Computer Graphics

- Shading -

Hendrik Lensch

Overview

- **So far**
  - Nuts and bolts of ray tracing
- **Today**
  - Reflectance
  - Reflection models

Material Samples

diffuse

glossy

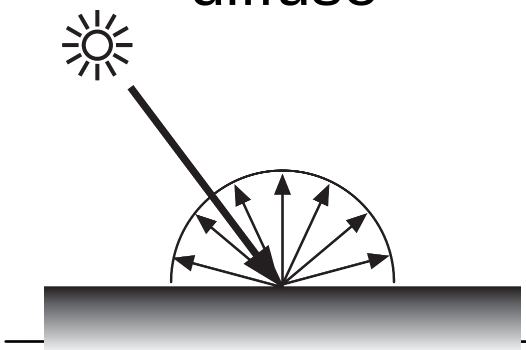
mirror

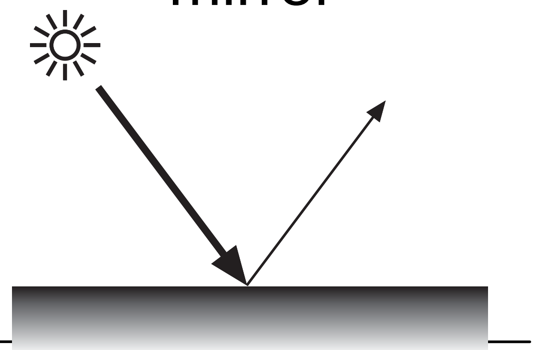
Material Samples

diffuse

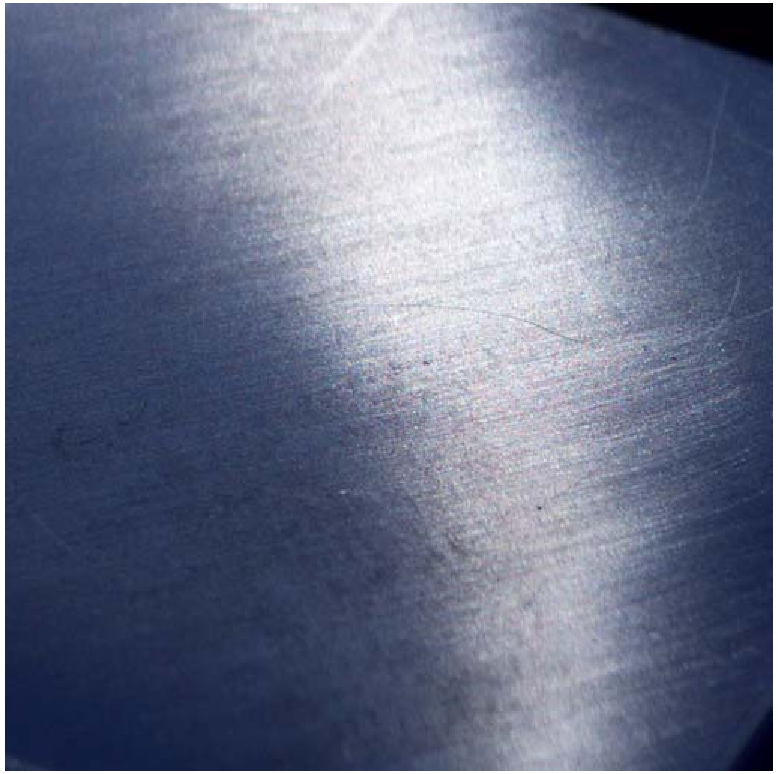
glossy

mirror





Material Samples



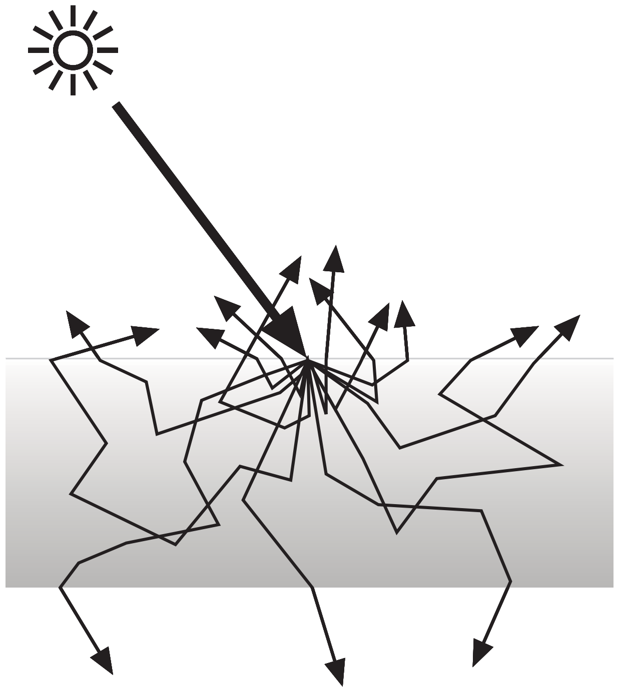
anisotropic

Material Samples

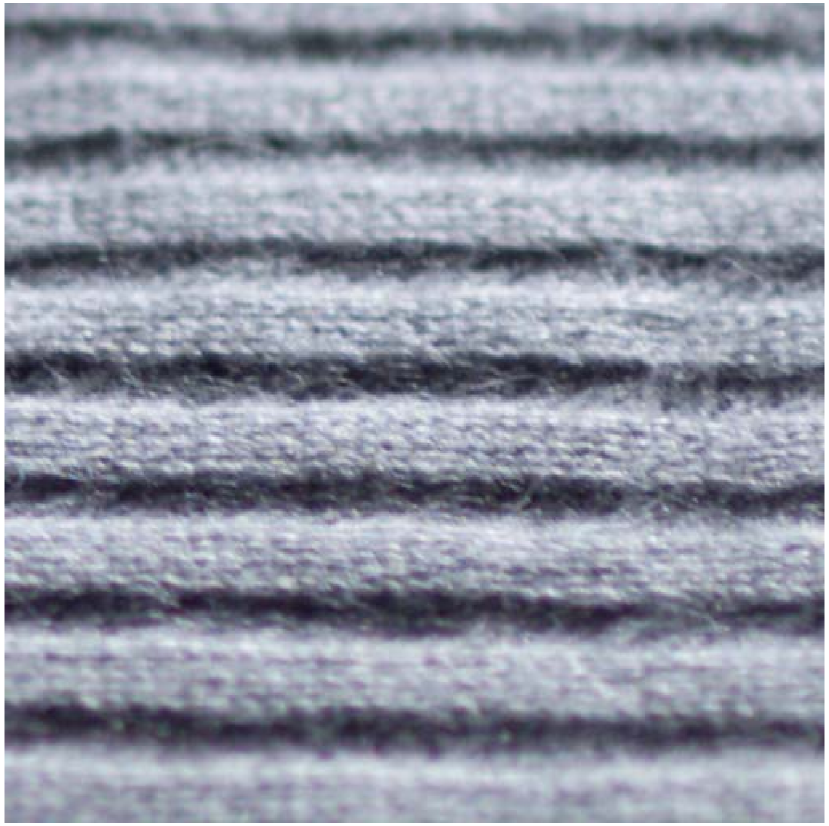
translucent

Material Samples

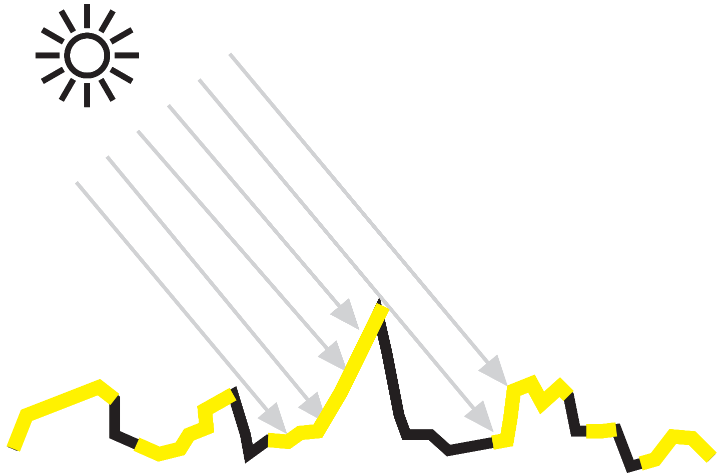
translucent



Material Samples



complex surface structure



Material Samples

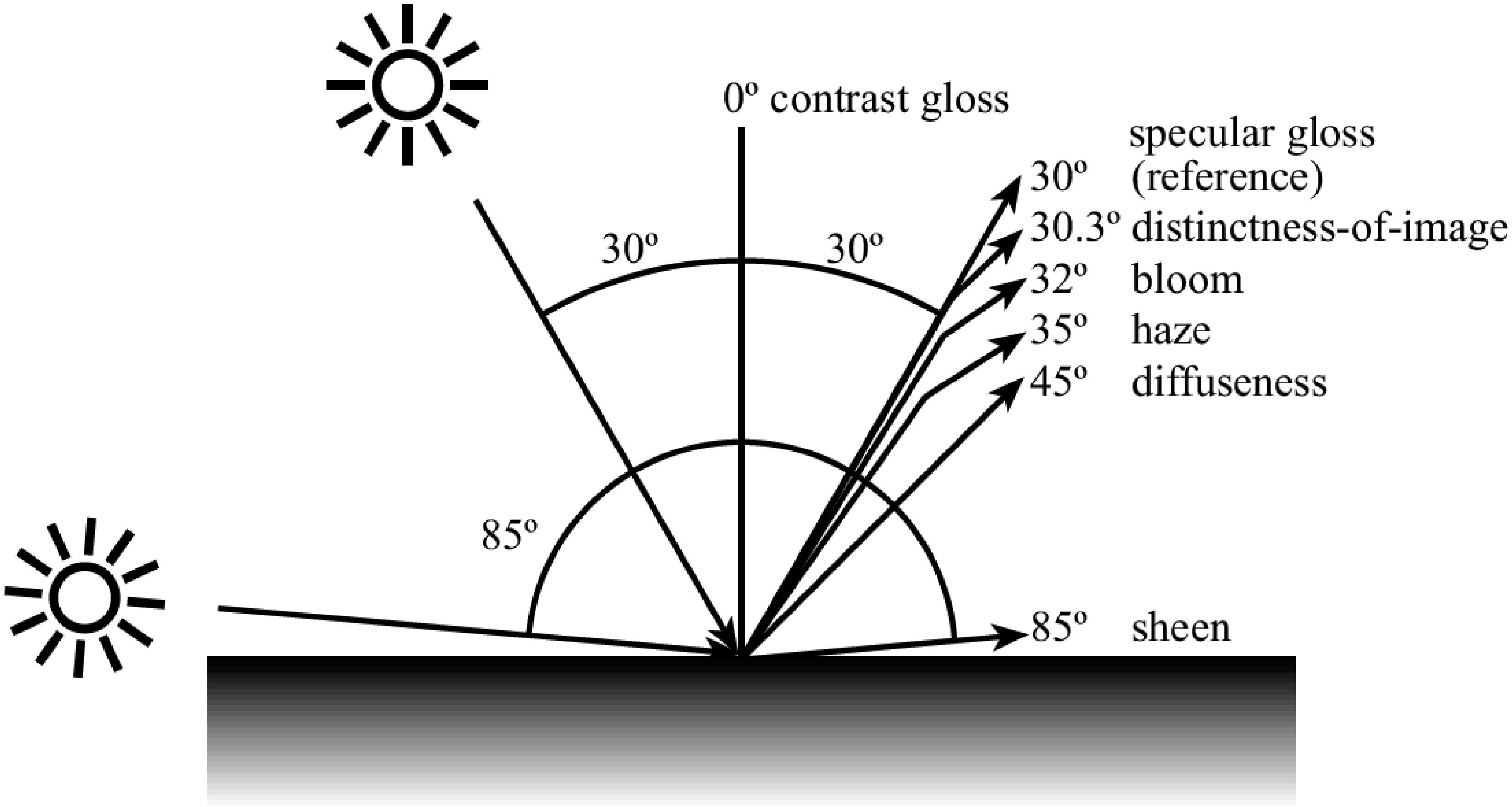
fibers

How to describe materials?

- **mechanical, chemical, electrical properties**
- **reflection properties**
- **surface roughness**
- **geometry/meso-structure**

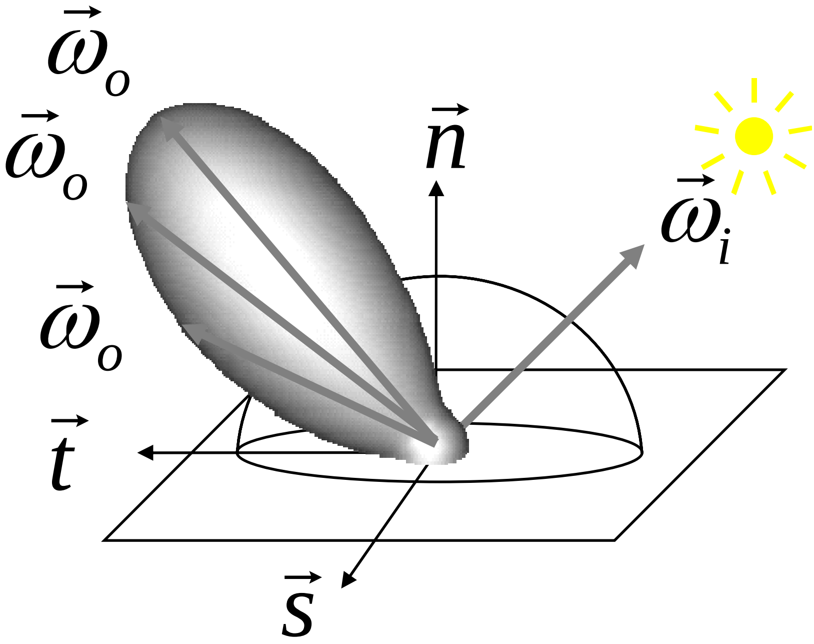
- relightable **representation of appearance**

Gloss Model

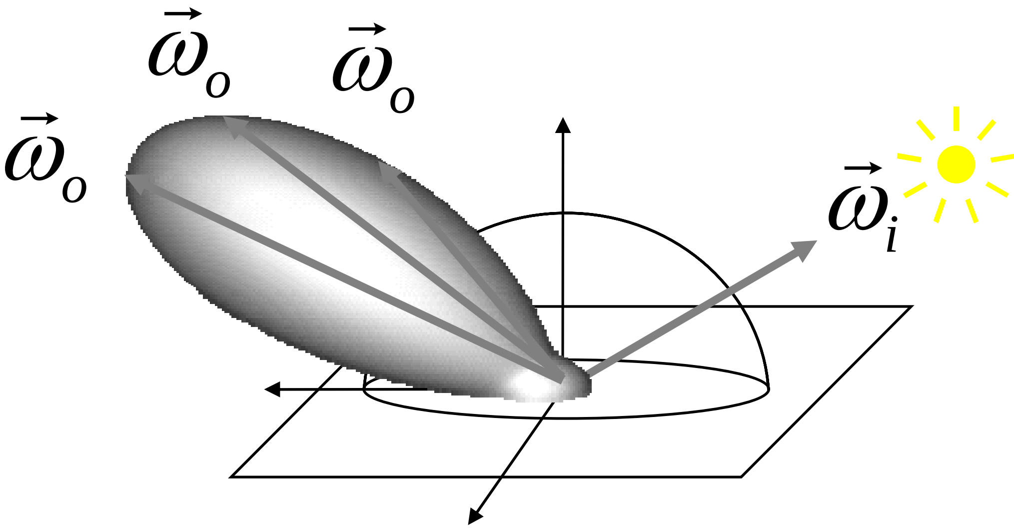


0° contrast gloss
30°
30°
85°
specular gloss
30° (reference)
30.3° distinctness-of-image
32° bloom
35° haze
45° diffuseness
85° sheen

Reflection of an Opaque Surface



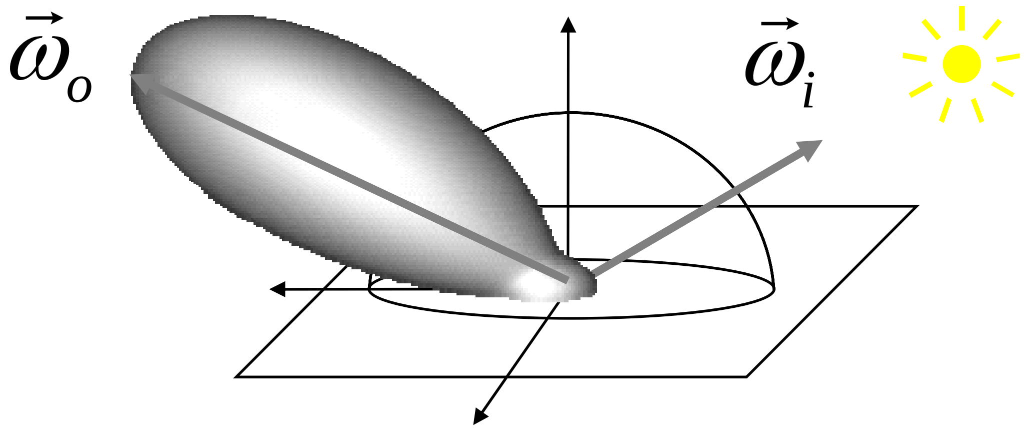
Reflection of an Opaque Surface



BRDF – 4D

(bidirectional reflectance distribution function)

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$

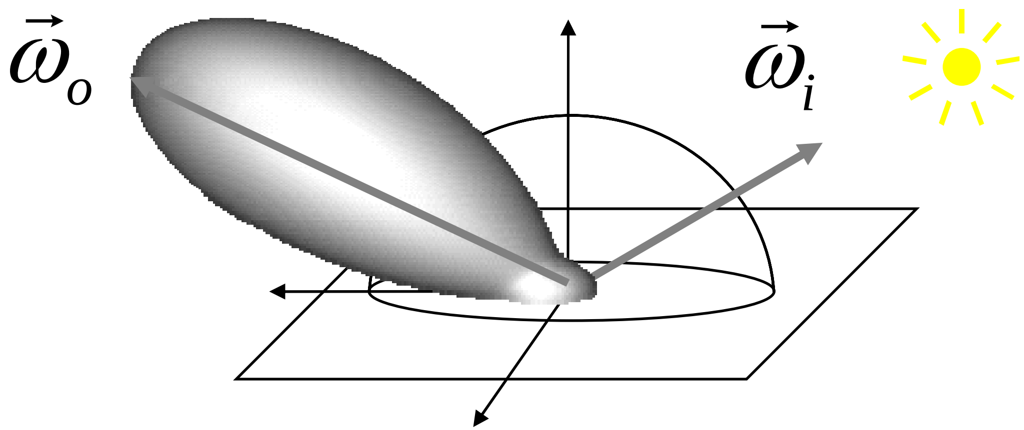


BRDF – 4D

(bidirectional reflectance distribution function)

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{\omega}_o)}{dE(\vec{\omega}_i)}$$

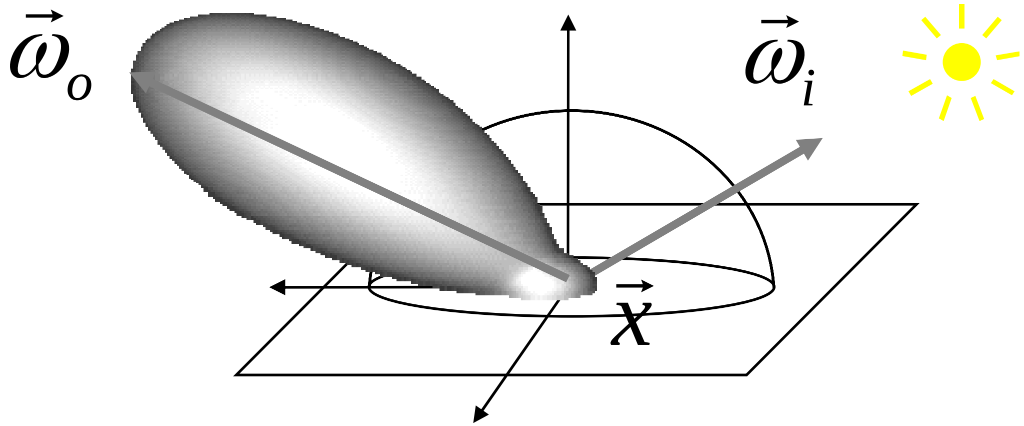
ratio of reflected radiance to incident irradiance



Spatially Varying BRDF – 6D

heterogeneous materials

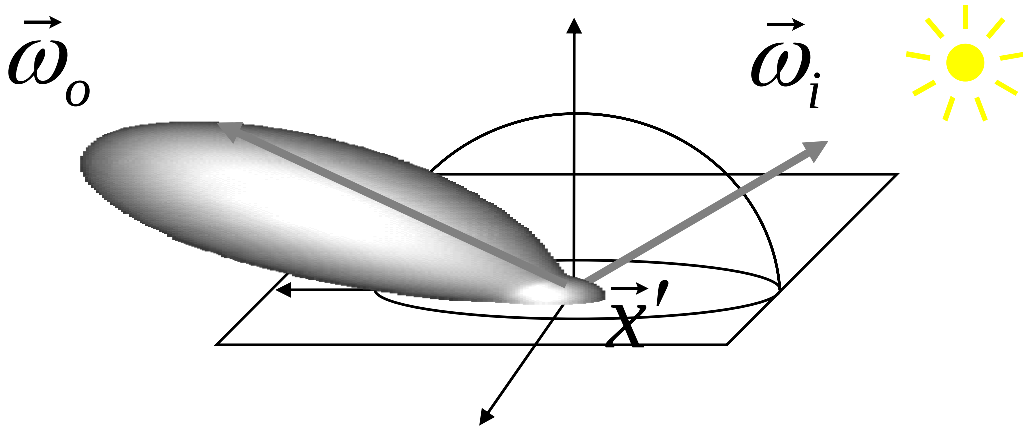
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Spatially Varying BRDF – 6D

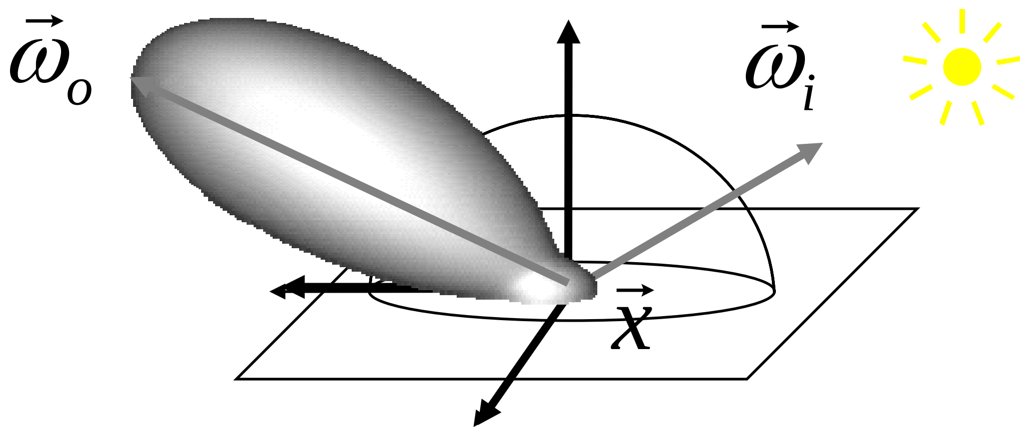
heterogeneous materials

$$f_r(\vec{x}, \vec{\omega}_i \to \vec{\omega}_o)$$



Isotropic BRDF – 3D

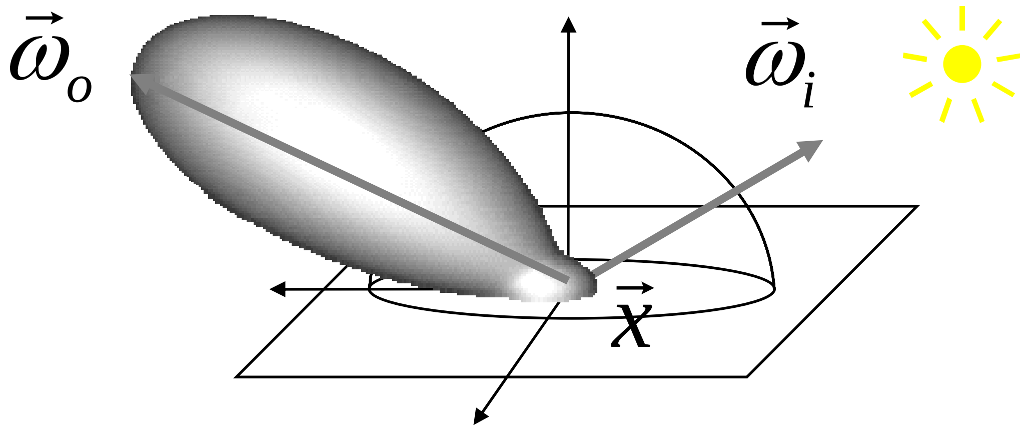
- **invariant with respect to rotation about the normal**



Isotropic BRDF – 3D

- **invariant with respect to rotation about the normal**

$$f_r(\vec{\omega}_i \to \vec{\omega}_o)$$

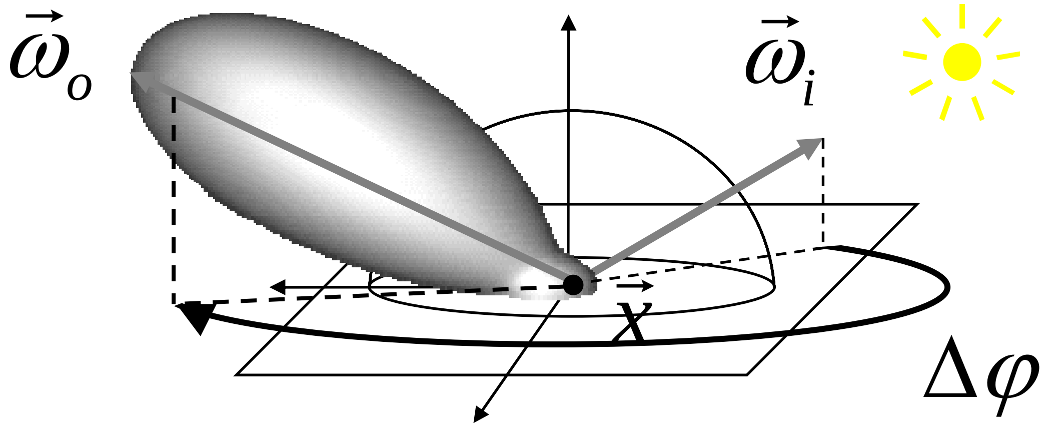


Isotropic BRDF – 3D

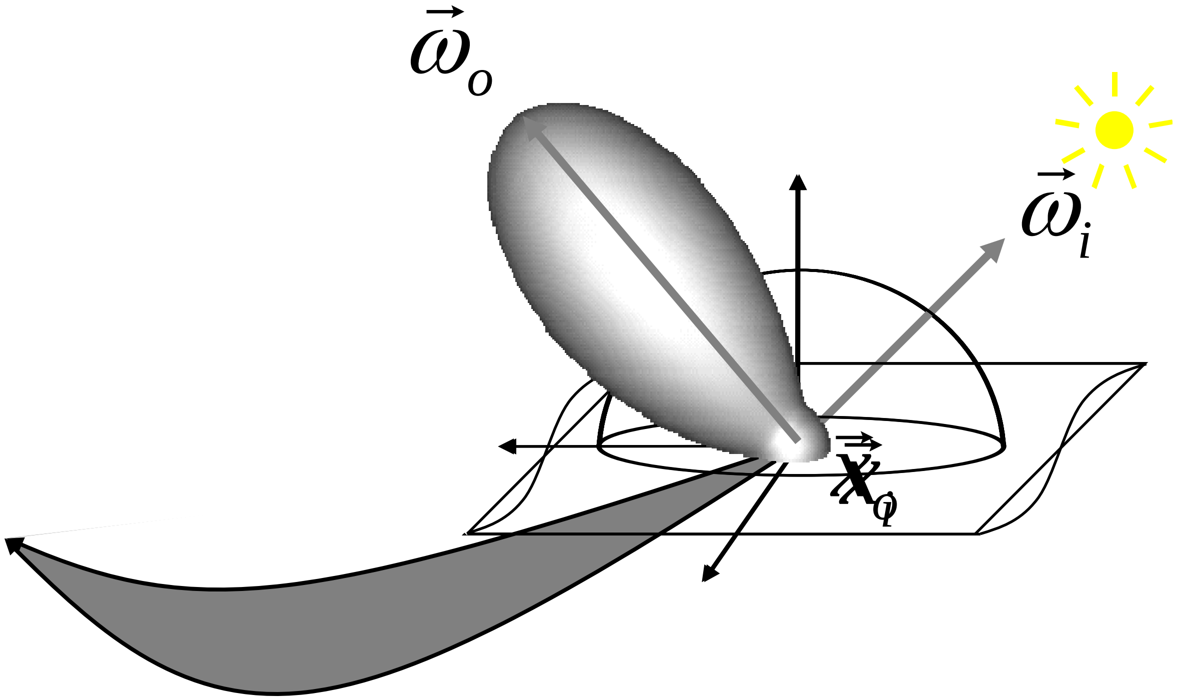
- **invariant with respect to rotation about the normal**

$$f_r((\theta_i, \varphi_i) \to (\theta_o, \varphi_o))$$

$$f_r(\Delta\varphi, \theta_i, \theta_o)$$



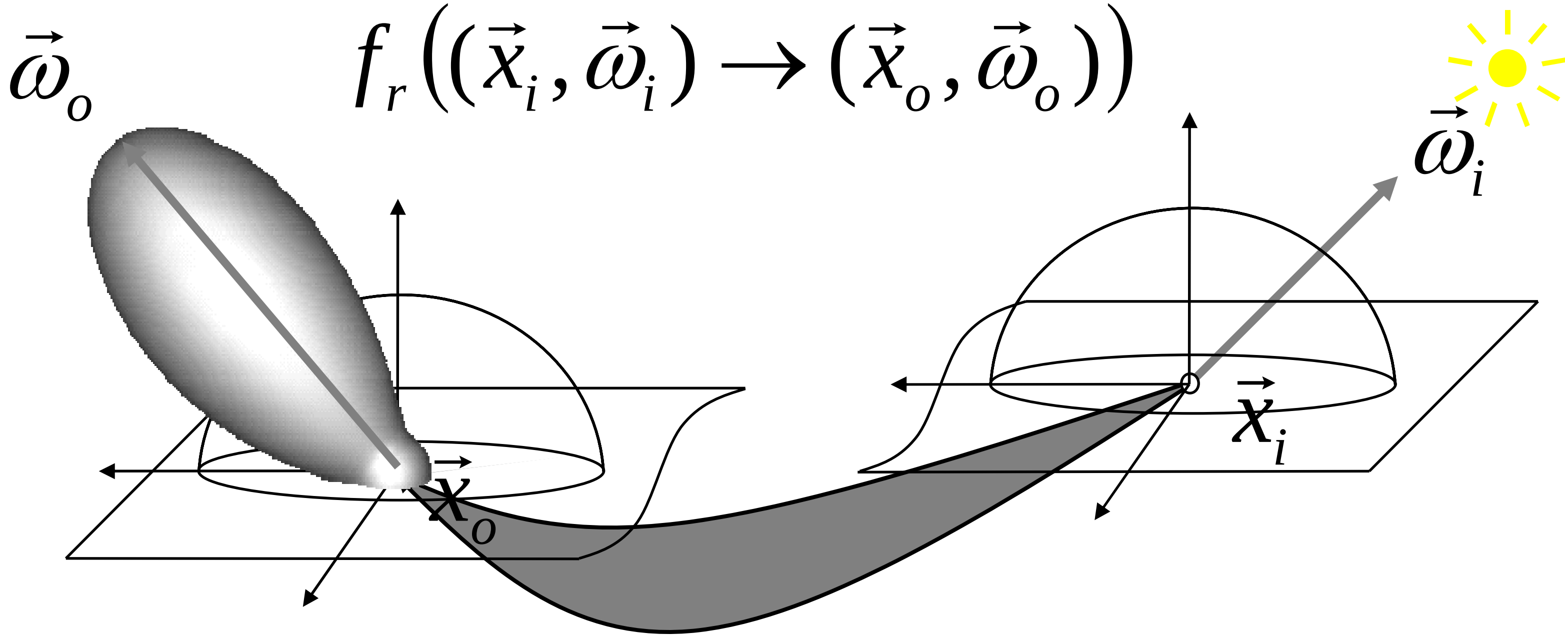
Subsurface Scattering



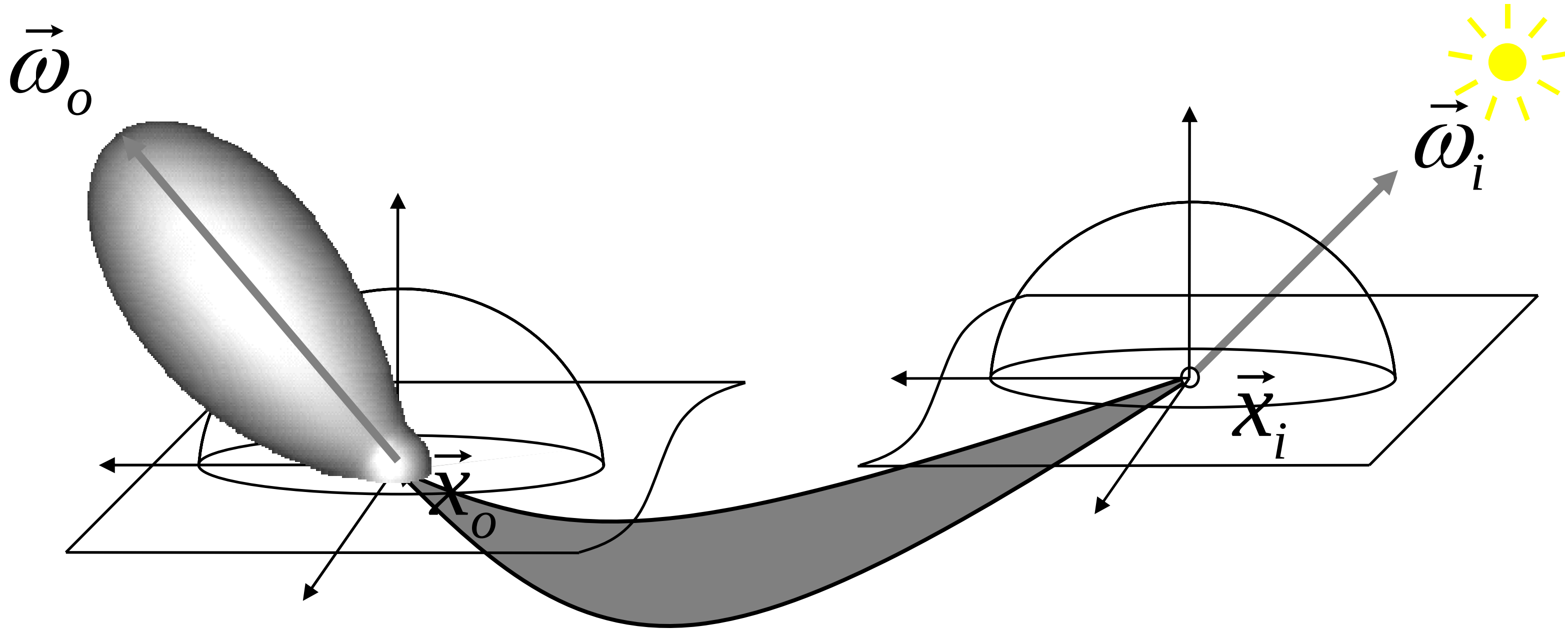
BSSRDF – 8D

(bidirectional scattering surface reflectance distribution function)

$$f_r\left((\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o)\right)$$



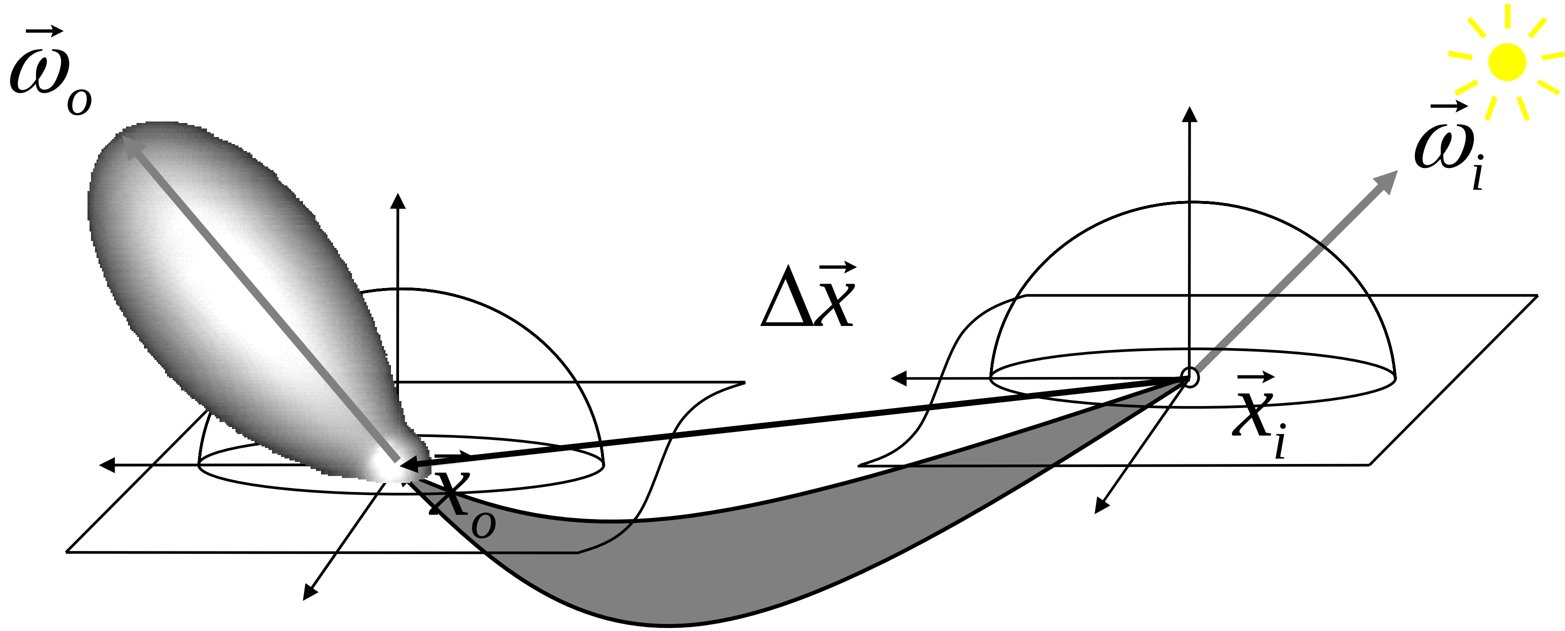
Subsurface Scattering Homogeneous Material



Homogeneous Material BSSRDF – 6D

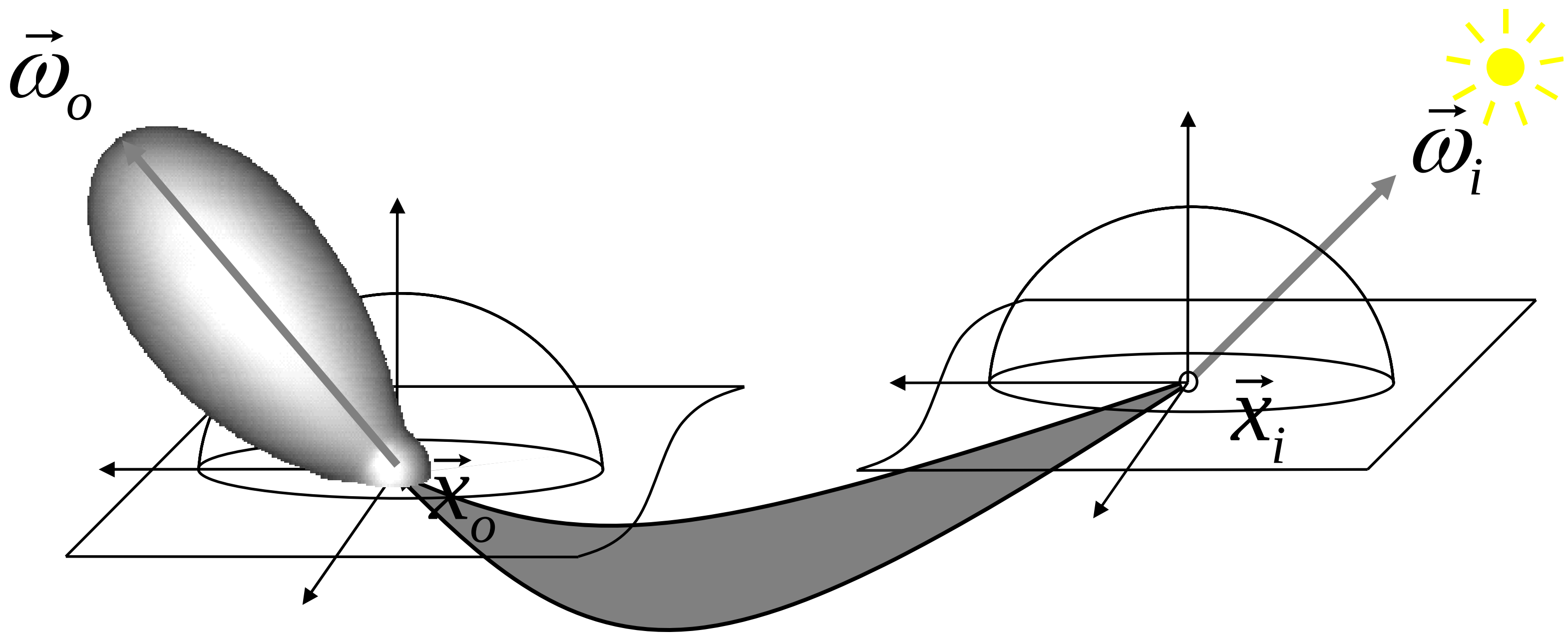
$$f_r\left((\vec{x}_i, \vec{\omega}_i) \to (\vec{x}_o, \vec{\omega}_o)\right)$$

$$f_r(\Delta\vec{x}, \vec{\omega}_i \to \vec{\omega}_o)$$



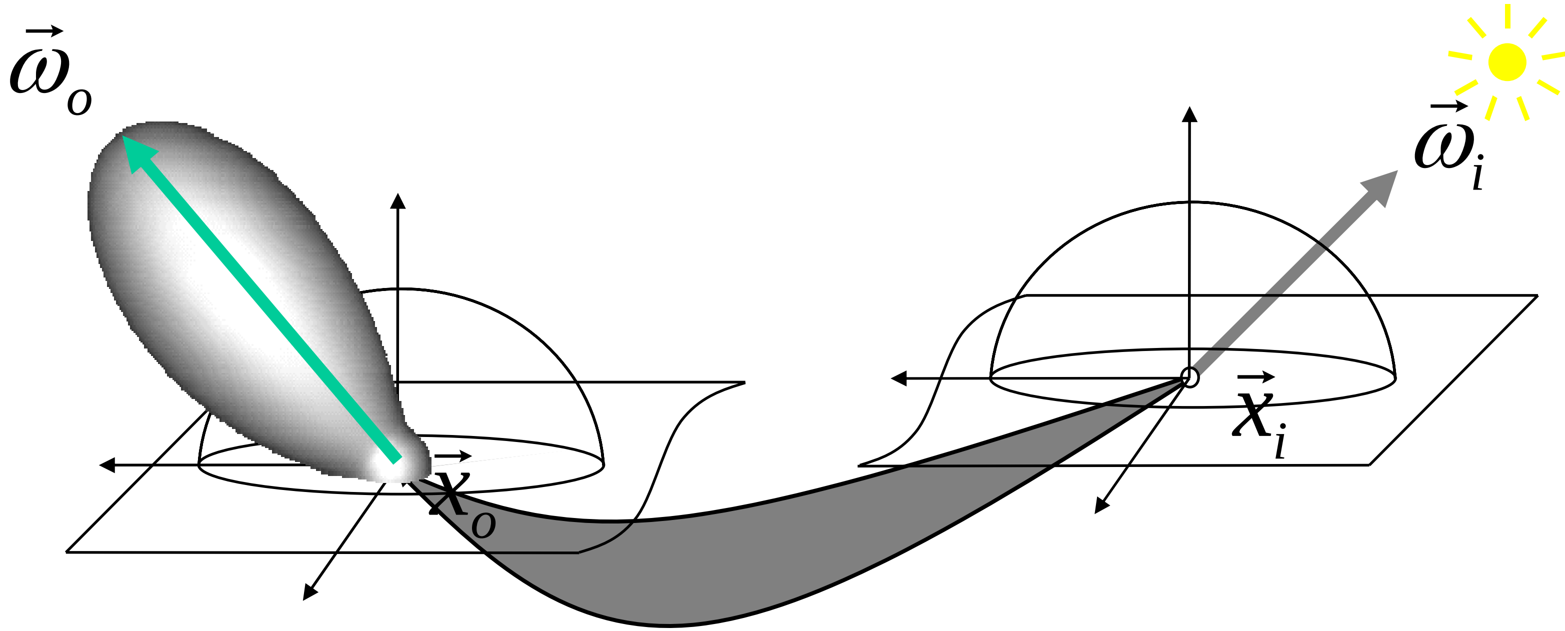
Generalization – 12D

$$f_r\left(\lambda;(\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Generalization – 12D

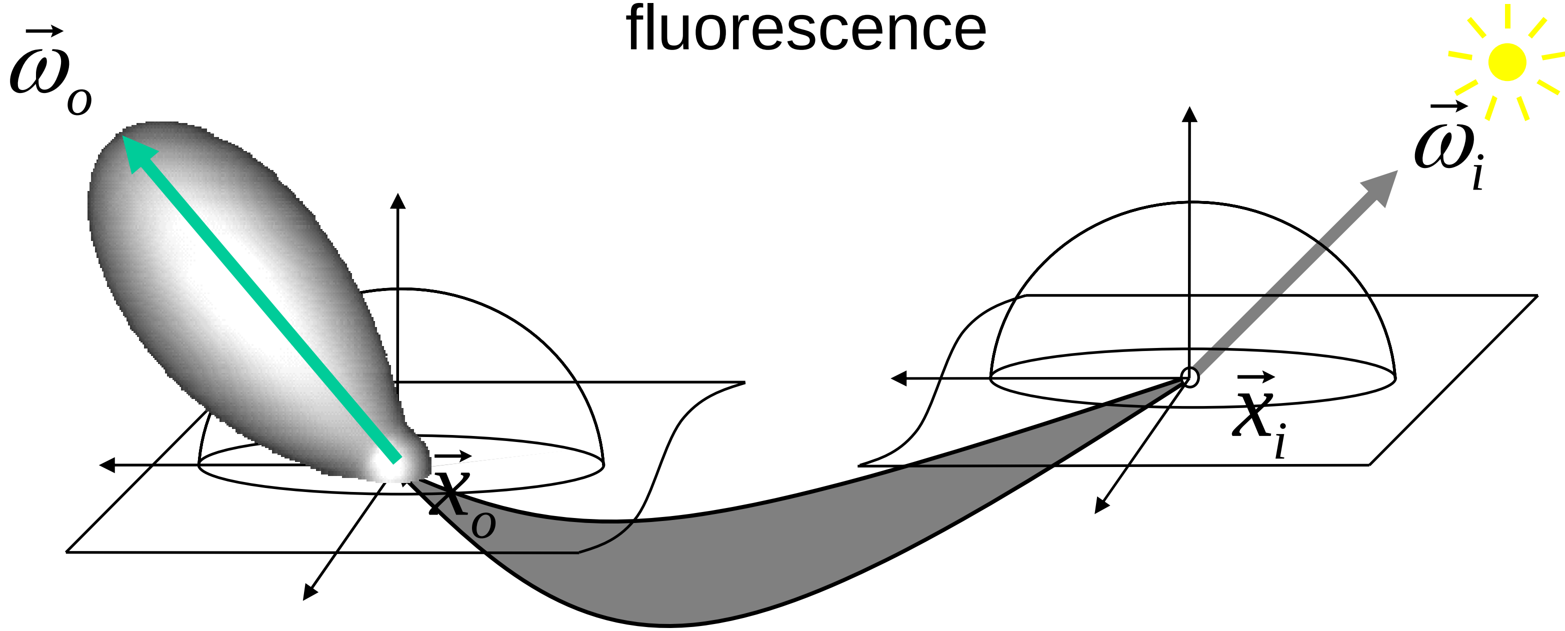
$$f_r\left(\lambda; (\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o)\right)$$



Generalization – 12D

$$f_r\left((\vec{x}_i, \vec{\omega}_i, \lambda_i) \rightarrow (\vec{x}_o, \vec{\omega}_o, \lambda_o)\right)$$

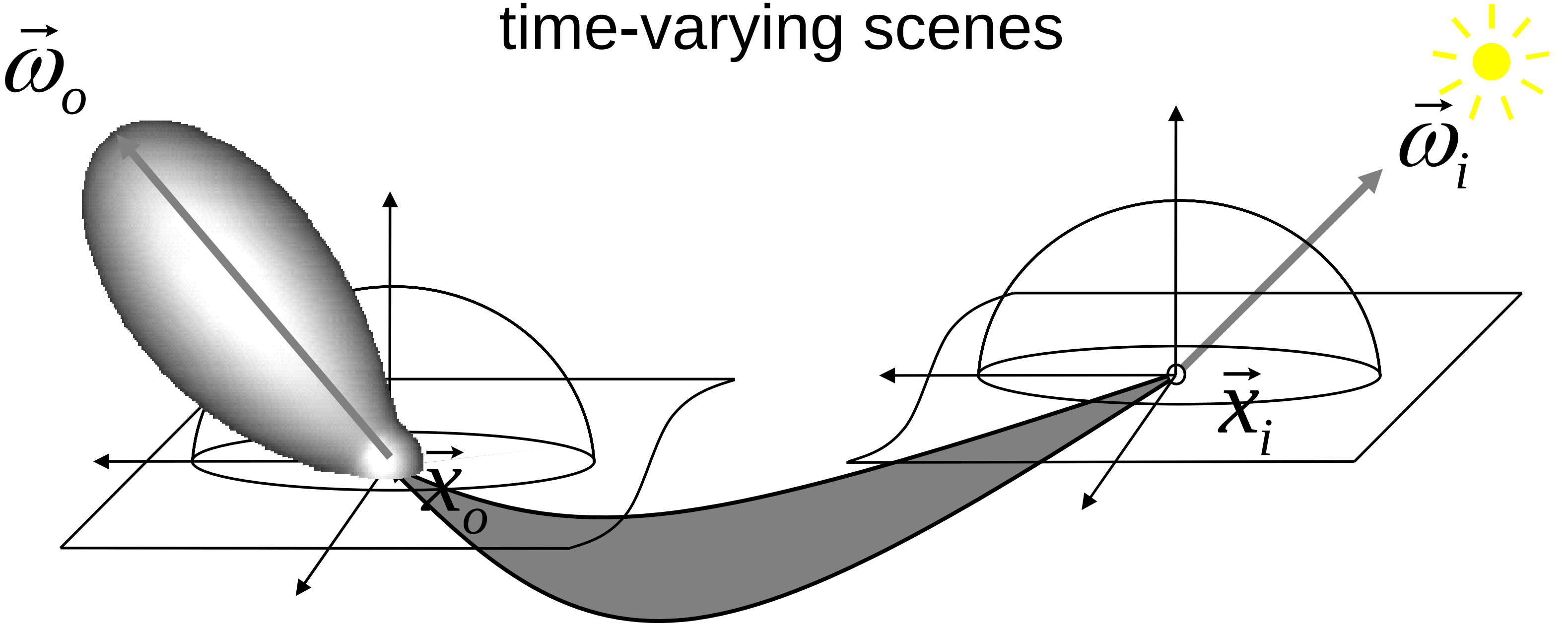
fluorescence



Generalization – 12D

$$f_r\left(t;(\vec{x}_i,\vec{\omega}_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,\lambda_o)\right)$$

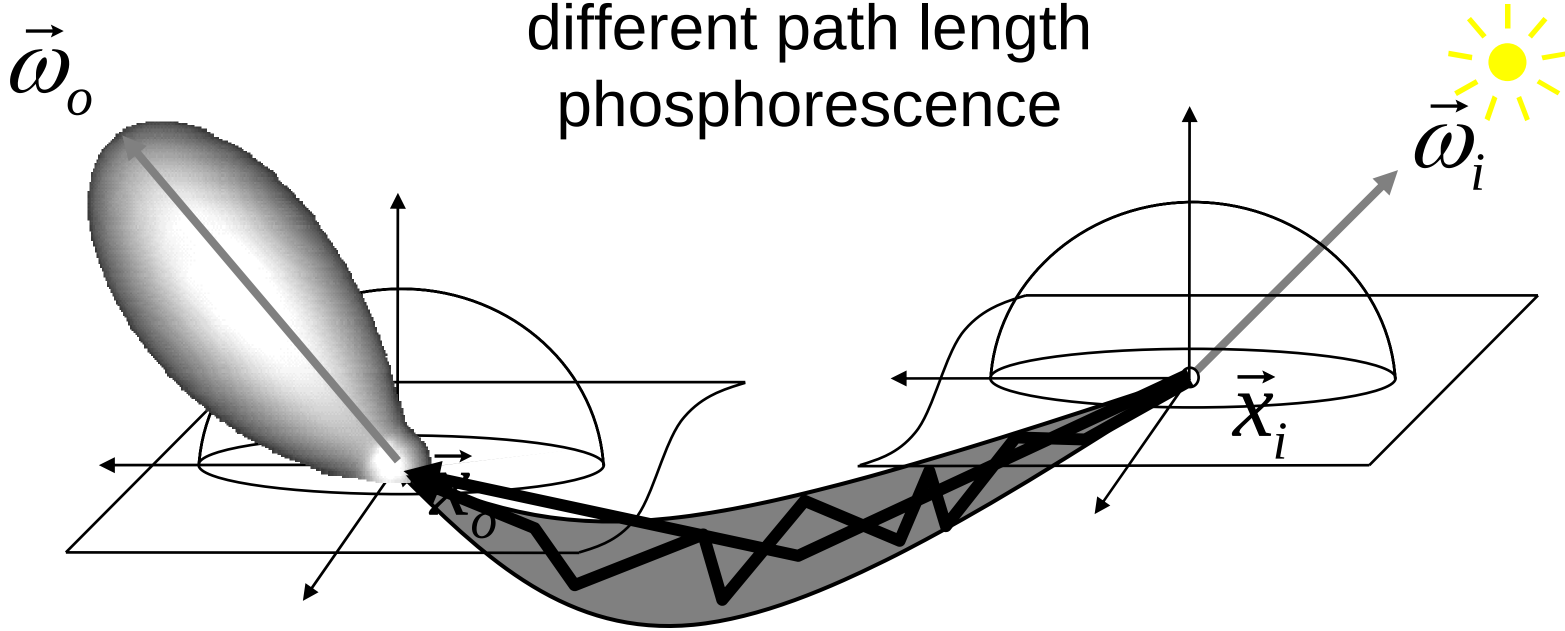
time-varying scenes



Generalization – 12D

$$f_r\left((\vec{x}_i,\vec{\omega}_i,t_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,t_o,\lambda_o)\right)$$

different path length
phosphorescence

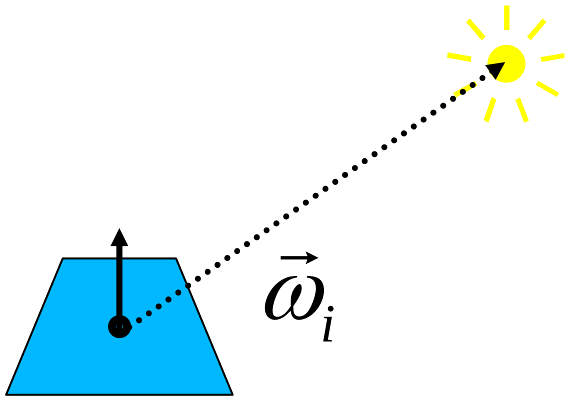


What is necessary?

- **Light source position**
- **View point**
- **Surface normal / local coordinate frame**
- **Reflectance model**

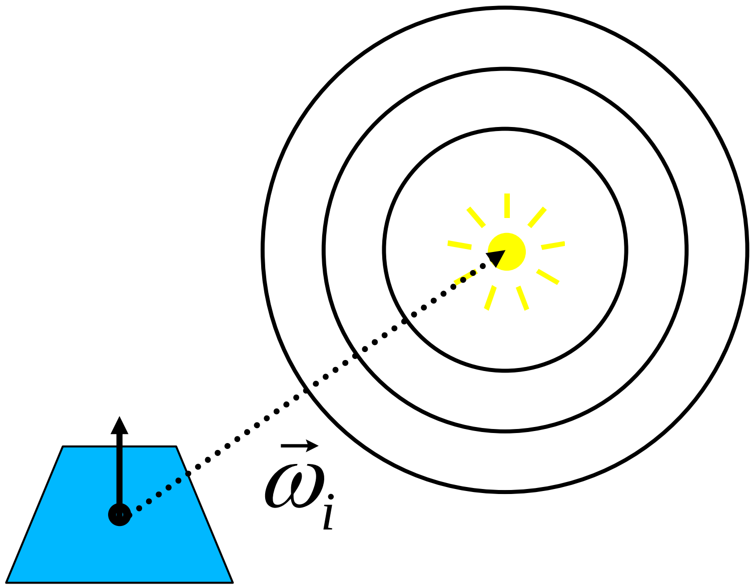
Light Source Description

- **Point light source**
- **Position**
- **Intensity**



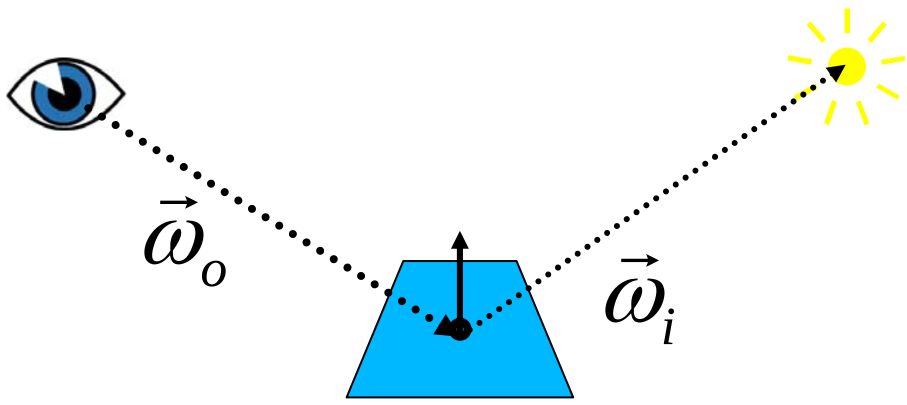
Light Source Description

- **Point light source**
- **Position**
- **Intensity ~ 1/r^2**



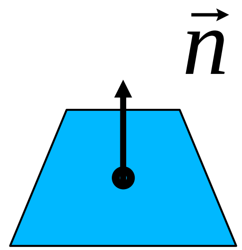
Viewpoint

- **Distance not so important for now**



Surface Normal

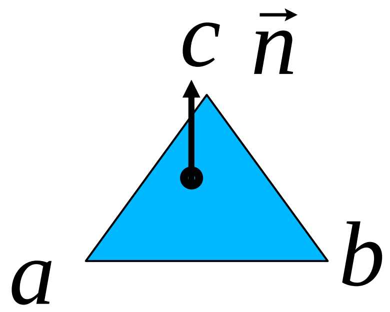
- **Trivial for a plane – Hesse form:** $(\vec{p}, \vec{n})$



Surface Normal - Triangle

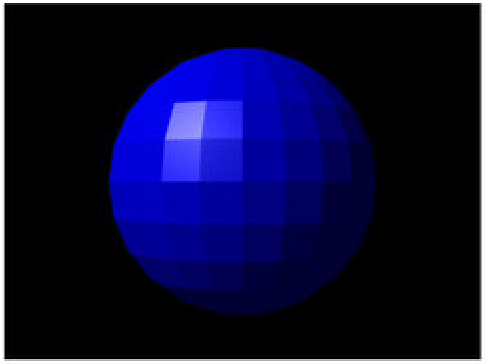
$$\vec{n} = \frac{(c-b)\times(a-b)}{\|(c-b)\times(a-b)\|}$$

- Orientation? Use right-hand rule.
- Normals should point towards the outside of an object.

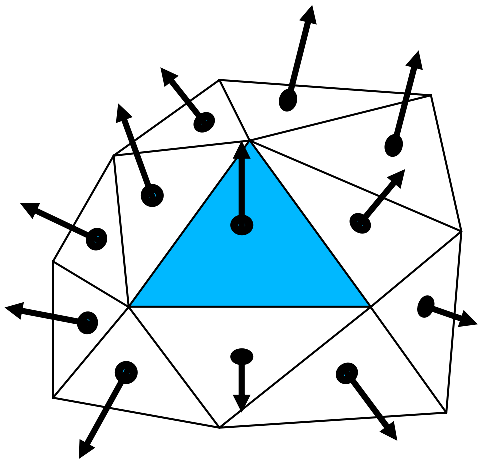


Surface Normals – Triangle Mesh

- **Per-surface normal**
- **Flat shading**

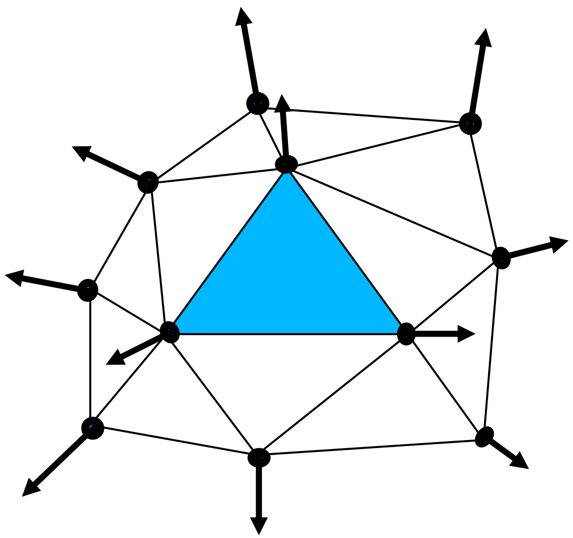


[wikipedia]



Surface Normals – Triangle Mesh

- **Per-vertex normal**

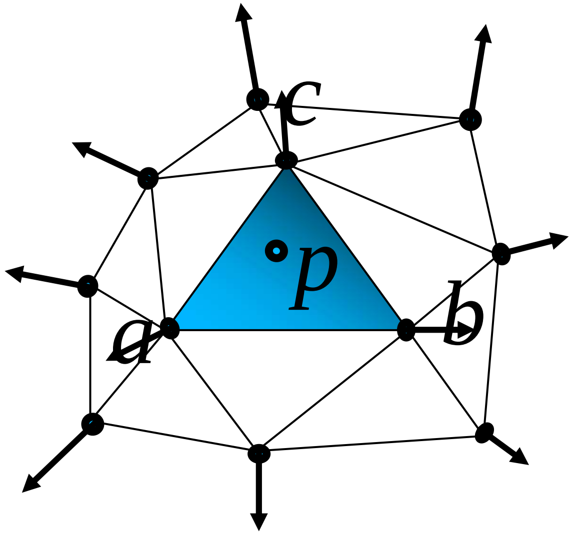


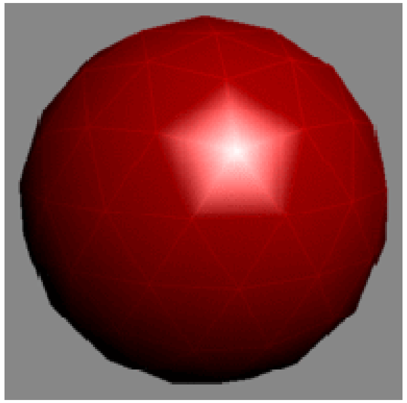
Surface Normals – Triangle Mesh

- **Per-vertex normal**
- **Goraud shading**
  - linear interpolation of the shaded colors

$$L_x \sim f(\vec{\omega}_o, \vec{n}_x, \vec{\omega}_i) L_i$$

$$L_p = \lambda_1 L_a + \lambda_2 L_b + \lambda_3 L_c$$





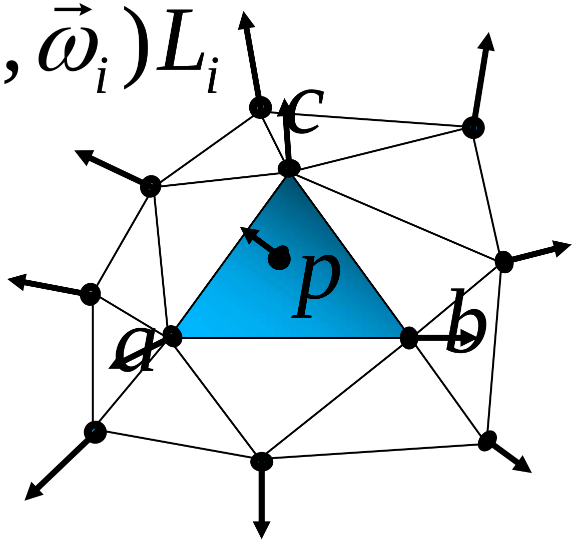
[wikipedia]

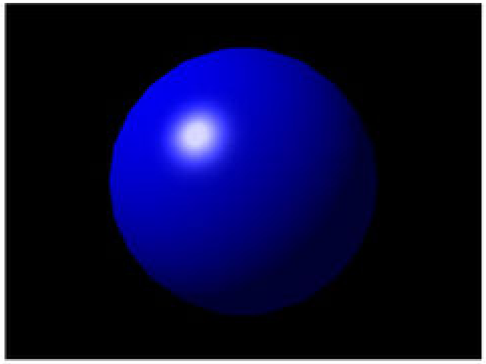
Surface Normals – Triangle Mesh

- **Per-vertex normal**
- **Phong shading**
  - linear interpolation of the surface normal

$$\vec{n}_p = \frac{\lambda_1 \vec{n}_a + \lambda_2 \vec{n}_b + \lambda_3 \vec{n}_c}{\| \lambda_1 \vec{n}_a + \lambda_2 \vec{n}_b + \lambda_3 \vec{n}_c \|}$$

$$L_p \sim f_r(\vec{\omega}_o, \vec{n}_p, \vec{\omega}_i) L_i$$





[wikipedia]

Surface Normals – Triangle Mesh

- **Per-vertex normal**
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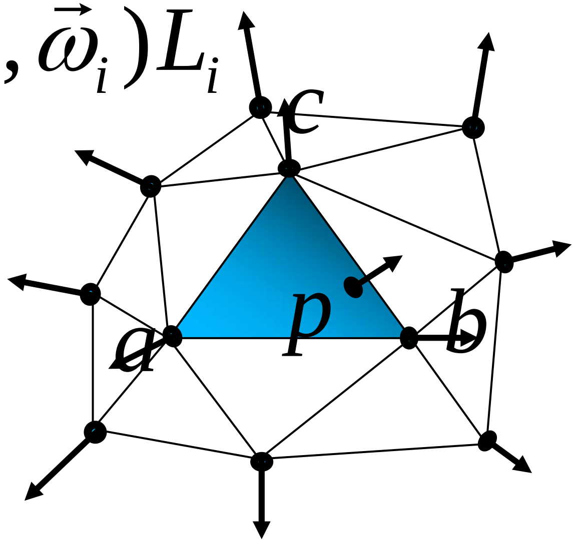
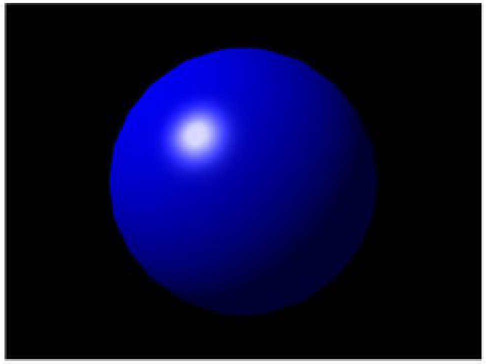
  - linear interpolation of the surface normal

$$\vec{n}_p = \frac{\lambda_1 \vec{n}_a + \lambda_2 \vec{n}_b + \lambda_3 \vec{n}_c}{\| \lambda_1 \vec{n}_a + \lambda_2 \vec{n}_b + \lambda_3 \vec{n}_c \|}$$

$$L_p \sim f_r(\vec{\omega}_o, \vec{n}_p, \vec{\omega}_i) L_i$$





[wikipedia]

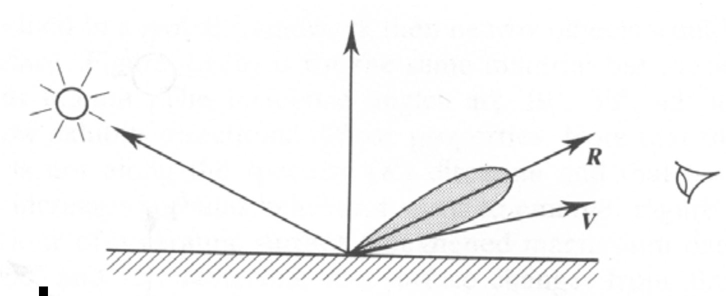
  - spherical interpolation

Phong Reflection Model

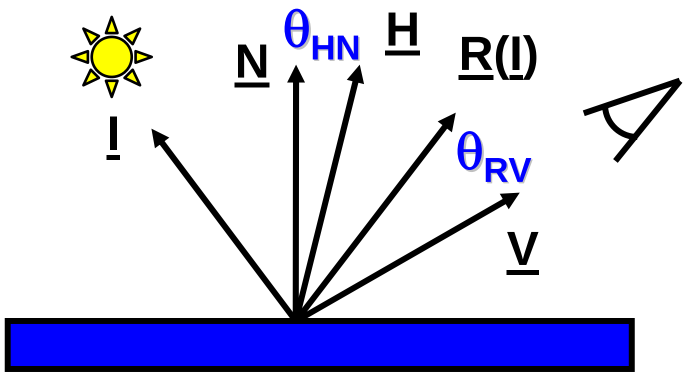
- **Cosine power lobe**

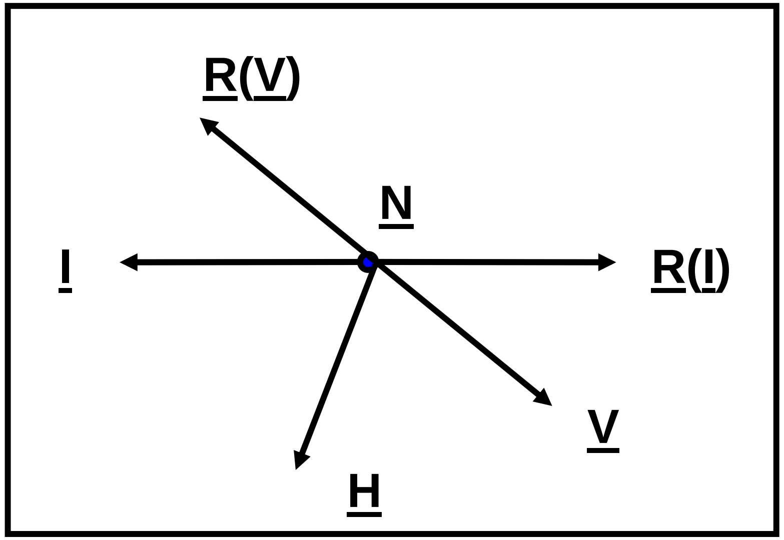
$$f_r(\omega_o, x, \omega_i) = k_s\left(\underline{R}(\underline{I}) \cdot \underline{V}\right)^{k_e}$$

  – $L_{r,s} = L_i \, k_s \cos^{ke} \theta_{RV}$



- **Dot product & power**
- **Not energy conserving/reciprocal**
- **Plastic-like appearance**

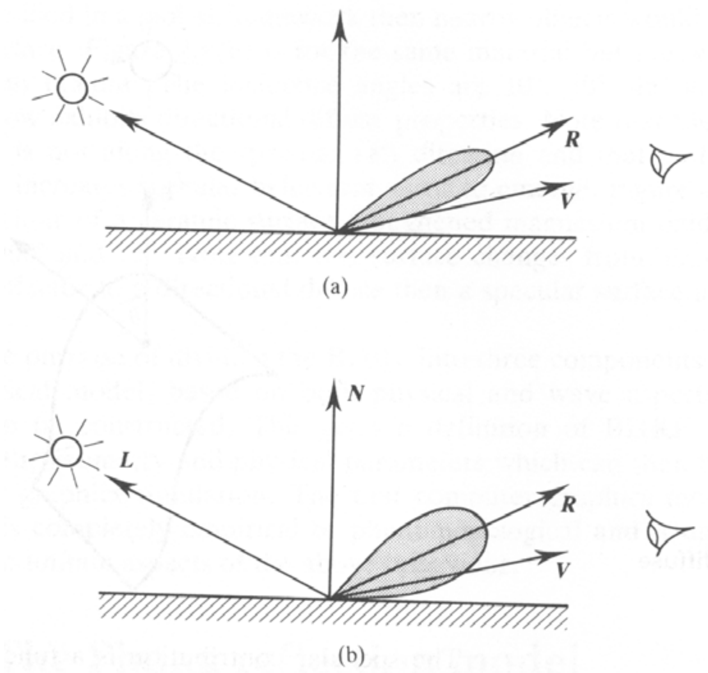


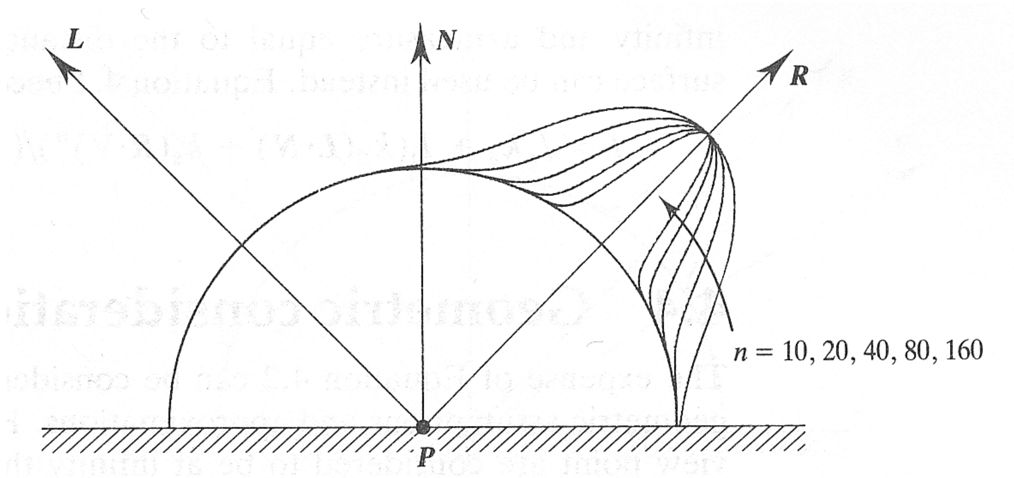


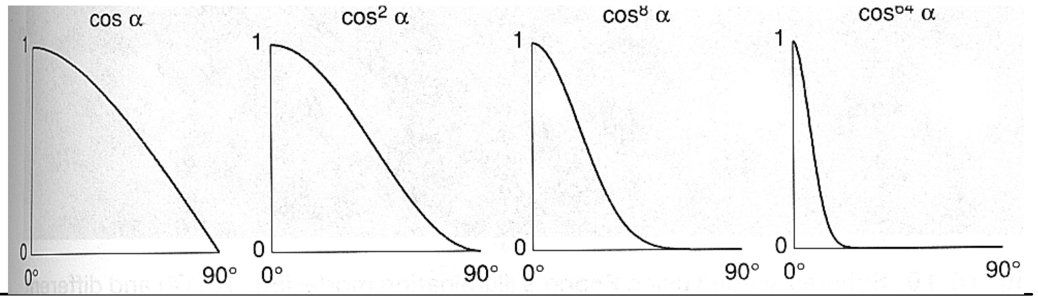
Phong Exponent k_e

$$f_r(\omega_o, x, \omega_i) = k_s \left(\underline{R}(\underline{I}) \cdot \underline{V}\right)^{k_e}$$

- **Determines size of highlight**







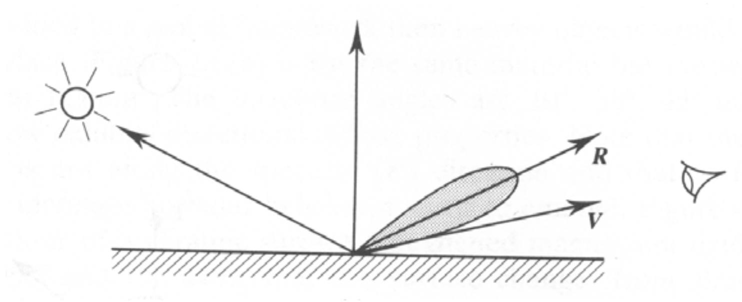
Blinn-Phong Reflection Model

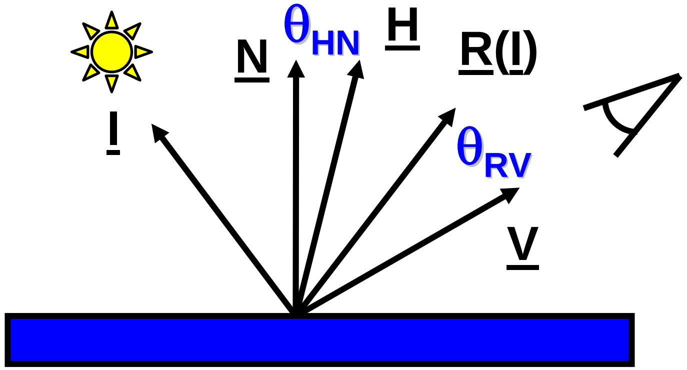
- **Blinn-Phong reflection model**

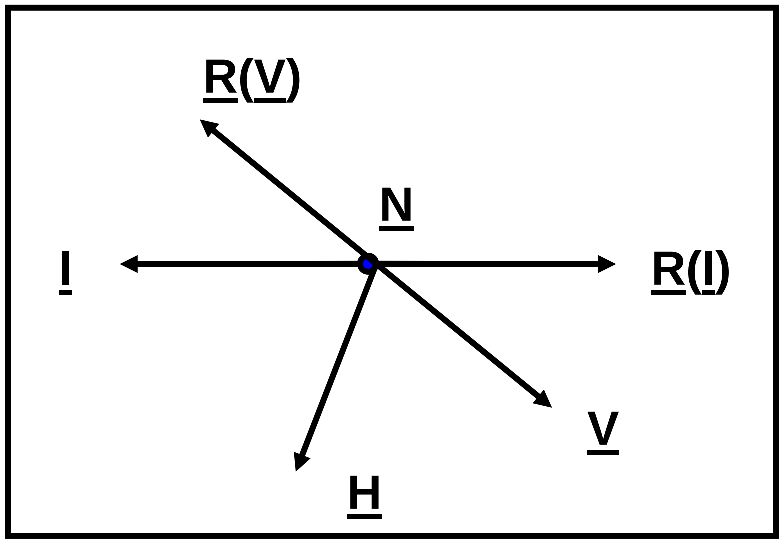
$$f_r(\omega_o, x, \omega_i) = k_s \left(H \cdot N\right)^{k_e}$$

  - $L_{r,s} = L_i\, k_s \cos^{ke} \theta_{HN}$
  - $\theta_{RV} \Rightarrow \theta_{HN}$
  - Light source, viewer far away
  - I, R constant: H constant

    θ_{HN} less expensive to compute







Phong Illumination Model

- **Extended light sources: *l* point light sources**

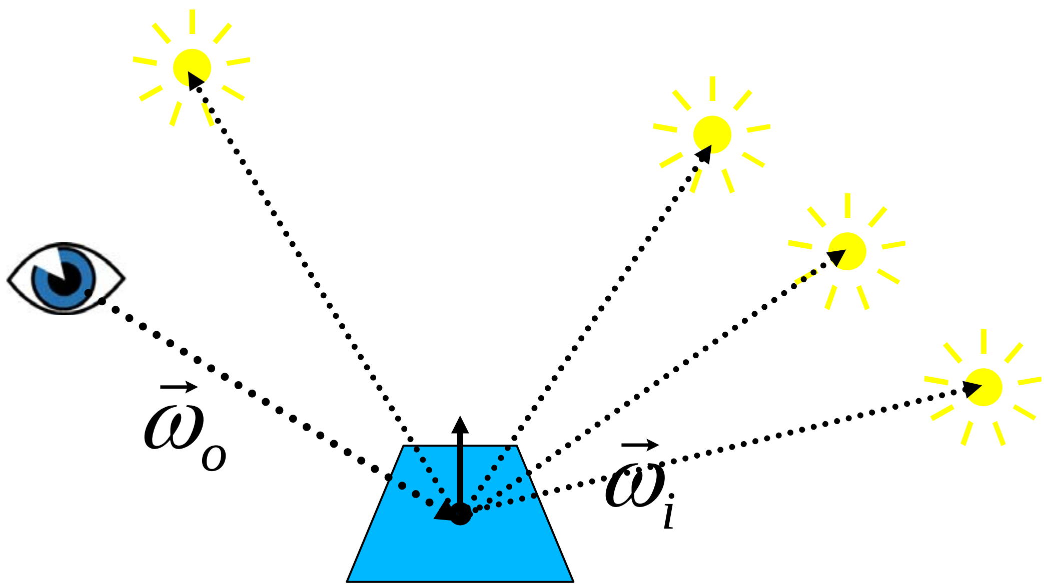
$$L_r = k_a L_{i,a} + k_d \sum_l L_l (I_l \cdot N) + k_s \sum_l L_l (R(I_l) \cdot V)^{k_e} \quad \text{(Phong)}$$

$$L_r = k_a L_{i,a} + k_d \sum_l L_l (I_l \cdot N) + k_s \sum_l L_l (H_l \cdot N)^{k_e} \quad \text{(Blinn)}$$

- **Color of specular reflection equal to light source**
- **Heuristic model**
  - Contradicts physics
  - Purely local illumination
    - Only direct light from the light sources
    - No further reflection on other surfaces
    - Constant ambient term
- **Often: light sources & viewer assumed to be far away**

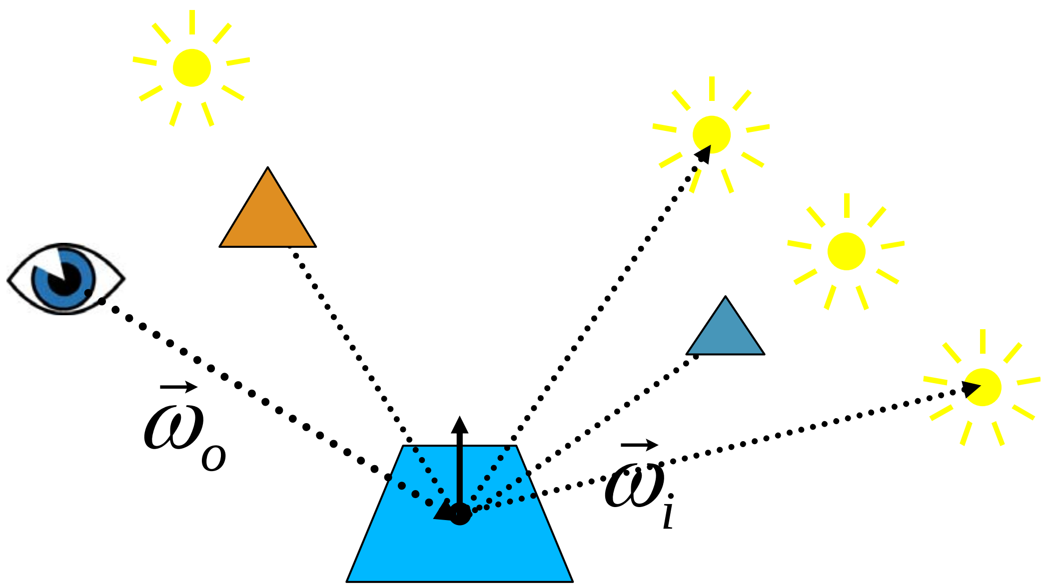
Multiple Light Sources

- **Add their contributions**



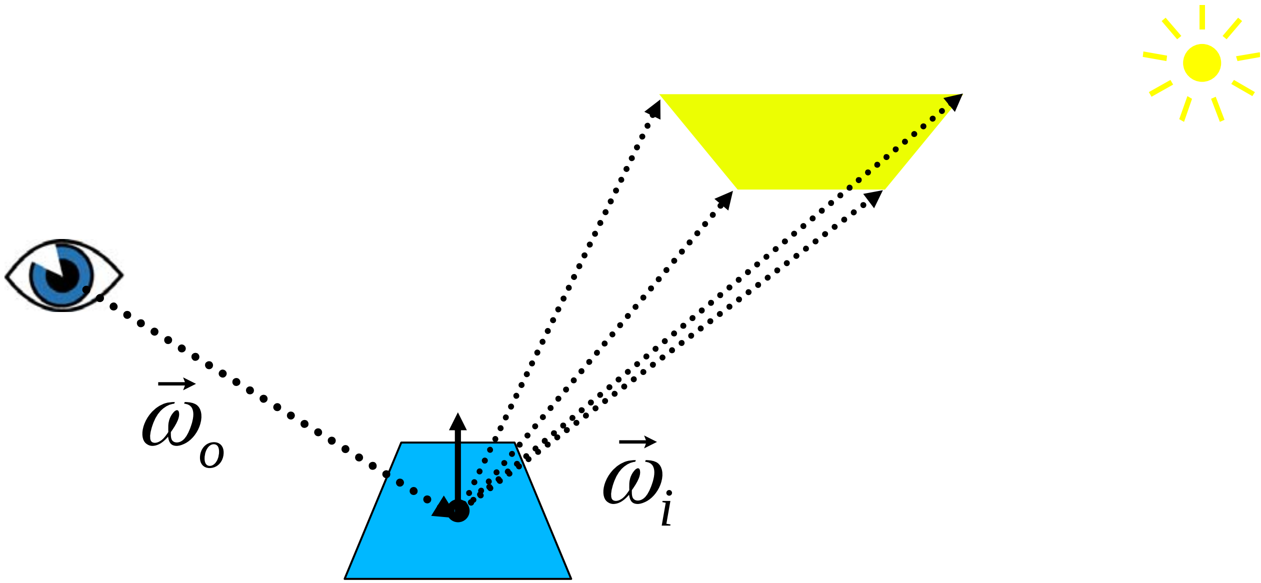
Occlusions

- **The point on the surface might be in shadow from some object**
- **Trace ray to light source and test for occlusion**



Area Light sources

- **Typically approximated by sampling**



Area Light sources

- **Typically approximated by sampling**