulate diffuse inter-reflections (e.g., the "bleeding" of colored light from a red wall onto a white floor, giving the floor a reddish tint)
- Can simulate clouds or smoke

Photon Mapping: Pros

- The photon map is view-independent, so only needs to be re-calculated if the lighting or positions of objects change
- Inter-object interaction includes:
  - Shadows
  - Indirect lighting
  - Color bleeding
  - Highlights and reflections
  - Caustics – *current method of choice*
- Works for procedurally defined surfaces

Photon Mapping: Cons

- Still time-consuming, although not as bad as comparable results from pure raytracing
- Photon map not easy to update if small changes are made to the scene

Summary

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