Eurographics 2009

Advanced Illumination Techniques for GPU-Based Volume Raycasting

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Scattering Effects

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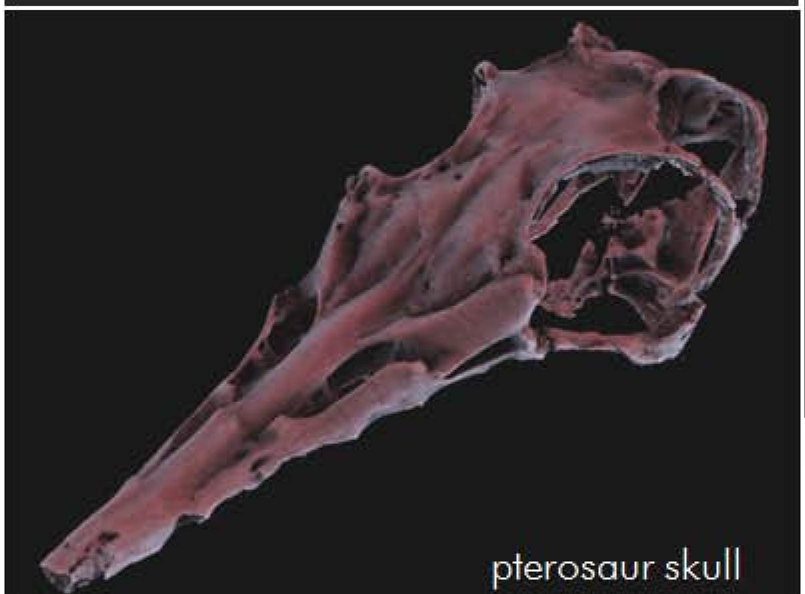
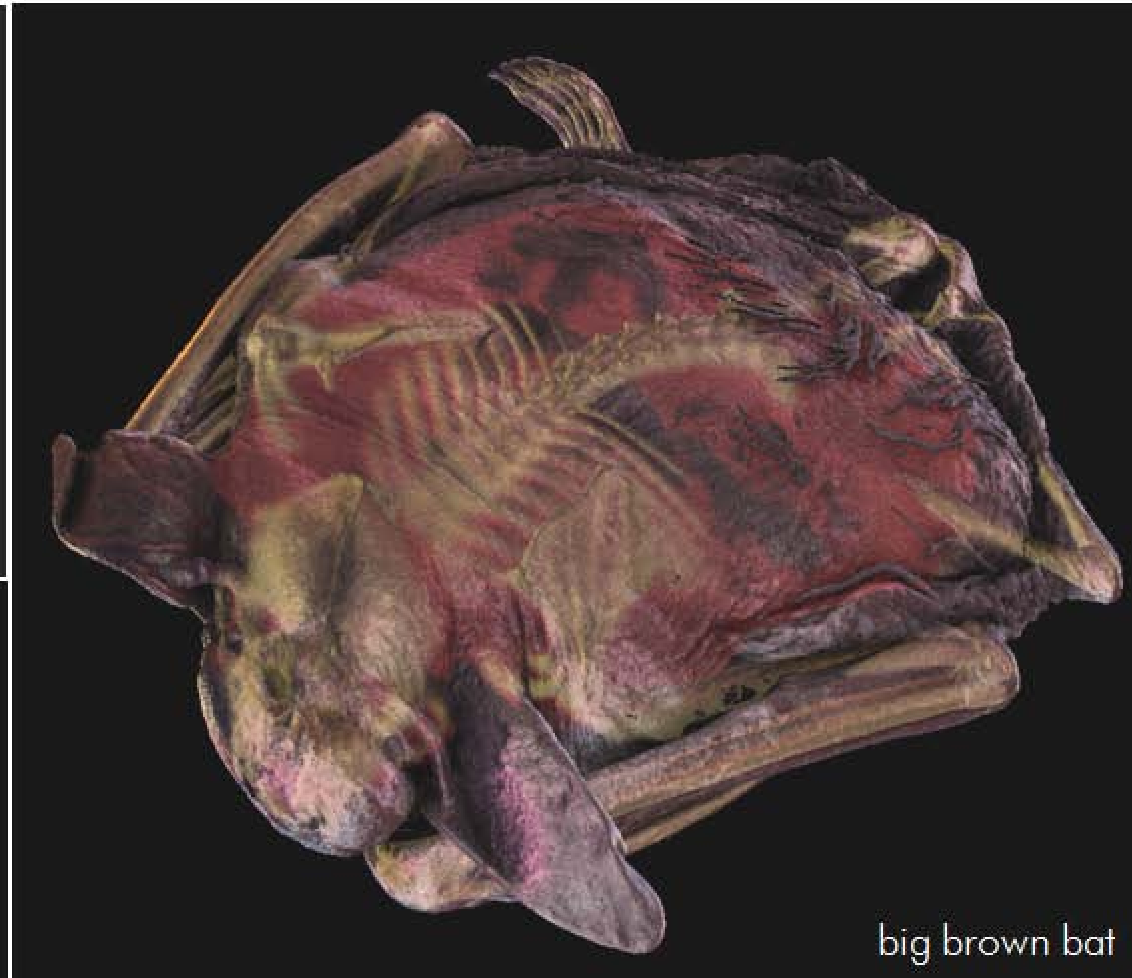
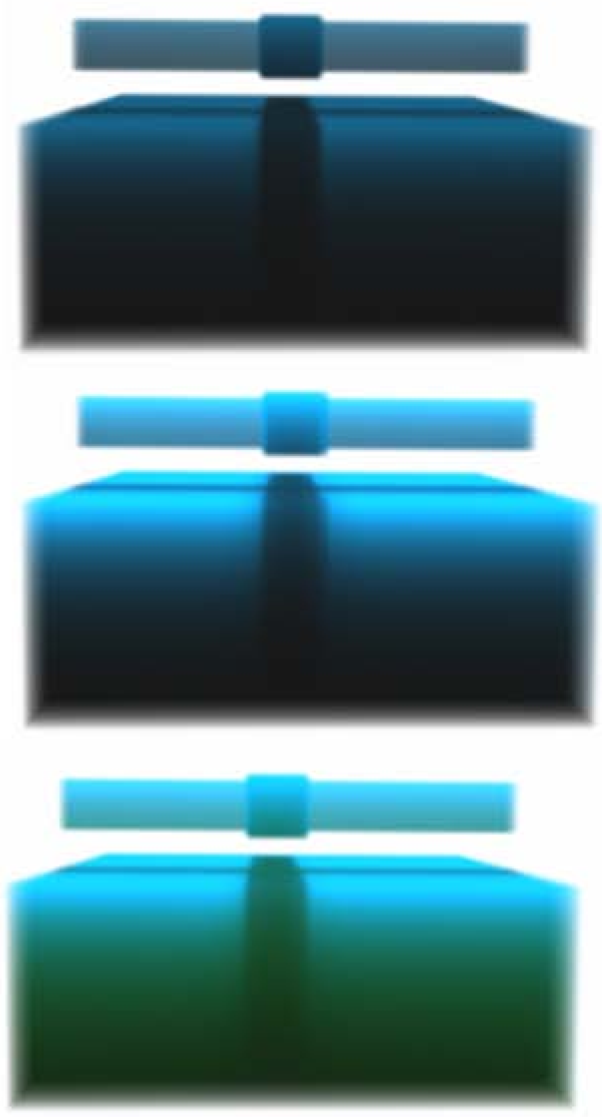
Advanced Illumination





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

Translucency



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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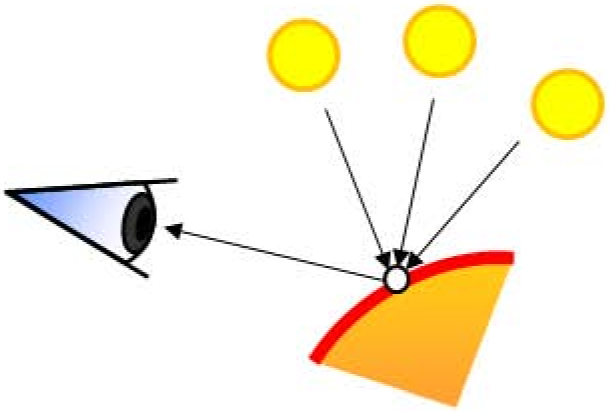
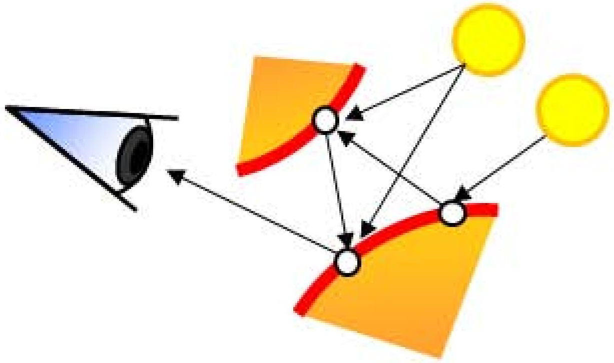
Scattering Effects

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

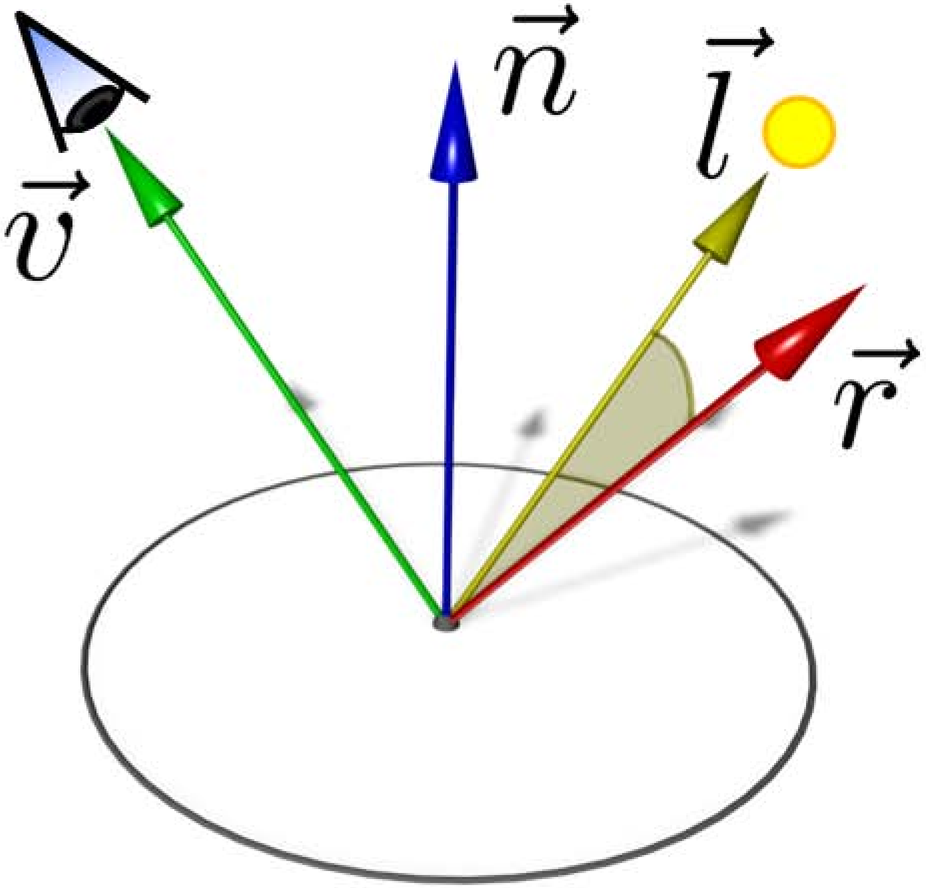


- *Multiple Scattering*
  - Soft shadows
  - Translucency
  - Color bleeding



Single Scattering

Phong illumination with point light sources

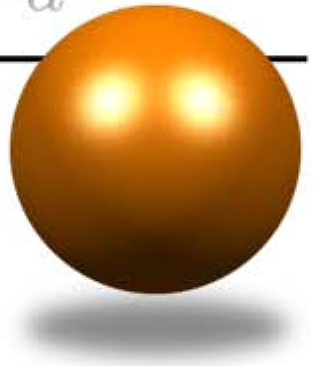


$$I_{\text{Lambert}} = L_d \, k_d \, (\vec{l} \cdot \vec{n})$$

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

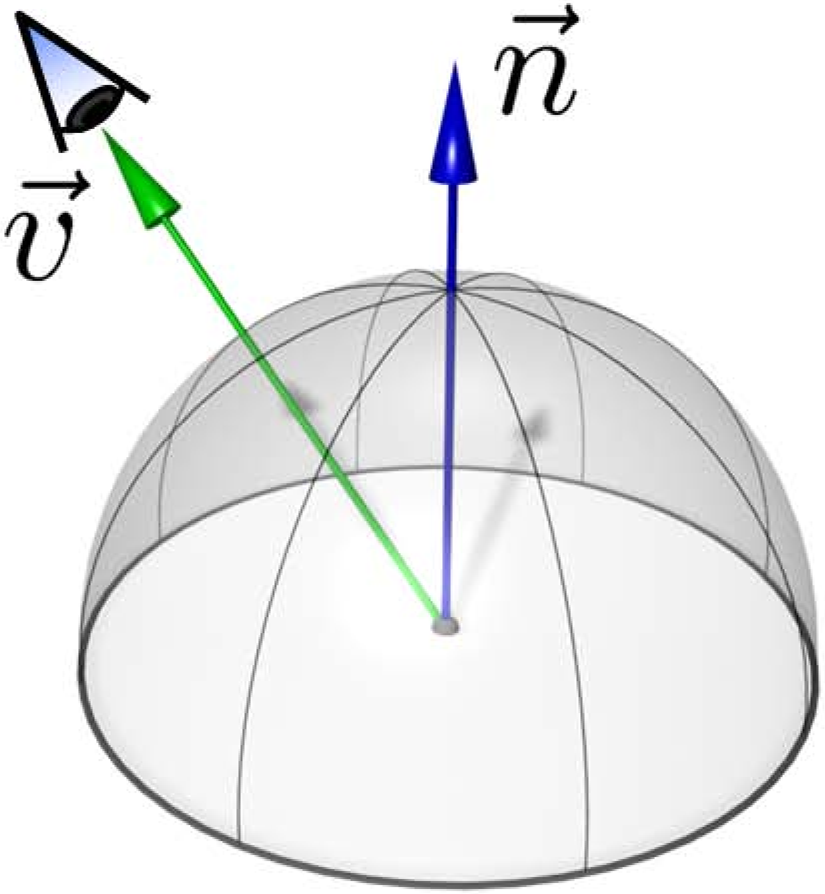
$$I_{\text{Ambient}} = L_a \, k_a$$

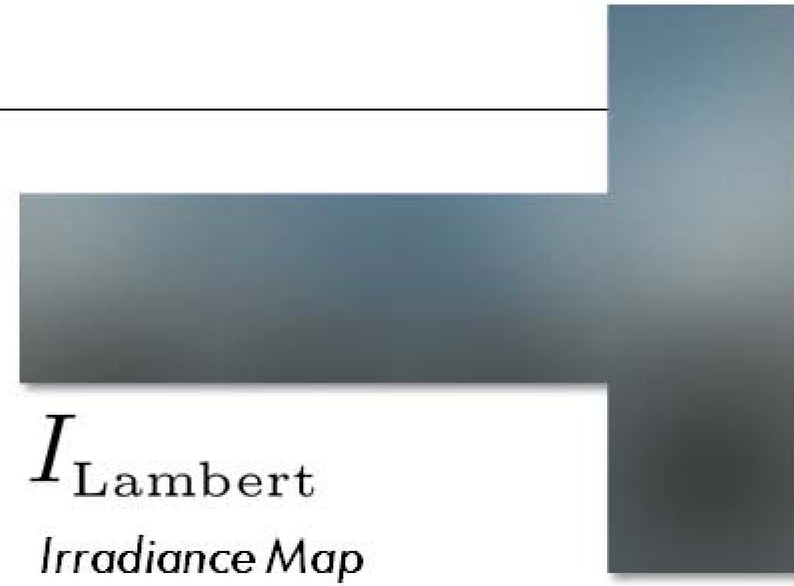
$$I_{\text{Phong}}$$



Single Scattering

Environment Light



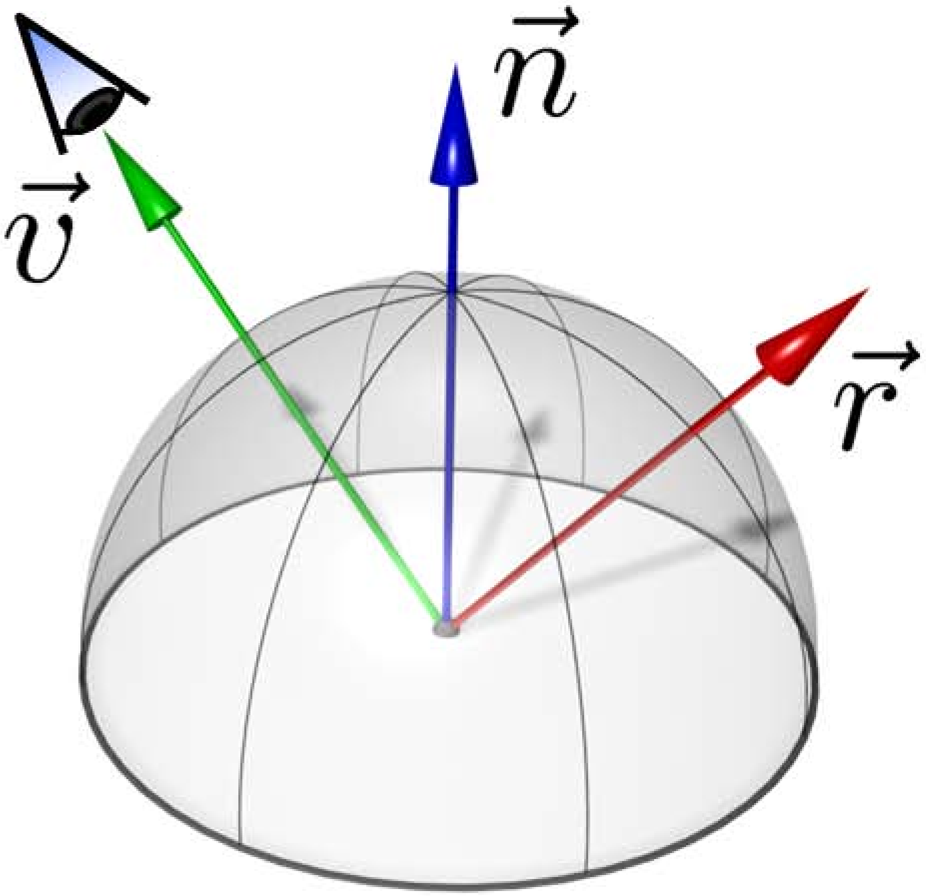


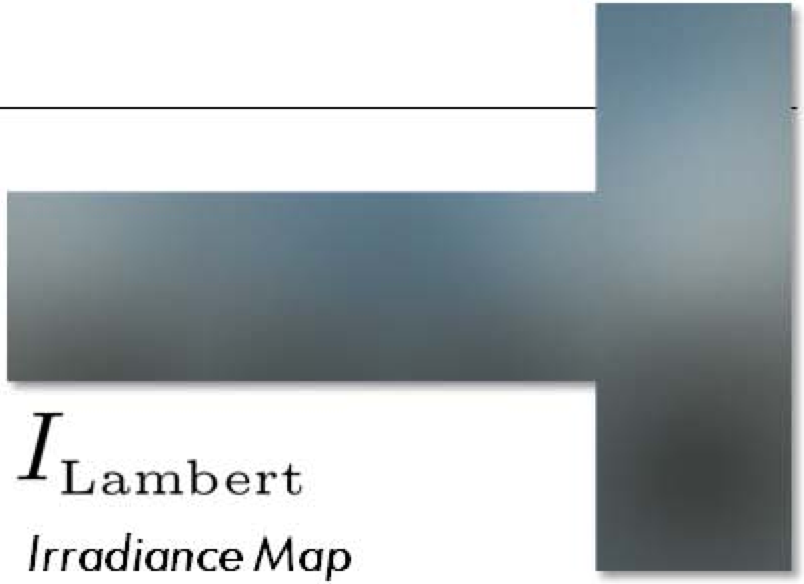
I_{Lambert}

Irradiance Map

Single Scattering

Environment Light





I_{Lambert}

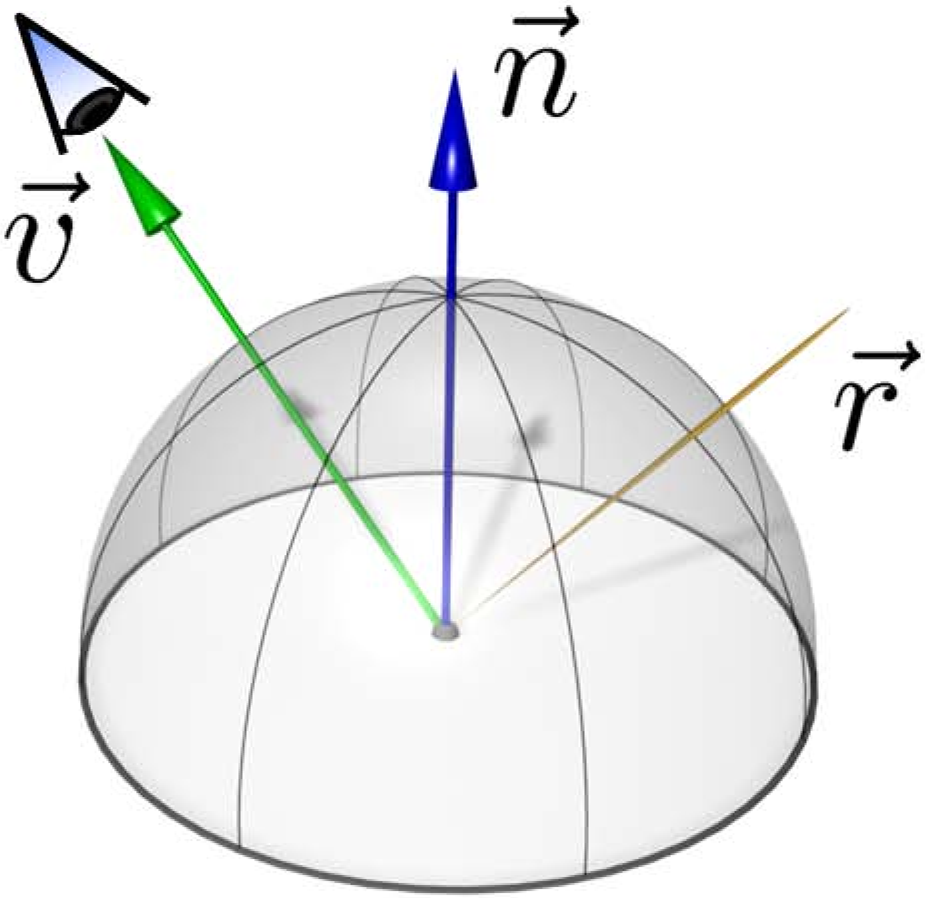
Irradiance Map

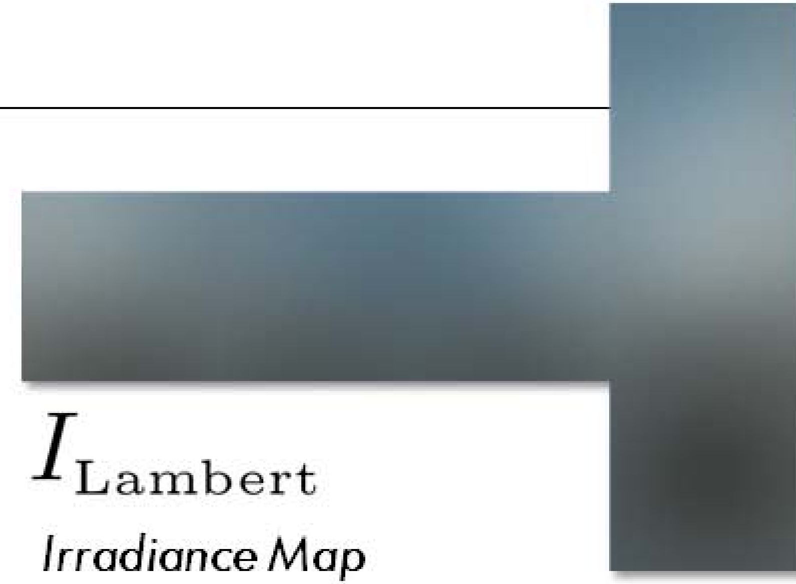
I_{Reflect}

Environment Map

Single Scattering

Environment Light





I_{Lambert}

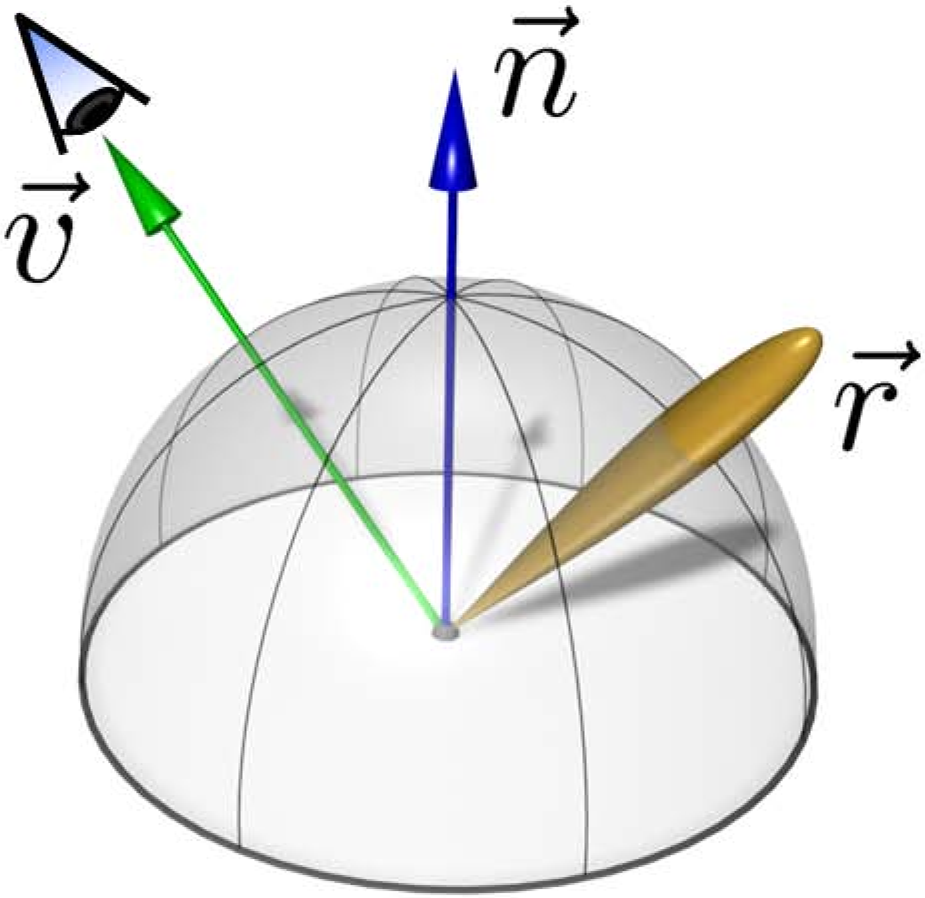
Irradiance Map

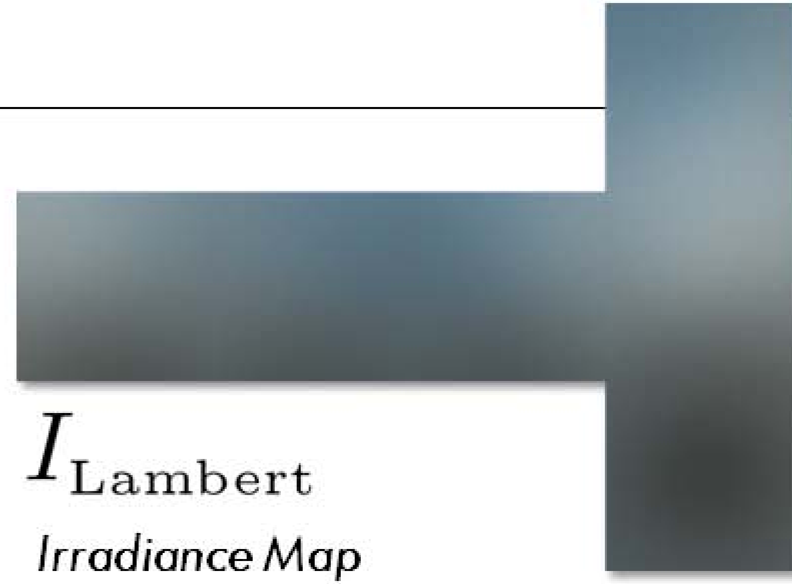
I_{Reflect}

Environment Map

Single Scattering

Environment Light





I_{Lambert}

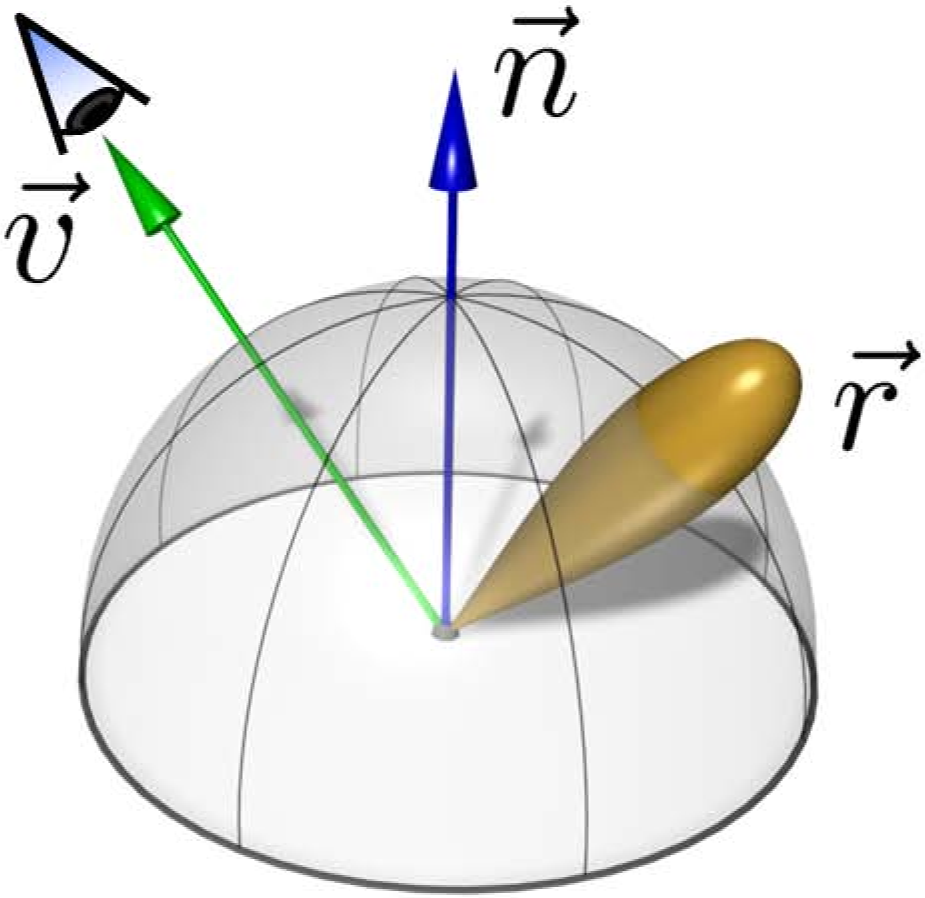
Irradiance Map

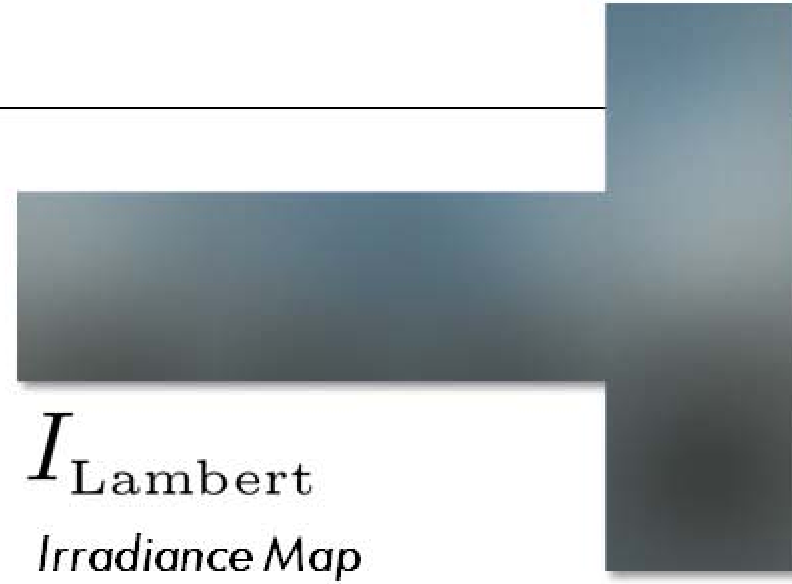
I_{Specular}

Reflection Map

Single Scattering

Environment Light





I_{Lambert}

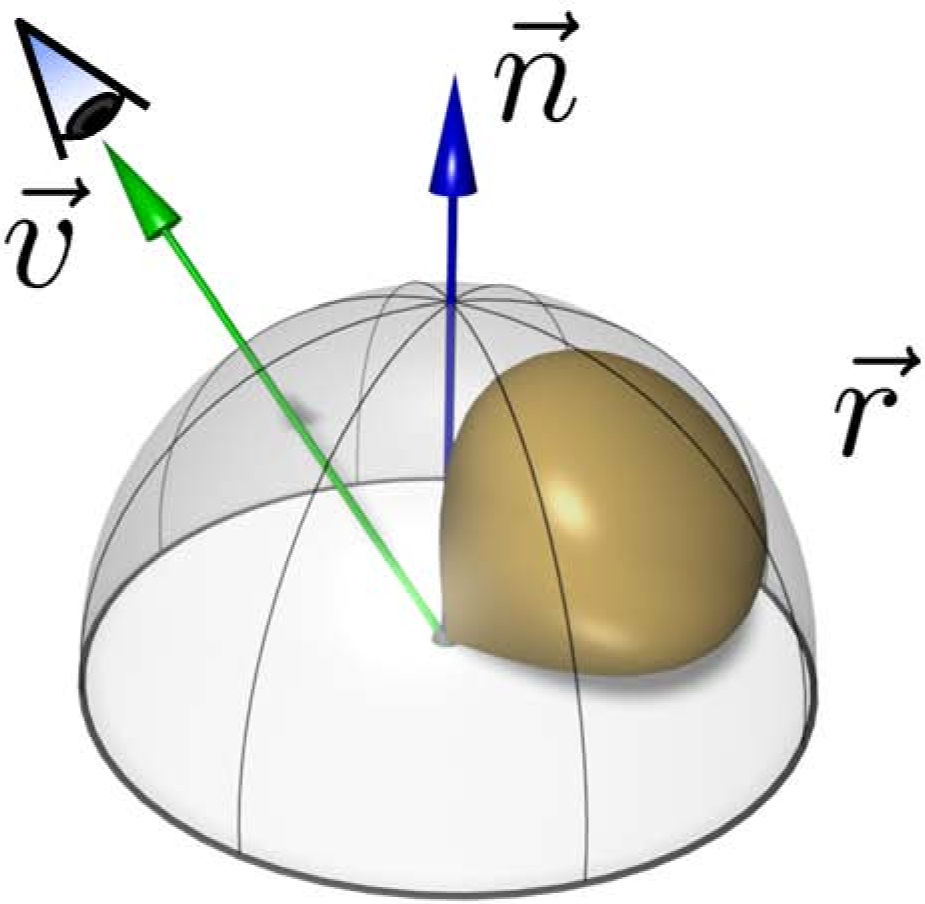
Irradiance Map

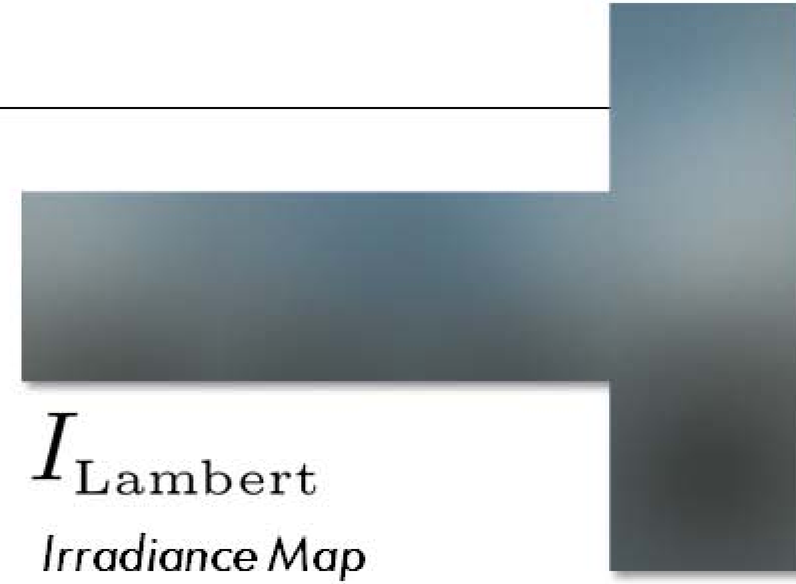
I_{Specular}

Reflection Map

Single Scattering

Environment Light





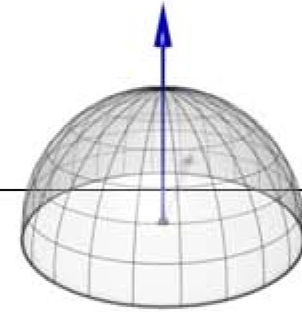
I_{Lambert}

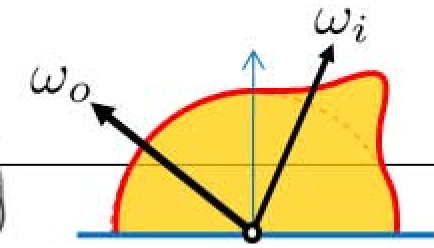
Irradiance Map

I_{Specular}

Reflection Map

Math Notation





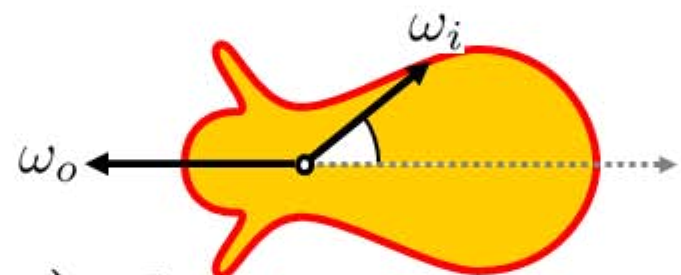
- **Surface Illumination**

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

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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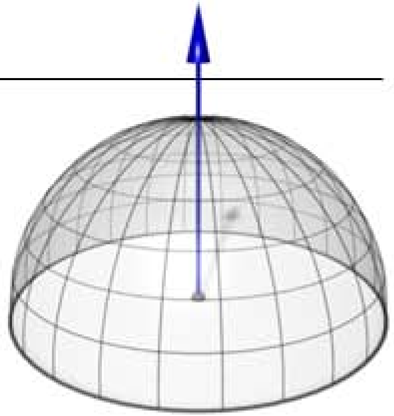
Math Notation

Mathematical Model

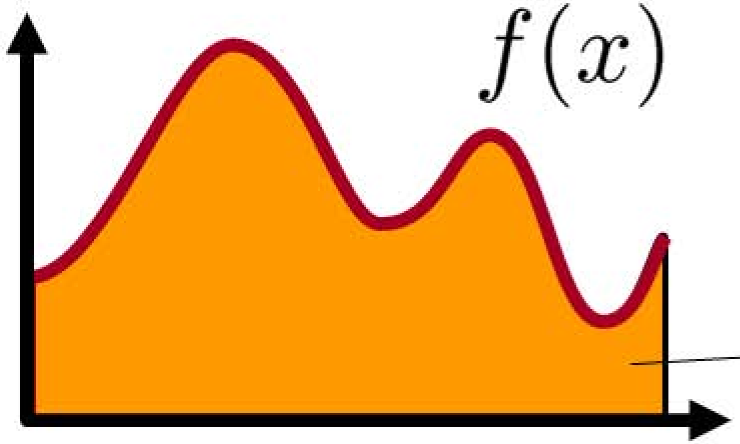
$$L(\mathbf{x},\omega_o) = \int_\Omega p(\mathbf{x},\omega_o \rightarrow \omega_i)\, L(\mathbf{x},\omega_i)\, d\omega_i$$



integrates over the entire sphere/hemisphere

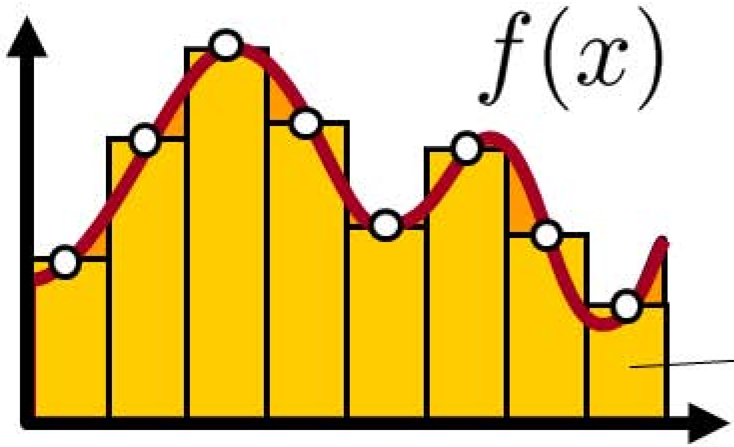
- Integral must be solved for every intersection point
- *Fredholm Equation* (cannot be solved analytically)

Numerical Integration



$$\int_a^b f(x)dx$$

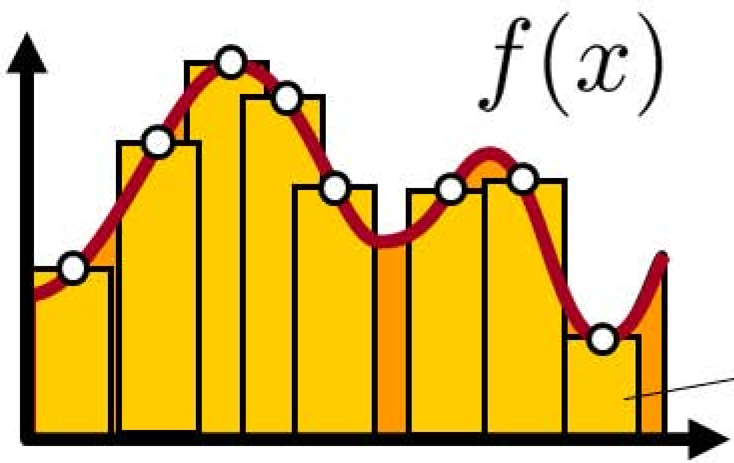
Numerical Integration



Equidistant Sampling

- Approximation integral by a Riemann sum

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

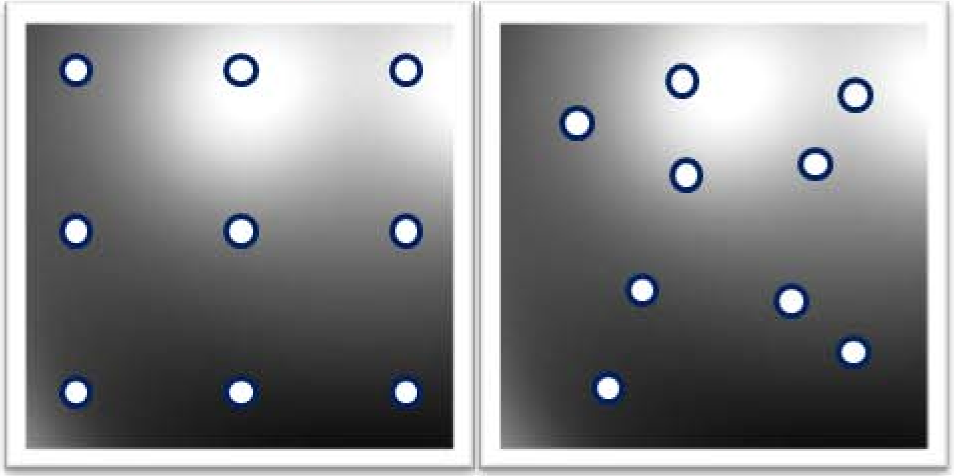


Stochastic Sampling

- 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

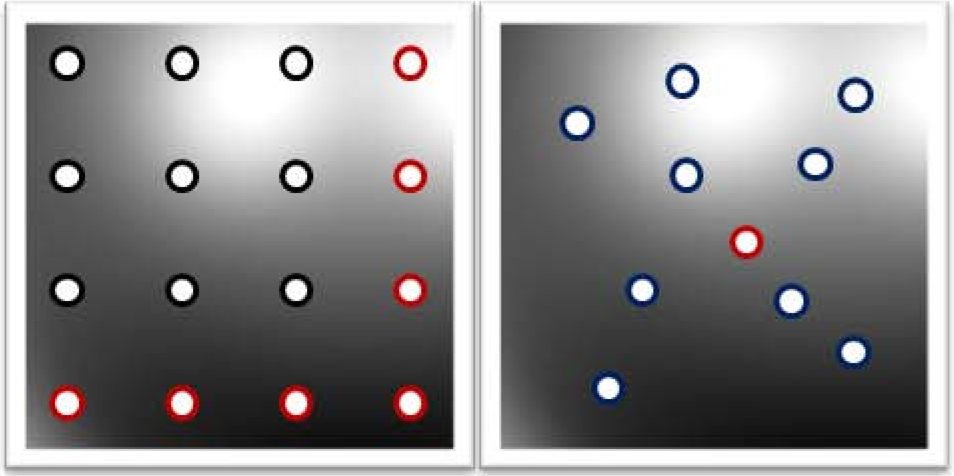
Pros:

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

Stochastic Sampling

Cons:

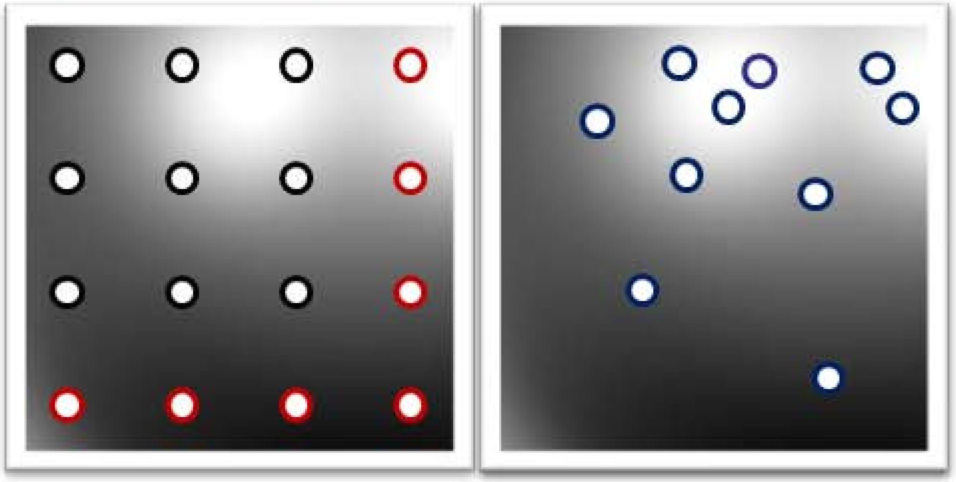
- Slower convergence than Riemann sum



Pros:

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

Stochastic Sampling

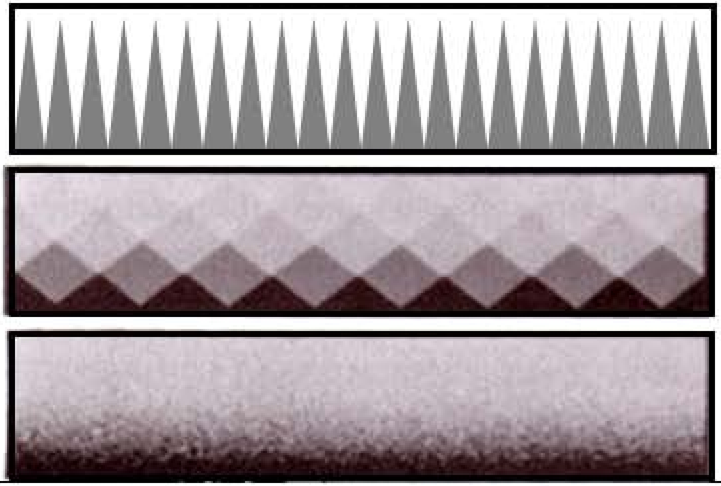


Cons:

- 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!



Blind Monte-Carlo Sampling

Example: Filtering an Environment Map

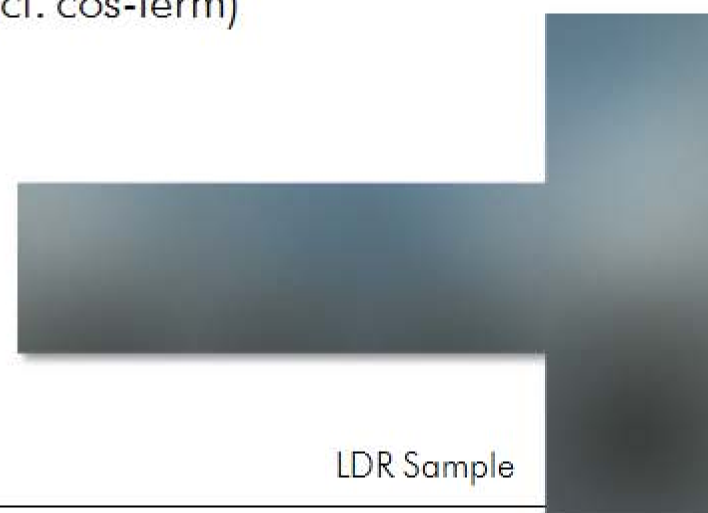
Given an Environment Map

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

Calculate an Irradiance Map

For each pixel of the irradiance map:

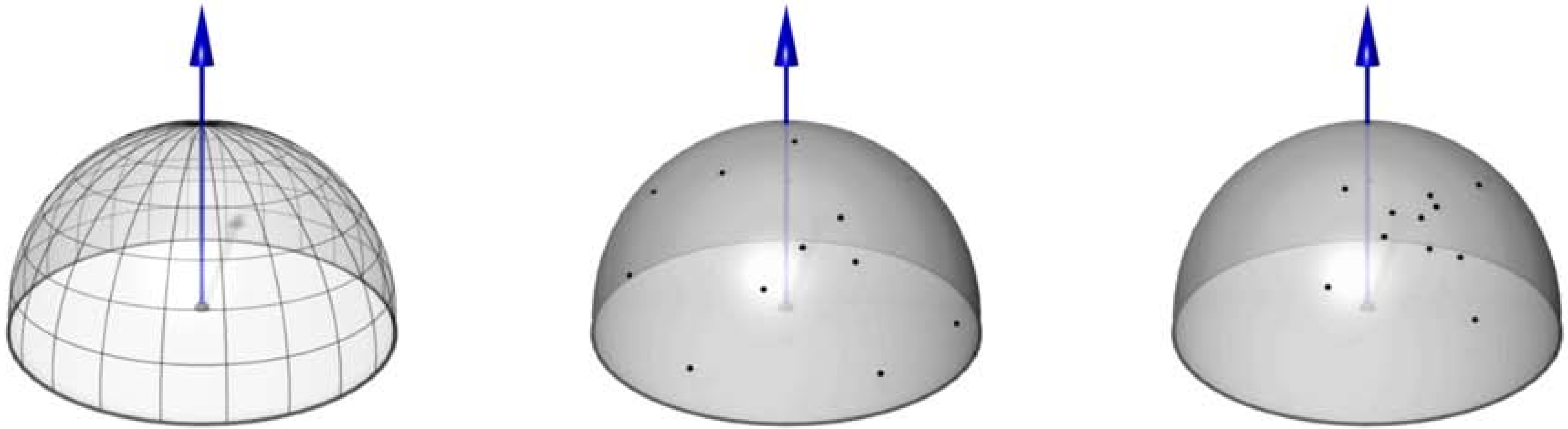
- Determine n random directions on the hemisphere
- Sample the Environment Map and
- Average the results (incl. cos-term)



LDR Sample

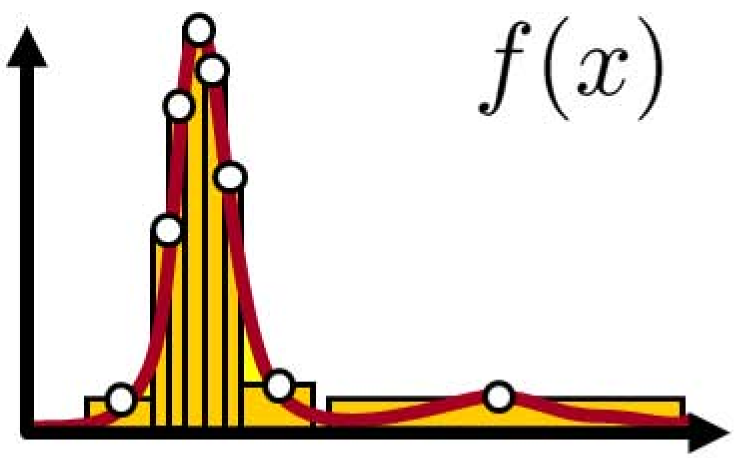
Rendering

- Calculate the radiance from a point
  - depending on the incoming light on the sphere/hemisphere
  - depending on the phase function/BRDF



Deterministic	*Blind Monte-Carlo*	*Importance Sampling*
Uniform sampling of the sphere/hemisphere.	Randomized sampling of the sphere/hemisphere.	*Place samples where* contribution is high
High computational load good approximation	Visually better images for fewer samples, slow convergence	Faster!

Importance Sampling



Stochastic Sampling

- Non-uniformly distributed samples
- Approximation by sum

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

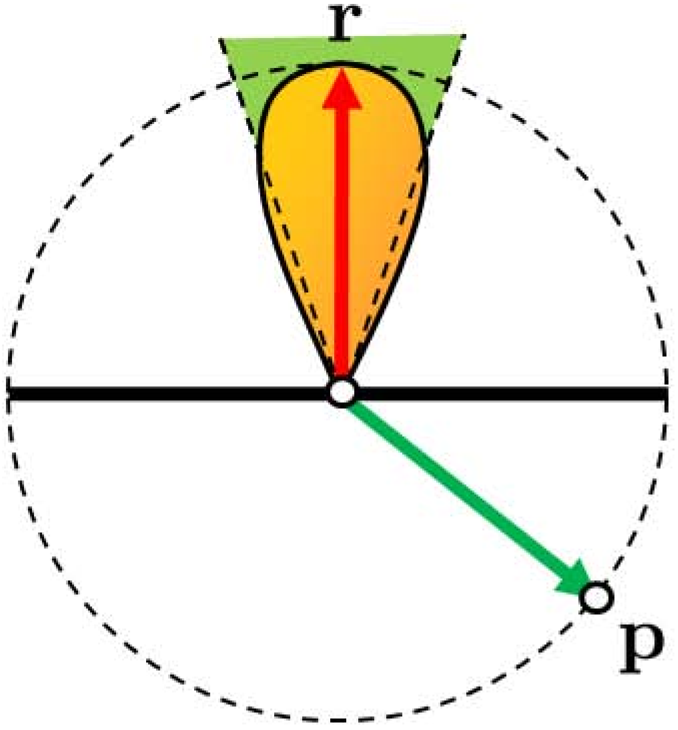
Probability Distribution Function (PDF)

Clever placement of samples

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

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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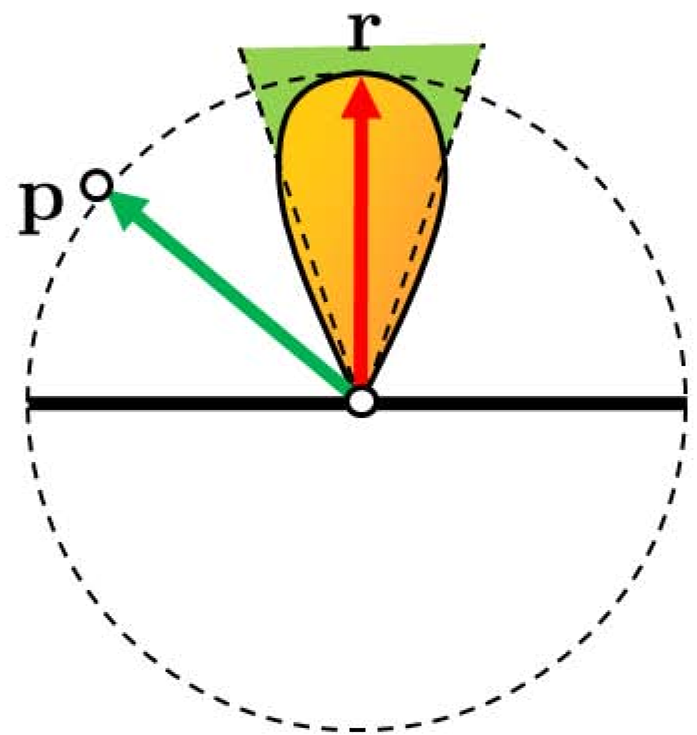
  Idea: uniform distribution of directions restricted to a cone

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



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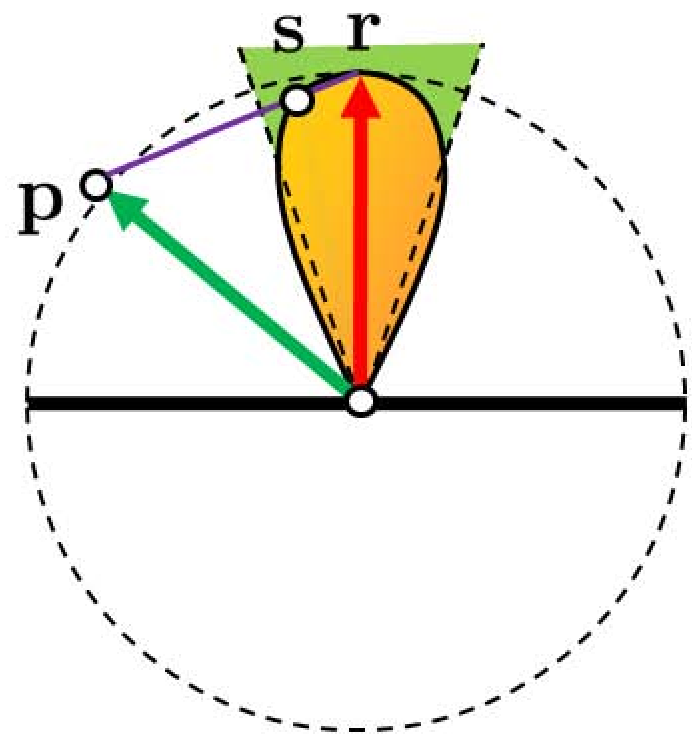
  - Precompute random unit vectors with uniform PDF
  - Randomly pick one vector $\mathbf{p}$
  - Negate vector, if $(\mathbf{r} \cdot \mathbf{p}) < 0$
  - Blend with vector $\mathbf{r}$ and normalize

    $\mathbf{s} = \alpha\,\mathbf{r} + (1 - \alpha)\mathbf{p}$



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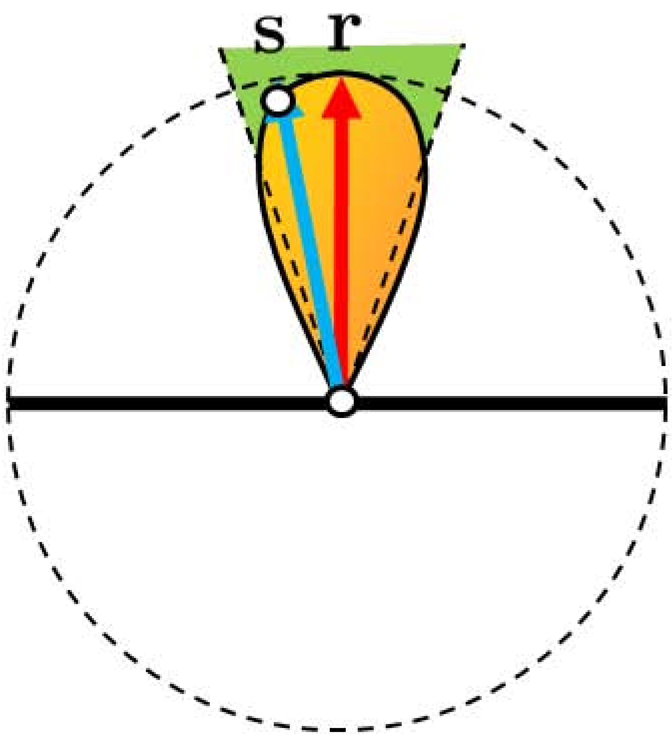
  - Blend with vector $\mathbf{r}$ and normalize

    $$\mathbf{s} = \alpha\,\mathbf{r} + (1 - \alpha)\mathbf{p}$$

  - Blend weight α controls the size of the specular highlight and can be calculated from shininess s



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

unknown

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

known

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

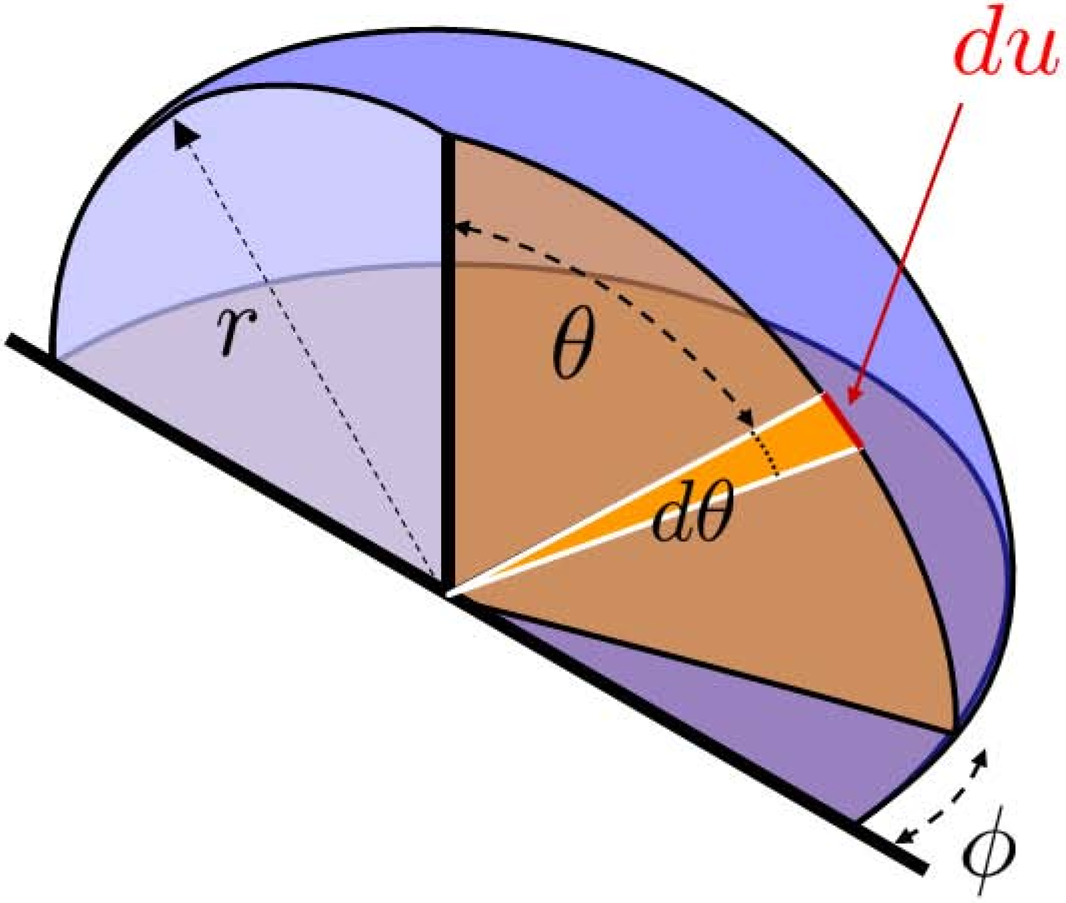
$$\hat{p}(\omega_i) = f(\mathbf{x}, \omega_i \rightarrow \omega_o) \; \cos\theta_i$$

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

Solid Angle

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

$$du = r\, d\theta$$

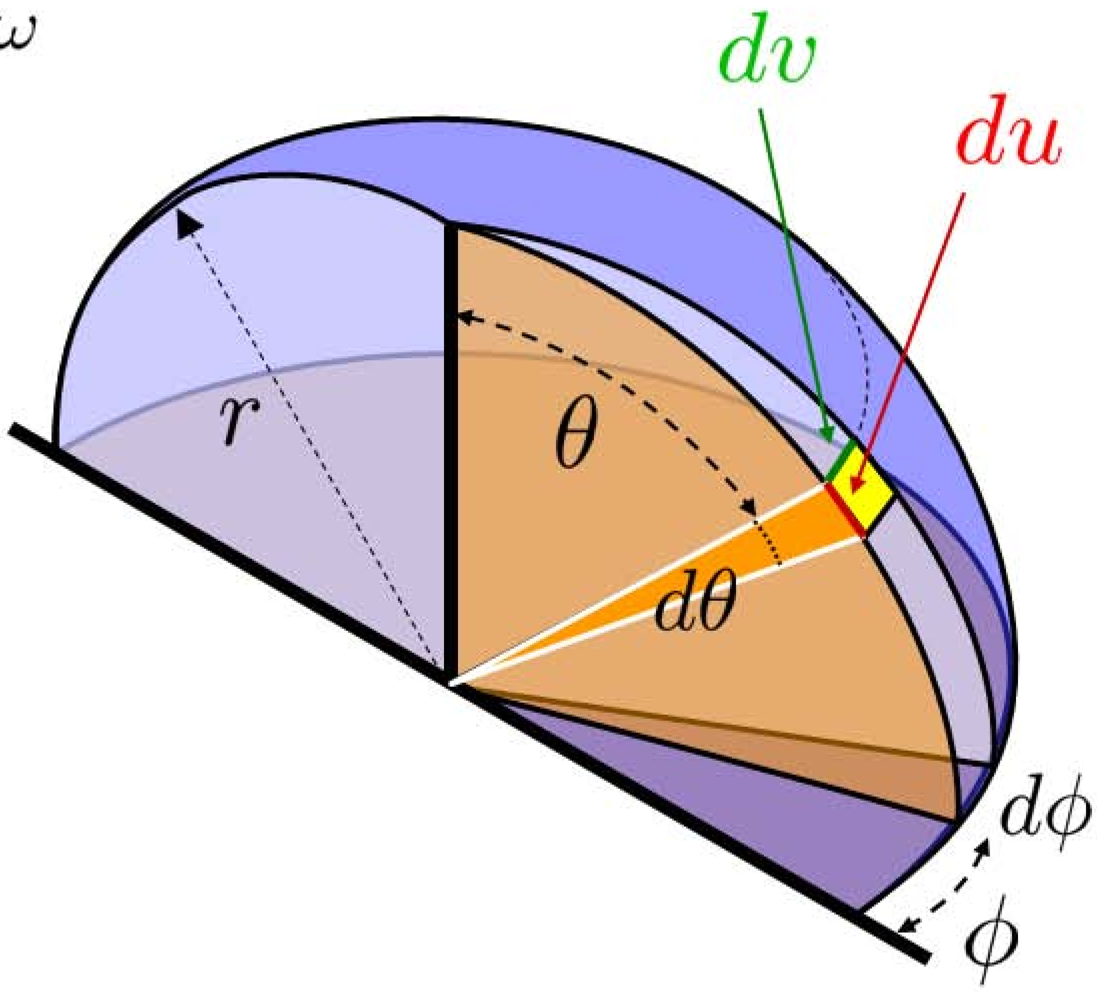


Solid Angle

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

$$du = r \, d\theta$$

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



Solid Angle

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

$$du = r\, d\theta$$

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

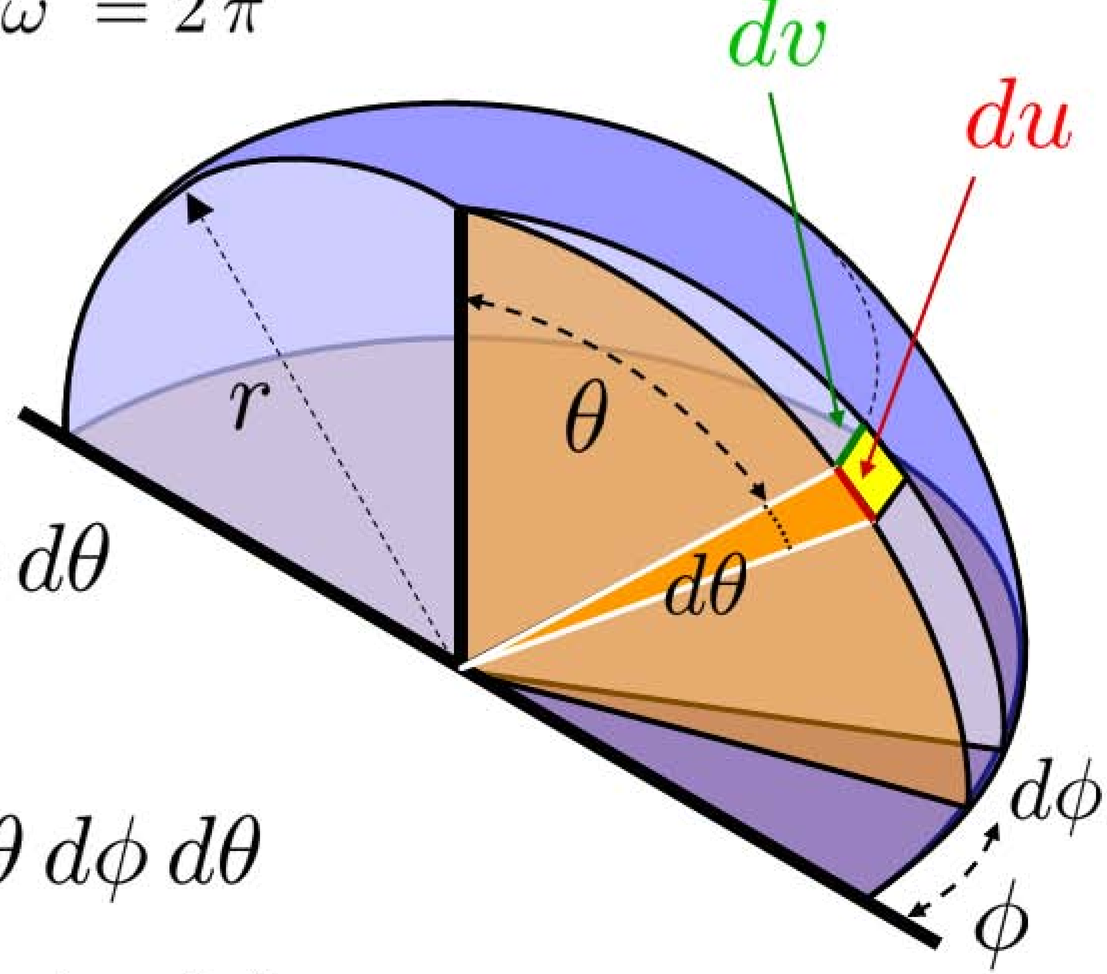
Area (yellow):

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

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**

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

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

Sampling a Specular Lobe

- **Ideal Sampling**

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

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

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

- Convert to CDF and invert

$$\theta_i = \cos^{-1} \xi_1^{\left(\frac{1}{n+1}\right)} \qquad \phi_i = 2\pi\xi_2$$

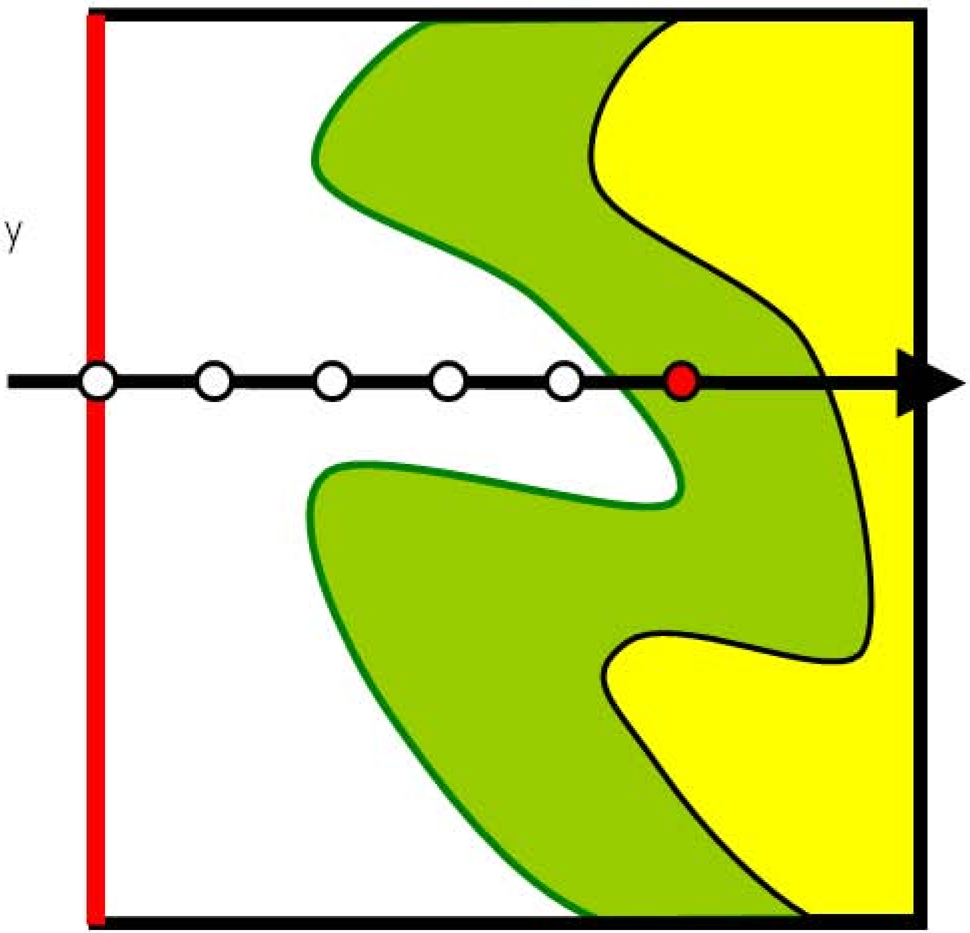
Importance Sampling

Literature:

- M. Pharr, G. Humphries: **Physically Based Rendering**, Morgan Kauffman (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 intersaction point with isosurface by sampling along the ray



GPU Ray-Casting

- Calculate First Intersection with Isosurface
  - Rasterize the front faces of the bounding box
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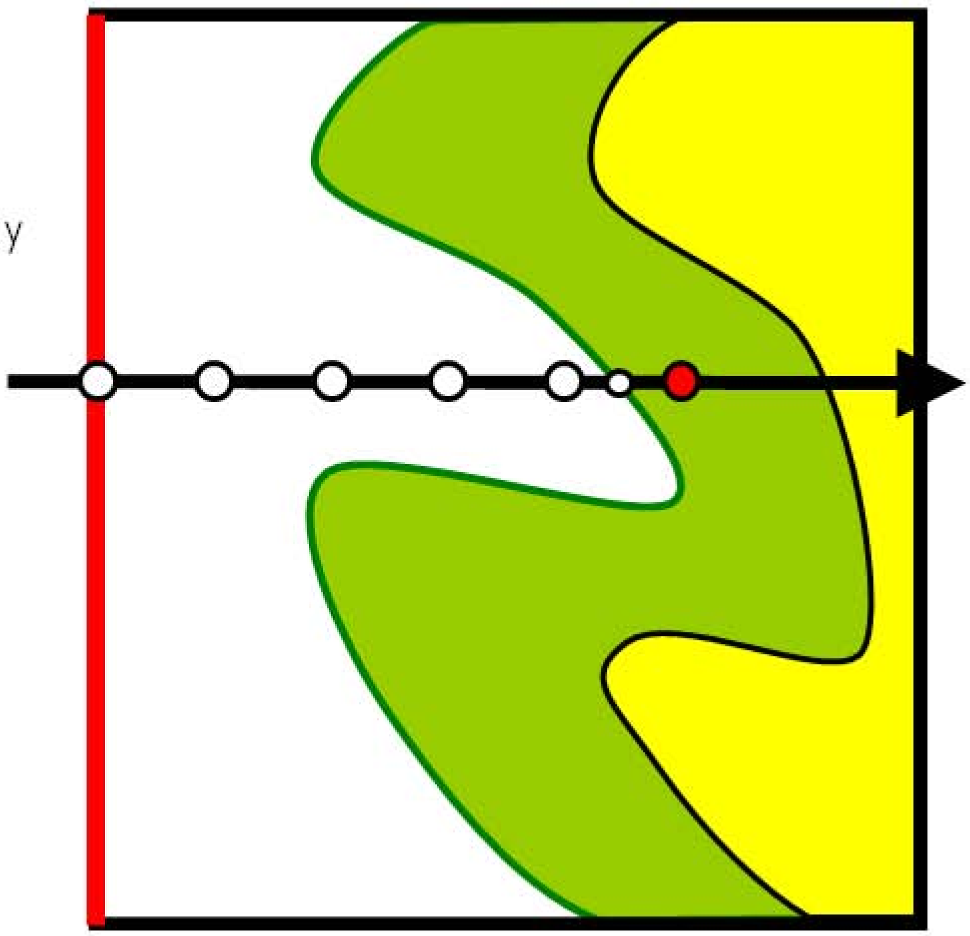
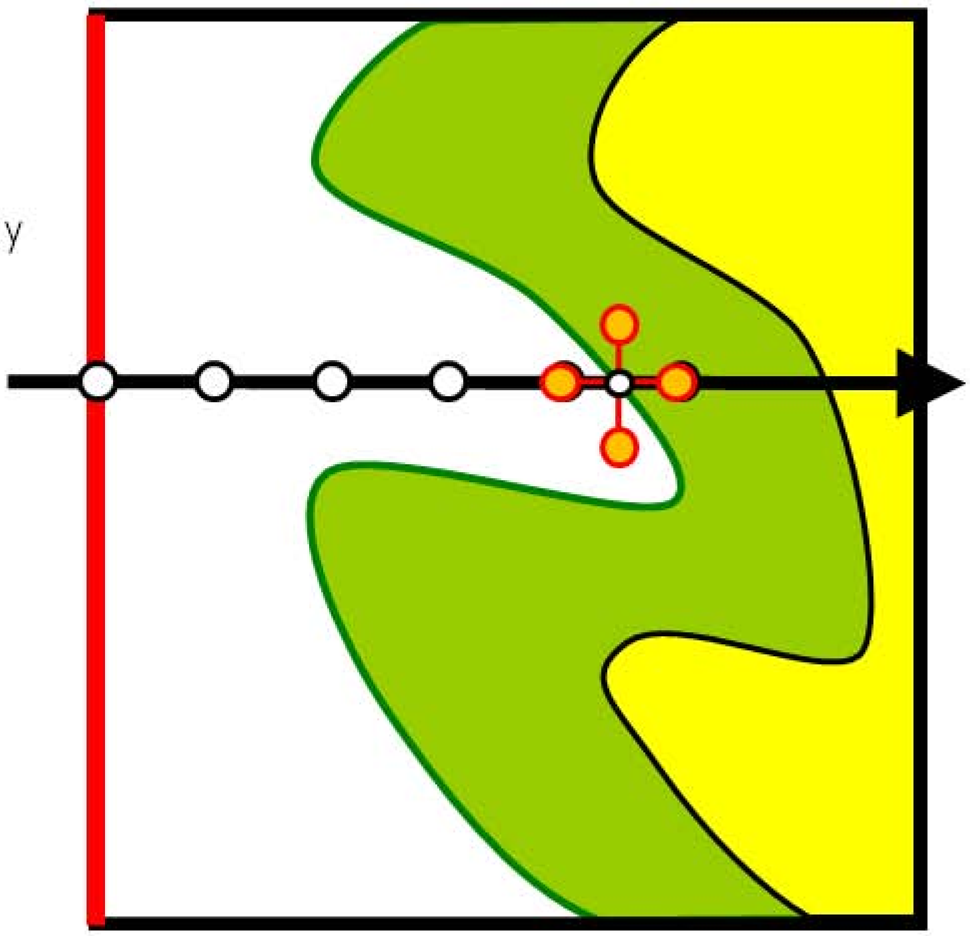
  - Find first intersaction point with isosurface by sampling along the ray
    - interval bisection



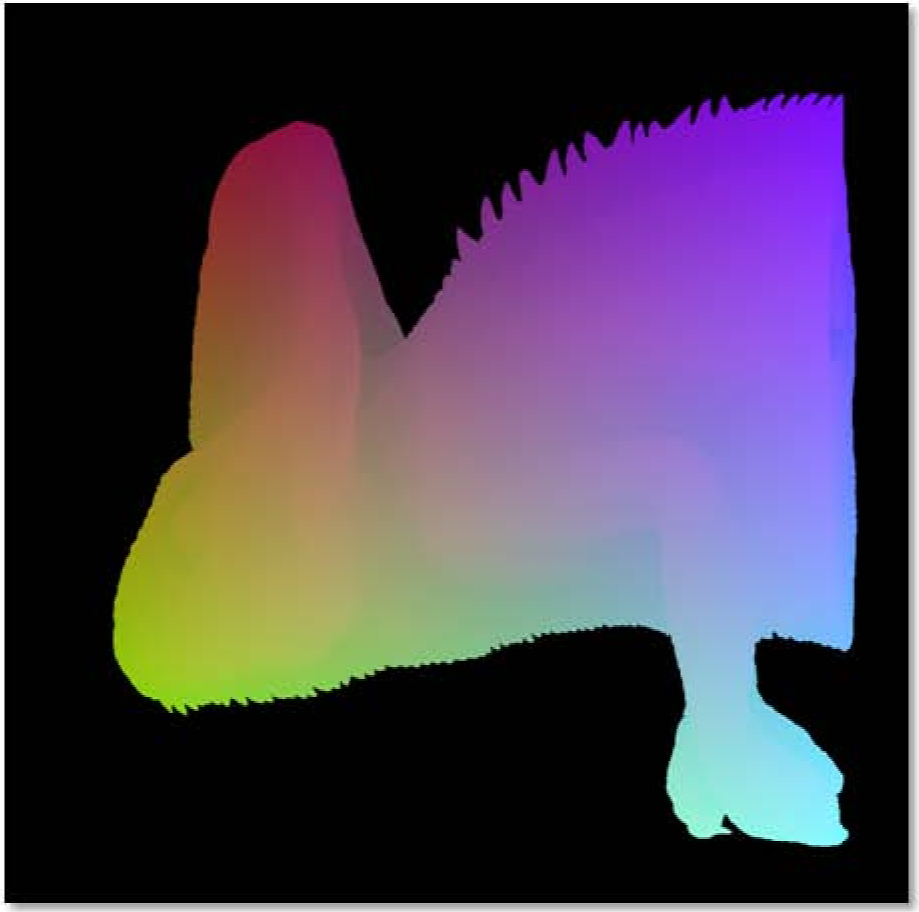
GPU Ray-Casting

Calculate First Intersection with Isosurface

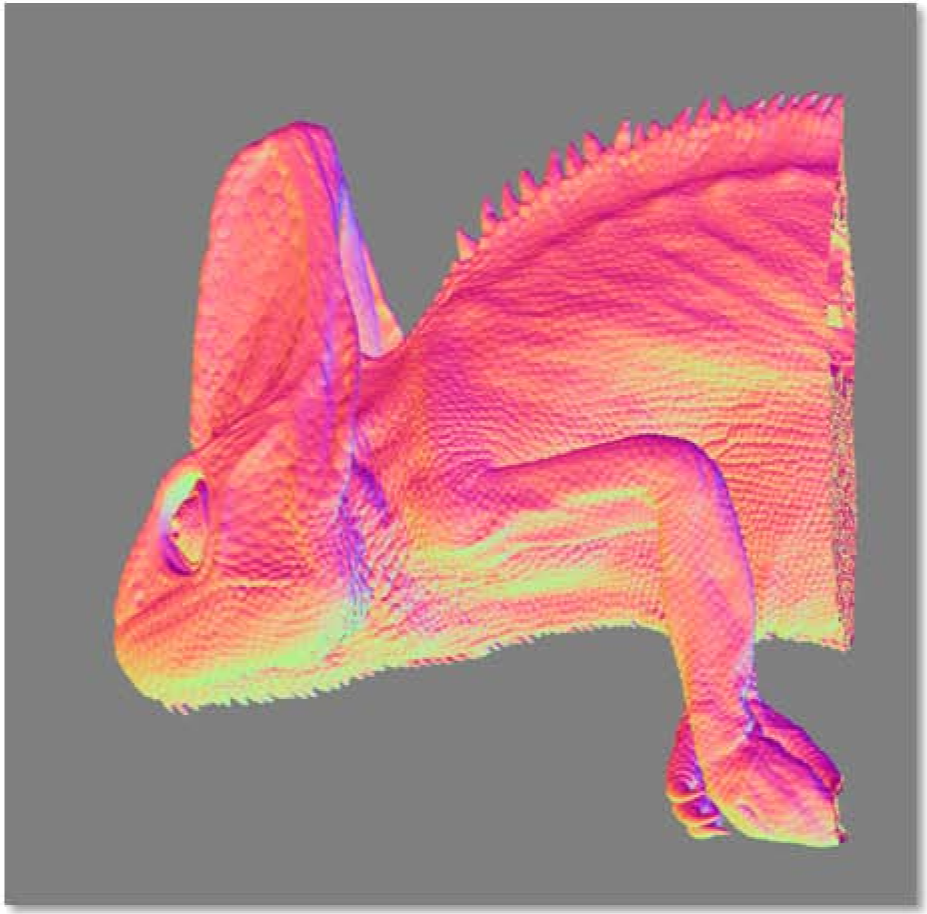
- Rasterize the front faces of the bounding box
- For each fragment, cast a ray
- Find first intersaction point with isosurface by sampling along the ray
    - interval bisection
- Store the intersection point in render target 0
- Estimate the gradient vector using central differences
- Store the gradient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



First Render Pass



MRT0: xyz-coordinates of first intersection point with isosurface

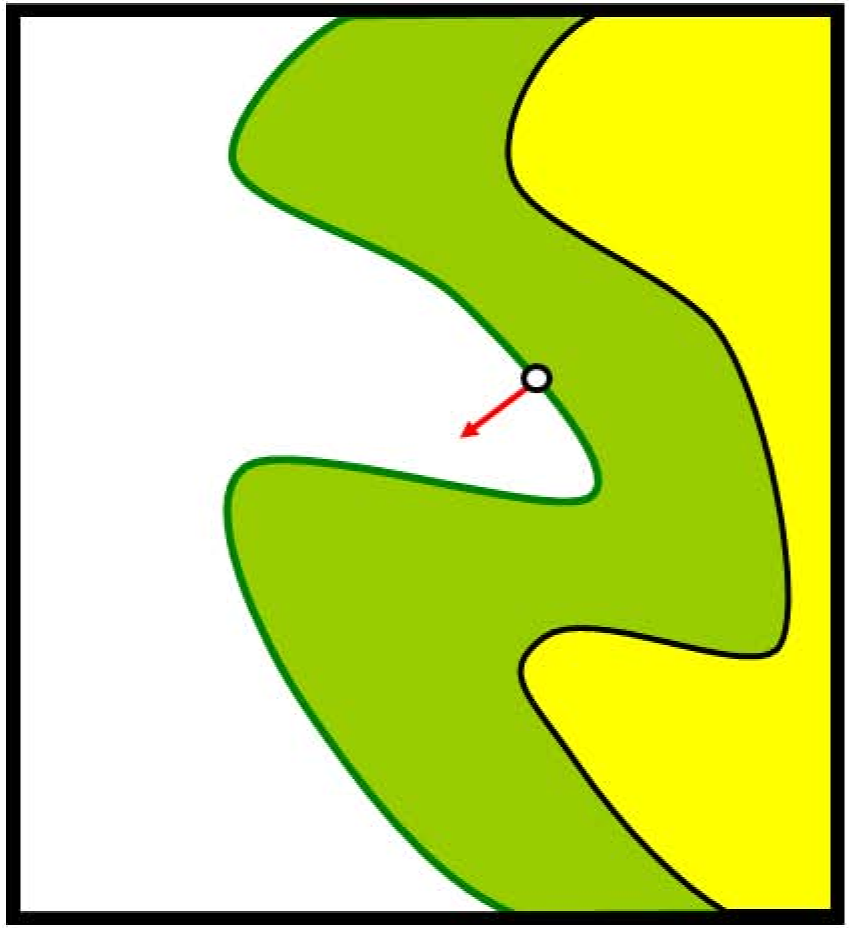


MRT1: xyz-components of gradient vector (color coded)

Deferred Shading

Single Scattering (no shadows)

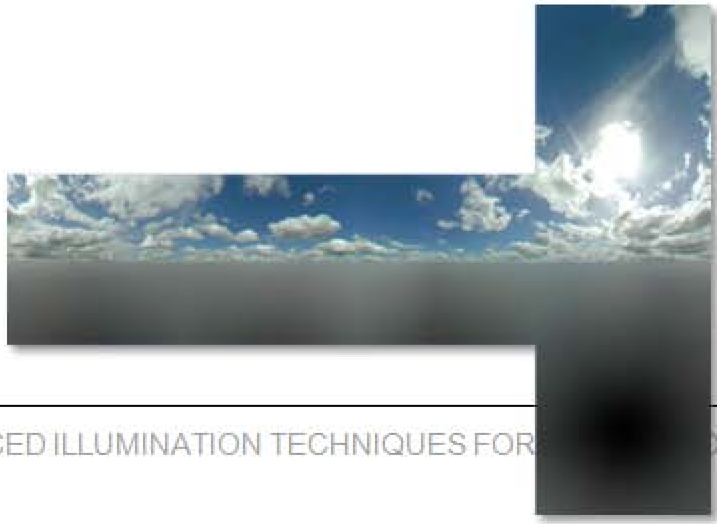
- Diffuse term:
  - Sample irradiance cube using gradient direction

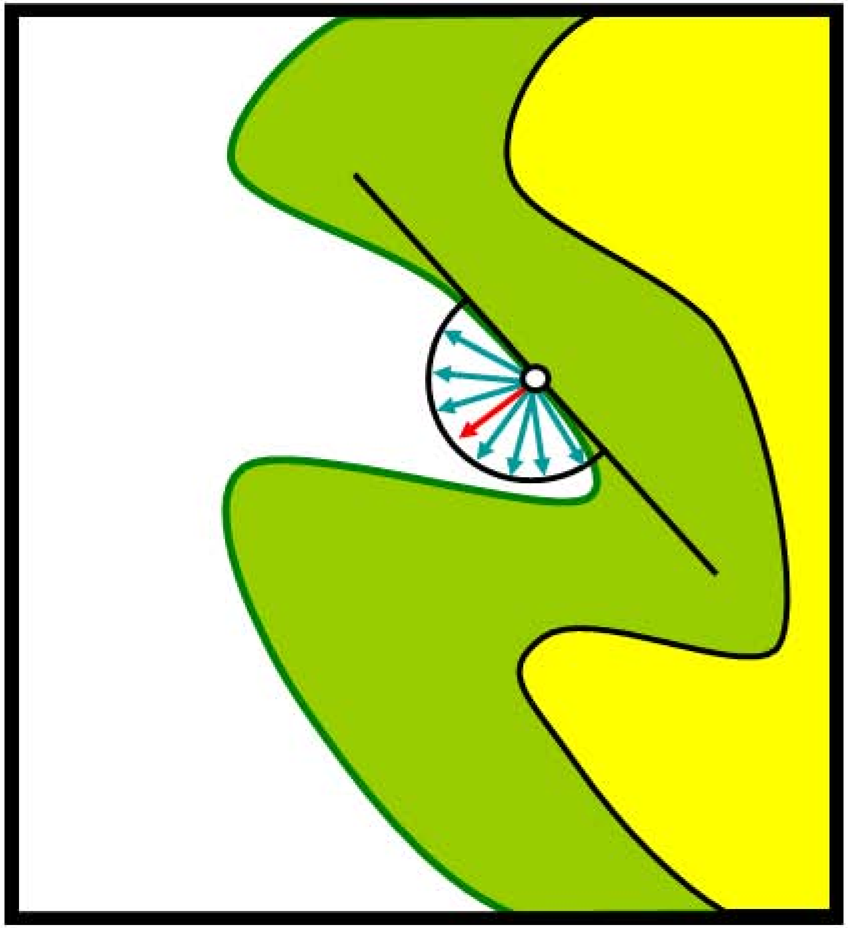


Deferred Shading

Single Scattering (no shadows)

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

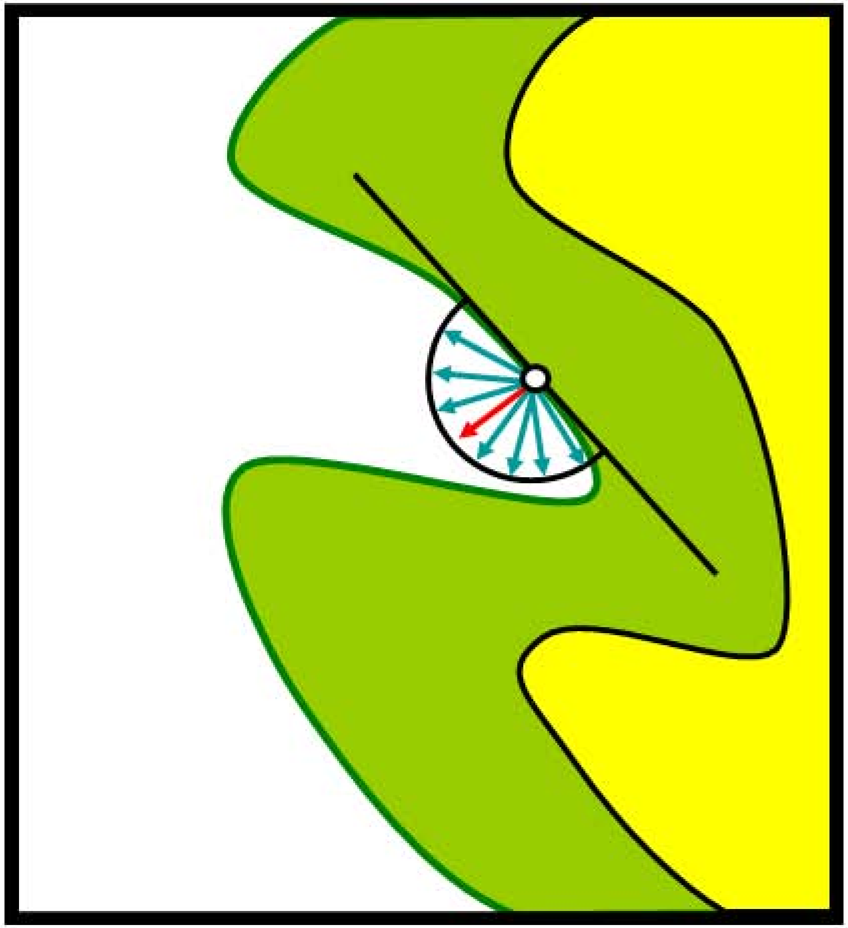




Deferred Shading

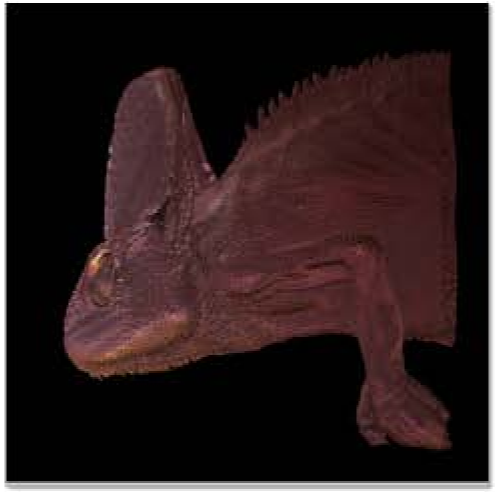
Single Scattering (no shadows)

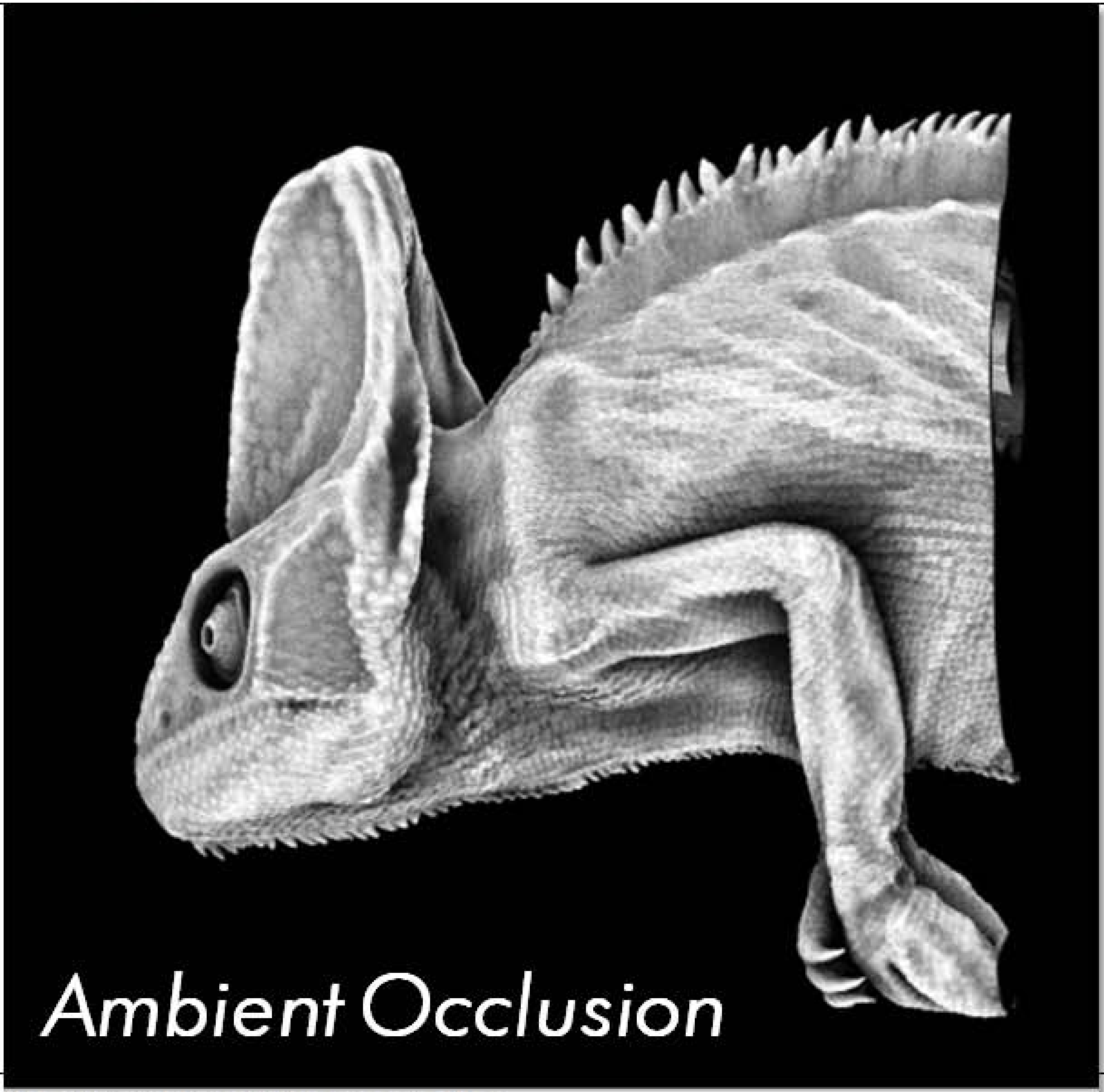
- Diffuse term:
  - Sample irradiance cube using gradient direction
- Specular term:
  - Calculate random directions on the specular lobe
  - Sample environment cube
  - Weight each sample with its BRDF/phase function and its probability distribution



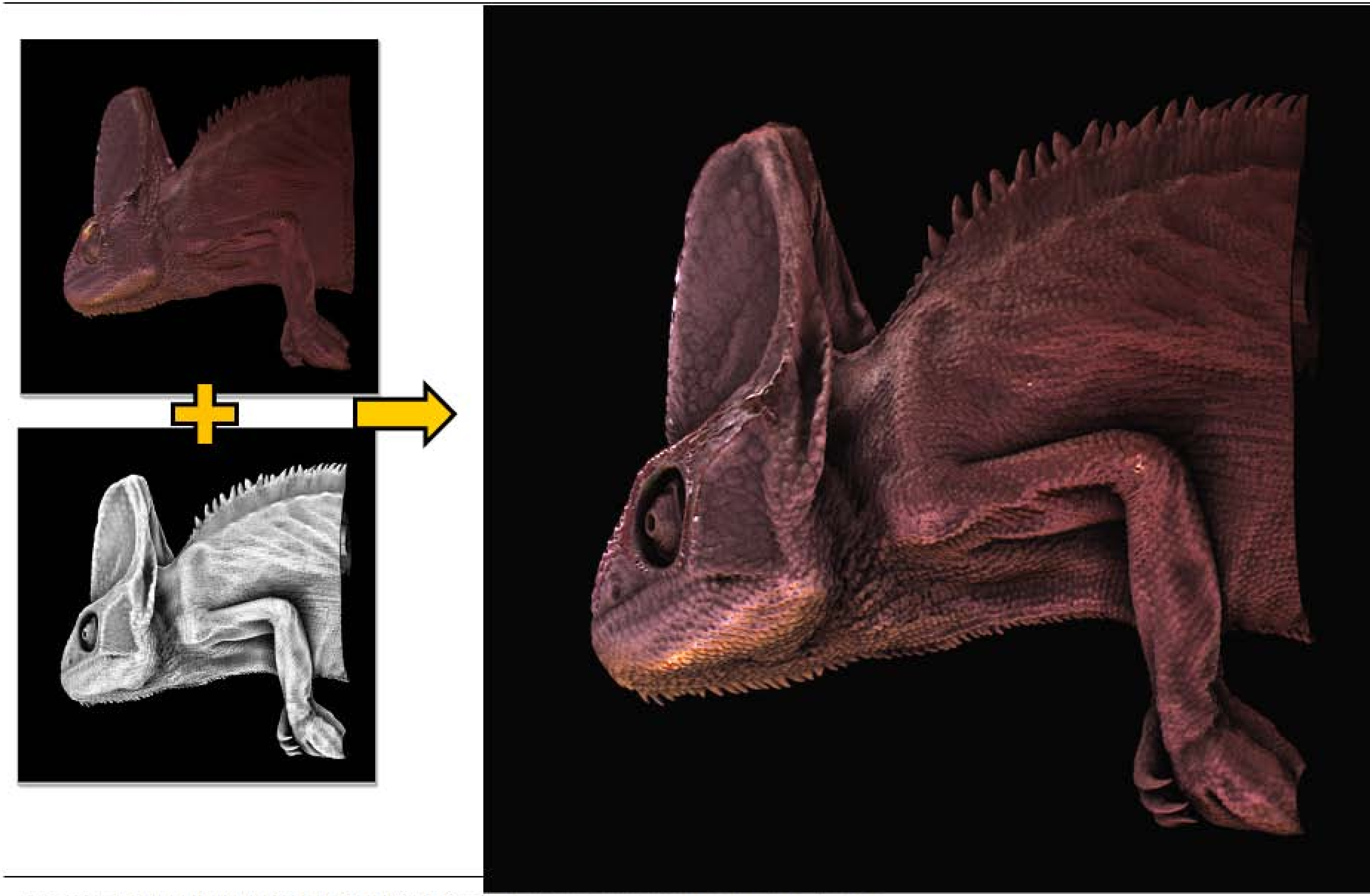
High Quality Isosurface

High Quality Isosurface





High Quality Isosurface



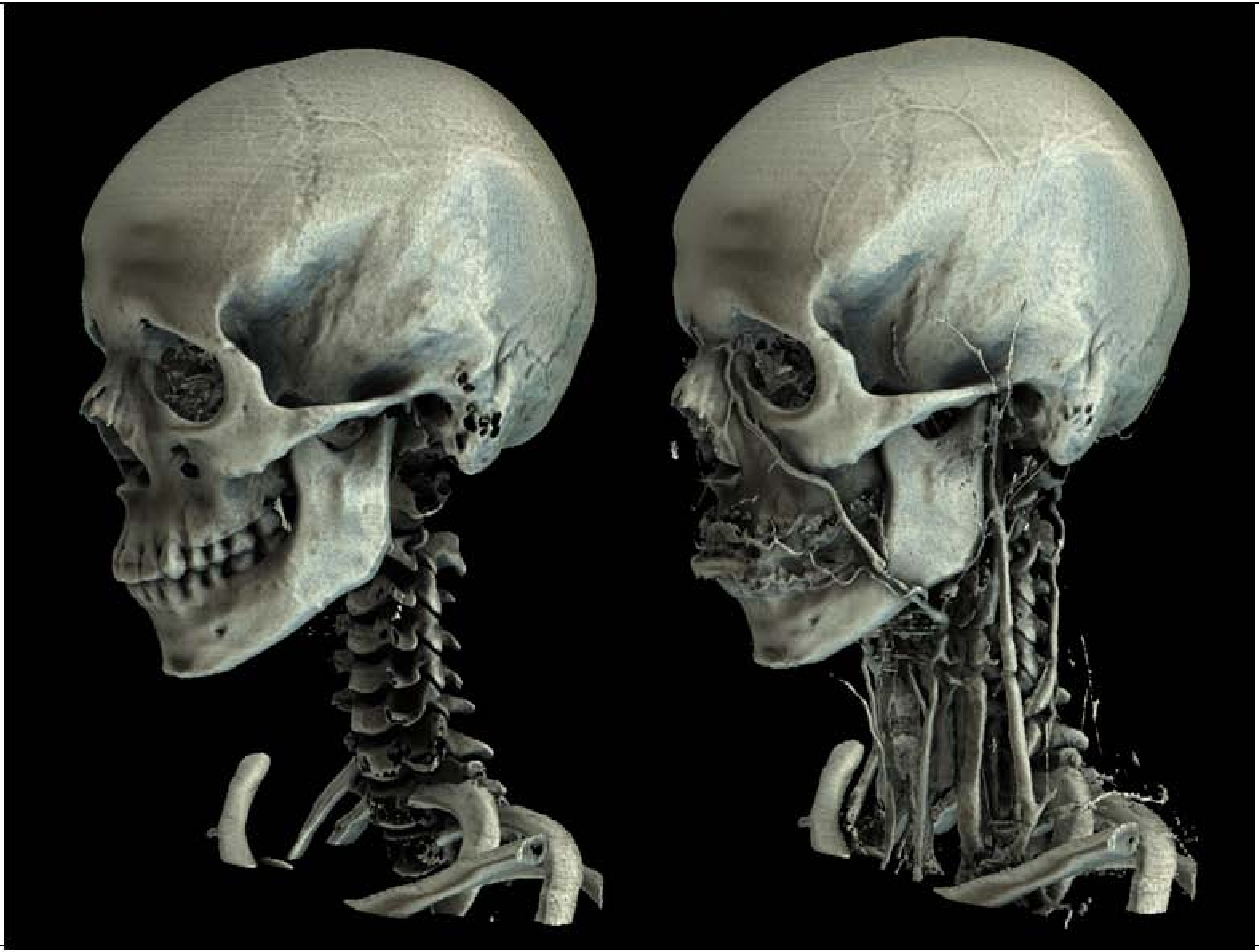
Our First Implementation

Why not use a pre-filtered environment map?

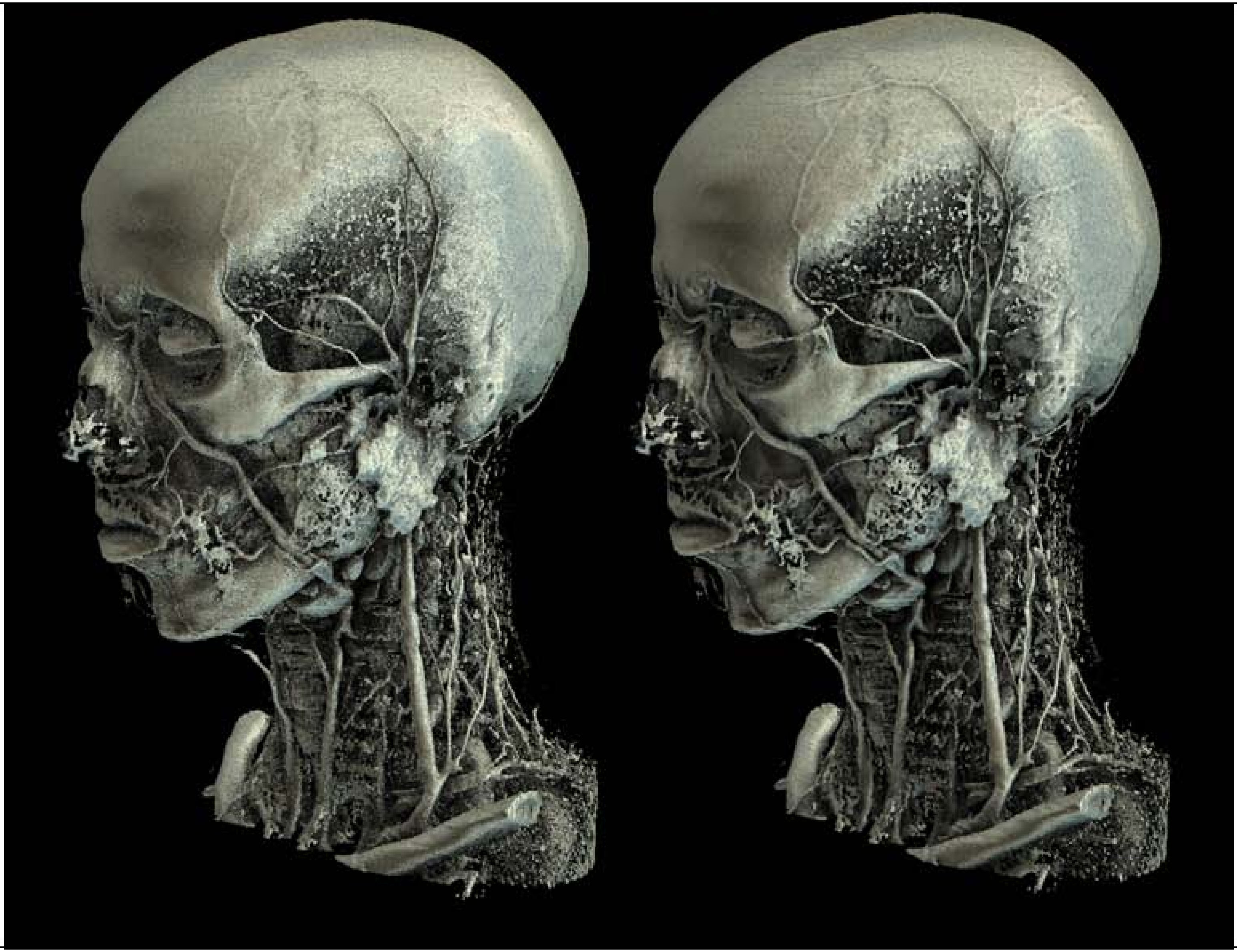
You can, but

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

Single Scattering Example



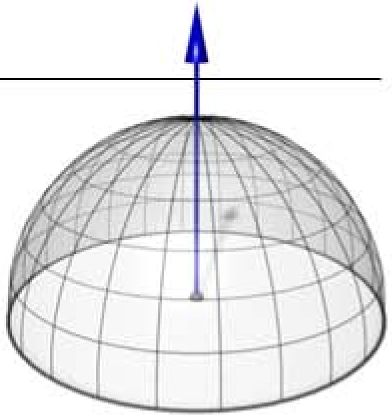
Single Scattering Example



Multiple Scattering

Mathematical Model

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

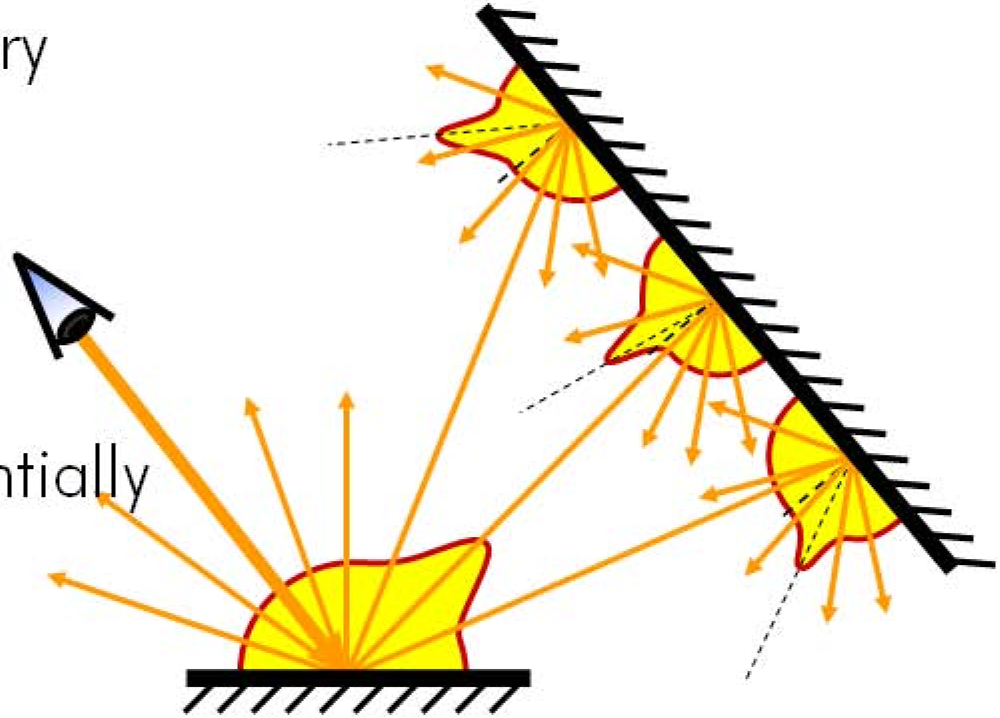


integrates over the entire sphere/hemisphere

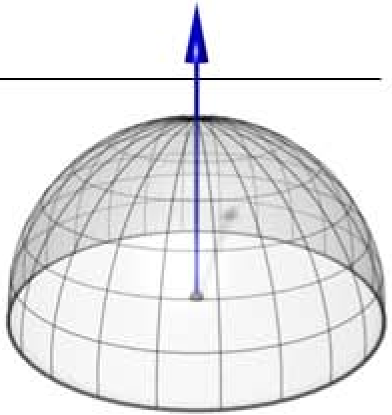
- Integral must be solved for every intersection point
- *Fredholm Equation* (cannot be solved analytically)

Numerical Solution:

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



Multiple Scattering

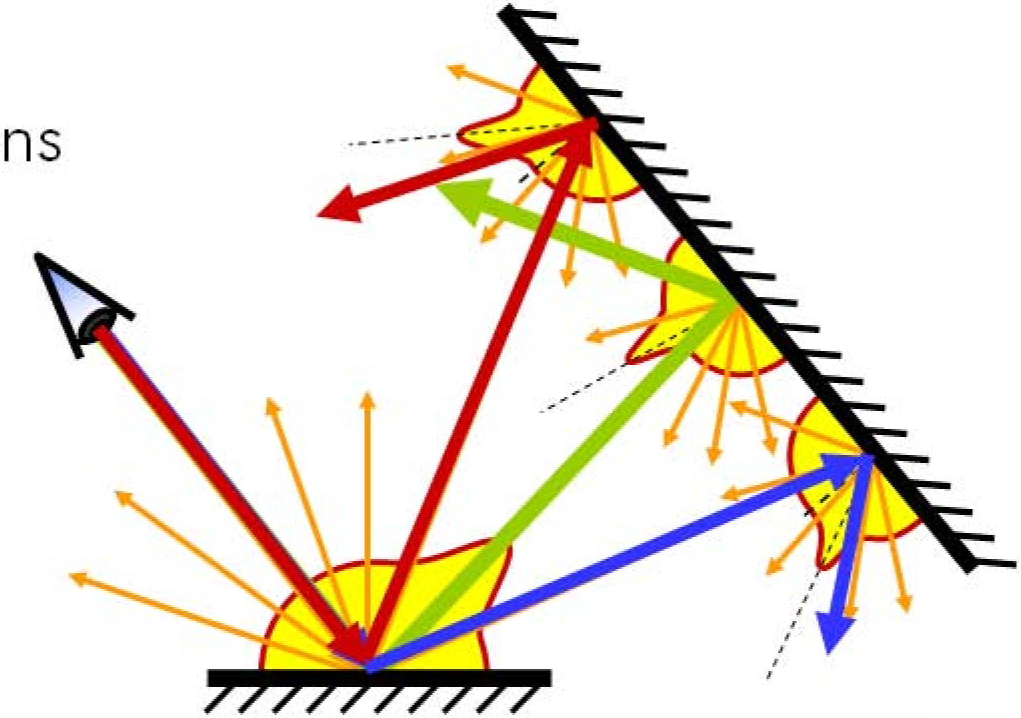


Mathematical Model

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

integrates over the entire sphere/hemisphere

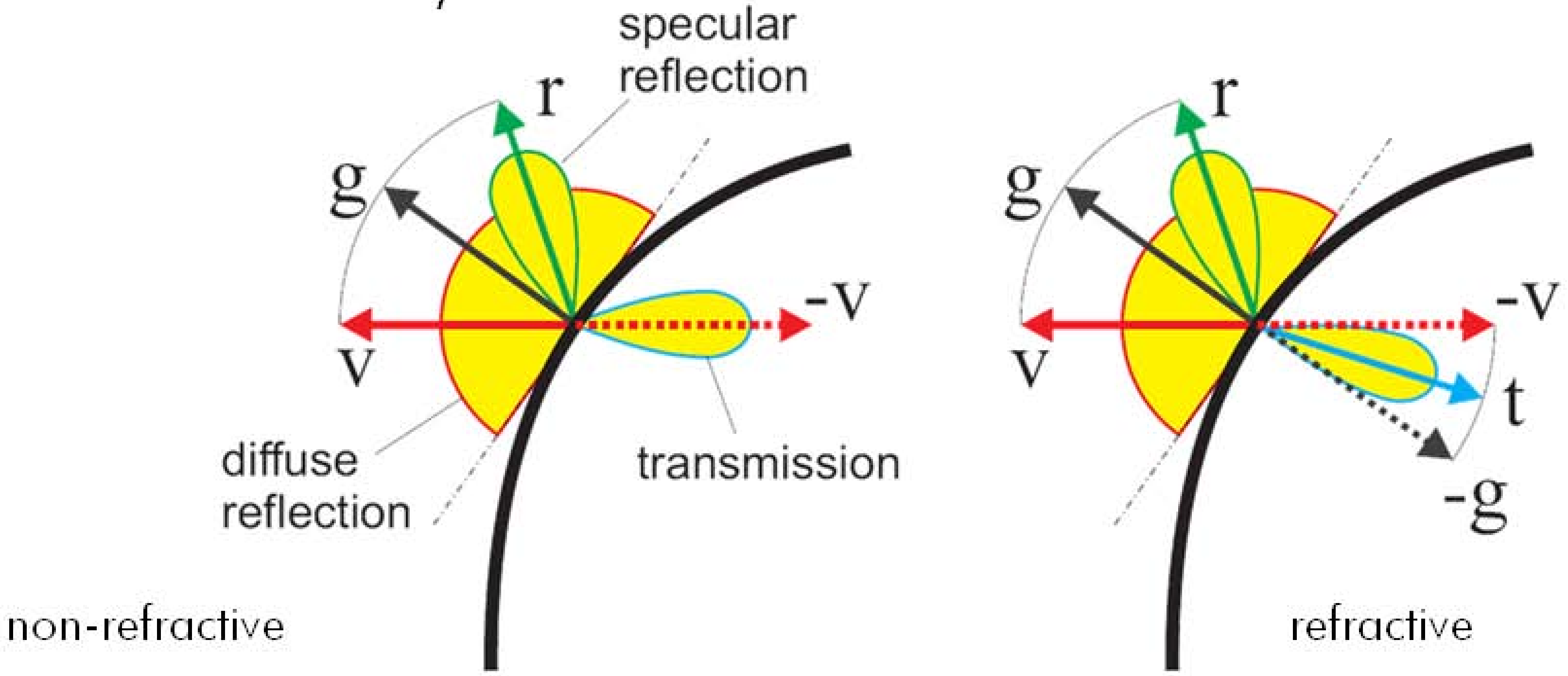
Quantum Optics



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

Phase Function Model

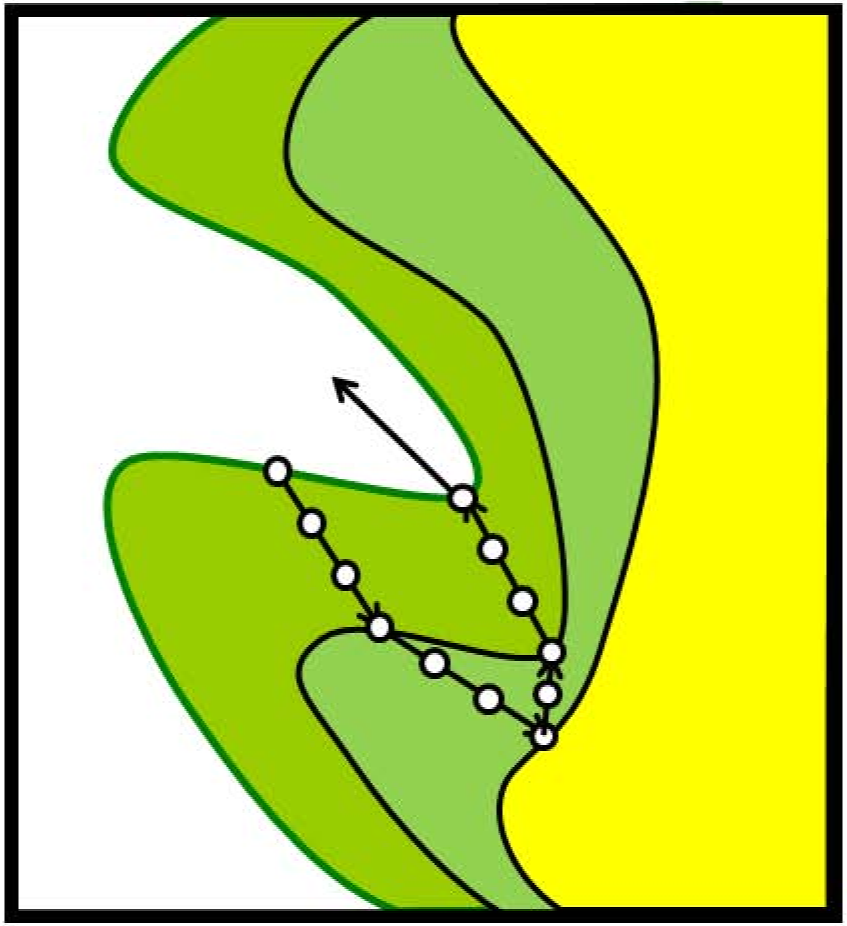
- Scattering of light at every point inside the volume
  - Too expensive (extremely slow convergence)
  - Not practicable. Controlling the visual appearance is difficult
- *Idea:* Restrict scattering events to a fixed number of isosurfaces only.



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



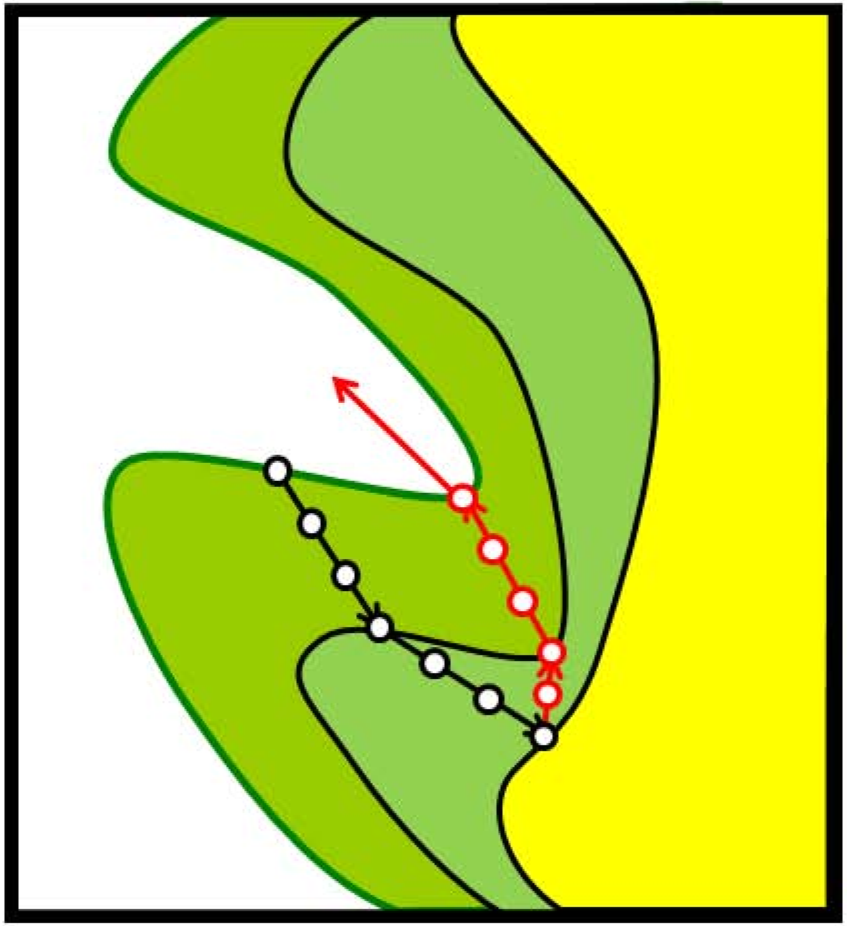
GPU Ray-Casting

Scattering Pass

Simplifying Assumption:

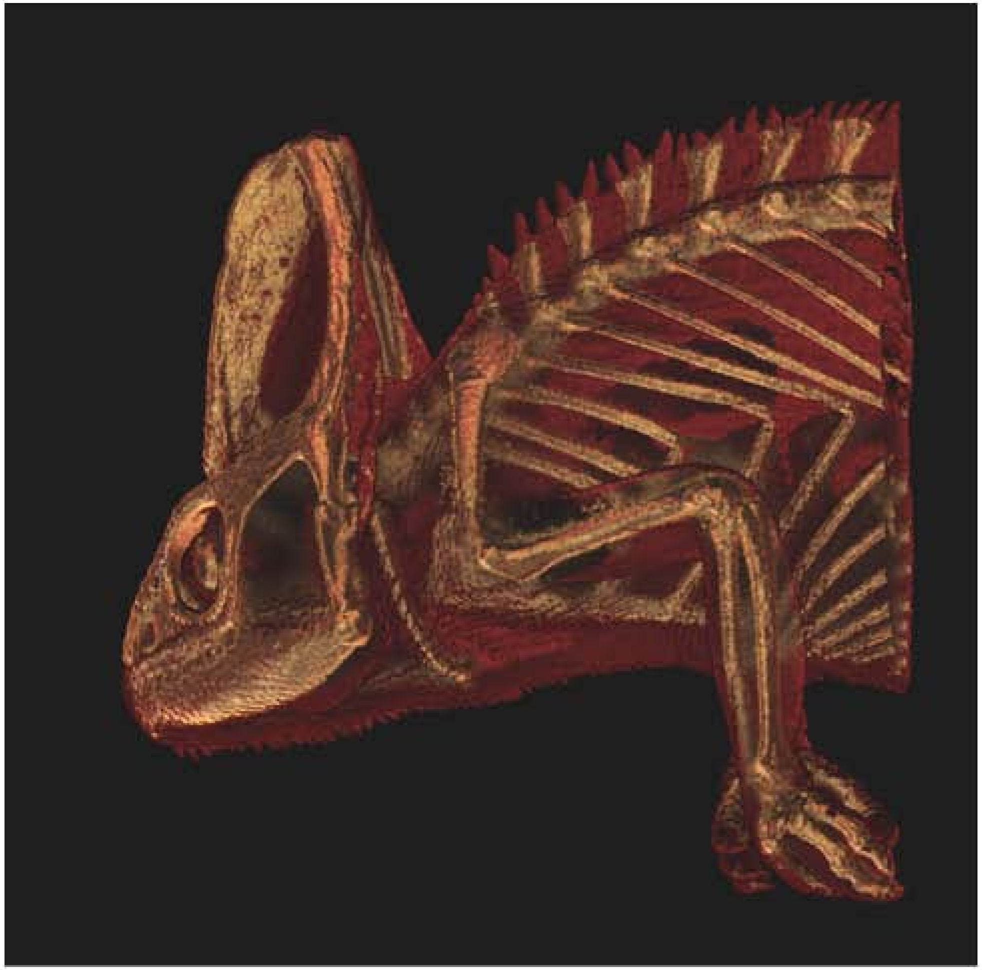
- Absorption on the „way in“ is same as on the „way out“
- Abort the ray inside the volume square the absorption and sample irradiance map

- *Not very accurate but good visual results*



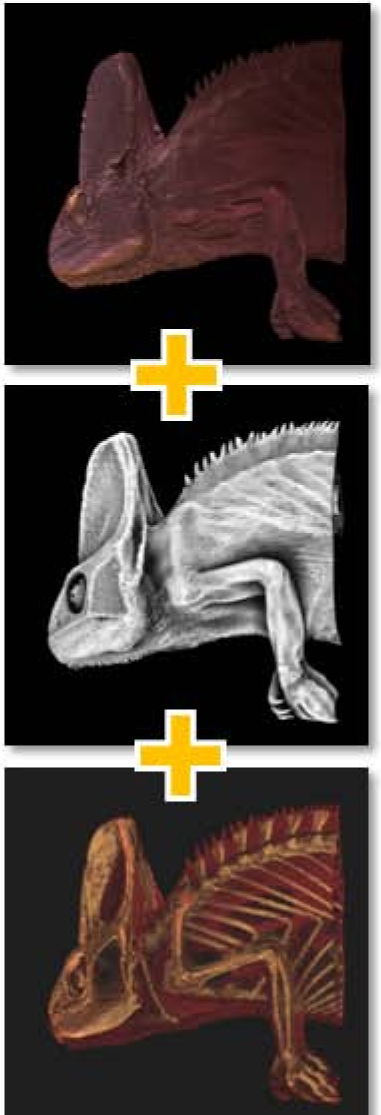
Scattering Pass

preview in real-time



final version in ½-1 seconds

Final Composite



Multiply

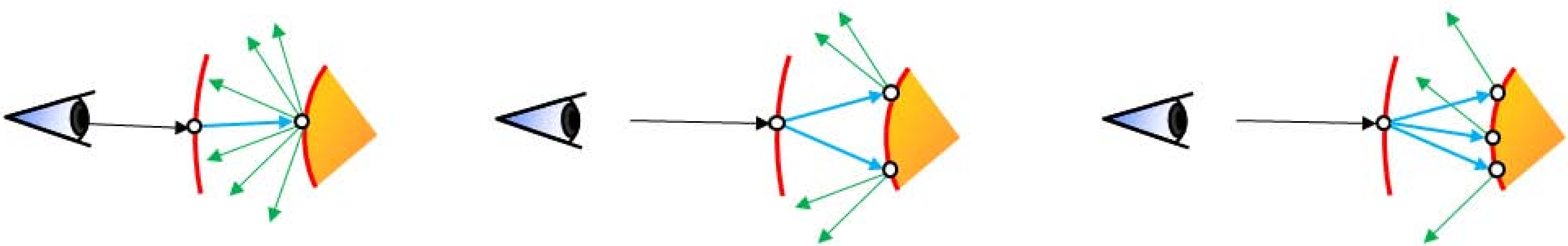
Blend using Fresnel term

Path Tracing

Primary rays: 1
Secondary rays: 64

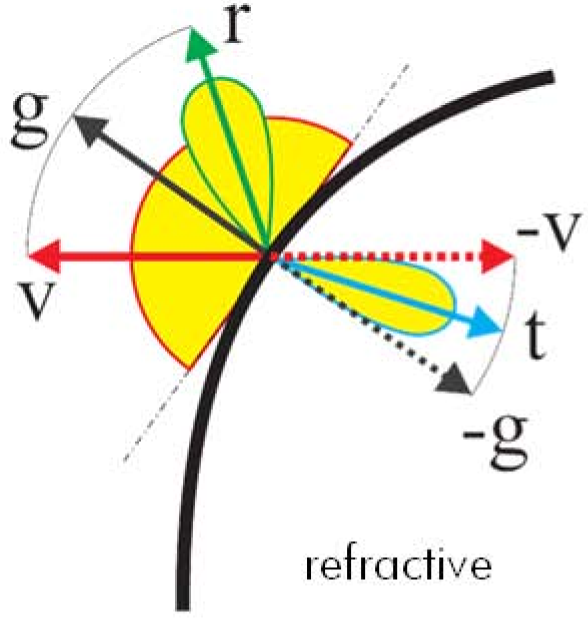
Primary rays: 8
Secondary rays: 8

Primary rays: 64
Secondary rays: 1



Examples

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



Eurographics 2009

Scattering Effects
Light Map Approaches

Markus Hadwiger
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Vienna, Austria

Patric Ljung
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Princeton, NJ, USA

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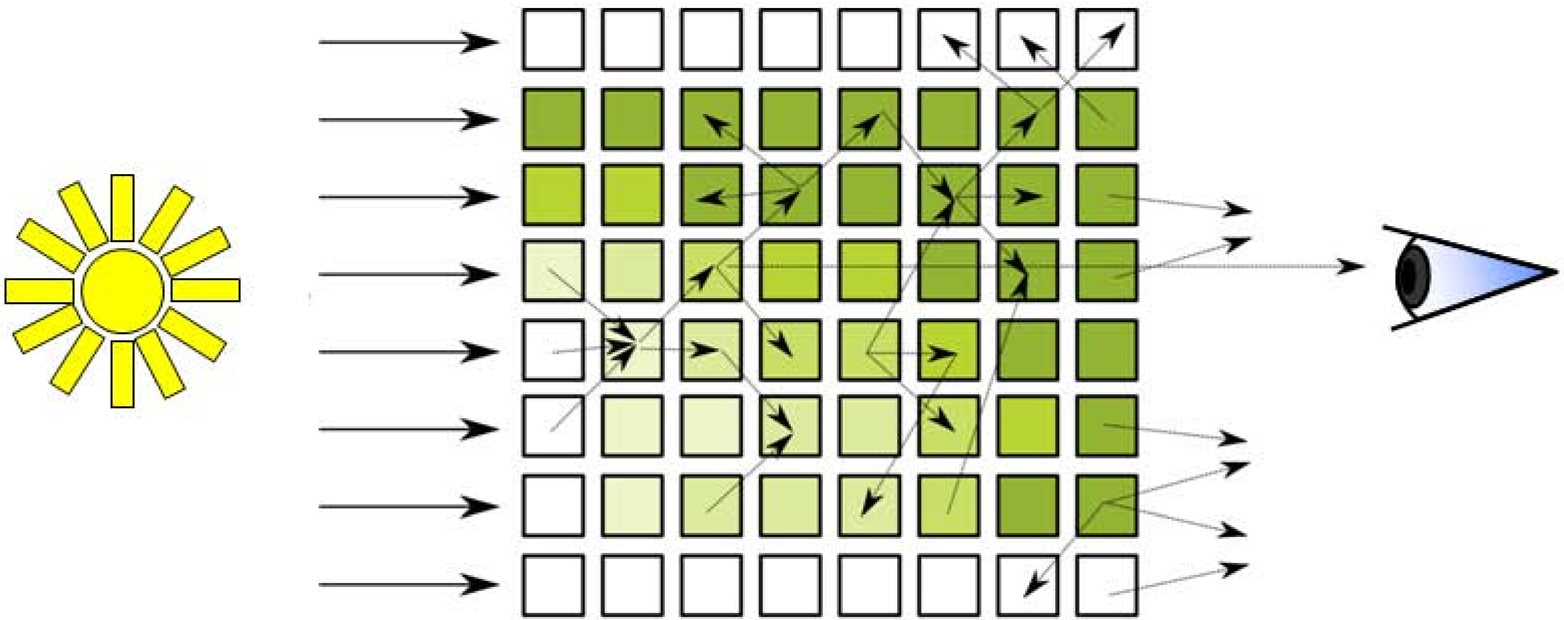
Institute for Vision and Graphics
University of Siegen, Germany

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

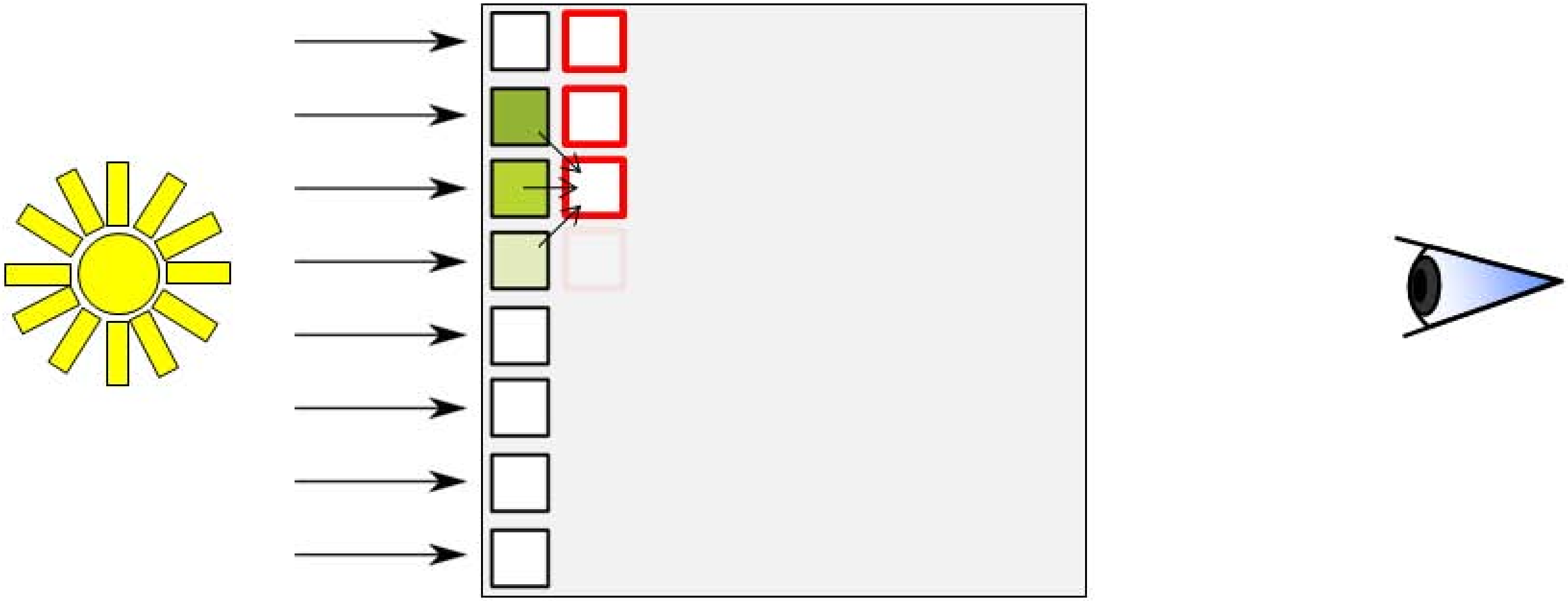
3D Light Map



- 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



Generate a 3D Light Map

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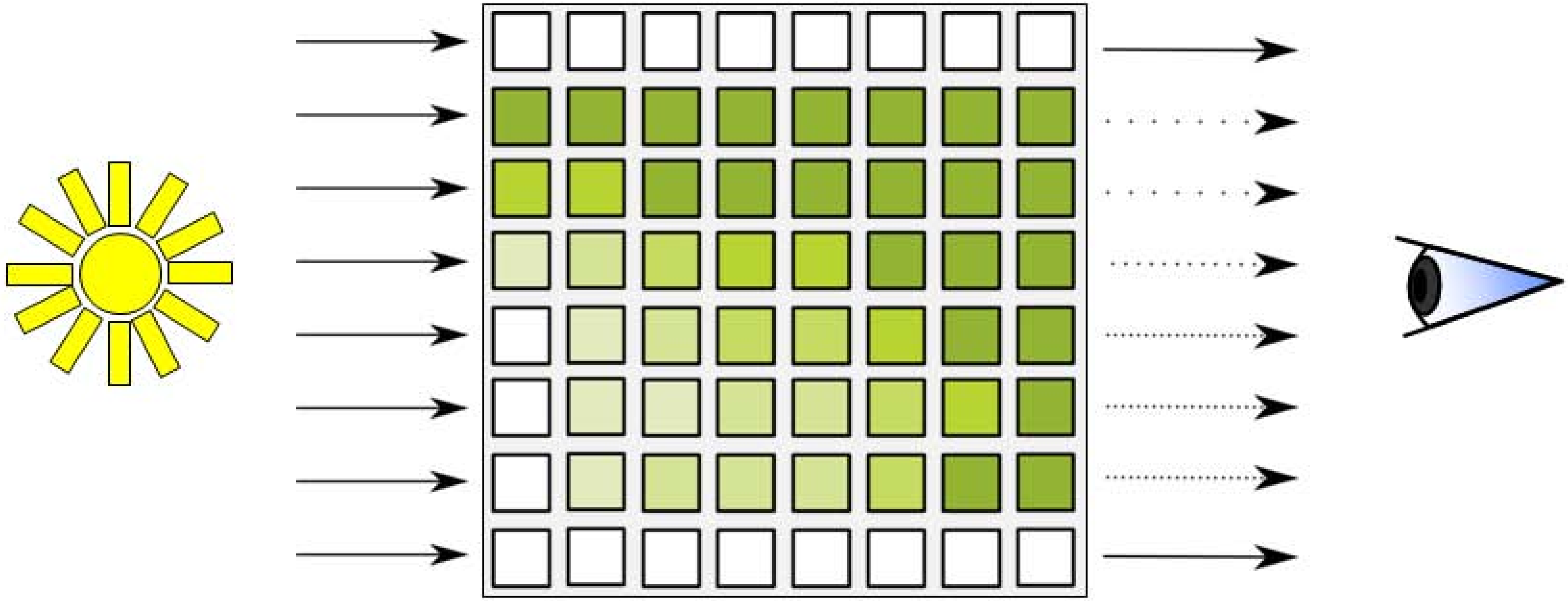
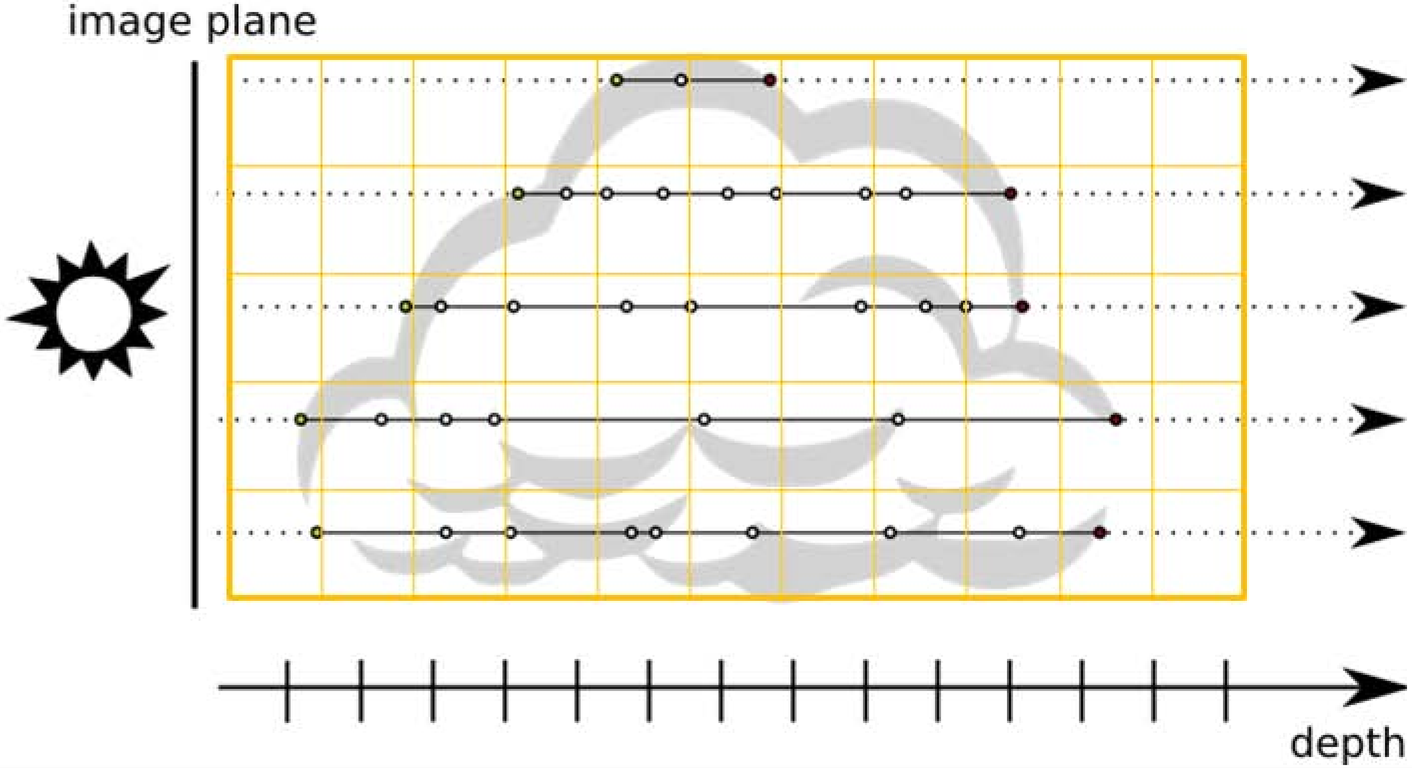


Scattering 3D Light Map

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-frequent nature of volumetric scattering



Scattering Deep Shadow Map

Direct light

Direct plus indirect light

Light Map Approaches

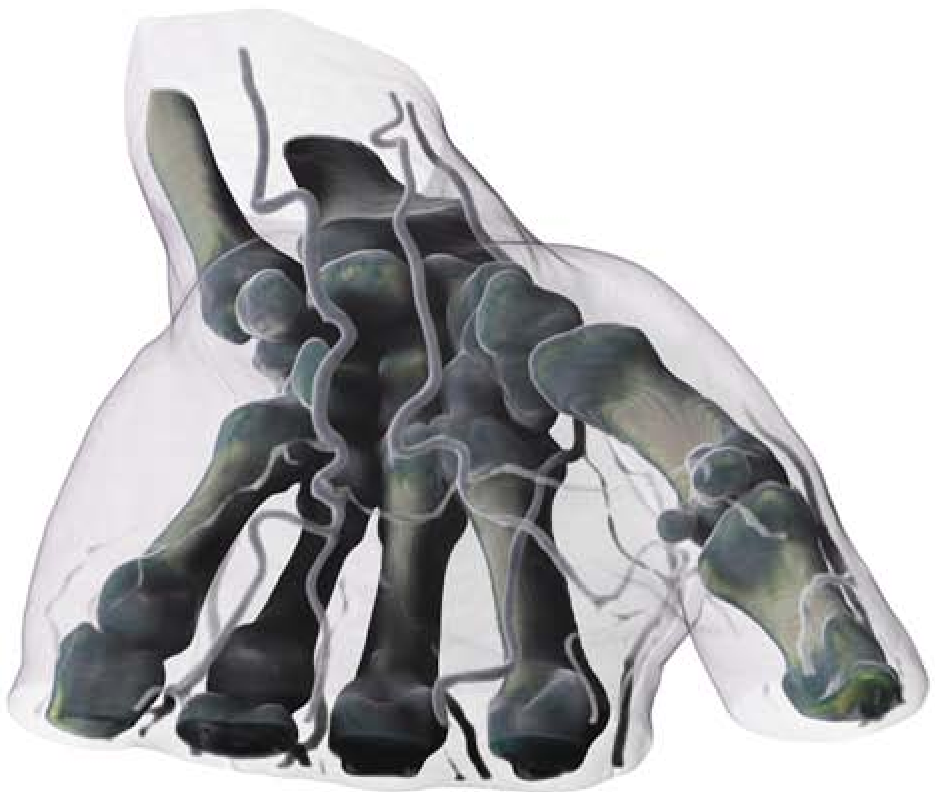
Shadow Volume Appraoch

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

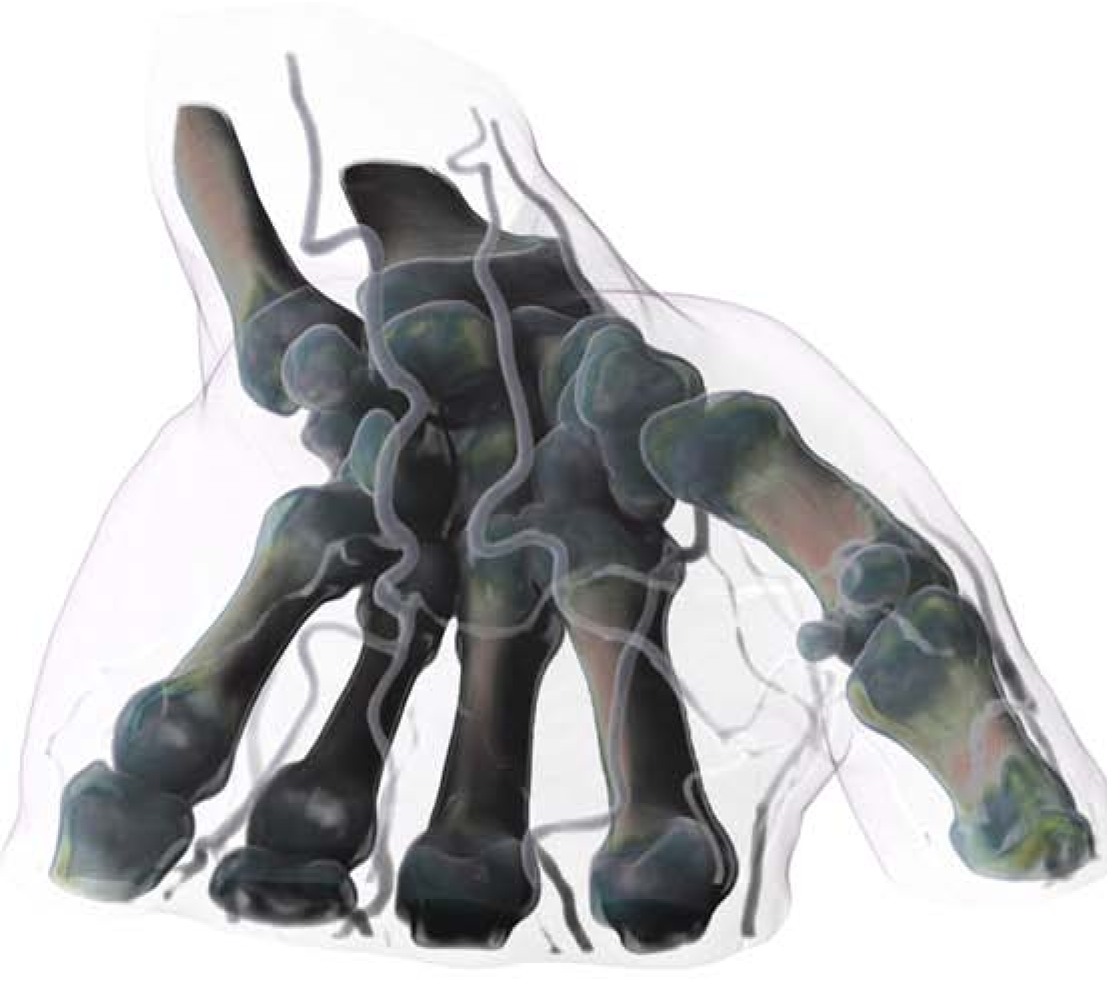
Deep Shadow Map Appraoch

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

High Dynamic Range



Direct light and shadows



Direct light, shadows and translucency

Summary

Scattering Effects

- **Single Scattering**
  - *Filtered Environment Maps*
  - *Monte-Carlo Integration*
- **Multiple Scattering**
  - *Monte-Carlo Integration*
  - *3D Light Maps (Shadow Volume/Deep Shadow Map)*

Acknowledgements

- Images and Slides on Deep Shadow Maps:
  Andrea Kratz, Zuse Institute, Berlin
  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*