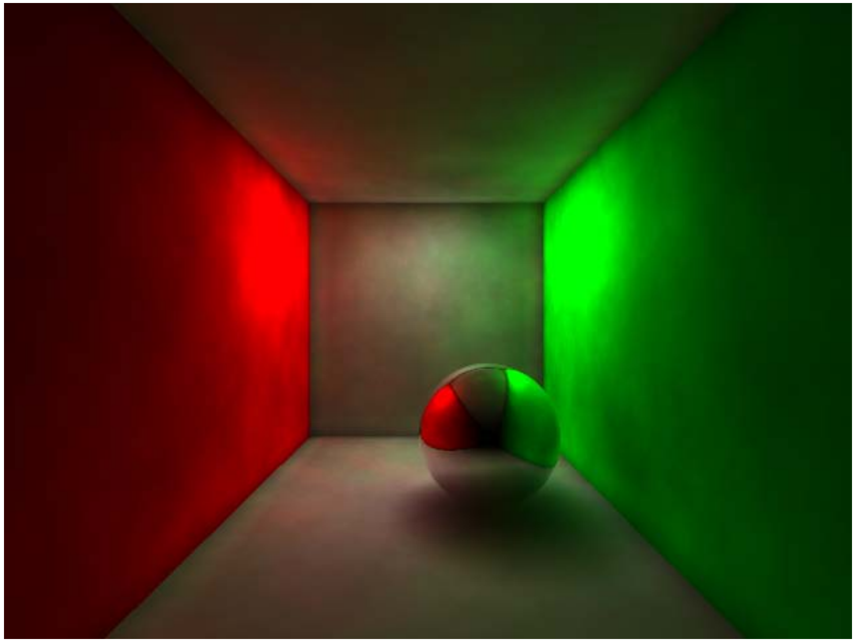
CS 563 Advanced Topics in Computer Graphics
Photon Mapping



by Emmanuel Agu

Introduction

Presentation

- Divided into two parts.
  - Overview of Photon Mapping
  - Detail look into the first pass of the Photon Mapping algorithm.

Overview

Photon Mapping

- More efficient alternative to pure Monte Carlo raytracing techniques. Not a replacement!
- Two pass global illumination algorithm.
    - Photon tracing
    - Rendering
- Illumination is decoupled from geometry.
- Best used in combination with other techniques such as path or ray tracing.
- Easy to integrate into existing renderers.

Two-Pass Method

Two pass algorithm

- Pass 1 - Photon tracing
  - Emit photons from light sources
  - Trace photons through scene.
  - Populate photon maps
- Pass 2 - Rendering
  - Render scene using information in the photon maps to estimate:
    - Reflected radiance at surfaces
    - Out-scattered radiance from volumes
    - In-scattered radiance from translucent materials.

Photon Tracing

Pass 1 - Photon tracing

- Photon emission
  - Emit photons from light sources.
- Photon scattering
  - Determine how photons are scattered through out the scene.
- Photon storing
  - How do we keep track of photons that are absorbed by diffuse surfaces.

Photon Tracing

Photon emission

- What is a photon?
  - Quantum of light with position, propagation drn & wavelength
  - **light particles,** created at light source, carry energy.
- Power of light source divided by no. emitted photons.
- Any type of light source can be used.

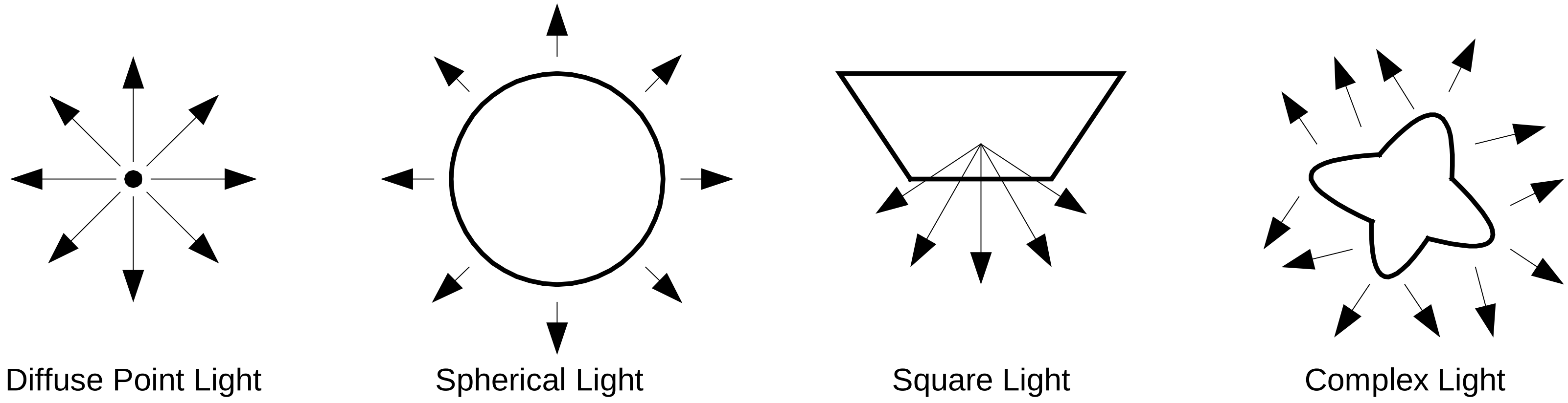


Illustration is based on figures from Jensen[1].

Photon Tracing

Photon scattering

- Emitted photons are probabilistically scattered through the scene and are eventually absorbed.
- Photon hits surface: can be reflected, refracted, or absorbed
- Photon hits volume: it can be scattered or absorbed.

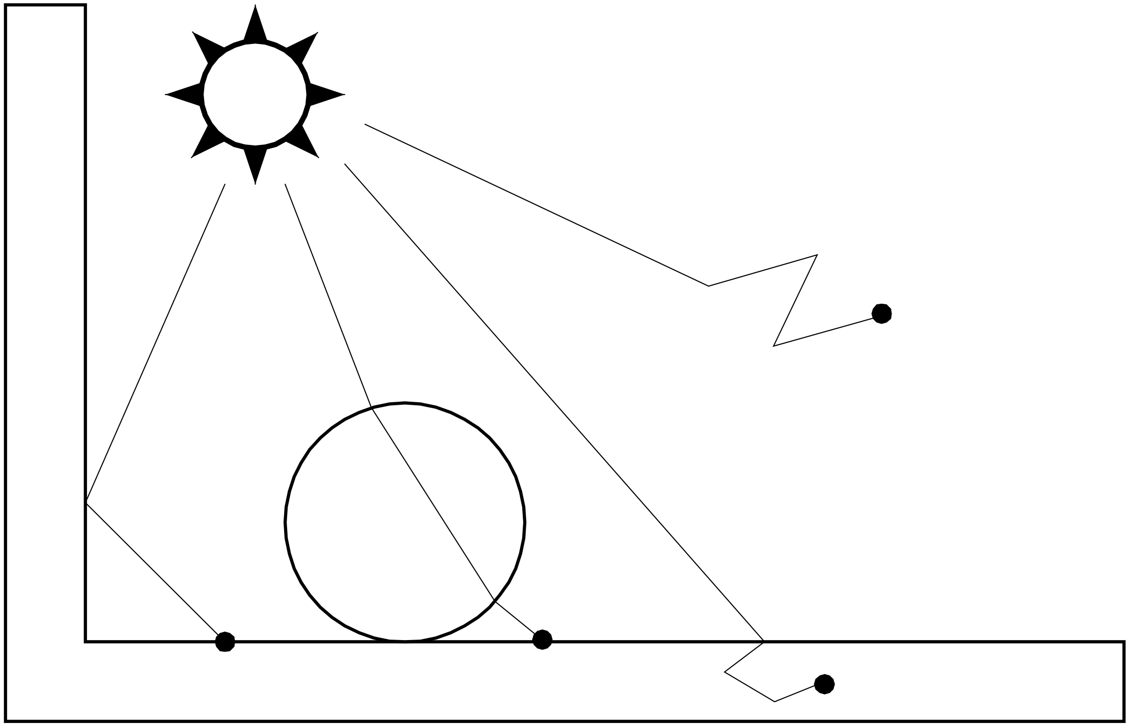


Illustration is based on figures from Jensen[1].

Photon Tracing

Photon storage

- Absorbed photons are stored in a spatial data structure called a “Photon Map”.
- Photon’s power, position & incident direction stored
- Photon map data structure
  - Fast spatial access to handle millions of queries during rendering phase.
  - Memory usage needs to be compact and aligned properly.

Photon Tracing

Photon storage

- Caustics and participating media would require large localized concentrations of photons.
- Single global photon map needs to be evenly distributed for better radiance estimates.
- Solution: Multiple photons maps are necessary.
  - Global photon map
  - Caustics map
  - Volume photon map (for participating media)

Photon Tracing

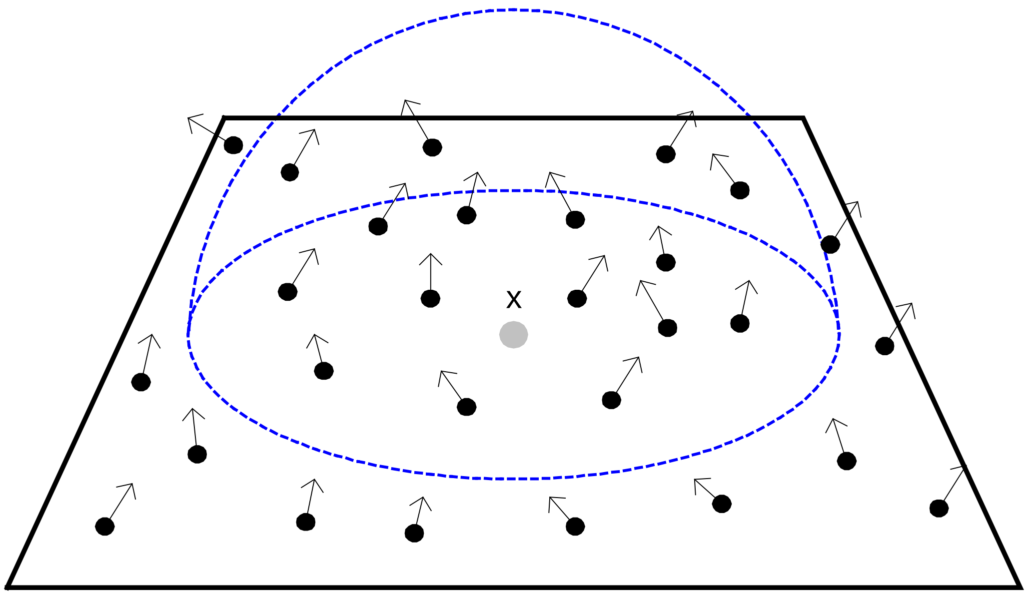
Photon storage

- Caustics Photon Map
  - Generated by shooting photons directly at specular objects in the scene and are absorbed when they reach a diffuse surface.
  - Photons are highly focused into a small area.
  - Requires fewer photons to be emitted.

Photon Tracing

Pass 2 - Rendering

- Imagine ray tracing a hitpoint x
- Information from photon maps used to estimate radiance from x
- Radius of circle required to encountering N photons gives radiance estimate at x



Photon Tracing

Pass 2 – Rendering

- What are we doing when we gather nearest N photons?
  - We are approximating reflected radiance.
  - We can use the direction $\vec{\omega}_p$ of each photon, p, along with the BRDF of the surface.

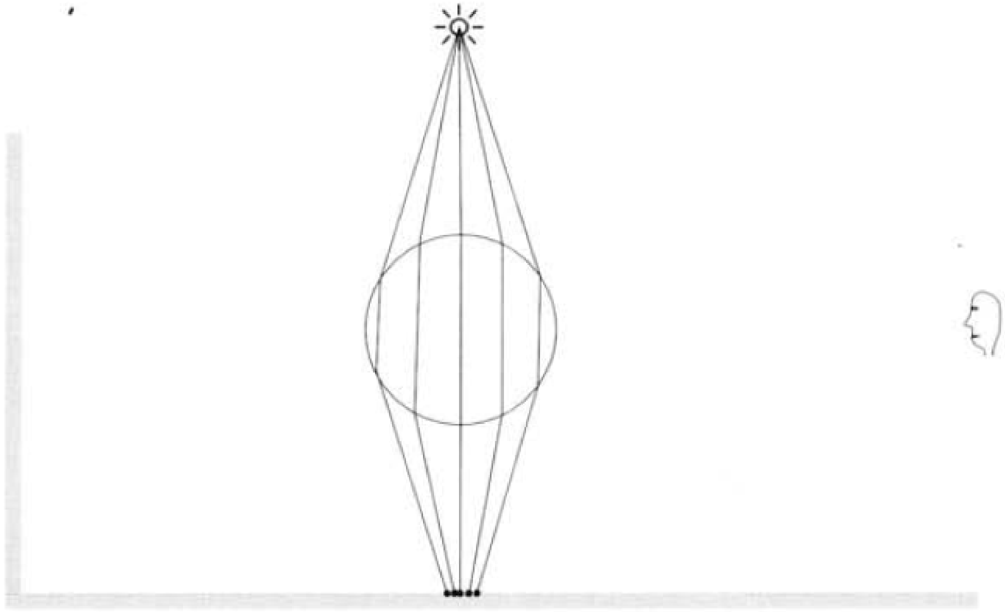
$$L_r(x,\vec{\omega}) = \frac{1}{\pi r^2} \sum_{p=1}^{N} f_r(x,\vec{\omega}_p,\vec{\omega}) \Delta\Phi_p(x,\vec{\omega}_p)$$

Radius of circle to gather N photons

Photon Tracing

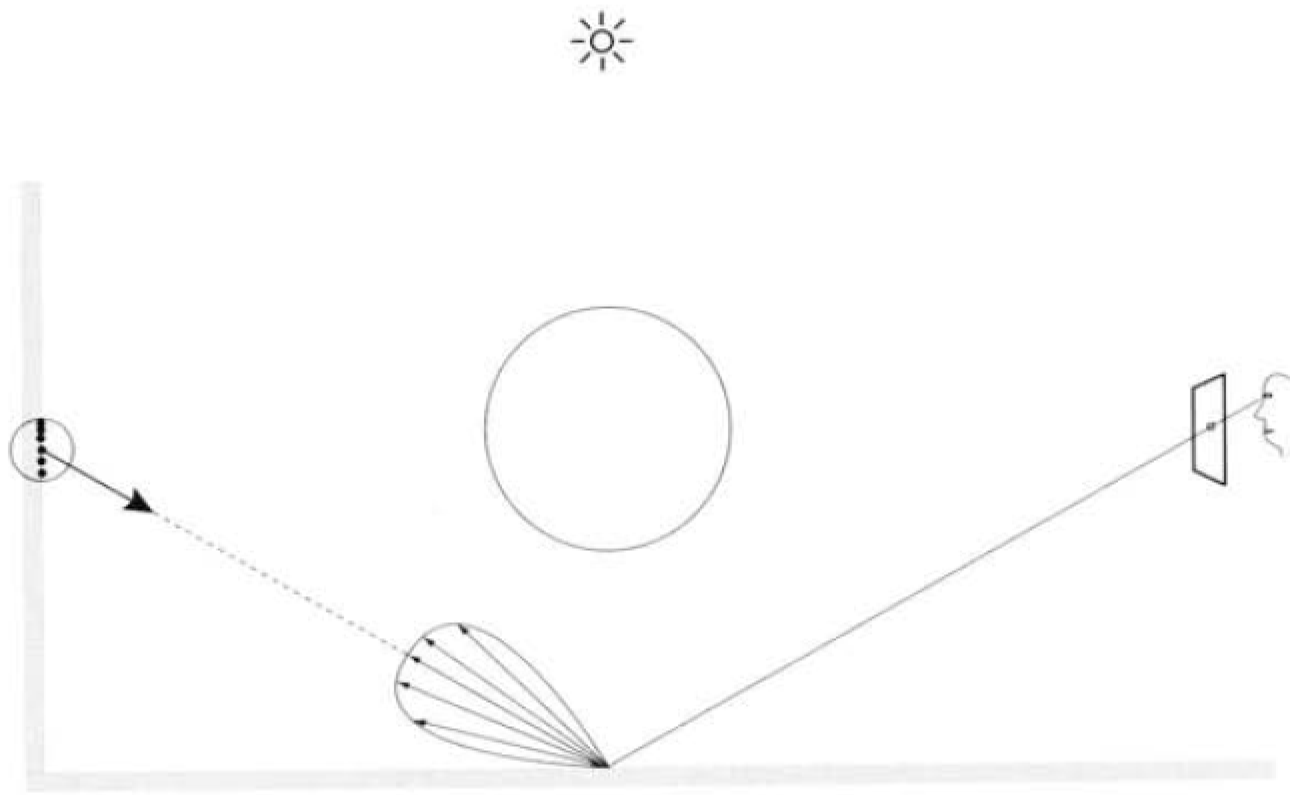
Pass 2 - Rendering

- Rendering equation integral is split into 4 terms.
  - Direct Illumination: ray tracing
  - Specular/Glossy: ray tracing
  - Indirect Illumination:
    - path tracing optimized using photon mapping
  - Caustics (hits specular then diffuse): photon mapping



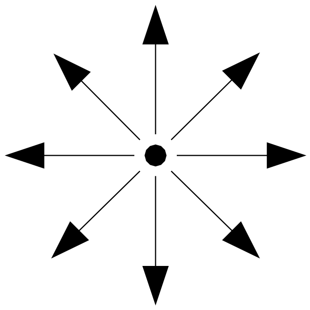
Rendering

- Indirect diffuse lighting: Use ray tracing
- Estimate in global photon map can be used



Photon Emission

- Diffuse Point Light



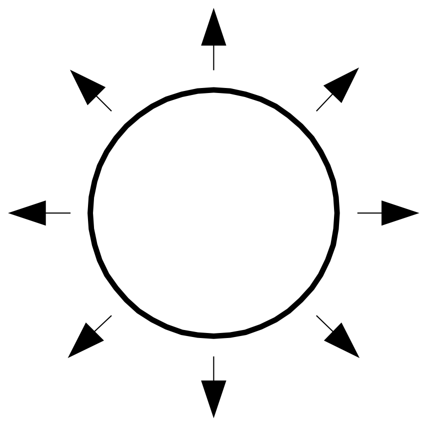
Diffuse Point Light

- Photons are emitted uniformly in all directions.
  - Sample sphere uniformly
  - Rejection sampling
    - Pick random direction in unit cube and then check to see if it’s in unit sphere. If not then reject and try again.

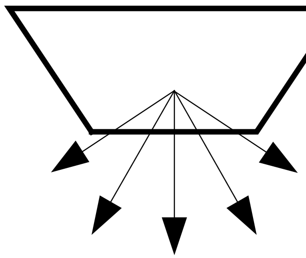
Photon Tracing

Photon Emission

- Spherical and Square Lights



Spherical Light



Square Light

- Pick random position on square or sphere surface
- Pick random direction in hemisphere above position.

Photon Tracing

Photon Emission

- Multiple Lights
  - Photons emitted from each light source
  - Total number of photons **in scene** same as for single light
  - Less photons are needed per light source since each light contributes less to overall illumination.
  - More photons emitted from brighter lights than dim lights
  - Complexity not increased with the more lights.

Photon Tracing

Photon Emission

- Projection Maps
  - Map of scene geometry as seen from light source
  - Cells have information on whether objects in that direction
  - Photons emitted in directions with objects
    - Improves efficiency in scene’s with sparse geometry
    - In caustic generation, the projection map directs photons toward specular surfaces

Photon Tracing

Photon Scattering

- Specular reflection
  - Photons hitting specular surfaces are reflected in mirror drn
  - Calculated same as specularly reflected rays in raytracing.
  - Power of photon should be scaled by the reflectivity or the mirror. Unless using Russian Roulette.

Photon Tracing

Photon Scattering

- Diffuse reflection
  - Pick random direction in hemisphere above hit point probability proportional to cosine of angle with normal
  - Power scaled by diffuse reflectance. Unless using Russian Roulette
  - Photons only stored in photon map at diffuse surfaces
- Arbitrary BRDF reflection
  - New photon direction is computed by importance sampling the BRDF.
  - Power scaled according to BRDF as well as reflectivity. Unless using Russian Roulette.

Photon Tracing

Photon Scattering

- Russian Roulette
  - Stochastic technique to remove unimportant photons and allow the effort to be focused on important photons.
  - Standard Monte Carlo technique
  - Basic Concept
    - Use probabilistic sampling to eliminate work and still get the correct result.

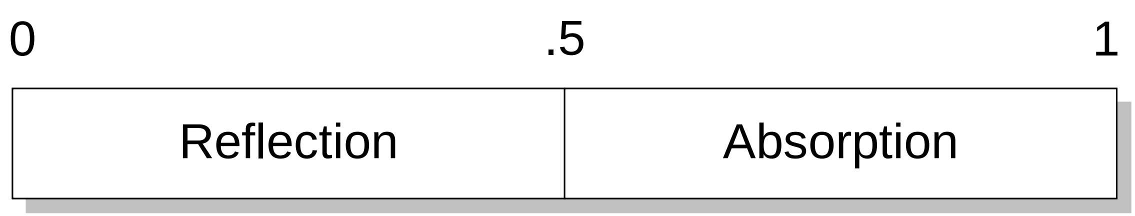
Photon Scattering

Russian Roulette

- At surface, photon reflection or Absorption?

Example:

If 1000 photons are shot at a surface with reflectivity 0.5 then we can reflect 1000 at half power or we can reflect 500 at full power.



Photon Tracing

Photon Scattering

- Russian Roulette

$\xi \in [0,1]$ is a random variable

$p \in [0,1]$ is probability that another radiance estimate, L_n, is made.

$$L_n = \begin{cases} \xi < p \text{ then } \dfrac{L}{p} \\ otherwise \quad 0 \end{cases}$$

Compute expected value to see why it works.

$$E\{L\} = (1-p)*0 + p*\frac{E\{L\}}{p} = E\{L\}$$

Photon Scattering

Russian Roulette

- Reflection or Absorption

$\xi \in [0,1]$ is a random variable

$p \in [0,1]$ is probability of reflection.

Φ_p is power of incoming photon

if $(\xi < p)$

then reflect photon at power Φ_p

else

photon is absorbed

- Reflected photon power is not modified. Correctness is ensured over many samples.

Photon Scattering

Russian Roulette

- Specular or Diffuse Reflection

$\xi \in [0,1]$ is a random variable

$p_d \in [0,1]$ is probability of diffuse reflection.

$p_s \in [0,1]$ is probability of specular reflection.

where $(p_d + p_s \leq 1)$

Decision is made

$\xi \in [0, p_d]$ diffuse reflection

$\xi \in (p_d, p_d + p_s]$ specular reflection

$\xi \in (p_d + p_s, 1]$ absorption

0 p_d p_s 1

Diffuse	Specular	Absorption

Photon Scattering

Photon Map Data Structure

- Photon Node
  - Position
  - Incident direction
  - Power
- Spatial data structure kd-trees are used to partition point sets. In our case photons.
  - Similar to BSP except partitioning planes are axis aligned
  - Balanced kd-trees give O(log N) searches.
    - Trees should be balanced if possible.
  - Each node contains a splitting plane that is orthogonal to it's parent's splitting plane.

Applications of Photon Mapping

- Photon Mapping can be used for
  - Caustics
  - Color Bleeding
  - Participating Media
  - Subsurface Scattering
  - Motion Blur

Applications of Photon Mapping

- Practical 2 pass algorithm

- the rendering equation for surface radiance:

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

Applications of Photon Mapping

- Expand the reflected radiance L_r

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

- BRDF component

$$f_r(x,\vec{w}',\vec{w}) = f_{r,S}(x,\vec{w}',\vec{w}) + f_{r,D}(x,\vec{w}',\vec{w})$$

- Incoming Radiance

$$L_i(x,\vec{w}') = L_{i,l}(x,\vec{w}') + L_{i,c}(x,\vec{w}') + L_{i,d}(x,\vec{w}')$$

Applications of Photon Mapping

- Separating the BRDF and incoming radiance

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

$$\int_{\Omega} f_r(x,\vec{w}',\vec{w}) L_{i,l}(x,\vec{w}')(\vec{w}'\cdot\vec{n})d\vec{w}' +$$

$$\int_{\Omega} f_{r,S}(x,\vec{w}',\vec{w})(L_{i,c}(x,\vec{w}') + L_{i,d}(x,\vec{w}'))(\vec{w}'\cdot\vec{n})d\vec{w}' +$$

$$\int_{\Omega} f_{r,D}(x,\vec{w}',\vec{w}) L_{i,c}(x,\vec{w}')(\vec{w}'\cdot\vec{n})d\vec{w}' +$$

$$\int_{\Omega} f_{r,D}(x,\vec{w}',\vec{w}) L_{i,d}(x,\vec{w}')(\vec{w}'\cdot\vec{n})d\vec{w}'$$

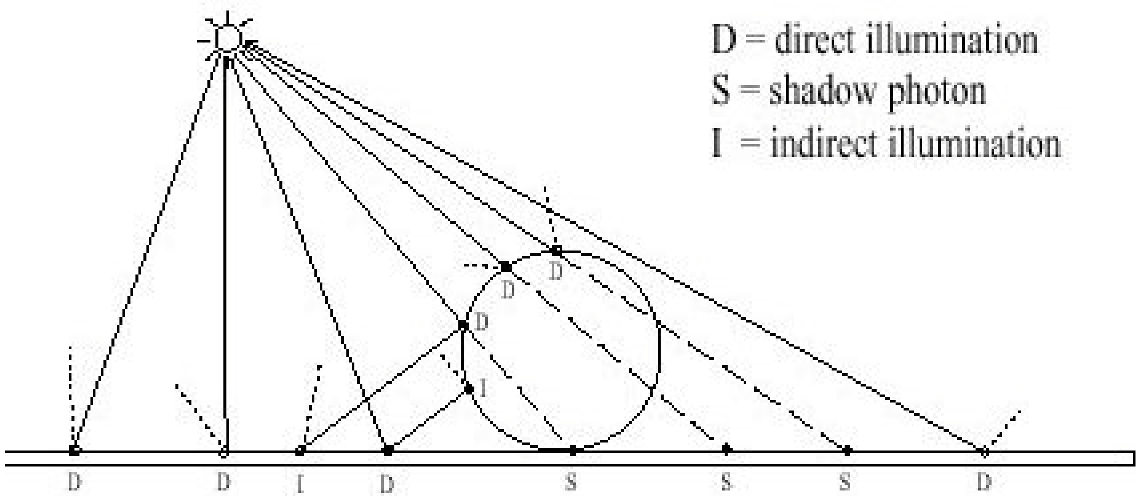
Applications of Photon Mapping

- Was broken down into the
  - Direct Illumination
  - Specular and Glossy Reflections
  - Caustics
  - Indirect Illumination

  - An accurate and approximate

Applications of Photon Mapping

- Global Photon Map
  - photons are emitted towards all objects
  - rough estimation
  - shadow photons

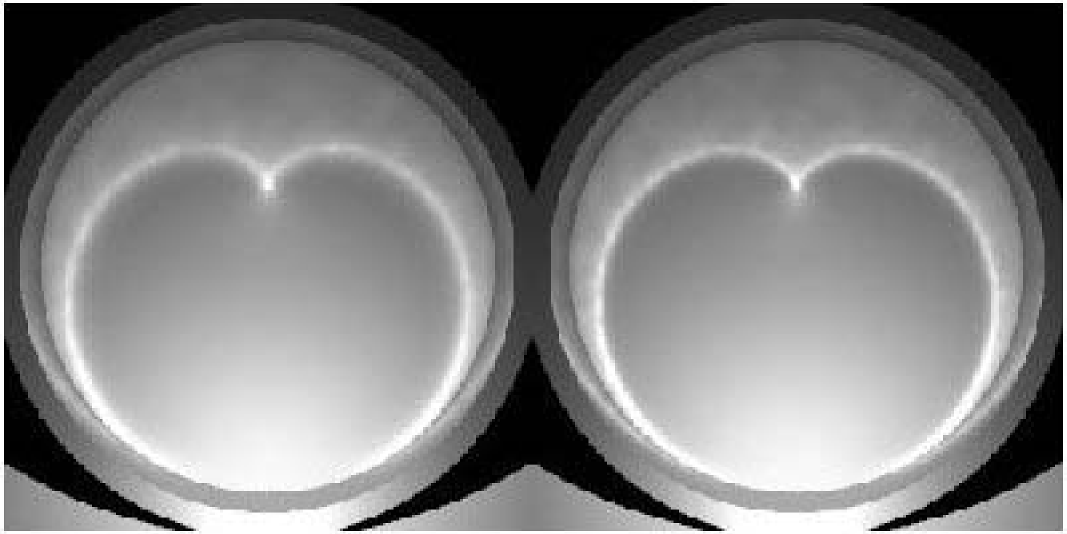


Applications of Photon Mapping

- Caustic Photon Map
  - only stores caustics
  - photons are emitted towards specular objects
  - high density

Applications of Photon Mapping

- Radiance Estimation is also applied
  - variable size sphere
  - fixed size sphere
- Filtering is also applied to the Caustics
  - Cone filter applied to the right Caustic



Applications of Photon Mapping

- Participating Media
  - not all photon interaction happens at the surface
  - translucent materials
  - Light Scattering of Photons
  - Volume Photon Map
  - Photons are
    - absorbed
    - scattered

Applications of Photon Mapping

- Previous Rendering Algorithms assumed that light traveling in a vacuum

- participating media allows:
  - dust
  - air
  - clouds

  - marble
  - skin
  - plants

Applications of Photon Mapping

- Change of radiance L_r in the direction $\vec{w}$
  - scattering coefficient

$$-\sigma_s(x)L(x,\vec{w})$$

  - absorption coefficient

$$-\sigma_a(x)L(x,\vec{w})$$

  - in-scattering

$$\sigma_s(x)\int_{\Omega 4\pi} p(x,\vec{w}',\vec{w})L_i(x,\vec{w}')d\vec{w}'$$

  - emission from the medium

$$\sigma_a(x)L_e(x,\vec{w})$$

Applications of Photon Mapping

- Volume Rendering Equation

$$L(x,\vec{w}) = \int_0^s e^{-r(x,x')}\sigma_a(x')L_e(x')dx' +$$

$$\int_0^s e^{-r(x,x')}\sigma_s(x') \int_{\Omega 4\pi} p(x',\vec{w}',\vec{w})L_i(x',\vec{w}')d\vec{w}'dx' +$$

$$e^{-r(x,x+s\vec{w})}L(x+s\vec{w}',\vec{w})$$

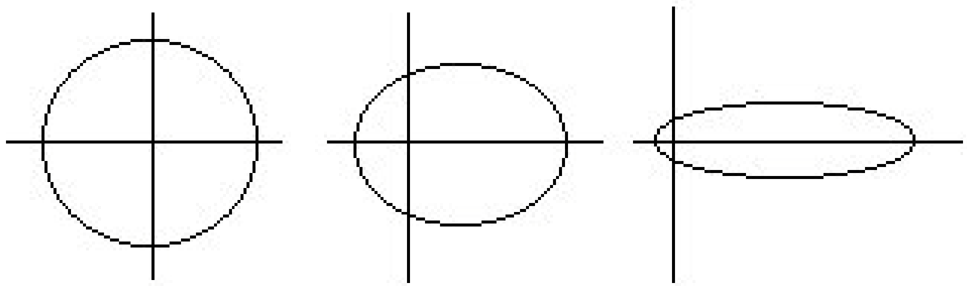
  - for an optical depth

$$r(x,x') = \int_x^{x'} \sigma_t(t)dt$$

Applications of Photon Mapping

- Phase Functions
  - distribution of scattered light in a participating media
  - Henyey-Greenstein phase function

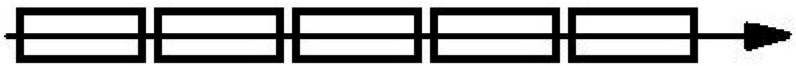
$$p(\theta) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos\theta)^{1.5}}$$



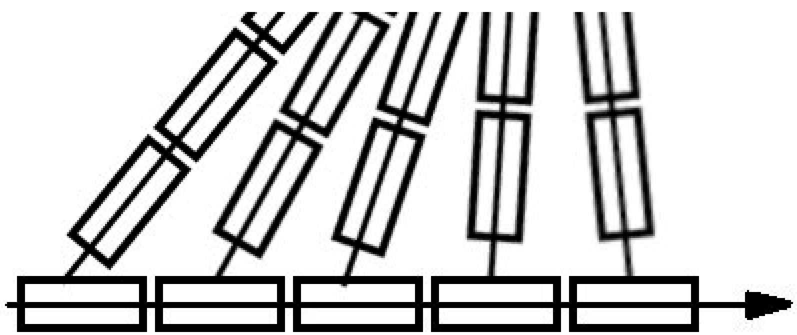
- g = 0.0,   g = 0.4,   g = 0.9

Applications of Photon Mapping

- Ray Marching
  - single ray



  - shadow rays



Applications of Photon Mapping

- Adaptive Ray Marching
  - non-homogeneous media
  - shadows
  - caustics

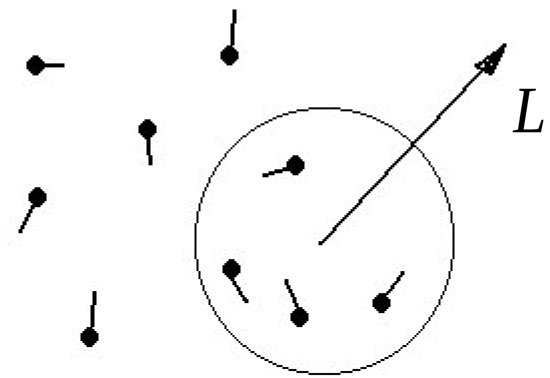
- Ray marching estimates in-scattered light

Applications of Photon Mapping

- Volume Radiance Estimate
  - 3 dimensional equivalence of surface radiance estimate

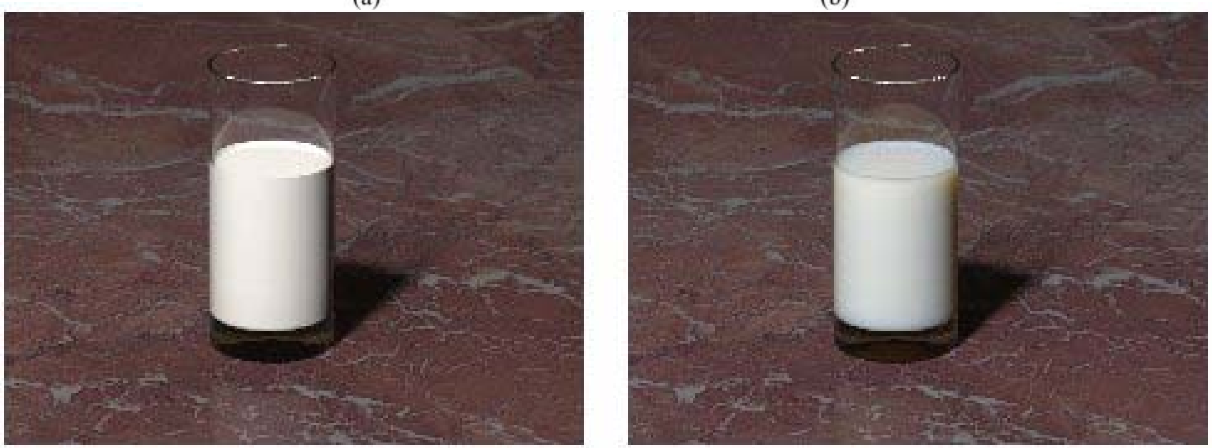
$$(\vec{w}\cdot\nabla)L_o(x,\vec{w}) = \sigma_s(x)\int_{\Omega 4\pi} p(x,\vec{w}',\vec{w})L(x,\vec{w}')d\vec{w}'$$

  - photon density is estimated by volume of sphere



Applications of Photon Mapping

(a) (b)



(a) (b)

(a) diffuse (BRDF), (b) skim (BSSRDF)

Applications of Photon Mapping

- Subsurface Scattering
  - denser version of participating media
  - Photon Tracing

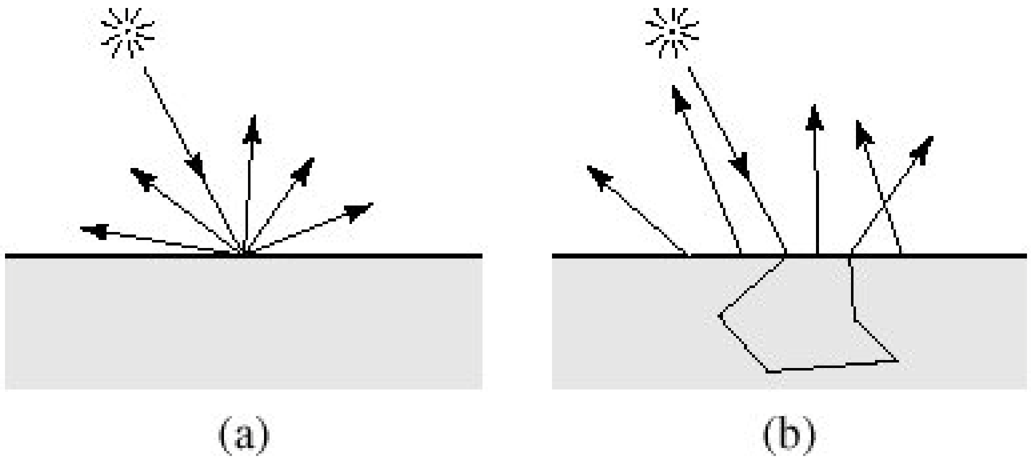


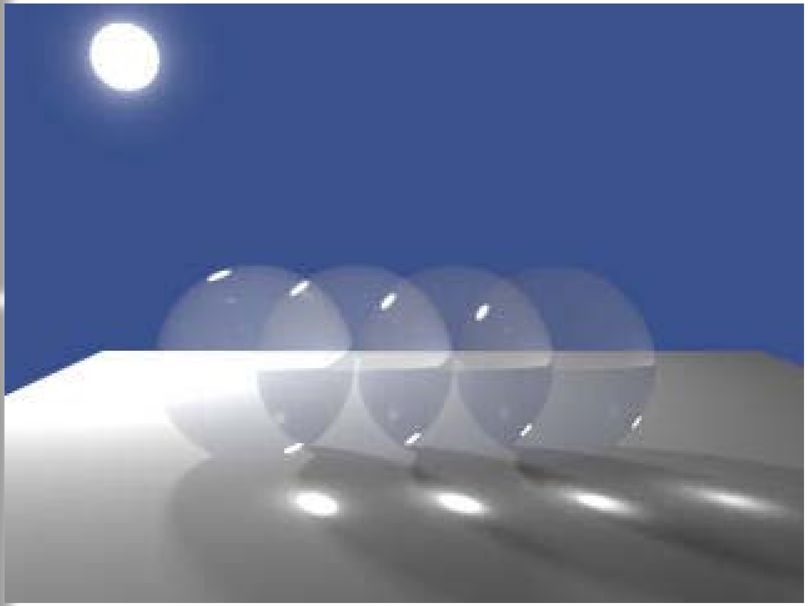
Figure 1: Scattering of light in (a) a BRDF, and (b) a BSSRDF.

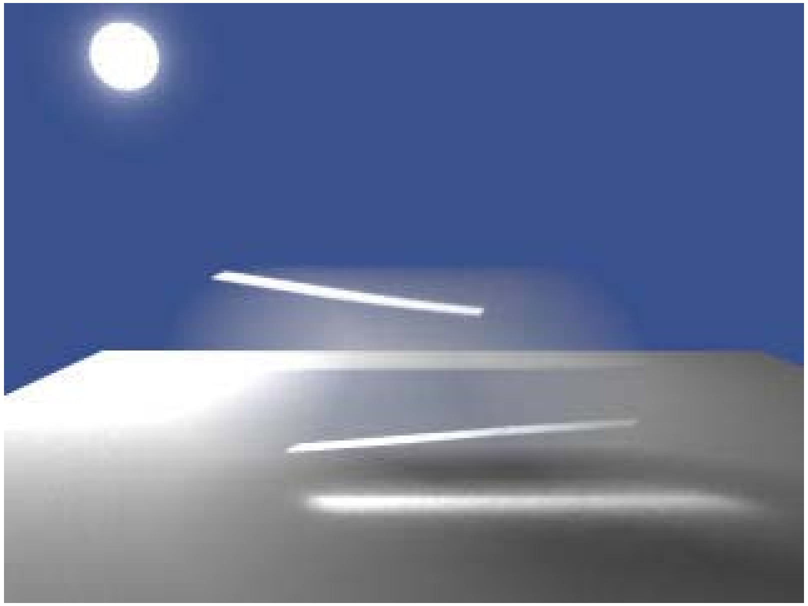
Applications of Photon Mapping

- Rendering of Subsurface Scattering
  - uses ray marching
  - Russian roulette sampling
  - in-scattered radiance

Applications of Photon Mapping

- Motion Blur
  - temporal supersampling

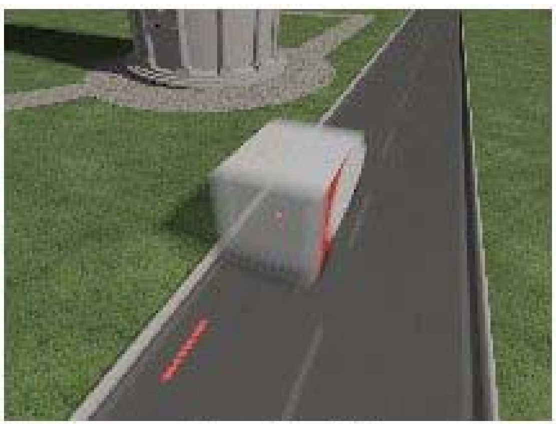




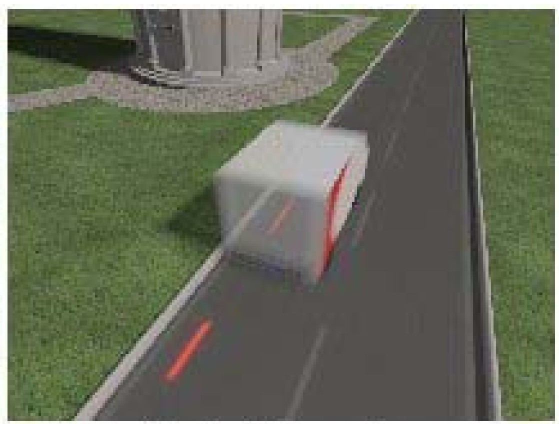
Applications of Photon Mapping

- accumulation buffer
- standard radiance estimate
- time dependent radiance estimate

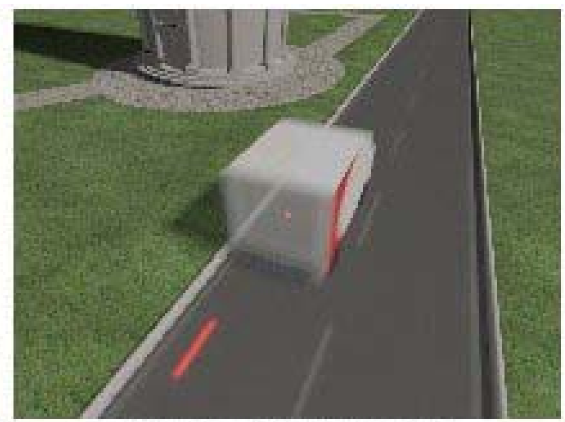
$$L_r(x,\vec{w},t) = \int_{\Omega} f_r(x,\vec{w}',\vec{w},t) L_i(x,\vec{w}',t)(\vec{w}' \cdot \vec{n})\, d\vec{w}'$$



a) Accumulation buffer.



b) Standard radiance estimate.



c) Time dependent radiance estimate.

Applications of Photon Mapping

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References

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Applications of Photon Mapping

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