Photon-Mapping

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Basics of Photon-mapping

Based on **light/photon tracing**

- arbitrary **scene geometry**
- utilization of efficient (long-term optimized) **ray-casting libraries, acceleration techniques,** etc.

Light is traced both **forwards** (from sources) and **backwards** (from the camera)

- camera represents importance (potential)
- lights are sources of photons

Separation of scene geometry and representation of light

- 3D scene can be very complex
- light representation can be optimized independently

Photon Map

Data structure – **impacts of individual photons**

- represents even very varying light conditions
- completely separated from scene geometry
- memory efficient

“Caching paths of bi-directional Path-tracing“

- light estimate is free of HF noise
- … much faster than classical Monte Carlo techniques (equal quality)

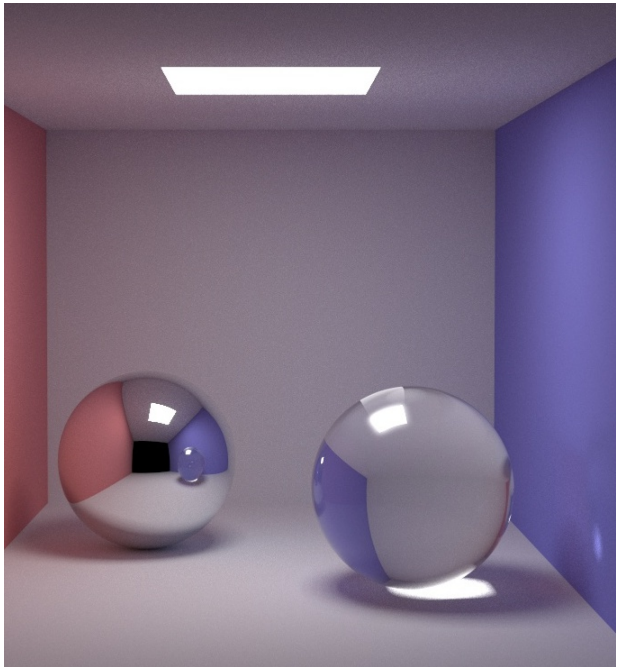
Biased method !

- but **consistent** (converges to better result)

Algorithm scheme

Photon-tracing

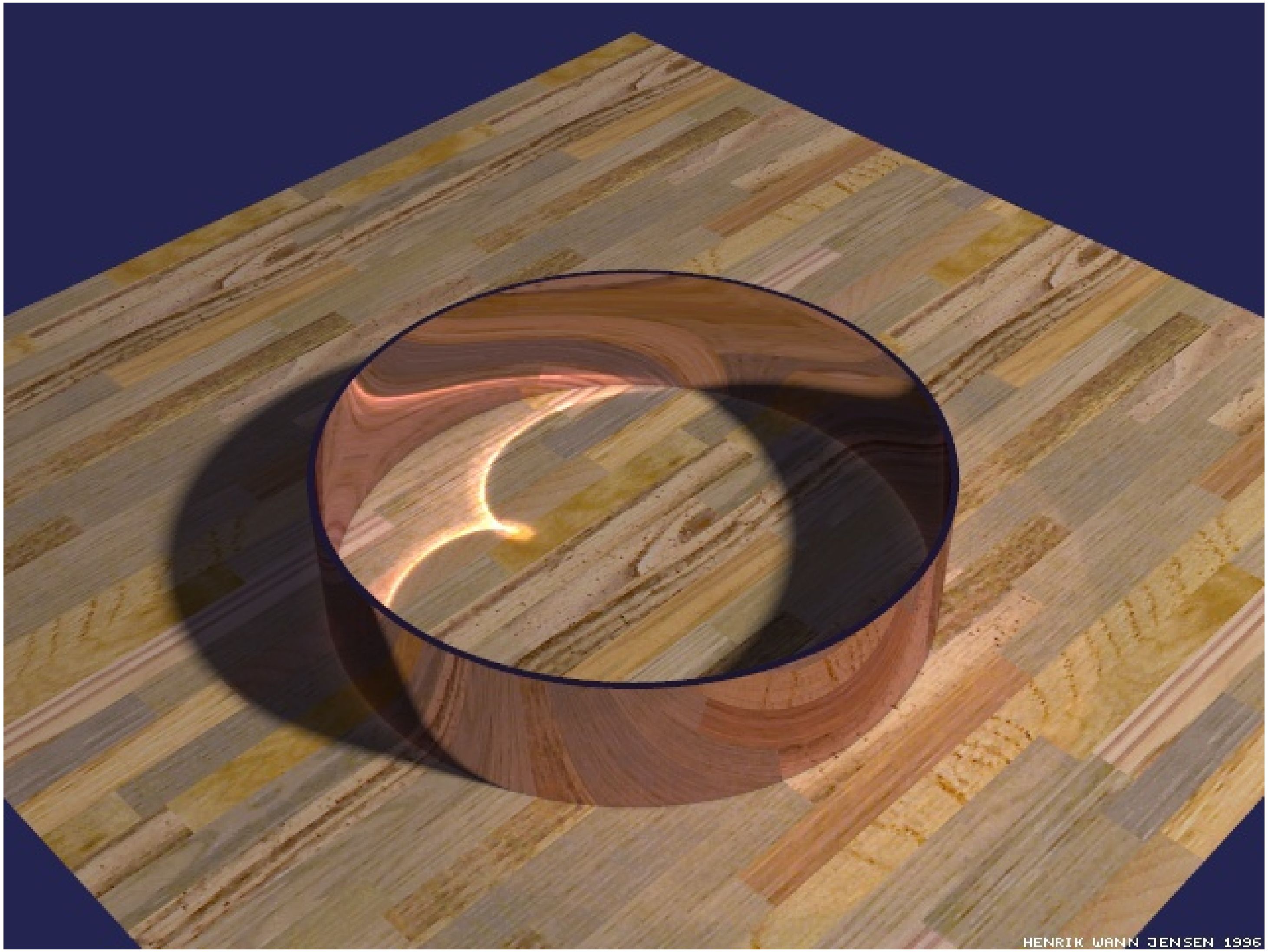
- photons are generated by light sources,
- propagated to the scene (Monte-Carlo)
- and finally stored in photon maps (**global maps** for smooth changes and **caustic maps** for sharp edges)



Rendering

- photon maps are used for efficient rendering of the scene
- plain Ray-tracing or
- a Monte Carlo method (Path-tracing)

Photon-mapping – examples



Photon-mapping – examples

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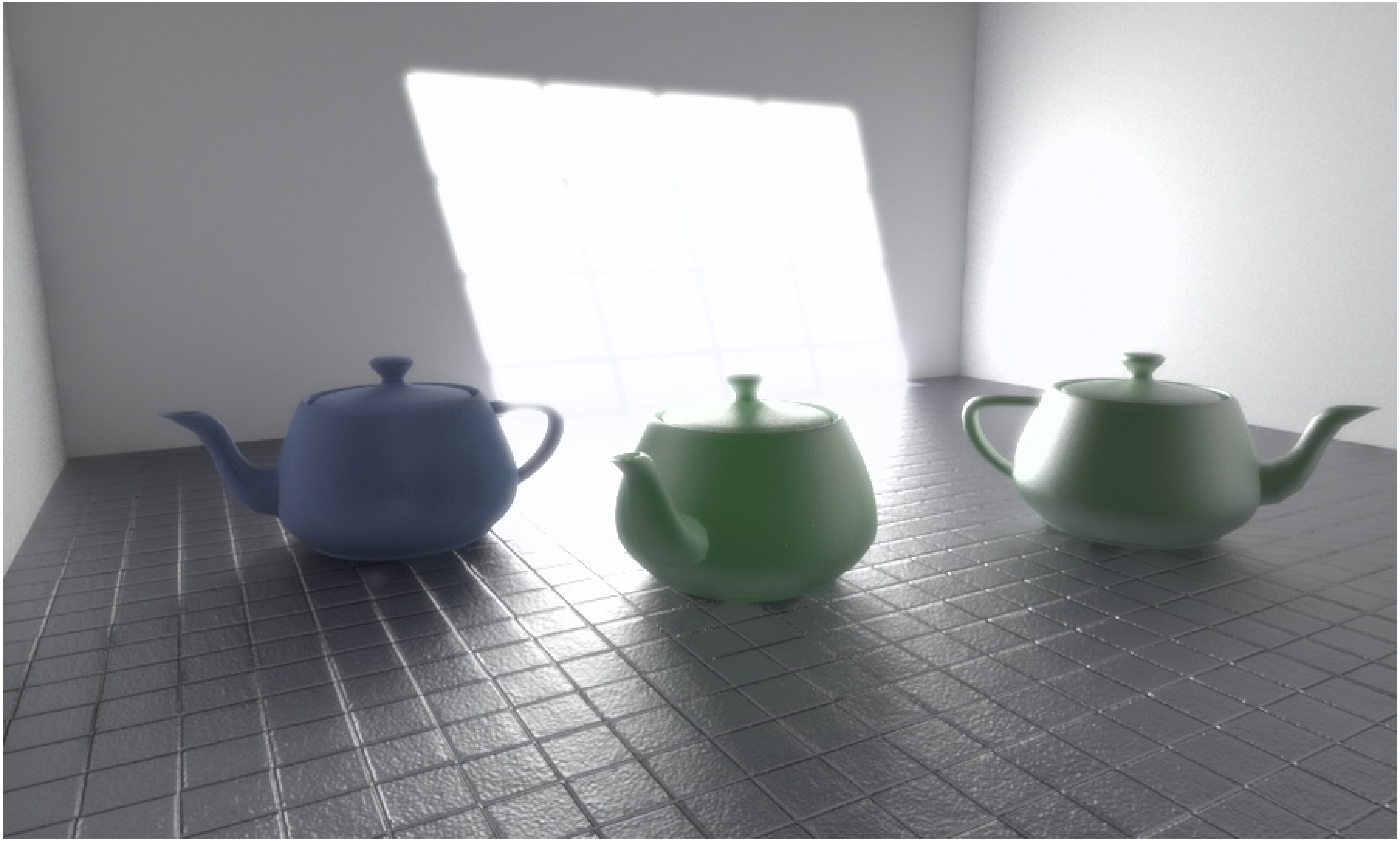
Photon-mapping – examples

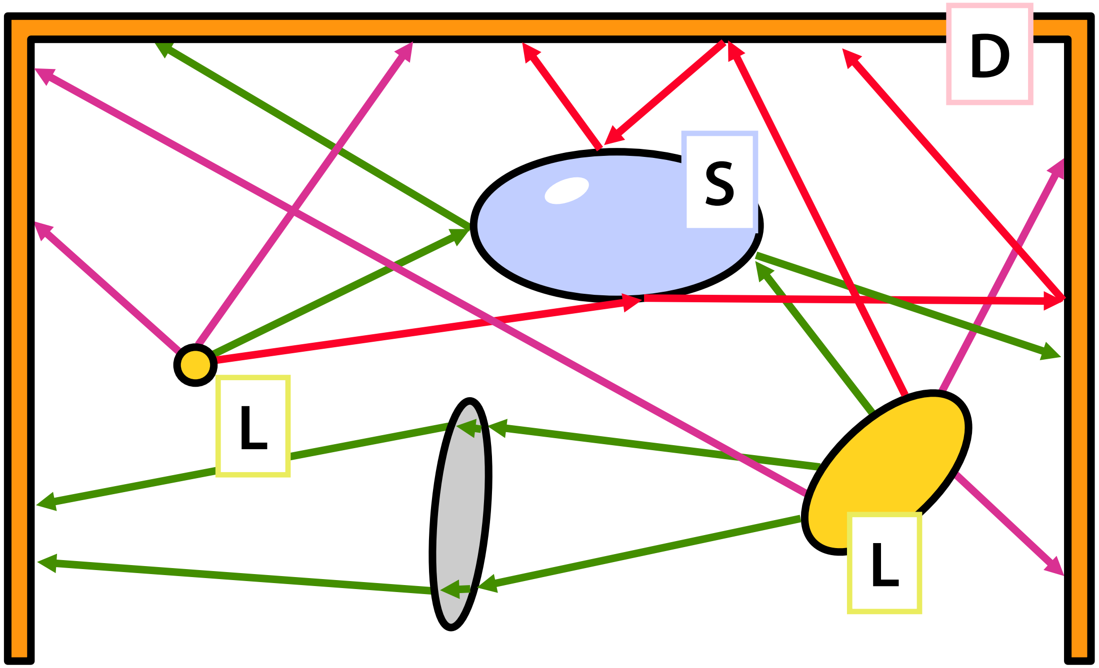


Photon-tracing

Photons are generated by light sources,

Randomly propagated through the scene and

Stored in photon maps



Photon generation

The most elegant approach – each photon carries **the same light energy**

Random sampling of light sources

- ”rejection sampling“ for difficult distributions

More light sources…

- distribution among them (based on their total contribution)

Efficient sampling

- pre-computed **projection maps** (see acceleration of Ray-tracing)

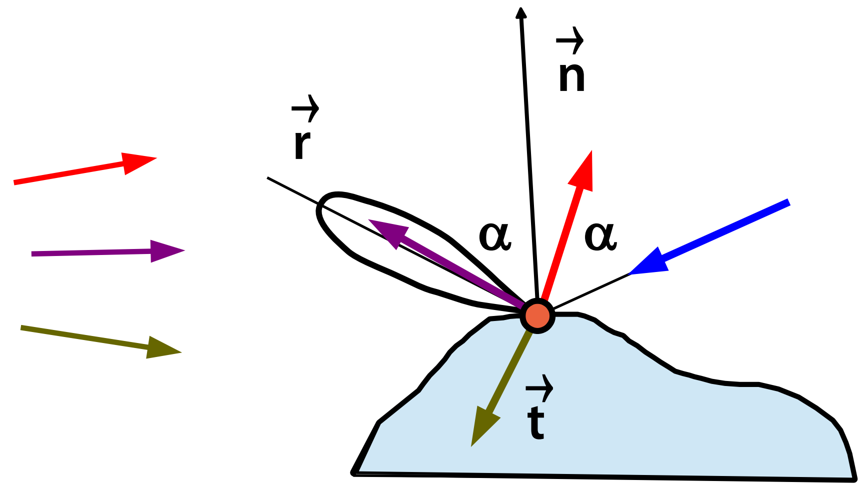
Photon scattering

Refraction and reflection should alter (reduce) **photon energy**

- photon map would contain nonequivalent entries

Keeping constant photon energy … **Russian roulette**

- photon is (randomly) **bounced with original energy** or **terminated**
- **three options**
  - » 1. diffuse reflection (D)
  - » 2. specular reflection (S, S_M)
  - » 3. refraction
  - » on every diffuse surface: photon-map contribution



Data structure for photon map

Photon

- impact **position** (float[3])
- impact **direction** (float[2] or compression into int8[2])
- photon **energy** (RGB, spectrum or RGBE = int8[4])
- tree construction attributes/flags (e.g. “splitting plane“)

The photon map has to be **very fast** event for very high **number of records**

- 10^5 to 10^7 individual records
- crucial operation: **fast nearest neighbor lookup**
  - » K nearest or all records in the given radius R
- **KD-trees** work well (binary, data in all nodes)

KD-tree

In the construction phase records are only gathered, it needs to be **balanced before actual usage**

Optimization for geometric lookup

- **splitting plane** can be determined from maximum range or variance
- stored in an array – **without pointers** !

à la **Jensen**

- heap-like system (descendants have indices: **2i**, **2i+1**)

à la **Hooley** ("cache-friendly")

- the median is fixed, two segments are heap-sorted

Nearest neighbor lookup

The heap for branches not yet visited

Pruning based on

- current distance of K-nearest neighbor photon (KNN approach)
- required radius of interest R

Radiance estimate I

Emitted radiance from **x**

$$L_r(x,\omega_o) = \int_{\Omega} f_r(x,\omega_i \to \omega_o) \cdot \underline{L_i(x,\omega_i)} \cdot \cos\theta_i \, d\omega_i$$

Expressed using **radiant flux**

$$L_r(x,\omega_o) = \int_{\Omega_x} f_r(x,\omega_i \to \omega_o) \cdot \frac{\partial^2 \Phi_i(x,\omega_i)}{\partial A_i}$$

Radiance estimate II

Radiance estimate from **photon map** surrounding **x**
(looking for **n** nearest photons)

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

For **circular** neighborhood (n-th photon has distance **r**)

$$L_r(x,\omega_o) \approx \frac{1}{\pi r^2} \sum_{p=1}^{n} f_r(x,\omega_p \rightarrow \omega_o) \cdot \Delta\Phi_p(x,\omega_p)$$

Filtering on photon map

If the number of photons is too low, radiance estimate is blurry ("box filter")

- problem in case of a caustic map

Filter can accent samples in the middle

- cone filter
- Gaussian filter
- **differential control** – monitoring change of average value (or variance) while adding more photons, stop the process if changes are marginal

Global illumination I

Survey of previous formulae

$$L_o(x, \omega_o) = L_e(x, \omega_o) + L_r(x, \omega_o)$$

Reflected radiance

$$L_r(x, \omega_o) = \int_{\Omega_x} f_r(x, \omega_i, \omega_o) \cdot L_i(x, \omega_i, \omega_o) \cdot \cos\theta_i \, d\omega_i$$

BRDF components

$$f_r(x, \omega_i, \omega_o) = f_{r,d}(x, \omega_i, \omega_o) + f_{r,s}(x, \omega_i, \omega_o)$$

Global illumination II

Incoming radiance classification $\mathbf{L_i}$

$L_{i,l}(x,\omega_i)$	direct light from light source **L**
$L_{i,c}(x,\omega_i)$	caustics – light from source concentrated by reflection/refraction **L S⁺**
$L_{i,d}(x,\omega_i)$	indirect light reflected diffusely at least once **L S* D (D|S)***

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

Global illumination III

Reflected radiance (bounce point **x** was left out)

$$L_r(\omega_o) = \int_{\Omega_x} f_r(\omega_i,\omega_o)\cdot L_{i,l}(\omega_i,\omega_o)\cdot\cos\theta_i \, d\omega_i +$$
$$\int_{\Omega_x} f_{r,s}(\omega_i,\omega_o)\cdot\left(L_{i,c}(\omega_i,\omega_o)+L_{i,d}(\omega_i,\omega_o)\right)\cdot\cos\theta_i \, d\omega_i +$$
$$\int_{\Omega_x} f_{r,d}(\omega_i,\omega_o)\cdot L_{i,c}(\omega_i,\omega_o)\cdot\cos\theta_i \, d\omega_i +$$
$$\int_{\Omega_x} f_{r,d}(\omega_i,\omega_o)\cdot L_{i,d}(\omega_i,\omega_o)\cdot\cos\theta_i \, d\omega_i$$

Accuracy

“Accurate“ computation

- if point **x** is visible (in the result image) … or
- if it is visible via a couple of specular reflections … or
- if the ray is too short (eliminates “color bleeding“)

Approximate computation

- in all other cases
- … if there is at least one diffuse reflection
- … if the ray has too small performance/importance (accumulated reflection coefficient)

Direct light

Light coming directly from light sources

$$\int_{\Omega_x} f_r(\omega_i,\omega_o)\cdot L_{i,l}(\omega_i,\omega_o)\cdot\cos\theta_i\ d\omega_i$$

In Ray-tracing "shadow rays" are used

- multiple test rays for area light sources ("distributed R-T")

Accurate case: shadow rays or photon map

- speedup … photon map can store **"shadow photons"**

Approximate case: only global photon map is used

- no secondary rays

Mirror and specular reflection

Indirect light from specular BRDF component

$$\int_{\Omega_x} f_{r,s}(\omega_i,\omega_o)\cdot\left(L_{i,c}(\omega_i,\omega_o)+L_{i,d}(\omega_i,\omega_o)\right)\cdot\cos\theta_i\; d\omega_i$$

Classical Monte Carlo technique (“distributed R-T“)

- accuracy is sufficient even in demanding situations (direct visibility)
- for reasonable accuracy only a few reflected rays need to be computer

Caustics

Light from light source concentrated on diffuse surface

$$\int_{\Omega_x} f_{r,d}(\omega_i, \omega_o) \cdot L_{i,c}(\omega_i, \omega_o) \cdot \cos\theta_i \, d\omega_i$$

Accurate case: caustic photon map

- very high density of photons, accuracy is high (sharp caustics)

Approximate case: using global photon map

Multiple diffuse reflection

Light reflected diffusely multiple times

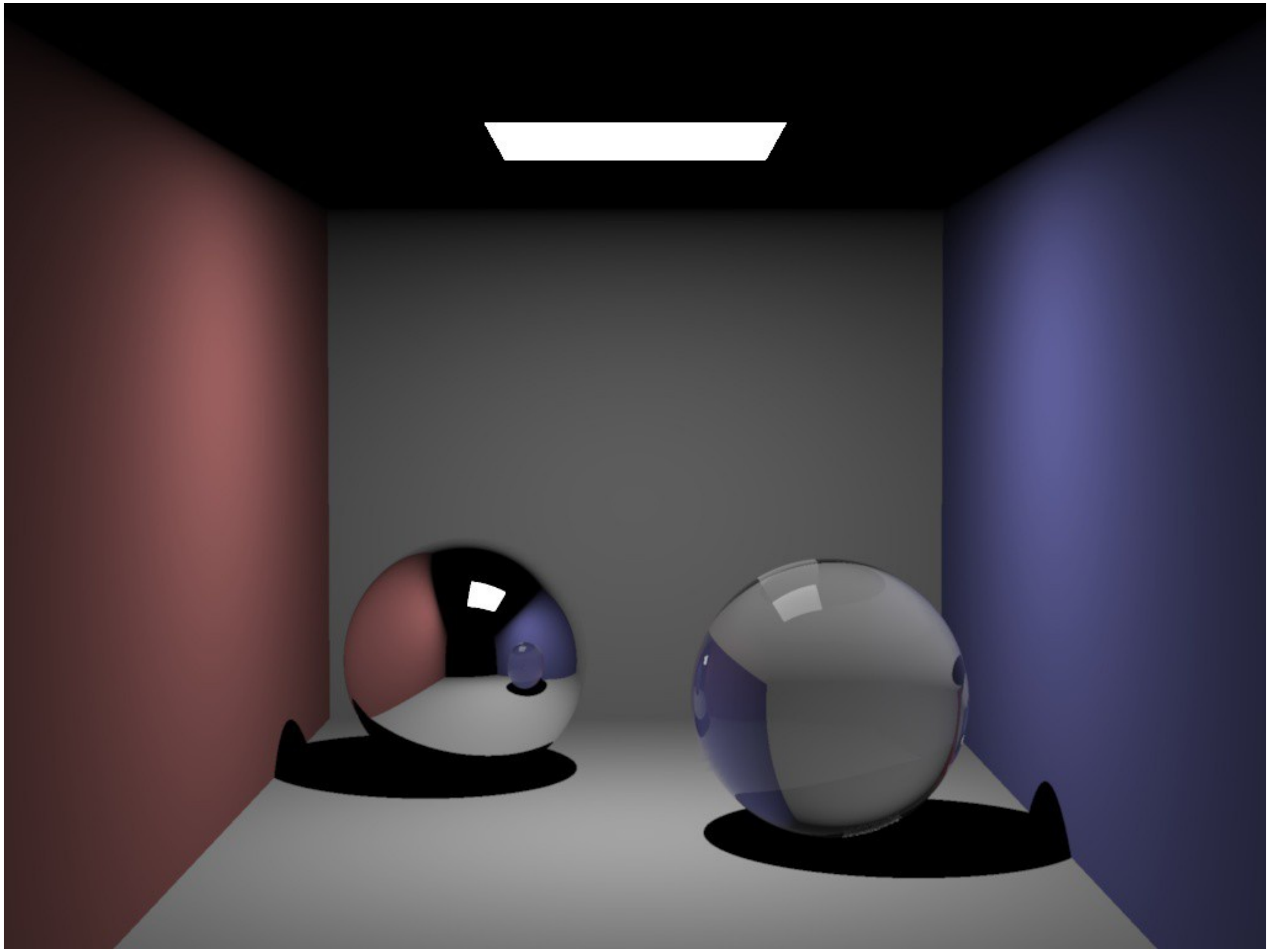
$$\int_{\Omega_x} f_{r,d}(\omega_i,\omega_o)\cdot L_{i,d}(\omega_i,\omega_o)\cdot\cos\theta_i \; d\omega_i$$

Accurate case: “distributed Ray-tracing“ (Monte Carlo)

- sampling optimized using global photon map (distribution of impact directions is known in the neighborhood)
- more speedup: “Irradiance caching“ (Ward 1988)

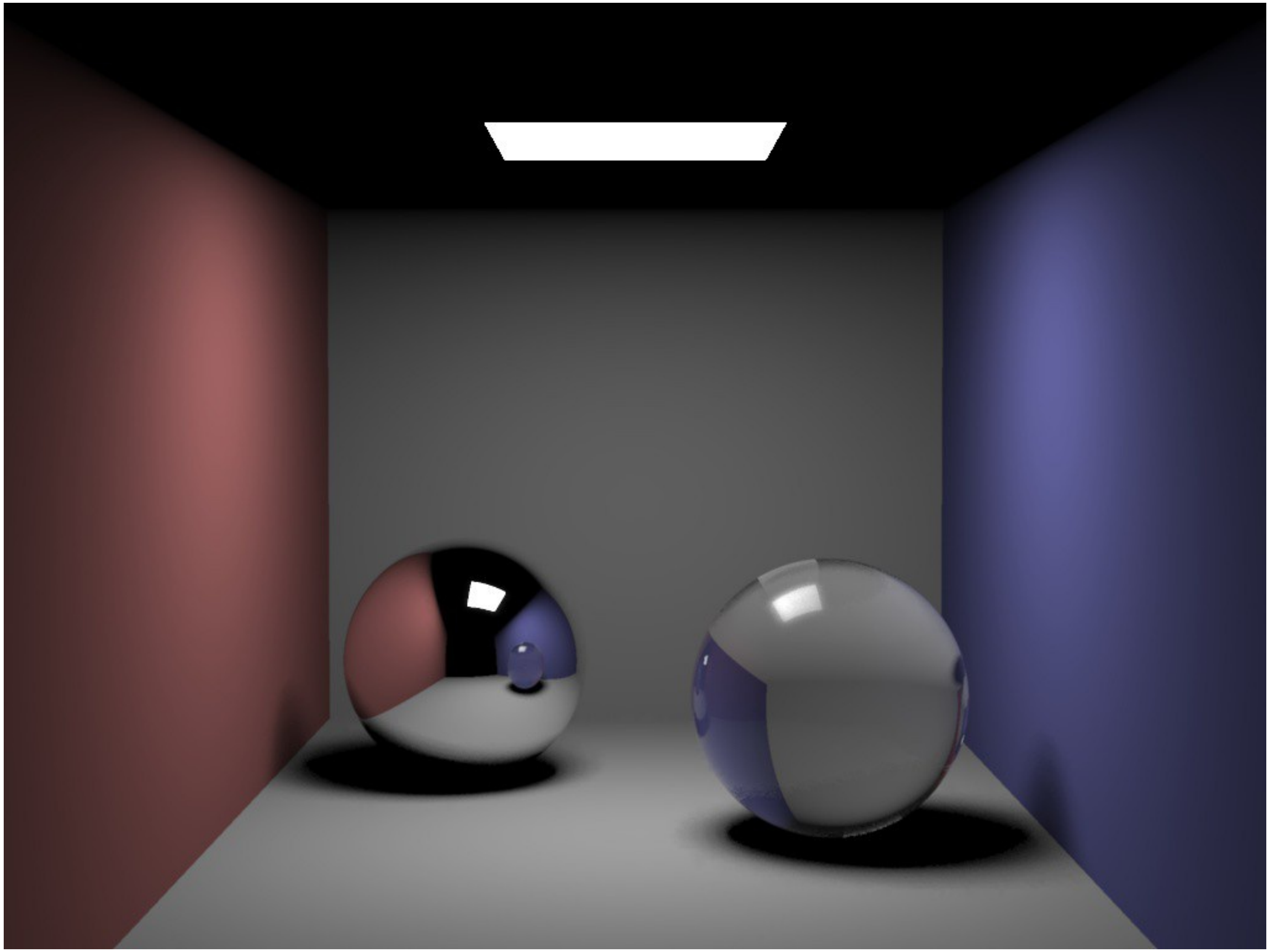
Approximate case: using global photon map

Samples – Ray-Tracing



3.5 sec

Ray-Tracing with soft shadows



21 sec

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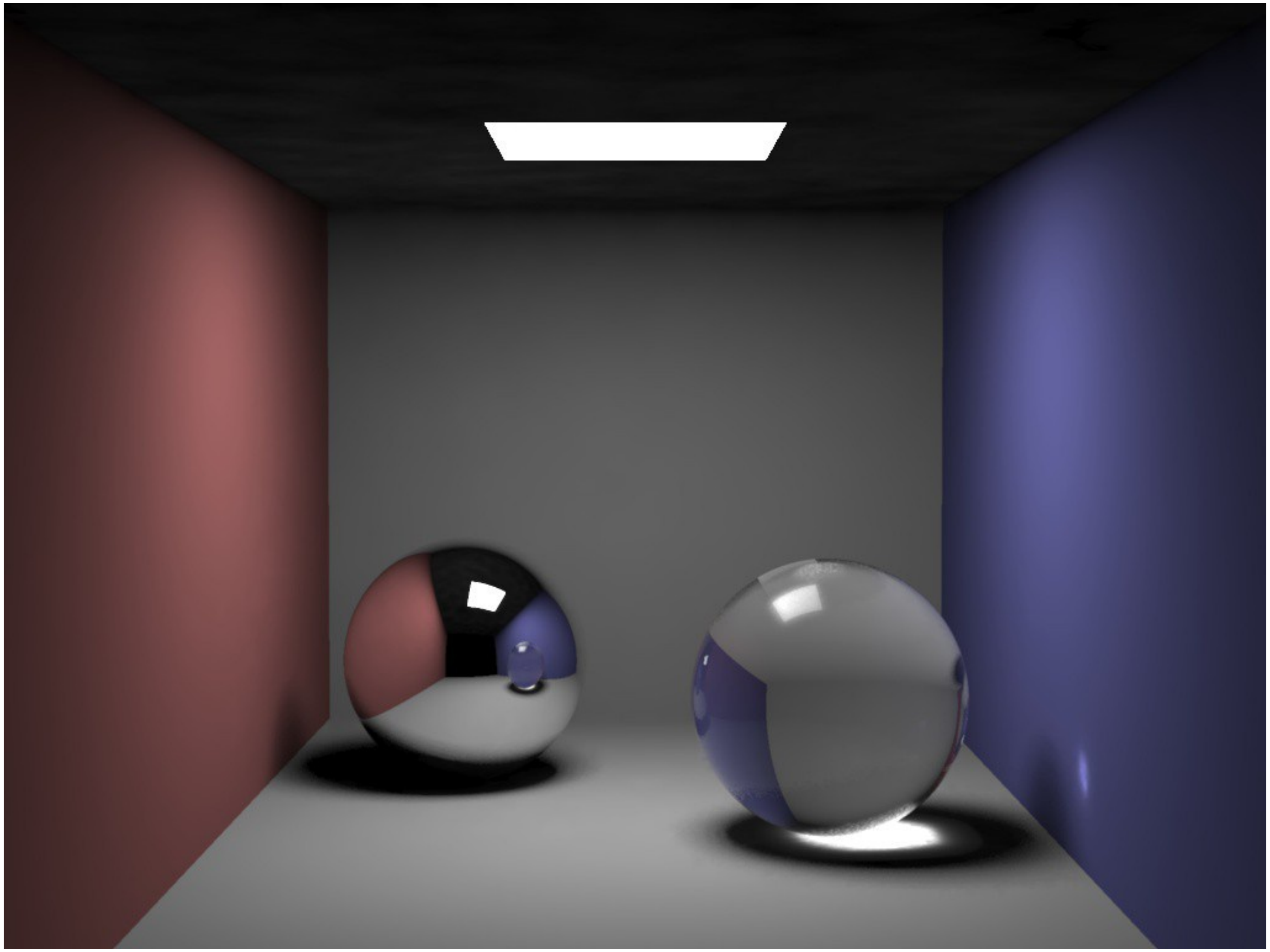
Ray-Tracing with caustics



2 + 34 sec (50k photons)

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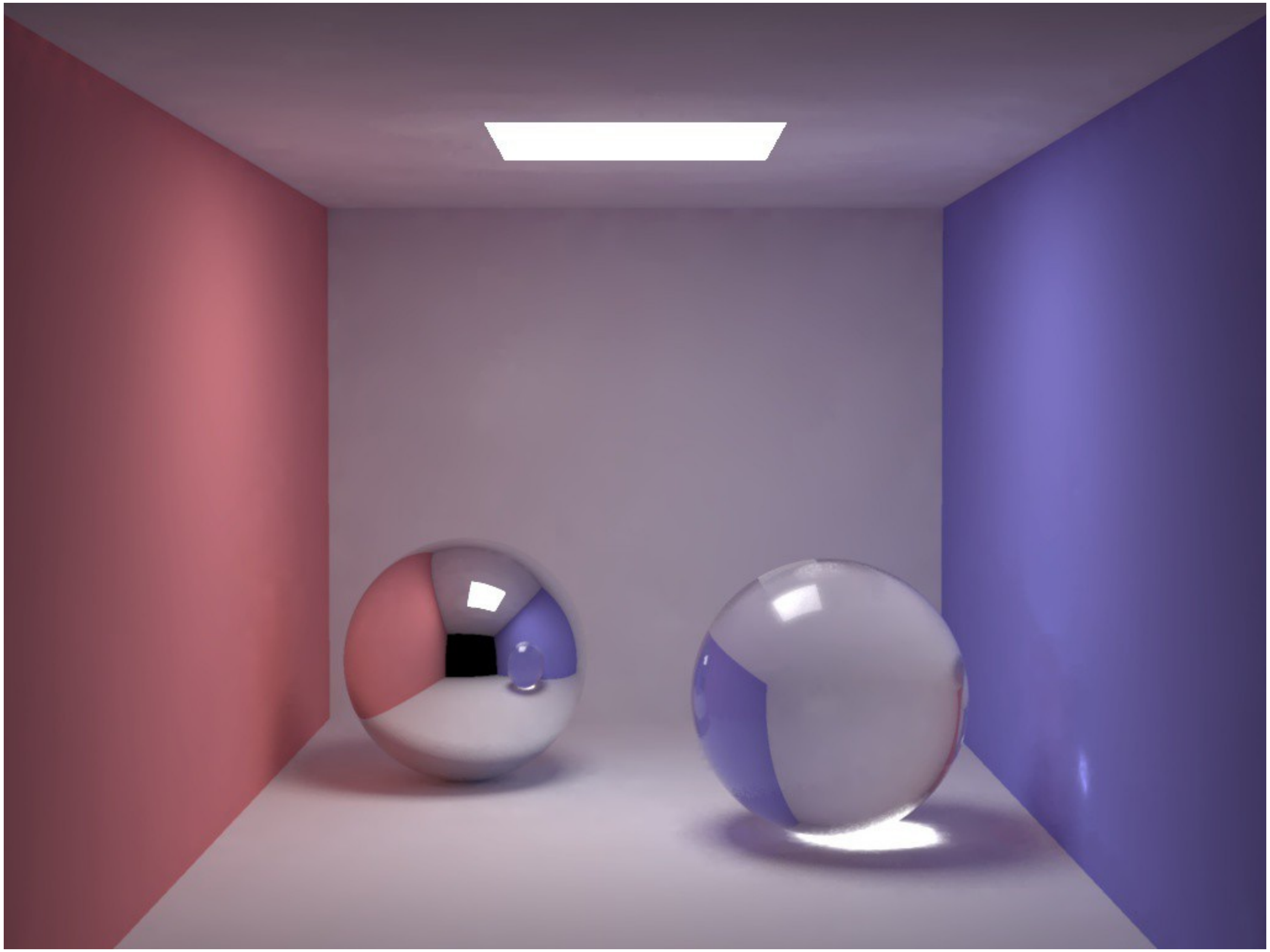
Photon-Mapping – Global illumination

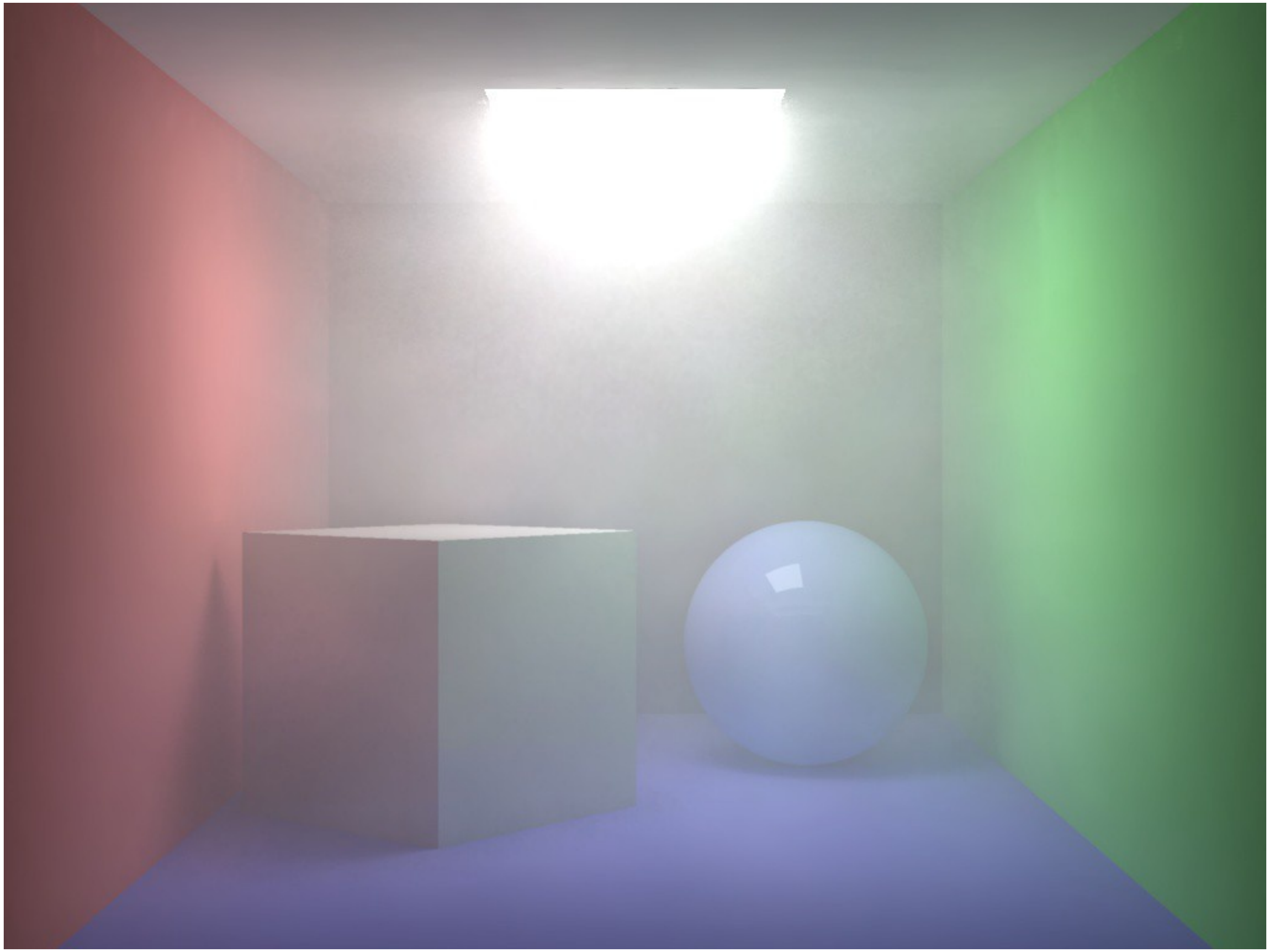


4 + 66 sec (50k caustics + 200k global)

Photon-Mapping + Water

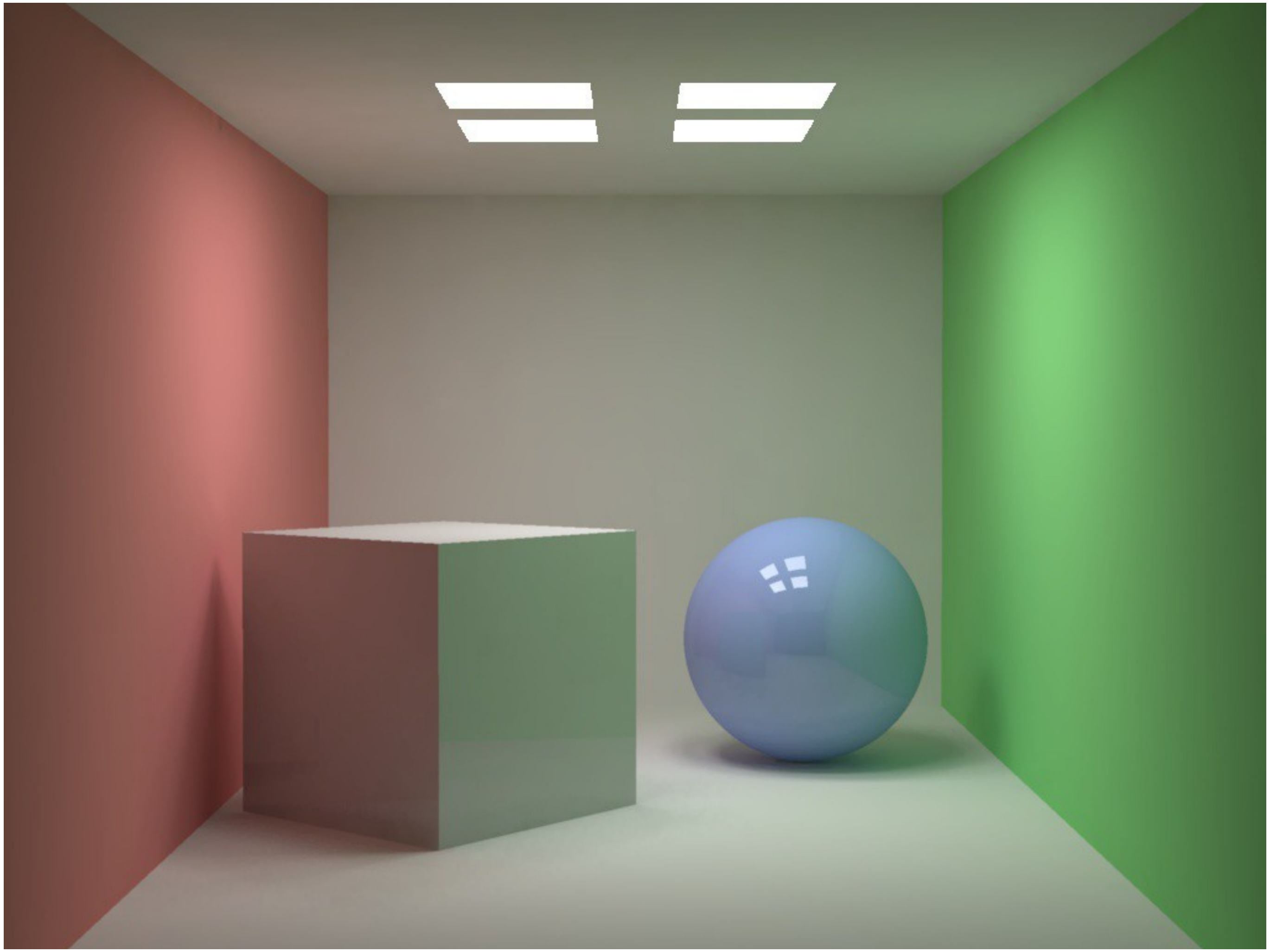
11 min (water – 500k photons)

Photon-Mapping + Fog



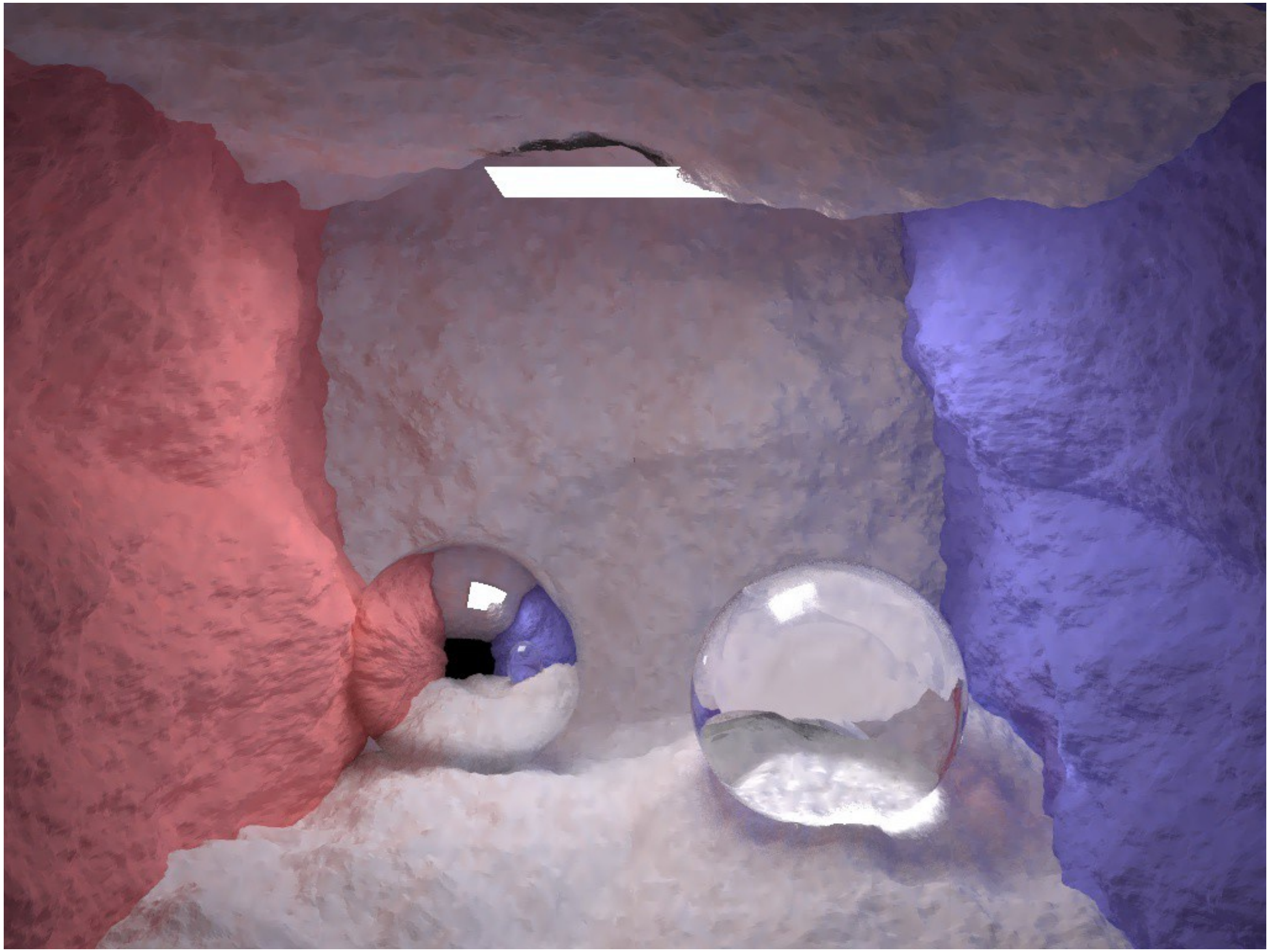
44 min (100k global + 150k volumetric)

Photon-Mapping – Four light sources



19 sec (100k photons for each light)

Photon-Mapping – Fractal surfaces



14 min (50k caustics + 200k global)

Example – Ray-tracing

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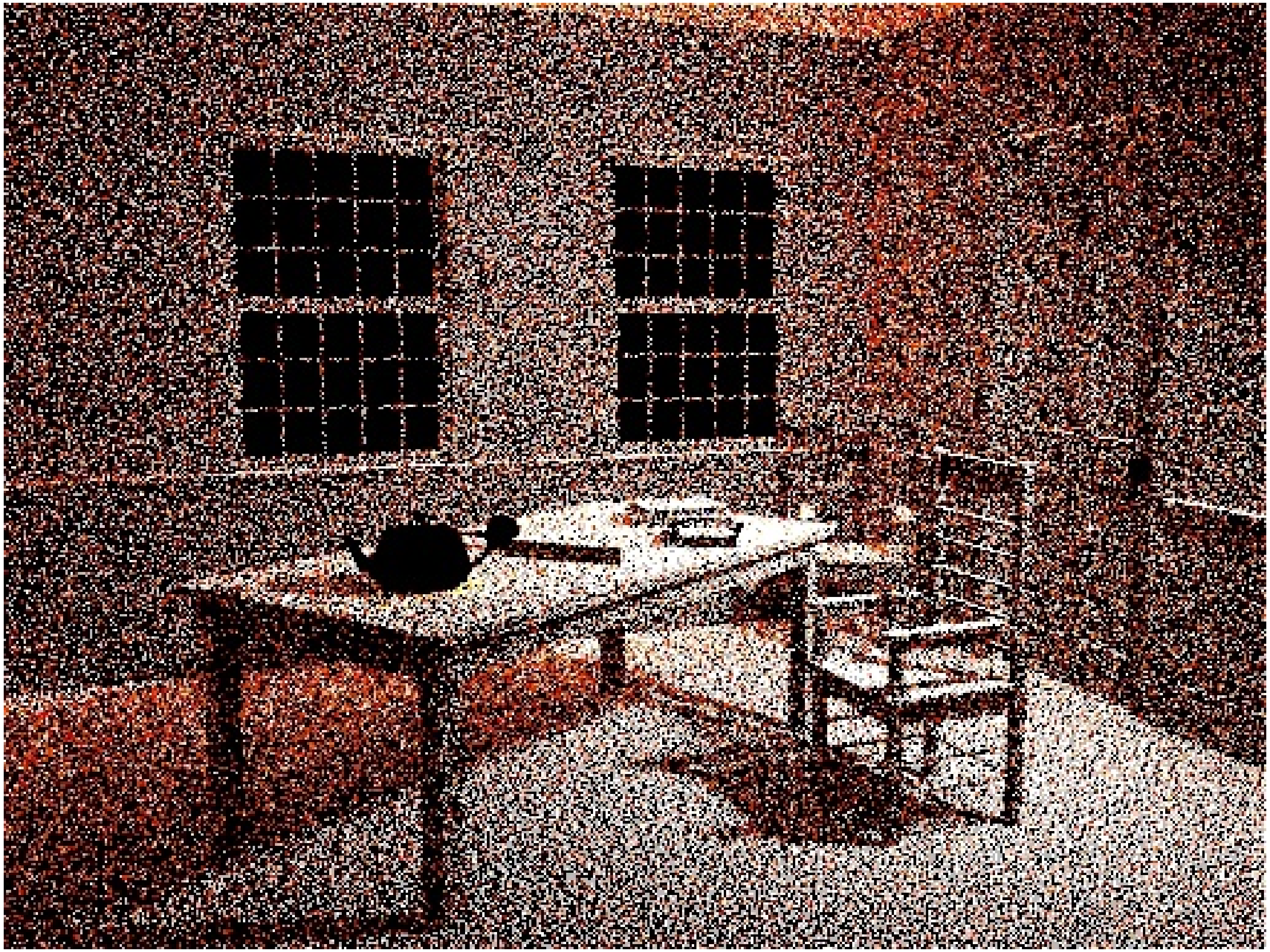
Example – Photon map



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Example – Radiance estimation (25% photons)

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Example – Complete global illumination

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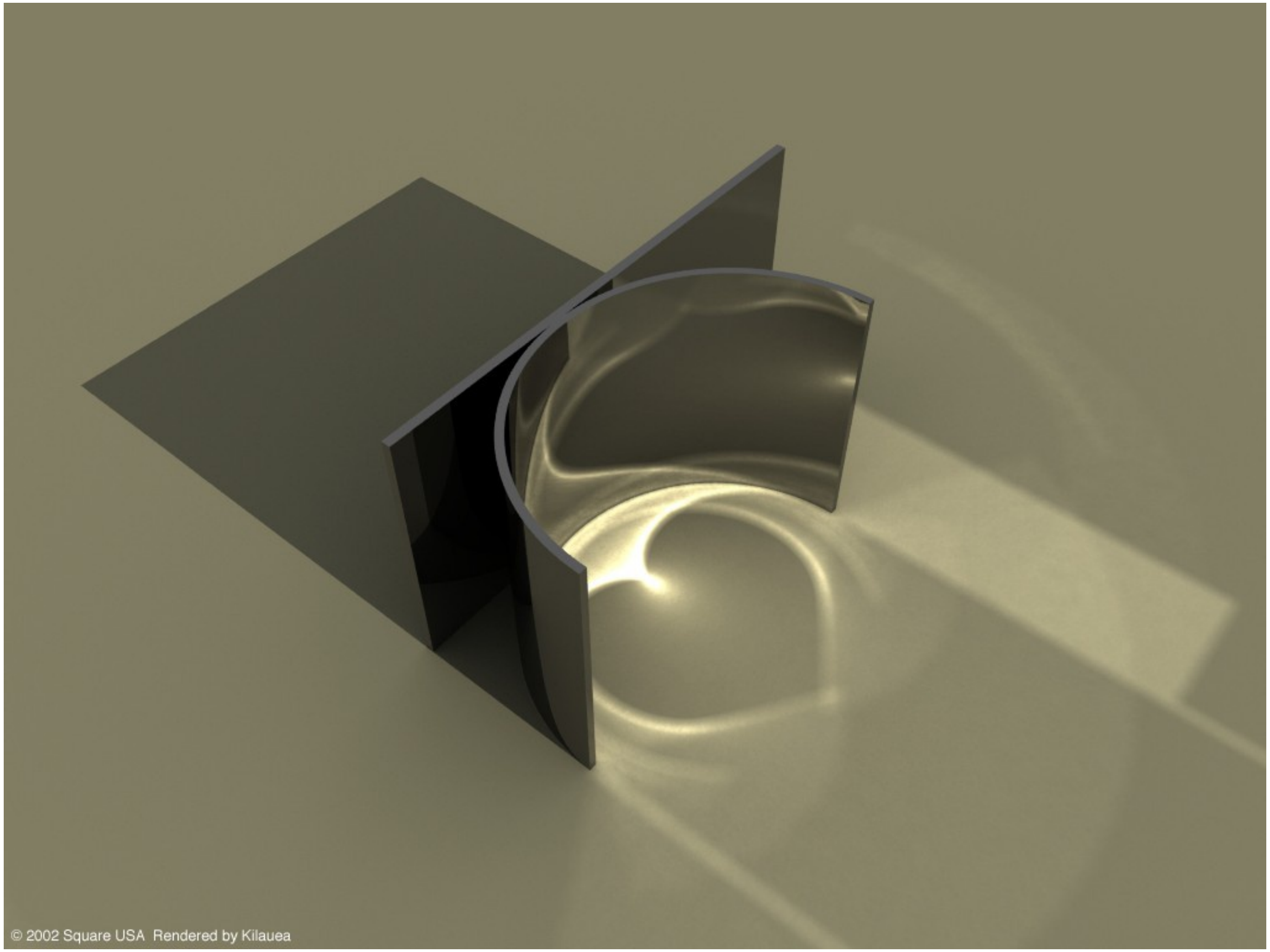
Photon-Mapping – Caustics (old code)

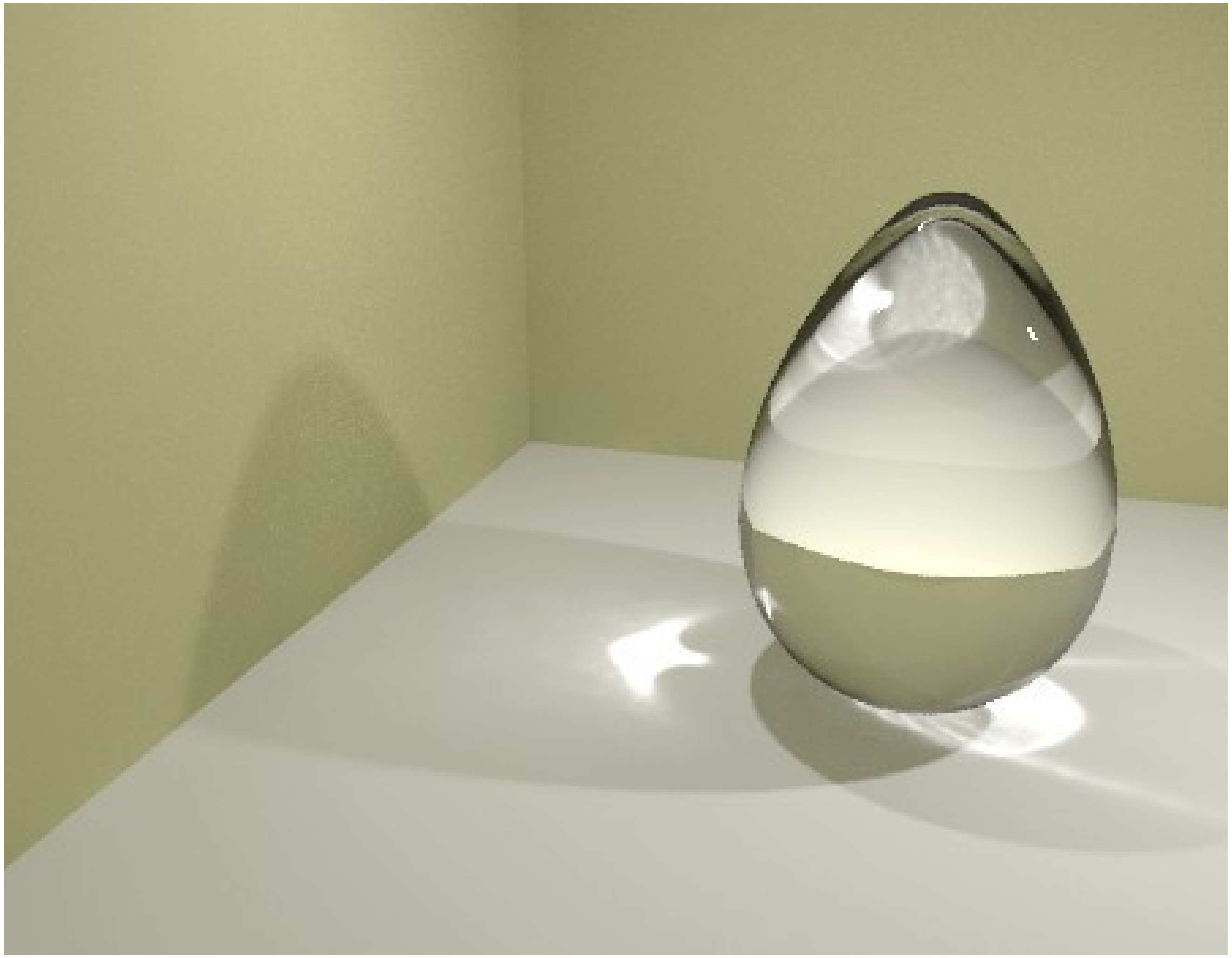


10 min (92k caustics + 152k global)

Photon-Mapping – Cognac (old code)

8.2 min (200k caustics)

Glass egg



80 min

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References

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Henrik Wann Jensen et al.: ***A Practical Guide to Global Illumination using Photon Mapping***, SIGGRAPH 2002 Course

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