Advanced Global Illumination

15-462 Computer Graphics

Announcements

- Ray tracer help session slides online
- Ray tracer assignment reminders
  - Read the bboard!

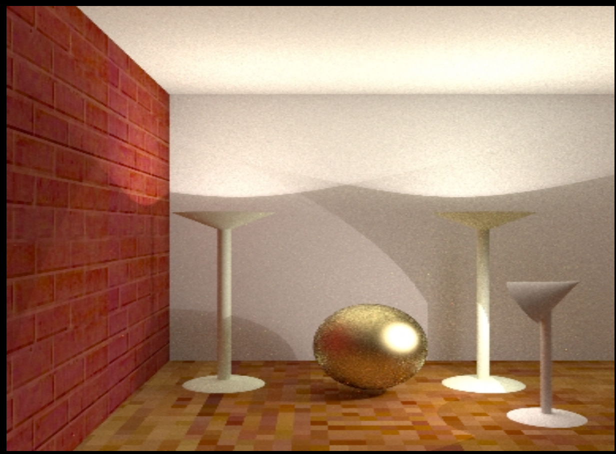
- Questions?

Overview

- Background
- Monte Carlo Integration Methods
- Path Tracing
- Bidirectional Path Tracing
- Metropolis Light Transport
- Photon Mapping
- BSSRDF's & Subsurface Scattering

Global Illumination

- The story so far
  - Local illumination
  - Ray tracing
  - Radiosity
- 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
- Energy conservation
- How can we solve this integral?
  - Cannot be done analytically

Simplifying assumptions

- Any global illumination solution **must** somehow closely approximate Kajiya's rendering equation
- Ray tracing?
- Radiosity?

Ray tracing + Radiosity

- Two-pass method
  - Pass 1: Enhanced Radiosity
    - View-independent
  - Pass 2: Enhanced Ray tracing
    - View-dependent
- Extremely slow!
  - Still many approximating assumptions

BRDF's

- Bidirectional Reflectance Distribution Function (BRDF)
  - General model of light reflection

- BRDF Isotropy
- Anisotropy
  - Brushed metals, satin, hair

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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

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

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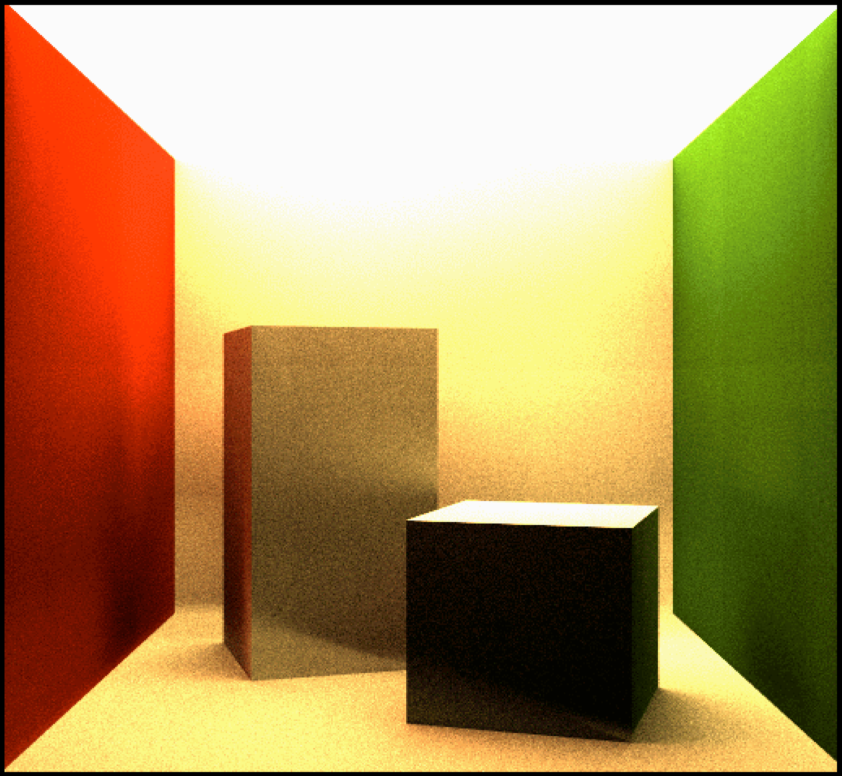
Heckbert's Light Transport Notation

- L – a light source
- S – a specular reflection
- D – a diffuse reflection
- E – the eye
- Regular expressions for combinations
  - 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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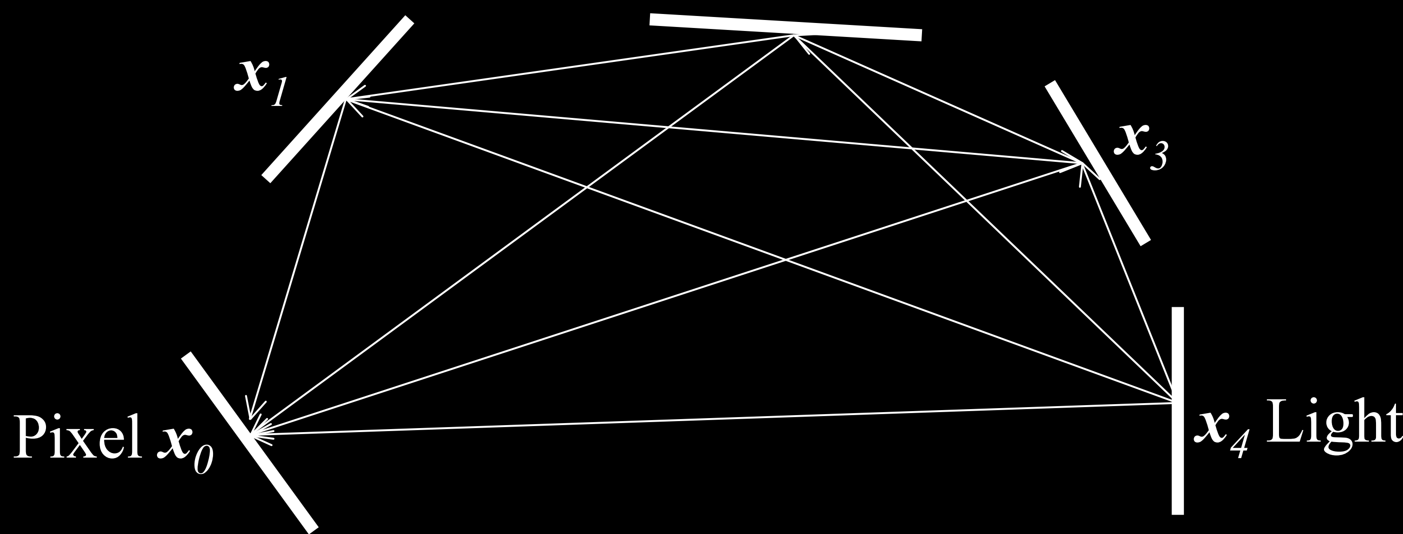
Bidirectional Path Tracing

- 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 bidirectional 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 corresp. 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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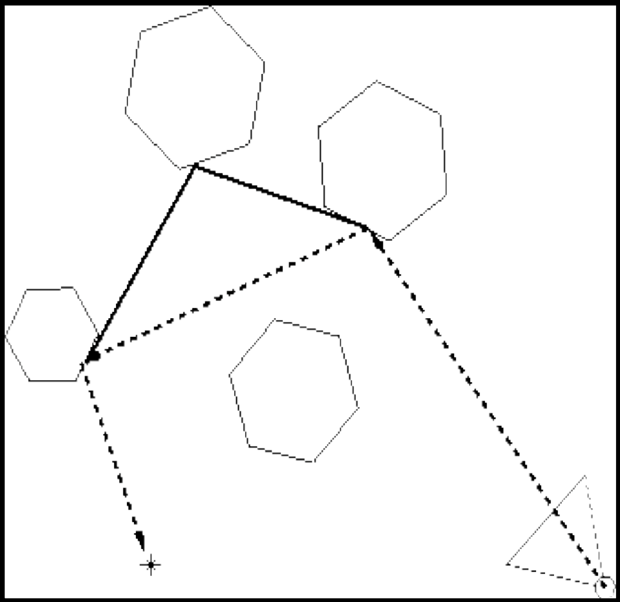
Metropolis Light Transport

- 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;
```



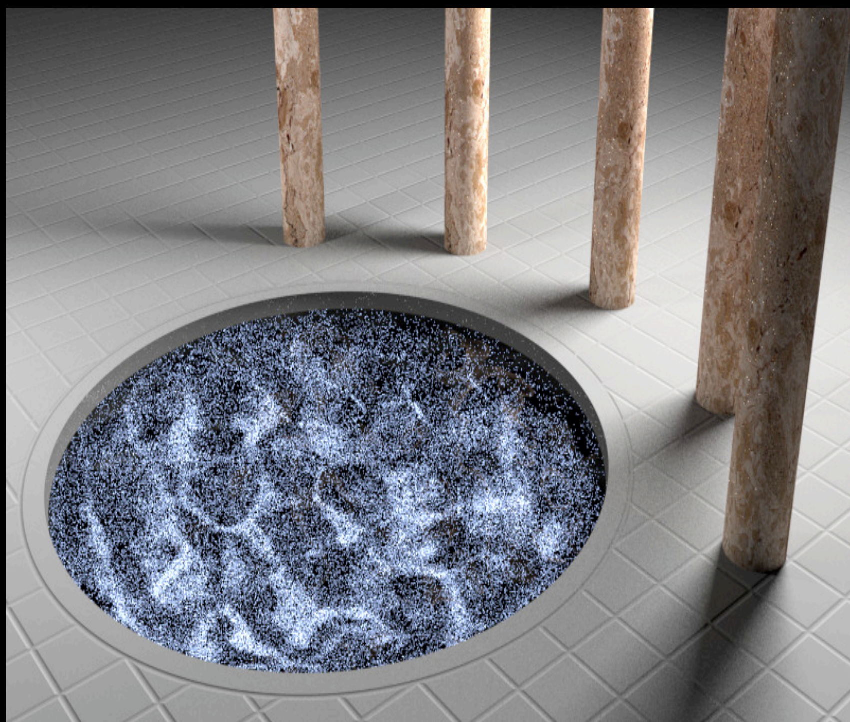
Exotic MLT Strategies

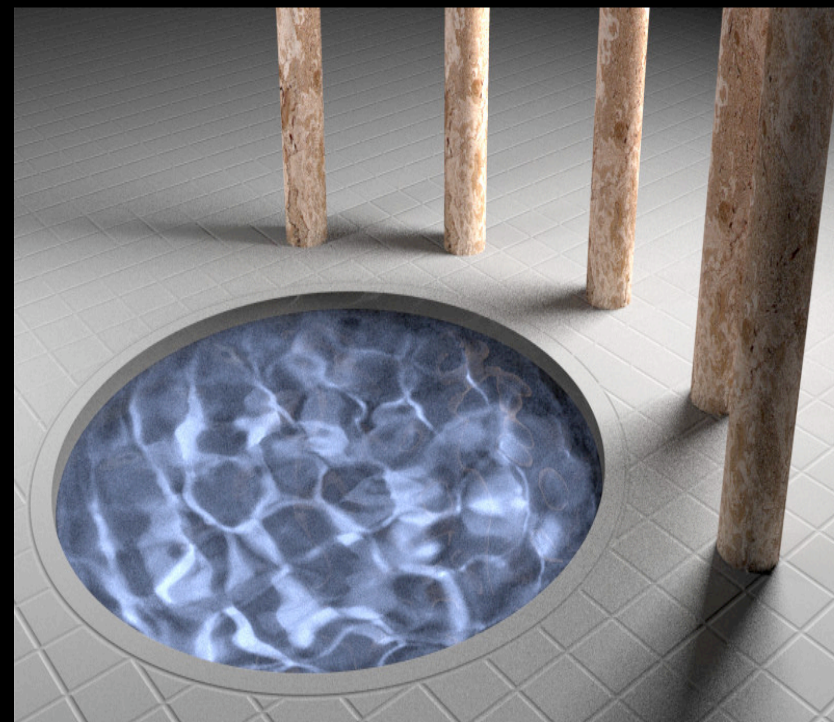
- Mutation
  - Bidirectional mutation
    - Sample space exploration
  - Lens subpath mutation
    - Sample stratification over image plane
- Lens perturbations
  - Rare convergence phenomena
- Caustic perturbations

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

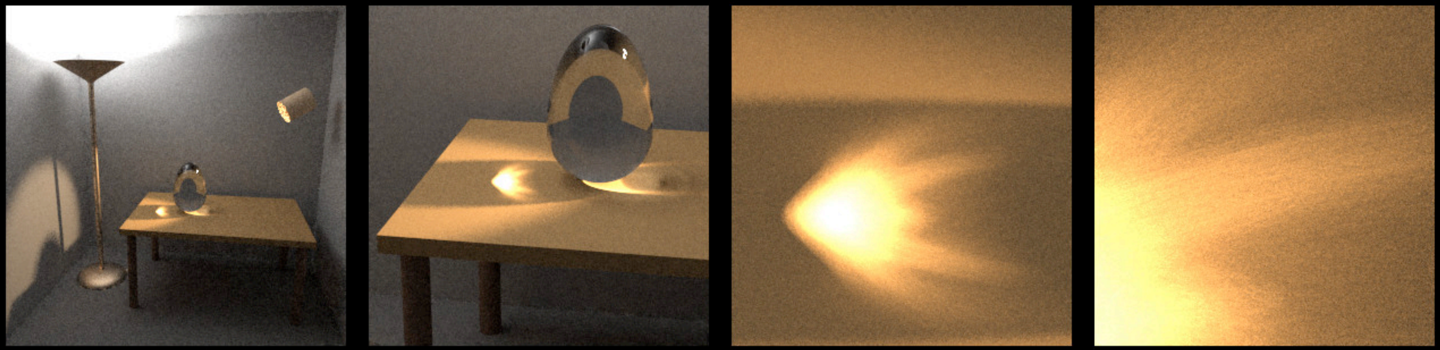
Path Tracing vs. MLT



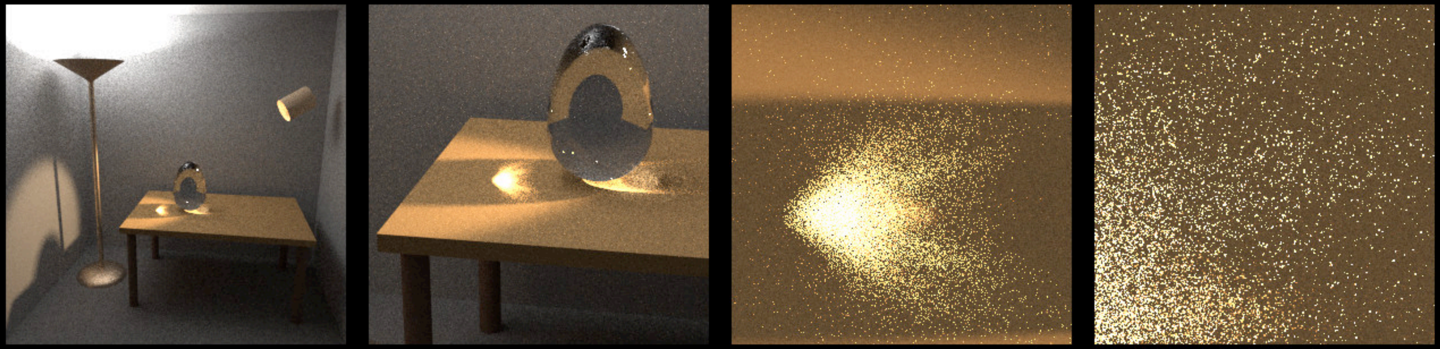


Veach & Guibas

MLT vs. Bidirectional Path Tracing



Metropolis light transport



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 Mapping

Henrik Jensen

Photon Mapping: The concept

- Motivation
  - Want to simulate all global illumination effects on complex surfaces with arbitrary BRDF's
  - As painlessly as possible
- Problems with Monte-Carlo techniques
  - Noise
    - Very costly to eliminate!

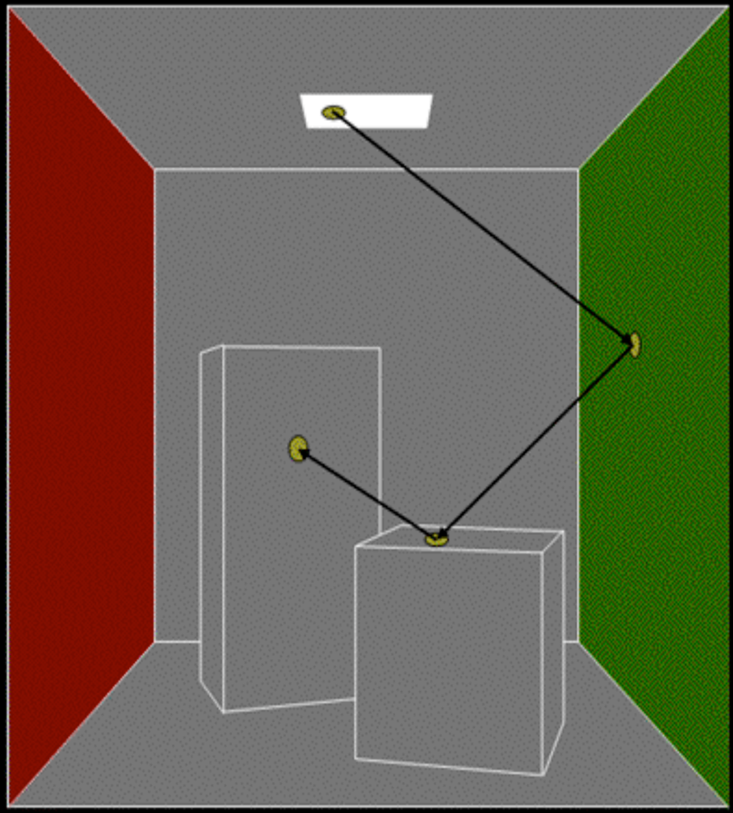
Two-pass algorithm

- 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 tracing

- Fire photons from light sources
- Contrast with ray tracing
  - Rays gather radiance
  - Photons propagate flux



CS 517, Cornell U.

Physical quantities

- Flux
  - Rate of flow of radiant energy
- Irradiance
  - Flux arriving at surface location
- Radiance
  - Radiant flux per unit solid angle per unit projected area
  - Most closely represents the color of an object
  - Number of photons arriving per time at a small area from a given direction
  - Constant along line of sight in vacuum
    - Important for ray tracing!

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

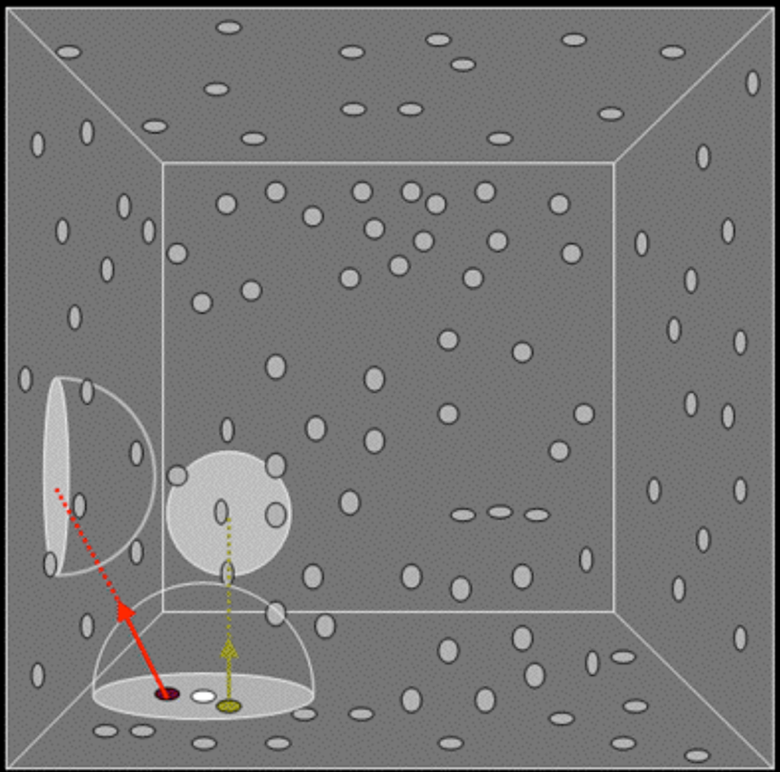
Second pass: rendering

- 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

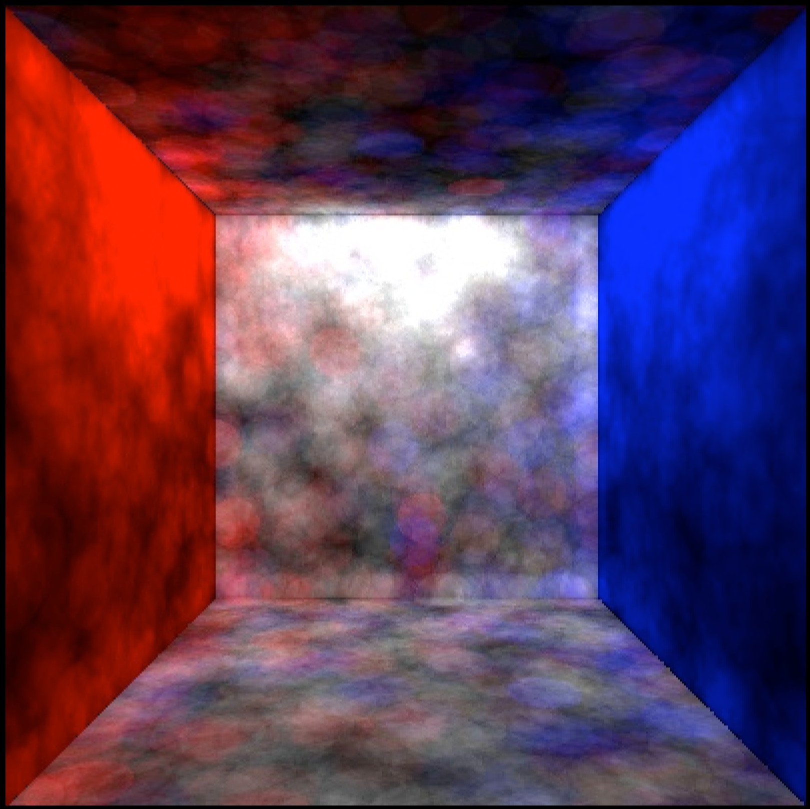


CS 517, Cornell U.

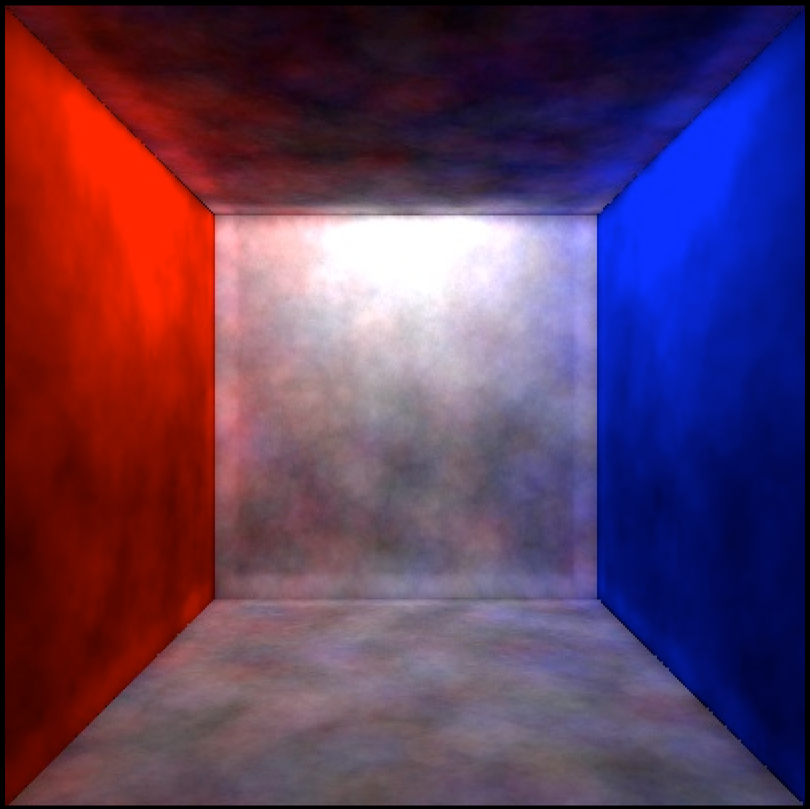
Radiance estimate

```
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 / r*r*pi
    return Lr
```

Direct Visualization



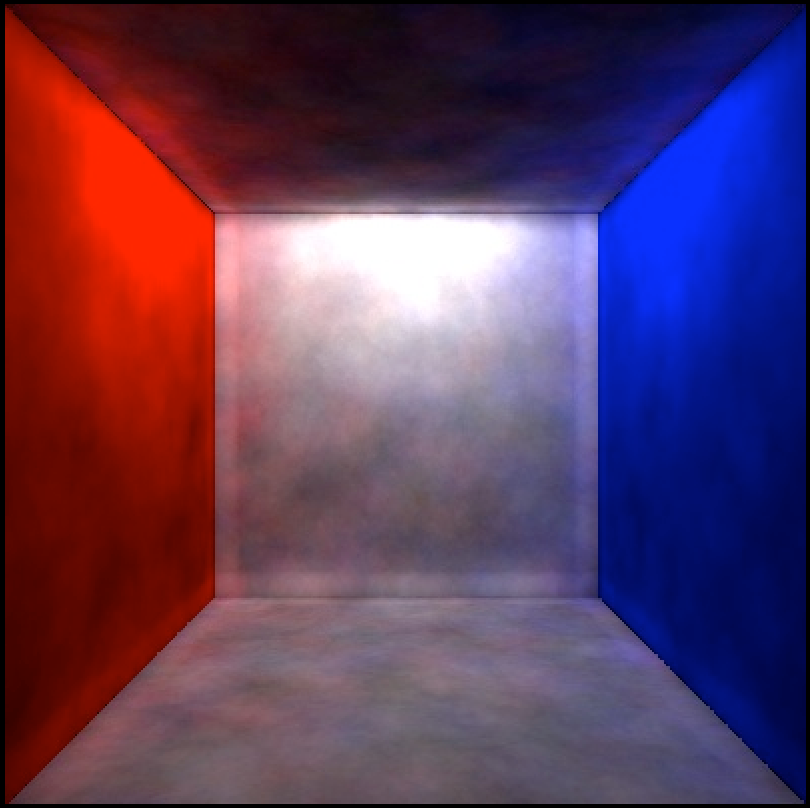
10,000 photons fired



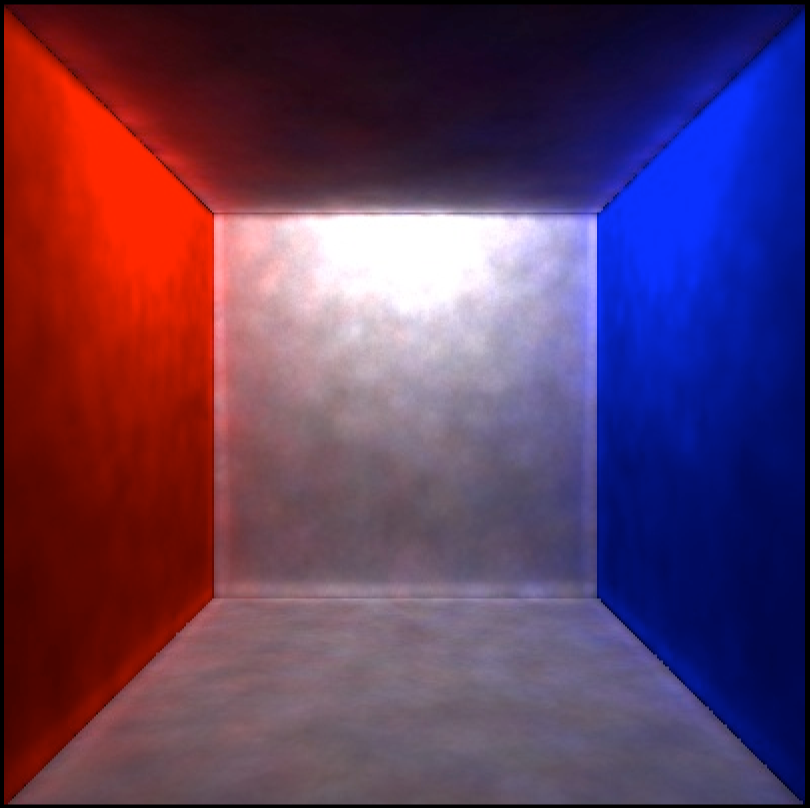
Kayvon Fatahalian and Jonathan Hui

50,000 photons fired

Direct Visualization - II



100,000 photons fired

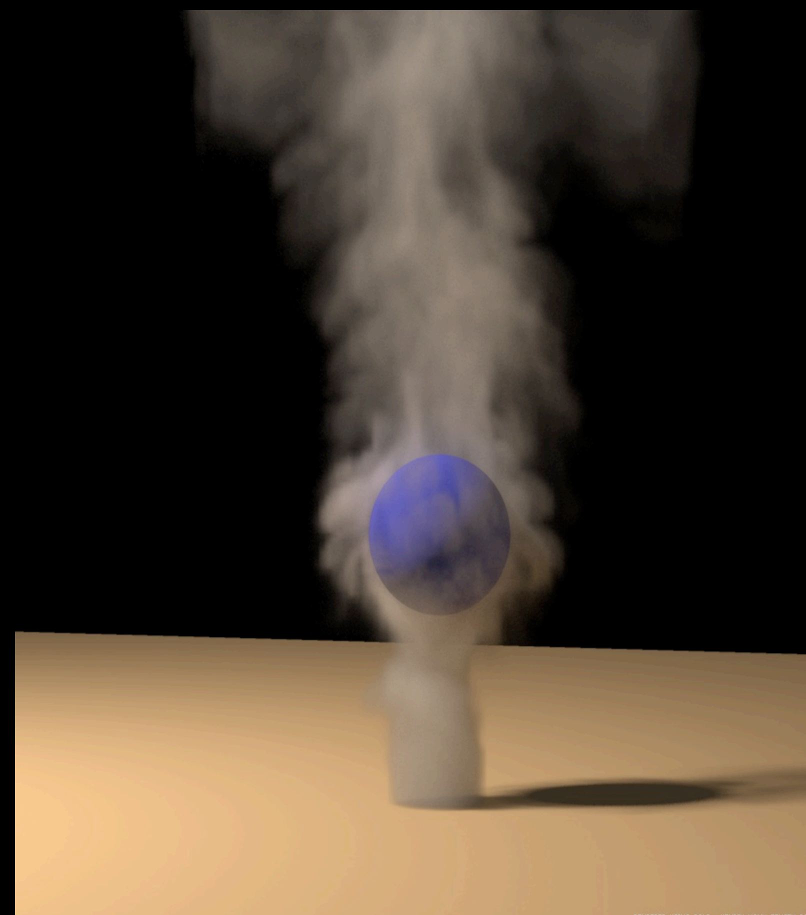


Kayvon Fatahalian and Jonathan Hui

500,000 photons fired

Photon mapping effects

- Caustics
  - Focused light
- Diffuse inter-reflections
  - Color bleeding
- Participating media
  - Clouds, smoke, fog

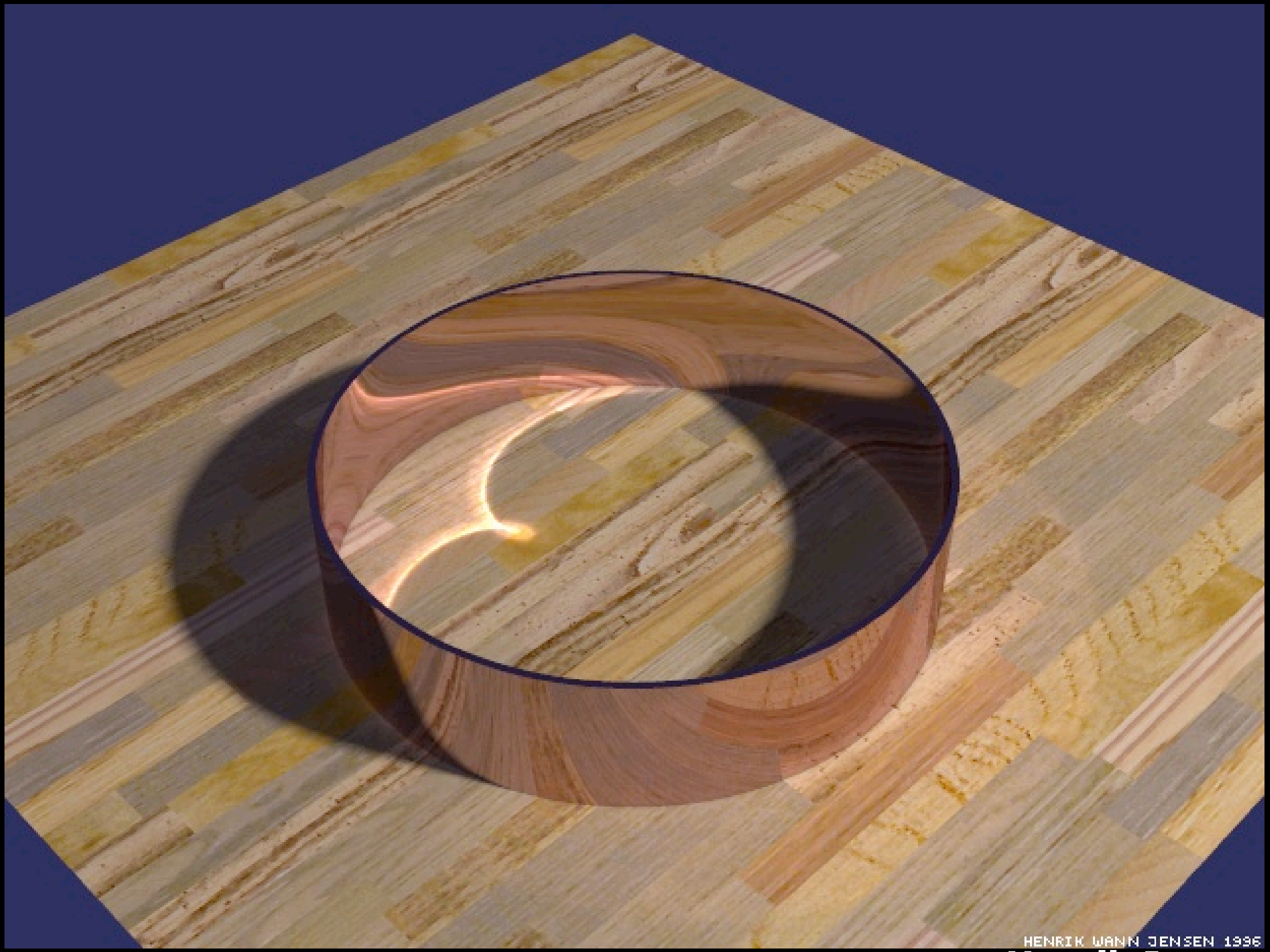


Henrik Jensen, Jos Stam, Ron Fedkiw

Caustics - I

Henrik Jensen

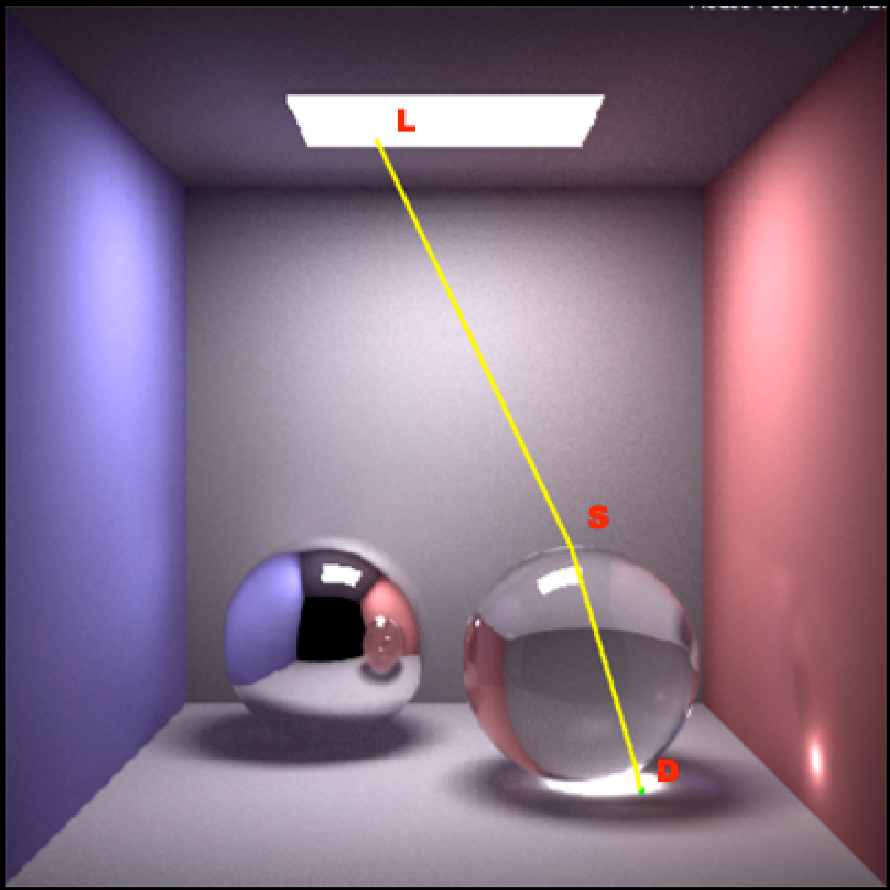
Caustics - II



Henrik Jensen

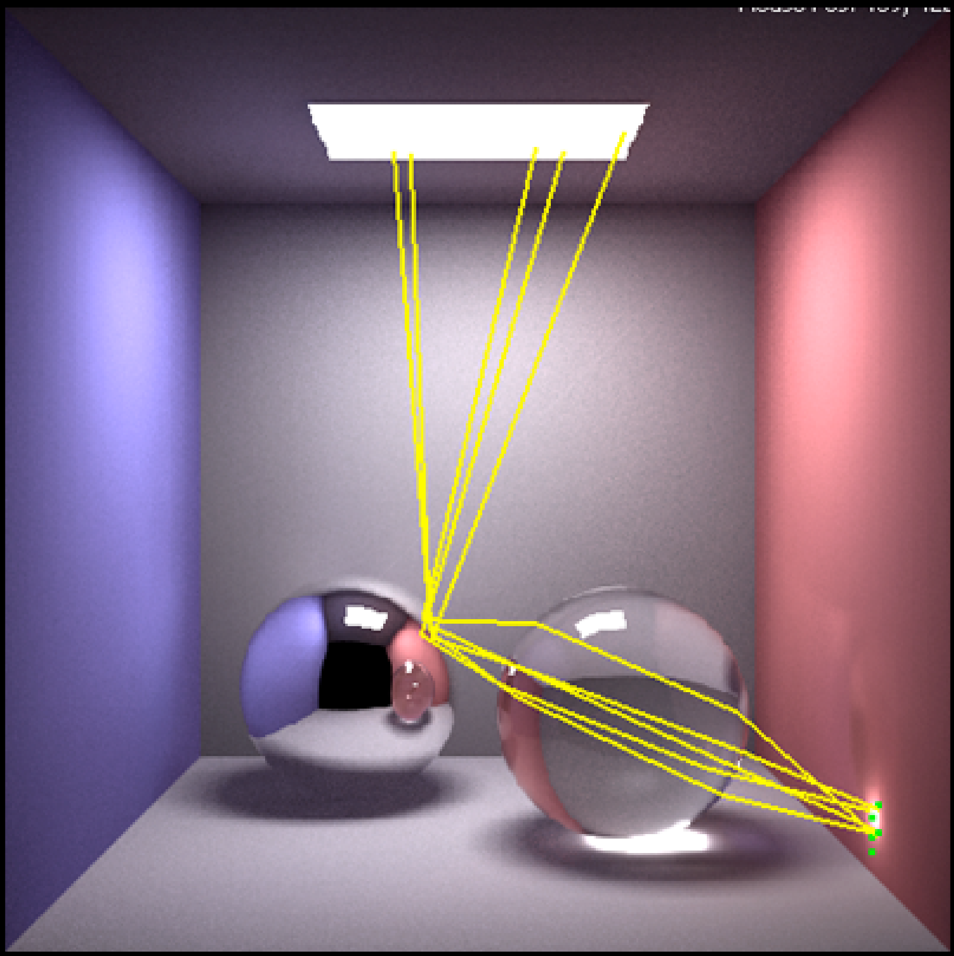
Formation of caustics - I

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



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

Formation of caustics - II



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

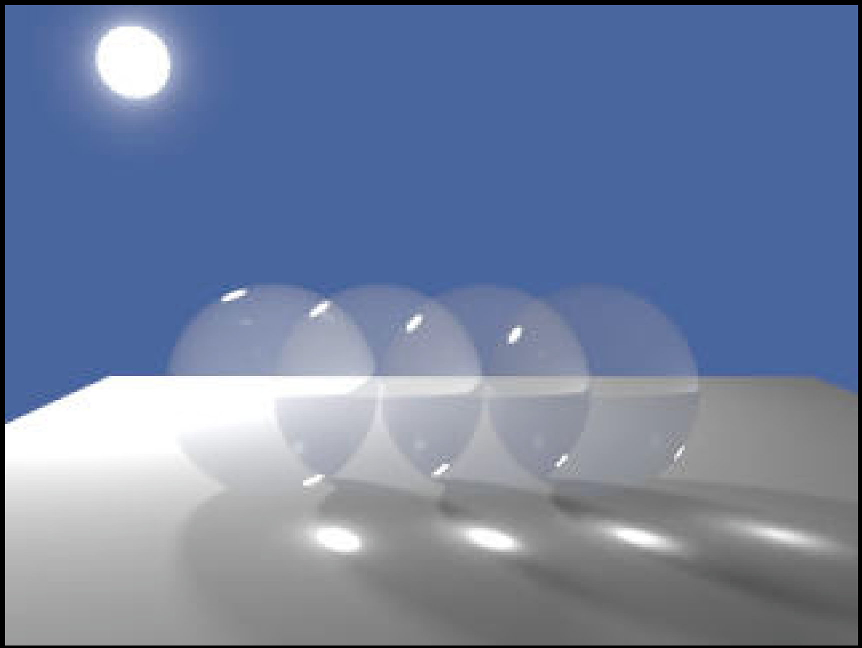
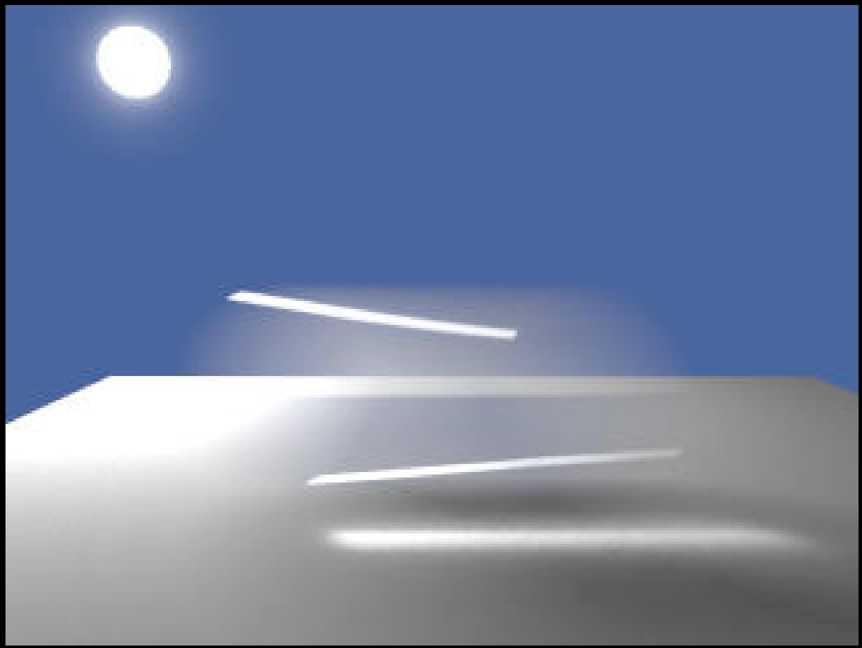
- Irradiance caching
  - Speedup for computing indirect illumination
- Visual Importance
  - “importons” from observer to determine important regions of the scene
- Efficient Stratification of Photons
  - Quasi-Monte Carlo methods

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 - must avoid strobing artifacts

Mike Cammarano, Henrik Jensen

Hardware photon mapping

- Speedups using programmable graphics hardware?
- Use GPU to compute nearest k neighbors for radiance estimate
- 8.3 seconds for the ring caustic
- 64.3 seconds for the Cornell box scene

Real world photon mapping

- Gaining wide acceptance and popularity!
- High-end rendering software packages
  - Dali, 3D Studio Max
- Games, movies
  - Kilauea, SquareUSA
    - Whisky glass from Final Fantasy movie

SquareUSA

Questions?

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Movies!

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BRDF Limitations

- Back to the BRDF…
- What are we missing from the BRDF?
  - What assumption are we making about light rays?
    - Think about non-metallic materials, like marble
  - BRDF's don't account for translucency effects

BSSRDF's

- Bidirectional Surface Scattering Reflectance Distribution Function

Henrik Wann Jensen, et. Al.

Glasses of milk

Movies!

Henrik Jensen

Appearance Modeling

- BSSRDF’s are good for translucent materials
  - Skin, marble, cloth, paper, cheese, bread, plants, fish, ocean water, snow
- Wide acceptance
  - Most renderers have BSSRDF functionality
  - Lord of the Rings’ Gollum, Harry Potter’s Dobby, T3’s Arnold
  - Technical Oscar winner, 2004
  - Expected in next-gen consoles

Questions?

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://graphics.ucsd.edu/~henrik/
  - http://och.phpwebhosting.com/tachyonic.htm