Local vs. Global Illumination & Radiosity

An early application of radiative heat transfer in stables.

Announcements: Final Projects

• *Everyone* should post one or more ideas for a final project on LMS (“due” Monday after Spring Break)
• Connect with potential teammates (teams of 2 strongly recommended)
• Start finding & reading background papers
• Proposal & summary of background research are due in a couple weeks

Last Time?

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

Today

• **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

BRDF

• Ratio of light coming from one direction that gets reflected in another direction
• Bidirectional Reflectance
  Distribution Function
  – 4D
  – \( R(\theta_i, \phi_i; \theta_o, \phi_o) \)
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: \( l \cdot n \)
    (dot product with normal)

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

- How much light is reflected “specularly”? 
  - Depends on the angle between the ideal reflection direction and the viewer direction \( \alpha \).
- \( L_r = k_s (\cos \alpha)^q \frac{L_i}{r^2} \)
  - \( k_s \): specular reflection coefficient
  - \( q \): specular reflection exponent

Effect of the \( q \) exponent
The Phong Model

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

Ambient Illumination

- In a typical room, everything receives at least a little bit of light
- Ambient illumination represents the reflection of all indirect illumination
  \[ L(\omega_s) = k_a \]
- This is a total hack!

Questions?

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

Why Radiosity?

- Sculpture by John Ferren
- **Diffuse** panels

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- Why is Global Illumination Important?
  - The Cornell Box
  - Radiosity vs. Ray Tracing
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**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

**Reading for Today:**

*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*

*images by Micheal Callahan*

*http://www.cs.utah.edu/~shirley/classes/cs684_98/students/callahan/bounce/*

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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

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

The equation is recursive, but it can be solved iteratively

Radiosity in Matrix Form

For $n$ patches with $n$ unknown $B_i$ values, the radiosity equation can be written in matrix form:

$$
\begin{bmatrix}
1 - \rho F_{i1} & -\rho F_{i2} & \cdots & -\rho F_{in} \\
-\rho F_{i1} & 1 - \rho F_{i2} & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
-\rho F_{in} & \cdots & \ddots & 1 - \rho F_{in}
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n
\end{bmatrix}
= 
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_n
\end{bmatrix}
$$

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

Solving the Radiosity Matrix

The radiosity of a single patch $i$ is updated for each iteration by gathering radiosities from all other patches:

$$
\begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n
\end{bmatrix}
= 
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_n
\end{bmatrix}
+ \rho
\begin{bmatrix}
F_{i1} \\
F_{i2} \\
\vdots \\
F_{in}
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n
\end{bmatrix}
$$

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 by extrapolation

Questions?

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

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

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-point
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  - Progressive Radiosity
  - Adaptive Subdivision
  - Discontinuity Meshing
  - Hierarchical Radiosity

Questions?

Stages in a Radiosity Solution

Form Factor Calculation

Solve the Radiosity Matrix

Radiosity Solution

Visualization (Rendering)

Radiosity Image

- Why so costly?
  - Calculation & storage of \( n^2 \) form factors
  - (\( n^3 \) for naive visibility calculation)

Emittance & Reflectance Properties

Camera Position & Orientation

Input Geometry

Why so costly?

> 90%

< 10%

~ 0%

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.

Progressive Refinement w/out Ambient Term

Reordering the Solution for PR

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

This method is fundamentally a Southwell relaxation
Progressive Refinement with Ambient Term

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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

Lightscape http://www.lightscape.com
Discontinuity Meshing

“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

- Diffuse limitation
  - extension to specular takes too much memory

Questions?

Readings for Friday 3/11 (pick one):

- “The Rendering Equation”, Kajiya, SIGGRAPH 1986
  \[ L(x',\omega') = E(x',\omega') + \int\rho,(\omega,\omega')L(x,\omega)G(x,x')V(x,x') \, dA \]