Photon-Mapping

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Bases 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 represent. of light
  - 3D scene can be very complex
  - light representation can be optimized independently

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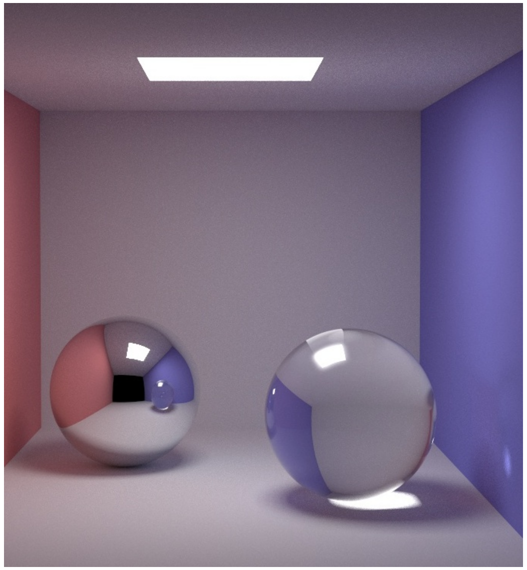
Photon Map

- 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
  - Monte Carlo method (Path-tracing)



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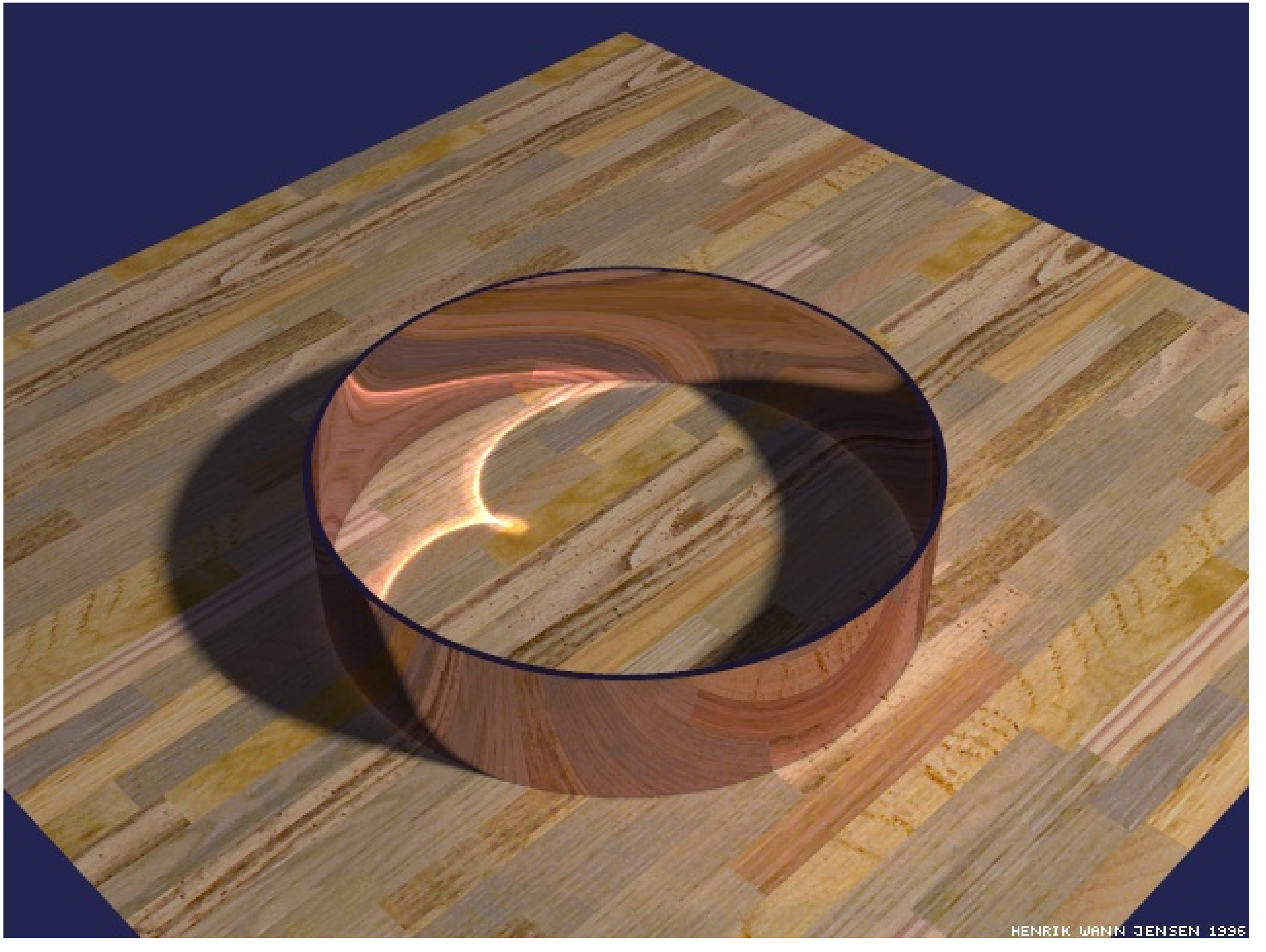
Photon-mapping – examples



Photon-mapping – examples

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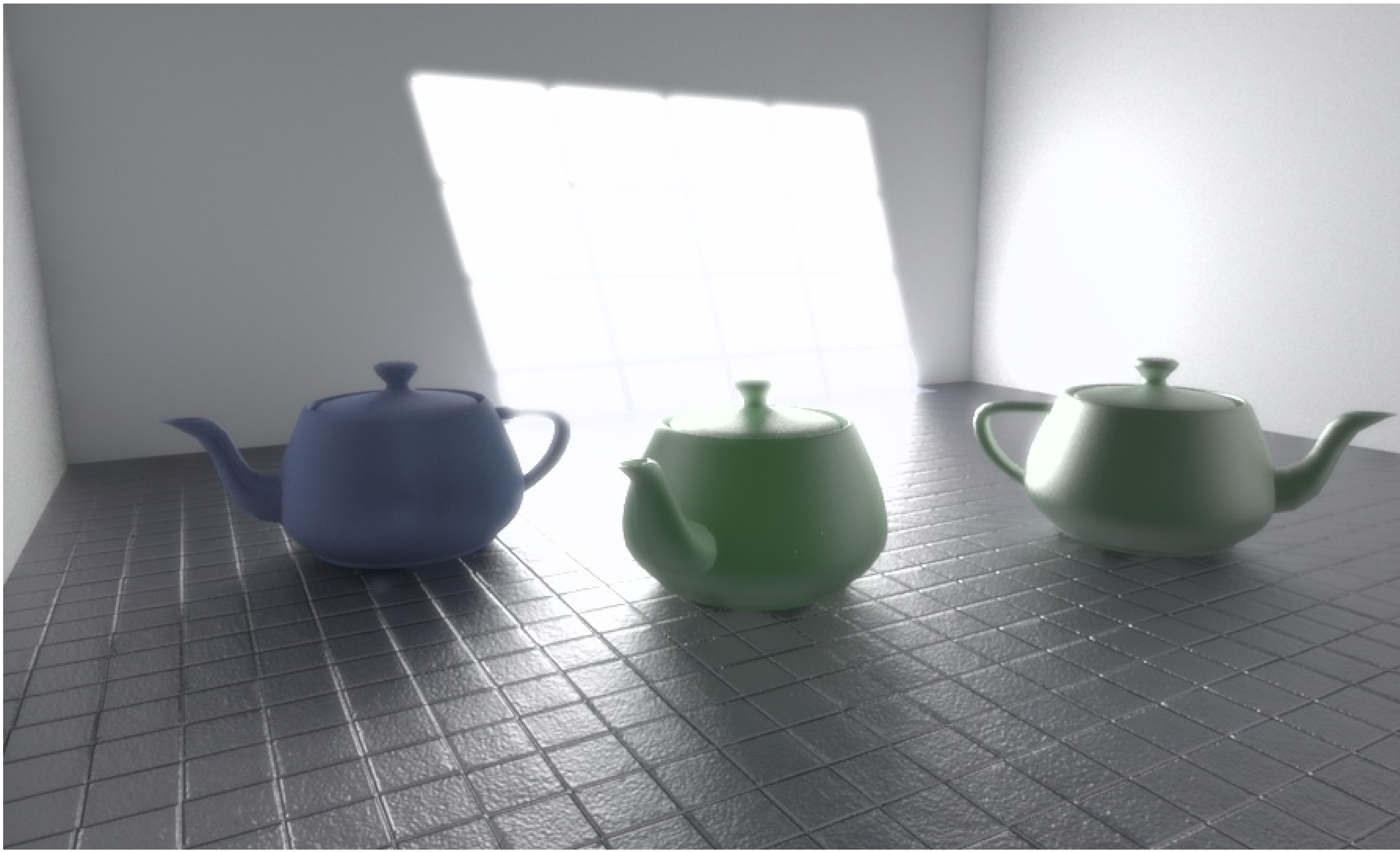
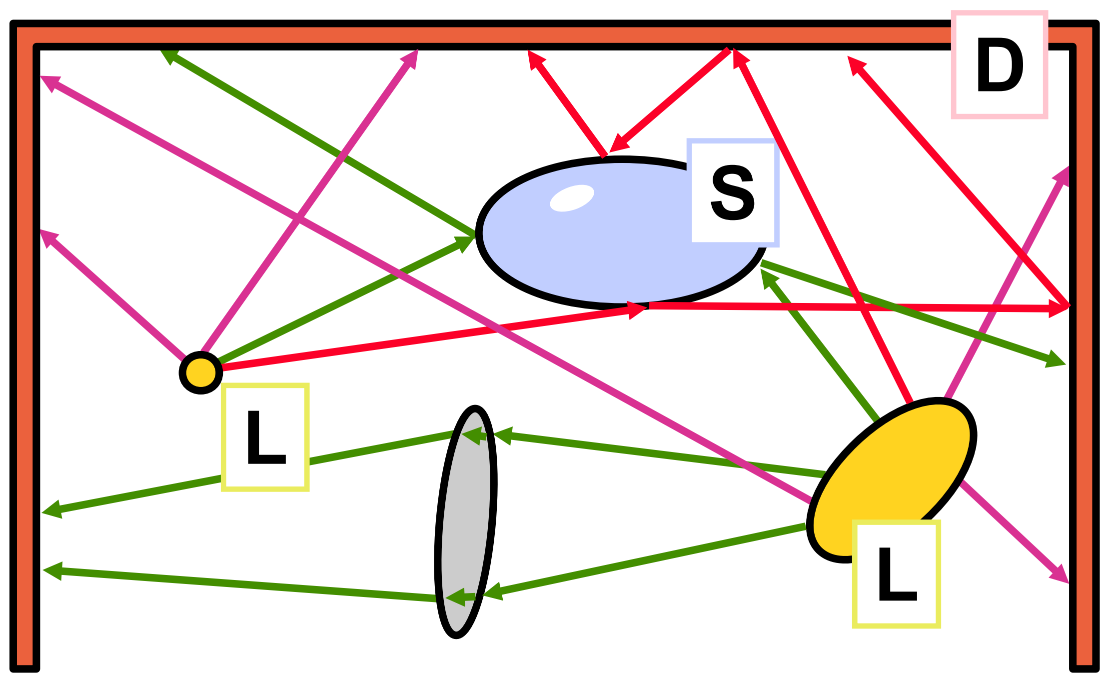


Photon–tracing

- **photons are generated** by light sources,
- **randomly propagated through the scene** and
- **stored in photon maps**

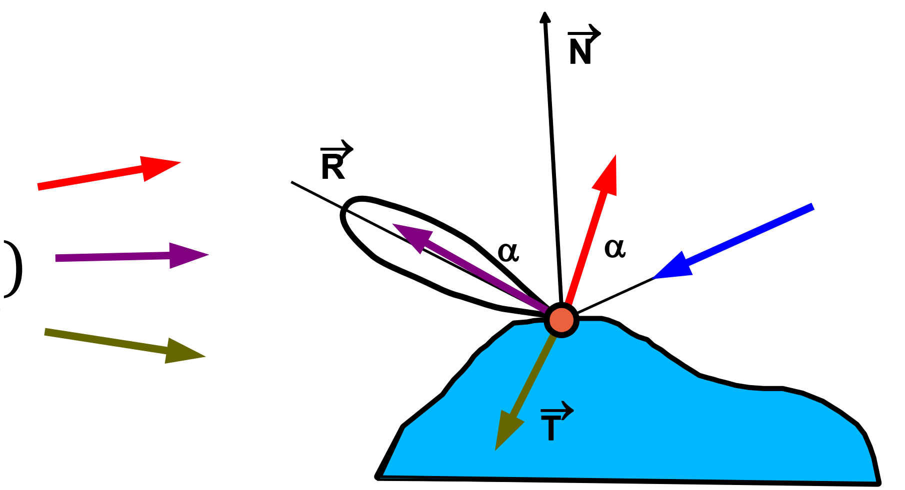


Photon generation

- 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“)

- photon map has to be **very fast** event for very high **number of records**
  - 10^5 to 10^7 individual records
  - 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 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“):
  - median is fixed, two segments are heap-sorted

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Nearest neighbor lookup

- **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)

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

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

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

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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:

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

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Global illumination II

Incoming radiance classification **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):

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

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 (“distrib. 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:

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

- 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

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