Computer graphics III – Photon mapping

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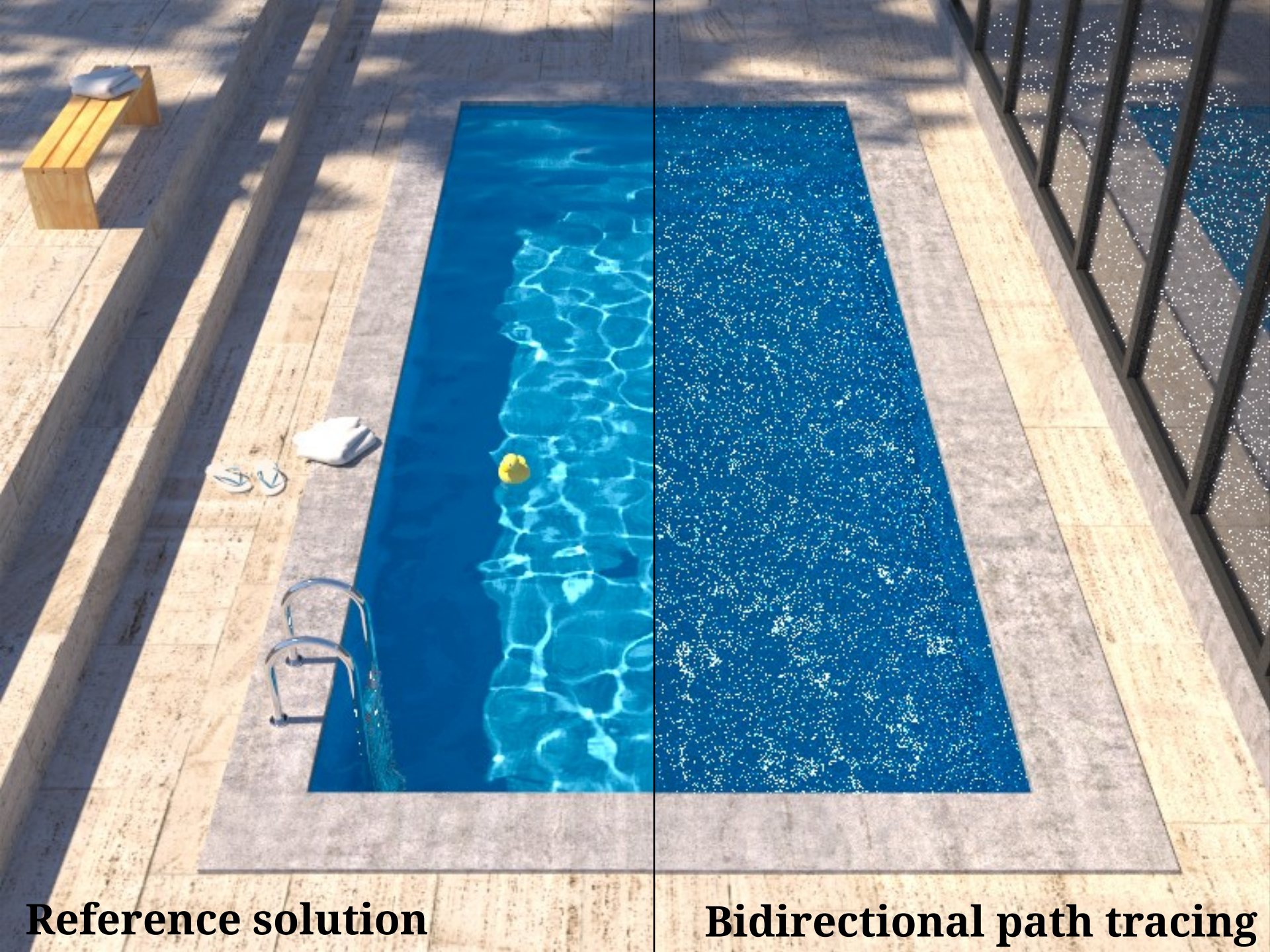
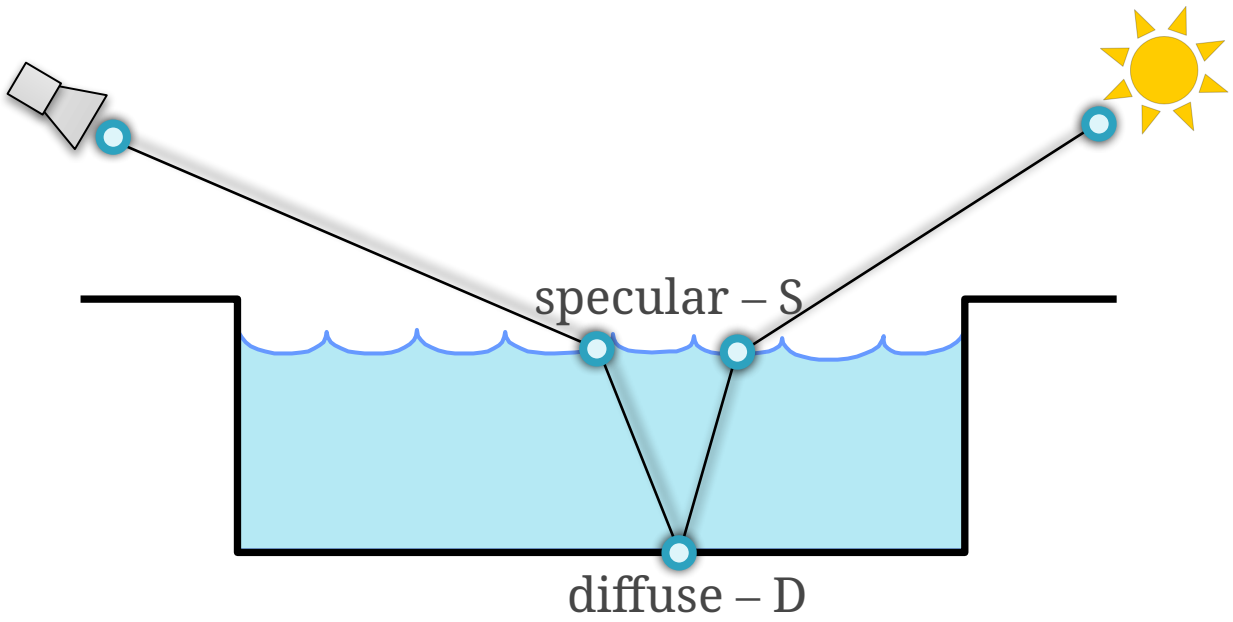

Reference solution
Bidirectional path tracing

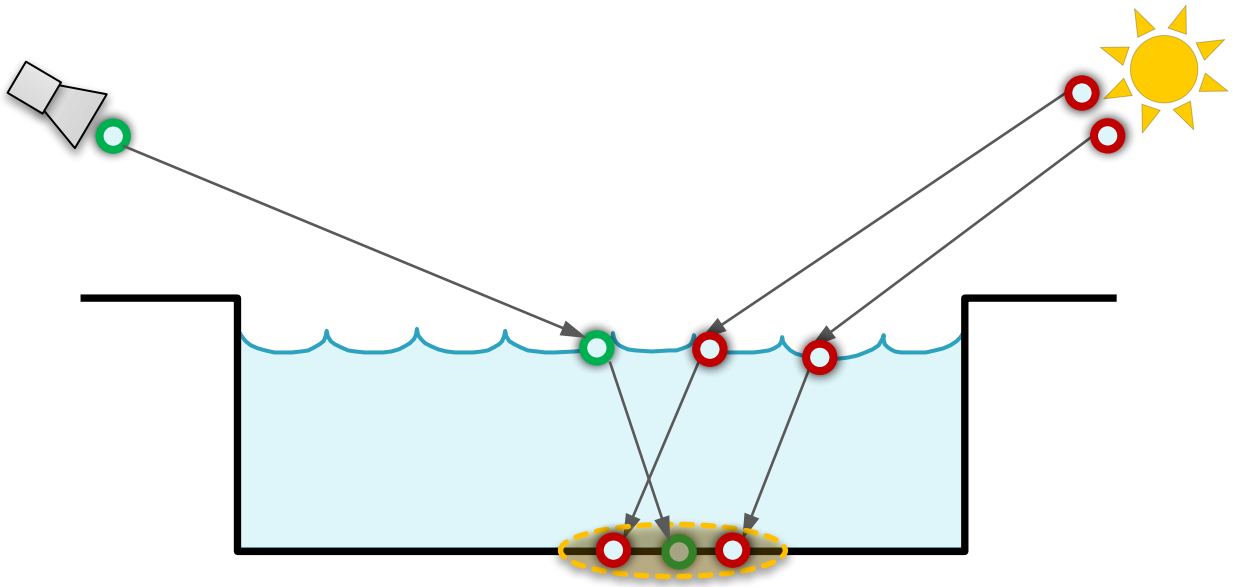
Insufficient path sampling techniques

- Some paths sampled with zero (or very small) probability



Photon mapping (Density estimation)

1. Many fwd walks + store particles (“photon map”)
2. Radiance estimate: (Kernel) **density estimation**



Photon mapping – SDS paths

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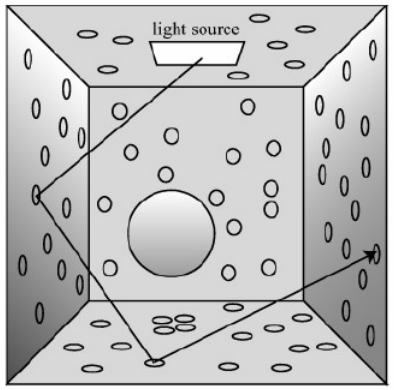
Photon mapping overview

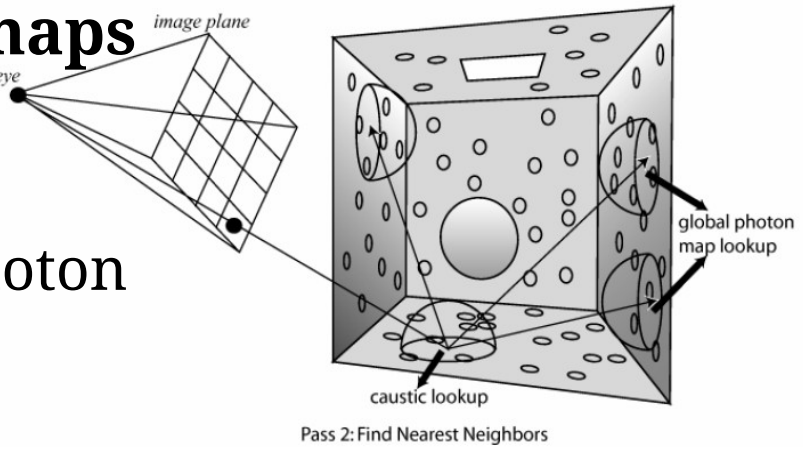
- Paths are followed both **from the light sources** and **from the camera**
- Similar to bidirectional path tracing
  - But the sub-path connection strategy significantly differs
- **Reuse of light sub-paths** for all pixels
  - Photon map = "**light sub-path cache**"
  - Essential for good performance
- For the same quality often faster than pure MC techniques
- **Biased!**
  - But **can be made consistent** (i.e. converges as the photon count increases, cf. **progressive photon mapping**)

Calculation steps

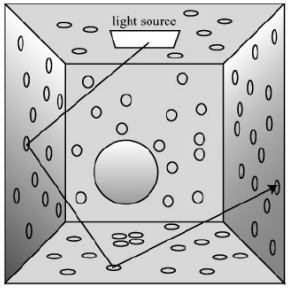
1. **Photon tracing**
   - "Photons" emitted from light sources,
   - traced through the scene (a la light tracing),
   - and stored in a photon map



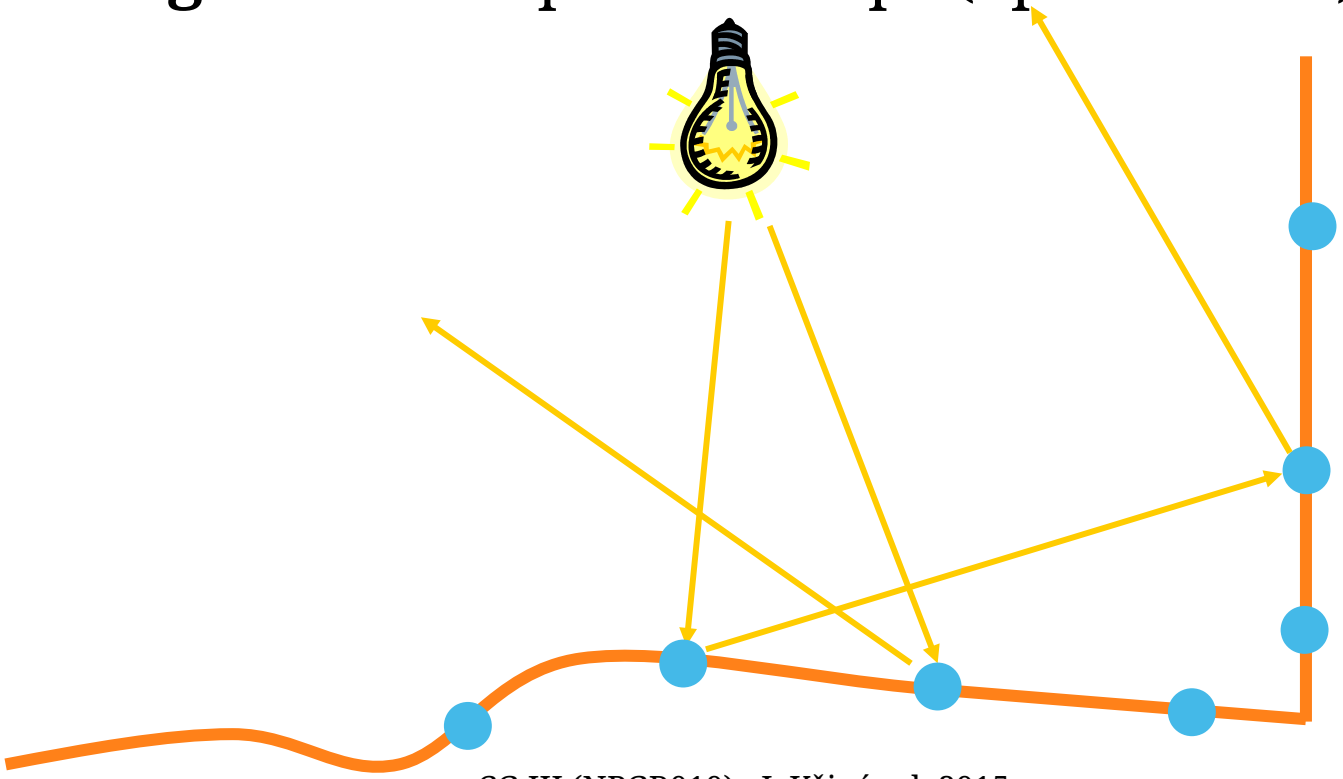
2. **Rendering with photon maps**
   - Similar to distributed path tracing
   - Recursion replaced by a photon map lookup



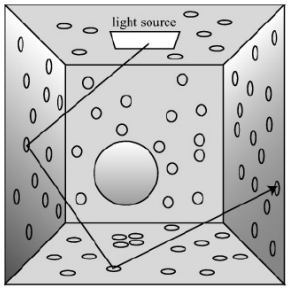
Phase 1: Photon tracing



1. **Emission** of photons from light sources
2. **Tracing** of photon paths
3. **Storage** into the “photon map” (=photon list)



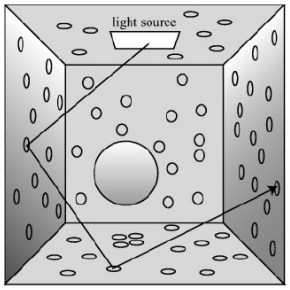
Photon emission



- **Goal**
  - All emitted photons carry the same (or similar) flux (so that the variance of photon map radiance estimates is low)

1. **Emission** of a single photon (i.e. of a single sub-path)
   1. **Choose the light source**
      - Randomly with a probability proportional to its total flux
   2. **Choose the photon origin**
      - The light position for point sources
      - Randomly chosen position for area sources
   3. **Choose the photon direction**
      - Randomly according to the emission distribution of the source

Photon emission



- Flux of the emitted photon:

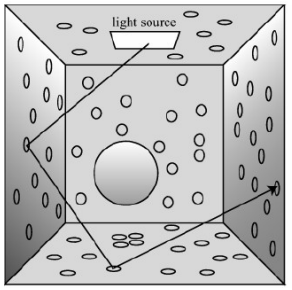
$$\Phi_{p,0} = \frac{1}{N} \frac{L_e(\mathbf{x}_0, \omega_0) |\cos\theta_0|}{P_l \; p(\mathbf{x}_0, \omega_0)}$$

Total number of emitted photon paths

(Discrete) probability of choosing the light source l

Pdf for sampling position $\mathbf{x}_0$ and direction ω_0

Photon emission



- "Ideal" sampling

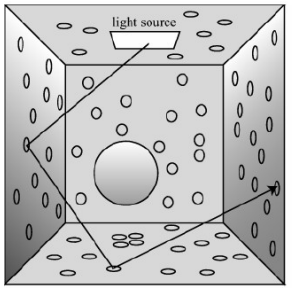
$$p(\mathbf{x},\omega) = \frac{L_e(\mathbf{x},\omega)\left|\cos\theta\right|}{\int_{A_{light}}\int_{H(\mathbf{x})} L_e(\mathbf{x},\omega)\left|\cos\theta\right| \,\mathrm{d}\omega\,\mathrm{d}A} = \frac{L_e(\mathbf{x},\omega)\left|\cos\theta\right|}{\Phi_l}$$

$$P_l = \frac{\Phi_l}{\sum_{i\in lights}\Phi_i} = \frac{\Phi_l}{\Phi_{total}}$$

  - All emitted photons carry the same flux:

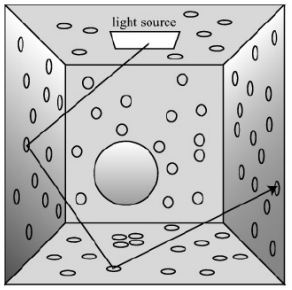
$$\Phi_{p,0} = \frac{\Phi_{\text{total}}}{N}$$

Tracing of photon paths



- Similar to light tracing
- Photon-surface intersection:
  1. **Store "photon"** into a photon map
     - photon = (position, incident direction, flux)
  2. **Generate reflected direction**
     - BRDF importance sampling
  3. **Update photon flux**
     - (next slide)
  4. **Russian roulette** – randomized absorption (termination)
     - (next slide)
- **Objective**
  - Keep the photon flux close to its original value

Photon tracing



3. **Update photon flux**

$$\Phi_{p,j+1}^{tentative} = \Phi_{p,j} \frac{f_r(\mathbf{x}, \omega_o \rightarrow \omega_i) \left|\cos\theta_o\right|}{p(\omega_o)}$$

4. **Russian roulette** – randomized photon absorption

$$q_{p,j+1} = \min\left\{1, \frac{\max_{r,g,b}[\Phi_{p,j+1}^{tentative}]}{\max_{r,g,b}[\Phi_{p,j}]}\right\}$$

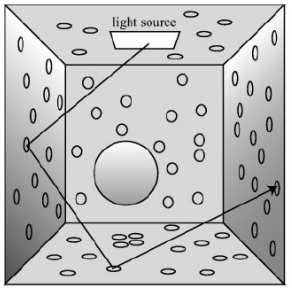
Survival probability

$$\Phi_{p,j+1} = \frac{\Phi_{p,j+1}^{tentative}}{q_{p,j+1}}$$

Updated photon flux on survival

- The above strategy keeps the photon flux roughly constant

Photon tracing

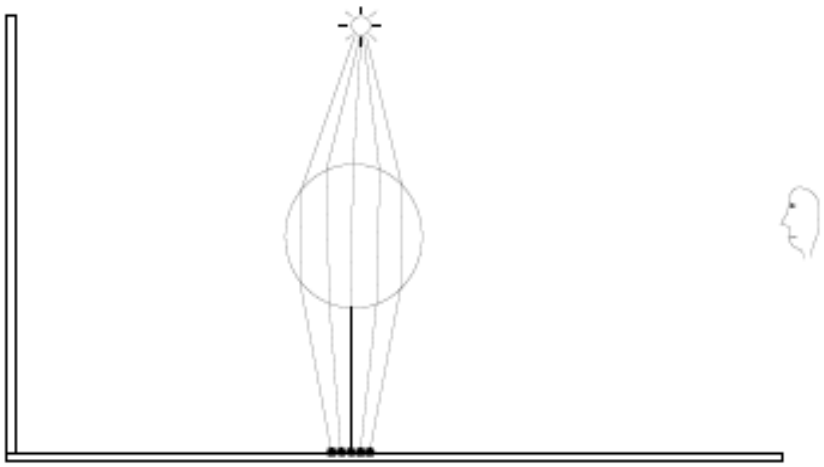


- Attention to **light refraction**
  - Recall: When tracing **paths from the camera**, we need to **update radiance** according to the 2nd power of the relative IOR
  - But photon do not carry radiance but flux – **no flux change upon refraction**

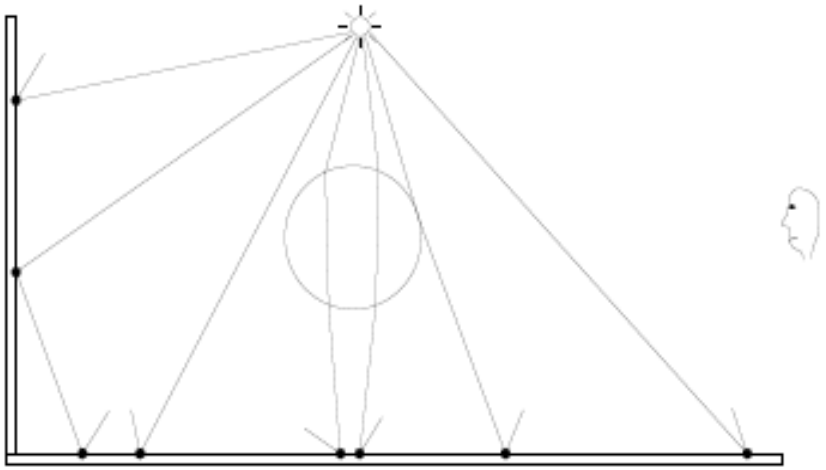
Photon map

- **Storage of photons** into a photon map
  - Upon each interaction of a photon with a diffuse (or moderately glossy, but not mirror) surface (even on absorption)
- **Photon map**
  - A simple linear list of photons during photon tracing
  - After photon tracing, we build a *kD*-tree for faster search
- **Photon**
  - position: $\mathbf{x}_p = (x, y, z)$
  - incident direction: $\omega_p = (\theta, \phi)$
  - energy (flux): $\Phi_p = (r, g, b)$
- Number of photons: $10^6 – 10^7$ sufficient in many scenes

Two photon maps



Caustics map



Global map

Two photon maps

1. **Global map**: **L[S|D]*D**
   - Contains even direct illumination
2. **Caustics map**: **$LS^{+}D$**
   - Contains indirect illumination only
   - Is a subset of the global map

- Different use of the two maps in image rendering
  - It's more advantageous to keep them separate

- **Light path grammar**

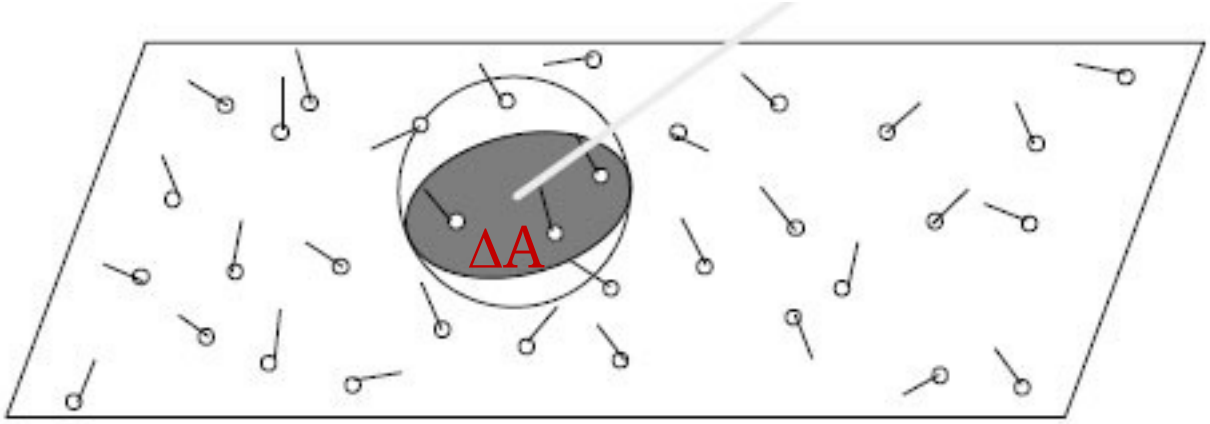
  E … eye, L … light, D … diffuse, S … specular

  G … glossy (often included in D)

Getting the photon maps ready for rendering

- During photon tracing, photons are simply appended into a linear list
- After that, we build a **spatial search acceleration structure**
  - In rendering we need to quickly locate *k* nearest photons
  - **kD-tree** or **hashed uniform grid**

Radiance estimate from a photon map



k .. #photons around **x**

incident direction of photon p

$$L_r(\mathbf{x},\omega_o) \approx \sum_{p=1}^{k} f_r(\mathbf{x},\omega_p,\omega_o)\frac{\Phi_p(\mathbf{x},\omega_p)}{\Delta A}$$

$$\approx \frac{1}{\pi r^2}\sum_{p=1}^{k} f_r(\mathbf{x},\omega_p,\omega_o)\Phi_p(\mathbf{x},\omega_p)$$

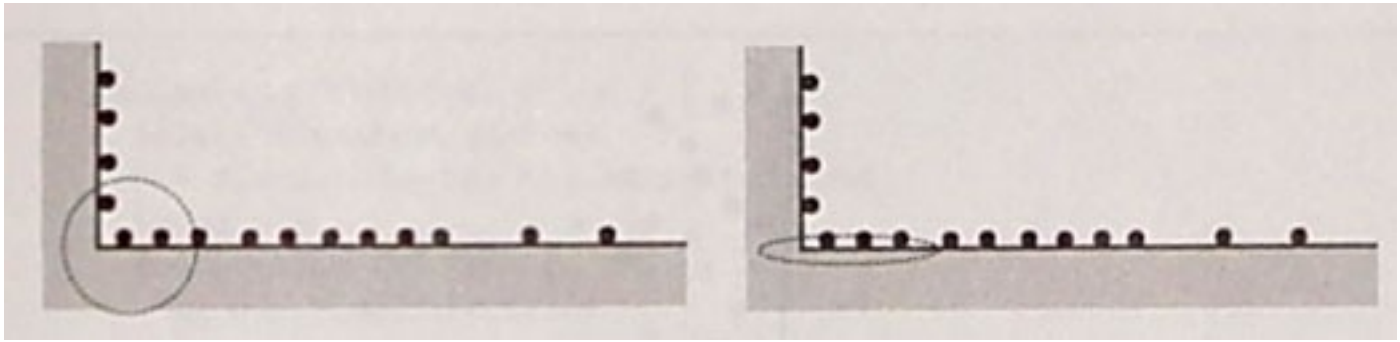
Surface area of ΔA

Radiance estimate from a photon map

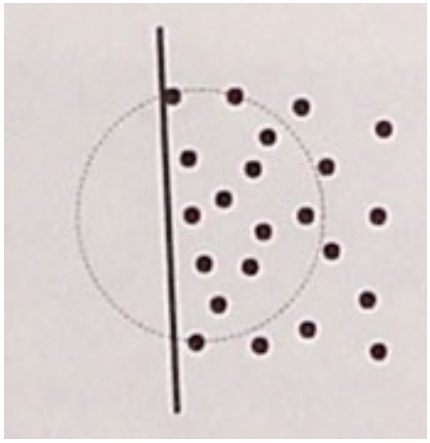
```
RadianceEstimate(x, wo):
   Color L = (0,0,0);
   int k = locateNearestPhotons(x, wo, nearest, r);
   // ‘nearest’ is an array of k nearest photons to x
   // r is the distance from x to the farthest of them
   if ( k < 5 ) return L;
   for p = 1 to k do
   {
      if( dot ( nearest[p].wi, N) <= 0 ) continue;
      L += fr(x, wo, nearest[p].wi) * nearest[p].flux;
   }
   return L / (M_PI * r*r);
```

Radiance estimate – issues

- Incorrect photons included in the search



- Incorrect estimate of the surface area ΔA
  - Next to a wall,
    a caustic or geometry edge



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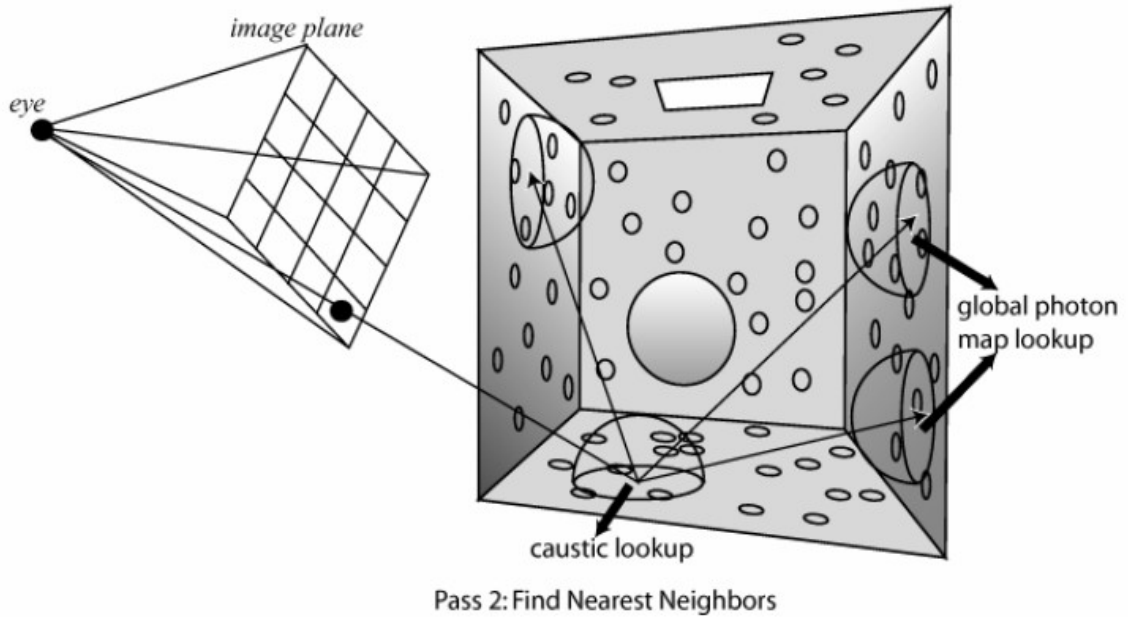
Fast search of nearest photons

- Needed for the radiance estimate
- Search of the nearest photons is an instance of

k-nearest neighbor search (k-NN)

Phase 2: Rendering with photon maps

- **Distributed ray tracing** from the camera
  - Recursion replaced by a photon map lookup
  - For highly specular surfaces we still use recursion as in classic path tracing



Reflected radiance calculation

- Reflected radiance: this is what we want to calculate

$$L_r(\mathbf{x}, \omega_o) = \int_\Omega L_i(\mathbf{x}, \omega_i)\, f_r(\mathbf{x}, \omega_i \rightarrow \omega_o) \cos\theta_i \, \mathrm{d}\omega_i$$

- Split the incoming radiance

$$L_i = L_{i,d} + L_{i,c} + L_{i,l}$$

- Split the BRDF

$$f_r = f_{r,D} + f_{r,S}$$

	$f_{r,D}$	$f_{r,S}$
$L_{i,d}$	direct illumination	highly specular reflections / refractions
$L_{i,c}$	caustics **(PM)**	
$L_{i,l}$	diffuse indirect **(FG +PM)**	

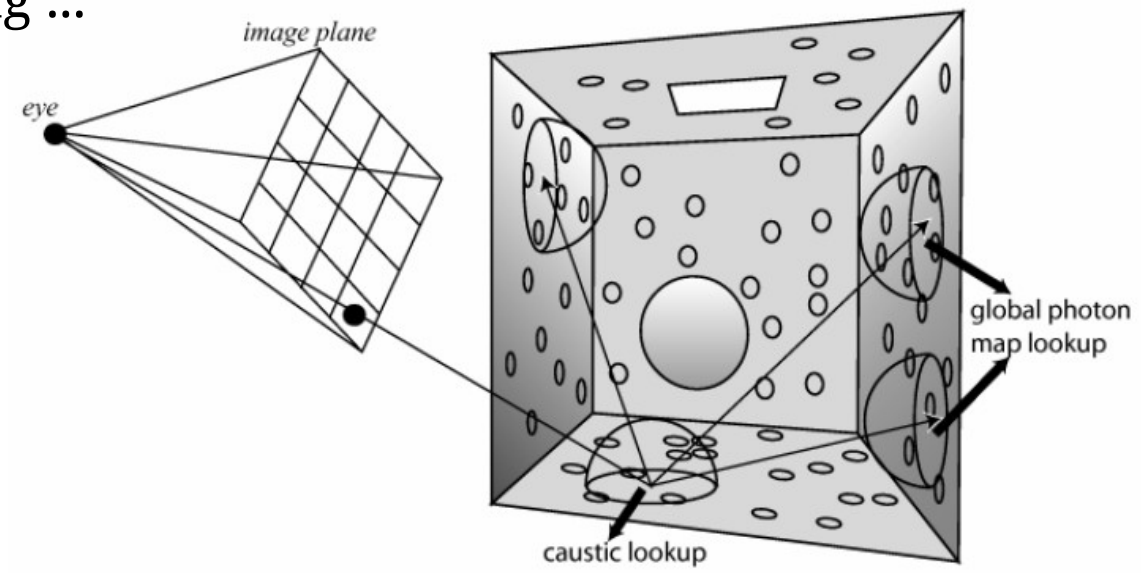
PM … photon map
FG … final gathering

Reflected radiance calculation

- When not using photon maps
  - Direct illumination
    - As usual: light source area sampling + shadow rays
  - Ideal mirror reflections / refractions
    - As usual: deterministic secondary rays

Illumination calculation for a primary ray (or after a mirror reflection)

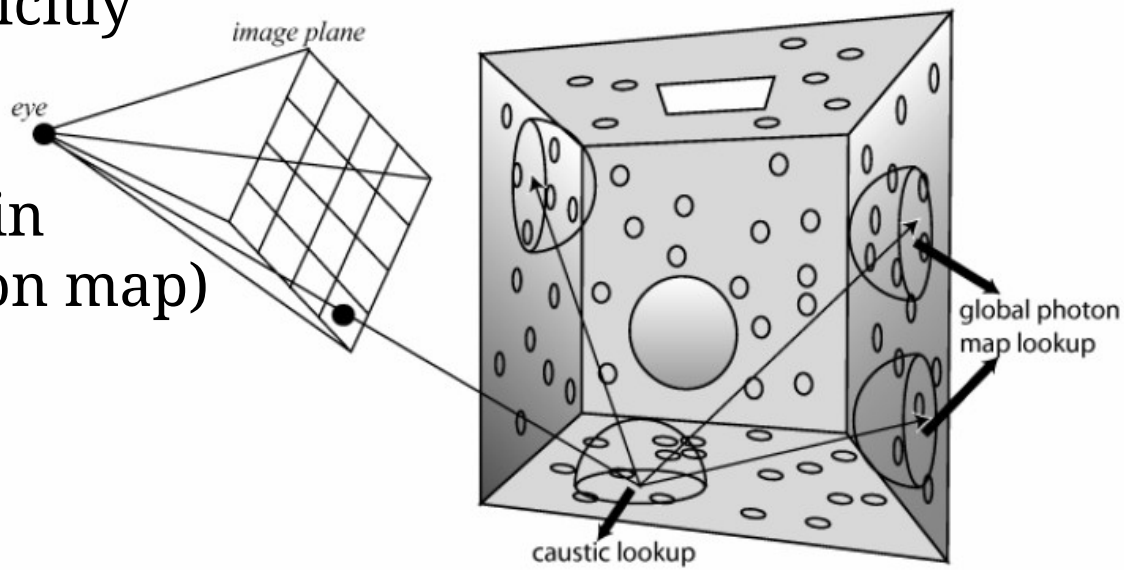
- Using the photon map
  - Caustics
    - Radiance estimate from the **caustic photon map**
  - Indirect illumination on diffuse or moderately glossy surfaces
    - Final gathering ...



[Dutré, Bekaert, Bala]

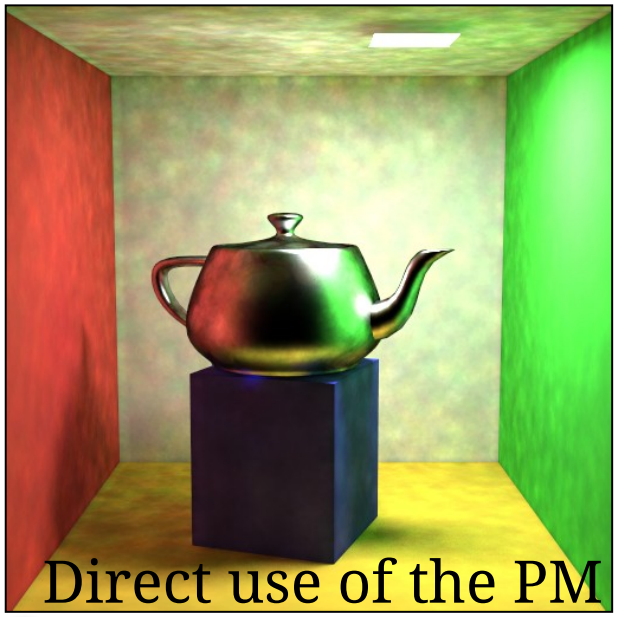
Final gathering (FG)

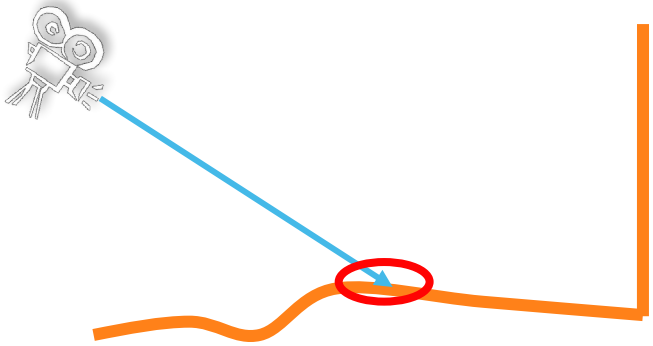
- Indirect illumination on diffuse and moderately glossy surfaces
- One level of recursion as in distributed ray tracing (i.e. path tracing with massive splitting)
- For the intersection of secondary rays, use radiance estimate from the **global photon map**
  - No need to explicitly calculate direct illumination (it is contained in the global photon map)

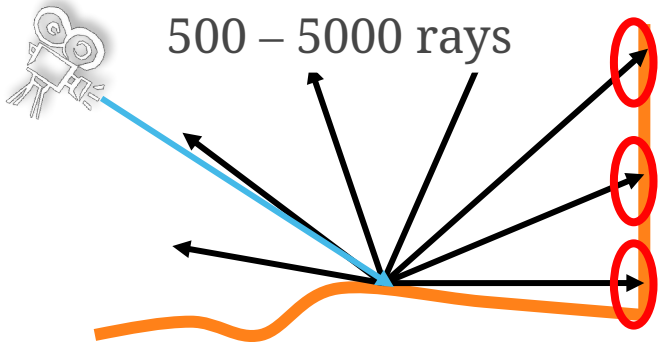


[Dutré, Bekaert, Bala]

Why do we need final gathering?







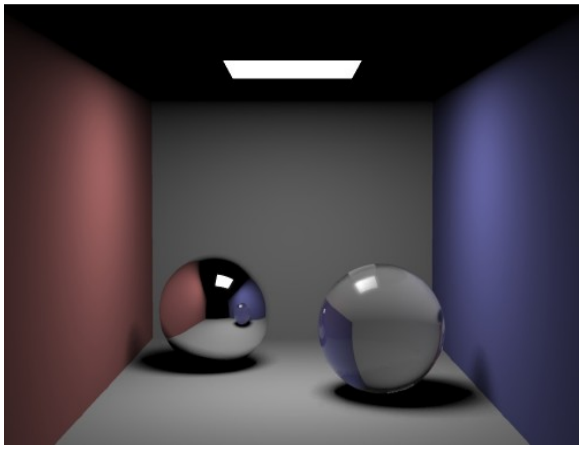
Information in the global photon map is too noisy for a direct use

Inaccuracy in the global photon map is “averaged out”

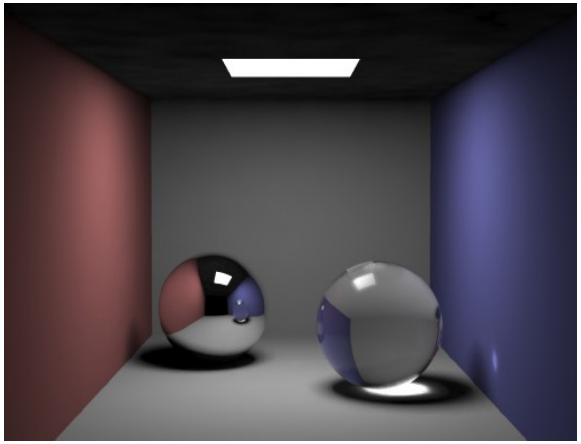
Why is there no final gathering for caustics?

- Caustics = light focusing => sufficient photon density (beware, it's just a heuristic, may not always work well)

Results

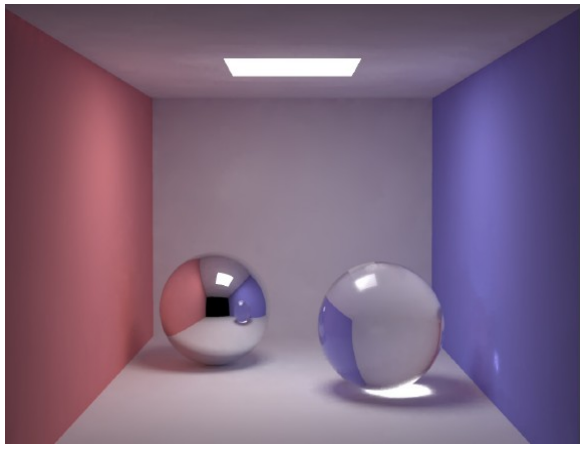


Direct illumination
(21 s)



Caustics
(45 s)

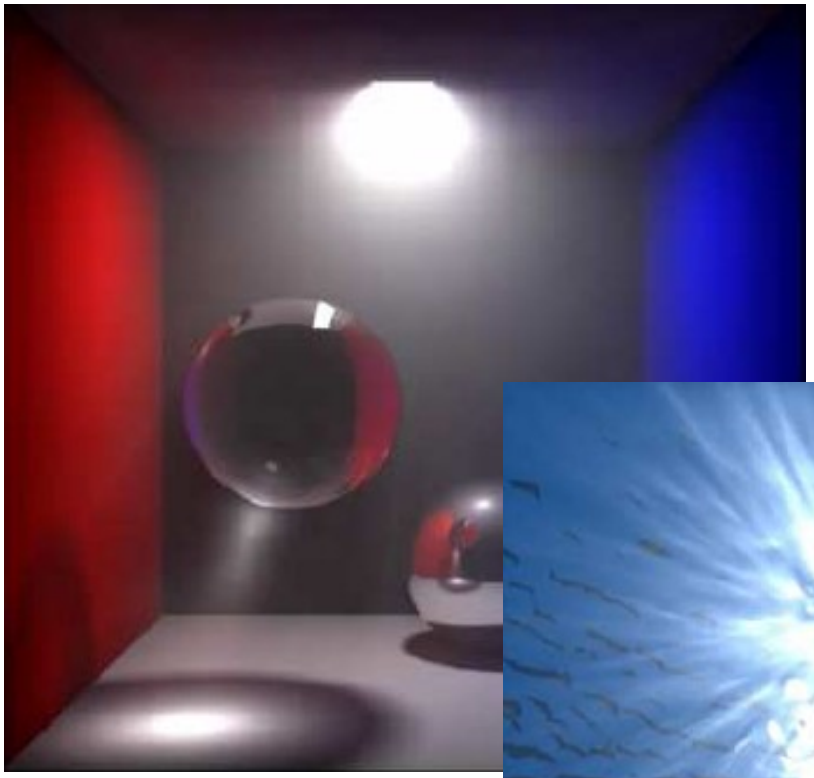
50 000 photons
in the caustic map

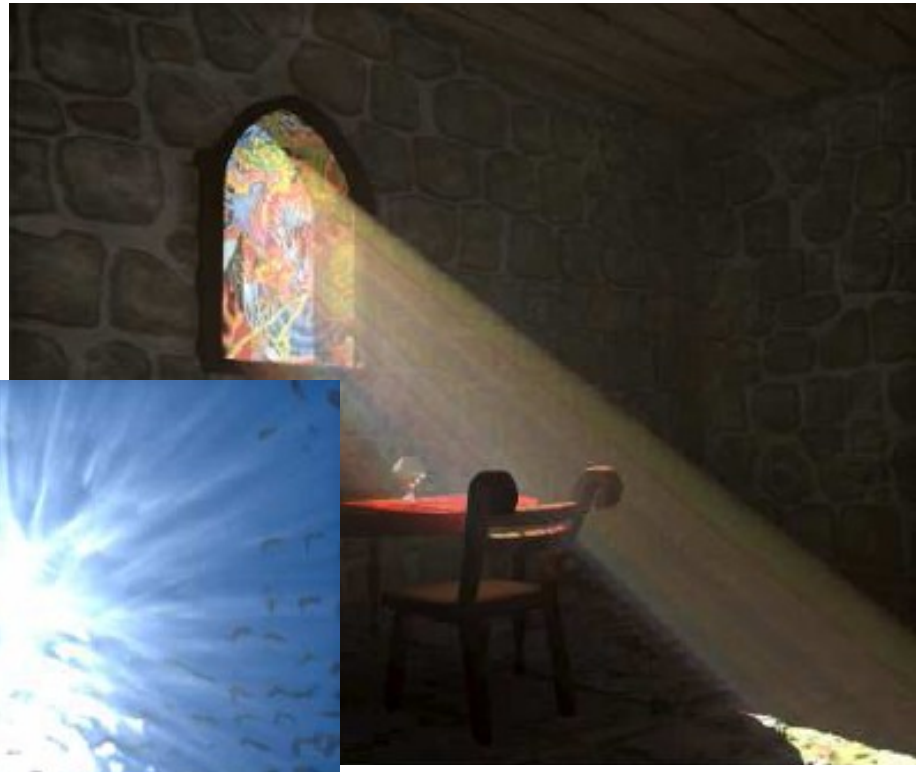


Global illumination
(66 s)

200 000 photons
in the global map

Photon mapping can be easily extended to handle scattering in media





Henrik Wann Jensen

… and subsurface scattering

Photon mapping problems

Does not work well on glossy surfaces

So, what's wrong?

Radiance estimate from the photon map on a glossy

Theoretical problems of photon mapping

- Result is not unbiased
  - Contains systematic error

- Result is **consistent**
  - It theoretically converges as the photon count goes to infinity
  - But this is practically unachievable
  - Solution: **progressive photon mapping**