EBERHARD KARLS UNIVERSITÄT TÜBINGEN
FACULTY OF SCIENCE
Computer Graphics

Computer Graphics (Graphische Datenverarbeitung)

- Shading -

WS 2021/2022

Corona

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

- Regular random lookup of the 3G certificates

- Contact tracing: We need to know who is in the class room
  - New ILIAS group for every lecture slot
  - Register via ILIAS or this QR code (only if you are present in this room)

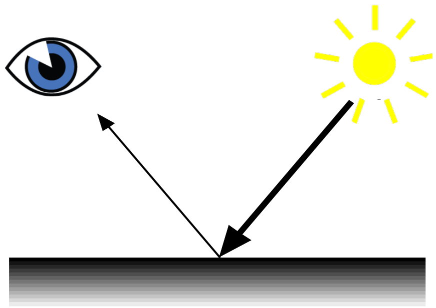
Ray Tracing Steps (repetition)

- Generation of primary rays
  - Rays from viewpoint along viewing directions into 3D scene
  - (At least) one ray per picture element (pixel)
- Ray tracing
  - Traversal of spatial index structures
  - Intersection of ray with scene geometry
- Shading
  - From intersection, determine “light color” sent along primary ray
  - Determines “pixel color”
  - Needed
    - Local material color and reflection properties
      - Object texture
    - Local illumination of intersection point
      - Can be hard to determine correctly

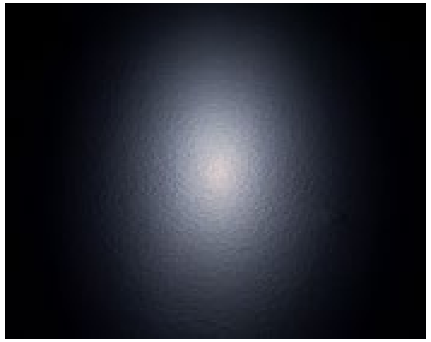
Reflectance Phenomena

Appearance Samples

- How do materials reflect light?
- Light source at exactly the same position

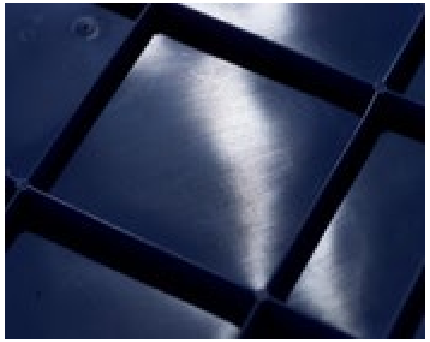


diffuse



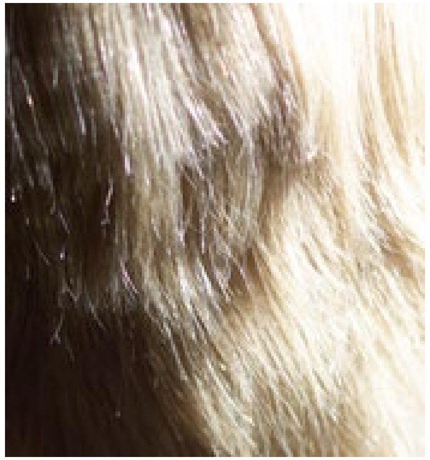
glossy

mirror



anisotropic

Appearance Samples (2)




fibers

translucency- subsurface scattering

opaque

Material Samples

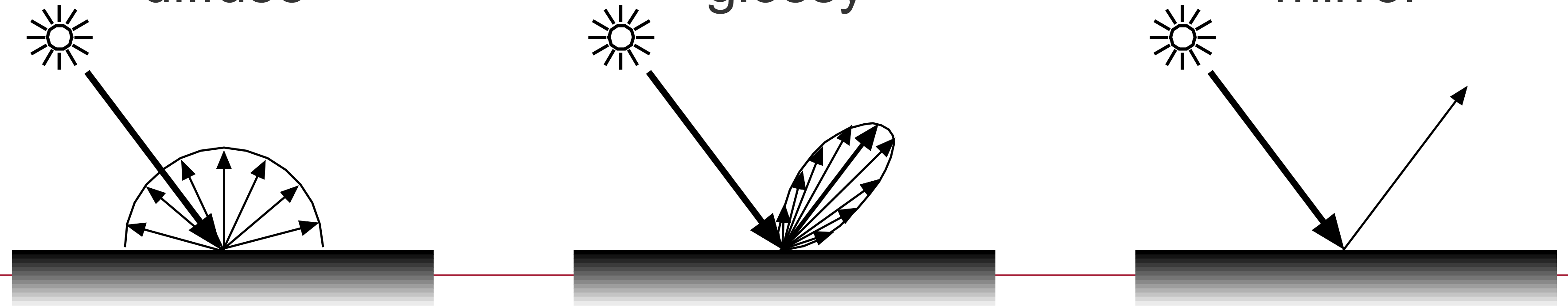
diffuse

glossy

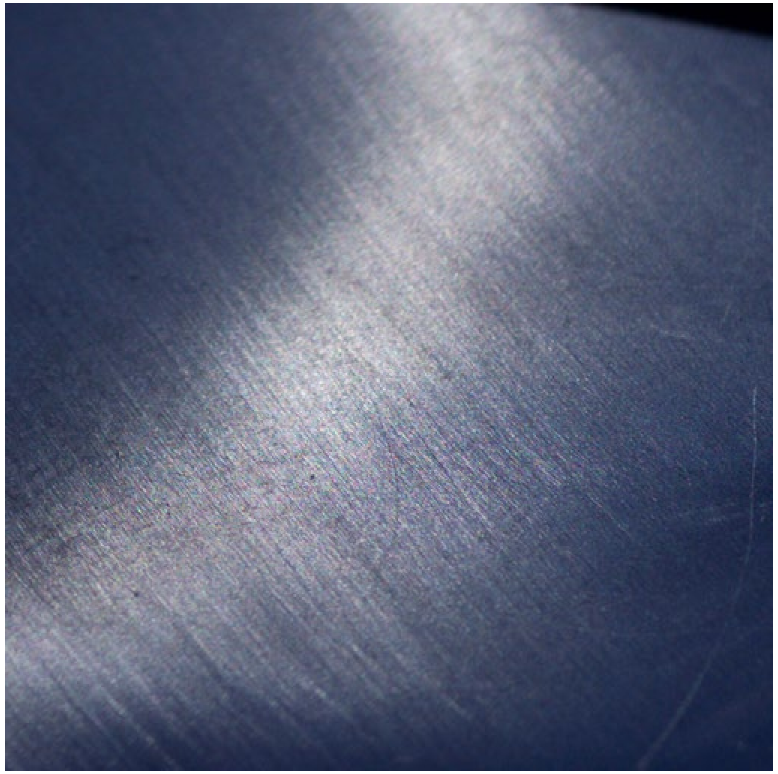
mirror

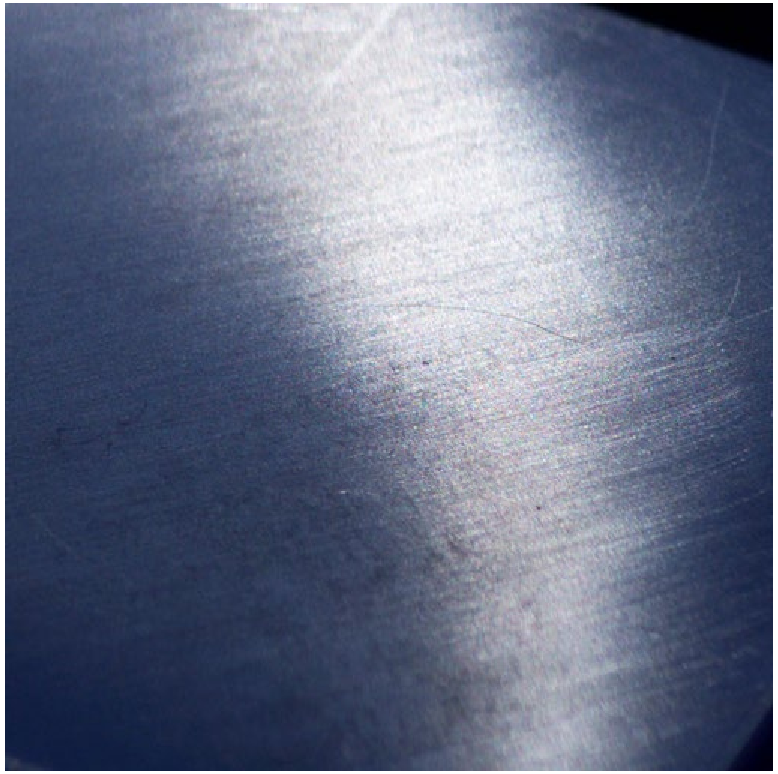
Material Samples

diffuse glossy mirror



Material Samples





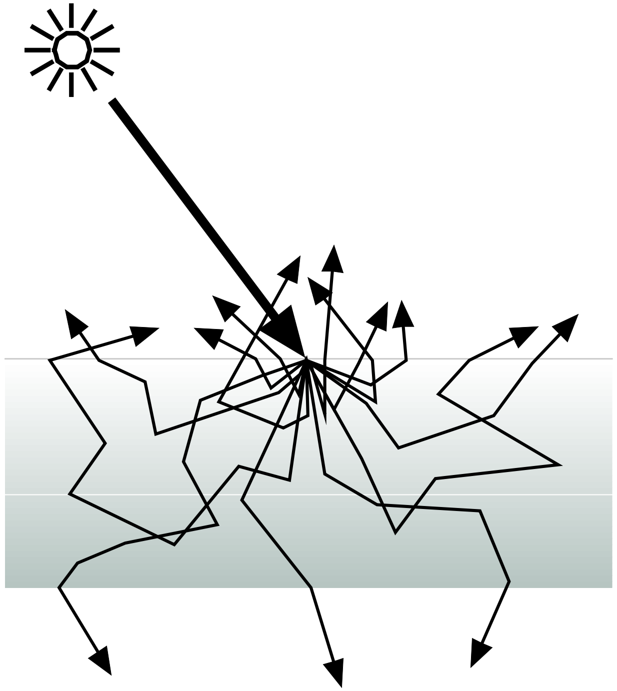
anisotropic

Material Samples

translucent

Material Samples

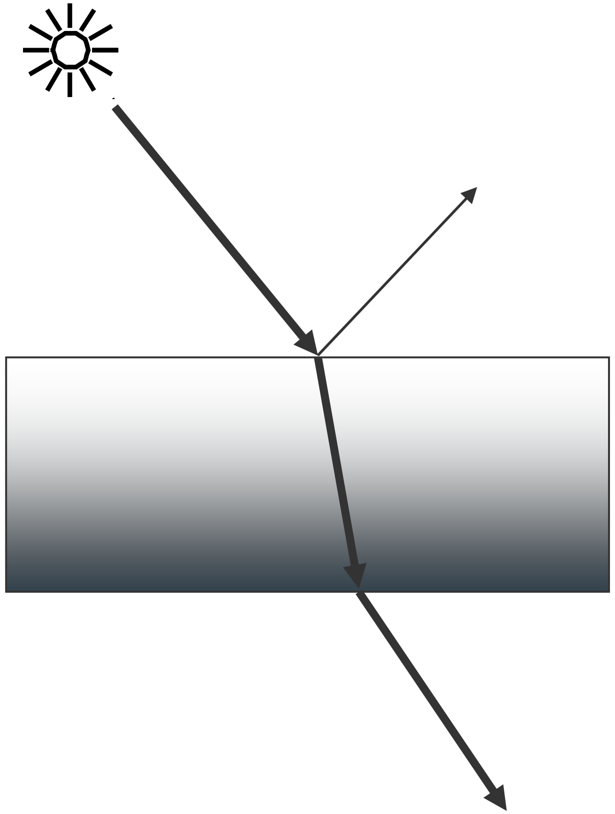
translucent



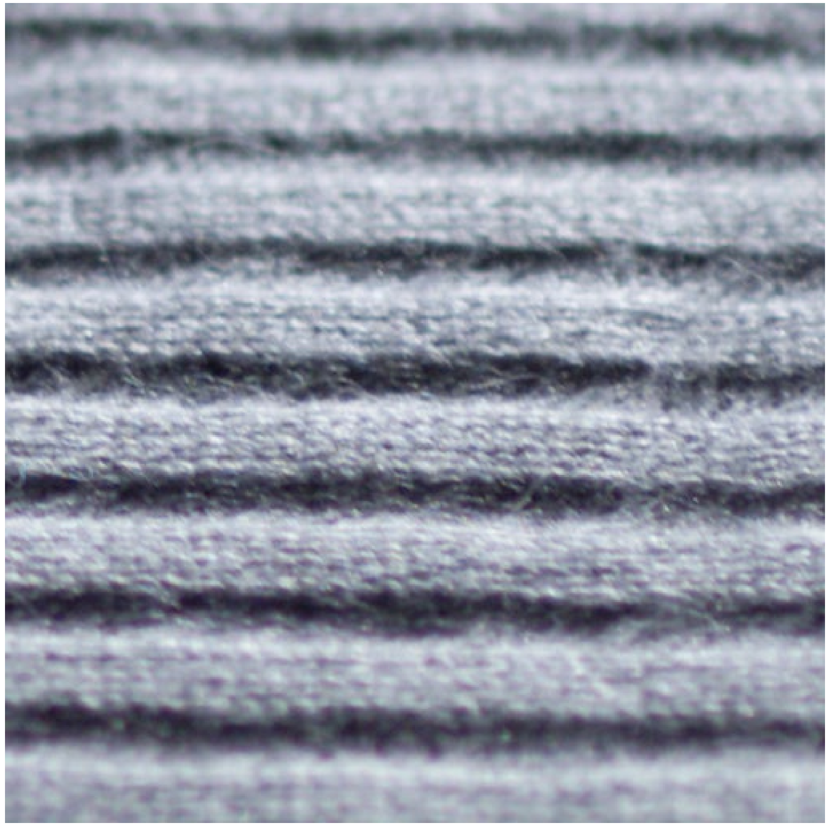
subsurface scattering

Material Samples

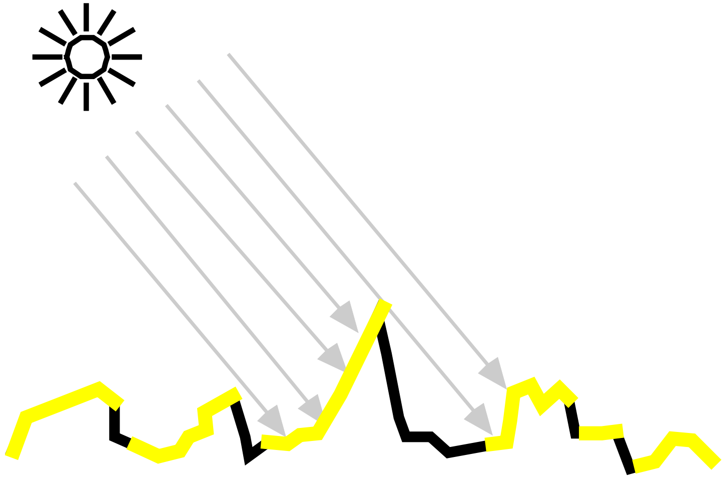
transparent



Material Samples

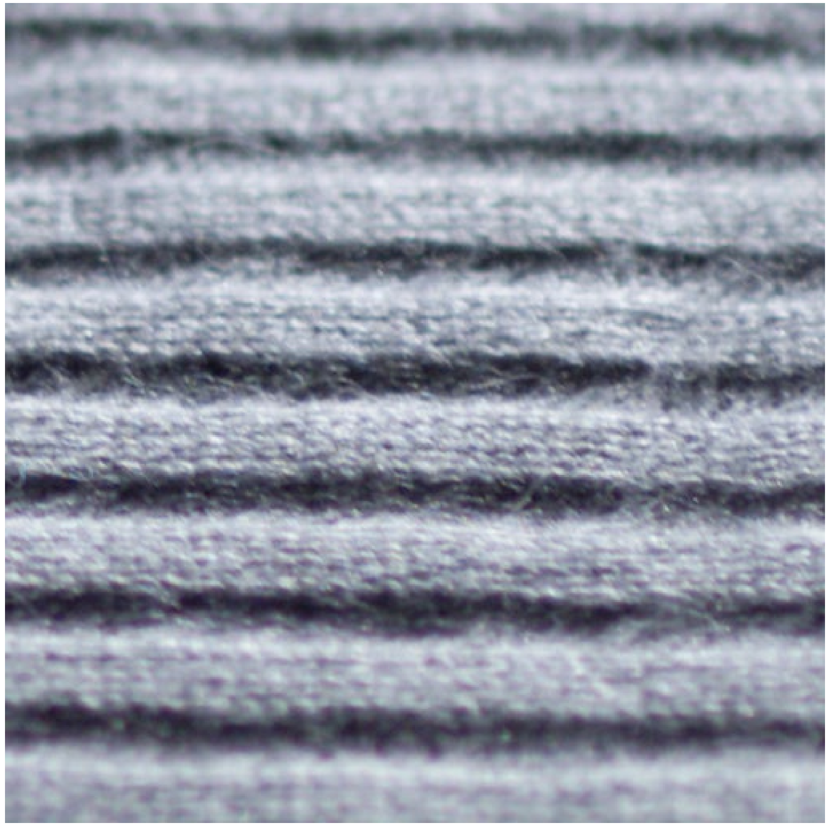


complex surface structure

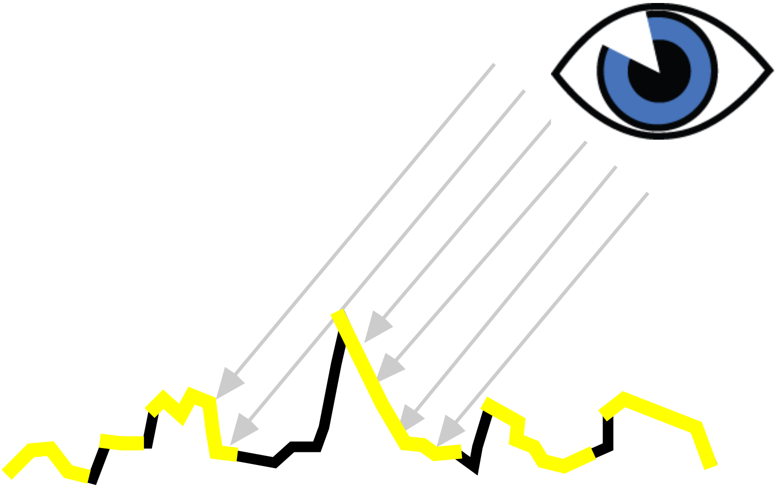


shadows

Material Samples



complex surface structure



occlusions

Material Samples

fibers

Reflection Models

How to describe materials?

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

- *relightable* representations of appearance

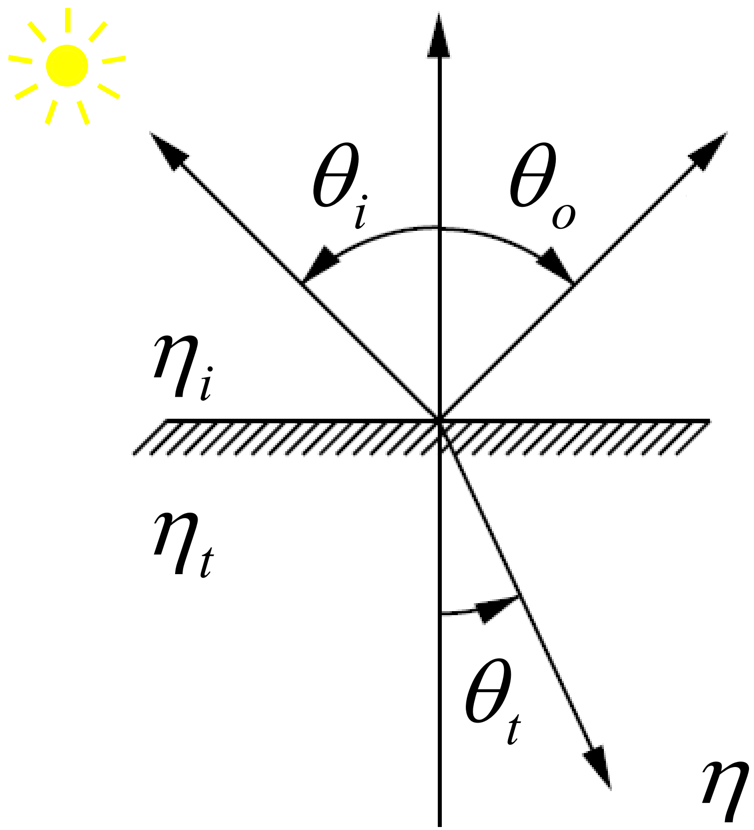
At the Intersection

What happens to the reflected/refracted light?

Snell's Law

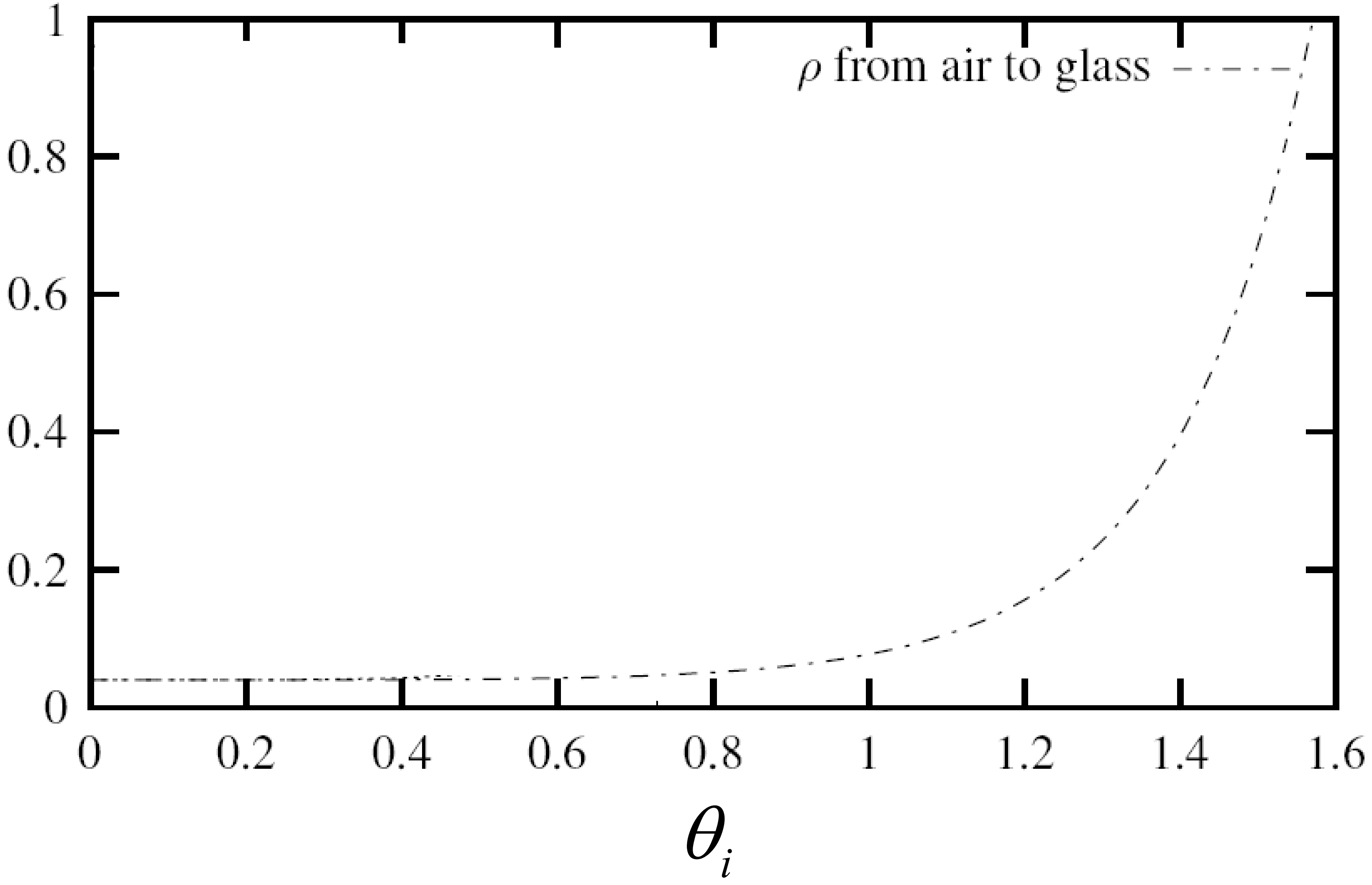
- For the refracted ray

$$\eta_i(\lambda)\sin\theta_i = \eta_t(\lambda)\sin\theta_t$$



η - index of refraction

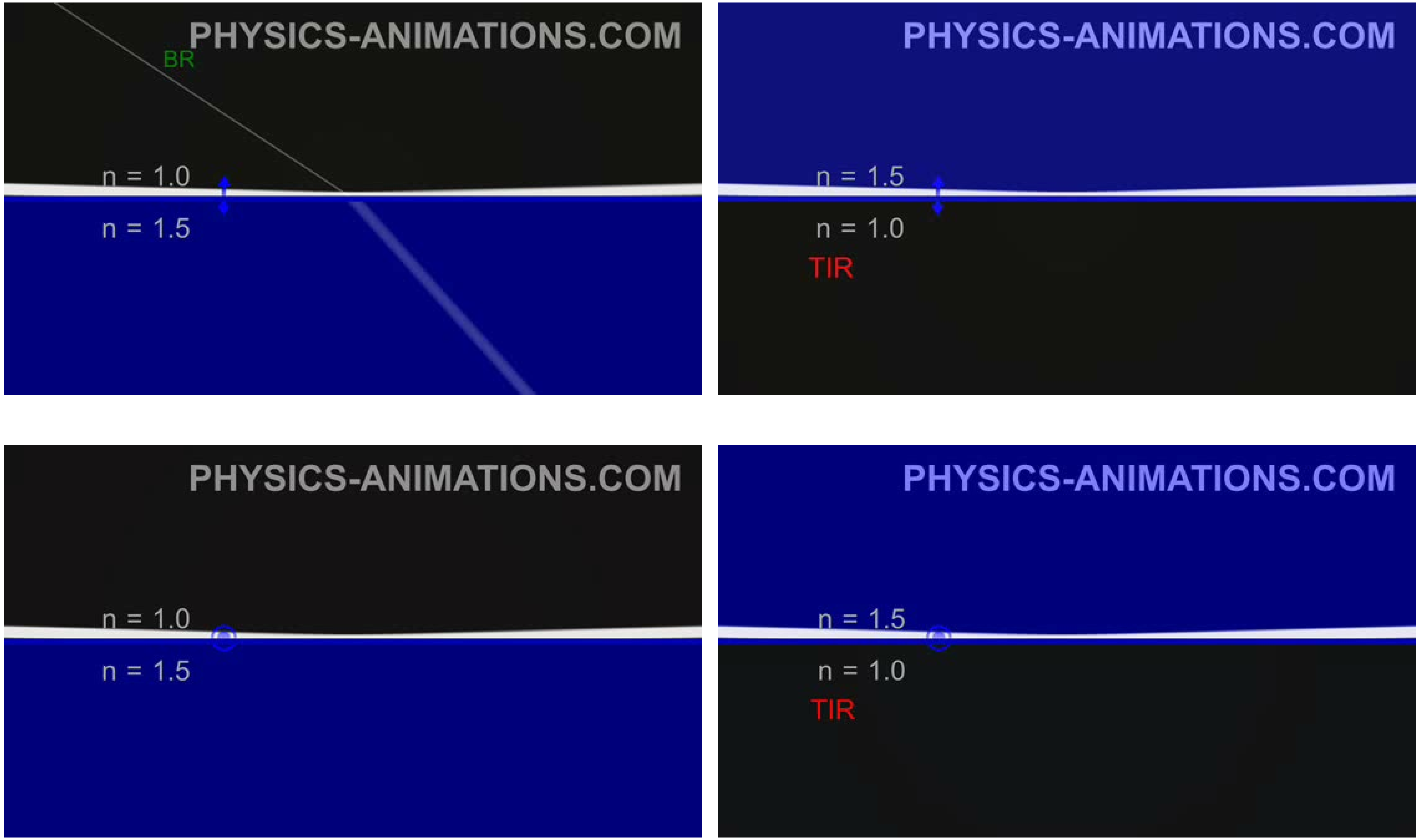
Fresnel Effect



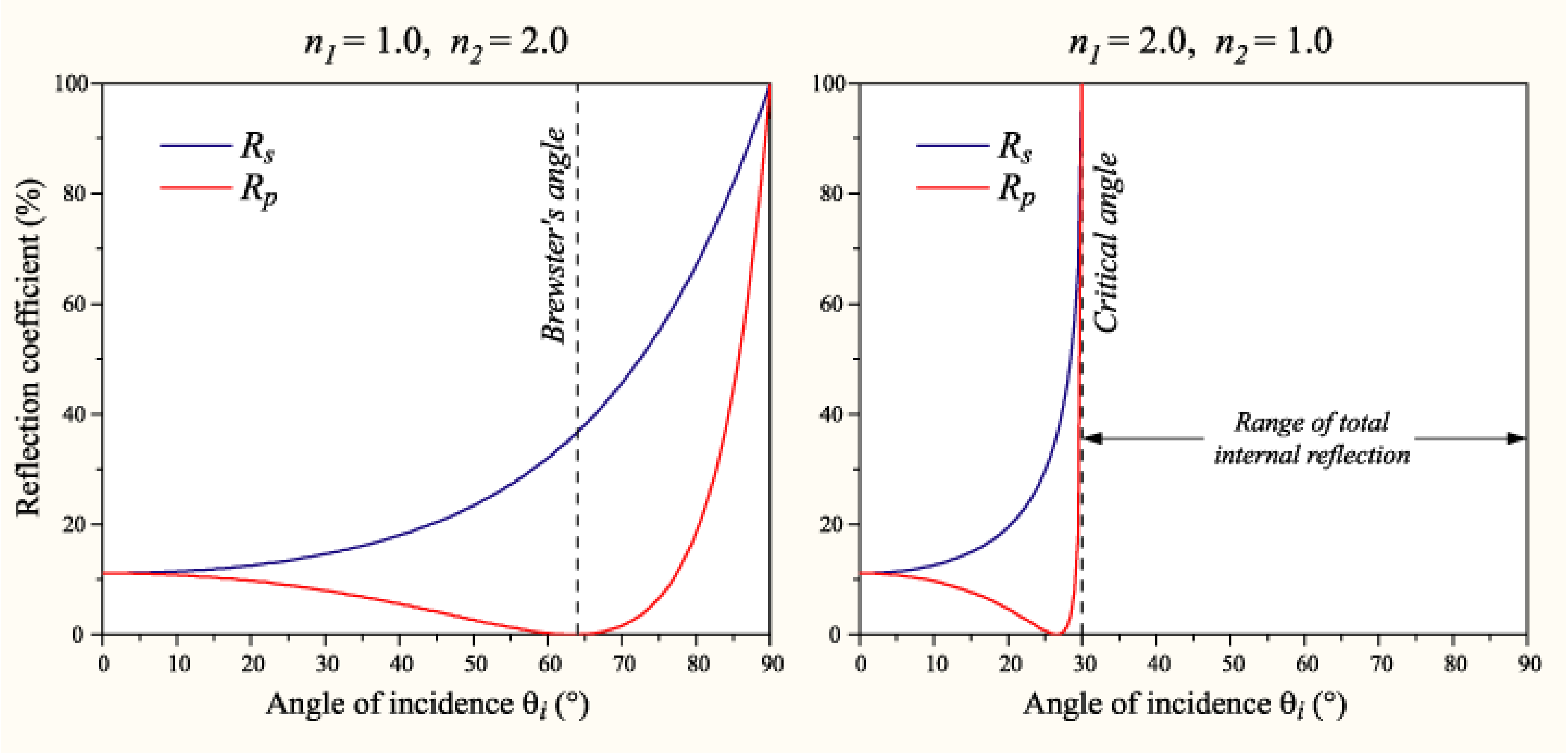
Fresnel Effect

air->glass glass->air

|| ⊥

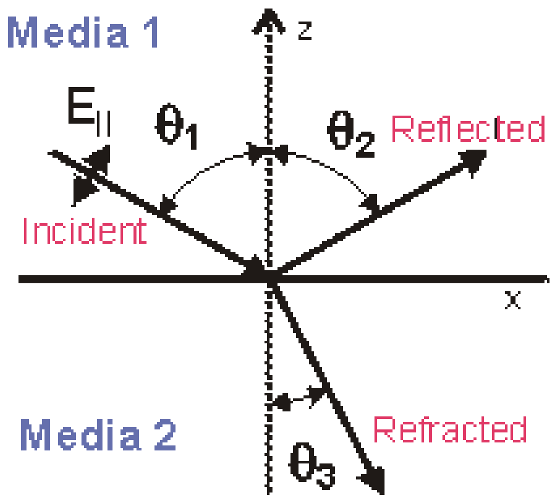


Reflection and Refraction



Fresnel Formula

- Reflectance and refraction depends on polarization
  - orientation of E field wrt. plane of reflection (given by incident direction + normal)



$$R_{||} = \frac{\tan^2(\theta_1 - \theta_3)}{\tan^2(\theta_1 + \theta_3)} \qquad T_{||} = \frac{\sin 2\theta_1 \sin 2\theta_3}{\sin^2(\theta_1 + \theta_3)\cos^2(\theta_1 - \theta_3)}$$

$$R_{\perp} = \frac{\sin^2(\theta_1 - \theta_3)}{\sin^2(\theta_1 + \theta_3)} \qquad T_{\perp} = \frac{\sin 2\theta_1 \sin 2\theta_3}{\sin^2(\theta_1 + \theta_2)}$$

Fresnel Formula

- For unpolarized light:

$$R = (R_{||} + R_{\perp})/2$$

- Schlick's approximation:
  - Based on normal reflection

$$\theta_1 = 0$$

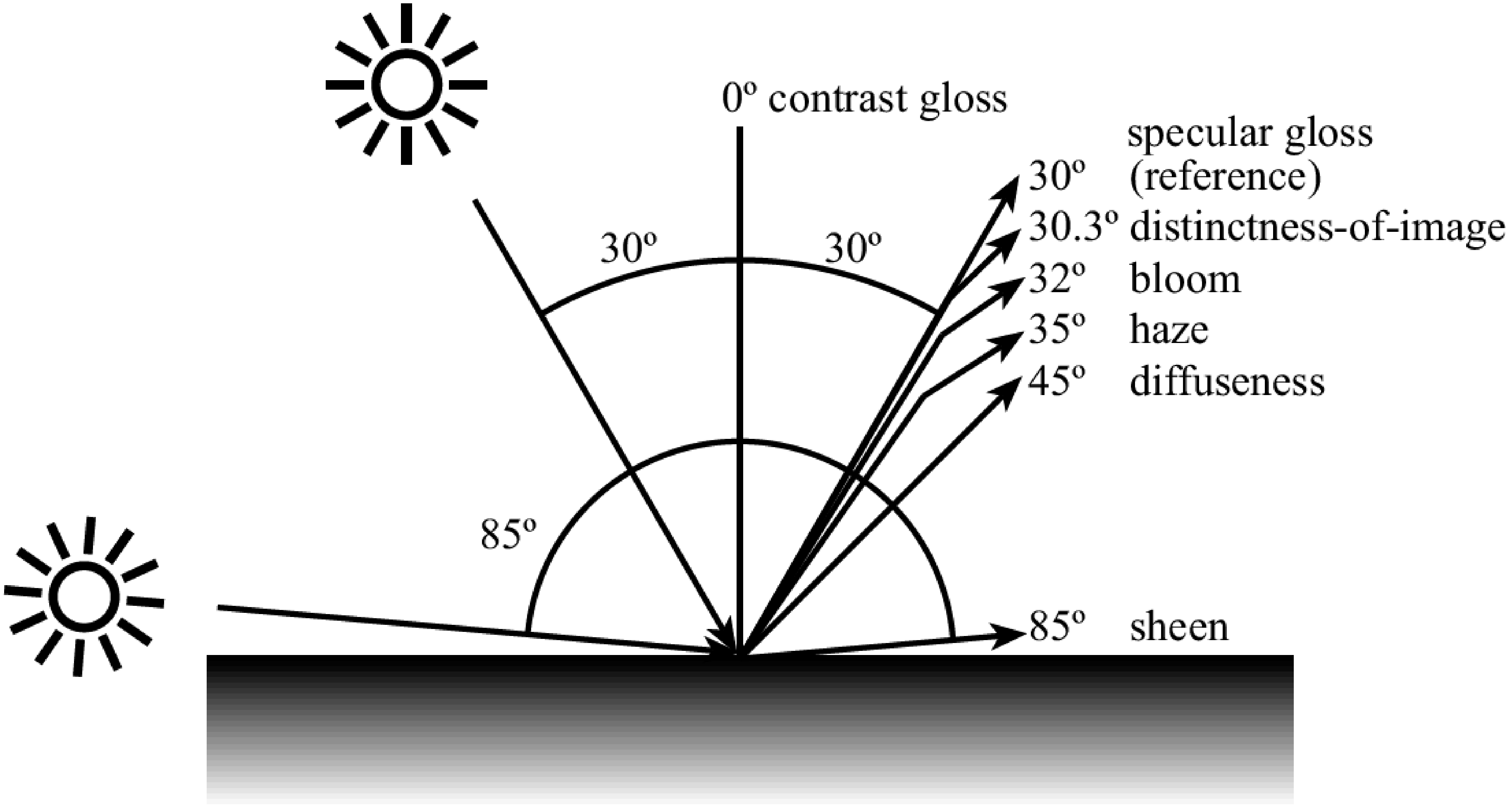
$$R_0 = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

$$R \approx R_0 + (1 - R_0)(1 - \cos\theta_1)^5$$

Appearance Representation

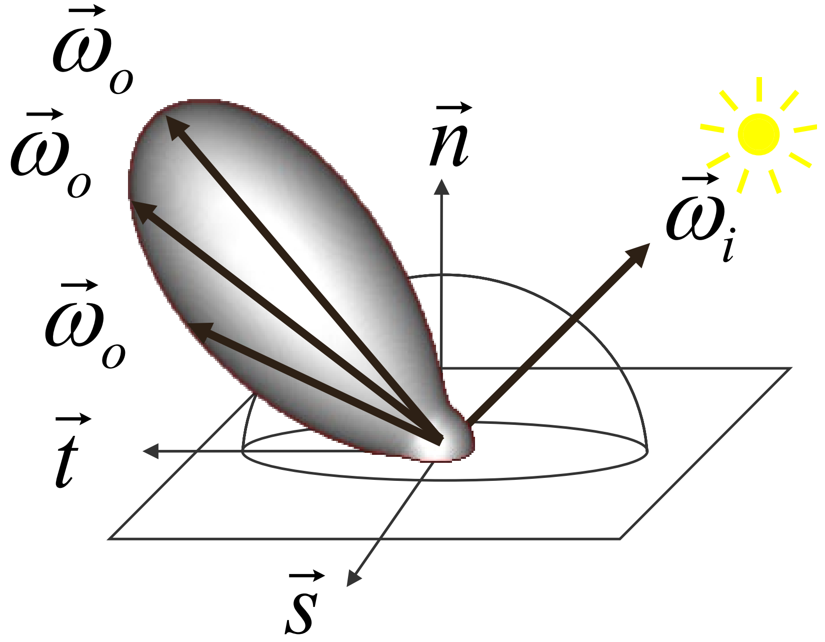
How can we represent / characterize reflectance?

Gloss Model

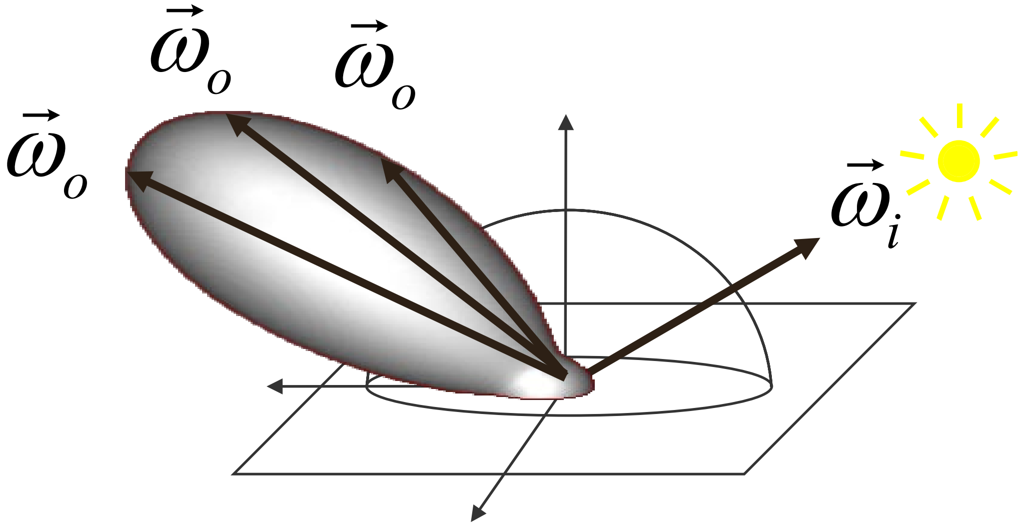


0° contrast gloss
30°
30°
85°
30° specular gloss (reference)
30.3° distinctness-of-image
32° bloom
35° haze
45° diffuseness
85° sheen

Reflection of an Opaque Surface



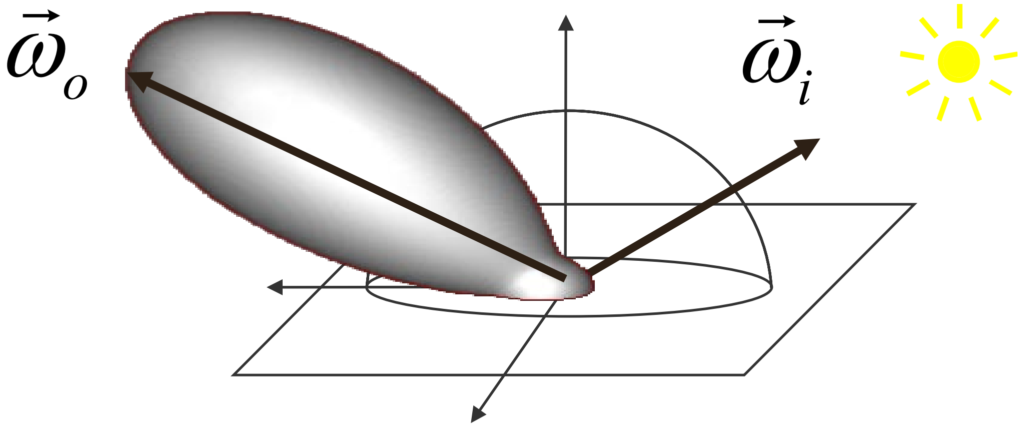
Reflection of an Opaque Surface



BRDF – 4D

(bidirectional reflectance distribution function)

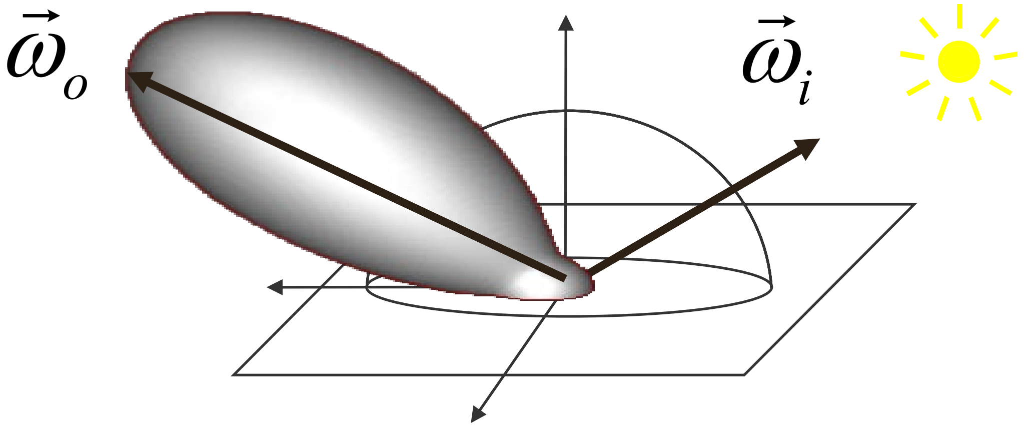
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



BRDF – 4D

(bidirectional reflectance distribution function)
ratio of reflected radiance to incident irradiance

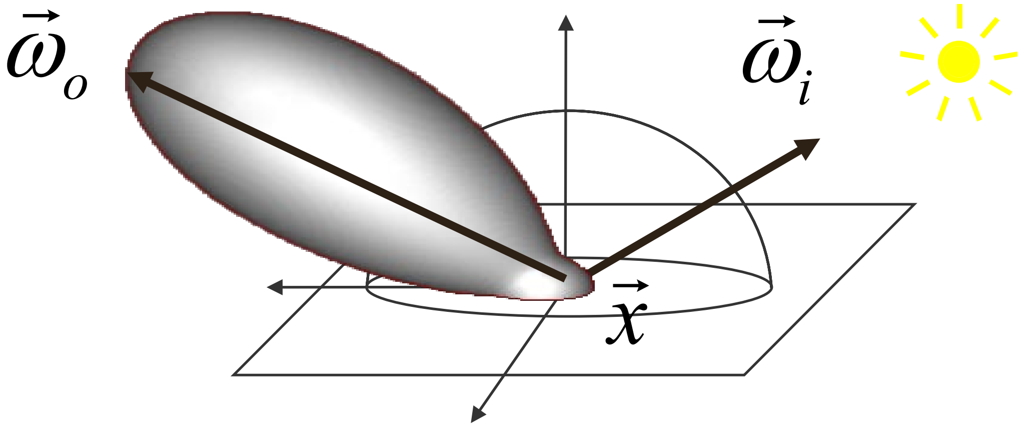
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{\omega}_o)}{dE(\vec{\omega}_i)}$$



Spatially Varying BRDF – 6D

heterogeneous materials

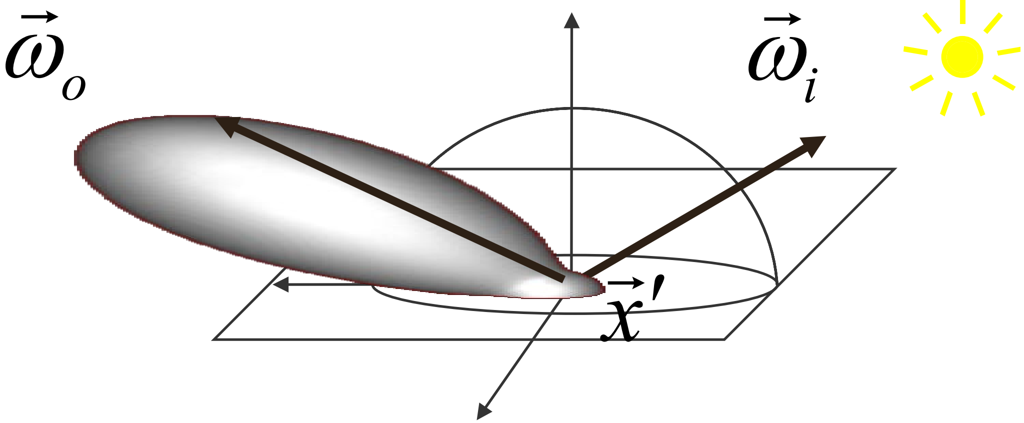
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Spatially Varying BRDF – 6D

heterogeneous materials

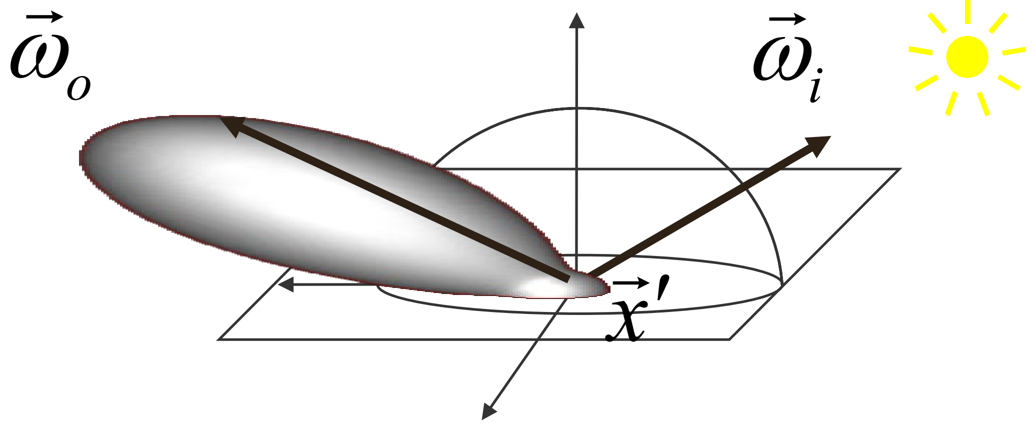
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Spatially Varying BRDF – 6D

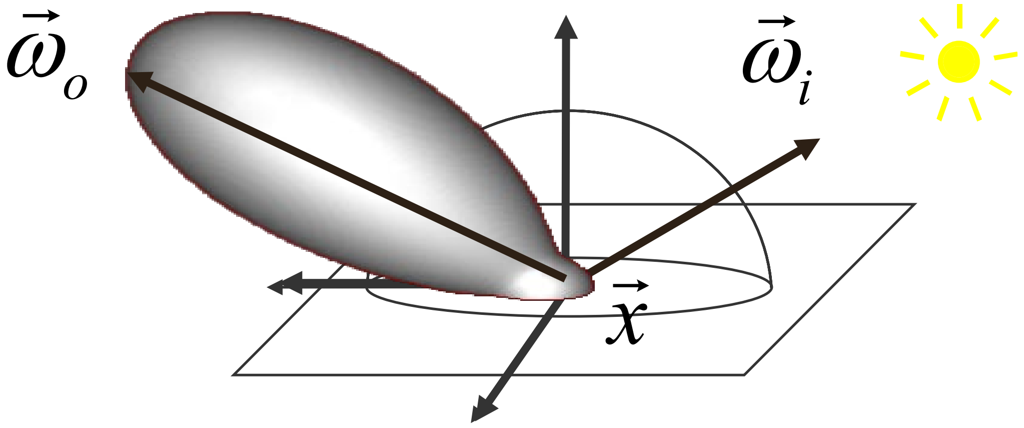
heterogeneous materials

$$f_r(\vec{x}\,;\overrightarrow{\omega_i} \rightarrow \vec{\omega}_o)$$



Isotropic BRDF – 3D

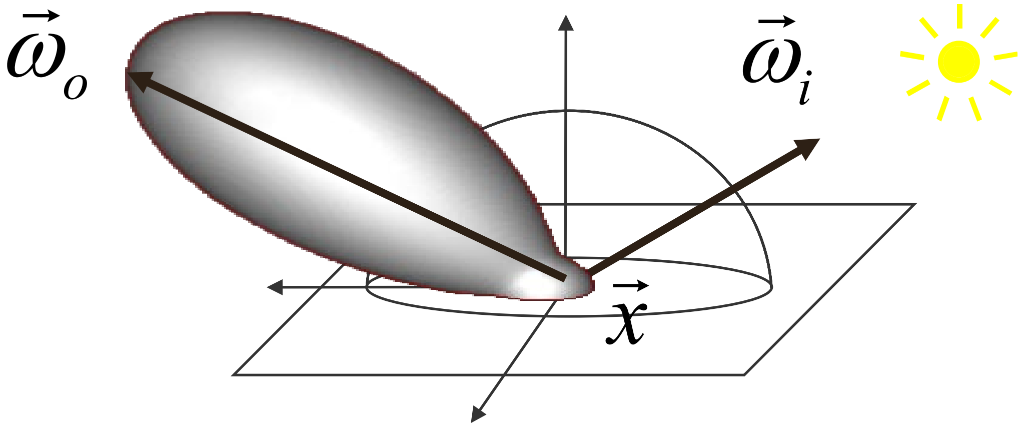
invariant with respect to rotation about the normal



Isotropic BRDF – 3D

invariant with respect to rotation about the normal

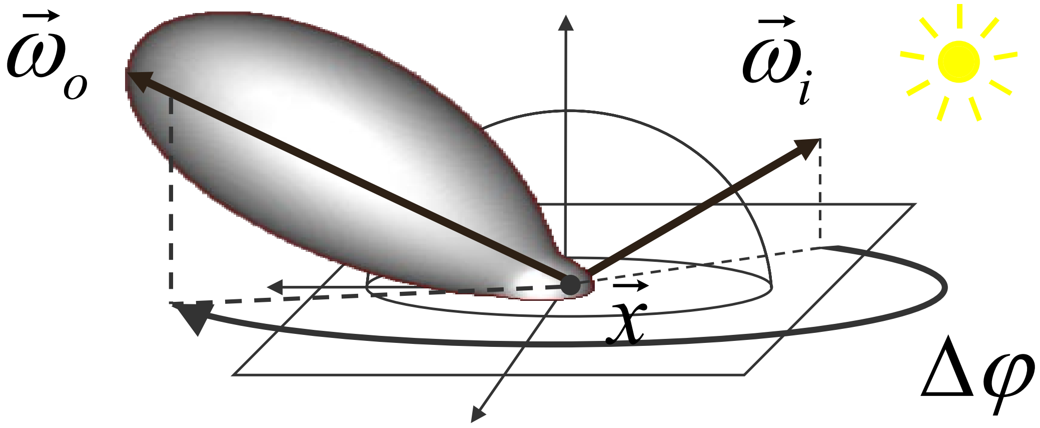
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Isotropic BRDF – 3D

invariant with respect to rotation about the normal

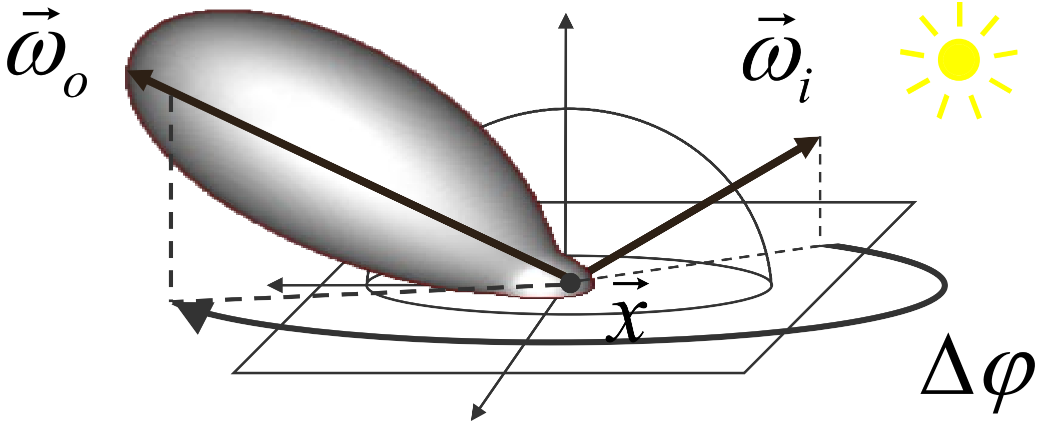
$$f_r((\theta_i, \phi_i) \rightarrow (\theta_o, \phi_o))$$



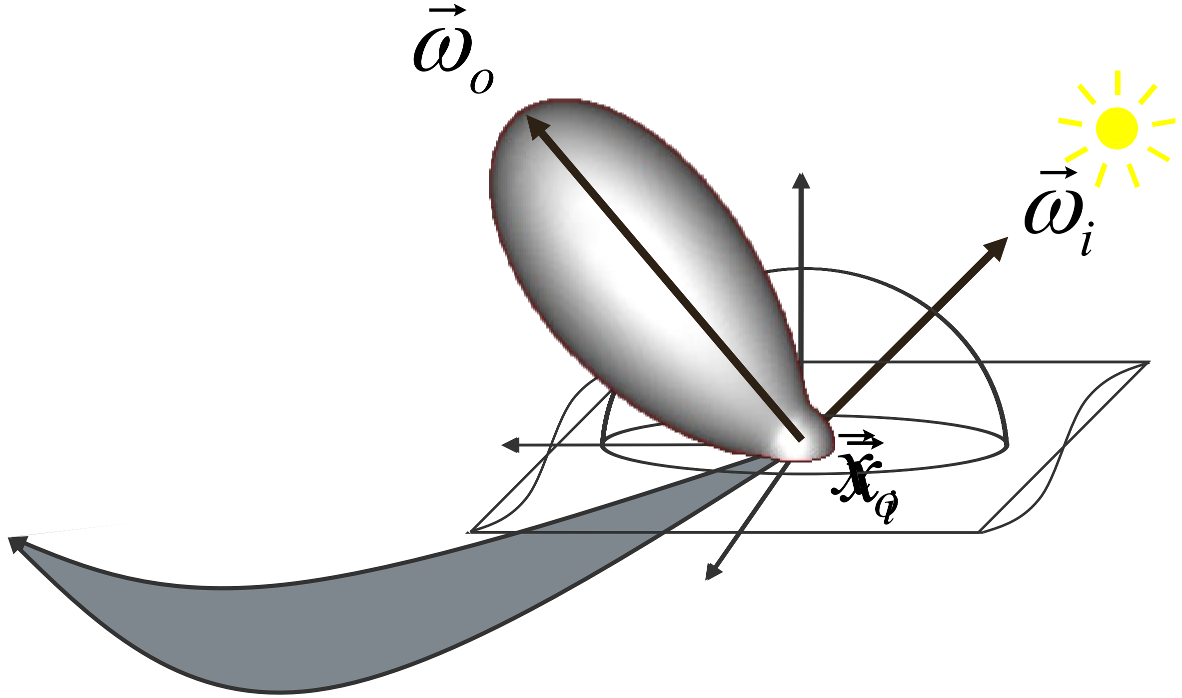
Isotropic BRDF – 3D

invariant with respect to rotation about the normal

$$f_r(\Delta\phi\,;\theta_i \rightarrow \theta_o)$$



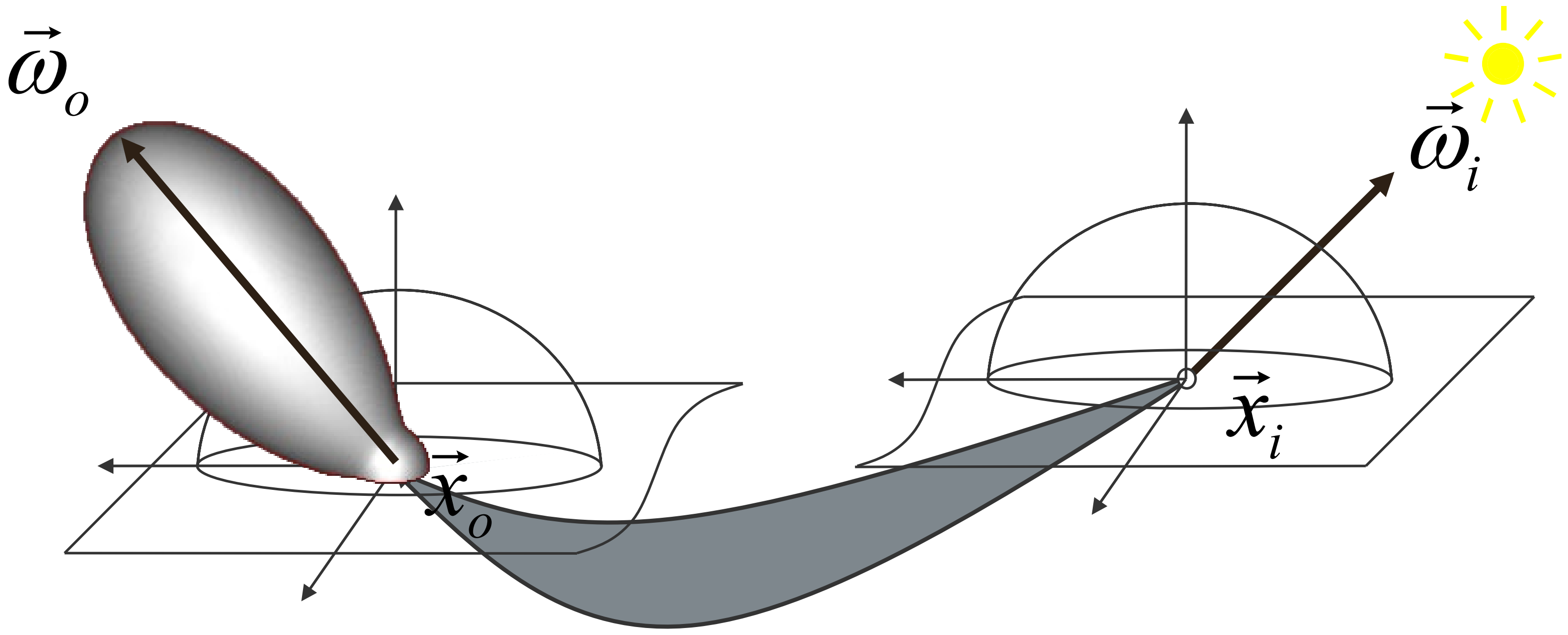
Subsurface Scattering



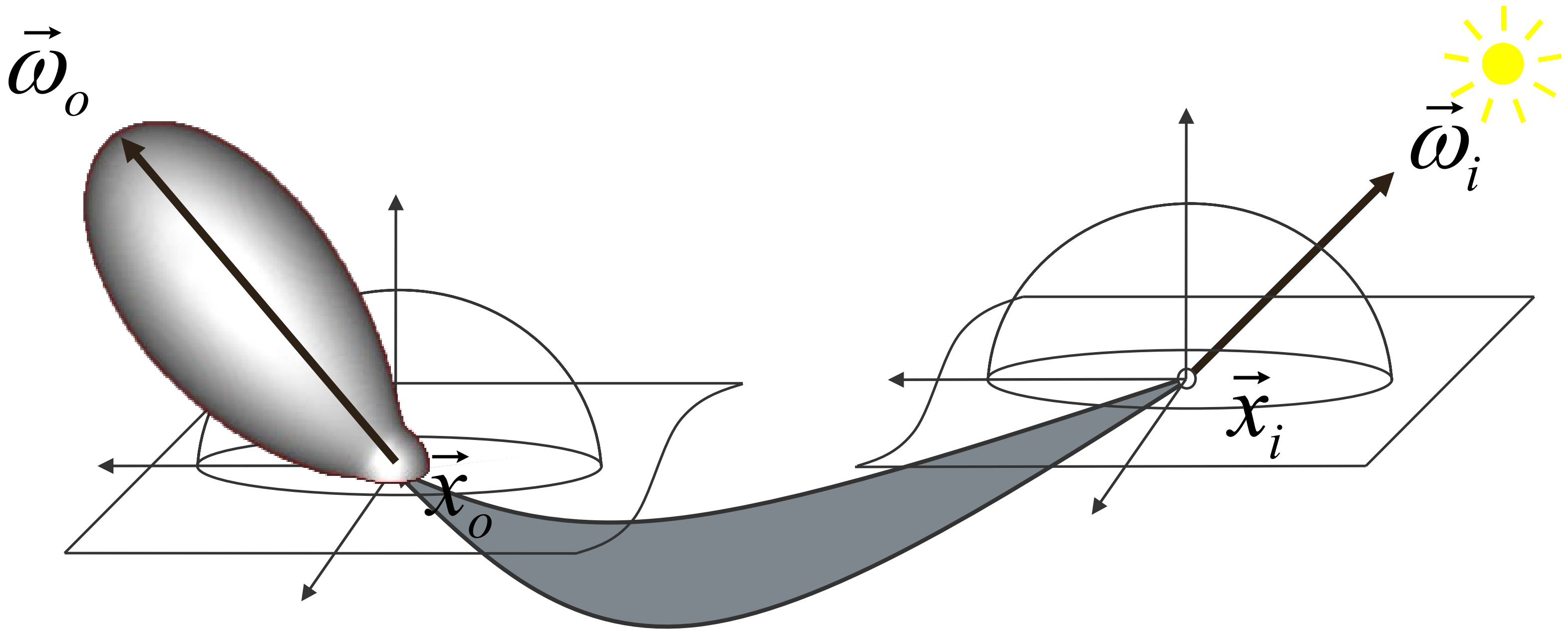
BSSRDF – 8D

(bidirectional scattering surface reflectance distribution function)

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

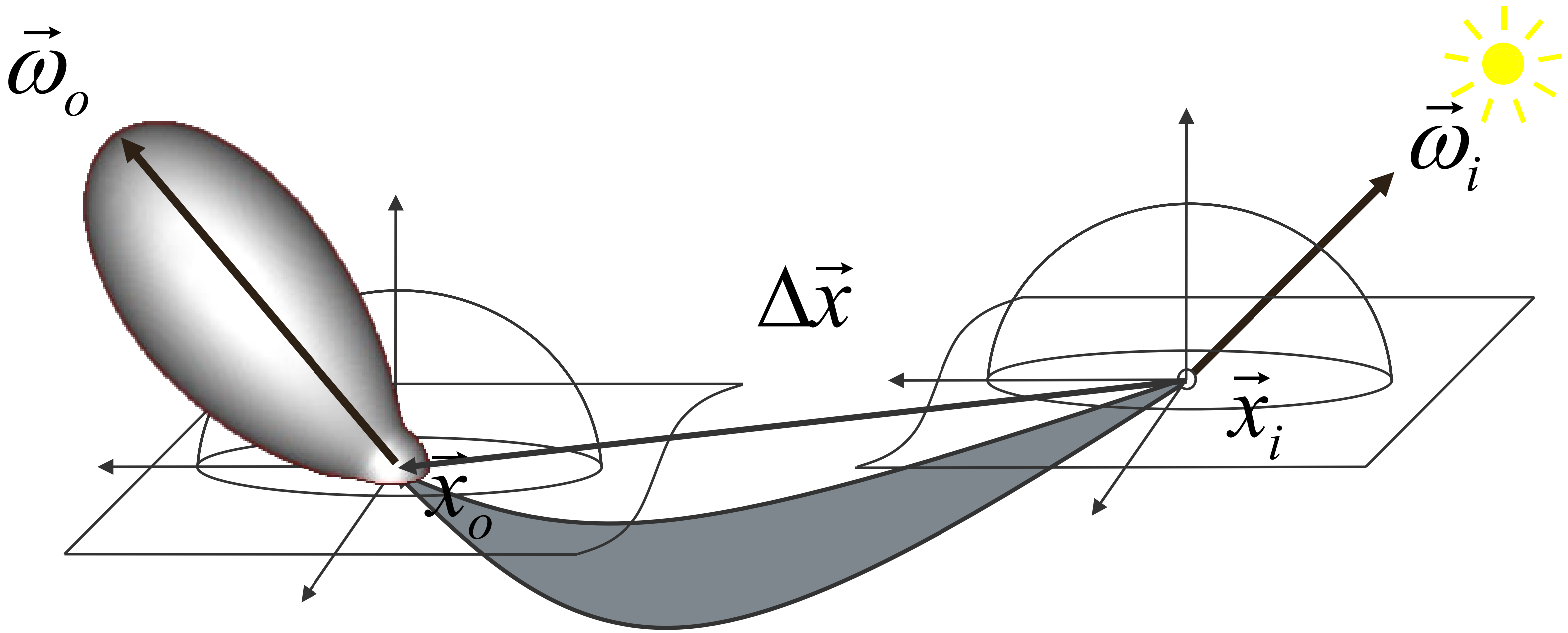


Subsurface Scattering Homogeneous Material



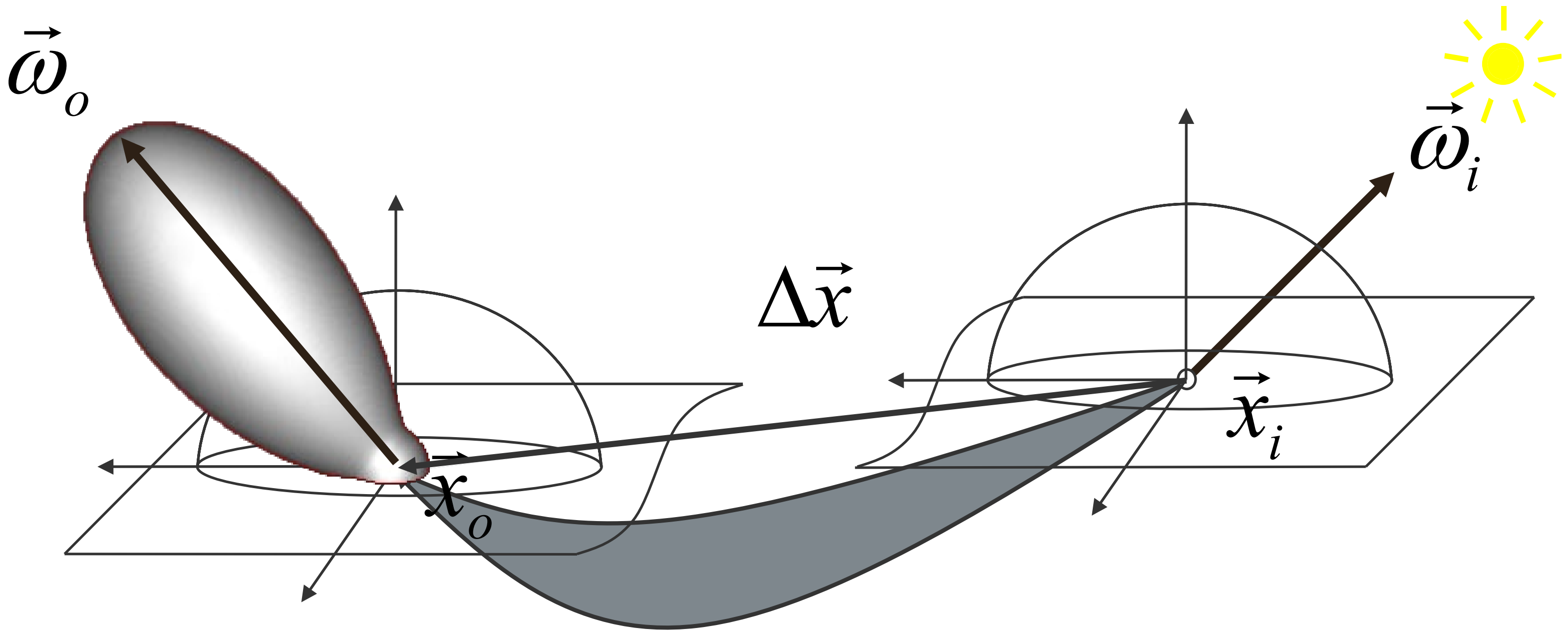
Homogeneous Material BSSRDF – 6D

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



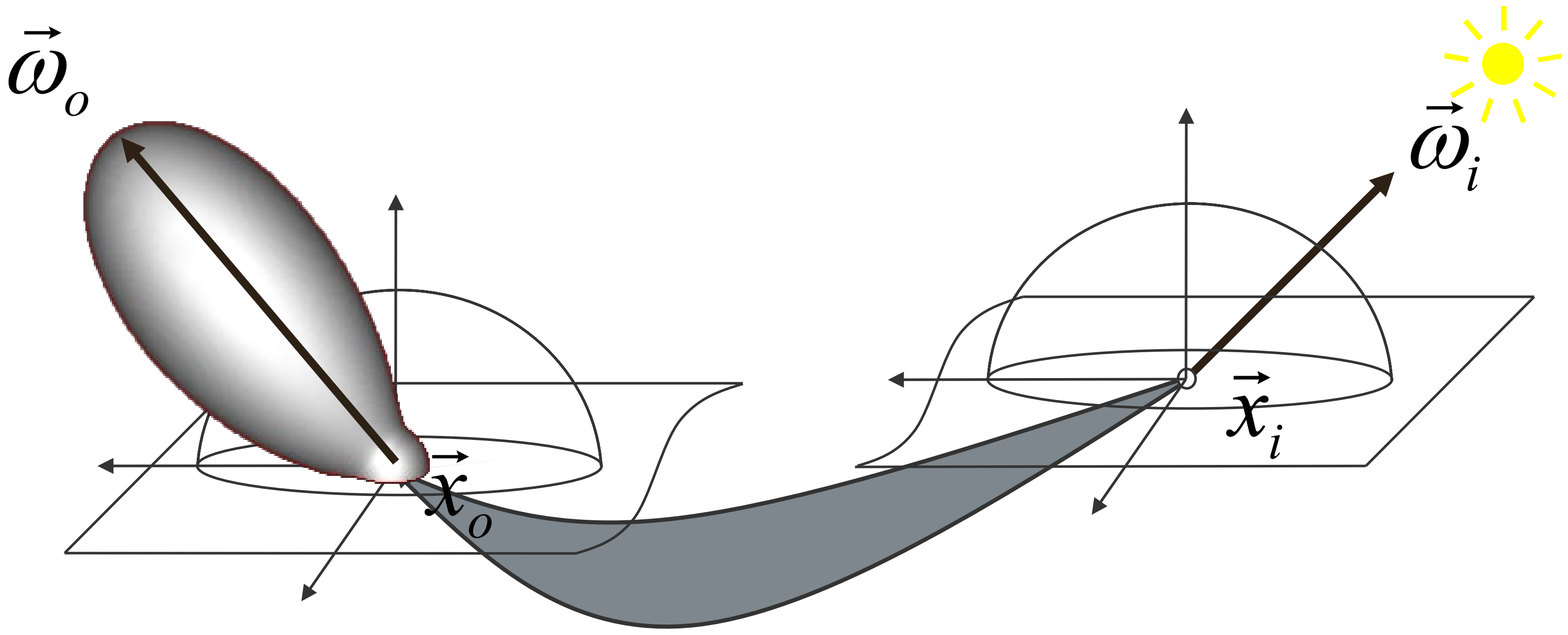
Homogeneous Material BSSRDF – 6D

$$f_r(\Delta\vec{x}\,;\overrightarrow{\omega_i} \rightarrow \vec{\omega}_o)$$



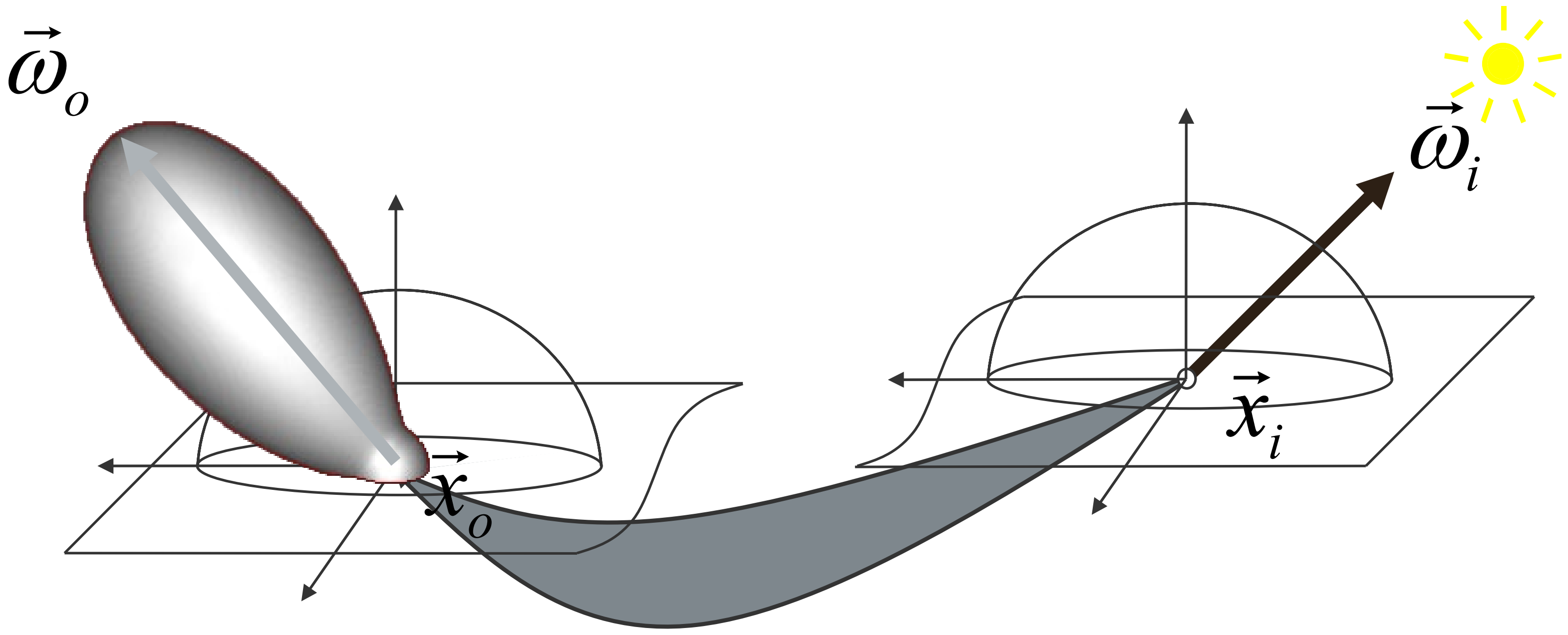
Generalization – 12D

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



Generalization – 12D

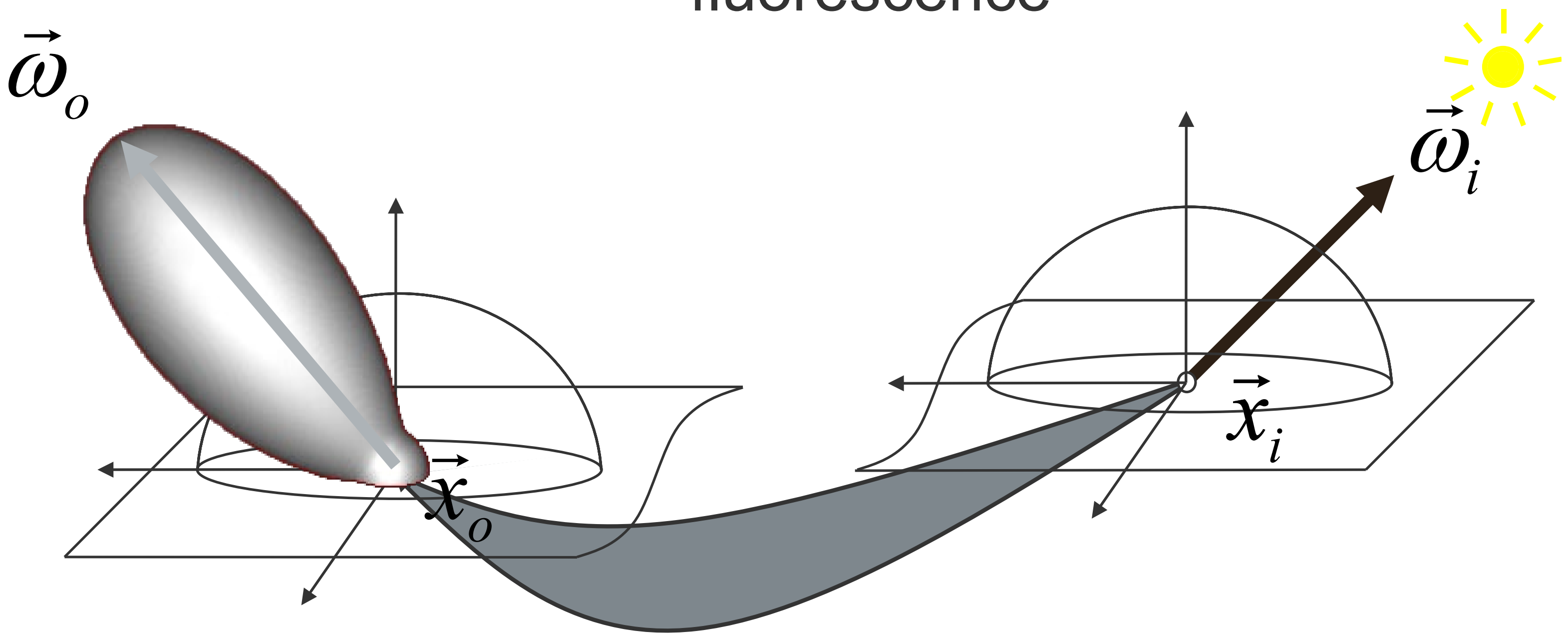
$$f_r(\lambda;(\vec{x}_i,\vec{\omega}_i) \rightarrow (\vec{x}_o,\vec{\omega}_o))$$



Generalization – 12D

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

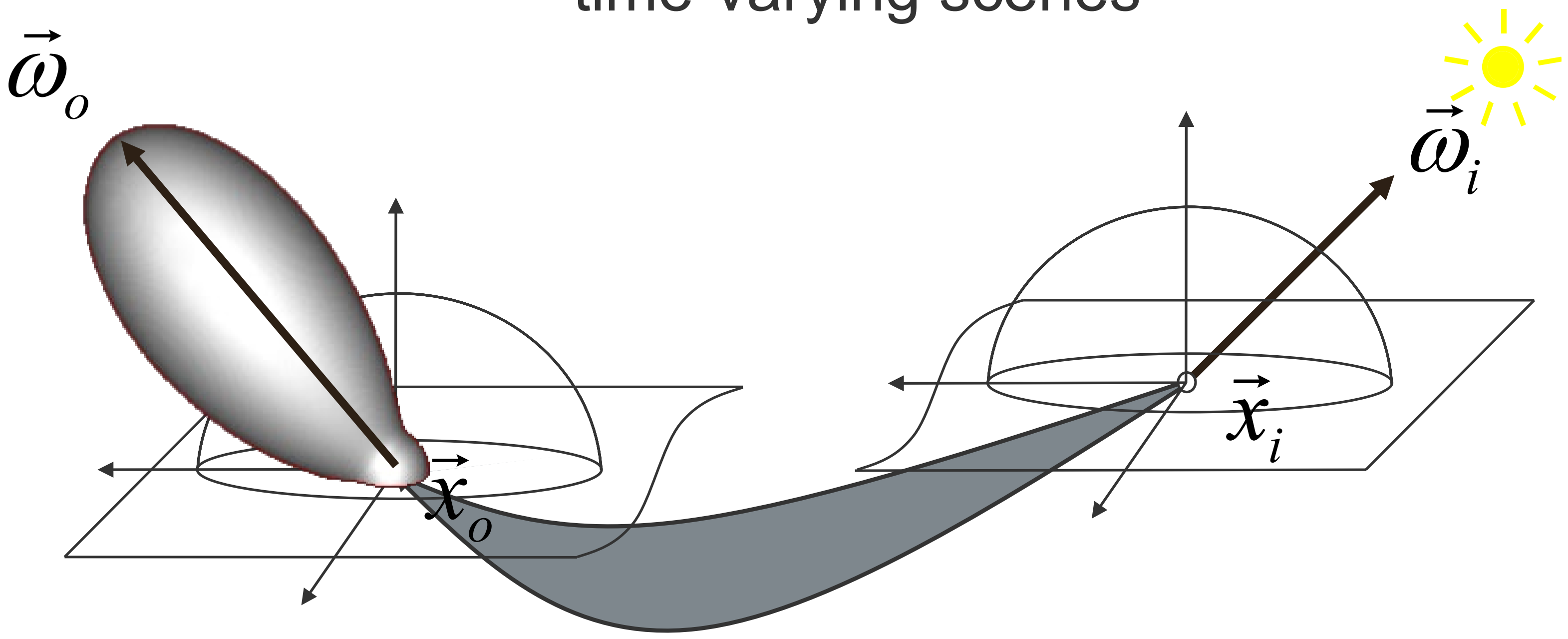
fluorescence



Generalization – 12D

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

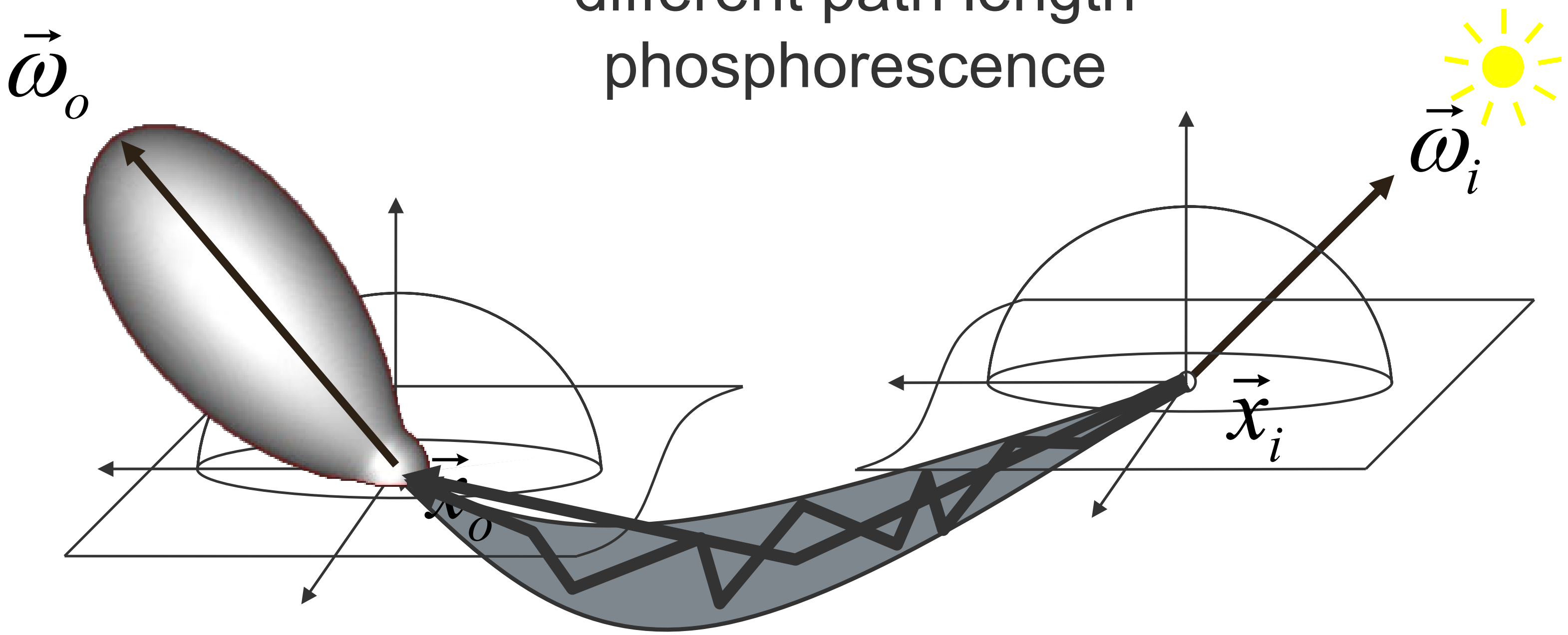
time-varying scenes



Generalization – 12D

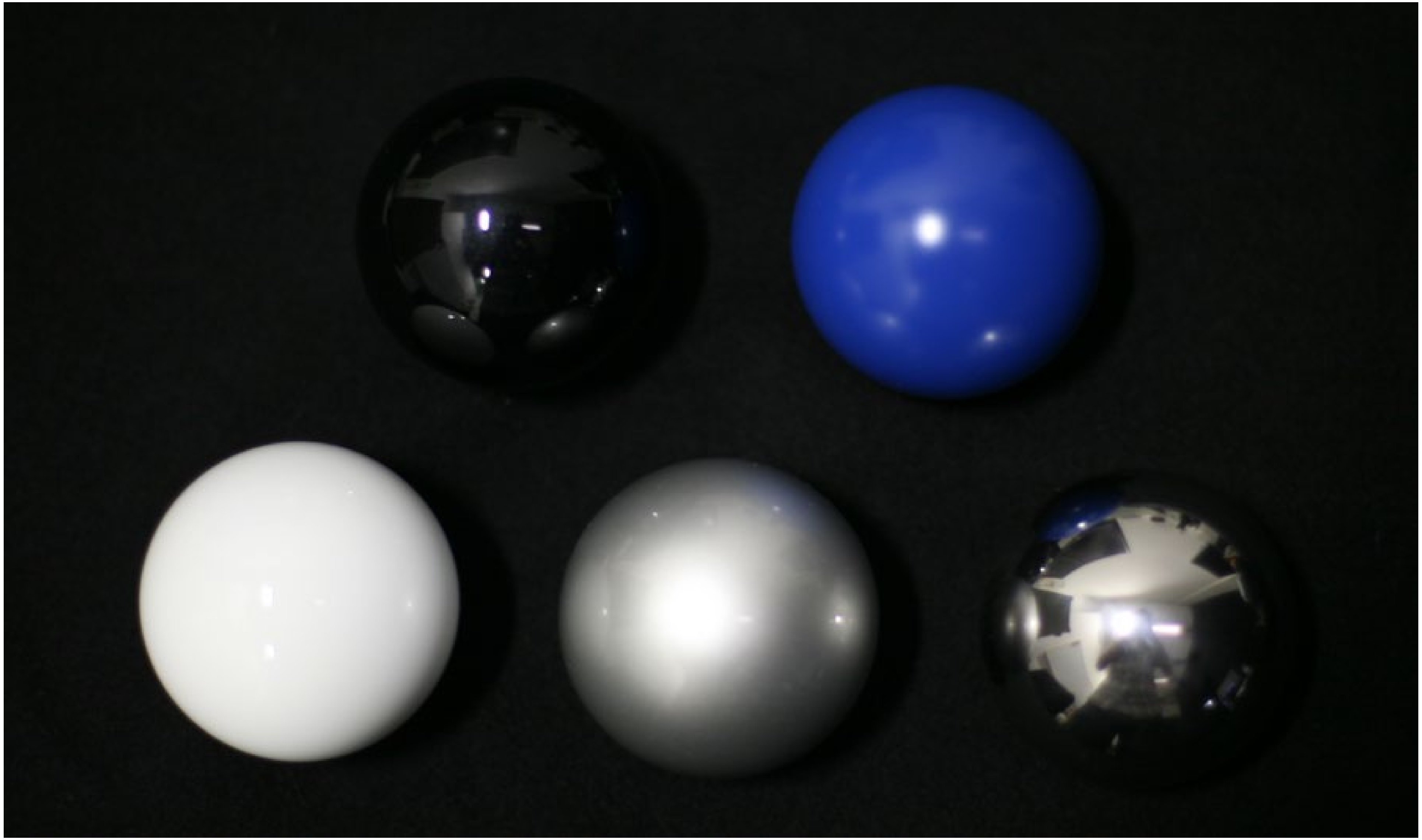
$$f_r((\vec{x}_i, \vec{\omega}_i, t_i, \lambda_i) \rightarrow (\vec{x}_o, \vec{\omega}_o, t_o, \lambda_o))$$

different path length
phosphorescence

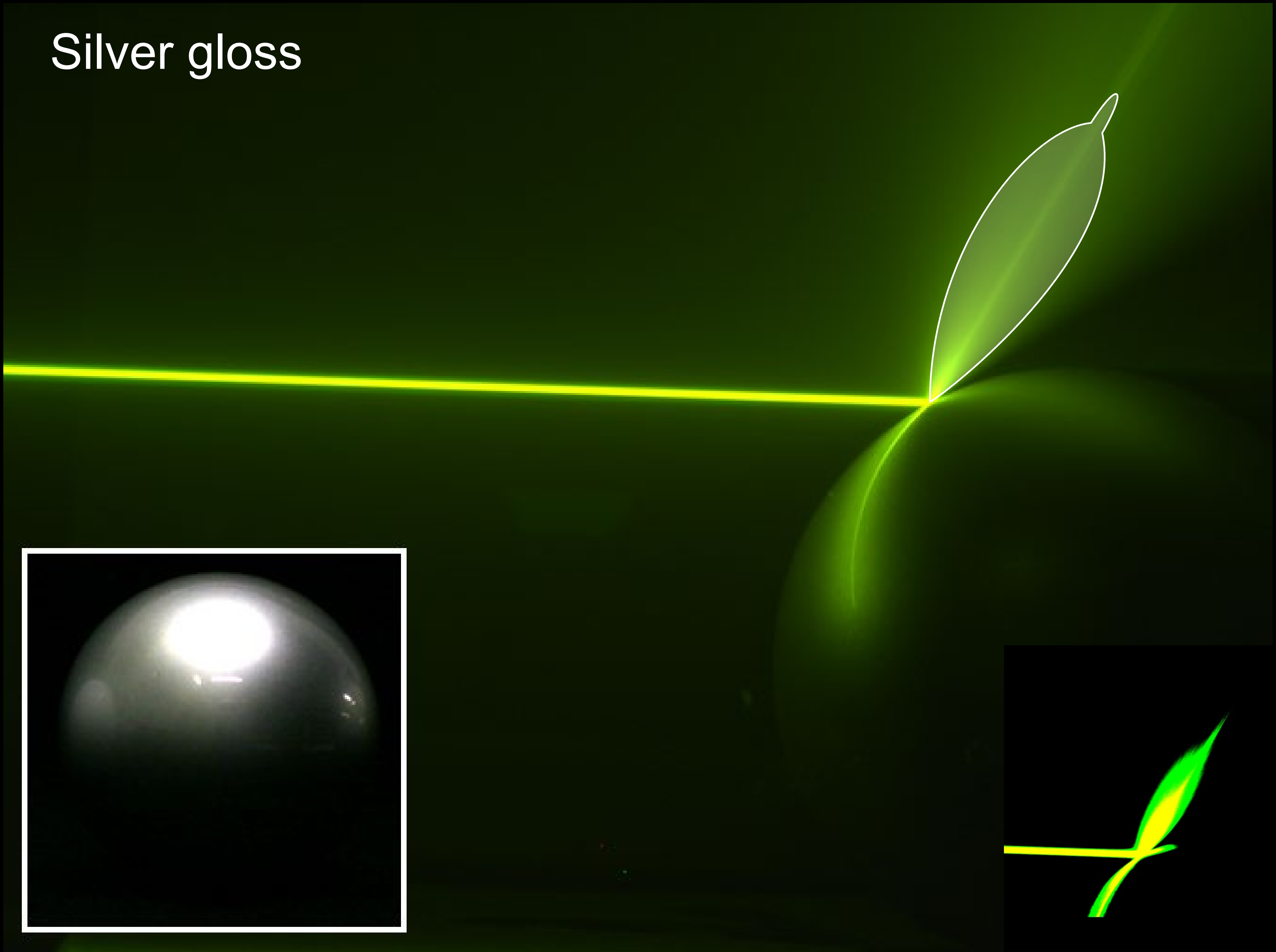


Real-World Examples

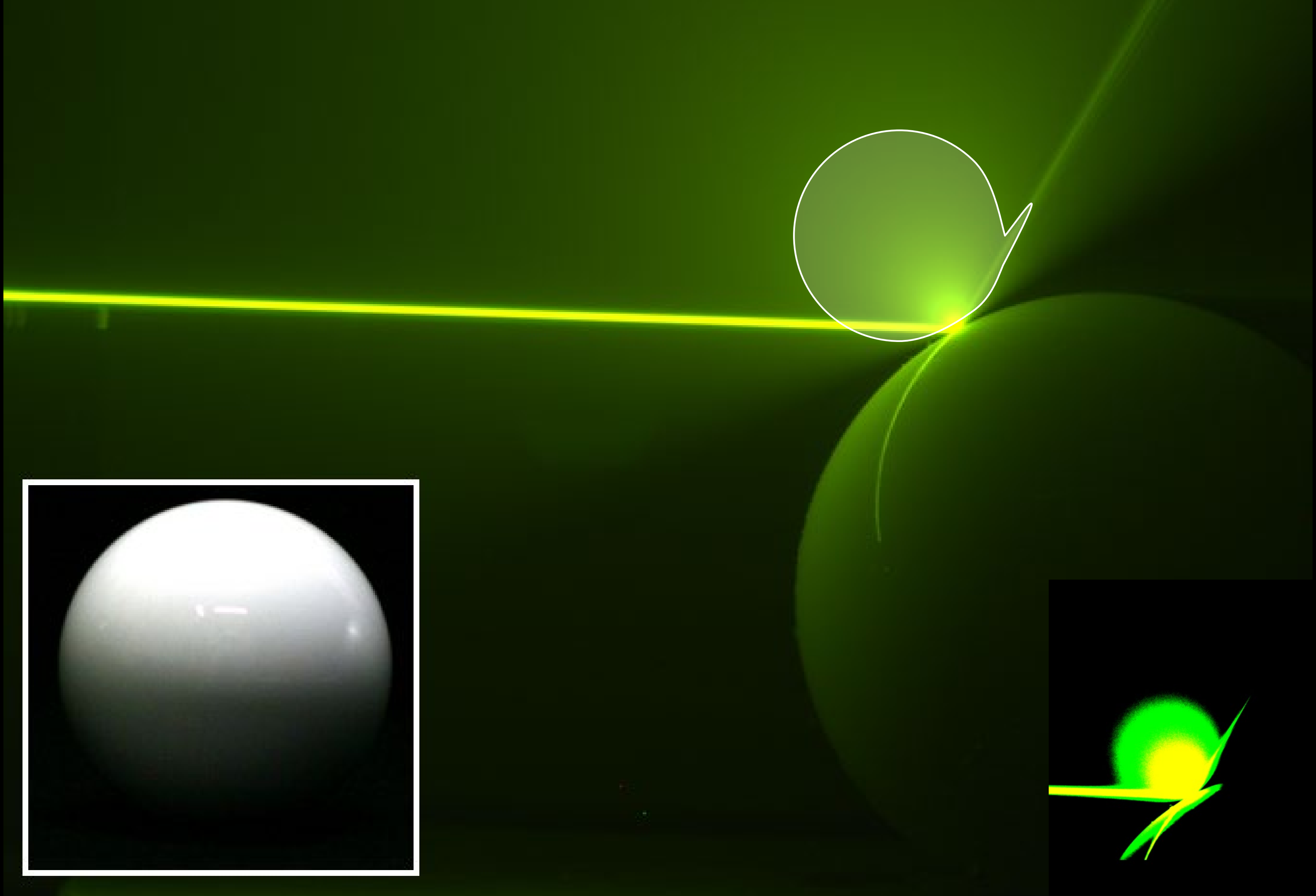
Reflectance

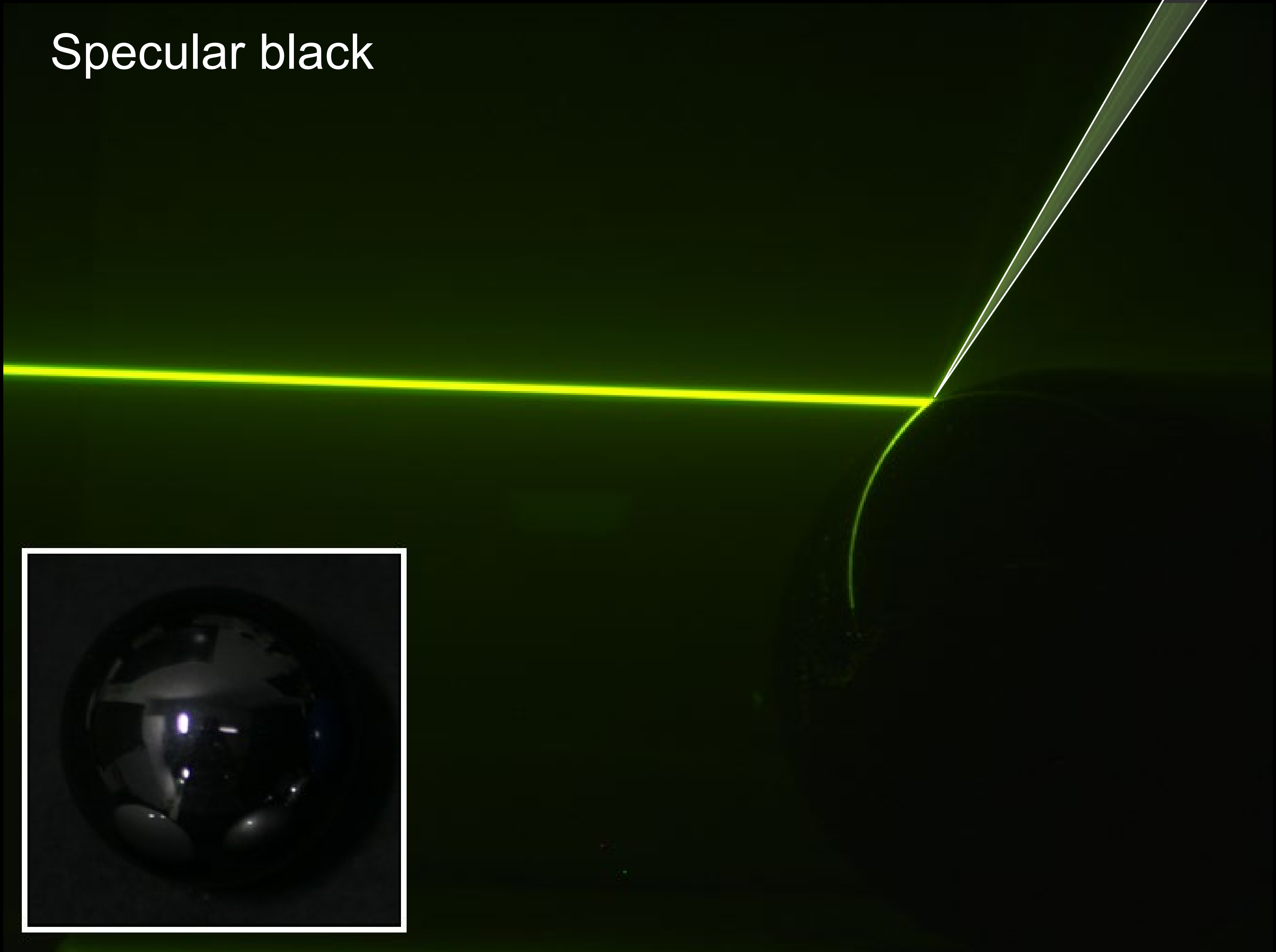


Mirroring

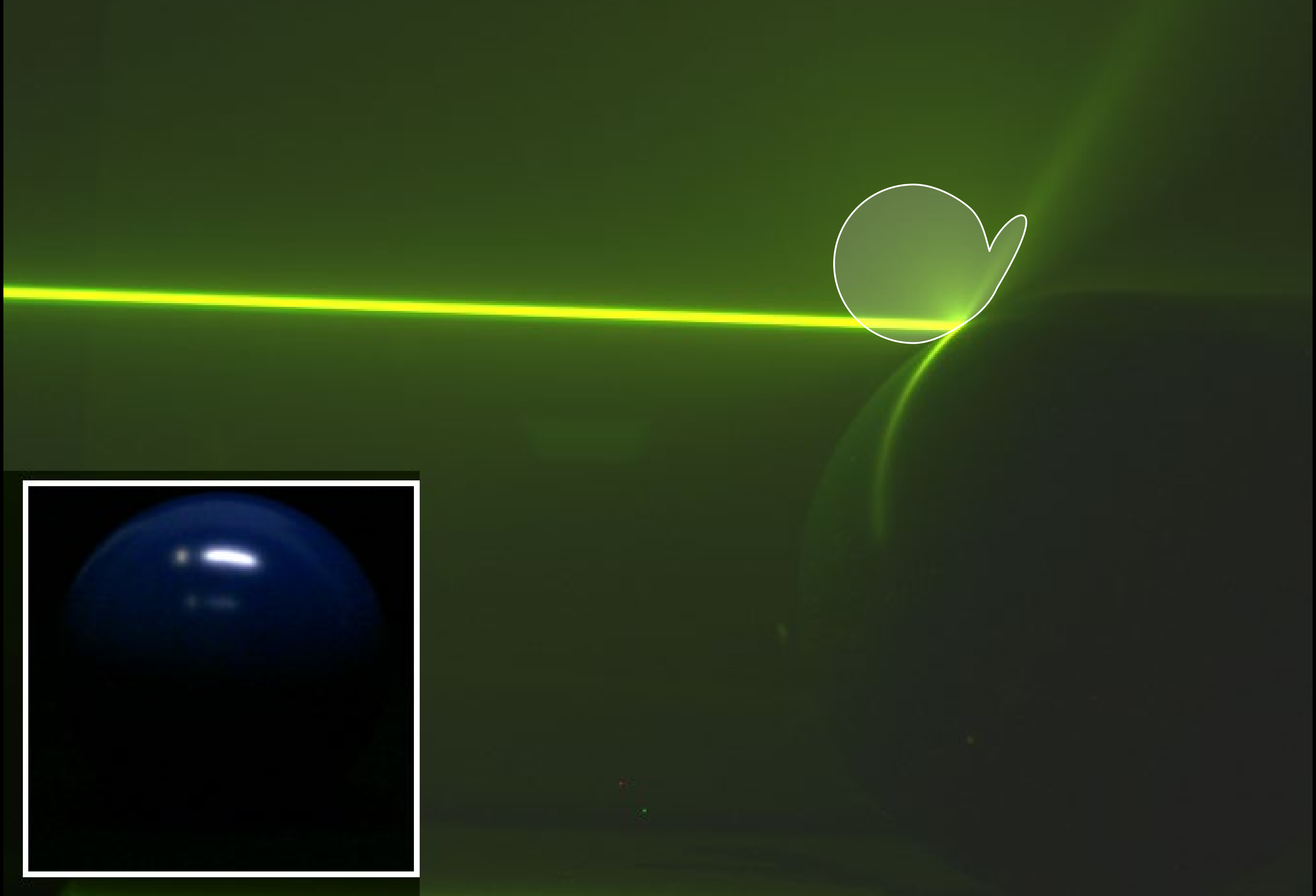

Silver gloss

Diffuse white

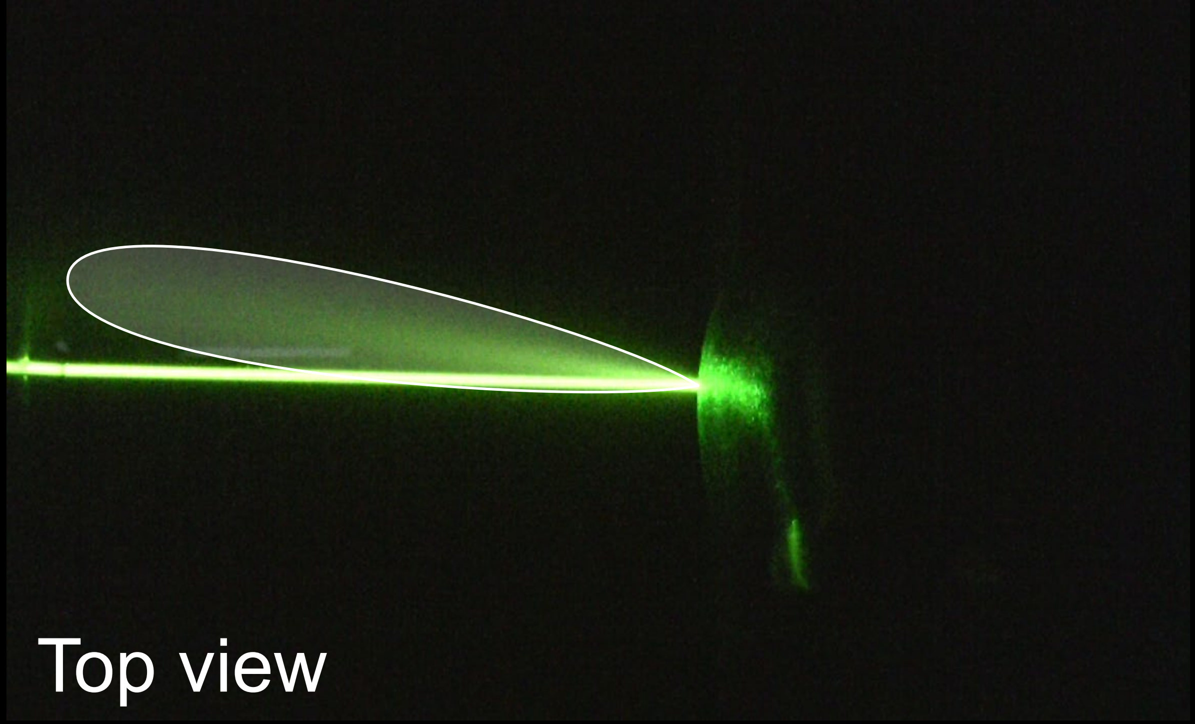



Specular black

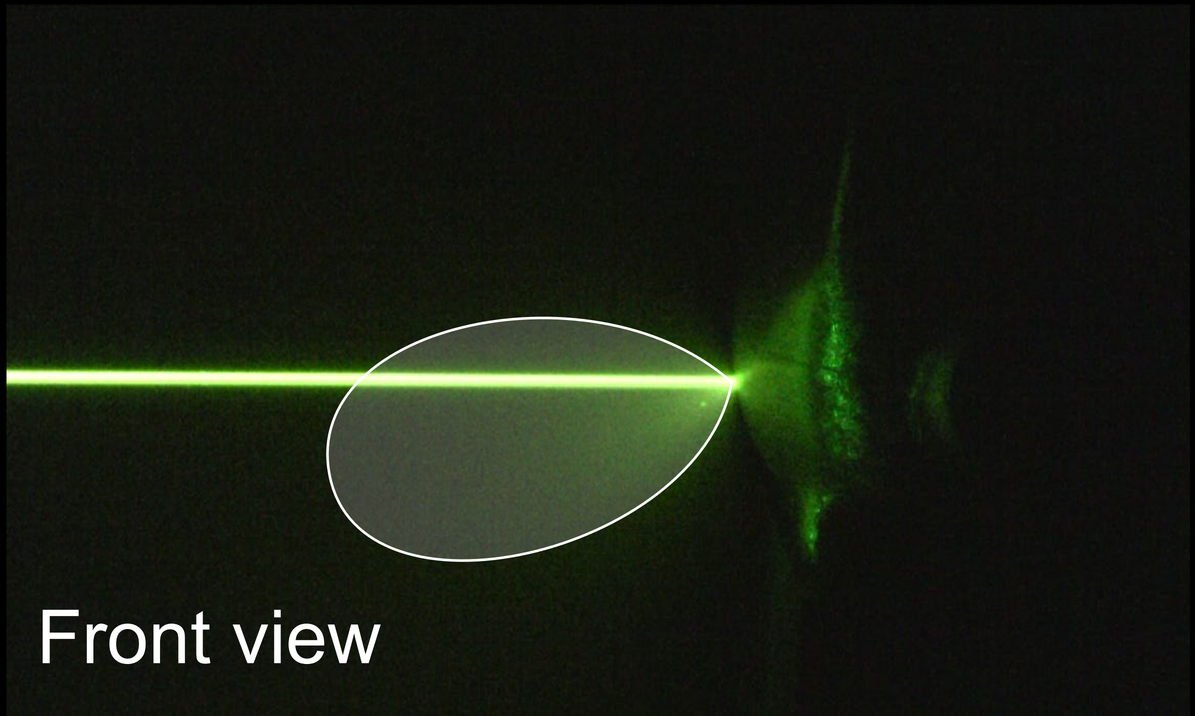
Diffuse + glossy



Brushed metal

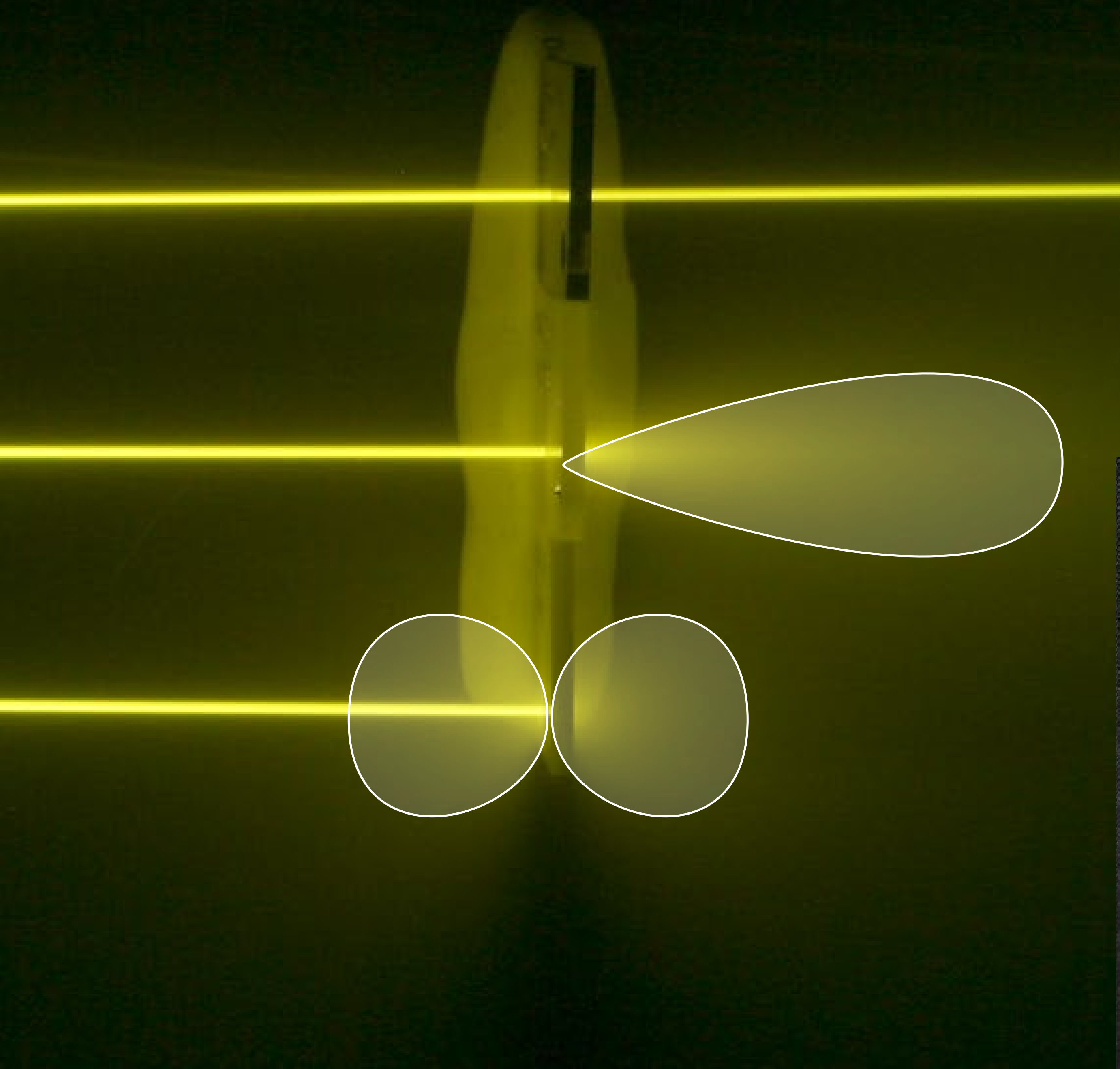


Top view

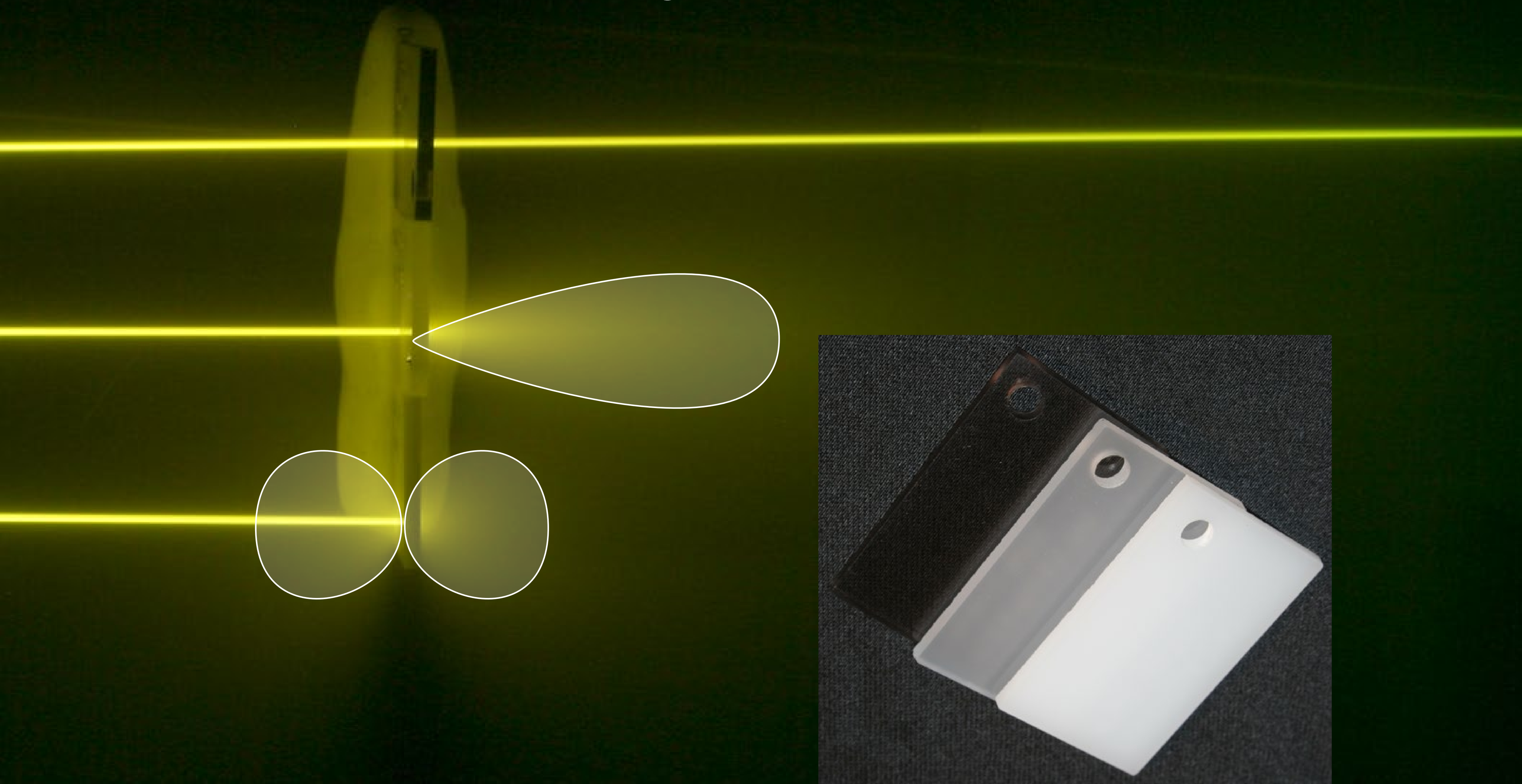


Front view

Bidirectional Transmission Distribution Function - BTDF



Bidirectional Scattering Distribution Function - BSDF



Shading
Evaluation of Reflections

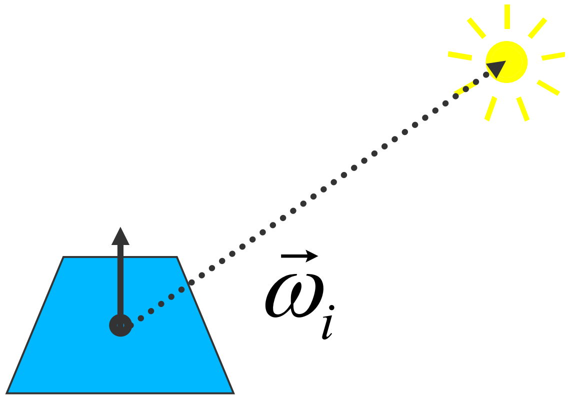
How to calculate the intensity of the reflected light?

What is necessary?

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

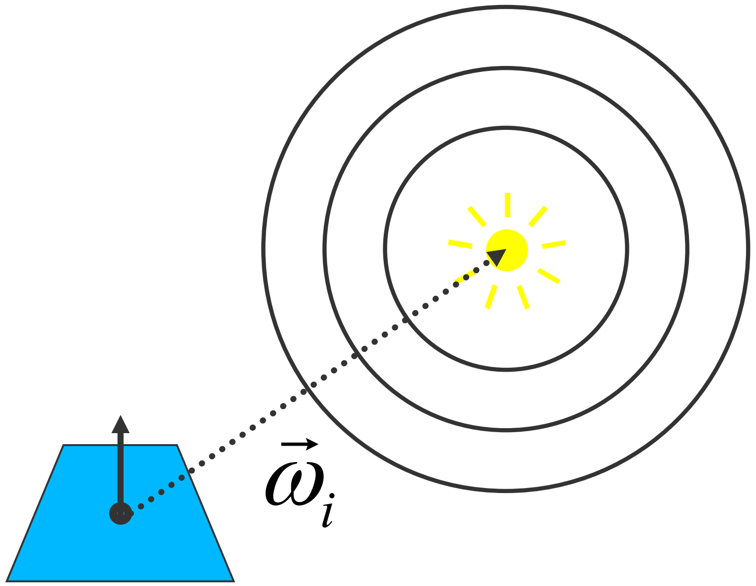
Light Source Description

- Point light source
- Position
- Intensity



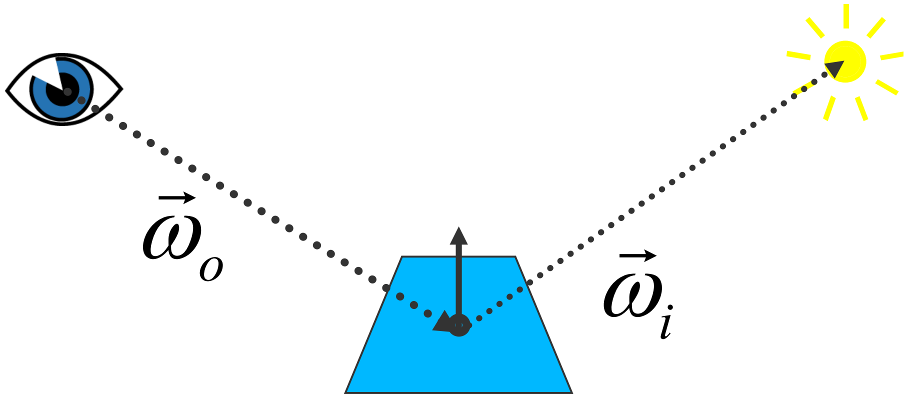
Light Source Description

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



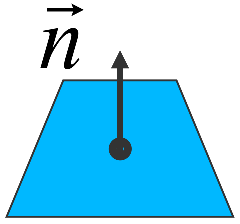
Viewpoint

- Distance not so important for now



Surface Normal

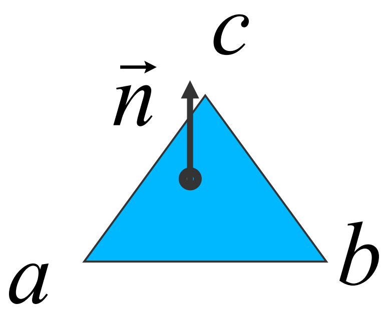
- Trivial for a plane – Hesse form: $(\vec{p}, \vec{n})$



Surface Normal - Triangle

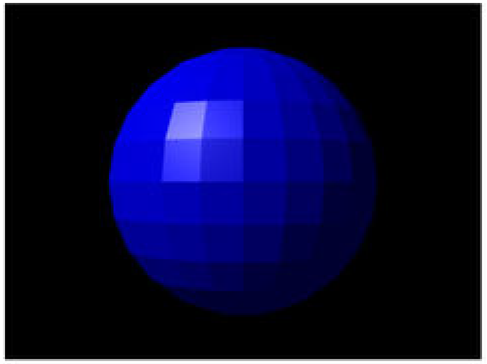
$$\vec{n} = \frac{(c-b) \times (a-b)}{||(c-b) \times (a-b)||}$$

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

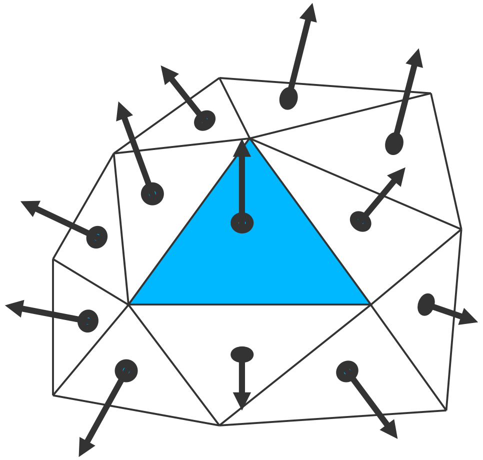


Flat Shading on a Triangle Mesh

- Per-surface normal
- Flat shading

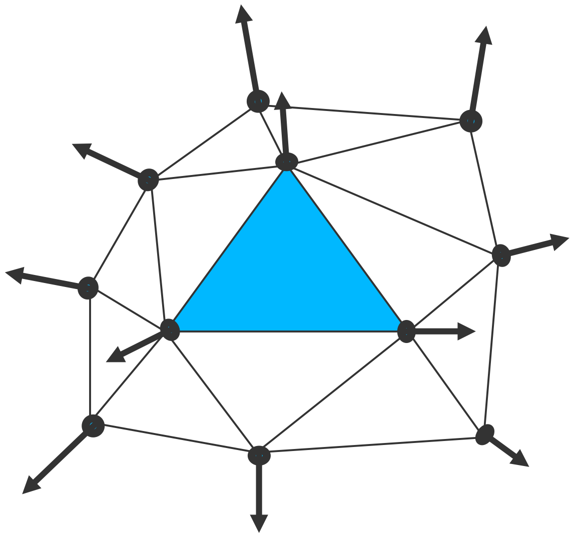


[wikipedia]



Goraud Shading

- Per-vertex normal



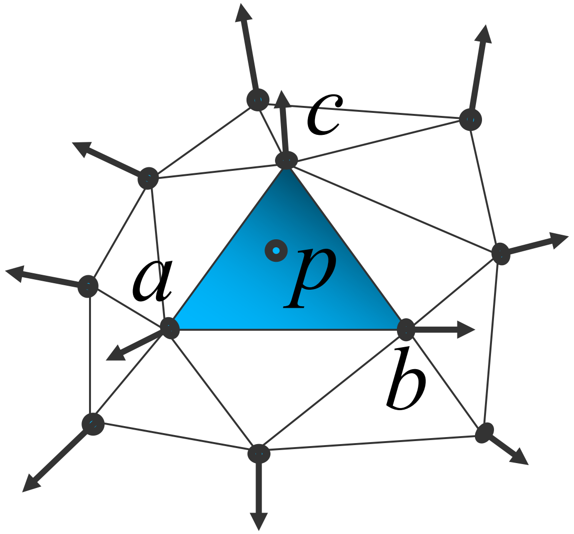
Goraud Shading

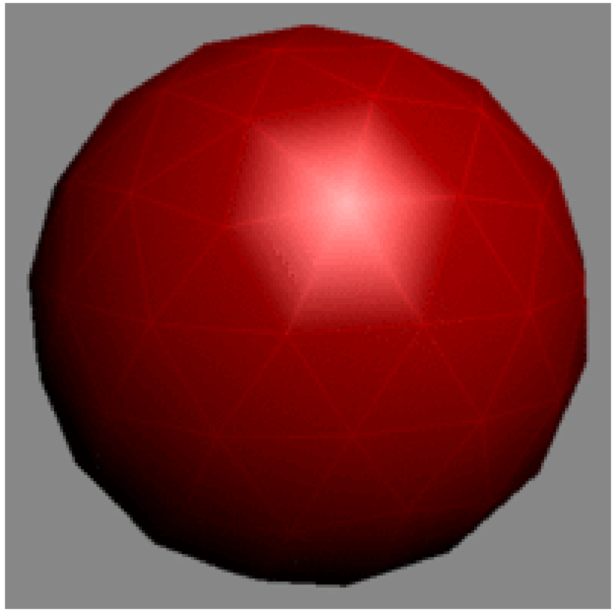
- Per-vertex normal
- Goraud shading
  - evaluate reflectance model at vertices only

$$L_v \sim f\,(\vec{\omega}_o, \vec{n}_v, \vec{\omega}_i) L_i$$

  - linear interpolation of the shaded colors

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





[wikipedia]

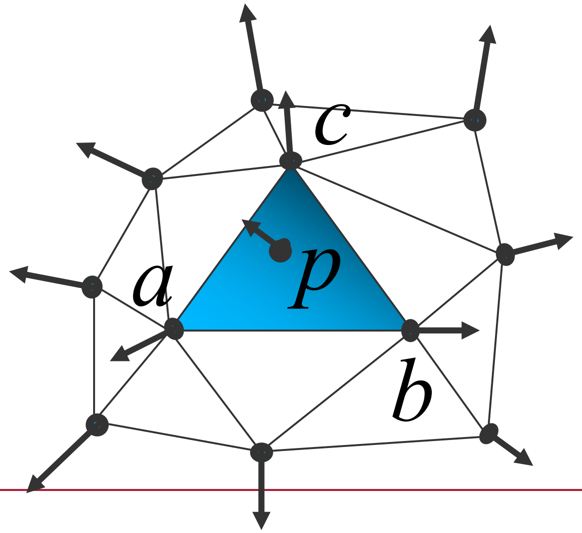
Phong Shading

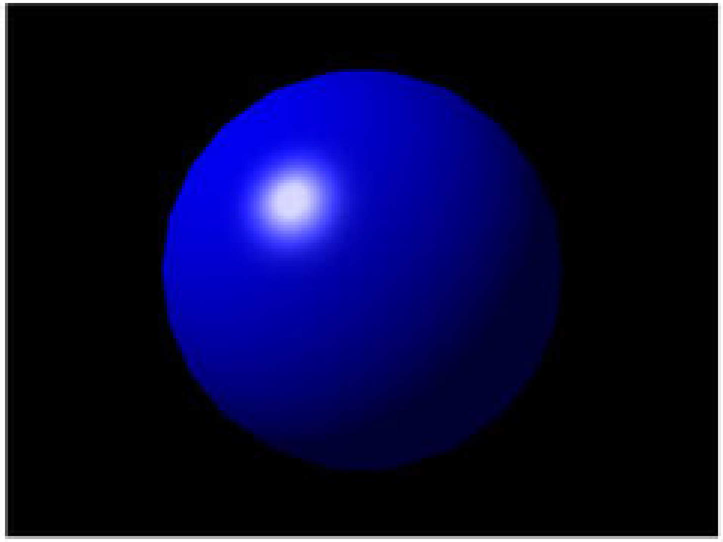
- Per-vertex normal
- Phong shading
  - linear interpolation of the surface normal

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

  - (spherical interpolation)
  - evaluate reflectance model at every point

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





[wikipedia]

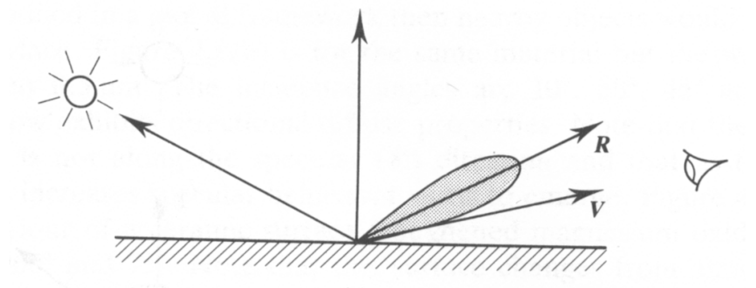
Phong Reflection Model

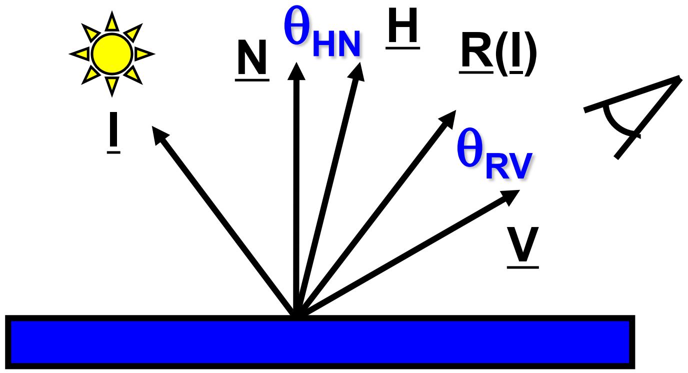
- Cosine power lobe

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

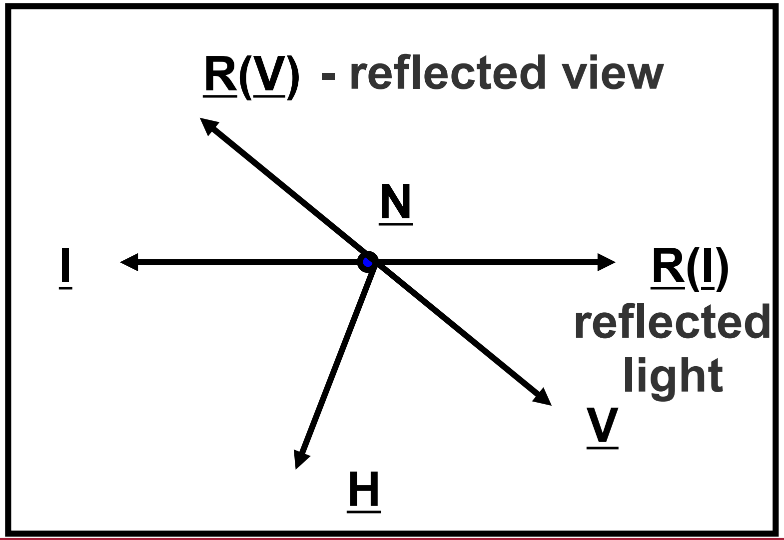
$$L_s = L_i k_s \cos^{k_e} \theta_{RV}$$

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





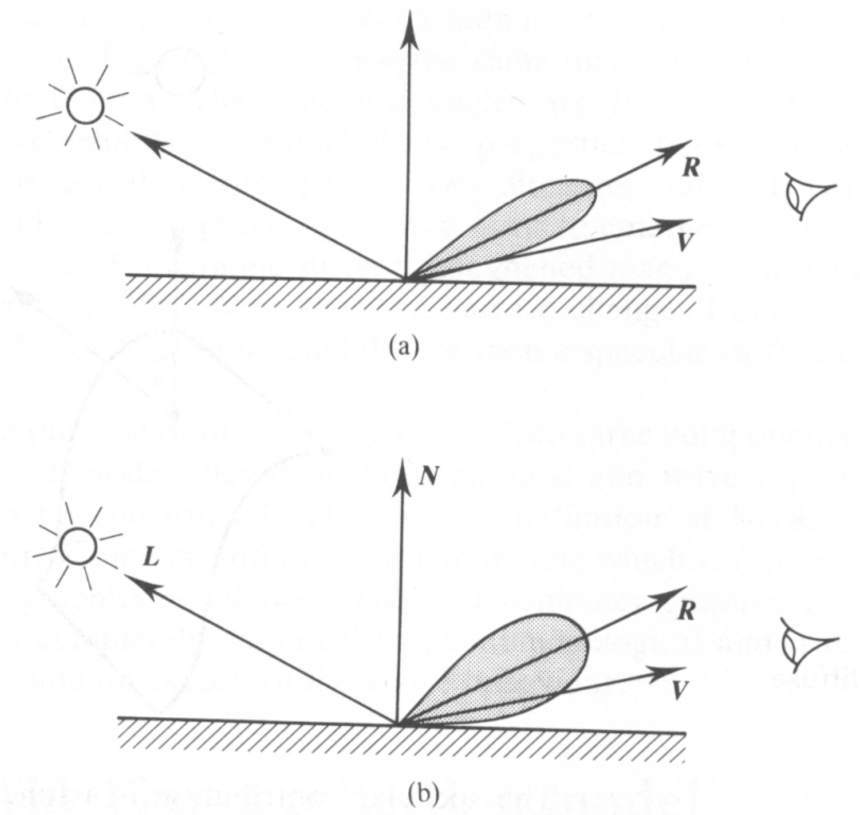
birds eye view at the surface

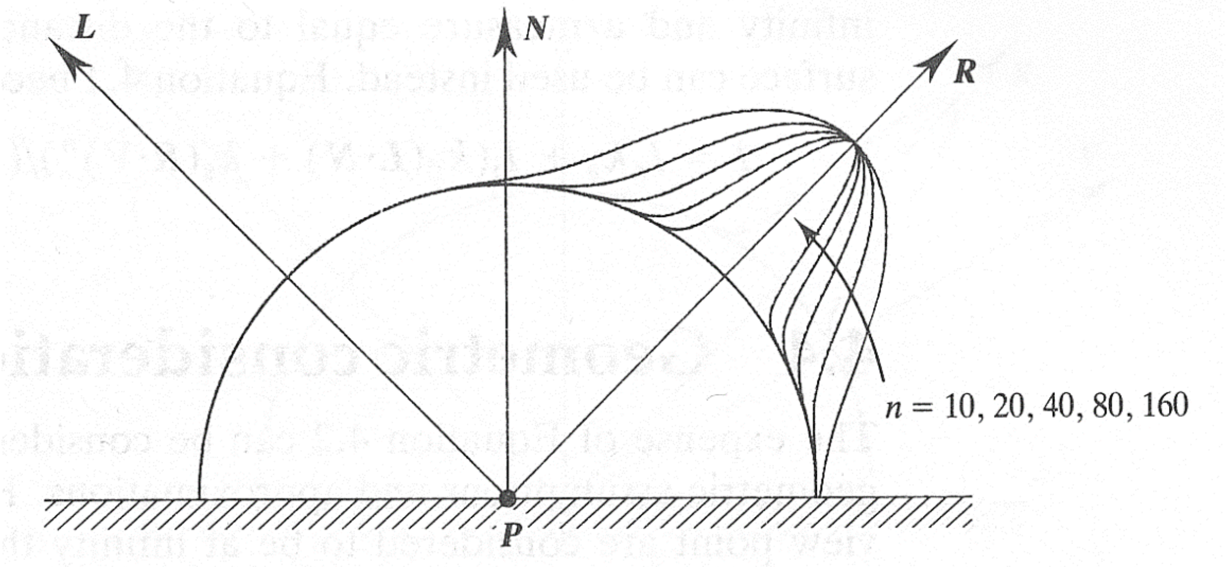


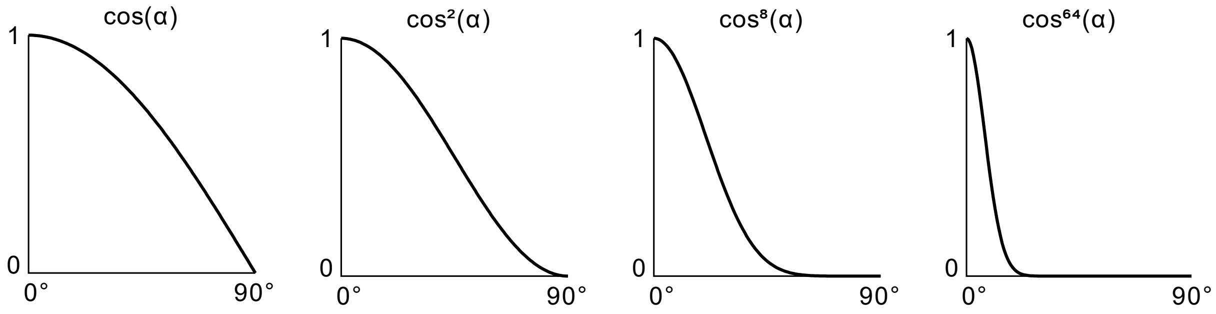
Phong Exponent k_e

- Determines size of highlight

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





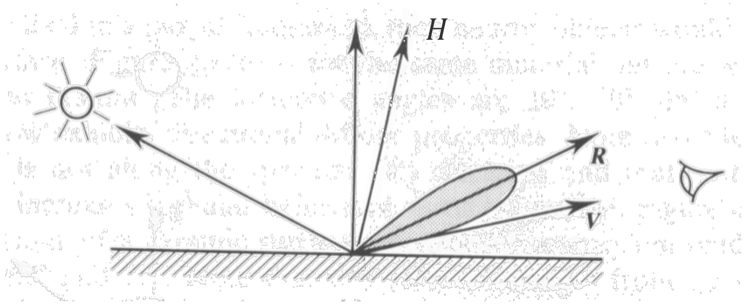


Blinn-Phong Reflection Model

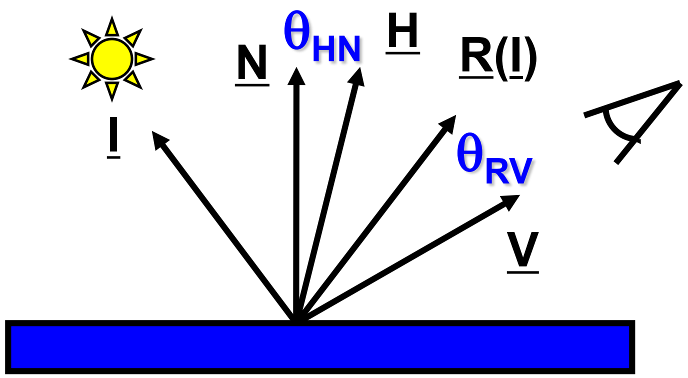
- Blinn-Phong reflection model: consider halfway vector $H = \frac{I+V}{2}$

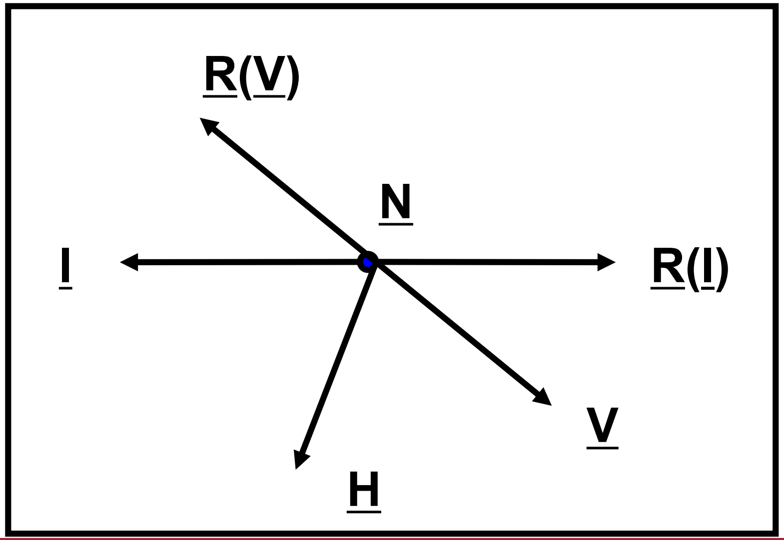
$$f_r(\omega_o, x, \omega_i) = k_s (H \cdot N)^{k_e}$$

$$L_s = L_i k_s \cos^{k_e} \theta_{HN}$$



  - Light source, viewer far away
  - $\theta_{RV} \Rightarrow \theta_{HN}$ less expensive to compute





Phong Illumination Model

- Extended light sources: l point light sources

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

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

- 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

Phong Illumination Model

- Extended light sources: l point light sources

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

$$L_r = \underbrace{\boxed{k_a L_{i,a}}}_{\text{ambient}} + k_d \sum_l L_l (I_l \cdot N) + k_s \sum_l L_l \left(H_l \cdot N\right)^{k_e} \qquad \text{(Blinn)}$$

- 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

Phong Illumination Model

- Extended light sources: l point light sources

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

$$L_r = k_a L_{i,a} + \underbrace{\boxed{k_d \sum_l L_l (I_l \cdot N)}}_{\text{diffuse}} + k_s \sum_l L_l \left(H_l \cdot N\right)^{k_e} \qquad \text{(Blinn)}$$

- 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

Phong Illumination Model

- Extended light sources: l point light sources

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

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

specular/glossy

- 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

Phong Illumination Model

- Extended light sources: l point light sources

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

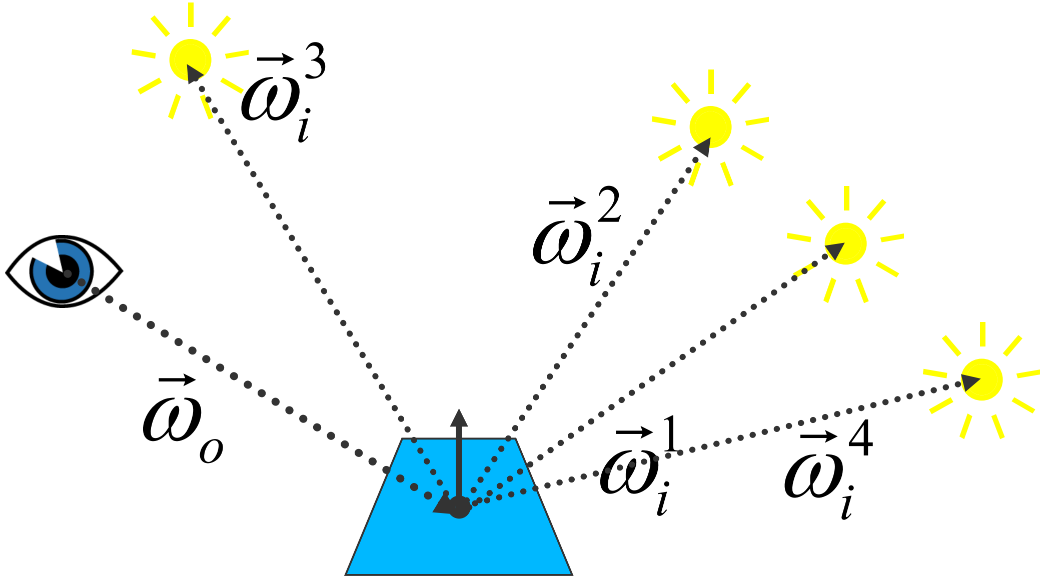
$$\mathrm{L_r} = \cancel{k_a L_{i,a}} + k_d \sum_l L_l (I_l \cdot N) + k_s \sum_l L_l \left(H_l \cdot N\right)^{k_e} \qquad \text{(Blinn)}$$

not physically plausible

- 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

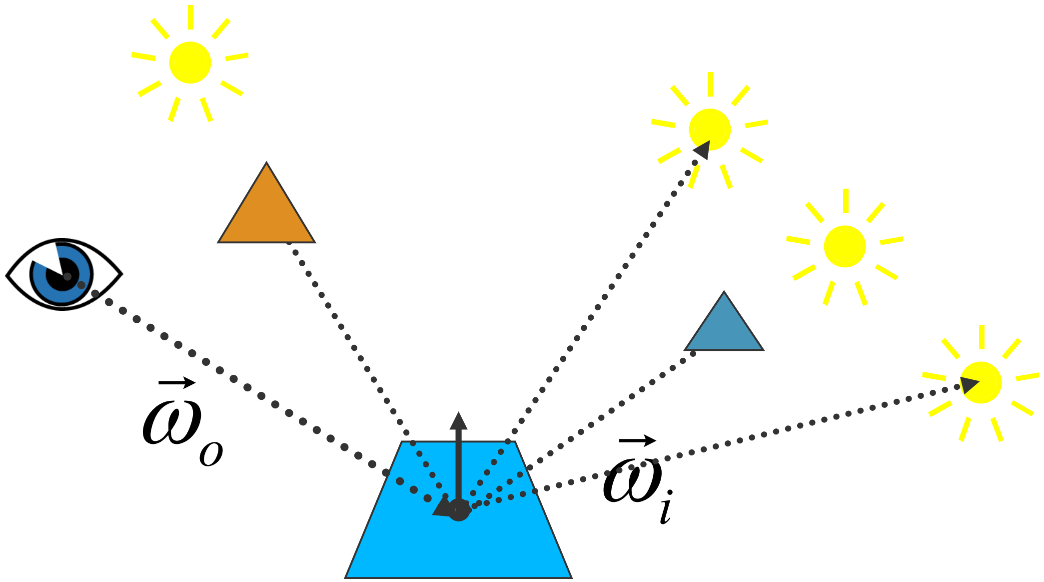
- Add their contributions



$$\mathrm{L_r} = \sum_N f(\vec{\omega}_o, \vec{\omega}_i^k) L_i^k \cos(\theta^k)$$

Occlusions

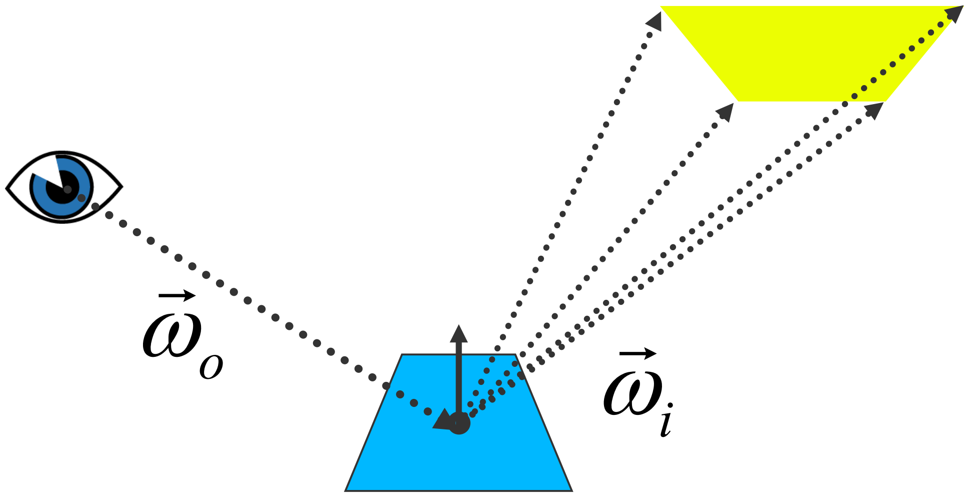
- The point on the surface might be in shadow from some object.
- Trace ray to light source and test for occlusion



$$L_r = \sum_N f(\vec{\omega}_o, \vec{\omega}_i^k) v(p, \vec{\omega}_i^k) L_i^k \cos(\theta^k)$$

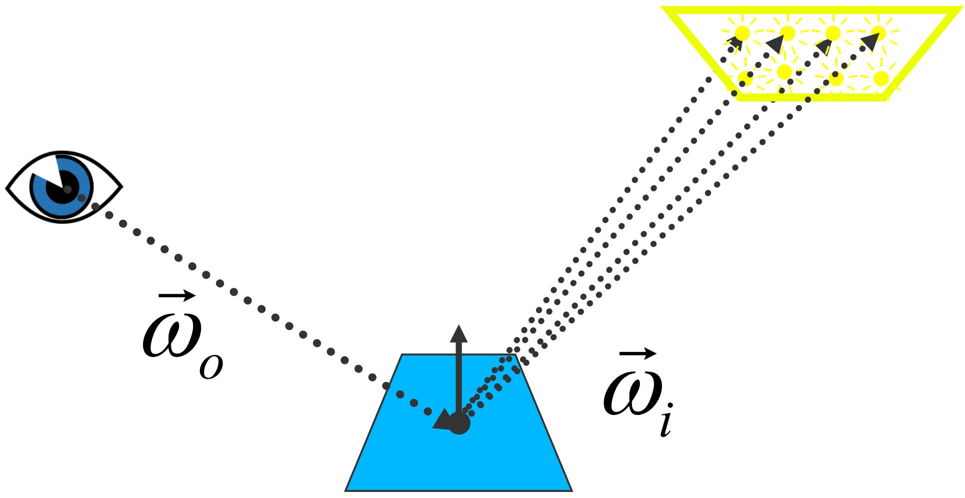
Area Light sources

- Typically approximated by sampling



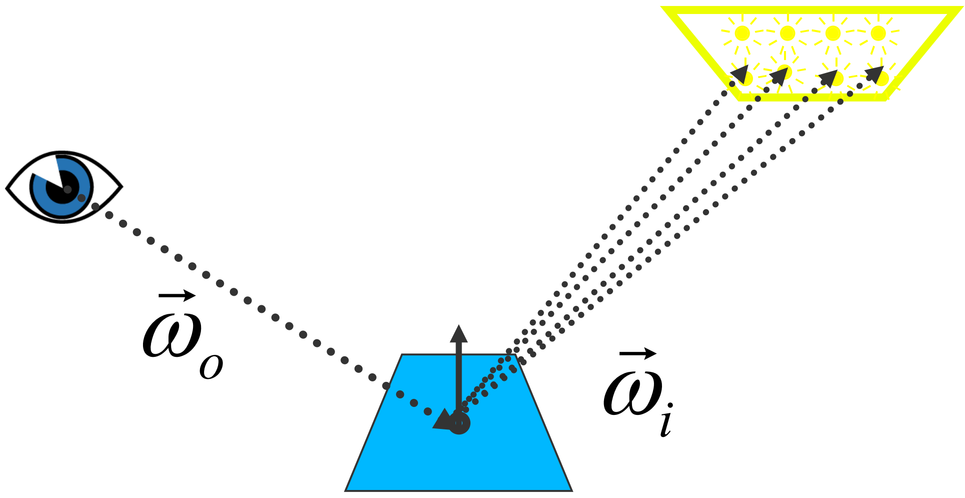
Area Light sources

- Typically approximated by sampling



Area Light sources

- Typically approximated by sampling



Wrap-Up

Appearance and Reflectance
- Phenomena
- Characterization
- Snell’s law / Polarization

Shading
- Goraud / Phong
- Blinn-Phong
- Multiple light sources

Questions

- What does “BRDF“ stand for? What is represented by a BRDF?
- Explain the differences between diffuse, glossy and mirror reflections.
- How can you control the specular lobe in the Blinn reflection model?