15-462 – Computer Graphics 1
Lecture 23

Radiosity

November 14, 2002

M. Ian Graham
Carnegie Mellon University

General Announcements

- Project 4 – The Raytracer – is online!
  Due **December 5th**.
- Tips:
  - Start early, start often
  - This assignment is very different from the first three—you will not be programming OpenGL
  - Start early
  - The starter code includes only the ability to write color to a single pixel on-screen or for output to an image file. You're responsible for all program structure, so plan carefully before you start!
  - Start early!

Outline

- A Brief Review/Introduction to Radiosity
- The Radiosity Equation, Form Factors
- Putting it all together, and Improving
- More Realism: A digression, and Two-Pass Rendering

Review: Local vs. Global Illumination

- Local illumination: Phong model (OpenGL, most real-time graphics)
  - Light to single surface point to viewer
  - FAST
  - Vastly simplified
  - No representation of many natural phenomena (shadows, inter-reflections) without additional hacks

Review: Local vs. Global Illumination

- Global illumination: Ray tracing
  - Realistic specular reflection/transmission
  - Simplified diffuse reflection*
- Global illumination: Radiosity
  - Realistic diffuse reflection
  - Diffuse-only: No specular interaction*

Advantages to diffuse-only model?

- Specular interaction depends on viewer position—diffuse does not
- Result: The color seen at any point on any visible surface is independent of viewer position
- Radiosity produces a 3D model of surface patches with colors assigned to each
- This can be rendered in OpenGL!

Classical Radiosity in a Nutshell

- Divide all surfaces into patches (squares are typical).
- Determine a set of linear equations to model inter-reflection between all patches.
- Solve.
- Render using standard hardware.

Assumptions of Classical Radiosity

- No participating media (no light interaction with air, fog, etc)
- Opaque surfaces—no transmission
- Colors (R, G, B) are independent

Assumptions of Classical Radiosity

- Diffuse-only reflection and emission, so outgoing light radiates equally in all directions
- Light radiating from a point on a surface is independent of position on the surface—constant "radiosity" across a single surface

Outline

- A Brief Review/Introduction to Radiosity
- The Radiosity Equation, Form Factors
- Putting it all together, and Improving
- More Realism: A digression, and Two-Pass Rendering

What *is* radiosity?

- Radiosity B(x) = dP/dA
  - P => Energy (light "intensity")
  - A => Area
- Integrating radiosity over a patch with respect to A will yield P for the patch
- Thus, radiosity is a representation of a patch's intensity of light per unit area

What *is* radiosity?

- Radiosity determined by the sum of the emitted and reflected energy: $B_i A_i = E_i A_i + R_i \sum_j B_j A_j F_{ji}$
- *i* identifies the patch whose radiosity is being determined
  j identifies a single other patch
  E is emitted energy (think light sources)
  R is reflectance (how much incoming light is reflected)
  F is the form factor between two patches

What *is* radiosity?

- Radiosity determined by the sum of the emitted and reflected energy: $B_i A_i = E_i A_i + R_i \sum_j B_j A_j F_{ji}$
- Outgoing energy =
  Emitted energy + Reflected energy

Form Factor?

- F_{ij}: Fraction of light leaving patch *i* arriving at patch *j*
- Determined by properties of *i* and *j*:
  – Shape
  – Distance
  – Orientation
  – Occlusion by other patches

Form Factor Equation

$$A_i F_{ij} = \int_{x \in P_i} \int_{y \in P_j} \frac{\cos\theta \cos\theta'}{\pi * r^2} v(x,y)\,dy\,dx$$

- *x* and *y* are points in *i* and *j* respectively
- *r* is distance from *x* to *y*
- Thetas are angles between patch normals and line between *x* and *y*
- *v*(*x*,*y*) is a visibility function
  (can points *x* and *y* see each other?)

Simplify

- Form factors are symmetric: (follows from previous equation) $A_i F_{ij} = A_j F_{ji}$
- Divide radiosity equation by A_i

$$B_i A_i = E_i A_i + R_i \sum_j B_j A_j F_{ji}$$

$$B_i = E_i + R_i \sum_j B_j A_j F_{ji} / A_i$$

$$B_i = E_i + R_i \sum_j B_j F_{ij}$$

Linear System

$$B_i = E_i + R_i \sum_j B_j F_{ij}$$

- Our new equation gives the radiosity (*B*) of a single patch, so to specify the radiosity of all *n* patches we need *n* radiosity equations, one for each patch
- Known values:
  E (given), *R* (given), *F* (computable)
- Unknown: *B*
- *n* equations, *n* unknowns

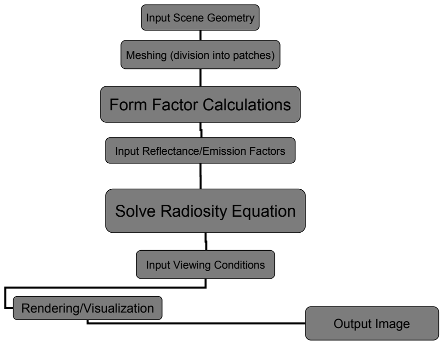
Linear System

- Restate as a matrix equation…and solve!

$$\begin{bmatrix} 1-R_1F_{11} & -R_1F_{12} & \dots & R_1F_{1n} \\ -R_2F_{21} & 1-R_2F_{22} & \dots & R_2F_{2n} \\ \dots & \dots & \dots & \dots \\ -R_nF_{n1} & R_nF_{n2} & \dots & 1-R_nF_{nn} \end{bmatrix} * \begin{bmatrix} B_1 \\ B_2 \\ \dots \\ B_n \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ \dots \\ E_n \end{bmatrix}$$

- Each of our *n* linear equations contains *n* double integrals, one for each form factor. Ouch.

The Radiosity "Pipeline"



Being Smart about Form Factors

- Form factors depend only on scene geometry. If geometry is constant, they only need to be calculated once.
- Solution of the radiosity system is independent of viewing conditions, so if only the viewer position changes, it only needs to be solved once. (We can walk around the scene in real-time after it's initially generated!)

Being Smart about Form Factors

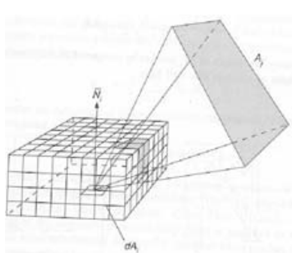
- Form factors each contain a double integral. Full numeric approximation of these is extremely expensive—many special cases may be solved analytically.
- Because we assume that radiosity is constant across a patch, two patches are typically assumed to be fully inter-visible or not at all inter-visible.

How to perform visibility testing?

- Two basic methods, both of which have aliasing problems:
  - Raycasting (typically slow)
  - Hemicube method (z-buffer exploit)
- Anti-aliasing may be performed in both cases

Hemicube Visibility Testing

- Render the entire scene from the perspective of the center of the current patch
- Rather than color, store patch identifiers, using the z-buffer to determine visibility
- Takes advantage of graphics hardware—very efficient



R. Ramamoorthi

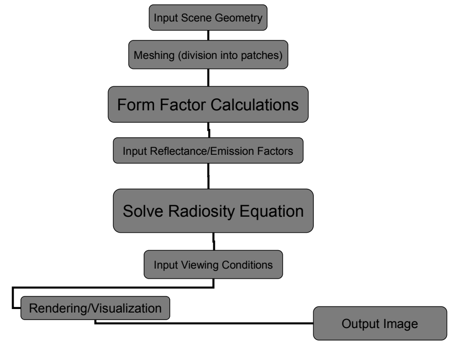
Outline

- A Brief Review/Introduction to Radiosity
- The Radiosity Equation, Form Factors
- Putting it all together, and Improving
- More Realism: A digression, and Two-Pass Rendering

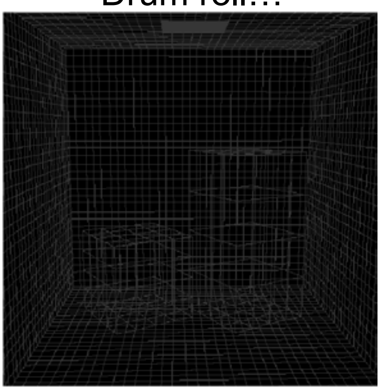
Classical Radiosity in a Nutshell, Revised

- Divide all surfaces into patches.
- Calculate form factors between all patches.
  - Lighting and viewer independent
- Solve the radiosity equation.
  - Viewer independent
- Render using standard 3D hardware.

The Radiosity "Pipeline"

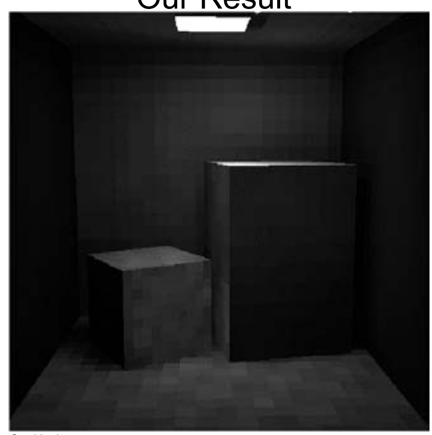


Drum roll…



F. Pfenning

Our Result



F. Pfenning

Yuck!

- What went right?
  - Inter-reflection effects—clearly visible between the box on the right and the wall

Yuck!

- What went wrong?
  - Blocky-looking—patch boundaries extremely obvious!
- Causes of blockiness
  - Aliasing in hemicube method causes significant differences in radiosity between adjacent patches
  - **Large patch size**

Fixes?

- Use antialiasing to clean up hemicube method
- Interpolation
  - Determine radiosity at each vertex of a patch and use bilinear interpolation to make things look smoother
- Increase patch resolution(decrease size)
  - Expensive if done uniformly – O(n^2)
  - How can we do this intelligently?

Antialiasing (on hemicube)

F. Pfenning

Adaptive Subdivision

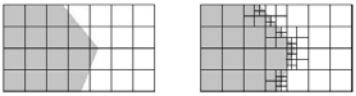
- Introduce a patch substructure—divide each patch into smaller *elements*.
- Keep distinction between patches and elements in order to avoid efficiency problems

Adaptive Subdivision

- Determine light transport one-way from **patches onto elements**, not analyzing element-to-element interaction
- O(mn) for m elements and n patches. More expensive than the original n^2 approach, since $m >> n$, but much better than O(m^2).

Adaptive Subdivision

- Subdivide elements adaptively:

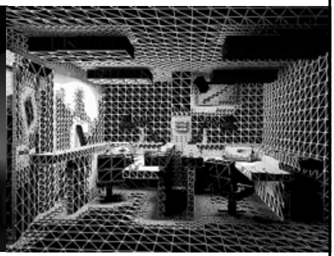


- Begin with elements identical to patches.
- Determine radiosity of an element, then compare to neighbors to obtain an error value. If within some error threshold, assign constant radiosity (or optionally interpolate).
- Otherwise, subdivide the element and recurse until the error threshold or a minimum element size is reached.

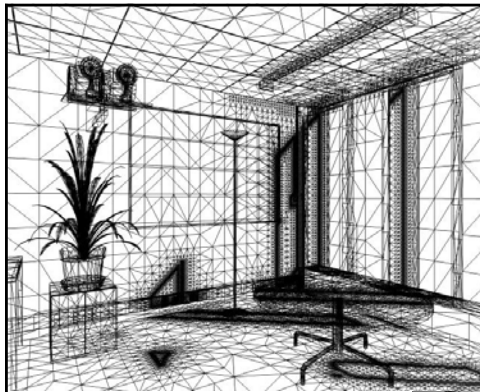
Adaptive Subdivision

- Results in very smooth-looking results for a relatively small amount of extra work
- Shadows, areas near lights, and edges in general look much better
- Not a term specific to radiosity! Adaptive subdivision is a general tool used in many areas of graphics and other fields as well

Adaptive Subdivision Examples



http://www.acm.org/jgt/papers/TeleaVanOverveld97/



http://aig.cs.man.ac.uk/gallery/vrad.html

A Bit More Realism

D. Lischinski

Outline

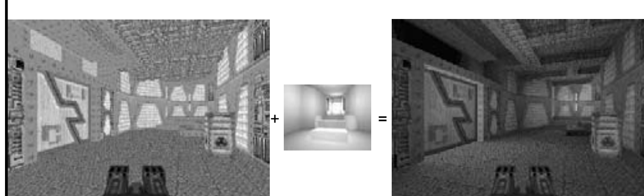
- A Brief Review/Introduction to Radiosity
- The Radiosity Equation, Form Factors
- Putting it all together, and Improving
- More Realism: A digression, and Two-Pass Rendering

A brief digression: Light mapping

- Because radiosity is viewer-independent, it’s possible to calculate radiosity effects for a static environment in advance.
- A game, for example, can precalculate and store this lighting information, and use it in real-time to add detail and realism to the environment.

A brief digression: Light mapping

- Quake did exactly this, texturing static environment objects with radiance texture maps and multiplying this with a separate “light map”
- Many games still use this technique



ID Software

A brief digression: Light mapping

- Disadvantages:
  - Terrain/environment must be fairly static to work well
  - Must separate dynamic objects and flag moving parts of environment as separate “details” with no effect on radiosity
- Many workarounds which are unfortunately beyond our scope

 +  = 

ID Software

Yet More Realism

D. Lischinski

Wait a minute…

D. Lischinski

Specular Radiosity???

- Keep viewer independence
- Light reflected differently in different directions
- Calculations for each source and each direction
- Impractical

A Better Idea: The Best of Both Worlds

- Combine radiosity and raytracing
- Goal: Represent four forms of light transport:
  - Diffuse -> Diffuse
  - Diffuse -> Specular
  - Specular -> Diffuse
  - Specular -> Specular
- Two-pass approach, one for each method

First Pass: Enhanced Radiosity

- Diffuse -> Diffuse
  - Normal diffuse reflection model
  - Diffuse transmission (translucent objects) – requires modified form factor
- Specular -> Diffuse
  - Specular transmission (transparent objects, e.g. windows) – involves extended form factor
  - Specular reflection (reflective objects, e.g. mirrors) – create actual “mirror image” environment with copies of all patches. Expensive!

Enhanced Radiosity - Evaluation

- Only accounts for a single specular reflection (try creating “mirror image” environments for two mirrors facing each other)
- Accurate diffuse model!
- Equations solved as in the classical method
- Still viewer-independent

Second Pass: Enhanced Raytracing

- Specular -> Specular
  – Reflection and transmission as in classical method
- Diffuse -> Specular
  – Use the radiosity calculated in the first pass!
  – Integrate incoming light over a hemisphere (or hemicube), or approximate with a tiny frustum in the direction of reflection
  – Recurse if visible surface is specular

First Pass Result

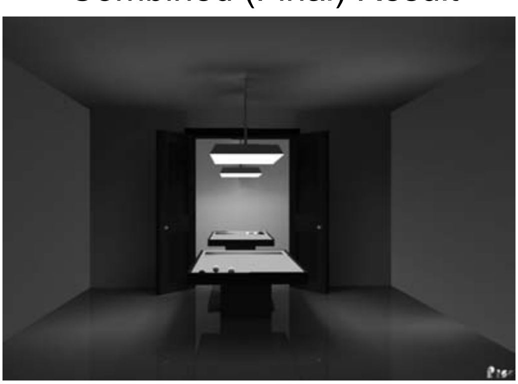
http://www.cg.tuwien.ac.at/research/rendering/rays-radio/

Second Pass Result

(radiosity info. not yet used, just raytracing)

http://www.cg.tuwien.ac.at/research/rendering/rays-radio/

Combined (Final) Result



http://www.cg.tuwien.ac.at/research/rendering/rays-radio/

Two-Pass Global Illumination: Evaluation

- Very, very expensive. Takes the cost of radiosity added to the cost of raytracing and then throws even more calculations into the mix
- Many approximations remain, particularly in specular -> diffuse and diffuse -> specular transport

Two-Pass Global Illumination: Evaluation

- Produces very convincing effects and works very well for scenes with small numbers of reflecting/transmitting objects
- Used in combination with other methods for extremely high-quality images

More Pretty Pictures

D. Lischinski

D. Lischinski

Summary: Classical Radiosity

- Divide all surfaces into patches.
- Calculate form factors between all patches.
  – Lighting and viewer independent
- Solve the radiosity equation
  – Viewer independent
- Render using standard 3D hardware.

Lecture Summary

- A Brief Review/Introduction to Radiosity
- The Radiosity Equation, Form Factors
- Putting it all together, and Improving
- More Realism: A digression, and Two-Pass Rendering

Acknowledgements/Resources

- Frank Pfenning (last semester's instance of this course)
  – http://www.cs.cmu.edu/~fp/courses/02-graphics/
- T. Yeap (many great radiosity resources)
  – http://www.scs.leeds.ac.uk/cuddles/rover/main.htm
- Cornell graphics group (many pretty pictures)
  – http://www.graphics.cornell.edu/online/research/