Advanced Global Illumination

15-462 Computer Graphics

April 24, 2003

Announcements

- Assignment 7: Ray Tracing due tonight
- Assignment 8: Radiosity and Image Processing due Thursday May 1
- No Late Days on Assignment 8!
- Questions about Assignment 7?

Advanced Global Illumination - Overview

- Monte Carlo Integration Methods
- Path Tracing
- Bidirectional Path Tracing
- Metropolis Light Transport
- Photon Mapping

Global Illumination

- The story so far
  - Local illumination
  - Ray tracing
  - Radiosity
  - Two-pass methods
- What's wrong?
  - Efficiency issues
  - Incomplete models

A mathematical model for global illumination

- Kajiya's rendering equation
  - States necessary conditions for equilibrium of light transport

$$L_o(x,\vec{w}) = L_e(x,\vec{w}) + L_r(x,\vec{w})$$

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

- How can we solve this integral?
  - Cannot be done analytically

Background: Monte Carlo Integration

- Estimate area under the curve (integral) using *samples* of the function being integrated
- Number of samples is inversely related to the standard deviation of estimation error
- Used often when integrals have no analytical solution

Sampling schemes

- At what points do we sample?
- Several schemes
  - Random sampling
  - Importance sampling
    - Pick more samples in parts where the function is large
  - Stratified sampling
    - Divide domain into strata
    - One sample in each stratum
    - Good for smooth functions

Solving the rendering equation

- Monte Carlo global illumination uses Monte Carlo sampling to estimate a solution to the rendering equation
  - Path tracing
  - Bidirectional path tracing
  - Metropolis Light Transport

Adv□nced Glob□l Illumin□tion - Overview

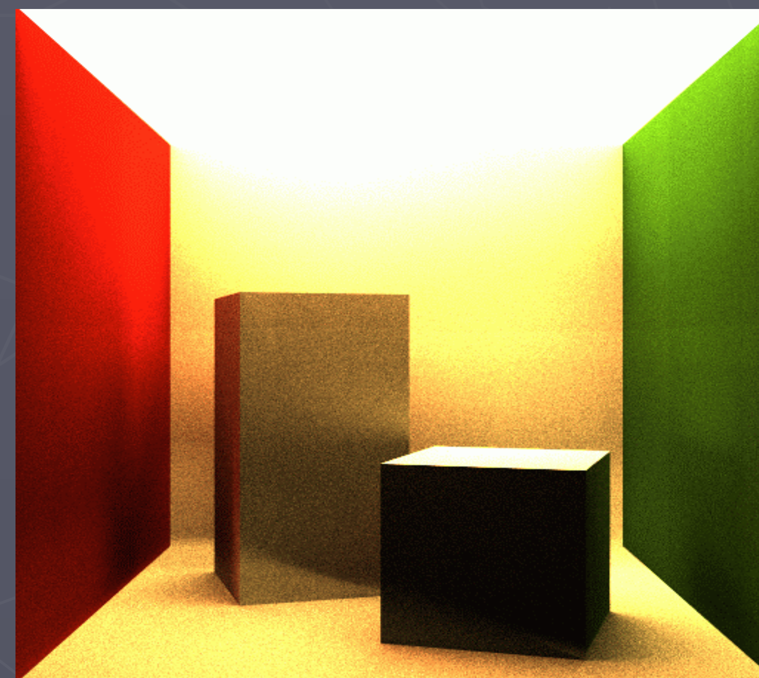
- Monte C□rlo Integr□tion Methods
- P□th Tr□cing
- Bidirection□l P□th Tr□cing
- Metropolis Light Tr□nsport
- Photon M□pping

Heckbert's Light Tr□nsport Not□tion

- L – □light source
- S – □specul□r reflection
- D – □diffuse reflection
- E – the eye
- Regul□r expressions for combin□tions
  - E.g. L(S|D)+DE

Path Tracing

- Simulates all possible light paths L(S|D)*E
- Requires a large number of samples per pixel to remove noise
  - 400 paths/pixel



Path Tracing - Algorithm

- Start at eye
- Build a path by, at each bounce, sampling a direction according to some distribution
  - Suggestions?
- At each point on the path, cast a shadow ray and add direct lighting contribution at that point
- Multiple paths per pixel
  - Average contributions to get intensity

Picking new path directions

- Importance sampling
  - Using BRDF
- Stratified sampling
  - Break possible directions into sub-regions, and cast one sample per sub-region
- Problems with path tracing
  - Too many paths/pixel required!

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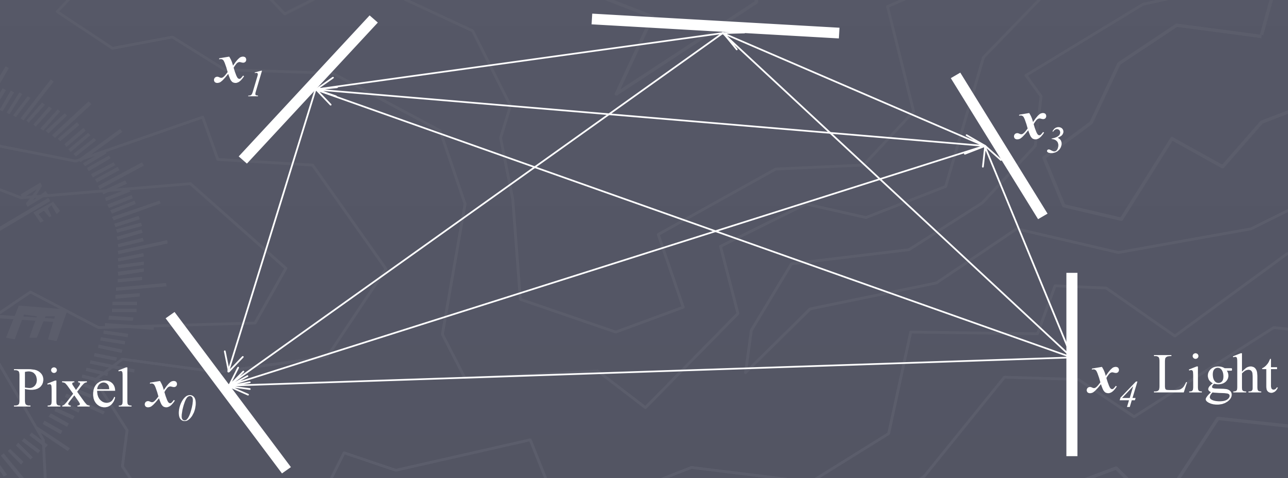
Bidirectional Path Tracing

- Build a path by working from the eye and the light and join in the middle
- Don't just look at overall path, also weigh contributions from all sub-paths



Bidirectional path tracing – the algorithm

```
Render image using bidrectional path tracing
    for each pixel and sample
        trace_paths(pixel position)

trace_paths(pixel position)
    trace ray through pixel – generate eye path
    trace photon from light – generate light path
    combine(eye path, light path)

combine(eye path, light path)
    for each vertex on eye path
        for each vertex on light path
            if vertices mutually visible
                compute weight for this path
                add in the contribution to the corresponding pixel
```

Bidirectional path tracing vs. path tracing

- Bidirectional path tracing
  - Fewer samples per pixel
  - Better for certain effects, e.g. caustics
- Path tracing
  - Better when light sources are easiest to reach from the eye

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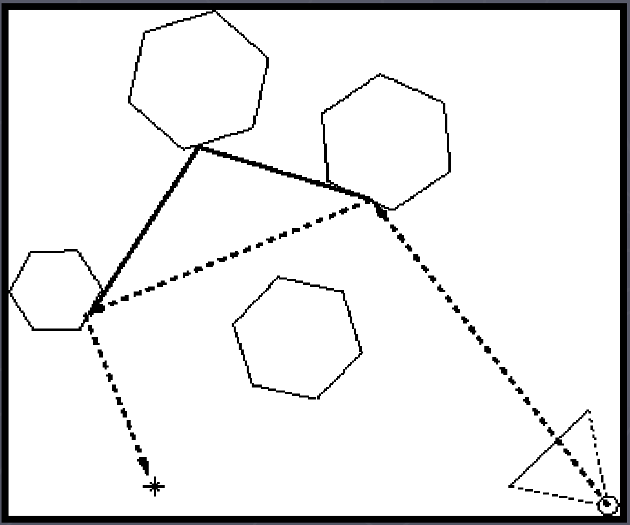
Metropolis Light Transport

- Veach and Guibas, 1997
- Similar concept
  - Metropolis sampling algorithm, 1953
- Mutate paths
  - Accept mutated path with some probability
- Implementation builds character!

Veach & Guibas

MLT Algorithm

```
x=initial_path();
zero_out_image();
for i= 1 to n
    y=mutate(x);
    a=accept_prob(y|x)
    if(random()<a)
        then x = y
    record_sample(image,x)
return image;
```



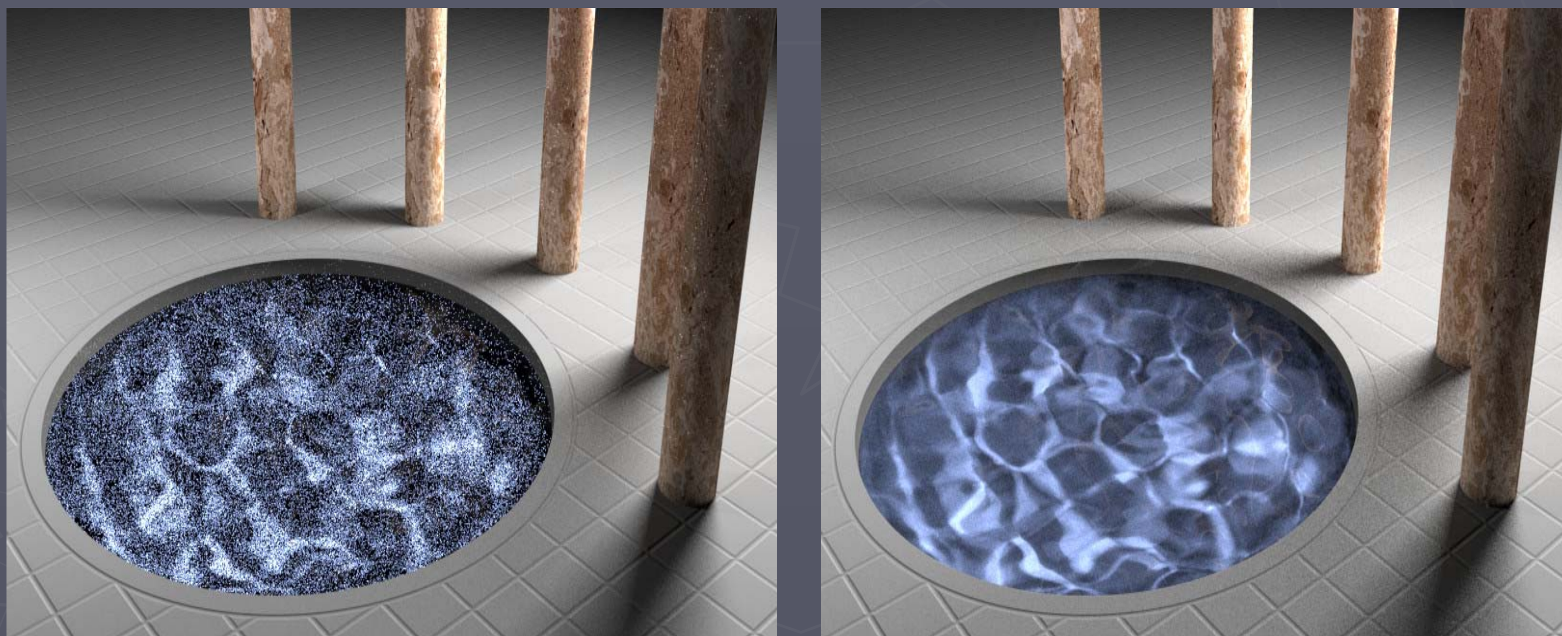
Exotic MLT Strategies

- Mutation
  - Bidirectional mutation
    - Sample space exploration
  - Lens subpath mutation
    - Sample stratification over image plane
- Lens perturbations
  - Rare convergence phenomena
- Caustic perturbations

MLT - Advantages

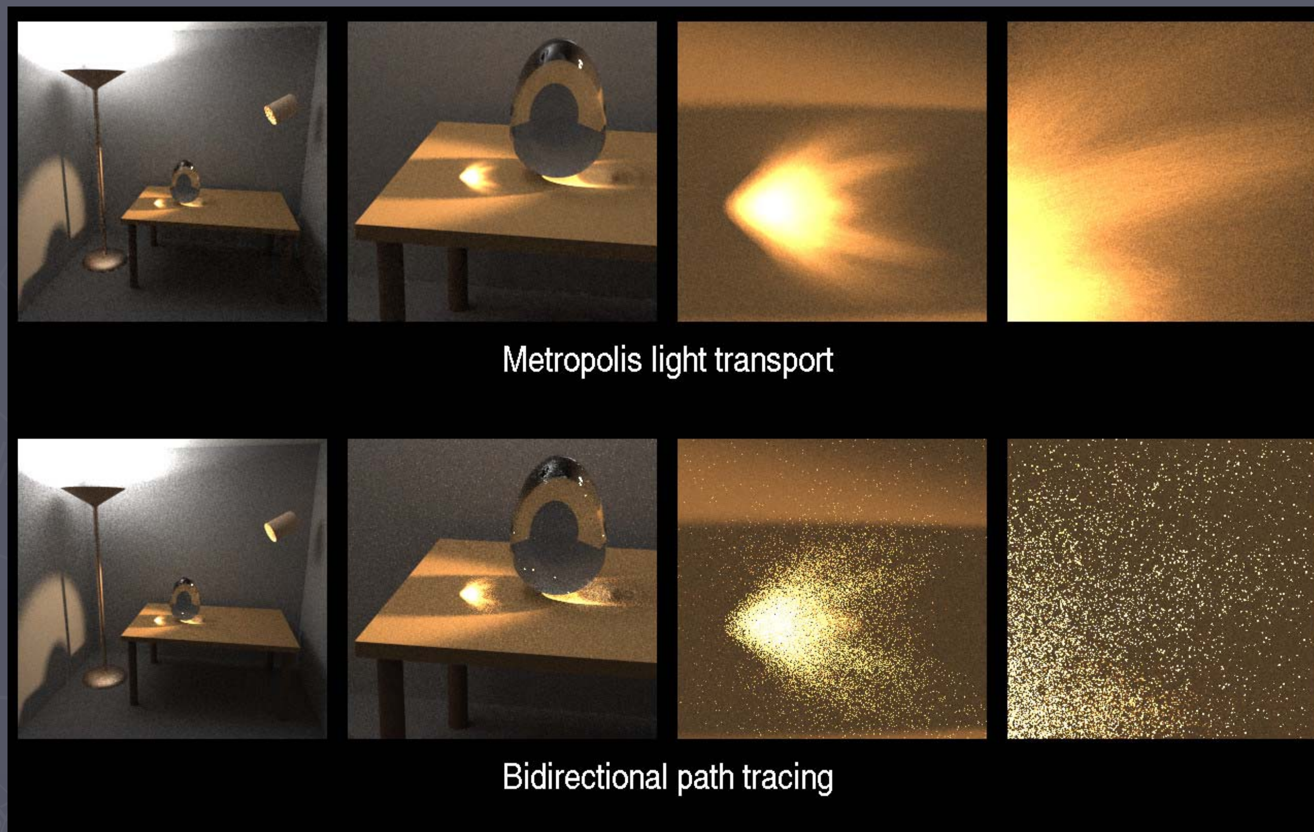
- Path space explored locally
  - Favor mutations that make small changes
- Small average cost per sample
  - Typically one or two rays
- Paths near important ones sampled as well
  - Expense amortized
- Easy extension of mutation set
  - Exploit coherence

Path Tracing vs. MLT



Veach & Guibas

MLT vs. Bidirectional Path Tracing



Veach & Guibas

Monte Carlo pro's and con's

- Pro's
  - Simulate all global illumination effects
  - Arbitrary geometry
  - Low memory consumption
- Con's
  - Noise
  - May be inefficient for complex lighting scenes

Noise elimination

- Obvious method
- Variance reduction techniques
  - Importance/stratified sampling!
  - Key idea: dump all problem information into selecting sampling technique
- Russian Roulette
  - Importance sampling using probability distribution function

Questions?

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Photon M□pping

Henrik Jensen

Photon M□pping: The concept

- Motiv□tion
  - W□nt to simul□te □ll glob□l illumin□tion effects on complex surf□ces with □rbitr□ry BRDF’s
  - As p□inlessly □s possible
- Problems with Monte-C□rlo techniques
  - Noise
    - Very costly to elimin□te!

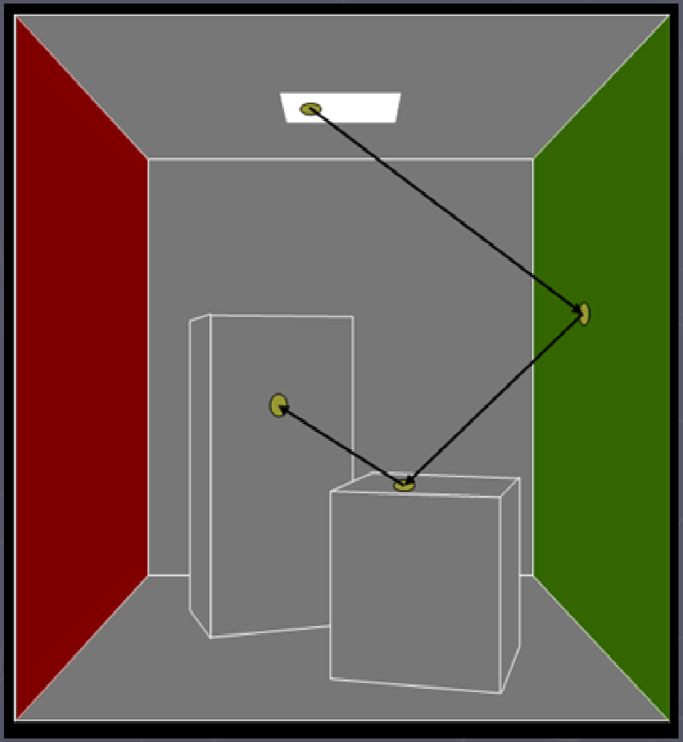
Two-pass algorithm

- First pass: photon tracing
  - Fire photons from light sources into the scene
  - Build photon map data structure
- Second pass: rendering

- The first pass is view-independent!

Photon tr□cing

- Fire photons from light sources
- Contr□st with r□y tr□cing
  - R□ys g□ther r□di□nce
  - Photons prop□g□te flux



CS 517, Cornell U.

Firing photons from light sources

- Different kinds of light sources
  - Diffuse point light
  - Spherical light
  - Square light
  - Directional light
  - Complex light
- Emit more photons from bright lights than dim ones to even-out power

The next step

- What happens once your photon hits something in the scene?
  - Reflection
  - Transmission
  - Absorption

Specular Reflection

- Photon hits a mirror surface
  - Reflect just like a ray
- Power of reflected photon scaled by reflectivity of mirror surface

Diffuse Reflection

- Photon hits a diffuse surface
  - Store in photon map!
  - Reflect the photon
    - How?
- Power scaled by diffuse reflectance

Arbitrary BRDF Reflection

- Compute the new photon direction by importance sampling the BRDF!
- Scale power using BRDF and reflectivity of material

Photon map data structure

- Requirements
  - Fast lookup of neighboring photons
    - For radiance estimates
- Ideas?
- Solution
  - kd-trees!

Kd-trees – quick review

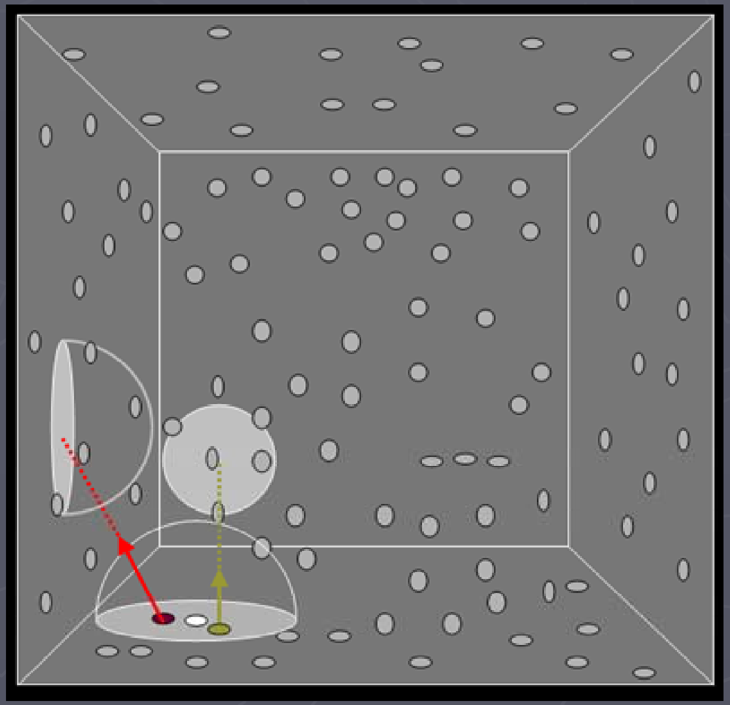
- Sort of like BSP trees
  - Anyone?
- Multidimensional binary search tree
  - Each node partitions one dimension
- O(k + log n) average for k nearest neighbors with n photons in the kd-tree
- Another solution
  - Voronoi diagrams
    - O(k log n), but O(n^2) in space

Second pass: rendering

- Ray trace as normal
- But when a ray hits a diffuse surface
  - We need to consult the photon map to compute the radiance of this surface

Radiance Estimate

- When a ray hits a diffuse surface, perform density approximation to get radiance
  - Use kd-tree

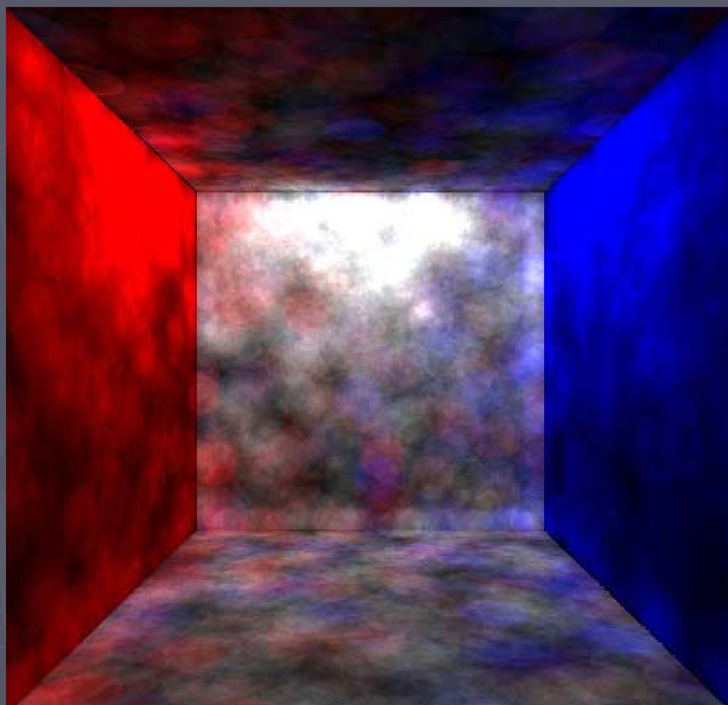


CS 517, Cornell U.

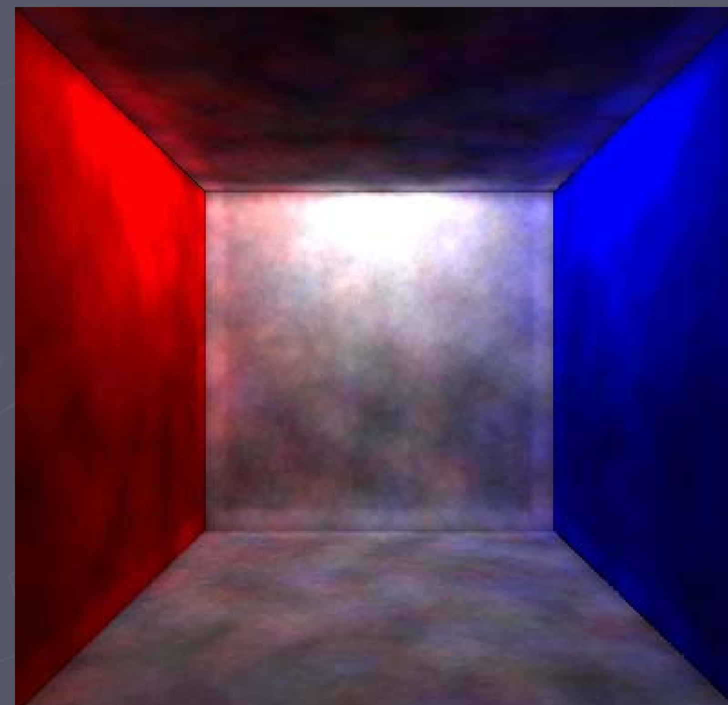
Radiance estimate pseudocode

```
radiance_estimate(x,w,n)
    locate k nearest photons
    r = distance to the kth nearest photon
    □flux = 0
    for each photon p
        pd = photon direction
        power = photon power
        □flux += fr(x,w,pd) * power
    Lr = □flux / 2*r*r*pi
    return Lr
```

Direct Visualization



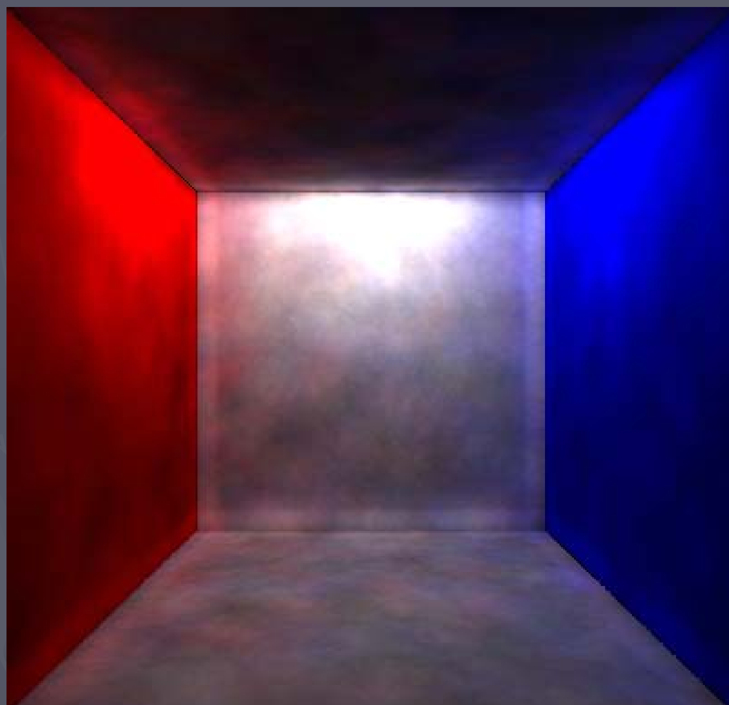
10,000 photons fired



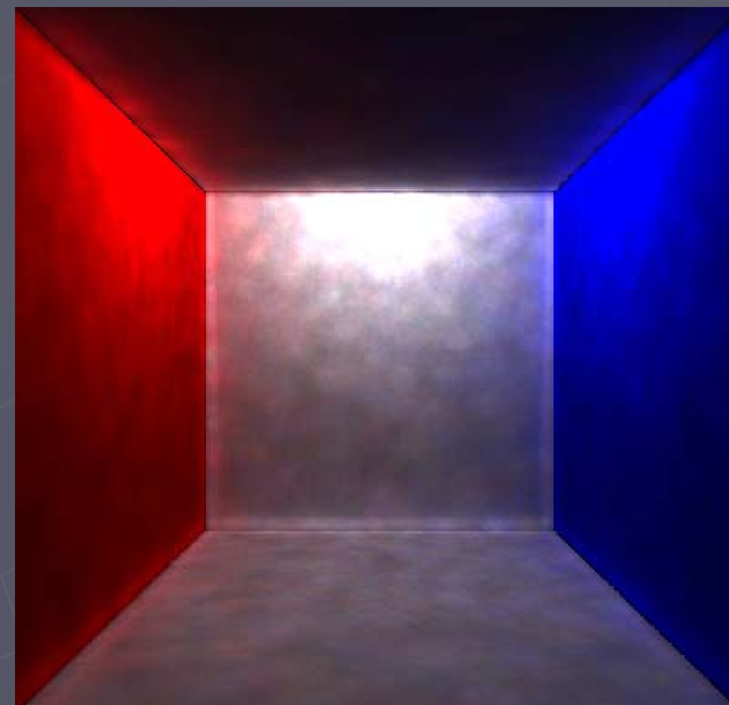
Kayvon Fatahalian and Jonathan Hui

50,000 photons fired

Direct Visualization - II



100,000 photons fired

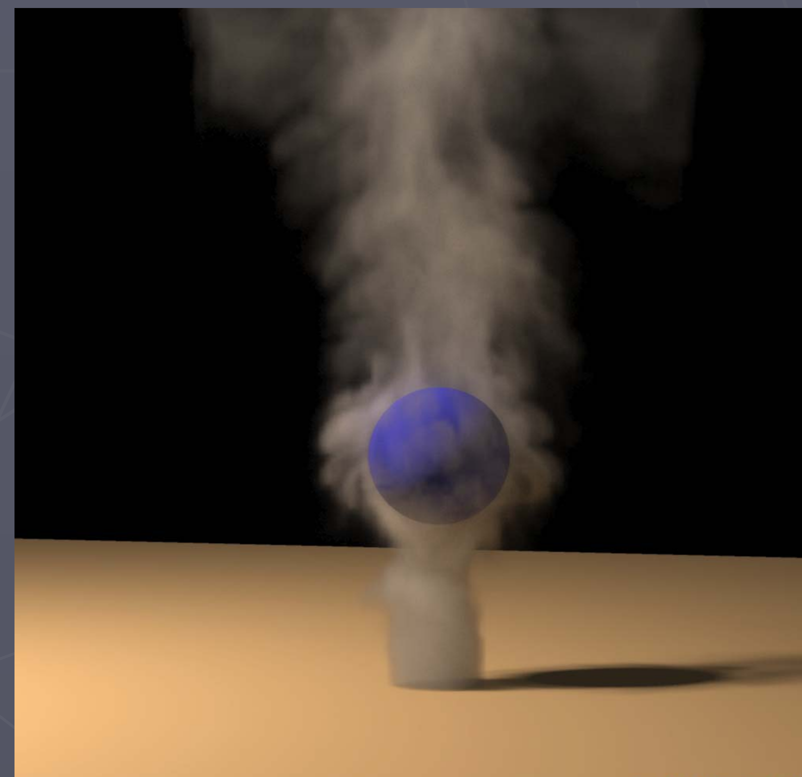


Kayvon Fatahalian and Jonathan Hui

500,000 photons fired

Photon m□pping effects

- C□ustics
  - Focused light
- Diffuse inter-reflections
  - Color bleeding
- P□rticip□ting medi□
  - Clouds, smoke, fog

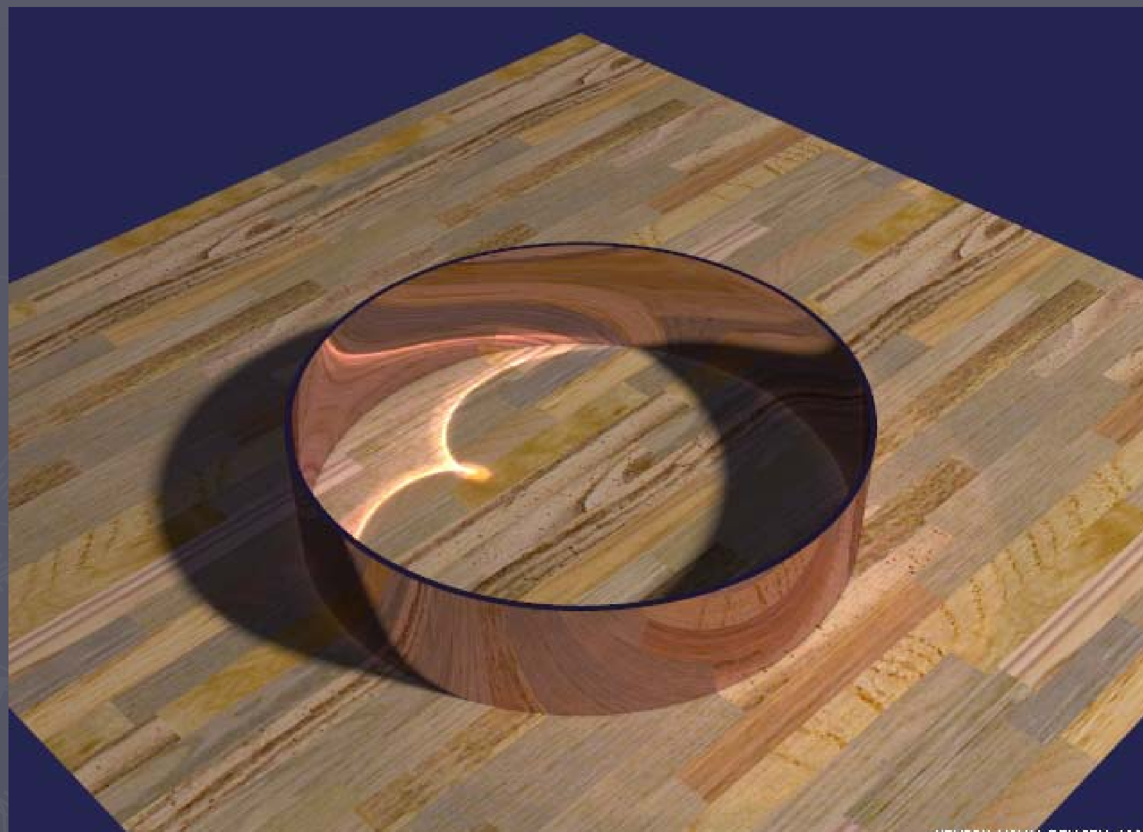


Henrik Jensen, Jos St□m, Ron Fedkiw

Caustics - I

Henrik Jensen

C□ustics - II



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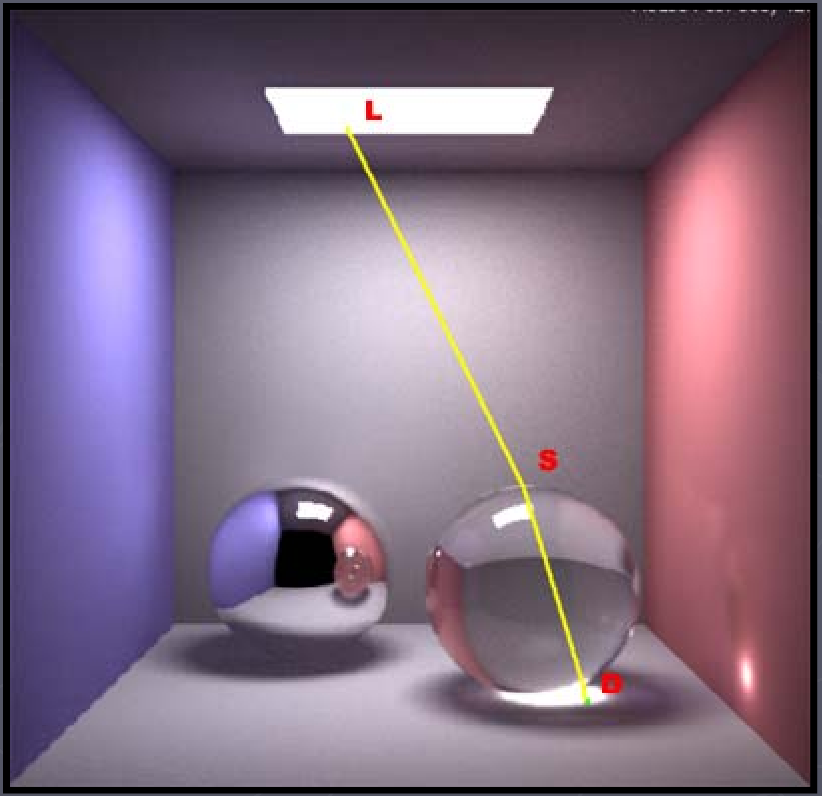
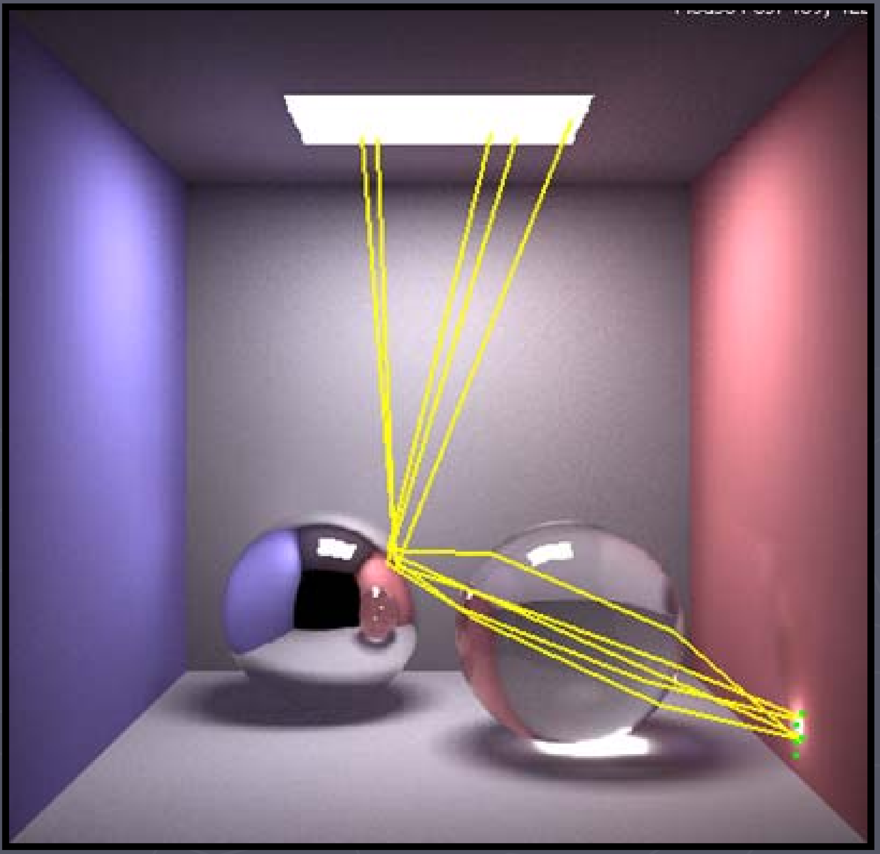
Formation of caustics - I

- LS+DE paths
  - One or more specular hits ending on diffuse
  - May not be extremely important in scene



http://och.phpwebhosting.com/tachyonic.htm

Form□tion of c□ustics - II



http://och.phpwebhosting.com/t□chyonic.htm

Multiple photon maps

- For efficiency, it is usually good to maintain a separate photon map for paths that lead to caustics
  - Caustic photon map
- Also maintain a global photon map for all paths
- Pick the right photon map during radiance estimation

Participating media

- Dust, air, clouds, fog, smoke
- Do photon interactions occur only at object surfaces?
  - Only in vacuum!
- Solution
  - Use volume photon map to store photon scattering/absorption with medium
- How do we get the radiance estimate?

Optimization strategies - I

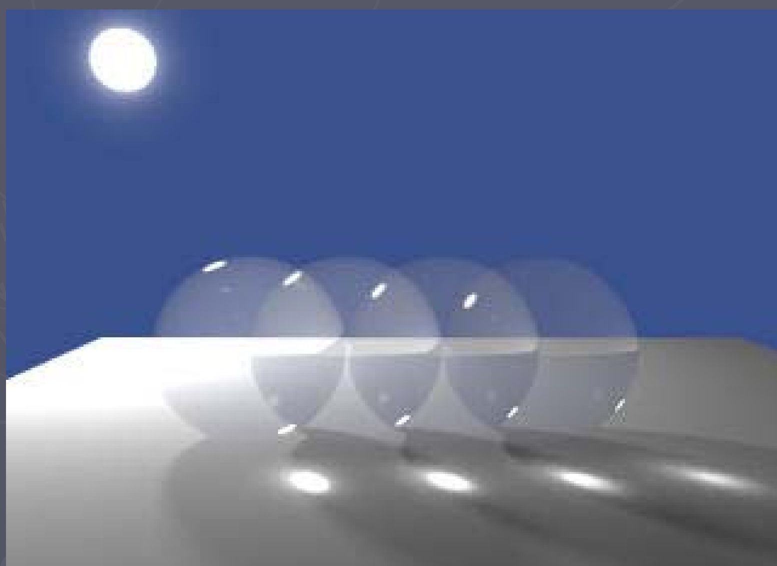
- Irradiance caching
  - Speedup for computing indirect illumination
- Visual Importance
  - "importons" from observer to determine important regions of the scene
- Efficient Stratification of Photons
  - Quasi-Monte Carlo methods

Optimization strategies - II

- Fast Shadows with Shadow Photons
- Precomputed Irradiance
  - Extend photon data structure to include irradiance
  - Speedup of a factor of six in some cases
- Parallel Number-Crunching
  - Easy to parallelize

Extensions to photon mapping

- Time dependent photon mapping
  - Motion blur while avoiding strobing artifacts



Mike Cammarano, Henrik Jensen

Real world photon mapping

- Gaining wide acceptance and popularity!
- High-end rendering software packages
  - Dali, 3D Studio Max 5
- Games, movies
  - Kilauea, SquareUSA
    - Final Fantasy, Matrix prequels

SquareUSA

Movies

- The Light of Mies van der Rohe
  - Rendered using Dali
- Caustic effects with rotating glass block

Questions?

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- Questions about Assignment 7?

Resources

- References
  - Realistic Image Synthesis Using Photon Mapping, Henrik Wann Jensen
  - 3D Computer Graphics, Alan Watt
- Internet Resources
  - http://www.daimi.au.dk/~lai/lysrapport/photonmapping.html
  - http://och.phpwebhosting.com/tachyonic.htm
  - http://graphics.ucsd.edu/~henrik/