Motivation

- Rendering Equation since 86, Path Tracer in HW 3
- So, is Monte Carlo rendering solved?
- Can it be made more efficient (90s until today)?
  - Multiple Importance Sampling (Homework 4)
  - Irradiance Caching takes advantage of coherence
  - Correct sampling: Stratified, Multiple Importance, Bidirectional Path Tracing, Metropolis, VCM/UPS, ...
  - Photon Mapping
  - Modern adaptive sampling, cut-based integration
- Advanced topics (next time)
- Denoising (next time)

Smoothness of Indirect Lighting

Irradiance Caching

- Empirically, (diffuse) interreflections low frequency
- Therefore, should be able to sample sparsely
- Irradiance caching samples irradiance at few points on surfaces, and then interpolates
- Ward, Rubinstein, Clear. SIGGRAPH 88, A ray tracing solution for diffuse interreflection

Irradiance Calculation

\[
E(x) = \int l(x, \omega) \cos \theta \, d\omega
\]

\[
E(x) = \sum_i w(x_i) E_i(x_i)
\]
Algorithm Outline

- Find all samples with \( w(x) > q \)
- if (samples found)
  - interpolate
- else
  - compute new irradiance
- N.B. Subsample the image first and then fill in

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Better Sampling

- Smarter ways to Monte Carlo sample
- Long history: Stratified, Importance, Bi-Directional, Multiple Importance, Metropolis
- Good reference is Veach thesis
- We only briefly discuss a couple of strategies

Stratified Sampling

Stratified sampling like jittered sampling
Allocate samples per region

\[
N = \sum_{i} N_i, \quad F_i = \frac{1}{N} \sum_{j} N_j F_{ij}
\]

New variance

\[
\text{Var}(F) = \frac{1}{N^2} \sum_{i,j} N_i N_j \text{Var}(F_{ij})
\]

Thus, if the variance in regions is less than the overall variance, there will be a reduction in resulting variance
For example: An edge through a pixel

\[
\text{Var}(F_{ij}) = \frac{1}{N^2} \sum_{i,j} N_i N_j \text{Var}(F_{ij})
\]

Comparison of simple patterns

- Latin Hypercube
- Quasi Monte Carlo
- Ground Truth
- Uniform
- Random
- Stratified

16 samples for area light, 4 samples per pixel, total 64 samples
If interested, see my paper "A Theory of Monte Carlo Visibility Sampling"

Figures courtesy Tianyu Liu
**Spectrally Optimal Sampling**

**Light Ray Tracing**

**Path Tracing: From Lights**

- Step 1. Choose a light ray
- Step 2. Find ray-surface intersection
- Step 3. Reflect or transmit
  - \( u = \text{Uniform}() \)
  - if \( u < \text{reflectance}(x) \)
    - Choose new direction \( d \sim \text{BRDF}(O|I) \)
    - goto Step 2
  - else if \( u < \text{reflectance}(x) + \text{transmittance}(x) \)
    - Choose new direction \( d \sim \text{BTDF}(O|I) \)
    - goto Step 2
  - else // absorption=1–reflectance-transmittance
    terminate on surface; deposit energy

**Path Pyramid (\( k = l + e = \text{total number of bounces} \))**

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**Comparison**

Bidirectional path tracing  Path tracing

From Veach and Guibas
Why Photon Map?

- Some visual effects like caustics hard with standard path tracing from eye
- May usually miss light source altogether
- Instead, store "photons" from light in kd-tree
- Look-up into this as needed
- Combines tracing from light source, and eye
- Similar to bidirectional path tracing, but compute photon map only once for all eye rays

Global Illumination

Direct Illumination

Specular Reflection

Caustics

Indirect Illumination

Cornell Box

200000 global photons, 50000 caustic photons
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**Lightcuts**

- Efficient, accurate complex illumination

**Complex Lighting**

- Simulate complex illumination using point lights
  - Area lights
  - HDR environment maps
  - Sun & sky light
  - Indirect illumination
- Unifies illumination
  - Enables tradeoffs between components

**Key Concepts**

- Light Cluster
- Light Tree
  - Binary tree of lights and clusters
Key Concepts

- Light Cluster
- Light Tree
- A Cut
  - A set of nodes that partitions the lights into clusters

Simple Example

Three Example Cuts

Three Example Cuts

Three Example Cuts

Three Example Cuts

Three Example Cuts

Three Example Cuts

Good Bad Bad

Bad Good Bad

Good Good Good
Tableau, 630K polygons, 13,000 lights, (EnvMap+Indirect)

Avg. shadow rays per eye ray 17 (0.13%)

NVIDIA ReSTIR RTX DI

- Bitterli et al. 20 Spatiotemporal reservoir resampling
- Real-Time Direct Lighting from millions of lights