From Global Illumination
To Inverse Global Illumination

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Computer Graphics & Vision

- **Graphics**
  - Solving forward simulation
  - Synthesizing images from geometry and reflectance
- **Vision**
  - Recovering geometry and reflectance
  - Extracting data from images
Global Illumination

- Reflectance Properties
- Geometry
- Light Sources
- Light Transport
- Radiance Maps
Reflectance Properties

Bidirectional Reflectance Distribution Function (BRDF) (wavelength dependent)

\[ \rho(\vec{x}, \vec{d}_i, \vec{d}_r) = \frac{\text{Reflected Light at } \vec{x} \text{ along } \vec{d}_r}{\text{Incident Light at } \vec{x} \text{ along } \vec{d}_i} \]
Geometry

• A polygonal mesh and/or a set of curved surface patches
Light Sources

• 3D positions and directional radiance distributions
Light Transport

The Rendering Equation \[ \text{[Kajiya’86]} \]

\[ L_r(\bar{x}, \bar{d}_r) = L_e(\bar{x}, \bar{d}_r) + \int_\Omega \rho(\bar{x}, \bar{d}_i, \bar{d}_r)L_i(\bar{x}, \bar{d}_i) \cos \theta_i d\omega \]
Example of Rendering Using Global Illumination

Yu & Wu [Eurographics’97] use bi-directional wavefront tracing to calculate illumination from area sources via curved ideal specular reflectors.
A Comparison
The Problem

- The physics of light transport has been well understood.

- In the absence of real-world geometry and reflectance, rendered images still look synthetic.

- Solution: Image-based Modeling and Rendering (IBMR)
Image-based Modeling and Rendering

• **1st Generation----vary viewpoint but not lighting**
  – Recover geometry (explicit or implicit)
  – Acquire texture maps
  – Facade, Virtualized Reality, View Morphing, Plenoptic Modeling etc.
Input Photographs and Geometric Model

Tower Photographs

Environment Photographs
Synthetic Renderings
A Synthetic Sunrise Sequence

5:00am 5:30am 6:00am 6:30am

7:00am 8:00am 9:00am 10:00am

One Day at the End of March
The Problem

- Texture Maps are *not* Reflectance Maps!

- Need to factorize images into lighting and reflectance maps
Image-based Modeling and Rendering

- **2nd Generation** -- vary viewpoint and lighting
  - Recover geometry
  - Recover reflectance maps
  - Permits rendering using physically based light transport methods
Outline of the Rest of the Talk

• **1st Generation IBMR**
  – Real-Time View-Dependent Projective Texture-Mapping

• **2nd Generation IBMR**
  – General Problem: closely positioned multiple objects
  – Simplified Situation: Isolated Objects
Outline

• 1st Generation IBMR
  ➔ Real-Time View-Dependent Projective Texture-Mapping

• 2nd Generation IBMR
  – General Problem: closely positioned multiple objects
  – Simplified Situation: Isolated Objects
Real-Time View-Dependent Texture Mapping

- VDTM was originally from Façade [Debevec, Taylor & Malik, Siggraph’96].
  - Software implementation
  - 10 seconds per frame
- Real-Time VDTM
  - Software object-space visibility preprocessing +
    hardware projective texture-mapping
  - 20 frames per second on SGI RealityEngine
  - 60 frames per second on SGI Onyx2 InfiniteReality
Motivation for Visibility Processing: Artifacts Caused by Hardware
Visibility Processing Results

The tower

The rest of the campus
Outline

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Previous Work

- **BRDF Measurement in the Laboratory**
  - [Ward 92], [Dana, Ginneken, Nayar & Koenderink 97]
- **Isolated Objects under Direct Illumination**
  - [Sato, Wheeler & Ikeuchi 97]

General case of multiple objects under mutual illumination has not been studied.
Image-based Reflectance Recovery

- Start from photographs
- Recover geometric model
- Measure and/or recover illumination
- Recover parametric models for reflectance
- Design or Predict Novel illumination
- Re-render the scene
Global Illumination

- Reflectance Properties
- Radiance Maps
- Geometry
- Light Sources
Inverse Global Illumination

Reflectance Properties

Radiance Maps

Geometry

Light Sources
Input Images
In Detail ...
Geometry Recovered Using Facade
Synthesized Images of the Room under Original and Novel Lighting
IGI Outline

• IGI for Lambertian surfaces
• IGI for isolated specular surface
• IGI for general surfaces
• Computing diffuse albedo maps
• Results
Inverse Radiosity with Lambertian Surfaces

\[ B_i = E_i + \rho_i \sum_{1 \leq j \leq n} B_j F_{ij} \]

- \( B_i, B_j, E_i \) measured using HDR photographs
- \( F_{ij} \) known because geometry is known
- Solve for diffuse albedo \( \rho_i \)
Recovering Specular Properties from Direct Illumination

\[
\min_{1 \leq i \leq m} \left( L_i - \frac{\rho_d}{\pi} I_r - \rho_s K_i (\bar{\alpha}) I_r \right)^2
\]

- Specular Kernel \( K_i \) as in \([\text{Ward 92}]\)
Parametric BRDF Model [ Ward 92 ]

$$\frac{\rho_d}{\pi} + \rho_s K(\bar{\alpha})$$

Isotropic Kernel

$$K(\bar{\alpha}) = \frac{1}{\sqrt{\cos \theta_i \cos \theta_r}} \frac{\exp[-\tan^2 \delta/\alpha^2]}{4\pi\alpha^2}$$

Anisotropic Kernel

$$K(\bar{\alpha}) = \frac{1}{\sqrt{\cos \theta_i \cos \theta_r}} \frac{\exp[-\tan^2 \delta(\cos^2 \phi / \alpha_x^2 + \sin^2 \phi / \alpha_y^2)]}{4\pi\alpha_x \alpha_y}$$
Recovering Diffuse and Specular Reflectance under Mutual Illumination

\[
\min_{\rho_d, \rho_s, \alpha} \left( L_{C_i Pi} - \rho_d \sum_{1 \leq j \leq n} L_{Pi Aj} F_{Pi Aj} - \rho_s \sum_{1 \leq j \leq n} L_{Pi Aj} K_{C_i Pi Aj} \right)^2
\]

- Specular component of \( L_{Pi Aj} \) is not known. (Unlike diffuse case, where \( L_{Pi Aj} = L_{Ck Aj} \))
Solution: iteratively estimate specular component.

\[
L_{P_i A_j} = L_{C_k A_j} + \Delta S_{C_k P_i A_j}
\]

• Initialize \( \Delta S_{C_k P_i A_j} = 0 \)
• Repeat
  – Estimate BRDF parameters for each surface
  – Update \( \Delta S_{C_k P_i A_j} \) and \( L_{P_i A_j} \)
Estimation of $\Delta S$

- Estimate specular component of $L_{PiA_j}$ by ray-tracing using current guess of reflectance parameters.
- Similarly for $L_{CkA_j}$
- Difference gives $\Delta S$
- Currently we use one-bounce approximation, but could be generalized.
Inverse Global Illumination

- Detect specular highlight blobs on the surfaces.
- Choose a set of sample points inside and around each highlight area.
- Build hierarchical links between sample points and facets in the environment and use ray tracing to detect occlusion.
- Assign to each facet one photograph and one average radiance value captured at the camera position.
- Assign zero to Delta\_S at each hierarchical link.
- For iter = 1 to n
  - For each hierarchical link, use its Delta\_S to update its radiance value.
  - For each surface having highlight areas, optimize its BRDF parameters.
  - For each hierarchical link, estimate its Delta\_S with the new BRDF parameters.
- End
Recovering Diffuse Albedo Maps

- Estimate specular component at each pixel from the recovered BRDF parameters using Monte Carlo ray-tracing.
- Subtract specular component to get the diffuse component of radiance, $L_d(x)$.
- Gather irradiance, $I_r(x)$, using Form-Factors over each surface.
- $\rho_d(x) = \frac{L_d(x)}{I_r(x)}$
- Combine $\rho_d(x)$ from multiple photographs by robust weighted average.
Results for a Simulated Cubical Room: I

Diffuse Albedo

- Real
- Recovered
Results for a Simulated Cubical Room: II

Specular Roughness
Real vs. Synthetic for Original Lighting
Diffuse Albedo Maps of Identical Posters in Different Parts of the Room
Inverting Color Bleed

Input Photograph

Output Albedo Map
Real vs. Synthetic for Novel Lighting
Video
Contributions

• A digital camera is the only data acquisition equipment used.

• Adopt an iterative procedure to obtain radiance distributions from specular surfaces.

• Exploit spatial coherence to recover specular reflectance models from one single photograph.

• Make use of multiple photographs to recover high-resolution diffuse albedo maps.
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Some Input Photographs
Modeling the Illumination

- **The sun**
  - Its diameter extends 31.8’ seen from the earth.

- **The sky**
  - A hemispherical area light source.

- **The surrounding environment**
  - May contribute more light than the sky on shaded side.
  - Modeled as a set of oriented Lambertian facets.
A Recovered Sky Radiance Model

R, G, B channels
Coarse-grain Environment Radiance Maps

- Partition the lower hemisphere into small regions
- Take photographs at several times of day
- Project pixels into regions and obtain the average radiance
Predicting Novel Illumination from the Environment

• Use photometric stereo to recover a Lambertian facet model for each region

Synthetic

Real
Comparison with Real Photographs

Synthetic

Real
Video
Facial Skin Reflectance and Wrinkles
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Publications

- Y. Yu and H. Wu, *A Rendering Equation for Specular Transfers and Its Integration into Global Illumination*, Eurographics’97

http://www.cs.berkeley.edu/~yyz