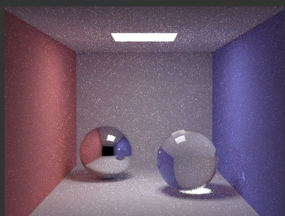
CSE168: Rendering Algorithms
Photon Mapping 1



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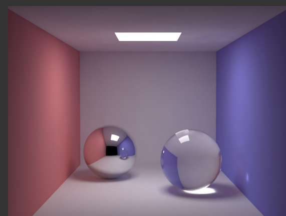

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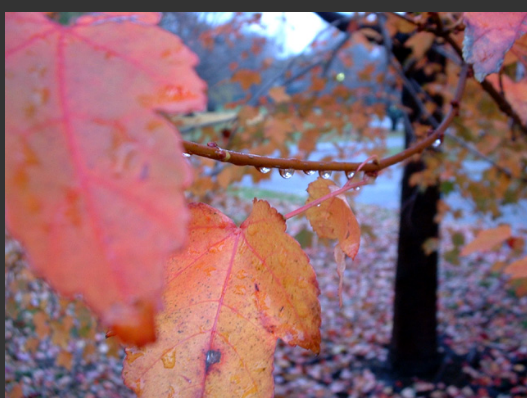
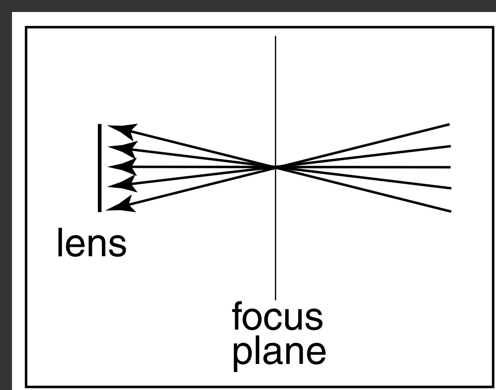
Depth of Field

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

Depth of Field



Basic 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

$$\begin{aligned} L(x,\vec{\omega}) &= L_e(x,\vec{\omega}) + L_r(x,\vec{\omega}) \\ &= L_e(x,\vec{\omega}) + \int_{2\pi} f_r(x,\vec{\omega},\vec{\omega}')L(x,\vec{\omega}')(\vec{\omega}\cdot\vec{n})\,d\vec{\omega}' \end{aligned}$$

Unbiased and Consistent

Unbiased estimator:

$$E\{X\} = \int \ldots$$

Consistent estimator:

$$\lim_{N \to \infty} E\{X\} \to \int \ldots$$

Unbiased and Consistent

Unbiased estimator:

$$\frac{1}{N} \sum_{i=1}^{N} f(\xi_i)$$

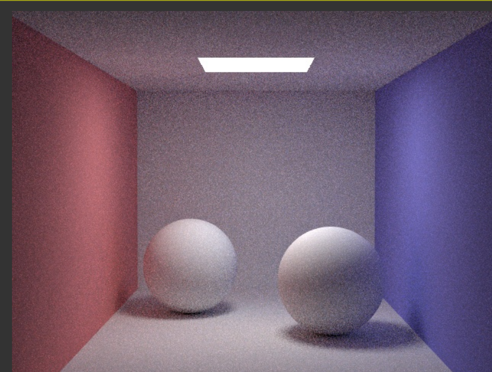
Consistent estimator:

$$\frac{1}{N+1} \sum_{i=1}^{N} f(\xi_i)$$

Unbiased Methods

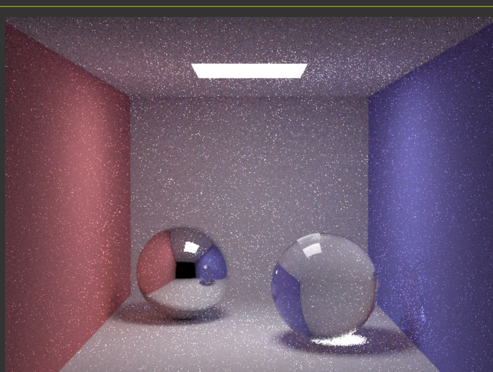
- Variance (noise) is the only error
- This error can be analyzed using the variance (i.e. 95% of samples are within 2% of the correct result)

Path Tracing (Unbiased)



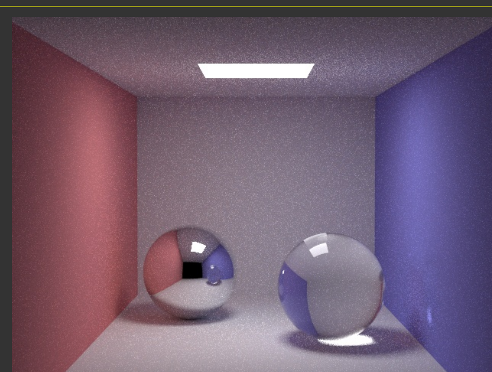
10 paths/pixel

Path Tracing (Unbiased)



10 paths/pixel

Path Tracing (Unbiased)



100 paths/pixel

How Can We Remove This Noise

The World is Diffuse!

Arnold Rendering

The World is Diffuse!

Arnold Rendering

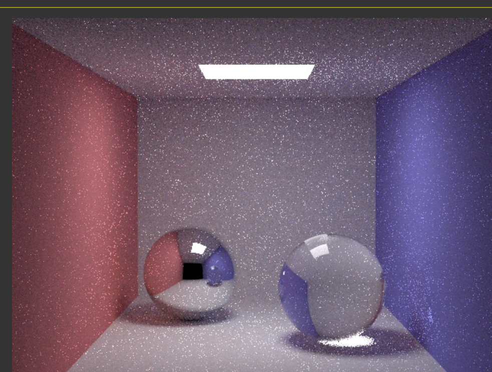
The World is Diffuse!

Arnold Rendering

Noise Reduction/Removal

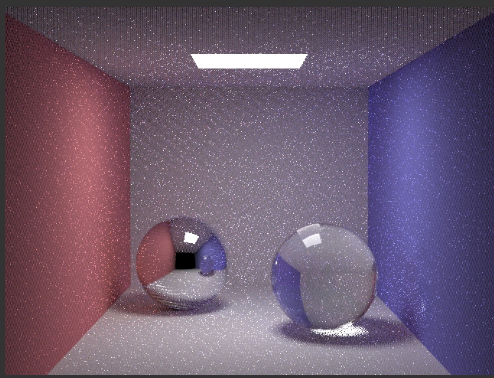
- More samples (slow convergence, $\sigma \propto 1/\sqrt{N}$)
- Better sampling (stratified, importance, qmc etc.)
- Adaptive sampling
- Filtering
- Caching and interpolation

Stratified Sampling



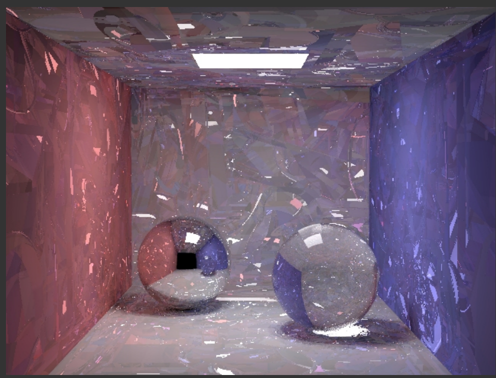
Latin Hypercube: 10 paths/pixel

Quasi Monte-Carlo



Halton-Sequence: 10 paths/pixel

Fixed (Random) Sequence

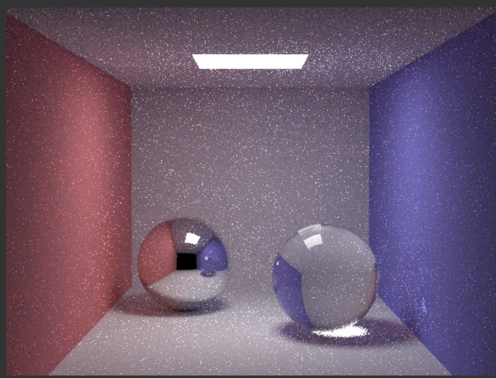


10 paths/pixel

Filtering: Idea

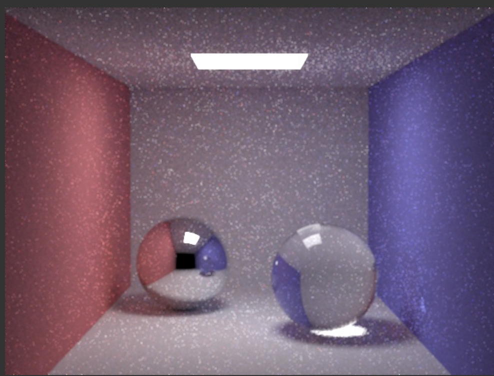
- Noise is high frequency
- Remove high frequency content

Unfiltered Image



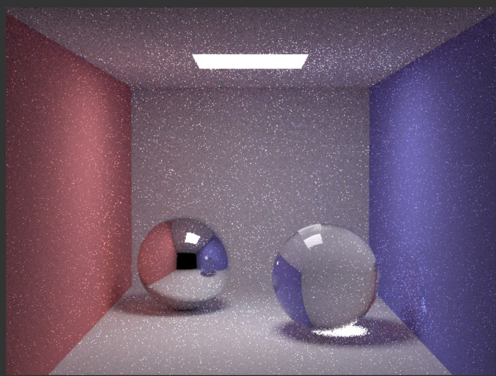
10 paths/pixel

3x3 Lowpass Filter



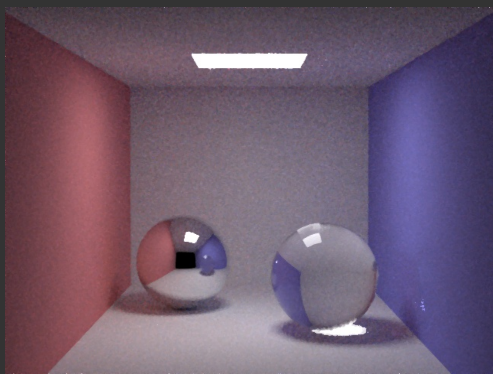
10 paths/pixel

Unfiltered Image



10 paths/pixel

3x3 Median Filter



10 paths/pixel

Energy Preserving Filters

- Distribute noisy energy over several pixels
- Adaptive filter width
  [Rushmeier and Ward 94]
- Diffusion style filters
  [McCool99]
- Splatting style filters
  [Suykens and Willems 00]

Problems With Filtering

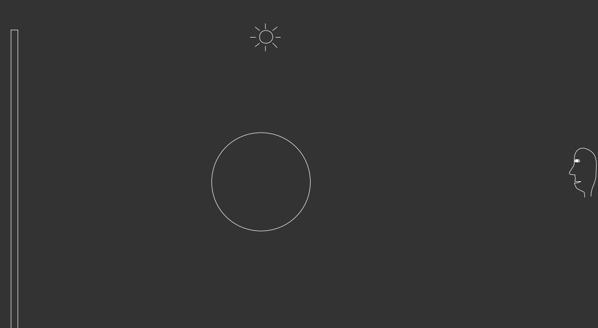
- Everything is filtered (blurred)
  - Textures
  - Highlights
  - Caustics
  - . . .

Photon Mapping

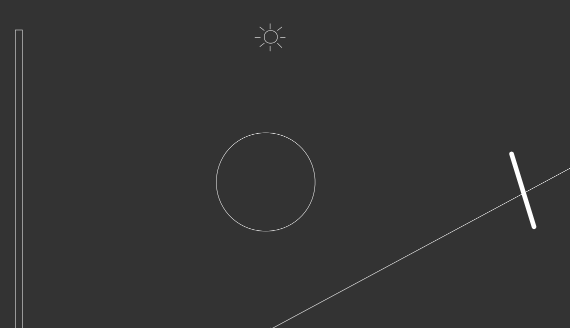
A two-pass algorithm:

- Pass 1: Trace photons from the light source
- Pass 2: Ray trace the scene and use the photons to compute indirect illumination

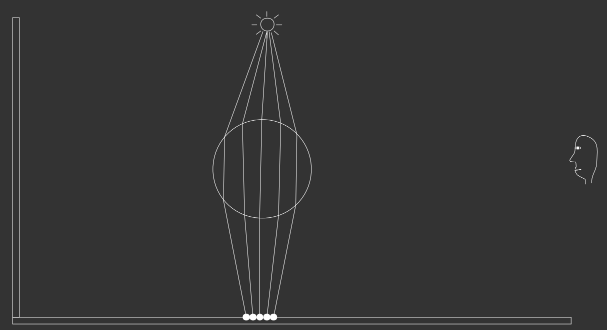
A simple test scene



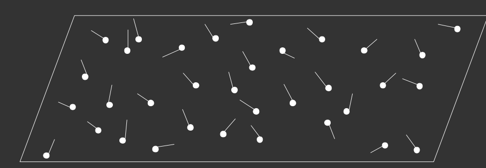
Rendering



Photon Tracing



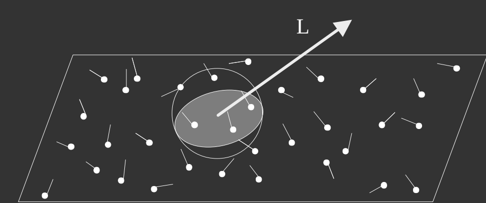
Photons



Radiance Estimate

$$
\begin{aligned}
L(x,\vec{\omega}) &= \int_{\Omega} f_r(x,\vec{\omega}',\vec{\omega}) L'(x,\vec{\omega}') \cos\theta' \, d\omega \\
&= \int_{\Omega} f_r(x,\vec{\omega}',\vec{\omega}) \frac{d\Phi^2(x,\vec{\omega}')}{d\omega \, \cos\theta' dA} \cos\theta' d\omega \\
&= \int_{\Omega} f_r(x,\vec{\omega}',\vec{\omega}) \frac{d\Phi^2(x,\vec{\omega}')}{dA} \\
&\approx \sum_{p=1}^{n} f_r(x,\vec{\omega}'_p,\vec{\omega}) \frac{\Delta\Phi_p(x,\vec{\omega}'_p)}{\pi r^2}
\end{aligned}
$$

Radiance Estimate



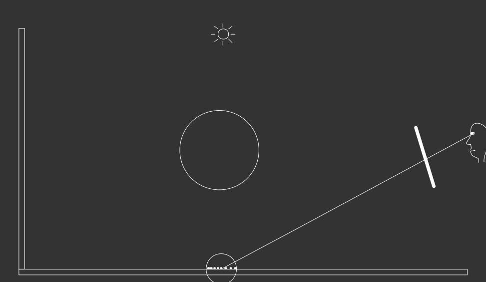
The photon map datastructure

The photons are stored in a left balanced kd-tree

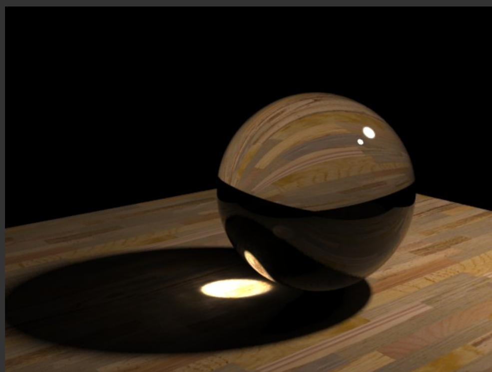
```
struct photon = {
  float position[3];
  rgbe power;         // power packed as 4 bytes
  char phi, theta;    // incoming direction
  short flags;
}
```

Code on the class webpage.

Rendering: Caustics

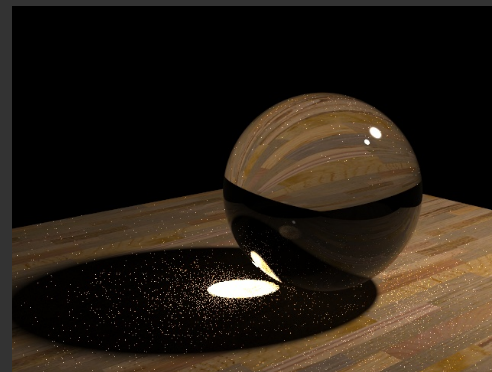


Caustic from a Glass Sphere



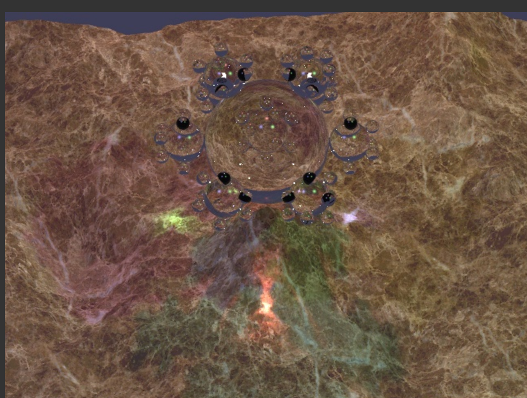
Photon Mapping: 10000 photons / 50 photons in radiance estimate

Caustic from a Glass Sphere

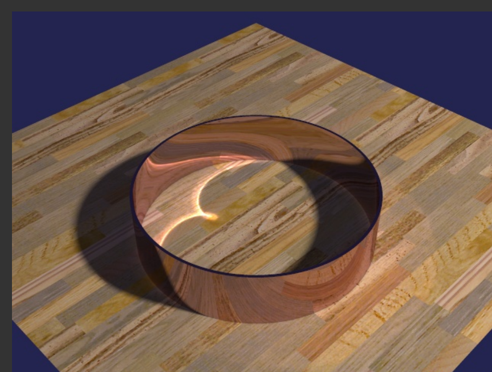


Path Tracing: 1000 paths/pixel

Sphereflake Caustic



Reflection Inside A Metal Ring



50000 photons / 50 photons in radiance estimate

Caustics On Glossy Surfaces

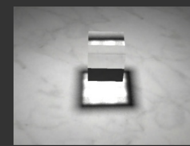
340000 photons / $\approx$ 100 photons in radiance estimate

HDR environment illumination

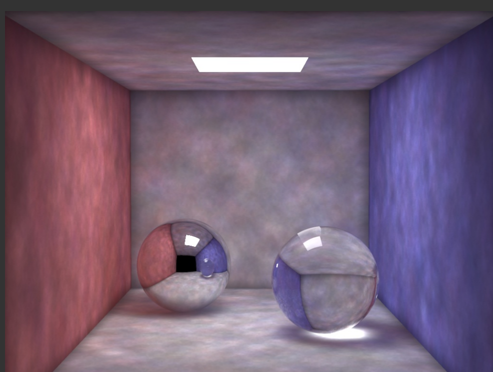
Using lightprobe from www.debevec.org

Cognac Glass

Cube Caustic

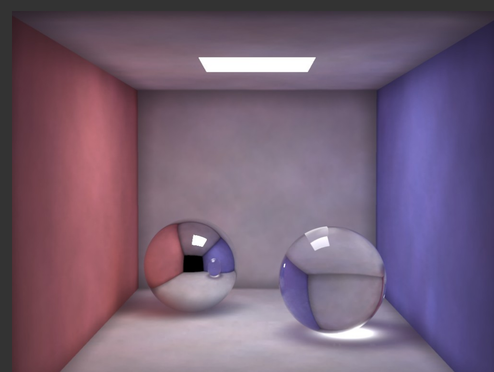


Global Illumination



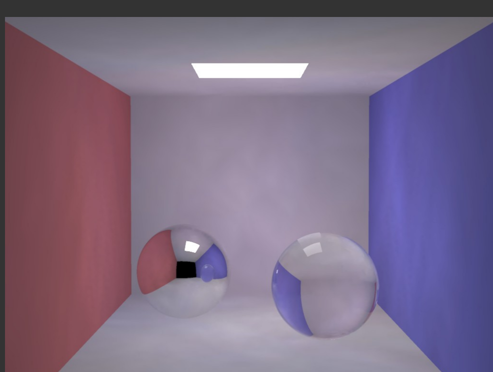
100000 photons / 50 photons in radiance estimate

Global Illumination



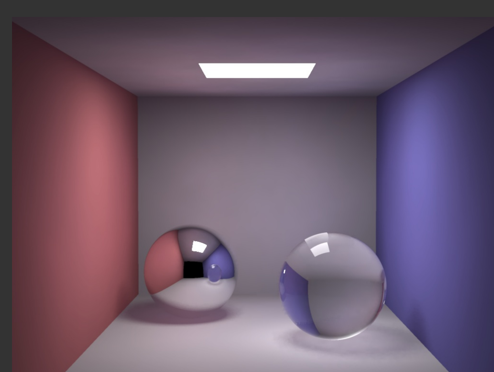
500000 photons / 500 photons in radiance estimate

Fast estimate



200 photons / 50 photons in radiance estimate

Indirect illumination



10000 photons / 500 photons in radiance estimate

Next Time

- More photons