Comprehensive Overview

CIS782

Advanced Computer Graphics
Based on notes of Raghu Machiraju and Torsten Moeller
Realism Through Synthesis
Holy Grail

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Photorealistic (Physically Based) Rendering

- **Visibility - sampling**
  - camera to surface
  - surface to surface
  - surface to light source

- **Optics**
  - Nature of Light & its Transport
  - Interaction with surface

- **Display - resampling**
  - Perception
Graphics Pipeline

Modeling → Transform → Visibility

Illumination + Shading

Perception, Interaction

Color

Texture/Realism
Review & Looking ahead

- Local illumination models
- Global illumination
- Ray tracing
- Light transport equations
Shading

- **Illumination Model**: determine the color of a surface (data) point by simulating some light attributes.
- **Local Illumination**: deals only with isolated surface (data) point and direct light light sources.
- **Global Illumination**: takes into account the relationships between all surfaces (points) in the environment.
- **Shading Model**: applies the illumination models at a set of points and colors the whole scene.
Local illumination: Light & Surface

- Usually only considering reflected part

\[
I = k_a I_a + k_d I_d + k_s I_s
\]
Tracing Specular Light Path

Light = reflected + absorbed + transmitted
Diffuse Light

\[ I_d = k_d (N \cdot L) \]
Specular Light

\[ I_s = k_s (E \cdot L)^n \]

\[ \cos^n a \]

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• $I_A$: ambient light
• $k_a$: material’s ambient reflection coefficient
• Models general level of brightness in the scene
• Accounts for light effects that are difficult to compute (secondary diffuse reflections, etc)
Phong Shading

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Physically Based Illumination

- Everything so far has been pretty heuristic
- Cannot model:
  - wavelength dependent phenomena
  - anisotropic behaviors
  - subsurface interactions of light & material
  - indirect diffuse illumination
  - many other physical phenomena (real physics)
- Ongoing research - main contributions
  - Hanrahan, Krüger (1993)
Physically Based Illumination

Incident light

Ideal diffuse
Directional diffuse
Ideal specular
Torrance-Sparrow

\[ \rho = \frac{F_\lambda}{\pi} \frac{DG}{(N \times V)(N \times L)} \]

- **D** - Microfacet Distribution Function
  - how many “cracks” do we have that point in our (viewing) direction?
- **G** - Geometrical Attenuation Factor
  - light gets obscured by other “bumps”
- **F** - Fresnel Term
  - which portion of the incoming light gets reflected?
  - Grazing Angle!
For now can do this
And This ...
It’s getting better ...
Can We Do Better?

Can Do This with GI
Holy Grail

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Local Illumination Problem

What is the intensity of the surface, from the light source, in the direction of the eye?
Global Illumination Problem

What is the “intensity” of this surface from all possible directions?
Determine ‘form factor’ - percentage element from environment is visible to element being considered

Set up equations so that, given light source intensities, compute diffuse-diffuse transfer of light from one surface to another
Energy Distribution
Energy Distribution

Illuminance Map for Daylit Art Gallery

© 1994 by John Mardaljevic – Radiance Software
Measure It!

Equipment in the Light Measurement Laboratory (circa 1995) of the Cornell University Program of Computer Graphics
Light Transport Equation

Outgoing radiance from specific point at specific direction

Integrated over all possible incoming directions

\[ L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{S^2} f(p, \omega_o, \omega_i) L_i(p, \omega_i) |\cos \theta_i| d\omega_i \]

Emitted radiance

differential solid angle

Bidirectional reflectance distribution function (BRDF)

Incoming radiance to specific point in specific direction
Challenges

• Complex primitives: area lights, materials, shapes
• Materials
  – Interfaces: reflectance and texture
  – Medium: scattering
• Camera - sampling
• Large number of paths that light can take
• Solutions:
  – Radiosity - Finite Elements
  – Ray Tracing - Monte Carlo - random sampling
Framework

Research Framework for Realistic Image Synthesis

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Global Illumination - path notation

- At a point incoming light may be scattered or reflected diffusely or specularly and may have come from a multitude of interactions itself.
- For pairs of surfaces we have 4 possible transfers of light:
  - diffuse to diffuse transfer
  - specular to diffuse transfer
  - diffuse to specular transfer
  - specular to specular transfer
Global Illumination - path notation

- Radiosity: diffuse to diffuse
- (Whitted) ray-tracing: specular to specular
- string notation (Heckbert 90):
  - L - light source
  - E - eye point
  - path: specify transfer mechanism
  - 4 possibilities: DD, DS, SD, SS
Global Illumination - path notation
Global Illumination - path notation

- Path of ‘complete’ algorithm: $L(DI)S^E$
  - e.g., $LDE$, $LSE$, $LDDDE$, $LDDSDE$, $LDDSDDE$,
- local reflection model: $L(D+S)$
- typical Z-buffer: $L(D+S)E$ - string of length 1
  - $LDE+LSE$
Global Illumination
(Whitted) ray tracing

- Traces light rays in reverse direction
  - light rays specularly reflected
- hence is view-dependent
- for each hit point we include the contribution of the direct light before we continue with the reflected (or transmitted) ray
Global Illumination
(Whitted) ray tracing

Viewpoint

Point light source

\( \vec{R}_1 \) Reflected ray
\( \vec{L}_1 \) Shadow ray
\( \vec{T}_1 \) Transmitted ray

\( \vec{N}_i \) Surface normal
Global Illumination
(Whitted) ray tracing

b) Ray tree for paths

EYE

Recursion Terminates

Eye

mirror sphere

no refraction

opaque sphere

Light ray (no contribution)

c) Contributions from global and local components

LSSE +

LDSE +

no local contribution

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Global Illumination (Whitted) ray tracing

- Includes direct diffuse reflection (LD), but not diffuse-diffuse (DD)
- restricted to specular reflection
- path characterization:
  - LS*E or LDS*E
- rendering equation:
  - integral over sphere of all possible angles simplifies to two (three) specific directions - light direction and perfect reflected (refracted) ray
Global Illumination - Radiosity

- Implements diffuse-diffuse
- no rays - “patches” interact
  - scene needs to be divided into “patches”
- view-independent
  - one pass computes light distribution in the whole scene: radiosity
  - second pass renders one particular viewpoint
Global Illumination - Radiosity

- Ray-traced with main light turned off
- typical for indoor scenes
- no diffuse interactions - problem!

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Global Illumination - Radiosity

- Same scene as before - main light turned off
- computed using a radiosity method
- scene accounts for diffuse interactions
Test Object - Cornell Box

This is the original Cornell box, as simulated by Cindy M. Goral, Kenneth E. Torrance, and Donald P. Greenberg for the 1984 paper Modeling the interaction of Light Between Diffuse Surfaces, Computer Graphics (SIGGRAPH '84 Proceedings), Vol. 18, No. 3, July 1984, pp. 213-222.

This simulation of the Cornell box was done by Michael F. Cohen and Donald P. Greenberg for the 1985 paper The Hemi-Cube, A Radiosity Solution for Complex Environments, Vol. 19, No. 3, July 1985, pp. 31-40.
Does Radiance Work?

Measured

Simulated
Difference

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Radiosity
indirect light & soft shadows
Radiosity Equations

\[ B_j \quad \text{Radiosity of element } i \]

\[ E_j \quad \text{energy emission of element } j \]

\[ \rho_j \quad \text{reflectivity of element } j \]

\[ F_{ij} \quad \text{form factor between element } i \text{ and element } j \]

\[ B_j = E_j + \rho_j \sum_{i=1}^{N} B_i F_{ij} \quad j = 1..N \]
Radiosity Matrix

\[
\begin{bmatrix}
1 - \rho_1 F_{11} & -\rho_1 F_{12} & \ldots & -\rho_1 F_{1N} \\
-\rho_2 F_{21} & 1 - \rho_2 F_{22} & \ldots & -\rho_2 F_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
-\rho_N F_{N1} & -\rho_N F_{N2} & \ldots & 1 - \rho_N F_{NN}
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_N
\end{bmatrix}
=
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_N
\end{bmatrix}
\]

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

Approximate form factor using projected hemicube method
Cannot do it all

- Finite element methods
- Not efficient - storage
- Meshing problems curved surfaces, hard shadows
- Complex effects beyond diffuse
Try This?

Monte Carlo Ray Tracing?

- Distributed Ray Tracing
  - distribute subsamples in time and space
- Path Tracing
  - incrementally generates paths of scattering events
- Metropolis Light Transport
  - distribute according to function’s PDF
- Photon Maps
  - randomly sample rays leaving the light source
- Bi-Directional Path Tracing
  - trace paths both ways: from camera, from light
Monte Carlo Integration

Can be about computing integrals

\[ I = \int_{a}^{b} f(x) \, dx \]

\[ I_m = (b-a) \frac{1}{N} \sum_{i=1}^{N} f(x_i) \]

\[ \lim_{N \to \infty} I_m = I \]

- \( I_m \) = Monte Carlo estimate
- \( N \) = number of samples
- \( x_1, x_2, \ldots, x_N \) are uniformly distributed random variables in \([a,b]\)
Ray Tracing
from eye, from light

Visibility/Ray Tracing
L[D]S*[E]

Photon Tracing
LS*[D][E]

Deposit photons in the environment
Path Tracing

Distributed Ray Tracing
L[S]D]*E

Path history
From eye, distribute rays until a light source is hit - save path
Bi-Directional Path Tracing

Combine photon mapping and path tracing
Path Tracing – Working?

Often Noisy and Slow!

Photon Map

- Two Pass
- Photon Hits are stored in various resolutions
- Essentially Monte Carlo Path Tracing
- No Dependence on Geometry
- Important Component is Data Structure
- Caustics, Shadow
- Rendering - Ray Tracing Algorithm
- Photon Maps can be large in size
Photon Map

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Photon Map at Work

Ray Tracing – No diffuse component

Caustics

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Indirect Illumination

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Other Related Topics

- Light-surface interaction
- Perceptual-based display
- Image interpolation
- etc.
"A Practical Model for Subsurface Light Transport"
Henrik Wann Jensen, Steve Marschner, Marc Levoy, and Pat Hanrahan
Proceedings of SIGGRAPH'2001, pages 511-518, Los Angeles, August 2001
Translucency
Combining With Modeling

"Visual Simulation of Smoke"
Ronald Fedkiw, Jos Stam, and Henrik Wann Jensen
Image Based Modeling and Rendering
Display Limitations

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Photo Modeling