

Computer Graphics

CSE 167 [Win 22], Lecture 19: High Quality Rendering
Ravi Ramamoorthi

<http://viscomp.ucsd.edu/classes/cse167/wi22>

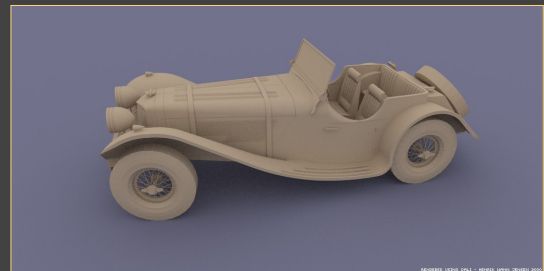
Summary

- This is the final lecture of CSE 167. (CAPE+TA)
- Good luck on HW 4, written assignment
- Please consider CSE 168 (Rendering), 291 (Physical Simulation) in spring

Monte Carlo Path Tracing

- General solution to rendering and global illumination
- Suitable for a variety of general scenes
- Based on Monte Carlo methods
- Enumerate all paths of light transport
- Long history, traces back to rendering eqn Kajiya 86
- (More advanced topic: Slides from CSE 168/274)
- Increasingly, basis for production rendering
- Path tracing today real-time in hardware (for example, using NVIDIA's Optix, Turing RTX)

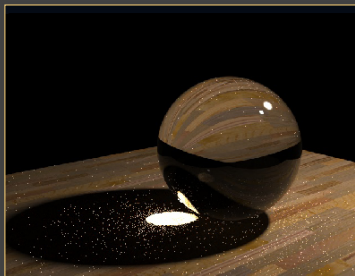
Monte Carlo Path Tracing



Big diffuse light source, 20 minutes

Jensen

Monte Carlo Path Tracing



1000 paths/pixel

Jensen

Monte Carlo Path Tracing

Advantages

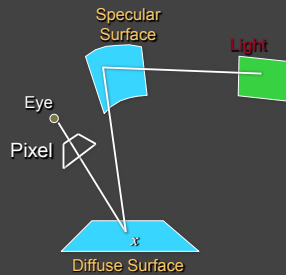
- Any type of geometry (procedural, curved, ...)
- Any type of BRDF or reflectance (specular, glossy, diffuse, ...)
- Samples all types of paths ($L(SD)^*E$)
- Accuracy controlled at pixel level
- Low memory consumption
- Unbiased - error appears as noise in final image

Disadvantages (standard Monte Carlo problems)

- Slow convergence (square root of number of samples)
- Noise in final image

Monte Carlo Path Tracing

Integrate radiance for each pixel by sampling paths randomly



$$L_o(x, \vec{w}) = L_e(x, \vec{w}) + \int_{\Omega} f_r(x, \vec{w}', \vec{w}) L_i(x, \vec{w}') (\vec{w}' \cdot \vec{n}) d\vec{w}'$$

Simplest Monte Carlo Path Tracer

For each pixel, cast n samples and average

- Choose a ray with $p=\text{camera}$, $d=(\theta, \phi)$ within pixel
- Pixel color += $(1/n) * \text{TracePath}(p, d)$

$\text{TracePath}(p, d)$ returns (r,g,b) [and calls itself recursively]:

- Trace ray (p, d) to find nearest intersection p'
- Select with probability (say) 50%:
 - Emitted:
 - return $2 * (L_{e_{\text{red}}}, L_{e_{\text{green}}}, L_{e_{\text{blue}}}) // 2 = 1/(50\%)$
 - Reflected:
 - generate ray in random direction d'
 - return $2 * f_r(d \rightarrow d') * (n * d') * \text{TracePath}(p', d')$

Simplest Monte Carlo Path Tracer

For each pixel, **cast n samples and average over paths**

- Choose a ray with $p=\text{camera}$, $d=(\theta, \phi)$ within pixel
- Pixel color += $(1/n) * \text{TracePath}(p, d)$

$\text{TracePath}(p, d)$ returns (r,g,b) [and calls itself recursively]:

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Weight = 1/probability
Remember: unbiased
requires having $f(x) / p(x)$

Simplest Monte Carlo Path Tracer

For each pixel, cast n samples and average

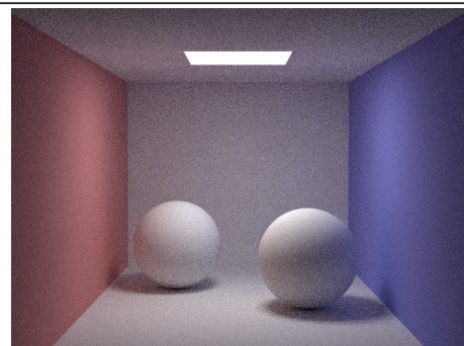
- Choose a ray with $p=\text{camera}$, $d=(\theta, \phi)$ within pixel
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 - generate ray in random direction d'
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Path terminated when
Emission evaluated

Path Tracing



CS348B Lecture 14

10 paths / pixel

Pat Hanrahan, Spring 2009

Arnold Renderer (M. Fajardo)

- Works well diffuse surfaces, hemispherical light



From UCB CS 294 a few years ago



[Daniel Ritchie and Lita Chu](#)

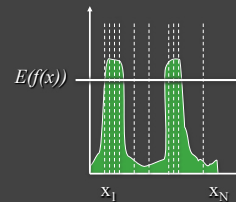
Importance Sampling

- Pick paths based on energy or expected contribution
 - More samples for high-energy paths
 - Don't pick low-energy paths
- At "macro" level, use to select between reflected vs emitted, or in casting more rays toward light sources
- At "micro" level, importance sample the BRDF to pick ray directions
- Tons of papers in 90s on tricks to reduce variance in Monte Carlo rendering
- Importance sampling now standard in production. I consulted on Pixar's system for movies from 2012+

Importance Sampling

Can pick paths however we want, but contribution weighted by 1/probability

- Already seen this division of 1/prob in weights to emission, reflectance



$$\int_{\Omega} f(x) dx = \frac{1}{N} \sum_{i=1}^N Y_i$$

$$Y_i = \frac{f(x_i)}{p(x_i)}$$

Importance sample Emit vs Reflect

TracePath(p, d) returns (r,g,b) [and calls itself recursively]:

- Trace ray (p, d) to find nearest intersection p'
- If $L_e = (0,0,0)$ then $p_{emit} = 0$ else $p_{emit} = 0.9$ (say)
- If $\text{random}() < p_{emit}$ then:
 - Emitted:
 - return $(1/p_{emit}) * (L_{e,red}, L_{e,green}, L_{e,blue})$
 - Else Reflected:
 - generate ray in random direction d'
 - return $(1/(1-p_{emit})) * f_r(d \rightarrow d') * (n \cdot d') * \text{TracePath}(p', d')$

More variance reduction

- Discussed "macro" importance sampling
 - Emitted vs reflected
- How about "micro" importance sampling
 - Shoot rays towards light sources in scene
 - Distribute rays according to BRDF

Path Tracing: Include Direct Lighting

```
Step 1. Choose a camera ray  $r$  given the  
       $(x, y, u, v, t)$  sample  
       $weight = 1;$   
       $L = 0$   
Step 2. Find ray-surface intersection  
Step 3.  
       $L += weight * L_r(\text{light sources})$   
       $weight *= reflectance(r)$   
      Choose new ray  $r' \sim \text{BRDF pdf}(r)$   
      Go to Step 2.
```

CS348B Lecture 14

Pat Hanrahan, Spring 2009

Monte Carlo Extensions

Unbiased

- Bidirectional path tracing
- Metropolis light transport

Biased, but consistent

- Noise filtering
- Adaptive sampling
- Irradiance caching

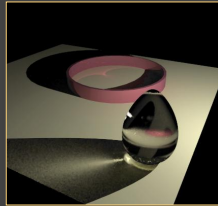
Monte Carlo Extensions

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RenderPark

Monte Carlo Extensions

Unbiased

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Biased, but consistent

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Heinrich

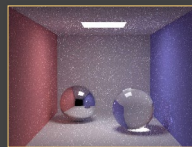
Monte Carlo Extensions

Unbiased

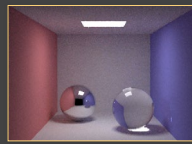
- Bidirectional path tracing
- Metropolis light transport

Biased, but consistent

- Noise filtering
- Adaptive sampling
- Irradiance caching



Unfiltered



Filtered

Jensen

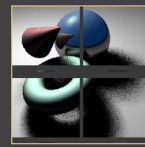
Monte Carlo Extensions

Unbiased

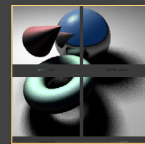
- Bidirectional path tracing
- Metropolis light transport

Biased, but consistent

- Noise filtering
- Adaptive sampling
- Irradiance caching



Fixed



Adaptive

Ohbuchi

Monte Carlo Extensions

Unbiased

- Bidirectional path tracing
- Metropolis light transport

Biased, but consistent

- Noise filtering
- Adaptive sampling
- Irradiance caching

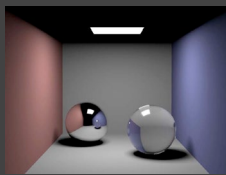


Jensen

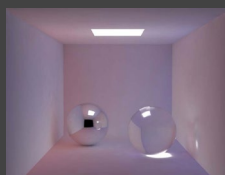
Summary

- Monte Carlo methods robust and simple (at least until nitty gritty details) for global illumination
- Must handle many variance reduction methods in practice
- Importance sampling, Bidirectional path tracing, Russian roulette etc.
- Rich field with many papers, systems researched over last 30 years
- Today, hardware for real-time ray, path tracing
- Promising physically-based GPU approach

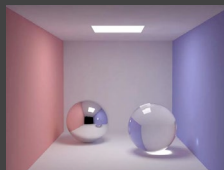
Smoothness of Indirect Lighting



Direct



Indirect



Direct + Indirect

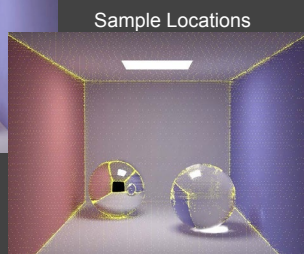
Irradiance Caching

- 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 Caching Example

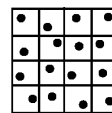


Final Image



Sample Locations

Stratified Sampling



Stratified sampling like jittered sampling

Allocate samples per region

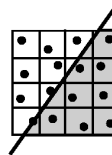
$$N = \sum_{i=1}^m N_i \quad F_N = \frac{1}{N} \sum_{i=1}^m N_i F_i$$

New variance

$$V[F_N] = \frac{1}{N^2} \sum_{i=1}^m N_i V[F_i]$$

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



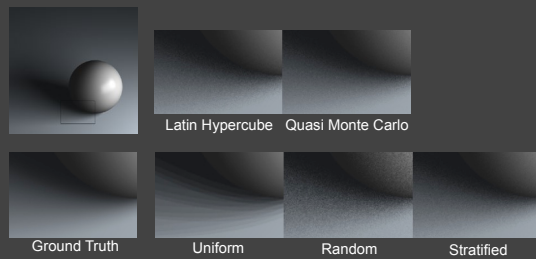
$$V[F_N] = \frac{1}{N^2} \sum_{i=1}^{\sqrt{N}} V[F_i] = \frac{V[F_e]}{N^{1.5}}$$

CS348B Lecture 9

Pat Hanrahan, Spring 2002

D. Mitchell 95, Consequences of stratified sampling in graphics

Comparison of simple patterns



16 samples for area light, 4 samples per pixel, total 64 samples

If interested, see my recent paper "A Theory of Monte Carlo Visibility Sampling"

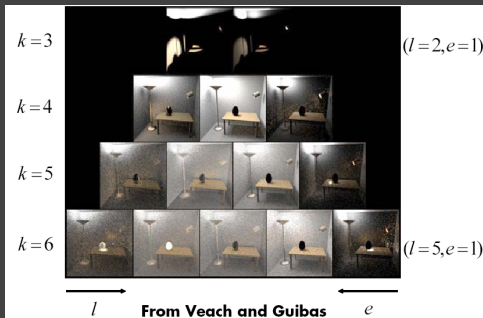
Figures courtesy Tianyu Liu

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

Bidirectional Path Tracing

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



From Veach and Guibas

Comparison



Bidirectional path tracing

Path tracing

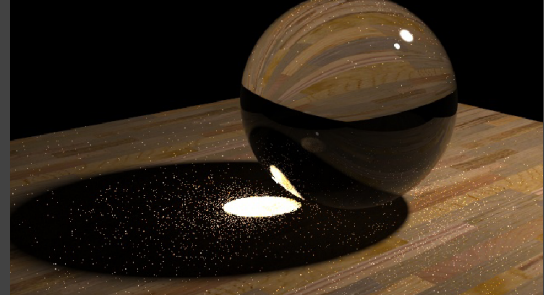
From Veach and Guibas

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 using Photon Maps* H. Jensen. *Rendering Techniques (EGSR 1996)*, pp 21-30. (Also book: *Realistic Image Synthesis using Photon Mapping*)

Caustics

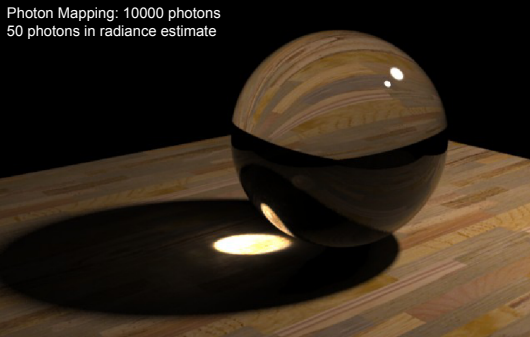
Path Tracing: 1000 paths/pixel
Note noise in caustics



Slides courtesy Henrik Wann Jensen

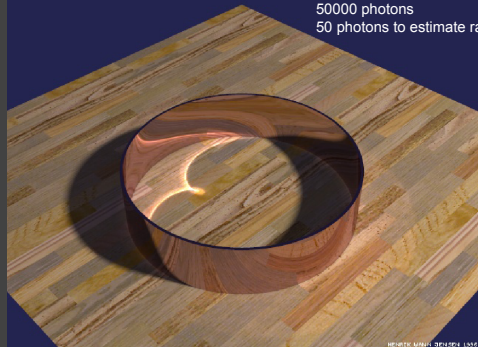
Caustics

Photon Mapping: 10000 photons
50 photons in radiance estimate



Reflections Inside a Metal Ring

50000 photons
60 photons to estimate radiance

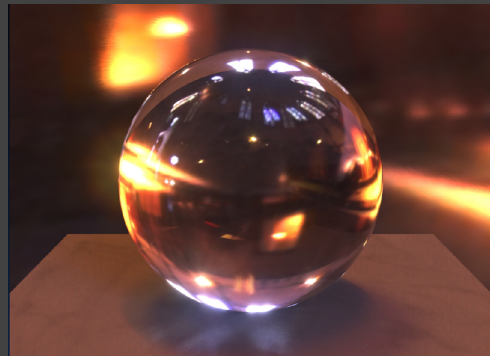


Caustics on Glossy Surfaces

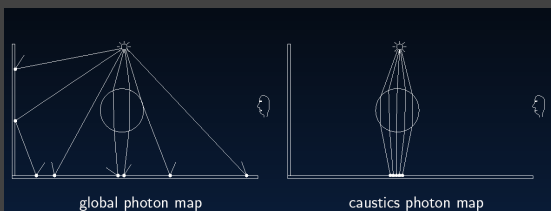


340000 photons, 100 photons in radiance estimate

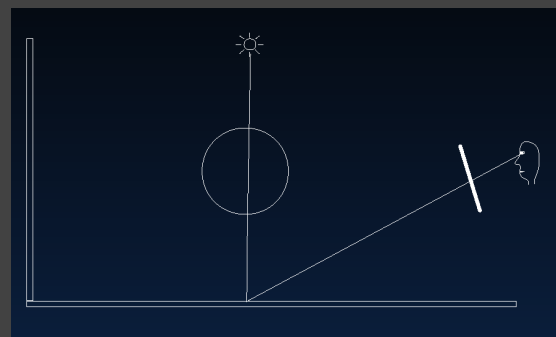
HDR Environment Illumination



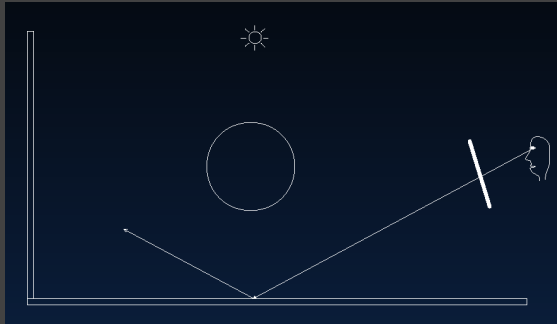
Global Illumination



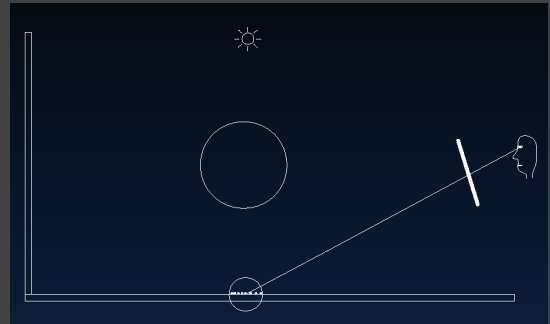
Direct Illumination



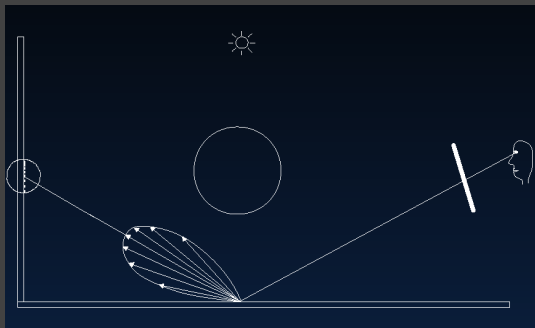
Specular Reflection



Caustics



Indirect Illumination



Mies House: Swimming Pool

