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

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

Soft Shadows

Caustics

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

Source: Dianne Hansford, Arizona State Univ.
**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

**Path Types**

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

**Images Rendered With Global Illumination**

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

**Outline**

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

**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 projection onto unit sphere at x
  - Measured in steradians (0 to 4π)

**Light Emitted from a Surface**

- Radiance (L): Power (φ) per unit area per unit solid angle
  - Measured in W / m²str
  - dA is projected area (perpendicular to given direction)
- Radiosity (B): Radiance integrated over all directions
  - Power from per unit area, measured in W / m²

\[
B = \int L(\theta, \phi) \cos \theta d\theta d\phi
\]
**Bidirectional Reflectance Distribution Function (BRDF)**

If a ray hits a surface point at angle $\omega_i$, how much light bounces into the direction given by angle $\omega_o$?

It depends on the type of material.

**Bidirectional Reflectance Distribution**

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

**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)

**Material Examples**

**BRDF Isotropy**

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

**Rendering Equation**

$$L(x, \omega) = E(x, \omega) + \int f(x, x', \omega) G(x, x') L(x', \omega') \, d\omega'$$

- $L$ is the radiance from a point on a surface in a given direction $\omega$
- $E$ 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 $\omega$, 0 otherwise
- $G$ is the geometry term, which depends on the geometric relationship between the two surfaces $x$ and $x'$
- It includes contributions from light bounced many times off surfaces
- $f$, is the BRDF
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Raytracing

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

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

Raycasting vs. Raytracing

Raycasting
Raytracing

Raytracing: Pros

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

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
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

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

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

(Idealized) Radiosity Computation

Radiosity: Pros

- Viewpoint independence means fast real-time display after initial calculation

- Inter-object interaction possible
  - Soft shadows
  - Indirect lighting
  - Color bleeding

- Accurate simulation of energy transfer
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

Radiosity Equation

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

The Form Factor

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

$F_{ij}$ is dimensionless

Visibility factor
- $V_{ij} = 0$ if occluded
- $V_{ij} = 1$ if not occluded

Radiosity Example

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

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Subsurface Scattering

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

- Jensen et al. 2001

Using only BRDF  
With subsurface light transport

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Photon Mapping Basics

- 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

- "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 Mapping

- 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: Pros

- Preprocessing step is view independent, so only needs to be re-done 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

Photon Mapping Example

- 224,316 caustic photons, 3095 global photons

Photon Mapping Example

Summary

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