CSE168: Rendering Algorithms
Photon Mapping 1

Depth of Field

- Depth of Field
- Rendering equation
- Specular transport
- Filtering
- Photon mapping
- Caustics

Depth of Field

Basic Depth of Field

For each primary ray:
- Compute point \( x \) on plane of focus
- Jitter (randomly move) camera location
- Compute new direction from camera to \( x \)
- Normalize direction and trace ray

The Rendering Equation

\[
L(x, \bar{\omega}) = L_e(x, \bar{\omega}) + L_r(x, \bar{\omega}) \\
= L_e(x, \bar{\omega}) + \int_{2\pi} f_r(x, \bar{\omega}, \bar{\omega}') L(x, \bar{\omega}') (\bar{\omega} \cdot \bar{n}) \, d\bar{\omega}'
\]
Unbiased and Consistent

Unbiased estimator:
\[ E(X) = \int \ldots \]

Consistent estimator:
\[ \lim_{N \to \infty} E(X) = \int \ldots \]

Unbiased Methods

- Variance (noise) is the only error
- This error can be analyzed using the variance (i.e., 95% of samples are within 2% of the correct result)

Path Tracing (Unbiased)

10 paths/pixel

Path Tracing (Unbiased)

100 paths/pixel
How Can We Remove This Noise

The World is Diffuse!

Noise Reduction/Removal

- More samples (slow convergence, $\sigma \propto 1/\sqrt{N}$)
- Better sampling (stratified, importance, qmc etc.)
- Adaptive sampling
- Filtering
- Caching and interpolation

Stratified Sampling
**Quasi Monte-Carlo**

- Halton Sequence: 10 paths/pixel

**Fixed (Random) Sequence**

- 10 paths/pixel

**Filtering: Idea**

- Noise is high frequency
- Remove high frequency content

**Unfiltered Image**

- 10 paths/pixel

**3x3 Lowpass Filter**

- 10 paths/pixel
3x3 Median Filter

Energy Preserving Filters
- Distribute noisy energy over several pixels
- Adaptive filter width
  [Rushmeier and Ward 94]
- Diffusion style filters
  [McCoy99]
- Splatting style filters
  [Sykes and Williams 00]

Problems With Filtering
- Everything is filtered (blurred)
  * Textures
  * Highlights
  * Caustics
  * ...

Photon Mapping
A two-pass algorithm:
- Pass 1: Trace photons from the light source
- Pass 2: Ray trace the scene and use the photons to compute indirect illumination

A simple test scene

Rendering
Photon Tracing

Radiance Estimate

\[ L(x, \omega) = \int_{\Omega} f_i(x, \omega', \omega) L'(x', \omega') \cos \theta' d\omega' \]
\[ = \int_{\Omega} f_i(x, \omega', \omega) \frac{d\Phi^2(x, \omega')}{d \omega'} \cos \theta' d\omega' \]
\[ = \int_{\Omega} f_i(x, \omega', \omega) \frac{d\Phi^2(x, \omega')}{dA} \]
\[ \approx \sum_{p=1}^{n} f_i(x, \omega'_p, \omega) \frac{\Delta \Phi_p(x, \omega'_p)}{\pi r^2} \]

The photon map datastructure

The photons are stored in a left balanced kd-tree

```
struct photon {
    float position[3];
    rgb power; // power packed as 4 bytes
    char phi, theta; // incoming direction
    short flags;
}
```

Code on the class webpage.

Rendering: Caustics
**Caustic from a Glass Sphere**

Photon Mapping: 10000 photons / 50 photons in radiance estimate

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**Caustic from a Glass Sphere**

Path Tracing: 1000 paths/pixel

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**Sphereflake Caustic**

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**Reflection Inside A Metal Ring**

50000 photons / 50 photons in radiance estimate

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**Caustics On Glossy Surfaces**

340000 photons / ≈ 100 photons in radiance estimate

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**HDR environment illumination**

Using lightprobe from www.debevec.org
Next Time

- More photons