

Advanced Illumination Techniques for GPU-Based Volume Raycasting

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Scattering Effects

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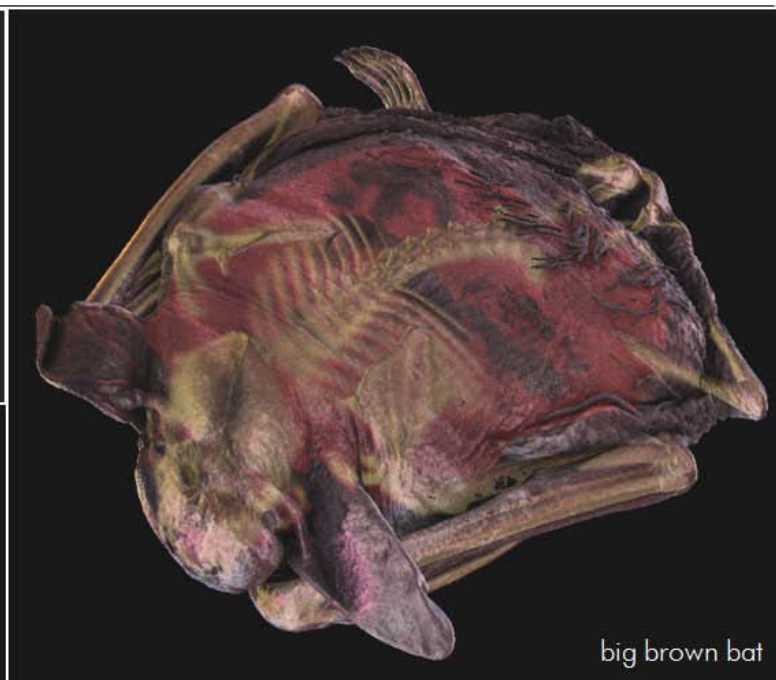
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Advanced Illumination

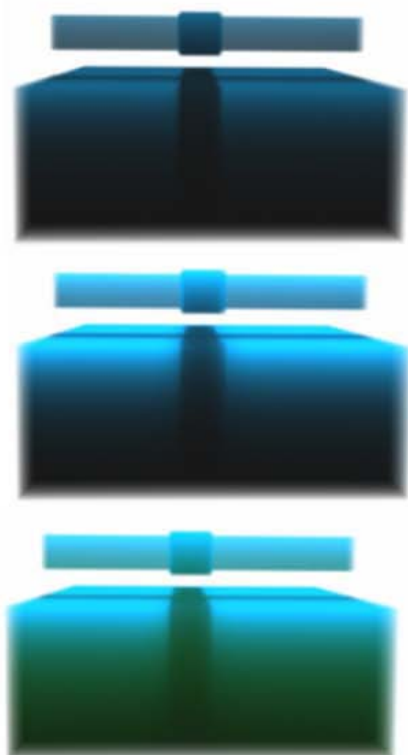


Data sets available at the
UTCT data archive, DIGIMORPH
<http://utct.tacc.utexas.edu>

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Translucency



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Light Transport

Wave-Particle Duality

● Photons

- Quantum of light (the smallest possible packet of light at a given wavelength)
- Photoelectric effect (van Lenard, 1902)

● Wave Theory (Maxwell)

- Electro-magnetic wave characteristics of light
- Effects such as interference and diffraction

● Quantum Mechanics (Einstein)

- *Universal theory of light transport*
- *probabilistic* characteristics of the motions of atoms and photons (quantum optics)

Light Transport

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Scattering Effects

Single and Multiple Scattering

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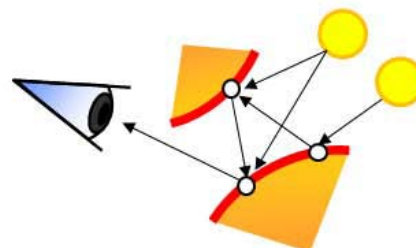
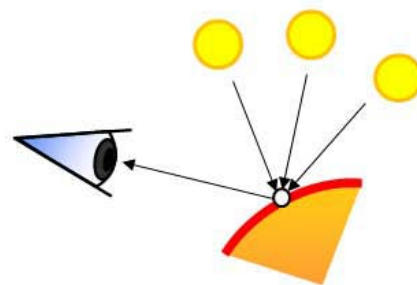
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Scattering Effects

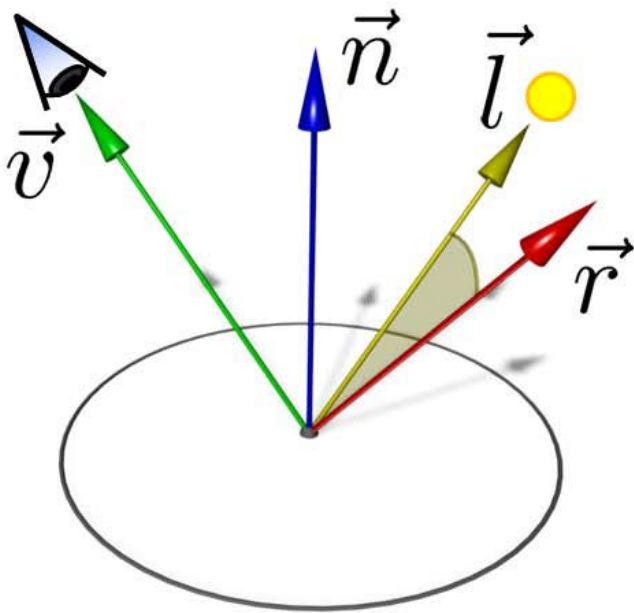
When a photon hits a surface, it changes both direction and energy

- **Single Scattering:**
 - Light is scattered *once* before it reaches the eye
 - Local illumination model
- **Multiple Scattering**
 - Soft shadows
 - Translucency
 - Color bleeding



Single Scattering

Phong illumination with point light sources

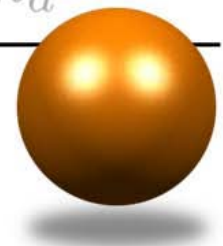


$$I_{\text{Lambert}} = L_d k_d (\vec{l} \cdot \vec{n})$$

$$I_{\text{Specular}} = L_s k_s (\vec{l} \cdot \vec{r})^s$$

$$I_{\text{Ambient}} = L_a k_a$$

$$I_{\text{Phong}}$$

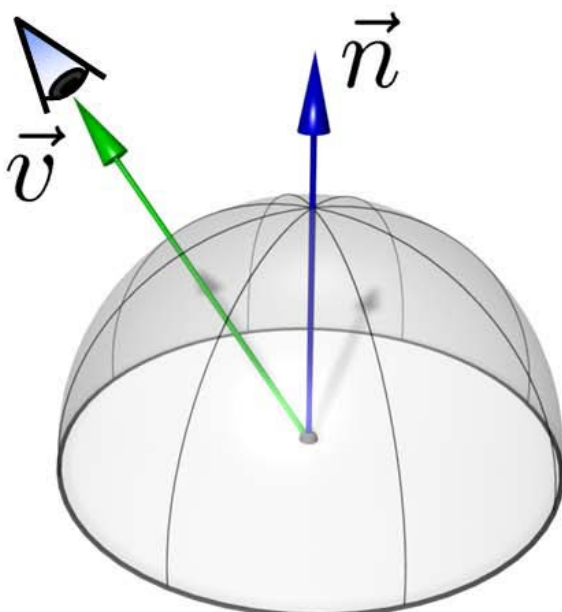


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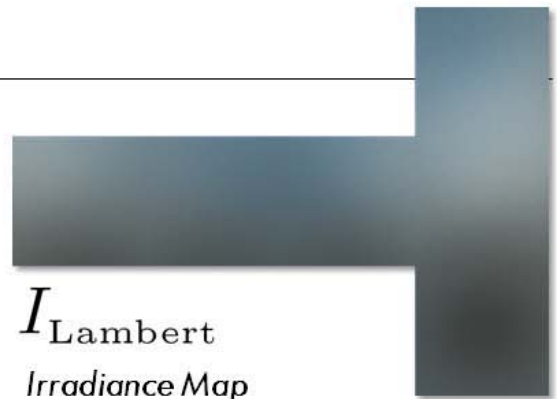
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Single Scattering

Environment Light



I_{Lambert}
Irradiance Map

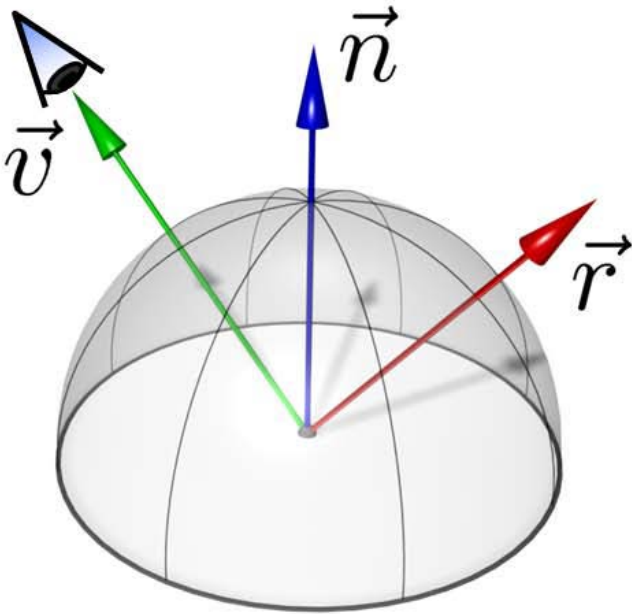


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Single Scattering

Environment Light



I_{Lambert}
Irradiance Map



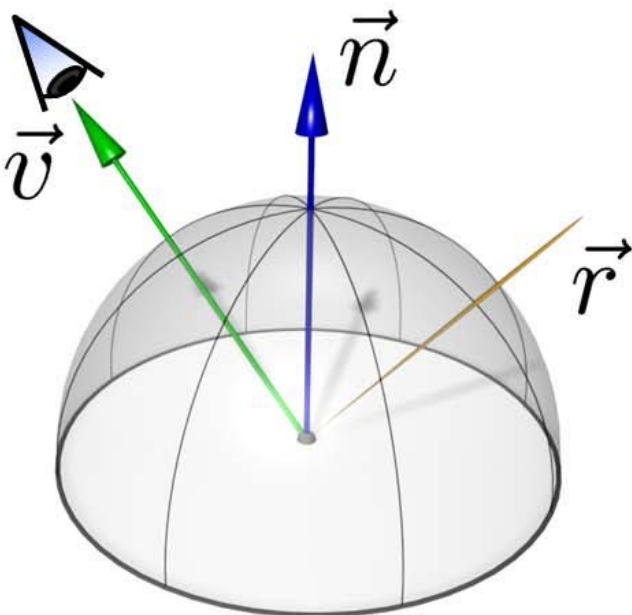
I_{Reflect}
Environment Map

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Single Scattering

Environment Light



I_{Lambert}
Irradiance Map



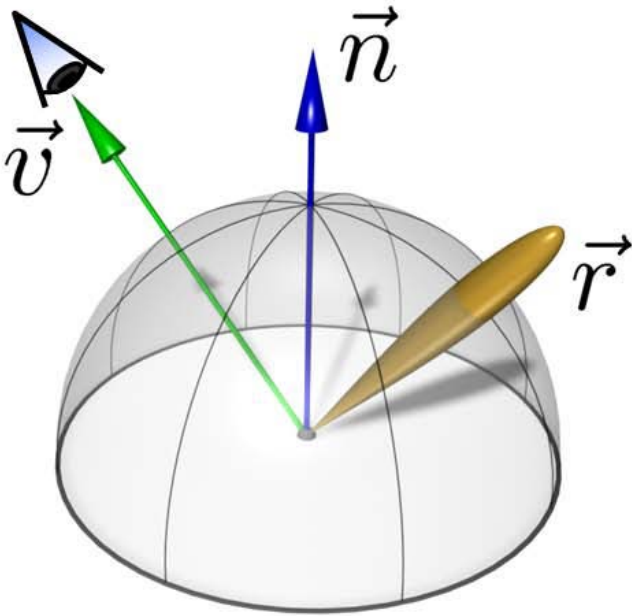
I_{Reflect}
Environment Map

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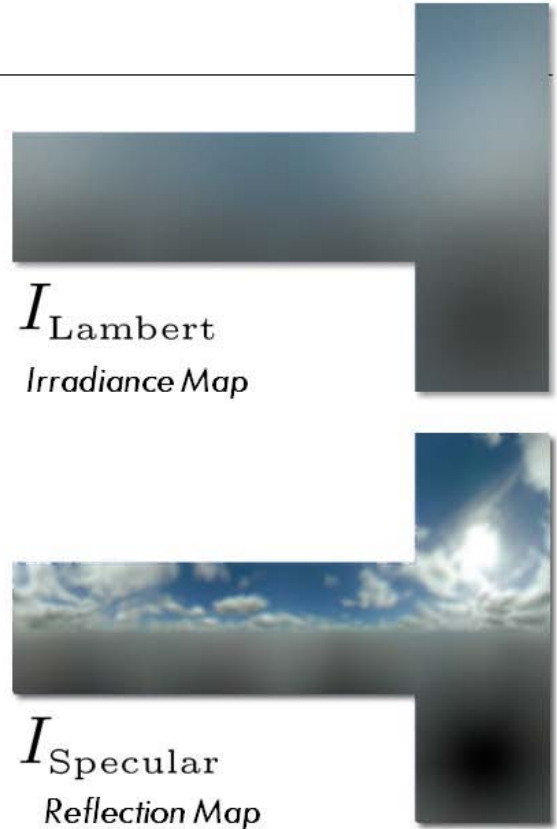
Single Scattering

Environment Light



I_{Lambert}
Irradiance Map

I_{Specular}
Reflection Map

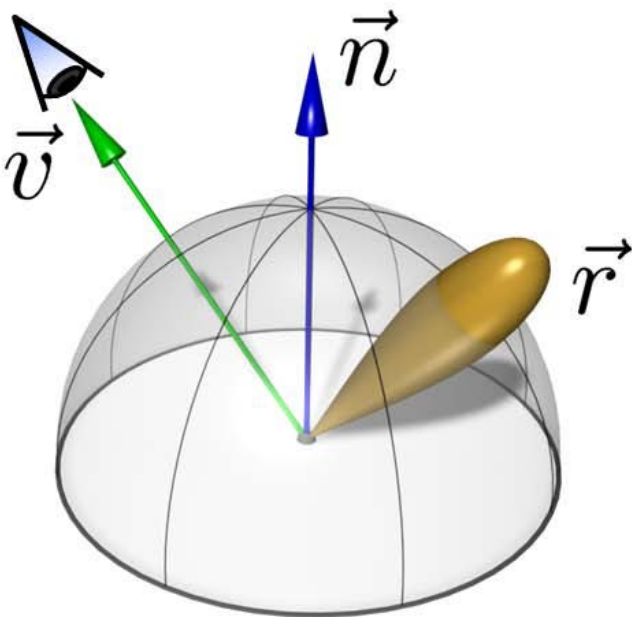


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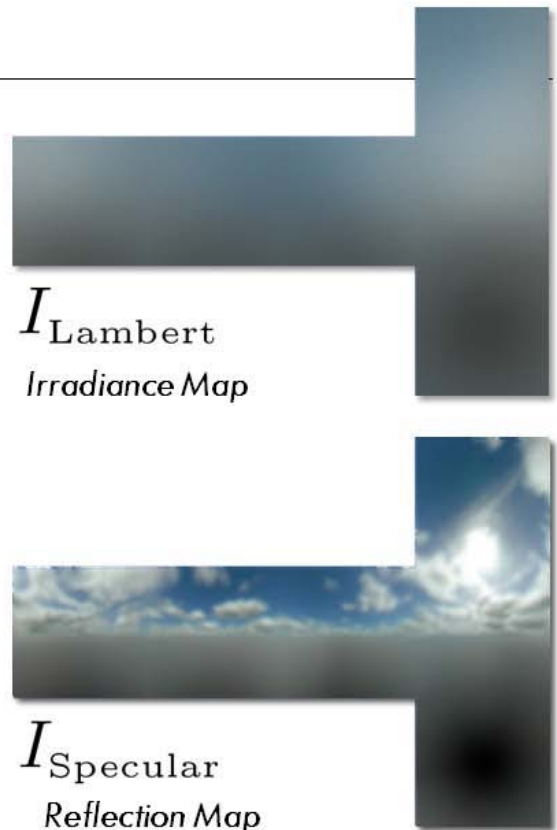
Single Scattering

Environment Light



I_{Lambert}
Irradiance Map

I_{Specular}
Reflection Map

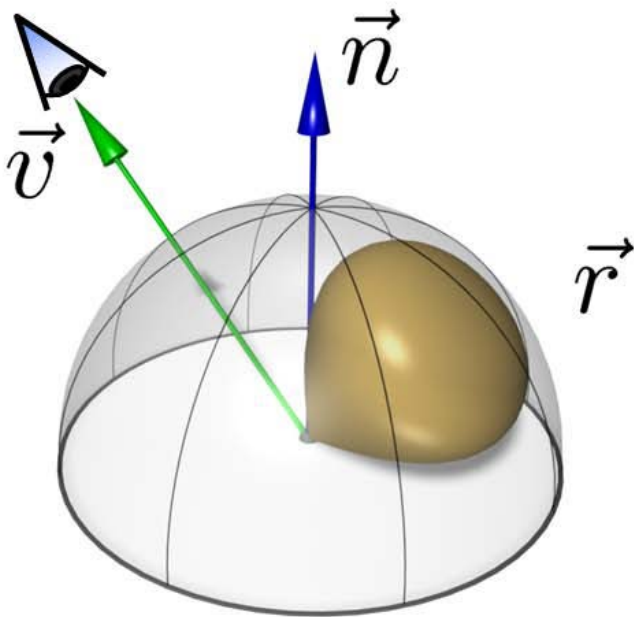


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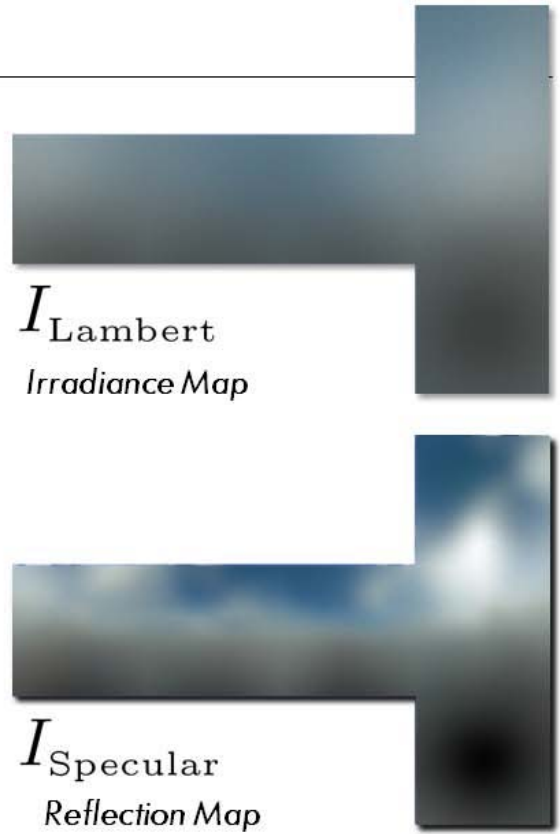
Single Scattering

Environment Light



I_{Lambert}
Irradiance Map

I_{Specular}
Reflection Map



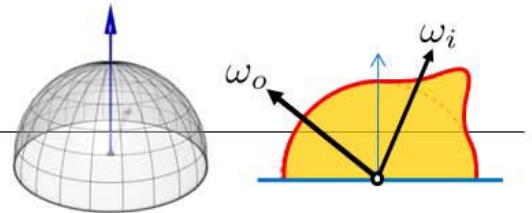
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Math Notation

● Surface Illumination

$$L(\mathbf{x}, \omega_o) = \int_{\Omega^+} f(\mathbf{x}, \omega_o \rightarrow \omega_i) \cos \theta_i d\omega_i$$



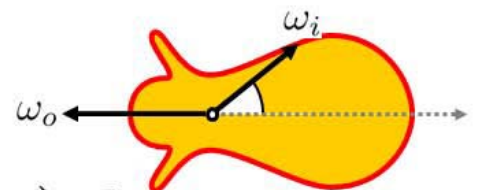
Hemisphere

BRDF

Elevation Angle

● Volume Illumination

$$L(\mathbf{x}, \omega_o) = \int_{\Omega} p(\mathbf{x}, \omega_o \rightarrow \omega_i) d\omega_i$$



Sphere

Phase Function

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Scattering Effects

Monte-Carlo Methods

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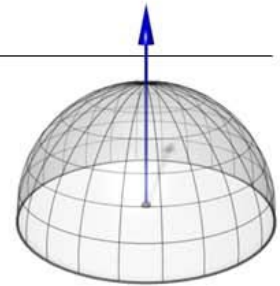
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Math Notation

Mathematical Model

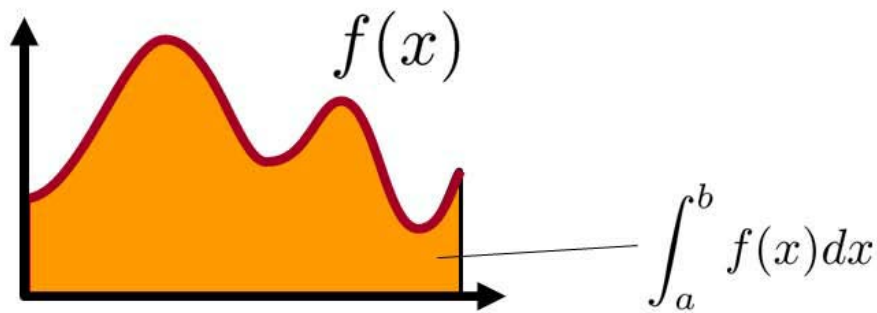
$$L(\mathbf{x}, \omega_o) = \int_{\Omega} p(\mathbf{x}, \omega_o \rightarrow \omega_i) L(\mathbf{x}, \omega_i) d\omega_i$$



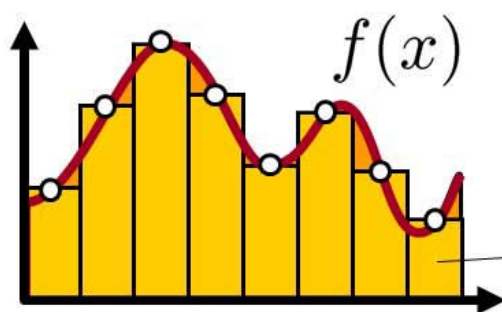
integrates over the entire sphere/hemisphere

- Integral must be solved for every intersection point
- *Fredholm Equation* (cannot be solved analytically)

Numerical Integration



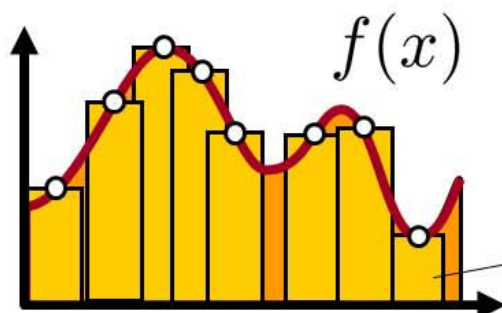
Numerical Integration



Equidistant Sampling

- Approximation integral by a Riemann sum

$$\int_a^b f(x) dx \approx \sum_{i=0}^N f(x_i) \frac{b-a}{N}$$



Stochastic Sampling

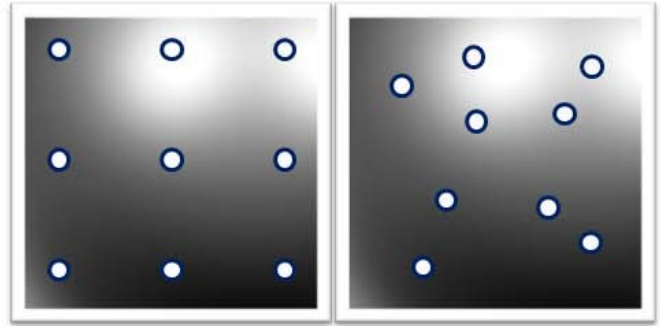
- Uniformly distributed samples
- Approximation by sum

$$\int_a^b f(x) dx \approx \sum_{i=0}^N f(x_i) \frac{b-a}{N}$$

Stochastic Sampling

Cons:

- Slower convergence than Riemann sum



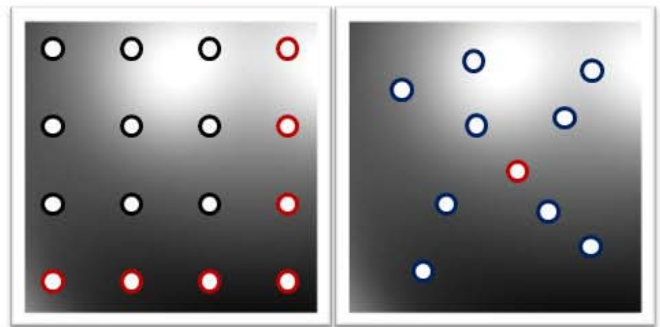
Pros:

- *Better Scalability for multidimensional functions:* increase number of samples in arbitrary steps

Stochastic Sampling

Cons:

- Slower convergence than Riemann sum



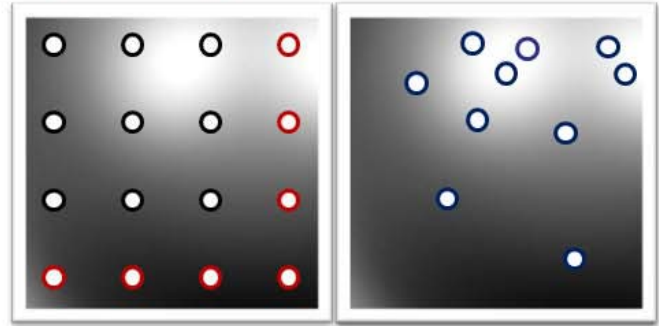
Pros:

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Stochastic Sampling

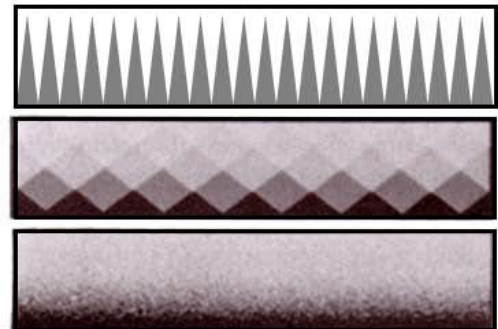
Cons:

- Slower convergence than Riemann sum



Pros:

- *Better Scalability for multidimensional functions:* increase number of samples in arbitrary steps
- *Noise* instead of Aliasing
- *Independent of sampling grid:* Clever placement of samples will improve the convergence!



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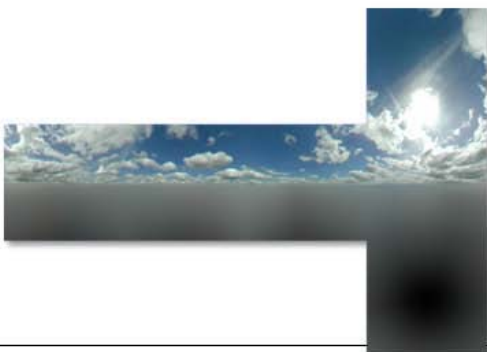
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Blind Monte-Carlo Sampling

● Example: Filtering an Environment Map

Given an Environment Map

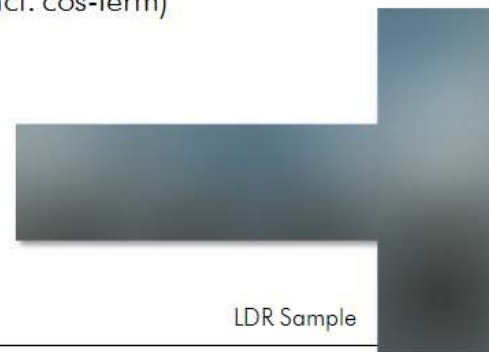
(i.e. photograph: fisheye or mirror ball)



Calculate an Irradiance Map

For each pixel of the irradiance map:

- Determine n random directions on the hemisphere
- Sample the Environment Map and
- Average the results (incl. cos-term)



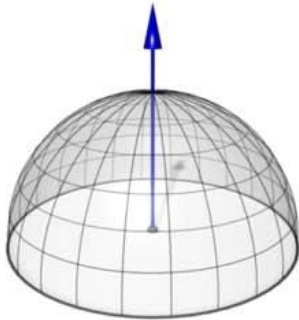
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Rendering

● Calculate the radiance from a point

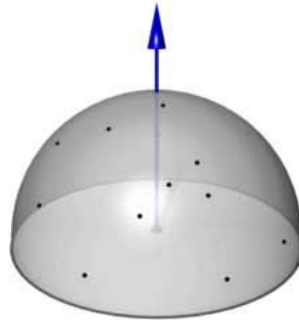
- depending on the incoming light on the sphere/hemisphere
- depending on the phase function/BRDF



Deterministic

Uniform sampling of the sphere/hemisphere.

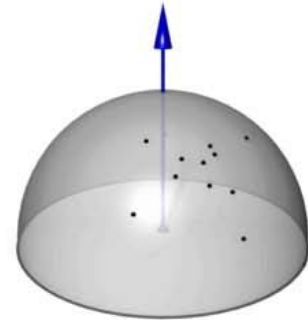
High computational load
good approximation



Blind Monte-Carlo

Randomized sampling of the sphere/hemisphere.

Visually better images for fewer samples, slow convergence



Importance Sampling

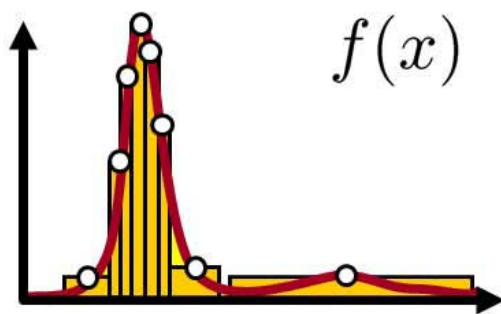
Place samples where contribution is high

Faster!

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Importance Sampling



Stochastic Sampling

- Non-uniformly distributed samples
- Approximation by sum

$$\int_a^b f(x) dx \approx \sum_{i=0}^N \frac{f(x_i)}{p(x_i)}$$

Clever placement of samples

- Many samples where function is high
- Few samples where function is low

Probability
Distribution
Function (PDF)

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Sampling a Specular Lobe

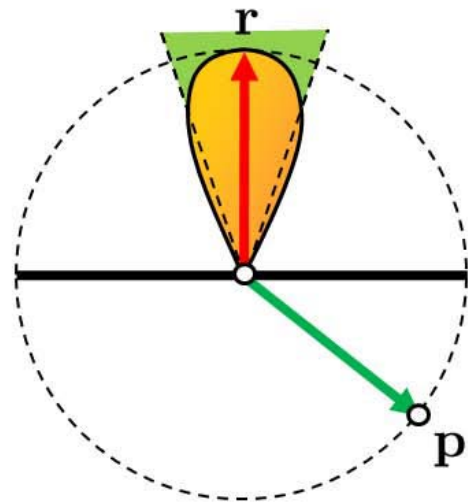
● Simple Approach

Specular term $f(\varphi) = \cos^s(\varphi) = (\mathbf{r} \cdot \mathbf{v})^s$

Non-optimal, but easy to implement

Idea: uniform distribution of directions restricted to a cone

- Precompute random unit vectors with uniform PDF
- Randomly pick one vector \mathbf{p}



Sampling a Specular Lobe

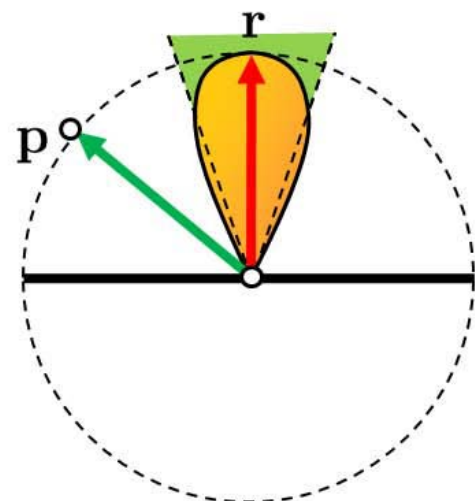
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Non-optimal, but easy to implement

Idea: uniform distribution of directions restricted to a cone

- Precompute random unit vectors with uniform PDF
- Randomly pick one vector \mathbf{p}
- Negate vector, if $(\mathbf{r} \cdot \mathbf{p}) < 0$



Sampling a Specular Lobe

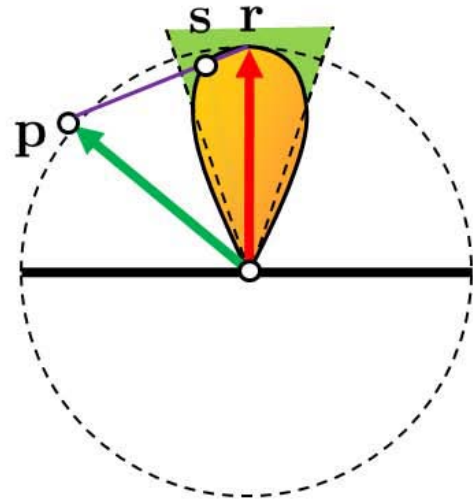
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- Precompute random unit vectors with uniform PDF
- Randomly pick one vector \mathbf{p}
- Negate vector, if $(\mathbf{r} \cdot \mathbf{p}) < 0$
- Blend with vector \mathbf{r} and normalize
$$\mathbf{s} = \alpha \mathbf{r} + (1 - \alpha)\mathbf{p}$$



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Sampling a Specular Lobe

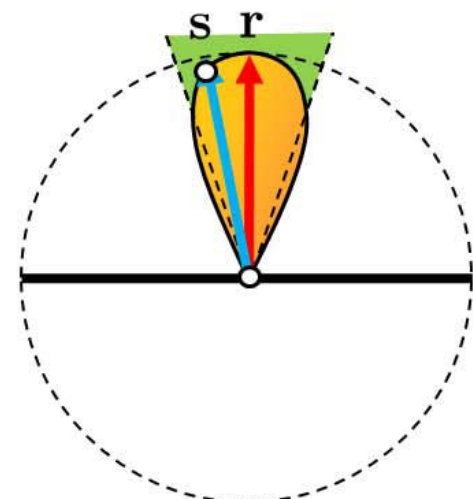
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- Negate vector, if $(\mathbf{r} \cdot \mathbf{p}) < 0$
- Blend with vector \mathbf{r} and normalize
$$\mathbf{s} = \alpha \mathbf{r} + (1 - \alpha)\mathbf{p}$$
- Blend weight α controls the size of the specular highlight and can be calculated from shininess s



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Stochastic Sampling

$$\int_a^b f(x) dx \approx \sum_{i=0}^N \frac{f(x_i)}{p(x_i)}$$

- What is the *ideal PDF* for sampling a given function $f(x)$?
- Variance is minimal, if

$$p(x) = \lambda \cdot f(x)$$

- λ must be chosen to normalize the distribution
- Problem:

$$\int_a^b p(x) dx = 1 \quad \Rightarrow \quad p(x) = \frac{f(x)}{\int_a^b f(x) dx}$$

- The ideal PDF requires knowing the integral beforehand!

Stochastic Sampling

$$L(\mathbf{x}, \omega_o) = \int_{\Omega} \underbrace{f(\mathbf{x}, \omega_i \rightarrow \omega_o)}_{\text{known}} \underbrace{L(\mathbf{x}, \omega_i)}_{\text{known}} \underbrace{\cos \theta_i}_{\text{known}} d\omega_i$$

unknown

Although we do not know the integral completely, we still know parts of it

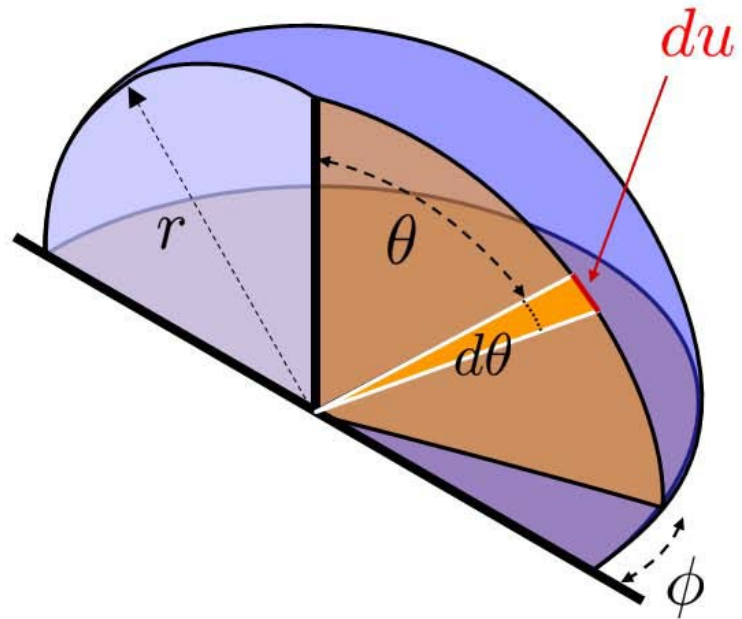
$$\hat{p}(\omega_i) = f(\mathbf{x}, \omega_i \rightarrow \omega_o) \cos \theta_i$$

$$p(\omega_i) = \frac{\hat{p}(\omega_i)}{\int_{\Omega} \hat{p}(\omega) d\omega}$$

Solid Angle

$$A_{\text{Hemisphere}} = \int_{\Omega^+} 1 d\omega$$

$$du = r d\theta$$

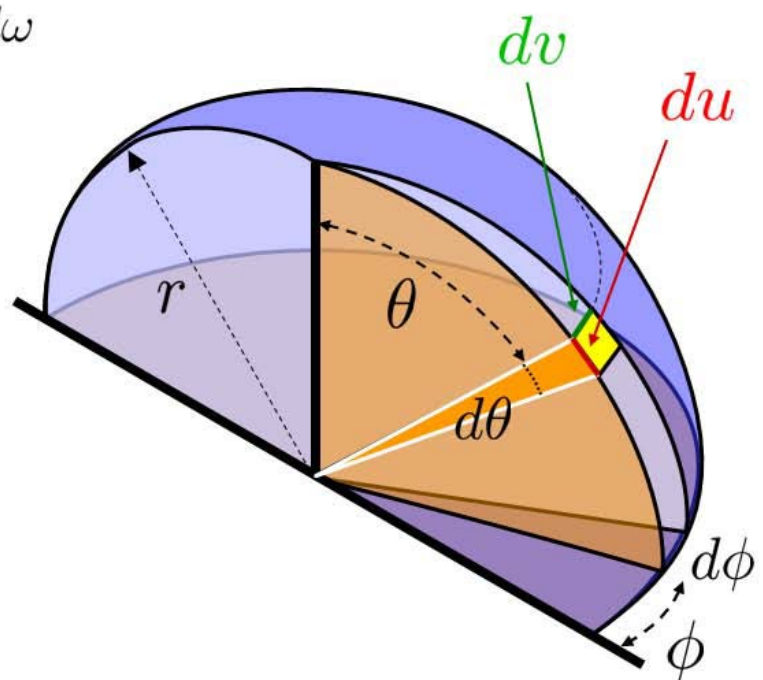


Solid Angle

$$A_{\text{Hemisphere}} = \int_{\Omega^+} 1 d\omega$$

$$du = r d\theta$$

$$dv = r \sin \theta d\phi$$



Solid Angle

$$A_{\text{Hemisphere}} = \int_{\Omega^+} 1 d\omega = 2\pi$$

$$du = r d\theta$$

$$dv = r \sin \theta d\phi$$

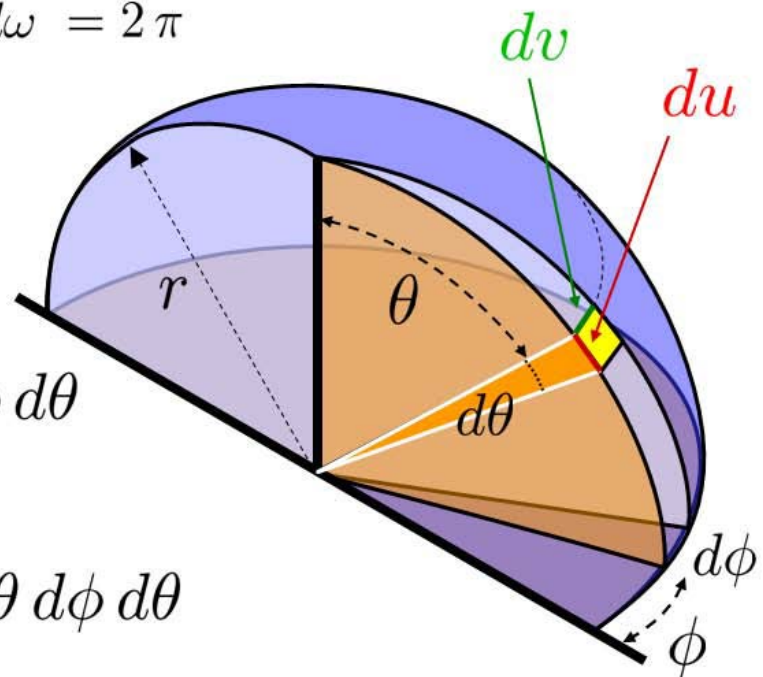
Area (yellow):

$$dA = r^2 \sin \theta d\phi d\theta$$

Solid Angle:

$$d\omega = \frac{dA}{r^2} = \sin \theta d\phi d\theta$$

Unit of solid angle: Steradian [sr]



Sampling a Specular Lobe

● Ideal Sampling

$$f(\omega_i) = \cos^n(\theta_i) \quad p(\omega_i) = \frac{f(\omega_i)}{\int_{\Omega^+} f(\omega_i) d\omega}$$

$$\int_{\Omega^+} \cos^n(\theta) d\omega = \int_0^{2\pi} \int_0^{\pi/2} \cos^n(\theta) \sin(\theta) d\theta d\phi = \frac{2\pi}{(n+1)}$$

Sampling a Specular Lobe

● Ideal Sampling

$$f(\omega_i) = \cos^n(\theta_i) \qquad p(\omega_i) = \frac{f(\omega_i)}{\int_{\Omega^+} f(\omega_i) d\omega}$$

$$p(\theta_i, \phi_i) = \frac{(n+1)}{2\pi} \cos^n \theta_i \sin \theta_i$$

$$p(\theta_i) = (n+1) \cos^n \theta_i \sin \theta_i$$

$$p(\phi_i|\theta_i) = \frac{1}{2\pi}$$

● Convert to CDF and invert

$$\theta_i = \cos^{-1} \xi_1^{\left(\frac{1}{n+1}\right)}$$

$$\phi_i = 2\pi \xi_2$$

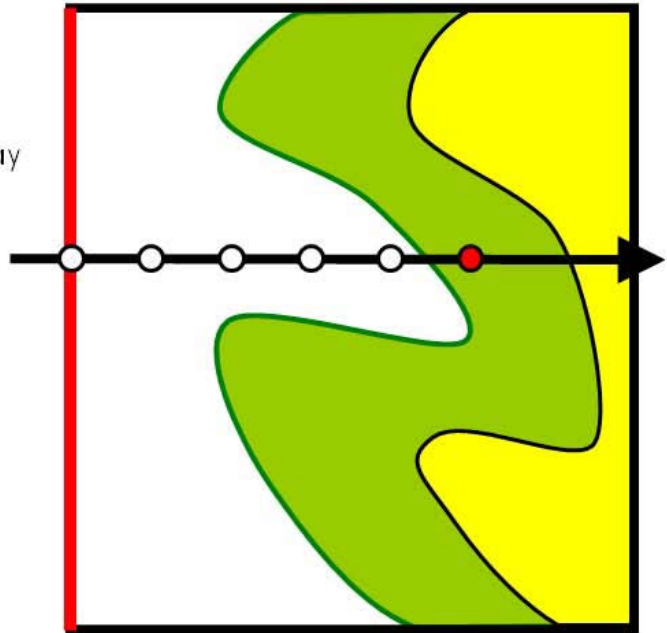
Importance Sampling

Literature:

- M. Pharr, G. Humphries: **Physically Based Rendering**, Morgan Kaufman (Elsevier), 2004
- M. Colbert, J. Křivánek, **GPU-Based Importance Sampling** in *H.Nguyen (edt.): GPU Gems 3, Addison-Wesley, 2008*

GPU Ray-Casting

- Calculate First Intersection with Isosurface
- Rasterize the front faces of the bounding box
- For each fragment, cast a ray
- Find first intersection point with isosurface by sampling along the ray

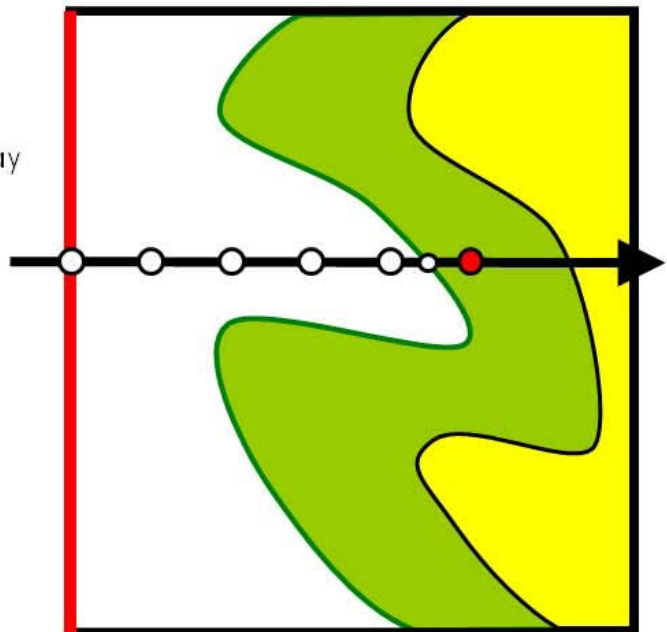


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GPU Ray-Casting

- Calculate First Intersection with Isosurface
- Rasterize the front faces of the bounding box
- For each fragment, cast a ray
- Find first intersection point with isosurface by sampling along the ray
 - interval bisection



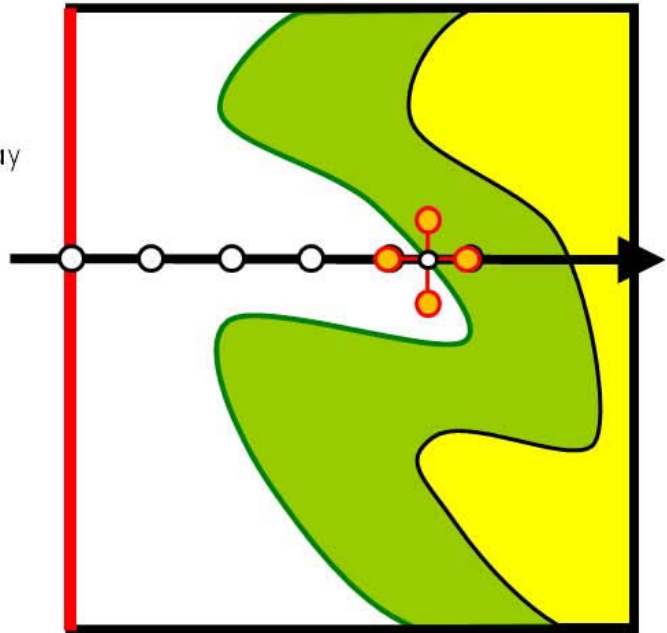
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GPU Ray-Casting

● Calculate First Intersection with Isosurface

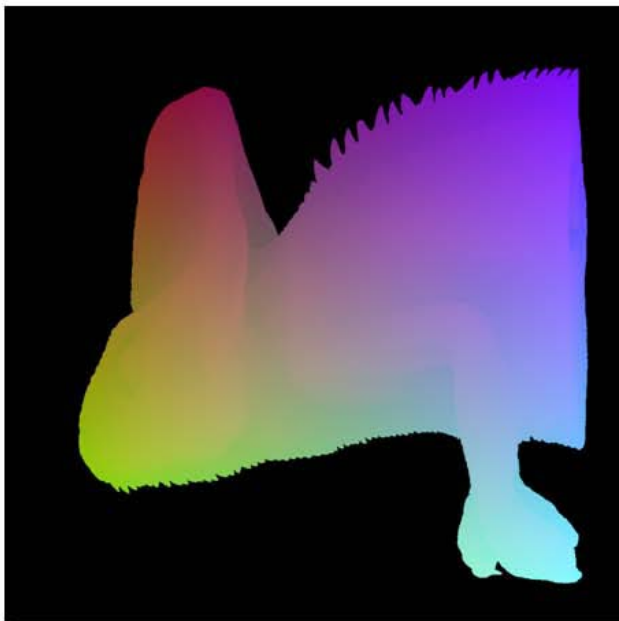
- Rasterize the front faces of the bounding box
- For each fragment, cast a ray
- Find first intersection point with isosurface by sampling along the ray
 - interval bisection
- Store the intersection point in render target 0
- Estimate the gradient vector using central differences
- Store the gradient vector in render target 1



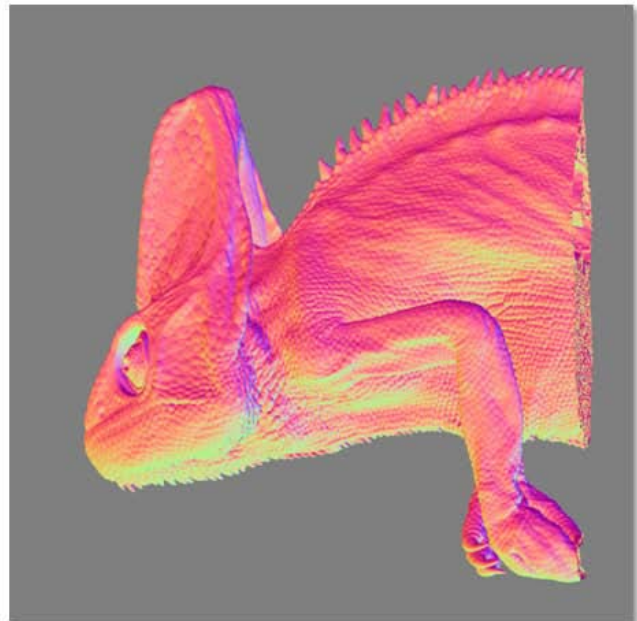
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First Render Pass



MRT0: xyz-coordinates of first intersection point with isosurface



MRT1: xyz-components of gradient vector (color coded)

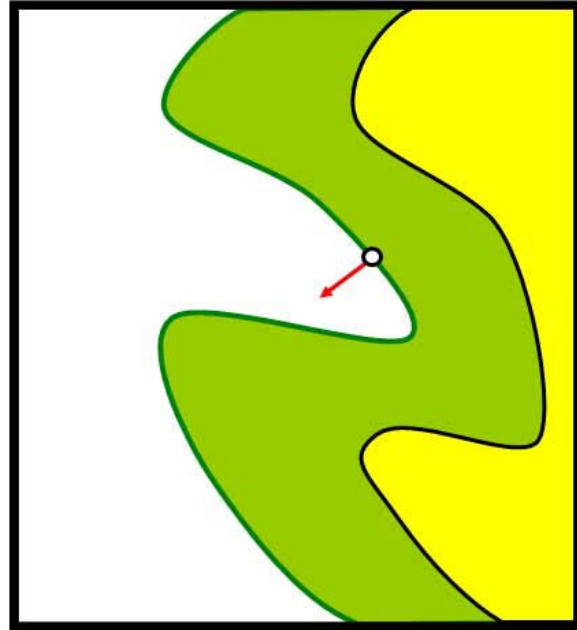
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Deferred Shading

Single Scattering (no shadows)

- Diffuse term:
 - Sample irradiance cube using gradient direction



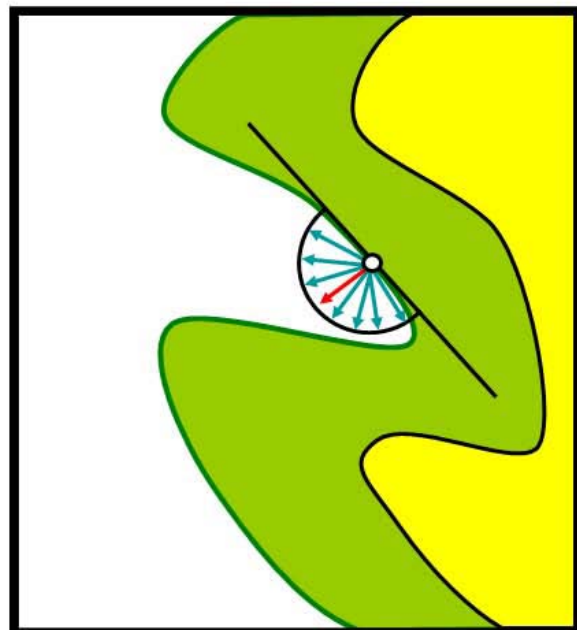
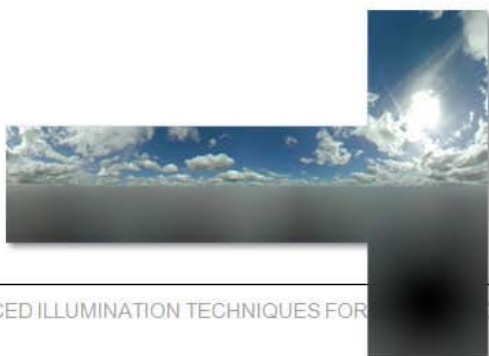
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Deferred Shading

Single Scattering (no shadows)

- Diffuse term:
 - Sample irradiance cube using gradient direction
- Specular term:
 - Calculate random directions on the specular lobe
 - Sample environment cube



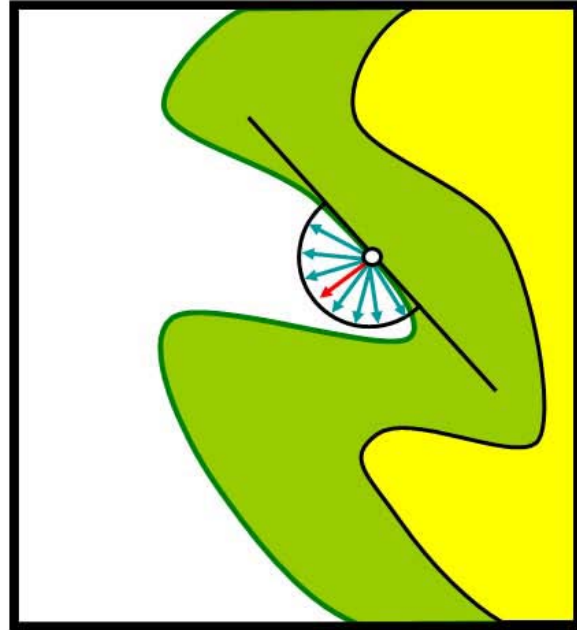
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Deferred Shading

Single Scattering (no shadows)

- Diffuse term:
 - Sample irradiance cube using gradient direction
- Specular term:
 - Calculate random directions on the specular lobe
 - Sample environment cube
 - Weight each sample with its BRDF/phase function and its probability distribution



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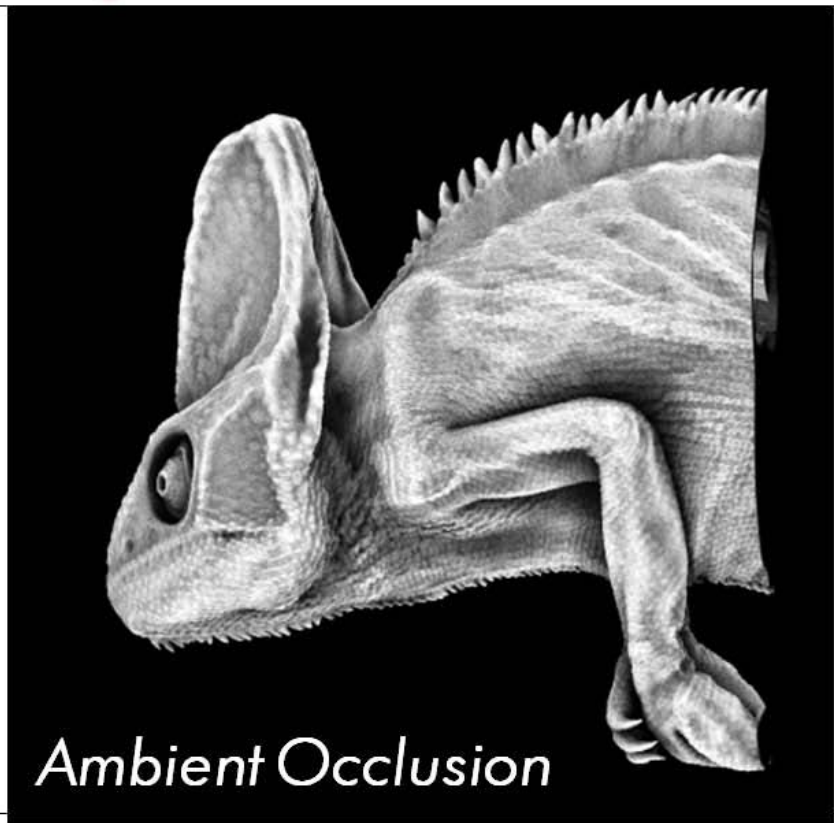
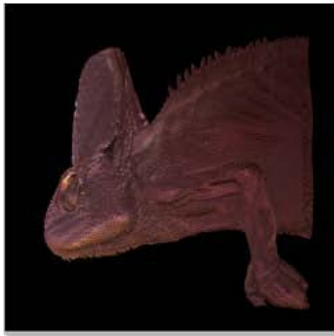
High Quality Isosurface



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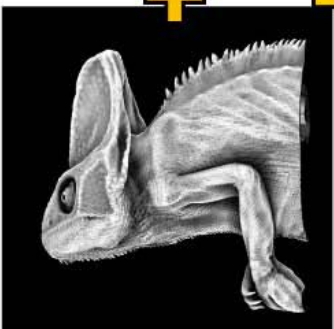
High Quality Isosurface



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High Quality Isosurface



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Our First Implementation

Why not use a pre-filtered environment map?

You can, but

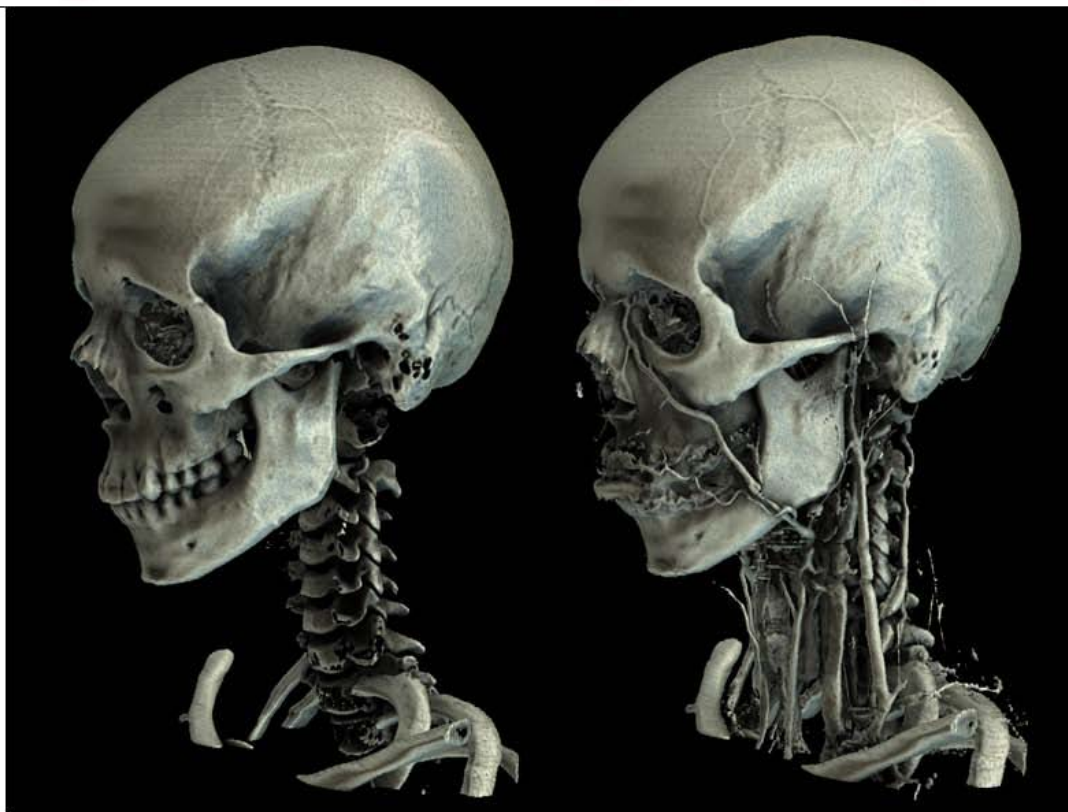
- it only works for **one** specular exponent per object
- Variable shininess may be used to *visualize additional surface properties* (e.g. gradient magnitude)



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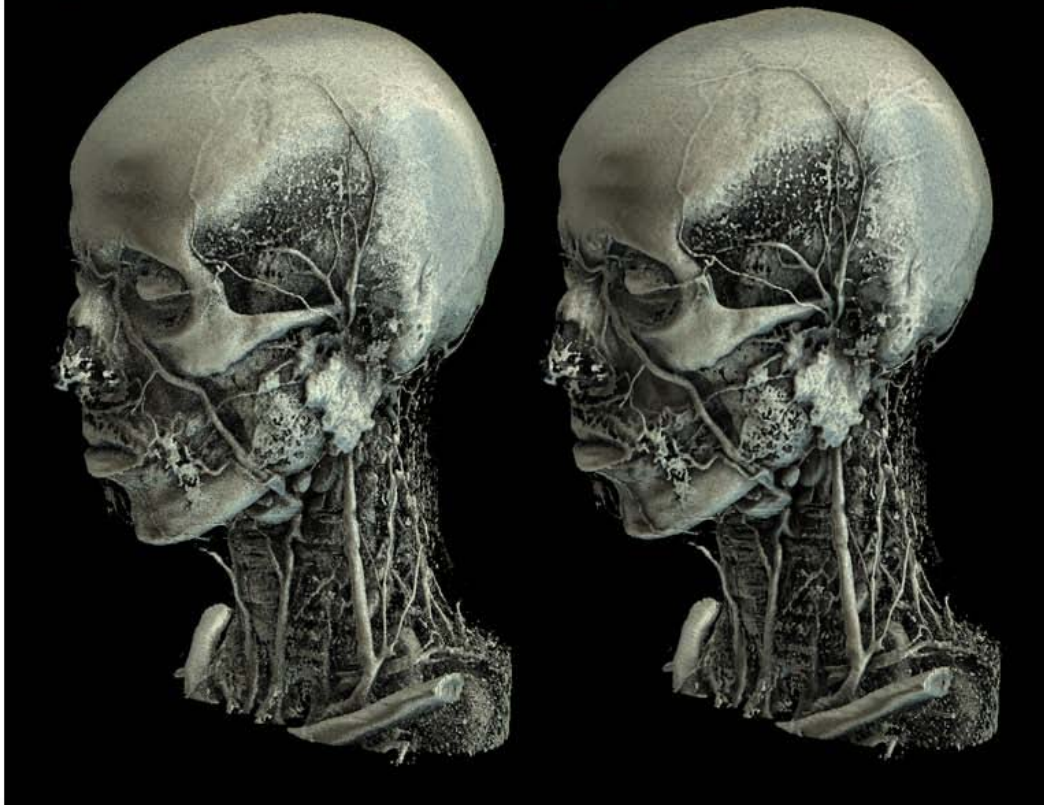
Single Scattering Example



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Single Scattering Example



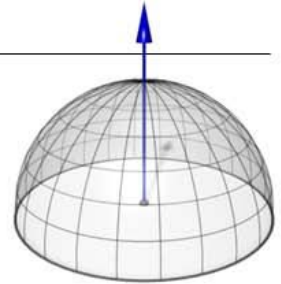
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Multiple Scattering

Mathematical Model

$$L(\mathbf{x}, \omega_o) = \int_{\Omega} p(\mathbf{x}, \omega_o \rightarrow \omega_i) L(\mathbf{x}, \omega_i) d\omega_i$$

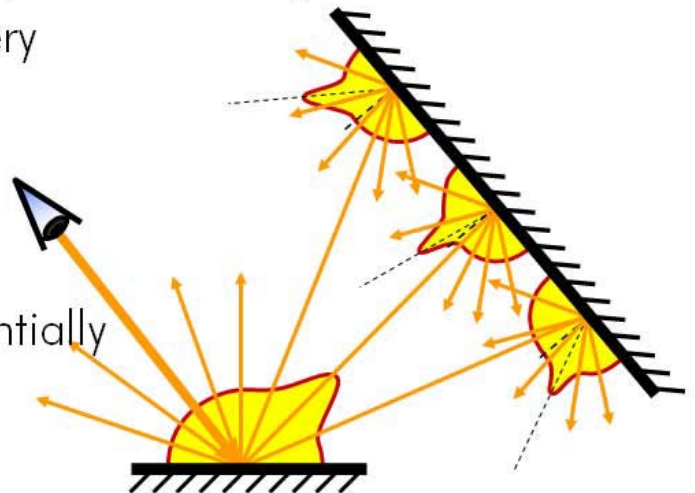


integrates over the entire sphere/hemisphere

- Integral must be solved for every intersection point
- *Fredholm Equation* (cannot be solved analytically)

Numerical Solution:

- Number of rays grows exponentially
- Much workload spent for little contribution



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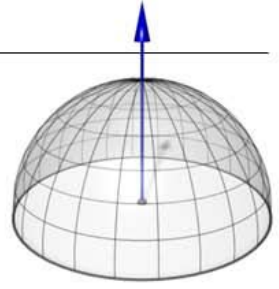
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Multiple Scattering

Mathematical Model

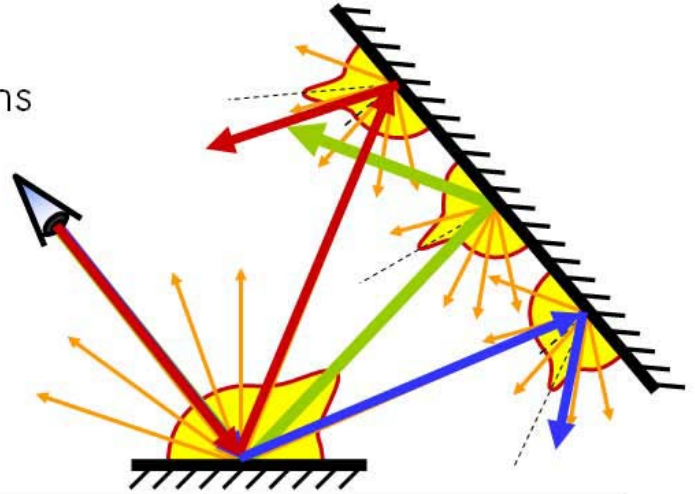
$$L(\mathbf{x}, \omega_o) = \int_{\Omega} p(\mathbf{x}, \omega_o \rightarrow \omega_i) L(\mathbf{x}, \omega_i) d\omega_i$$

integrates over the entire sphere/hemisphere



Quantum Optics

- Trace the path of single photons
- Photons are scattered randomly
- Probability of scattering direction given by BRDF/phase function
- *Monte Carlo path tracing*

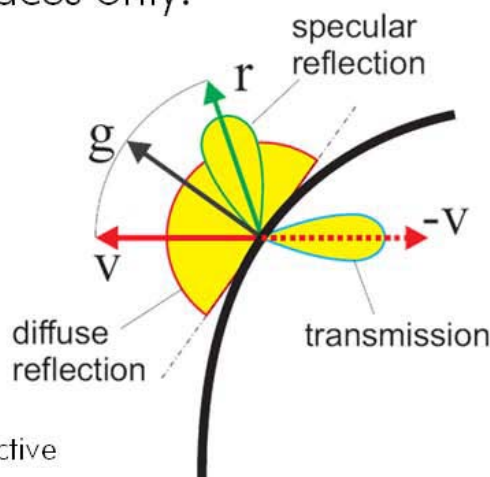


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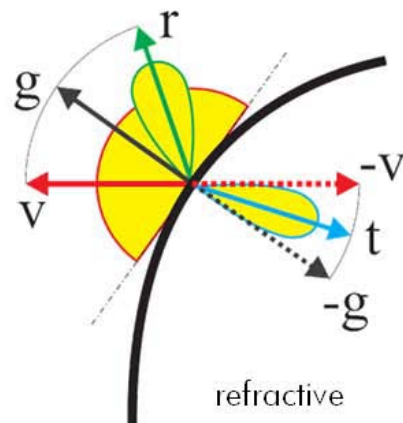
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Phase Function Model

- Scattering of light at every point inside the volume
 - Too expensive (extremely slow convergence)
 - Not practicable. Controlling the visual appearance is difficult
- *Idea:* Restrict scattering events to a fixed number of isosurfaces only.



non-refractive



refractive

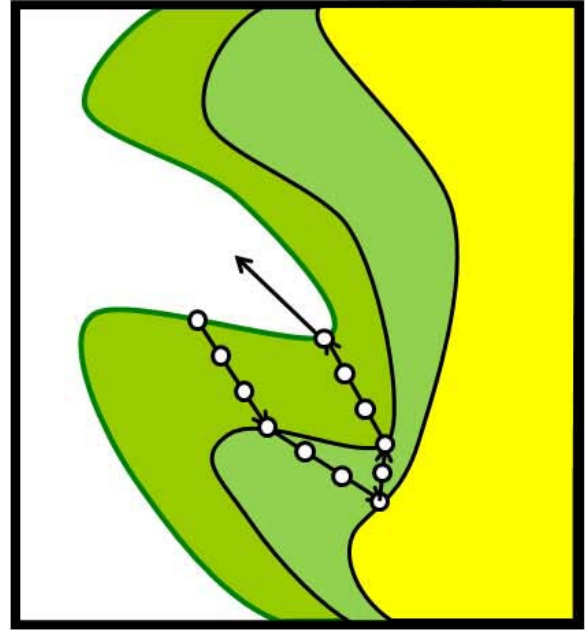
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GPU Ray-Casting

Scattering Pass

- Start at first isosurface and trace inwards
- Account for absorption along the rays
- Proceed until next isosurface
- Calculate scattering event
- Sample the environment on exit



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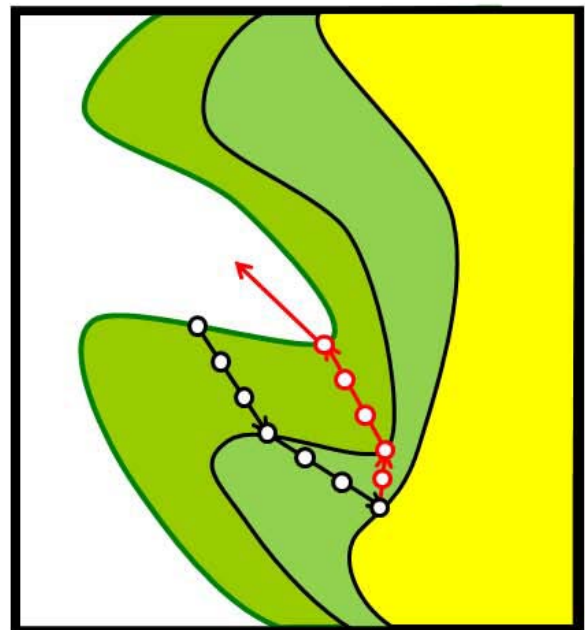
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GPU Ray-Casting

Scattering Pass

Simplifying Assumption:

- Absorption on the „way in“ is same as on the „way out“
- Abort the ray inside the volume square the absorption and sample irradiance map
- *Not very accurate but good visual results*



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Scattering Pass



preview in real-time



final version in 1/2-1 seconds

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Final Composite



Multiply



Blend using Fresnel term



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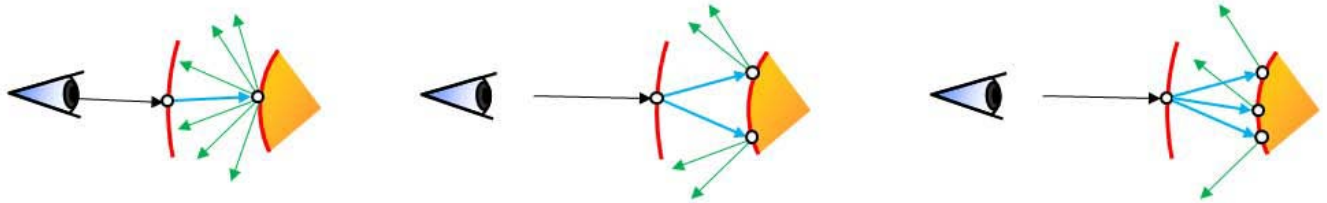
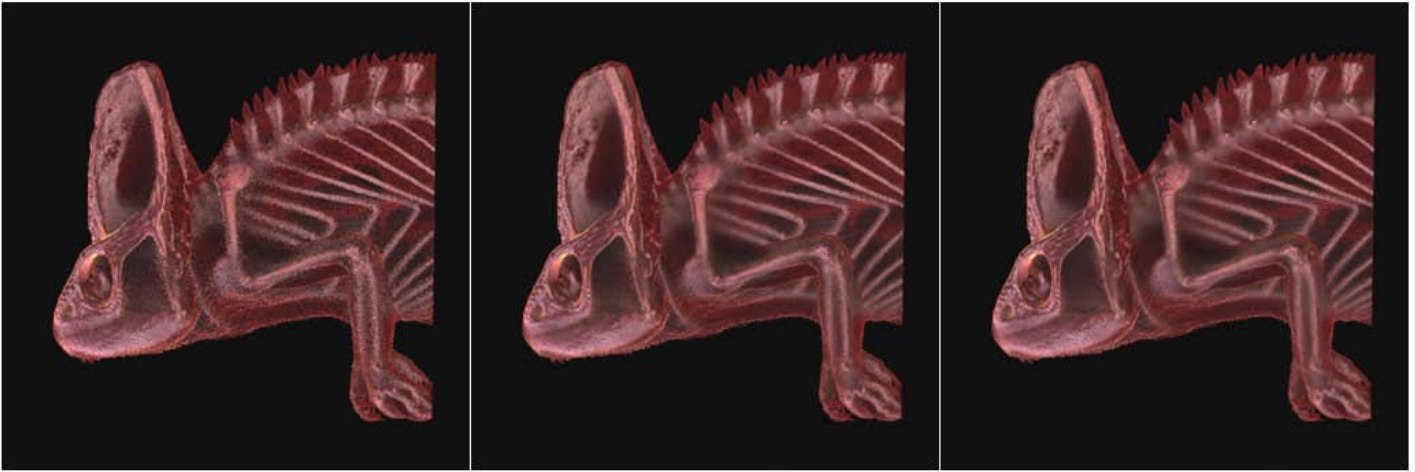
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Path Tracing

Primary rays: 1
Secondary rays: 64

Primary rays: 8
Secondary rays: 8

Primary rays: 64
Secondary rays: 1

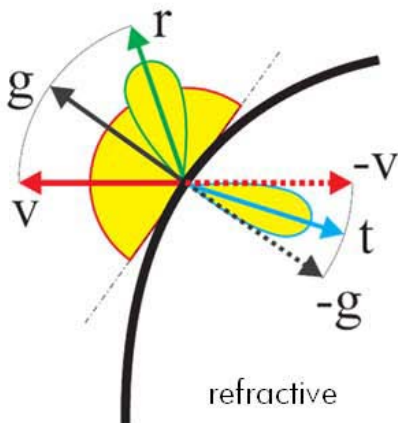


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Examples

Different scattering cone angles for the „inward-looking“ (transmissive) Phong-lobe



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Scattering Effects

Light Map Approaches

Markus Hadwiger
VR VIS Research Center
Vienna, Austria



Patric Ljung
Siemens Corporate Research
Princeton, NJ, USA



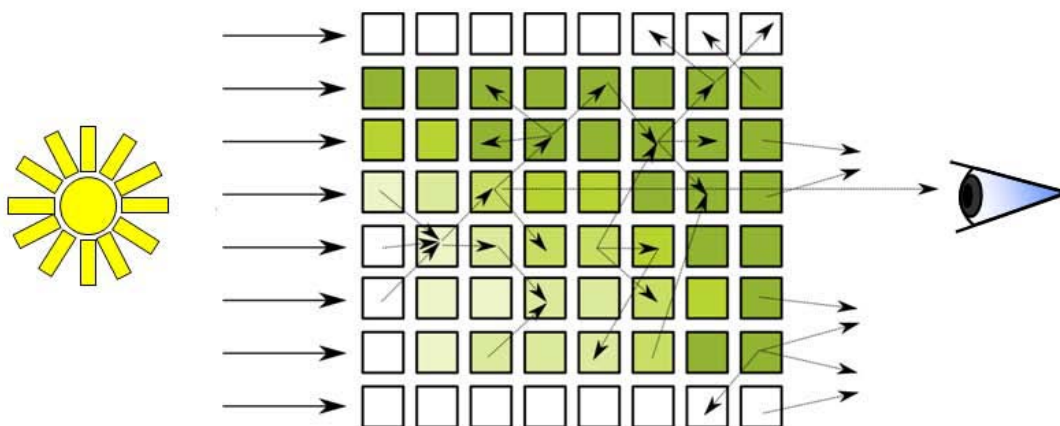
Christof Rezk Salama
Computer Graphics Group
Institute for Vision and Graphics
University of Siegen, Germany



Timo Ropinski
Visualization and Computer
Graphics Research Group,
University of Münster, Germany



3D Light Map



- Direct light by shadow volume or deep shadow map
- Consider the *exchange of radiant energy between neighbouring voxels*
- Approximate by blur operation (*like [Kniss, 2002]*)

Generate a 3D Light Map

- **Based on Shadow Volume**

- Calculate shadow volume for direct light as in
 - U. Behrens and R. Ratering. **Adding Shadows to a Texture-Based Volume Renderer**. In Proc. IEEE Symposium on Volume Visualization, 1998, p.39-46.
- Blur the direct light slice by slice



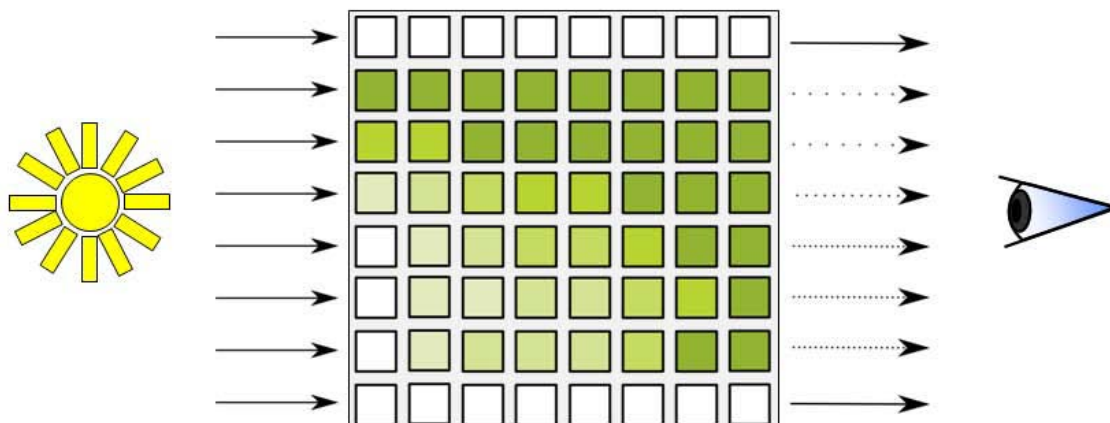
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Generate a 3D Light Map

- **Based on Shadow Volume**

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- Blur the direct light slice by slice



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Scattering 3D Light Map

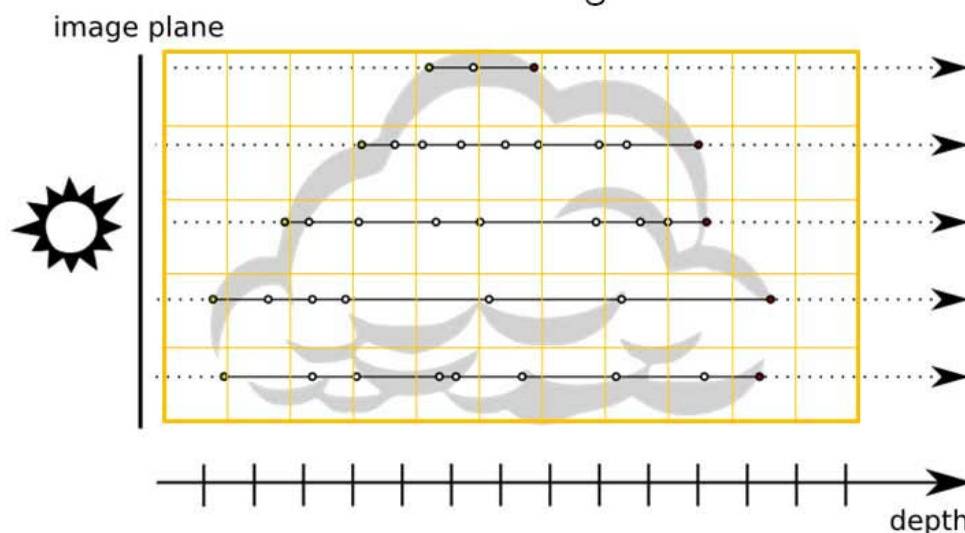


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Calculate a 3D Light Map

- Based on Deep Shadow Map
- Resample the deep shadow map on a *uniform voxel grid*
- *Coarse grid resolution* is sufficient due to the low-frequency nature of volumetric scattering



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Scattering Deep Shadow Map

Direct
light



Direct plus
indirect light

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Light Map Approaches

Shadow Volume Approach

- Calculated in Model Space
 - Limited by Resolution of Shadow Volume
- High Memory Requirements

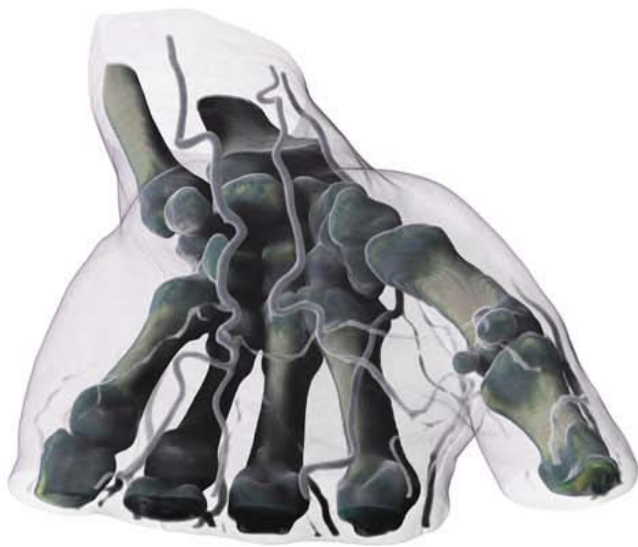
Deep Shadow Map Approach

- Calculated in Screen Space
 - Limited by Resolution of Shadow Volume
- Reduced Memory Requirements
- High Precision

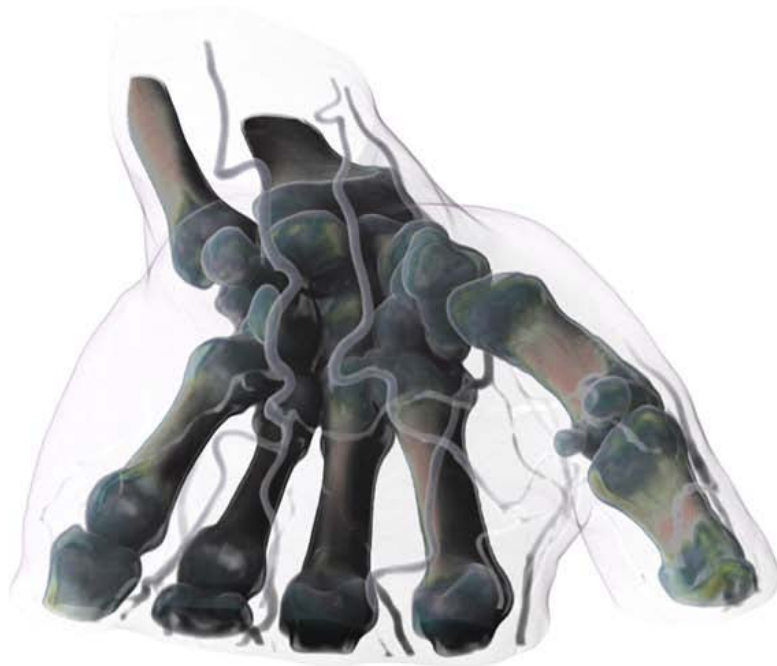
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High Dynamic Range



Direct light and shadows



Direct light, shadows and translucency

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Summary

Scattering Effects

● Single Scattering

- *Filtered Environment Maps*
- *Monte-Carlo Integration*

● Multiple Scattering

- *Monte-Carlo Integration*
- *3D Light Maps*
(*Shadow Volume/Deep Shadow Map*)



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- Images and Slides on Deep Shadow Maps:
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Markus Hadwiger, VRVis, Vienna
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 - Medical data sets courtesy of *Agfa Vienna and Dept. Of Neurosurgery, Medical University Vienna*
 - Chameleon, Cheetah, Bat, Pterosaur
courtesy of *UTCT data archive, University of Texas at Austin*
 - Carp Data set courtesy of *Univ. of Erlangen-Nuremberg*