CS-184: Computer Graphics

Lecture #16: Global Illumination

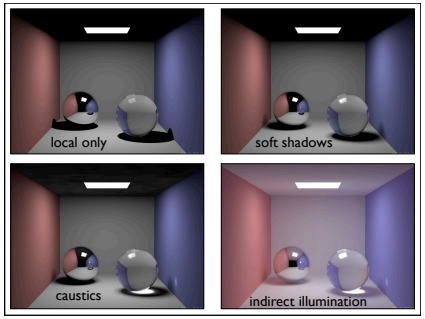
Prof. James O'Brien
University of California, Berkeley

1

Today

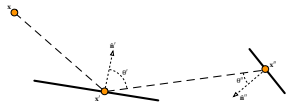
- The Rendering Equation
- Radiosity Method
- Photon Mapping
- Ambient Occlusion

2



3

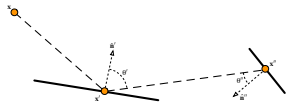
The Rendering Equation



The light shining on x from x' is equal to:
- the emitted light from x' toward x, plus
- for each bit of surface in the scene, how much light shines from that bit onto x' and is reflected toward x, scaled appropriately

4

The Rendering Equation



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$$L_s(\mathbf{x},\mathbf{x}') = \delta(\mathbf{x},\mathbf{x}')\left[E(\mathbf{x},\mathbf{x}') + \int_S \rho_{x'}(\mathbf{x},\mathbf{x}'')L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$

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The Rendering Equation

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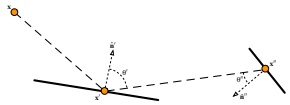

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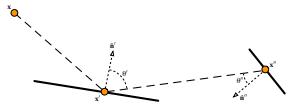
The Rendering Equation

$$\boxed{L_s(\mathbf{x},\mathbf{x}')} = \delta(\mathbf{x},\mathbf{x}')\left[E(\mathbf{x},\mathbf{x}') + \int_S \rho_{x'}(\mathbf{x},\mathbf{x}'')L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$

Light energy hitting x from x'



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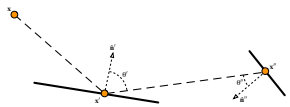

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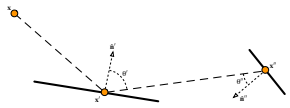
Can x see x' ?



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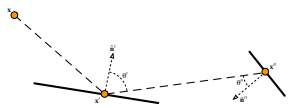

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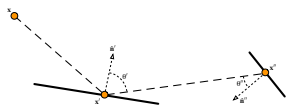
Light emitted from x' toward x



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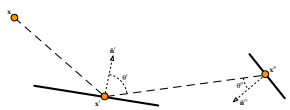

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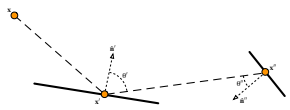
sum over every bit of surface in the scene



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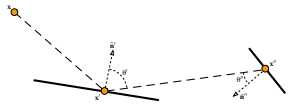

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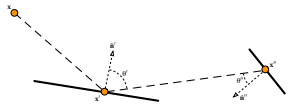
Light emitted from x'' toward x'



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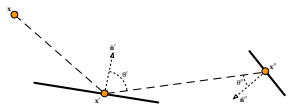

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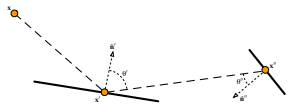
scaled down by the BRDF of x'



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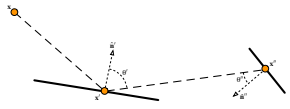

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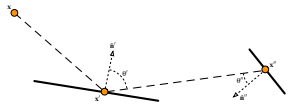
scaled down by distance and relative orientation ("form factor")



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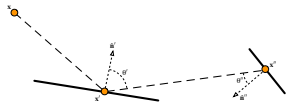


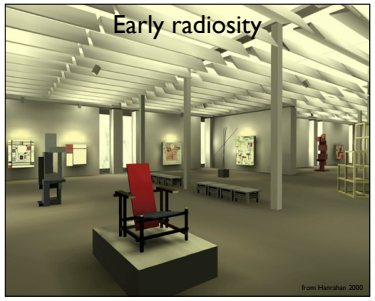
5

Radiosity

- Assume all materials are perfectly Lambertian (diffuse only, no specularities)
  - Removes all dependance on directions
  - Reduces dimensionality of lightfield
  - Allows a FEM solution (break up into chunks)
- Can also relax assumption slightly...

6

Early radiosity

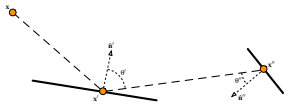


7

Assume Lambertian

$$L_s(\mathbf{x},\mathbf{x}') = \delta(\mathbf{x},\mathbf{x}')\left[E(\mathbf{x},\mathbf{x}') + \int_S \rho_{x'}(\mathbf{x},\mathbf{x}'')L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$

$$L_s(\mathbf{x},\mathbf{x}') = \delta(\mathbf{x},\mathbf{x}')\left[E_{x'} + \int_S \rho_{x'}L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$



8

Assume Lambertian

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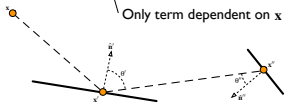
$$L_s(\mathbf{x},\mathbf{x}') = \underline{\delta(\mathbf{x},\mathbf{x}')}\left[E_{x'} + \int_S \rho_{x'}L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$

Only term dependent on $\mathbf{x}$



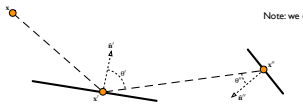
8

Rewrite in Terms of Radiosity

$$L_s(\mathbf{x},\mathbf{x}') = \delta(\mathbf{x},\mathbf{x}')\left[E_{x'} + \int_S \rho_{x'} L_s(\mathbf{x}',\mathbf{x}'')\frac{\cos(\theta')\cos(\theta'')}{||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''\right]$$

$$H_{x'} = E_{x'} + \rho_{x'}\int_S \delta(\mathbf{x}',\mathbf{x}'')\frac{H_{x''}\cos(\theta')\cos(\theta'')}{2\pi\ ||\mathbf{x}'-\mathbf{x}''||^2}d\mathbf{x}''$$

Note: we changed defn of E here.



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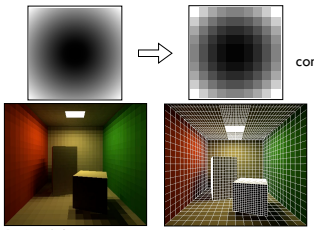
9

Discretize into Patches



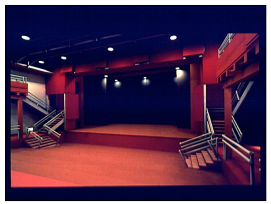
Piece-wise constant patches

Example mesh for Cornell Box by Mark Schmelzenbach

10

10

Discretize into Patches



The Candlestick Theater, Mark Mack Architects.

11

11

Discretize into Patches

The Candlestick Theater, Mark Mack Architects.

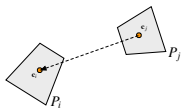
12

12

Rewrite in Terms of Patches

$$H_{x'} = E_{x'} + \rho_{x'} \int_S \delta(\mathbf{x}', \mathbf{x}'') \frac{H_{x''} \cos(\theta') \cos(\theta'')}{2\pi \quad ||\mathbf{x}' - \mathbf{x}''||^2} d\mathbf{x}''$$

$$H_i = E_i + \rho_i \sum_j H_j \int_{S_j} \delta_{ij} \frac{\cos(\theta_j) \cos(\theta_j)}{2\pi ||\mathbf{c}_i - \mathbf{x}||^2} d\mathbf{x}$$



13

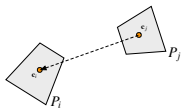
13

Rewrite in Terms of Patches

$$H_{x'} = E_{x'} + \rho_{x'} \int_S \delta(\mathbf{x}', \mathbf{x}'') \frac{H_{x''} \cos(\theta') \cos(\theta'')}{2\pi \quad ||\mathbf{x}' - \mathbf{x}''||^2} d\mathbf{x}''$$

$H_i = E_i + \rho_i \sum_j H$

Form factor from j to i, F_{ij}



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13

Rewrite in Terms of Patches

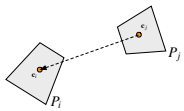
$$H_{x'} = E_{x'} + \rho_{x'} \int_S \delta(\mathbf{x}', \mathbf{x}'') \frac{H_{x''} \cos(\theta') \cos(\theta'')}{2\pi \quad ||\mathbf{x}' - \mathbf{x}''||^2} d\mathbf{x}''$$

$H_i = E_i + \rho_i \sum_j H$

Form factor from j to i, F_{ij}

Example of a rough approximation:

$$F_{ij} \approx \delta_{ij} \frac{\cos(\theta_i) \cos(\theta_j)}{2\pi ||\mathbf{c}_i - \mathbf{c}_j||^2} A_j$$



13

13

Radiosity Method

- Given the E_i and ρ_i
- First compute F_{ij}
- Then solve $H_i = E_i + \rho_i \sum_j H_j F_{ij}$ $\rightarrow$ $\mathbf{h} = \mathbf{e} + \mathbf{A}\mathbf{h}$, $(\mathbf{I} - \mathbf{A})\mathbf{h} = \mathbf{e}$
- Comments:
  - The matrix $\mathbf{A}$ is typically very large
  - It is also sparse (why?)
  - Should be solved with an iterative method
    - e.g.: Jacobi or Gauss-Seidel
  - **Solution is view independent**

14

14

Radiosity Method

- Given the light emitted and surface properties
- First compute F_{ij}, form factors between patches
- Then **solve a linear system to balance energy between all patches**
- Comments:
  - The system is very large
  - It is also sparse (why?)
  - Should be solved with an iterative method
    - e.g.: Jacobi or Gauss-Seidel
  - **Solution is view independent**

15

15

Progressive Radiosity

- If magnitude of eigenvalues of $\mathbf{A}$<1

$$(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots$$

  - True for form-factor matrices
  - $\mathbf{h}^{k+1} = \mathbf{h}^k + \mathbf{u}^{k+1}$
    $\mathbf{u}^{k+1} = \mathbf{A}\,\mathbf{u}^k$
    $\mathbf{h}^0 = 0 \quad \mathbf{u}^0 = \mathbf{e}$

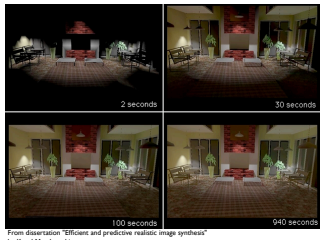
    Idea: let important sources of light energy emit first, maybe don't even bother with dark things
  - Use Gauss-Seidel-like iteration but reorder by priority

Southwell Relaxation

16

16

Progressive Radiosity



From dissertation "Efficient and predictive realistic image synthesis" by Karol Myszkowski

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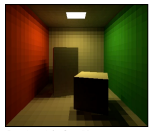
17

Touchup

- Each patch will have a constant color
  - Smooth solution (e.g. average to vertices)



Example mesh for Cornell Box by Mark Schmalzenbach

Does not match but you get the idea...

18

18

Other Things

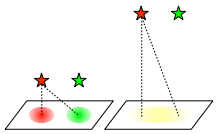
- Each patch will have a constant color
  - Smooth solution (e.g. average to vertices)
- No specular reflection
  - Add Phong specular term or raytraced specular reflection
- Grid artifacts
  - Be clever with grid...

19

19

Hierarchical Radiosity

- Light smoothes with distance
  - Compare $1/h^2$ with $1/(h^2+d^2)$ as h gets large



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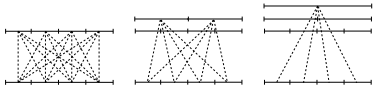
Hierarchical Radiosity

- Light smoothes with distance
  - Compare $1/h^2$ with $1/(h^2+d^2)$ as h gets large
- Group patches into hierarchy
  - Far interactions use lower-res form factors

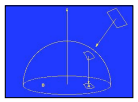


21

21

Computing Form Factors

- Form factors have a geometric meaning



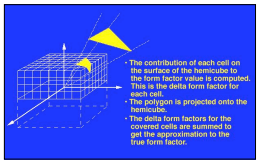
Images from
SIGGRAPH 93 Education Slide Set
by Stephen Spencer

22

22

Computing Form Factors

- Form factors have a geometric meaning
- "Hemicube" algorithm uses regular scan conversion



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23

23

Computing Form Factors

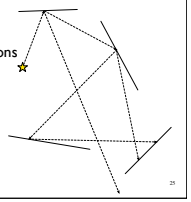
- Form factors have a geometric meaning
- "Hemicube" algorithm uses regular scan conversion
- Also computed by ray-based sampling
- **In practice, computing form factors is the bottleneck**

24

24

Photon Mapping

- Lights cast "photons" into environment
  - Cast in random directions
  - Trace into environment
  - Store records at intersections

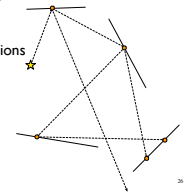


25

25

Photon Mapping

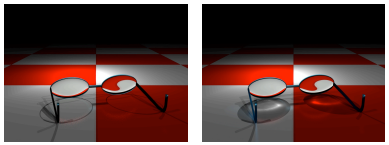
- Lights cast "photons" into environment
  - Cast in random directions
  - Trace into environment
  - Store records at intersections
    - With KD-Trees...



26

26

Comparison



Ray Tracing

Ray Tracing w/ Photon Map

Catherine Bendebury and Jonathan Michaels
CS 184 Spring 2005

27

27

Photon Mapping

A ray traced image

Note:
- Dark shadows
- Unlit corners
- Nice reflections

Image by Per Christensen

28

28

Photon Mapping

Raw photons

Note:
- Noisy
- Sparse

Image by Per Christensen

29

29

Photon Mapping

Interpolated Photons

Note:
- Still noisy
- Biased

Image by Per Christensen

30

30

Photon Mapping

Image by Per Christensen

Interpolated Photons
(multiplied by diffuse)

Note:
Still noisy
Biased

31

31

Photon Mapping

- Final Gather
  - Ray trace scene
  - Direct and specular rays as normal
  - Diffuse rays traced into photon map
  - *Diffuse reflection smoothes noise*

32

32

Photon Mapping

Image by Per Christensen

Final Image

Note:
Not noisy
Nice lighting
Reflections
May still be biased

Final gather often bottleneck...

33

33

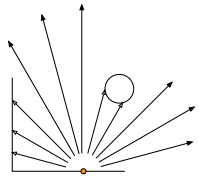
Ambient Occlusion

- A "hack" to create more realistic ambient illumination cheaply
- Assume light from everywhere is partially blocked by local objects
  - At a point on the surface cast rays at random
  - Ambient term is proportional to percent of rays that hit nothing
  - Weight average by cosine of angle with normal
  - Take into account how far before occluded

34

34

Ambient Occlusion



35

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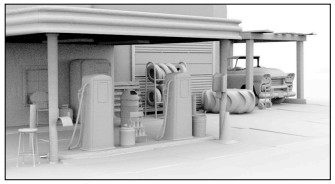
Ambient Occlusion

Diffuse Only Ambient Occlusion Combined

36

36

Ambient Occlusion



nVidia Gelato Demo Image

37

37