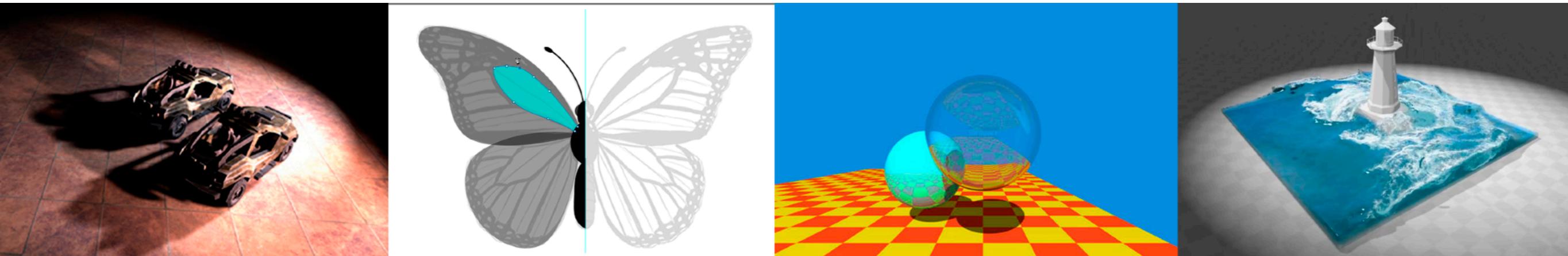


# Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

## Lecture 17: Materials and Appearances



# Announcements

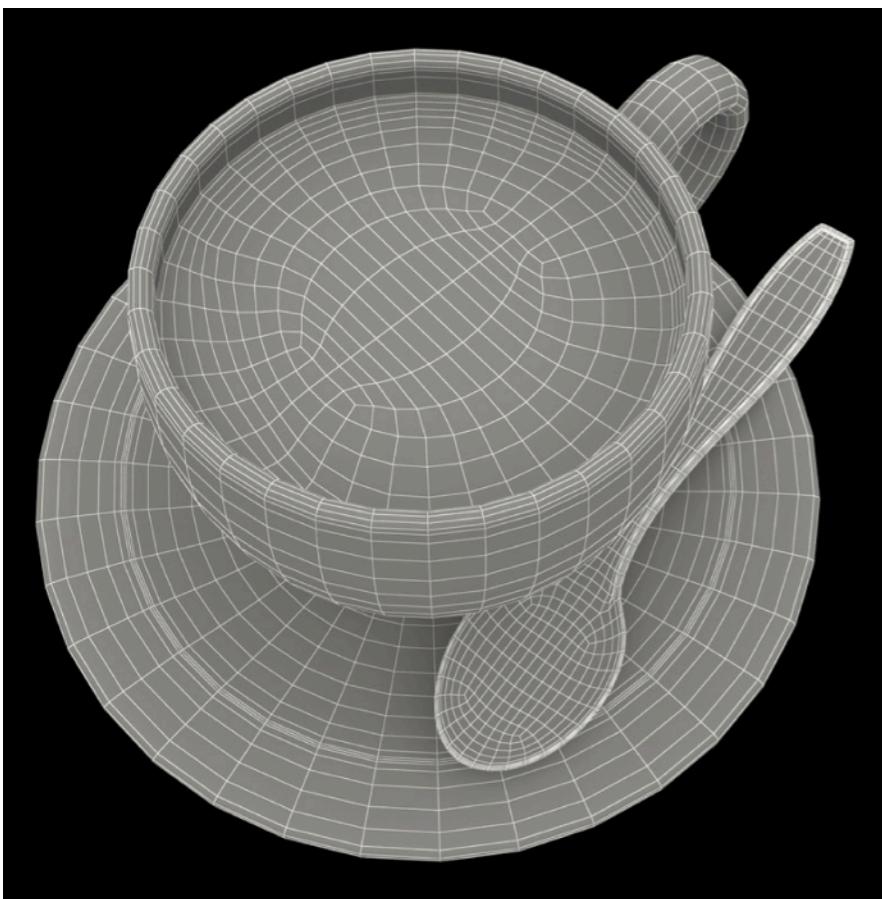
- Homework 6: 82 submissions so far (note: 1.5 weeks for it)
- New assignment on path tracing has been worked out!
  - Followed the pseudocode in the last lecture as much as possible
  - Will be released this Friday
- Final project ideas: to be released soon
- From today: the lectures will be much easier!

# The Appearance of Natural Materials



[Courtesy of Prof. Henrik Wann Jensen, UCSD]

# What is Material in Computer Graphics?



3D coffee mug model



Rendered

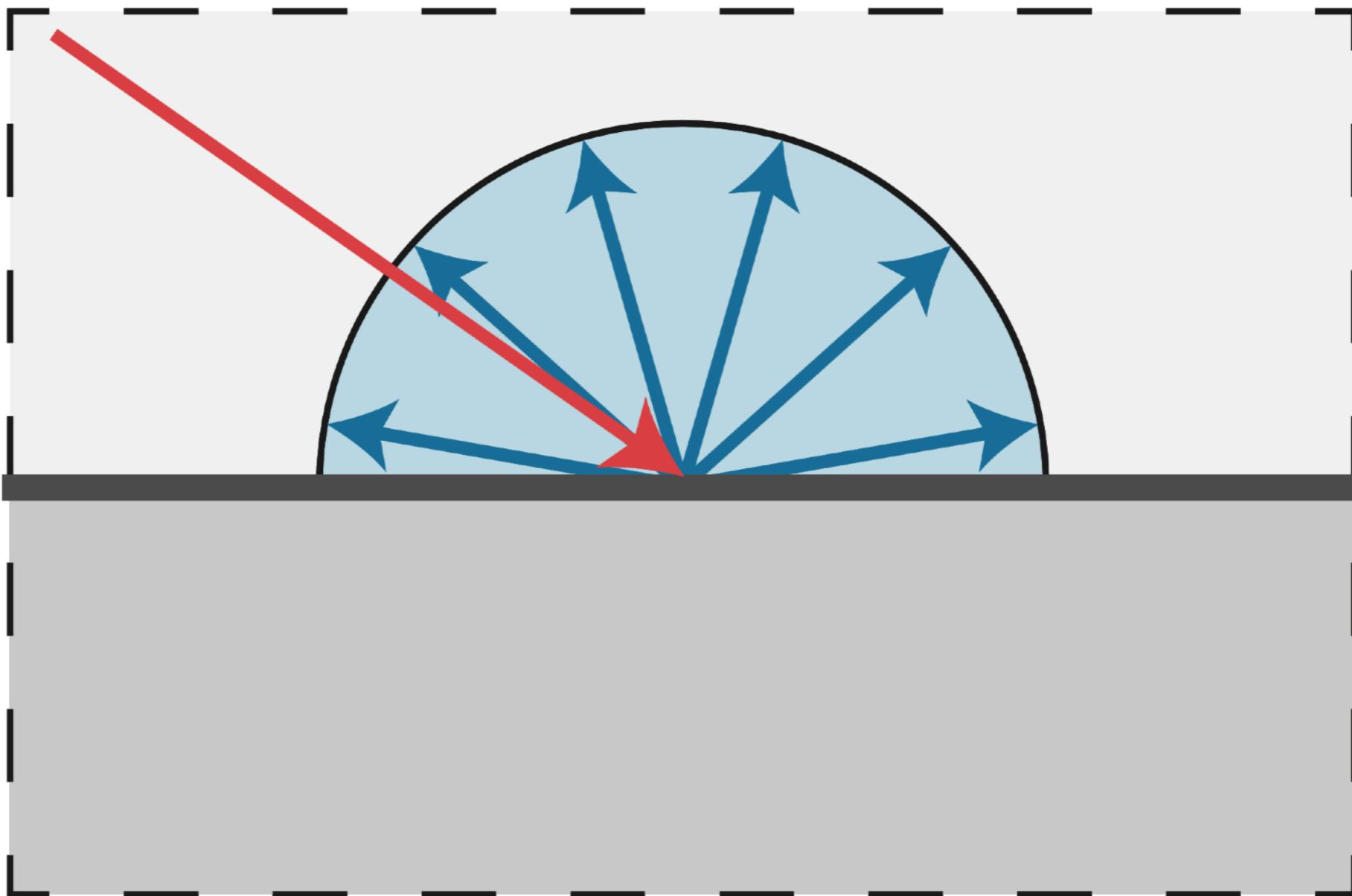


Rendered

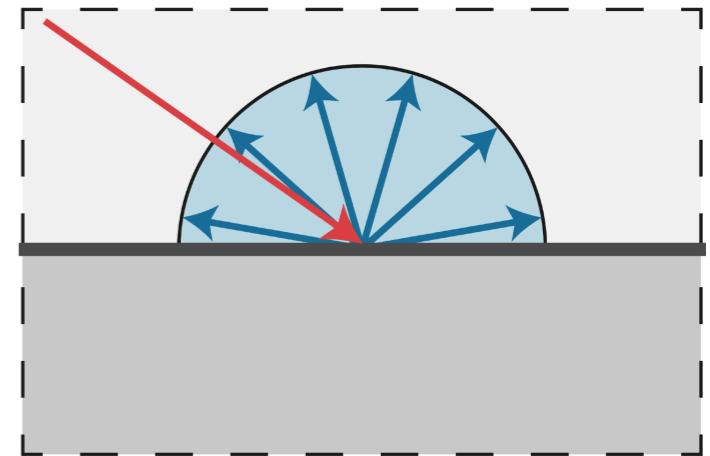
[From TurboSquid, created by artist 3dror]

Material == BRDF

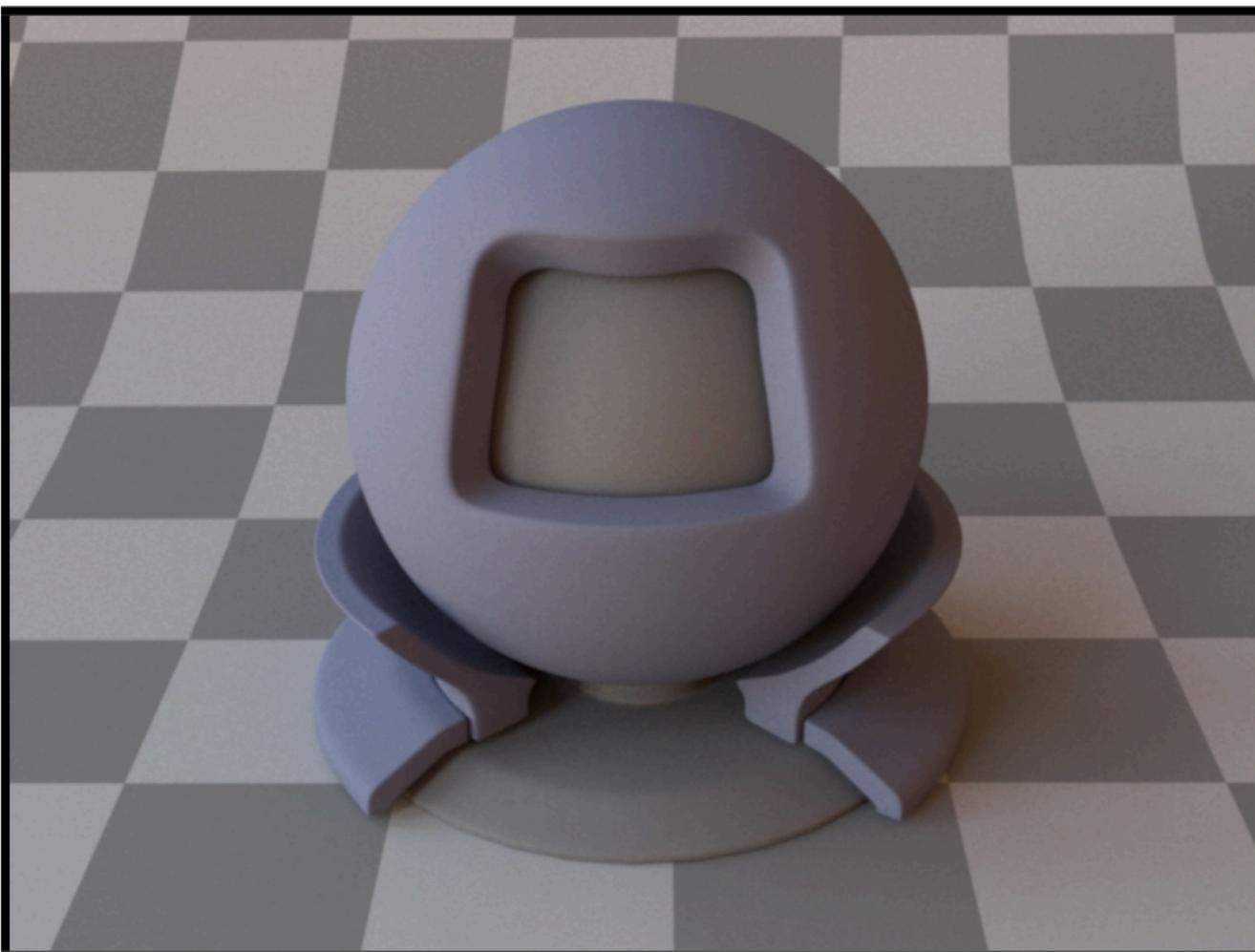
# What is this material?



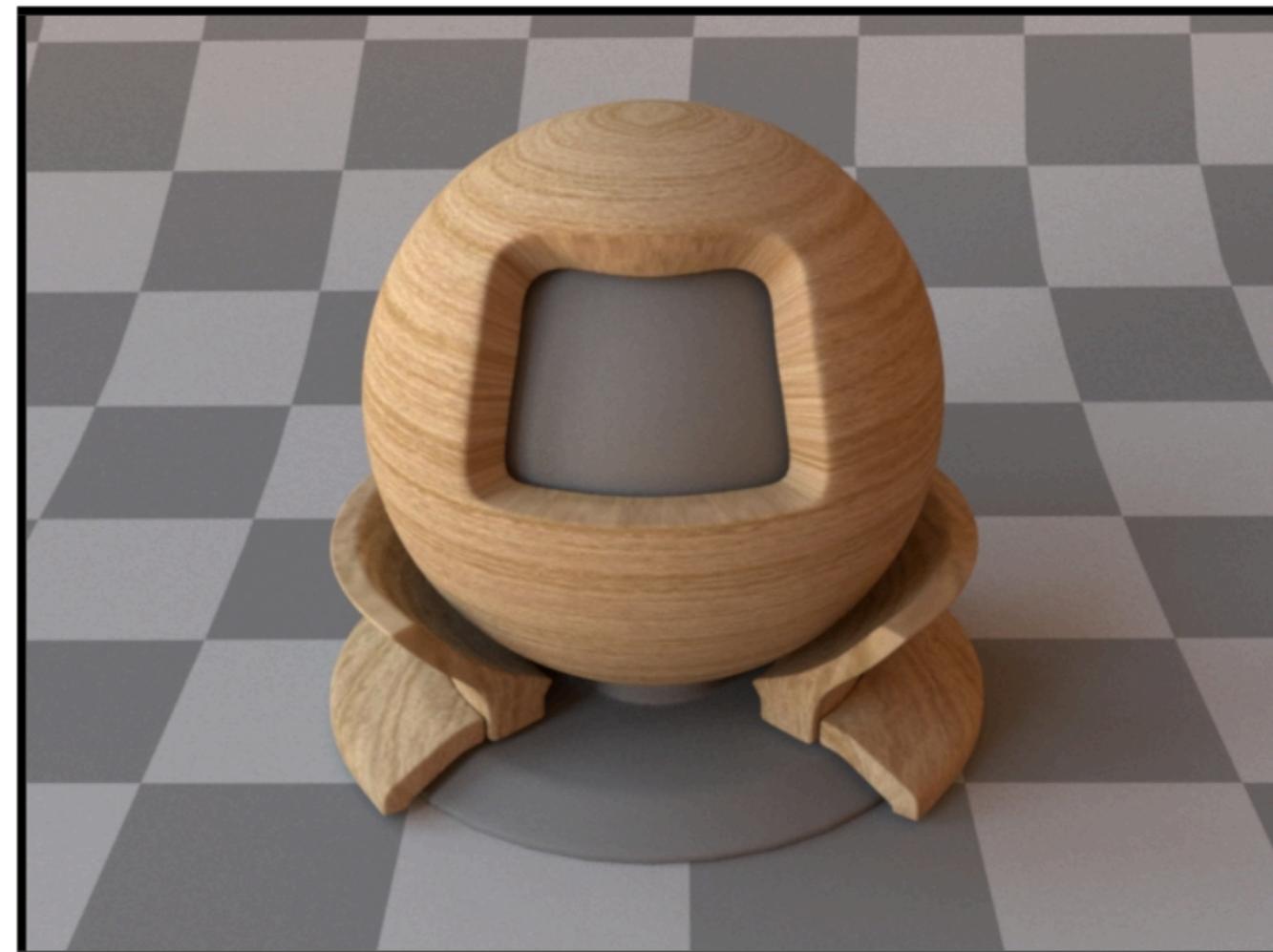
# Diffuse / Lambertian Material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]



Uniform colored diffuse BRDF

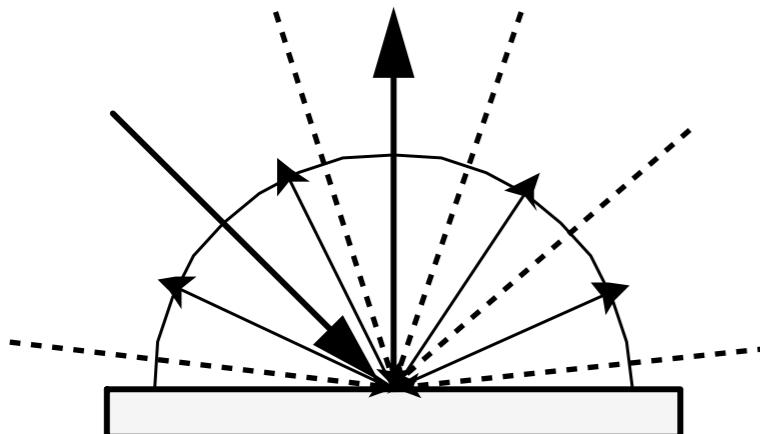


Textured diffuse BRDF

# Diffuse / Lambertian Material

Light is equally reflected in each output direction

Suppose the incident lighting is **uniform**:

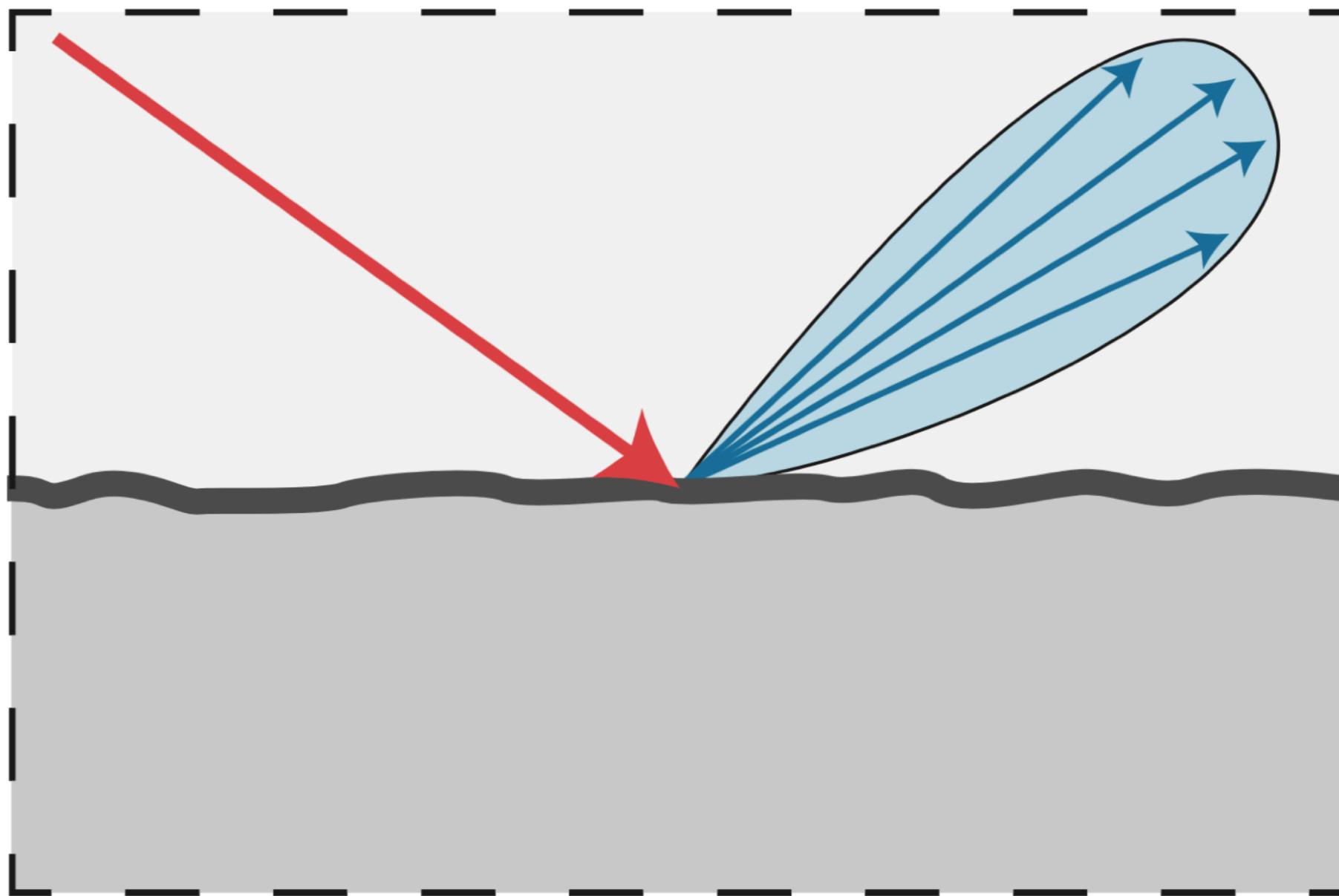


$$f_r = c$$

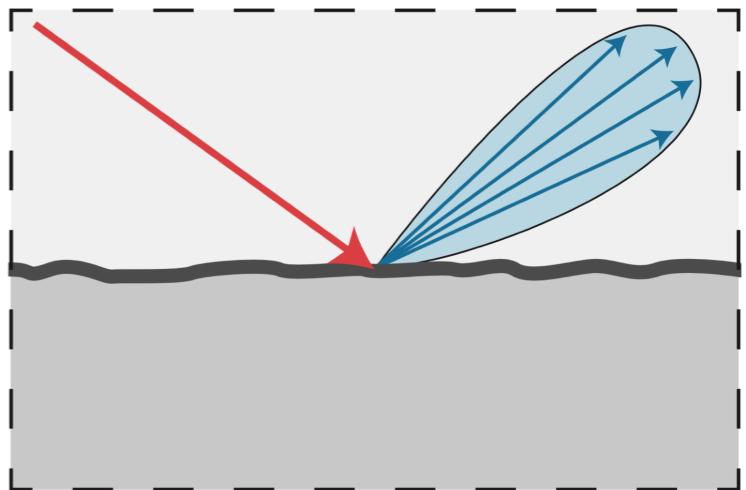
$$\begin{aligned} L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos \theta_i d\omega_i \\ &= f_r L_i \int_{H^2} (\omega_i) \cos \theta_i d\omega_i \\ &= \pi f_r L_i \end{aligned}$$

$$f_r = \frac{\rho}{\pi} \quad \text{— albedo (color)}$$

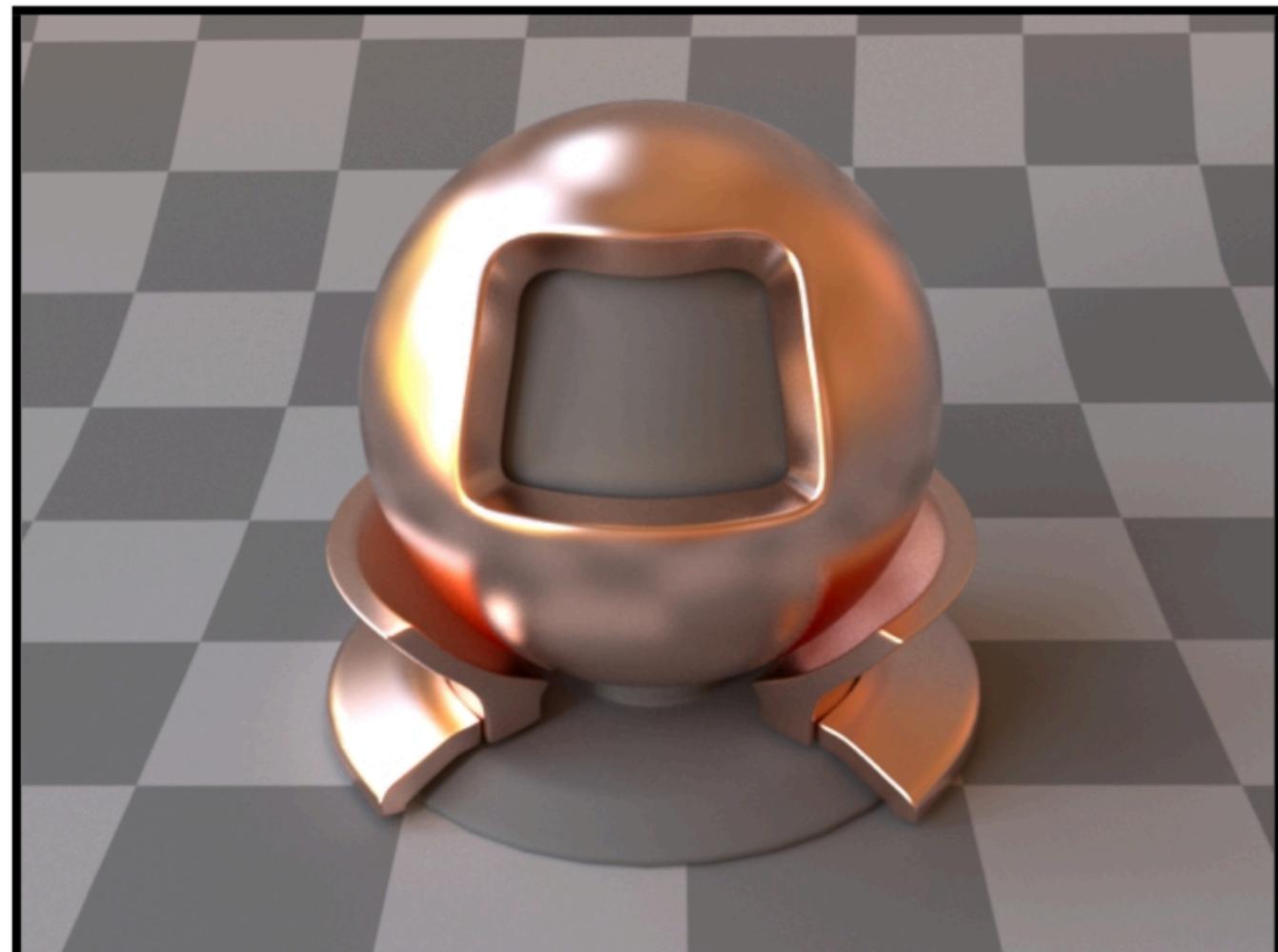
# What is this material?



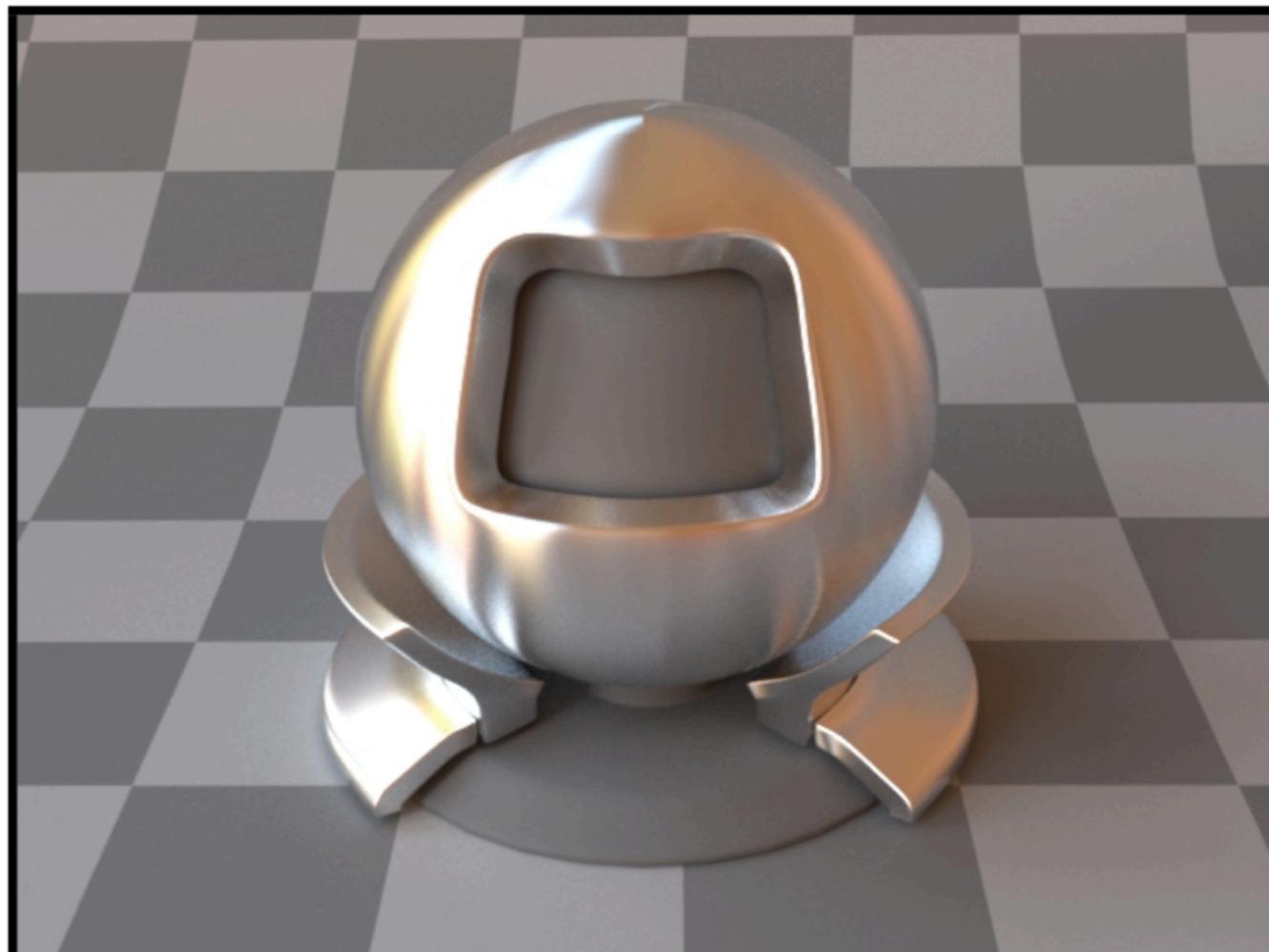
# Glossy material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]

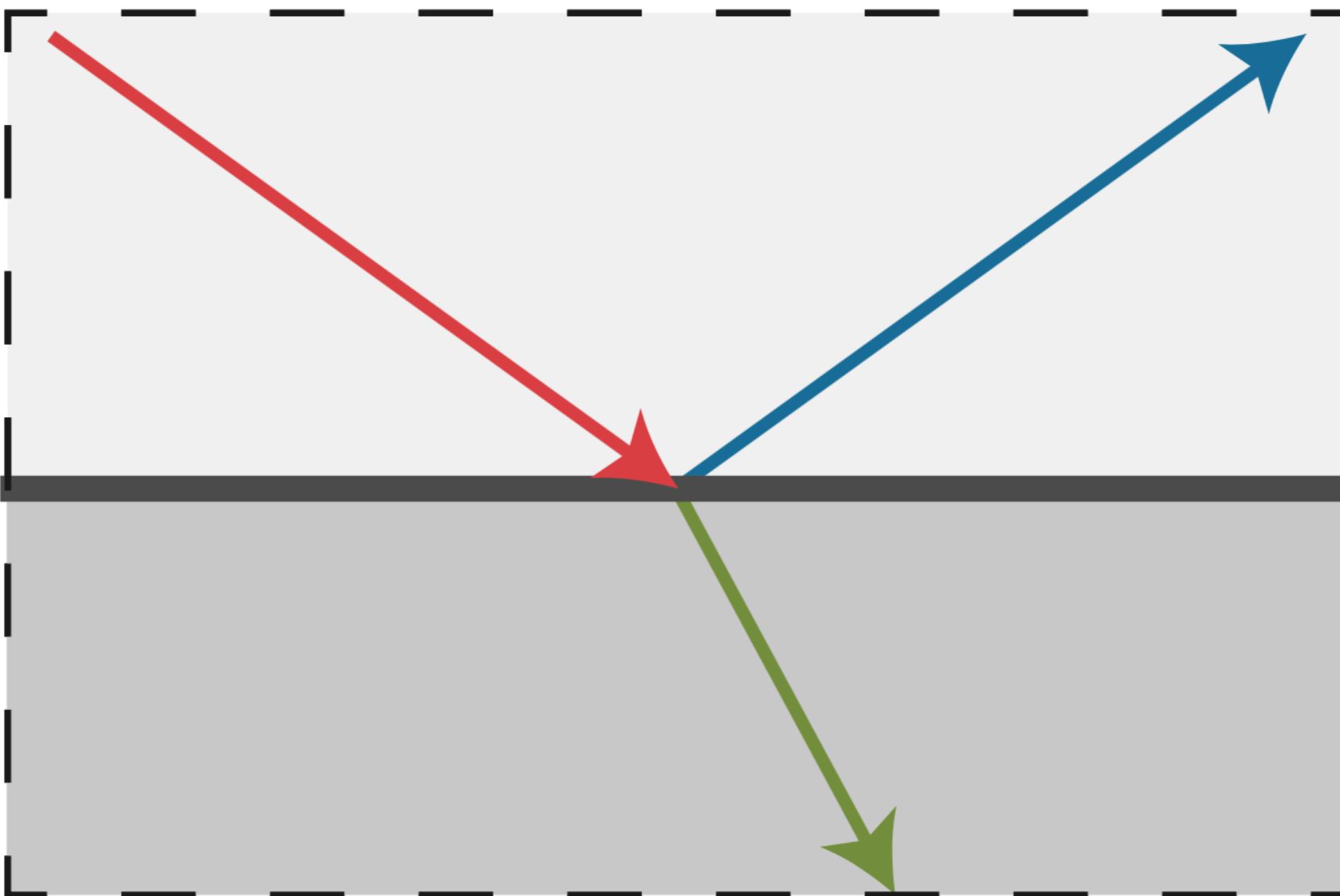


Copper



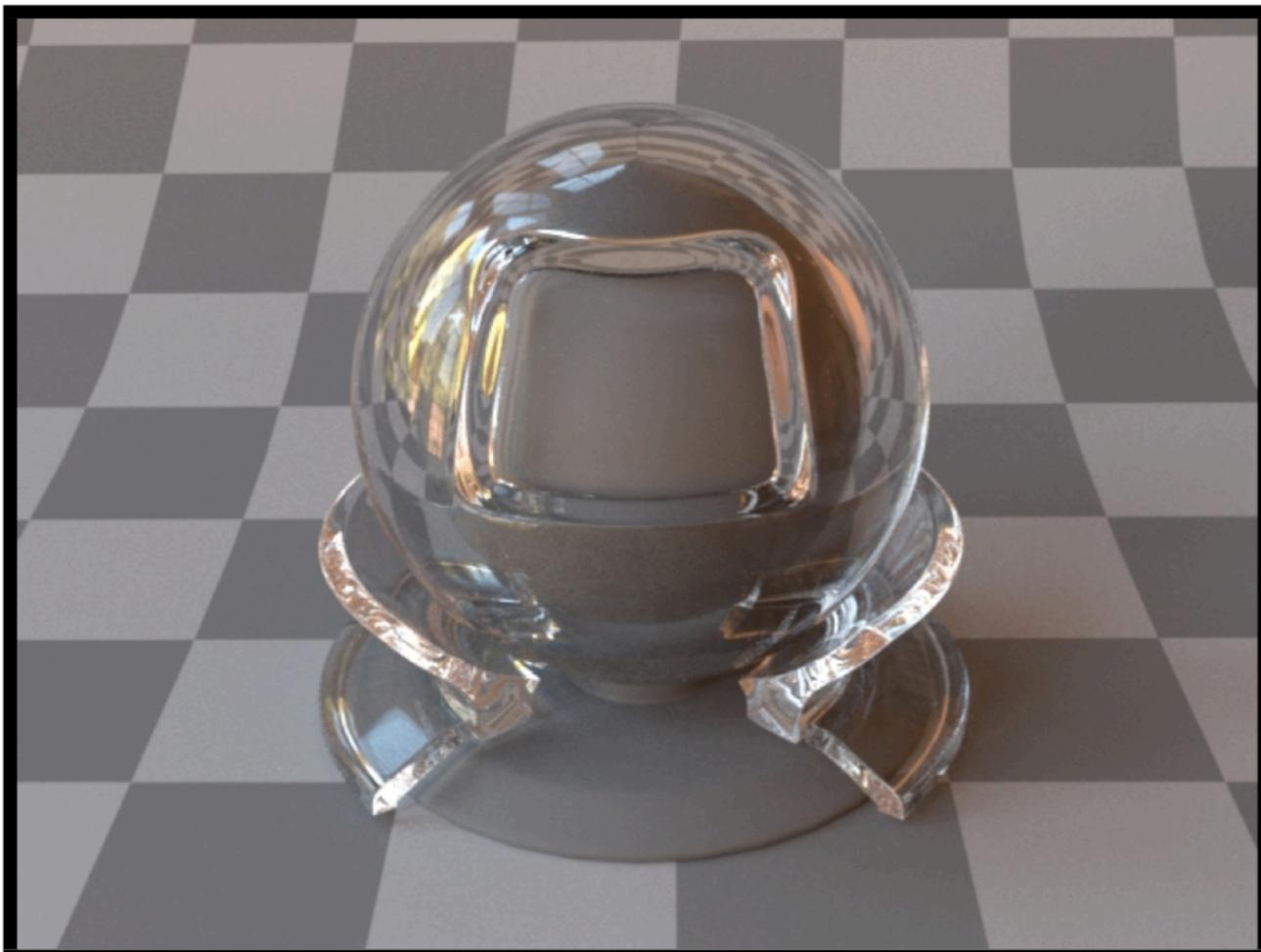
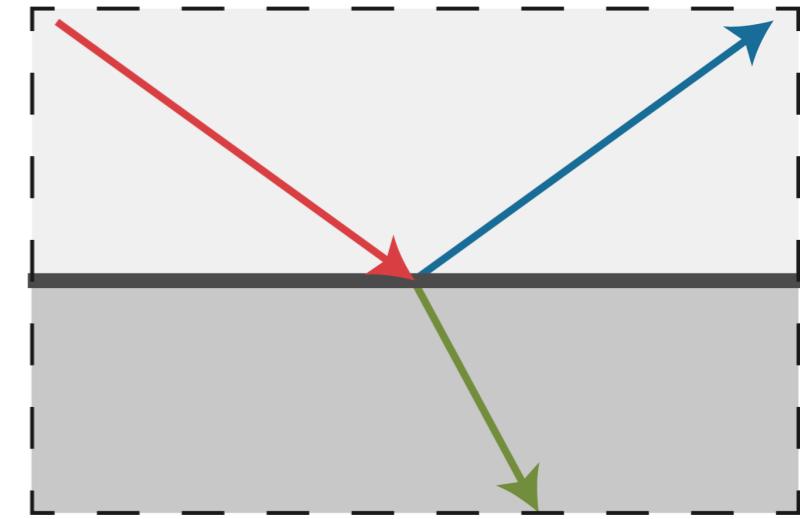
Aluminum

# What is this material?

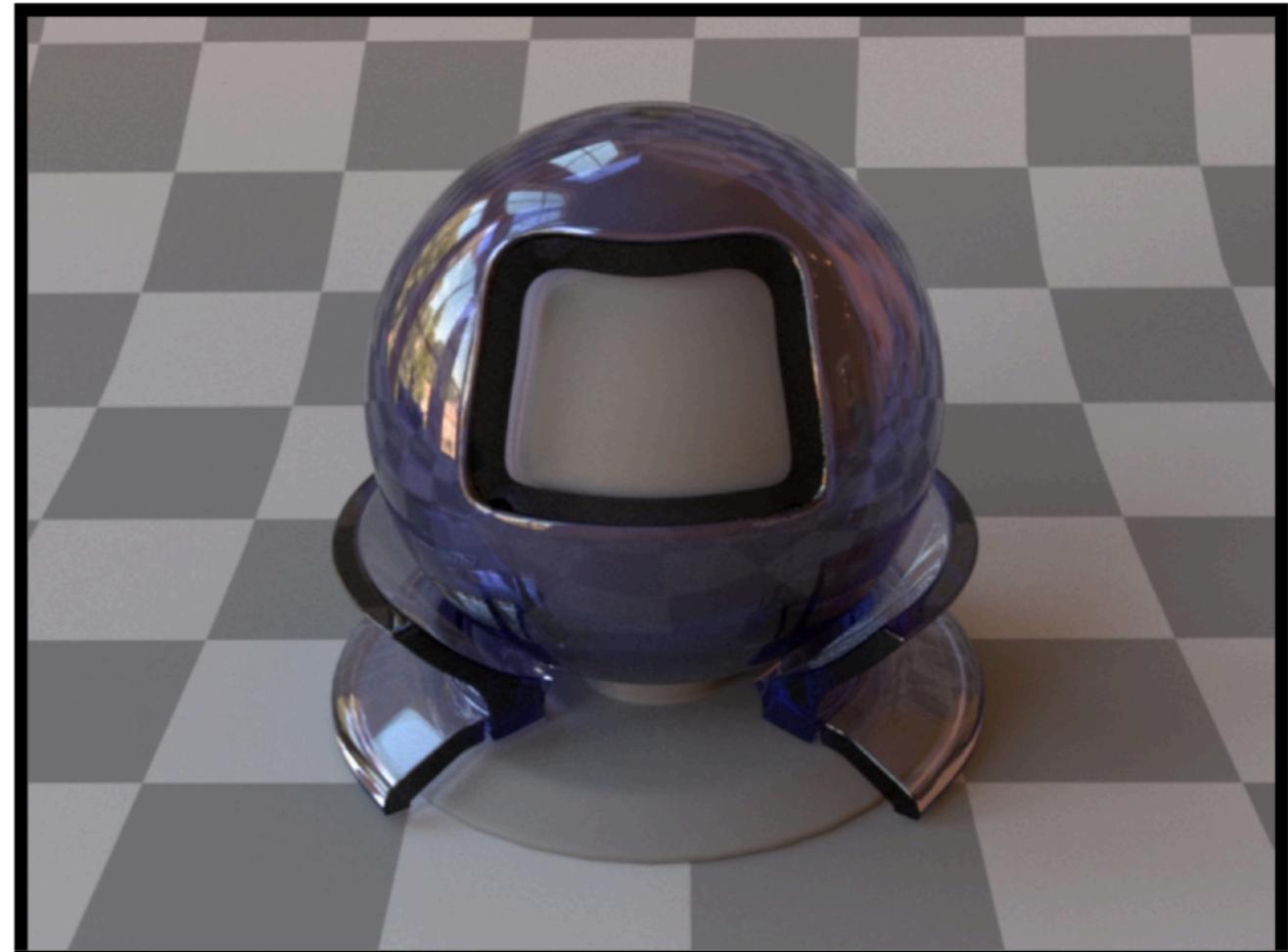


# Ideal reflective / refractive material (BSDF\*)

[Mitsuba renderer, Wenzel Jakob, 2010]

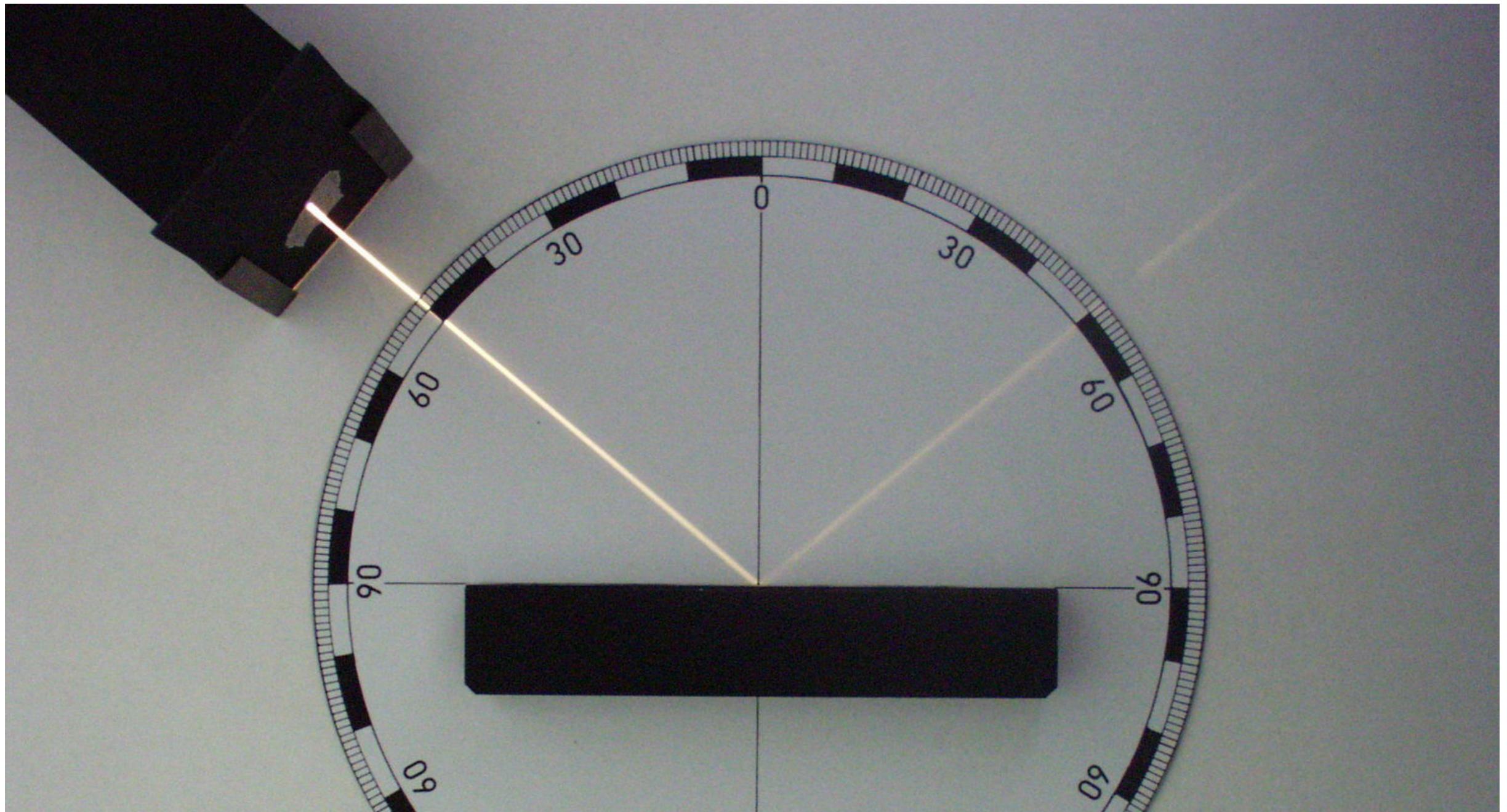


Air <-> water interface



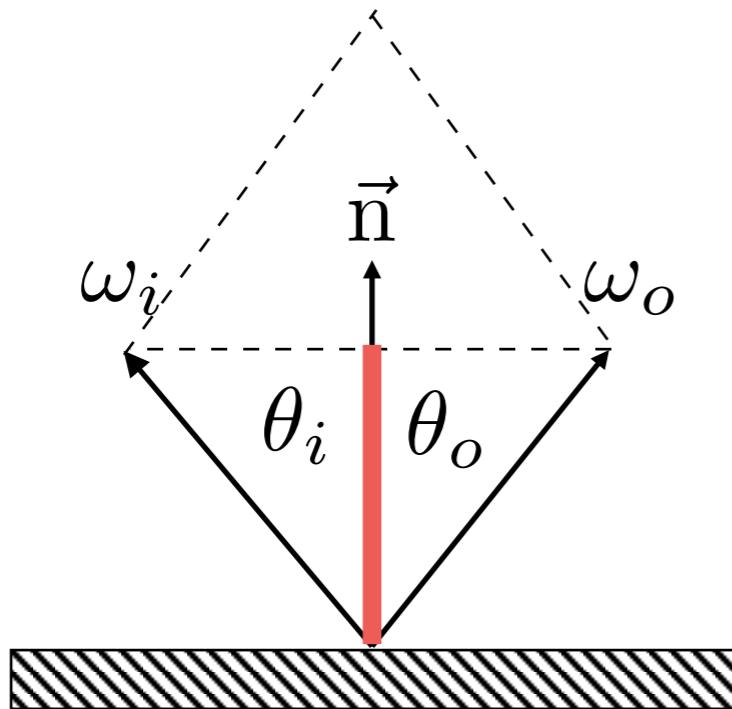
Air <-> glass interface  
(with absorption)

# Perfect Specular Reflection

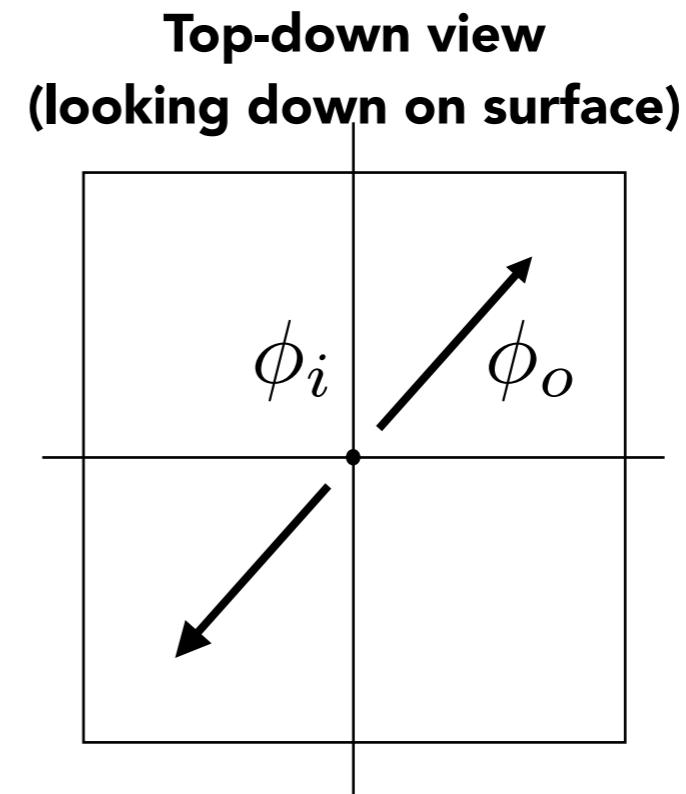


[Zátonyi Sándor]

# Perfect Specular Reflection



$$\theta = \theta_o = \theta_i$$

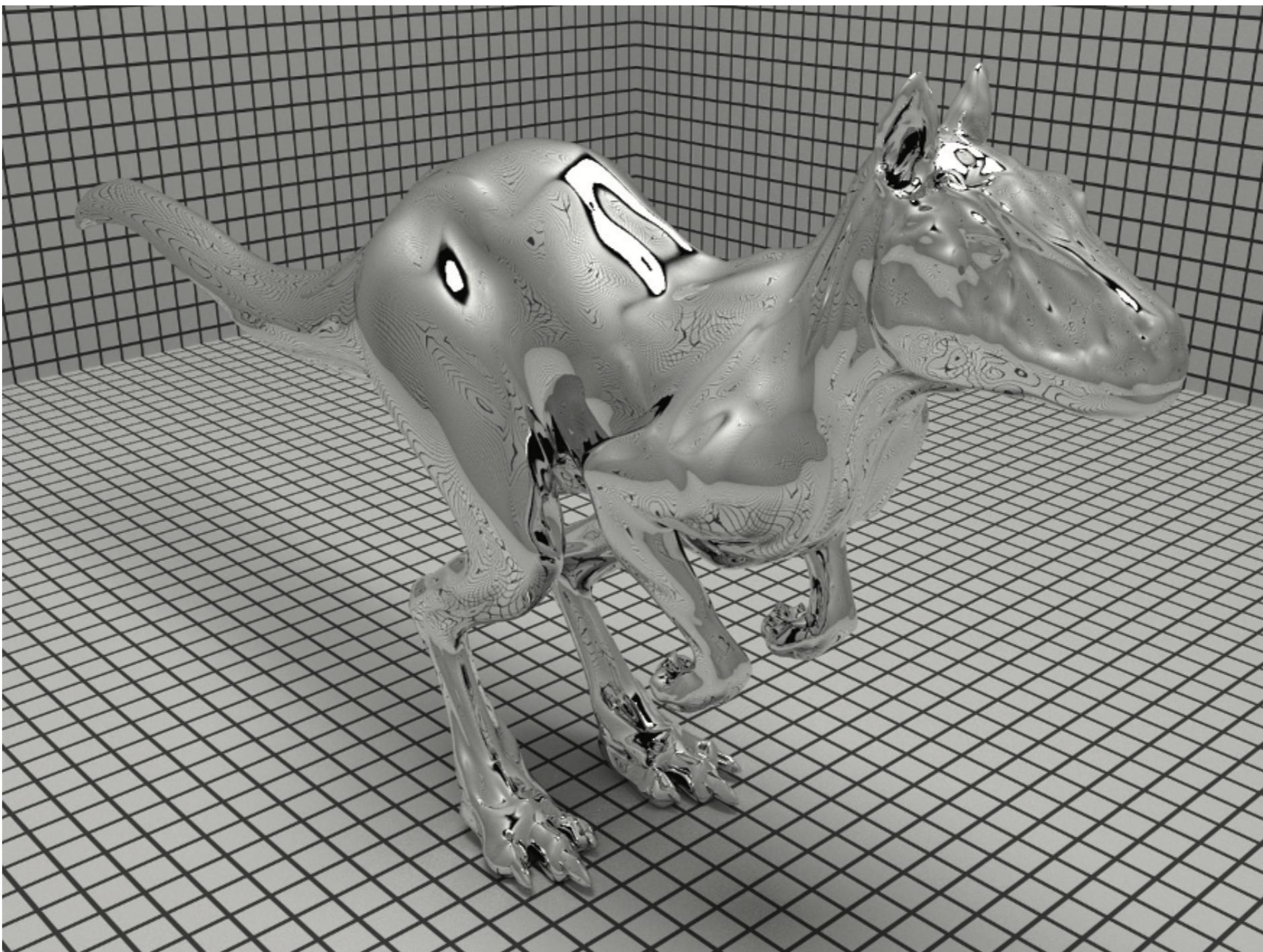


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

$$\omega_o + \omega_i = 2 \cos \theta \vec{n} = 2(\omega_i \cdot \vec{n})\vec{n}$$

$$\omega_o = -\omega_i + 2(\omega_i \cdot \vec{n})\vec{n}$$

# Perfect Specular Reflection BRDF

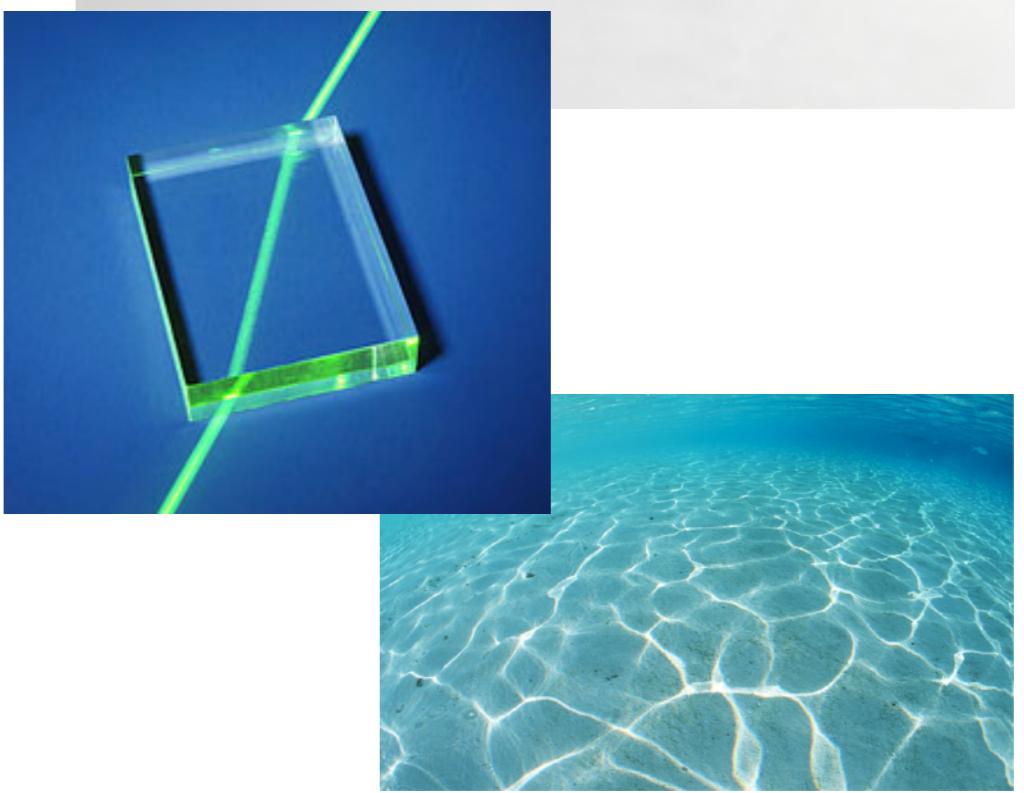


PBRT

# Specular Refraction

In addition to reflecting off surface, light may be transmitted through surface.

Light refracts when it enters a new medium.

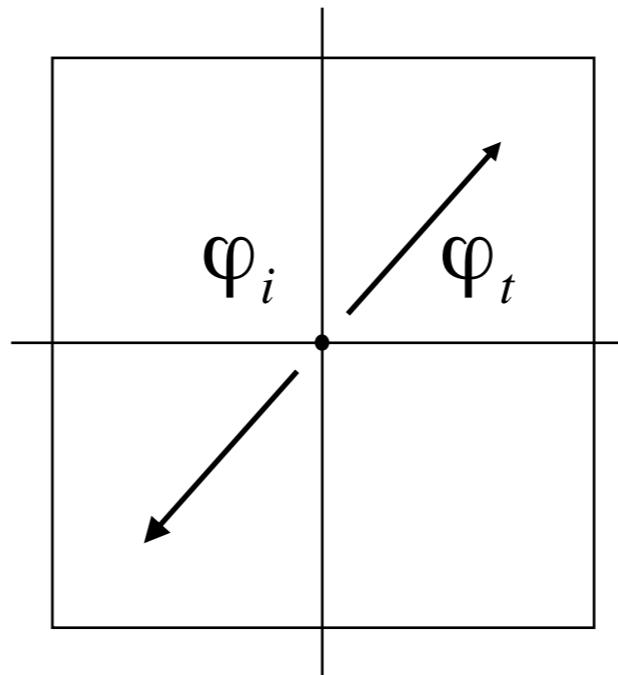
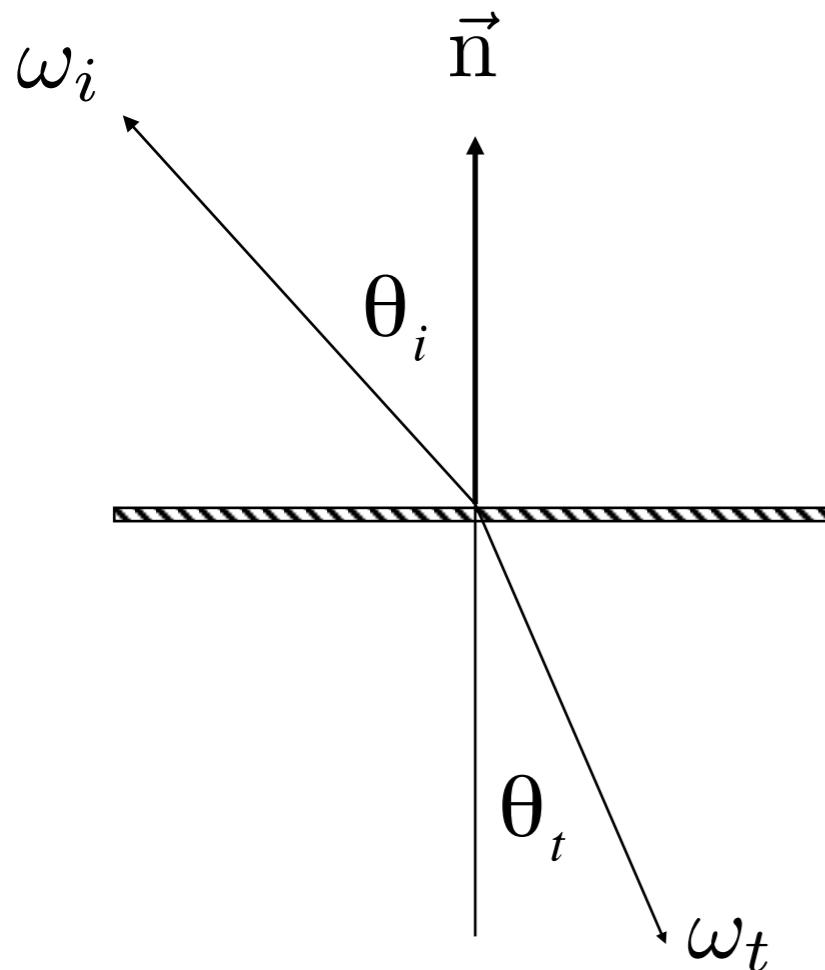


# Snell's Law

Transmitted angle depends on

index of refraction (IOR) for incident ray

index of refraction (IOR) for exiting ray



$$\varphi_t = \varphi_i \pm \pi$$

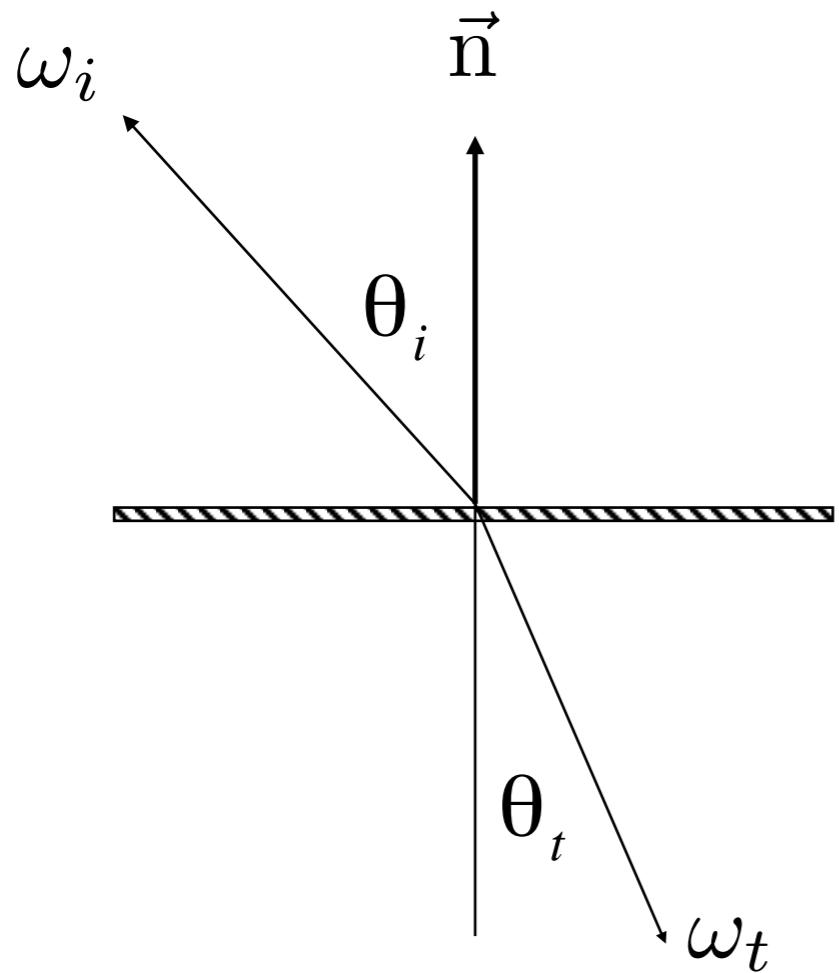
$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

Medium	$\eta^*$
Vacuum	1.0
Air (sea level)	1.00029
Water (20°C)	1.333
Glass	1.5-1.6
Diamond	2.42

\* index of refraction is wavelength dependent  
(these are averages)

# Law of Refraction

$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$



$$\begin{aligned}\cos \theta_t &= \sqrt{1 - \sin^2 \theta_t} \\ &= \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 \sin^2 \theta_i} \\ &= \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2 \theta_i)}\end{aligned}$$

## Total internal reflection:

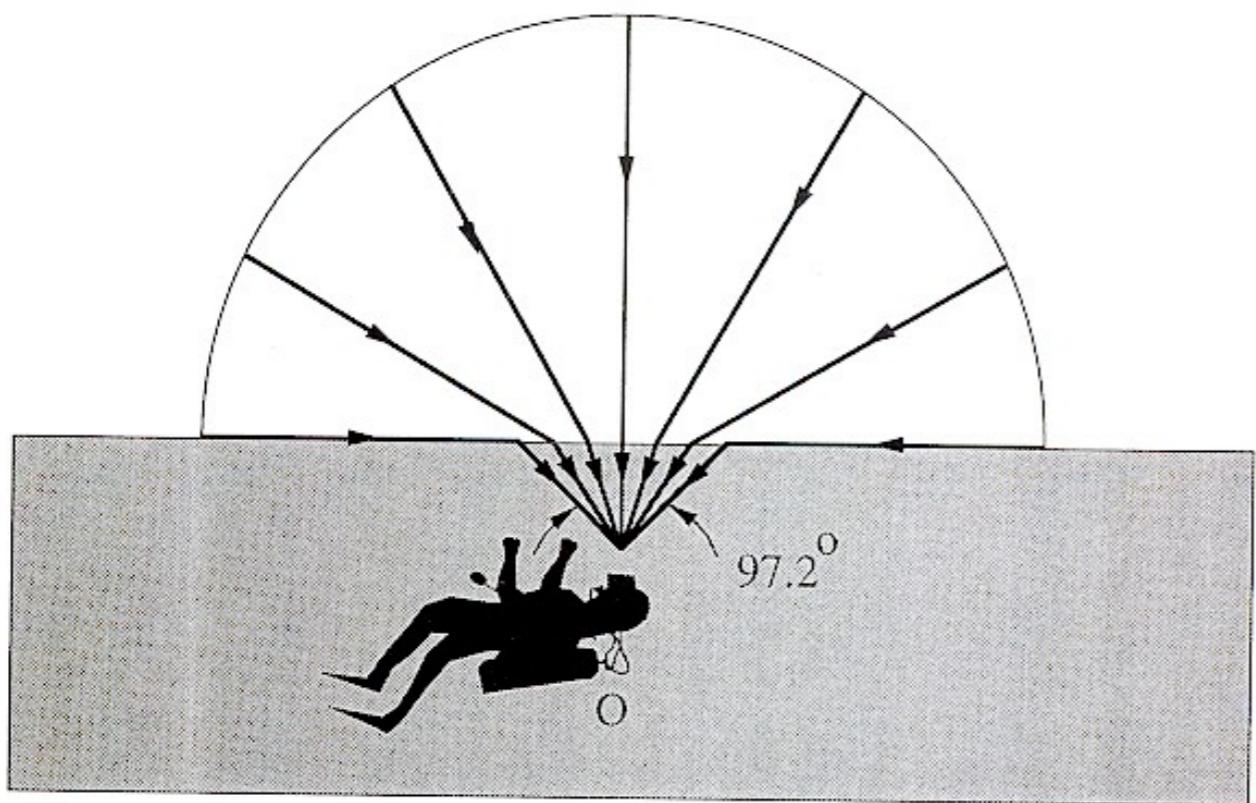
$$1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2 \theta_i) < 0$$

When light is moving from a more optically dense medium to a less optically dense medium:  $\frac{\eta_i}{\eta_t} > 1$

Light incident on boundary from large enough angle will not exit medium.

# Snell's Window / Circle

Total internal reflection



[Livingston and Lynch]

# Fresnel Reflection / Term

(菲涅耳项)

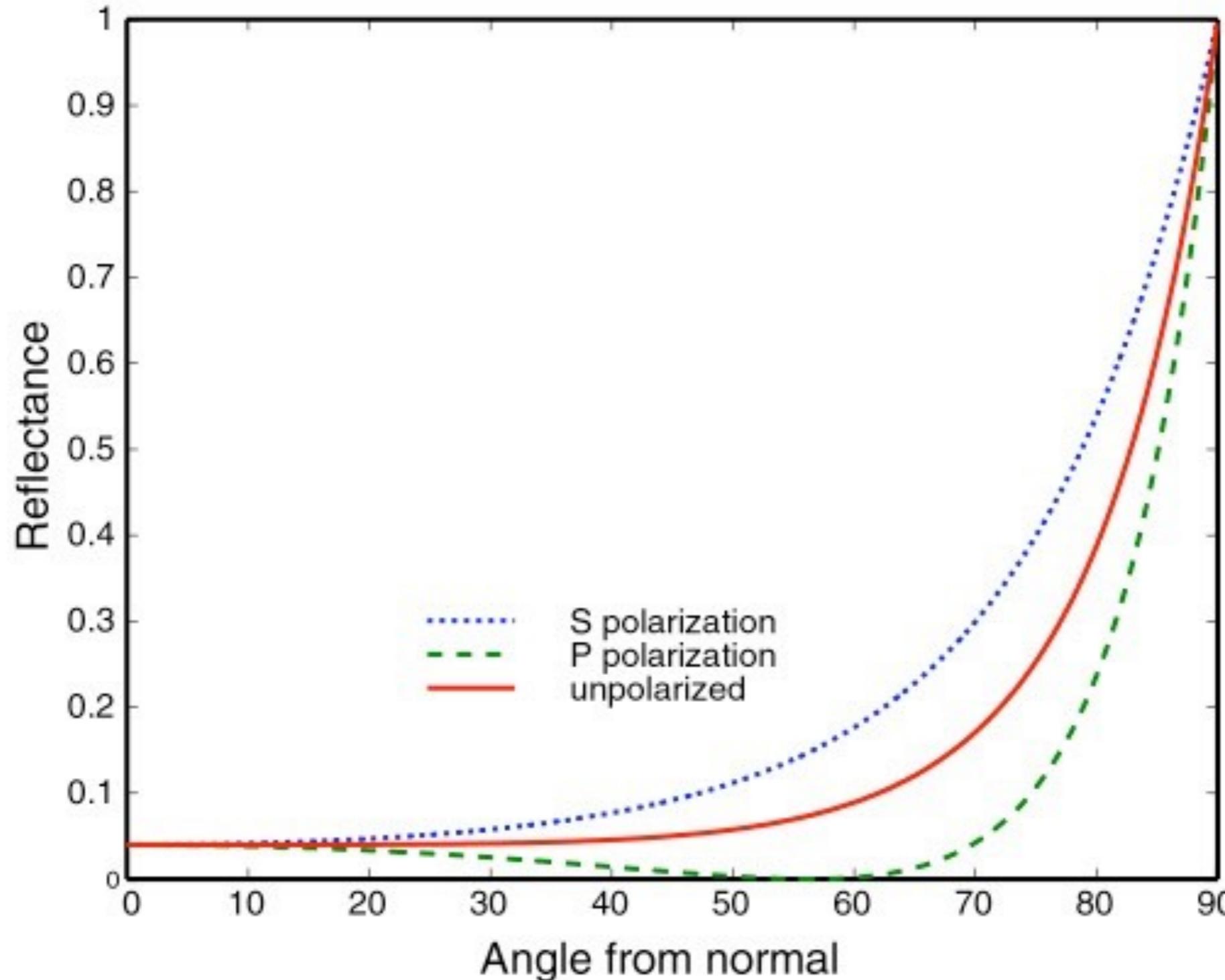
Reflectance depends on incident angle (and polarization of light)



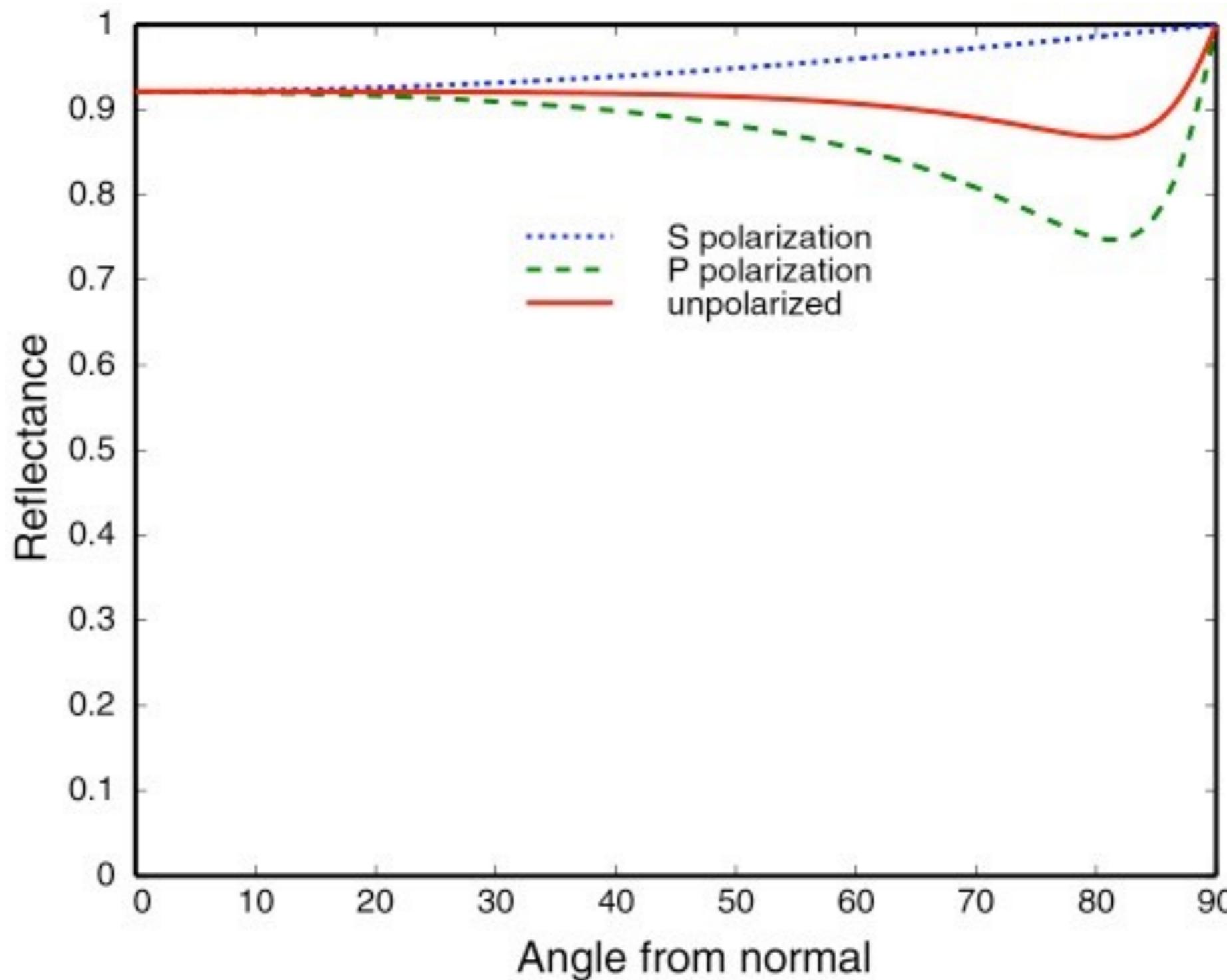
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

# Fresnel Term (Dielectric, $\eta = 1.5$ )



# Fresnel Term (Conductor)



# Fresnel Term — Formulae

Accurate: need to consider polarization

$$R_s = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 = \left| \frac{n_1 \cos \theta_i - n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2}}{n_1 \cos \theta_i + n_2 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2}} \right|^2,$$
$$R_p = \left| \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2} - n_2 \cos \theta_i}{n_1 \sqrt{1 - \left( \frac{n_1}{n_2} \sin \theta_i \right)^2} + n_2 \cos \theta_i} \right|^2.$$

$$R_{\text{eff}} = \frac{1}{2} (R_s + R_p).$$

Approximate: Schlick's approximation

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos \theta)^5$$

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

# Microfacet Material

# Microfacet Material: Motivation

[https://twitter.com/Cmdr\\_Hadfield/status/318986491063828480/photo/1](https://twitter.com/Cmdr_Hadfield/status/318986491063828480/photo/1)

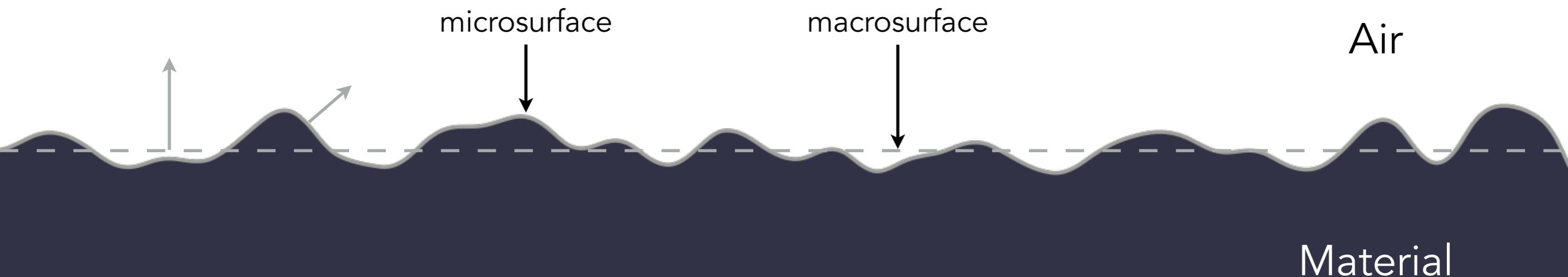
# Microfacet Theory

Rough surface

- Macroscale: flat & rough
- Microscale: bumpy & **specular**

Individual elements of surface act like **mirrors**

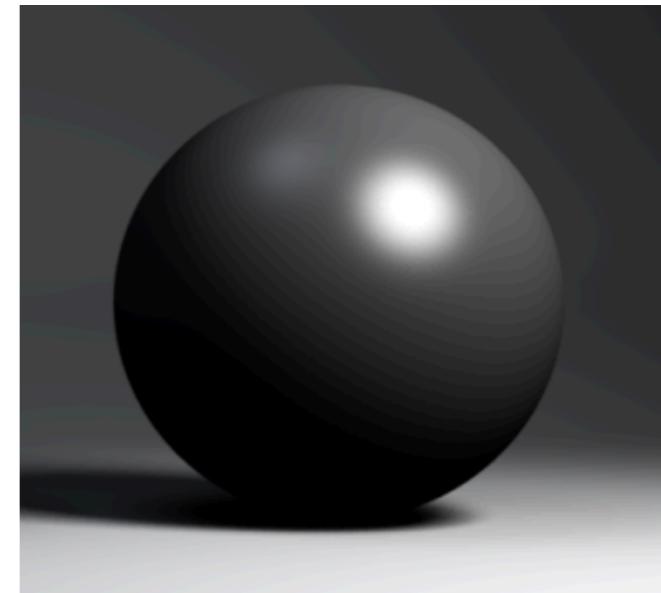
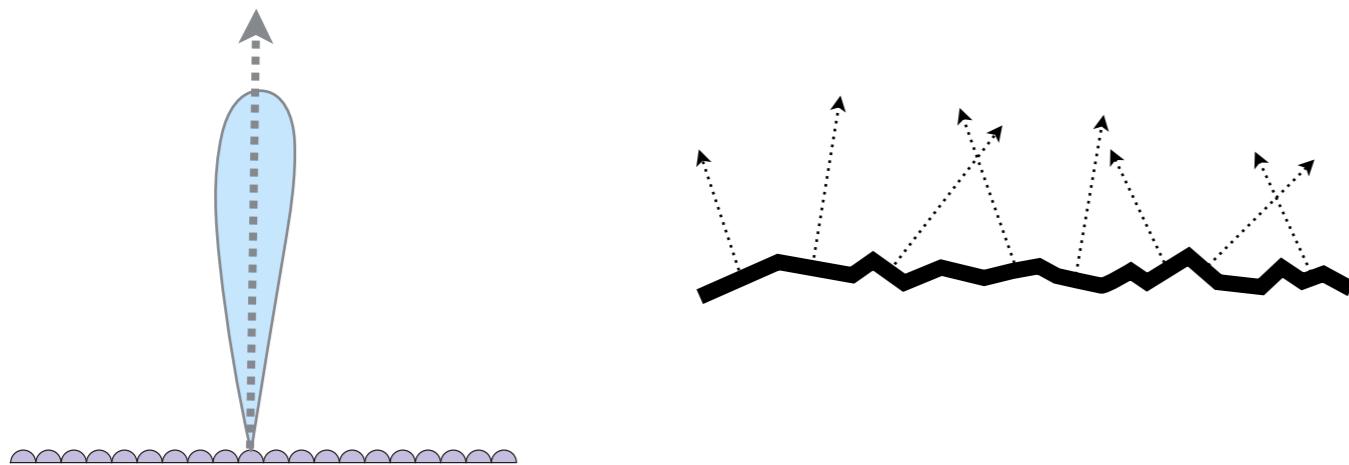
- Known as Microfacets
- Each microfacet has its own normal



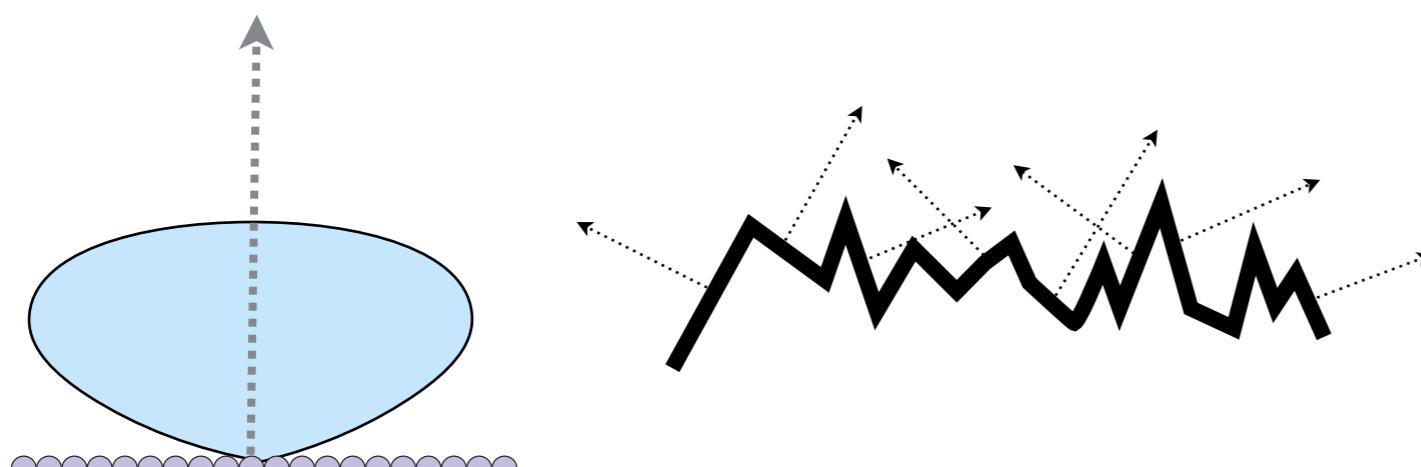
# Microfacet BRDF

- Key: the **distribution** of microfacets' normals

- Concentrated  $\Leftrightarrow$  glossy

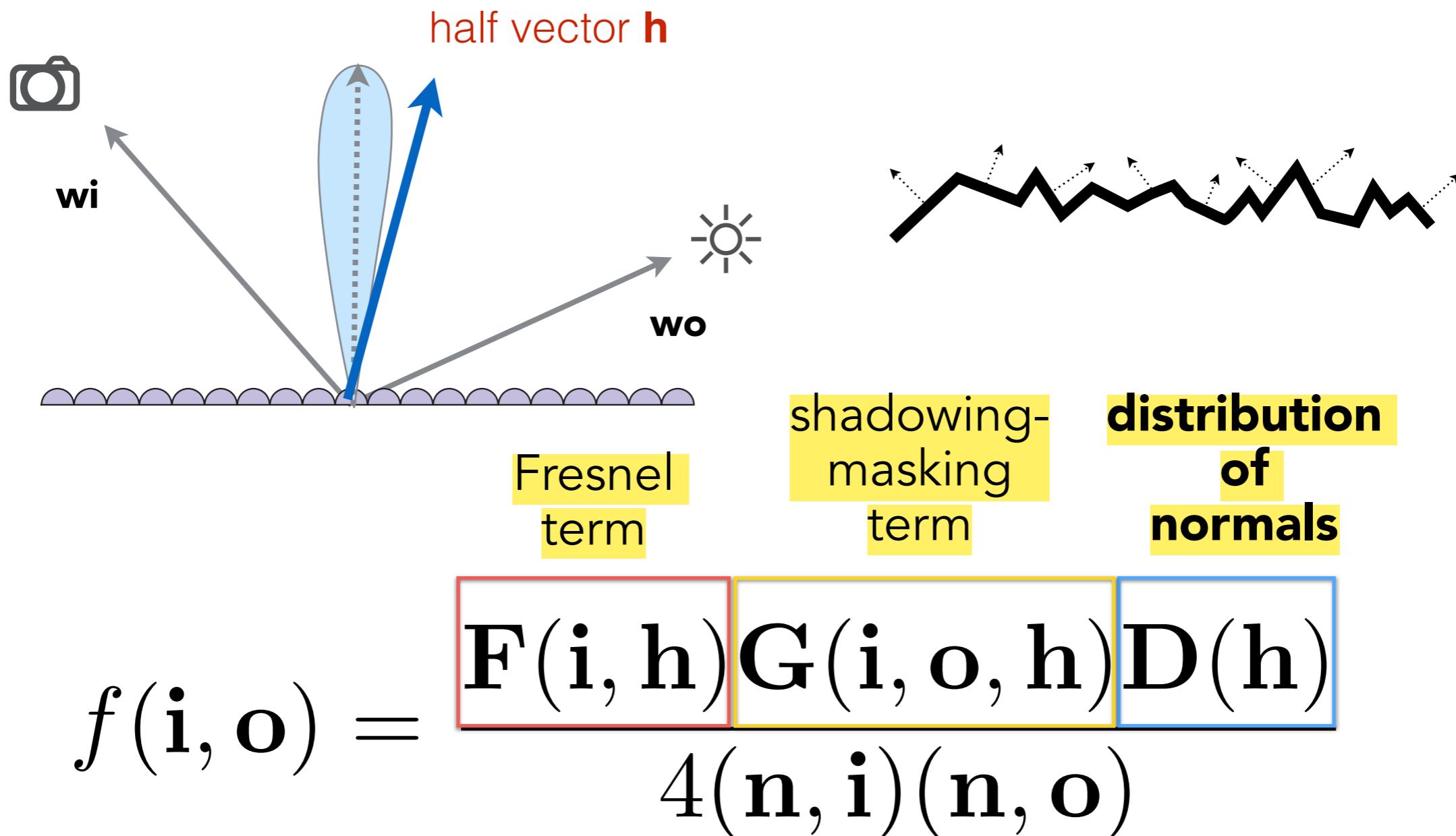


- Spread  $\Leftrightarrow$  diffuse



# Microfacet BRDF

- What kind of microfacets reflect  $w_i$  to  $w_o$ ?  
(hint: microfacets are mirrors)



# Microfacet BRDF: Examples



[Autodesk Fusion 360]

# Isotropic / Anisotropic Materials (BRDFs)



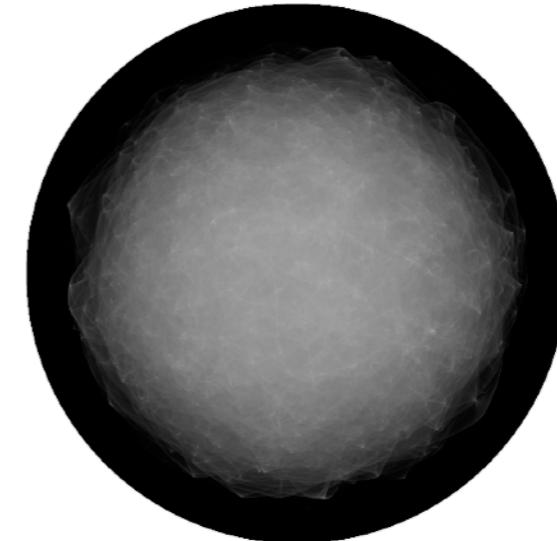
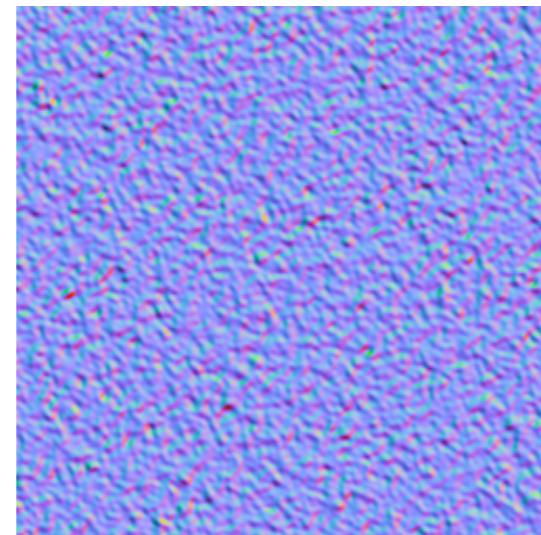
Inside an elevator

Slide courtesy of Prof. Ren Ng, UC Berkeley

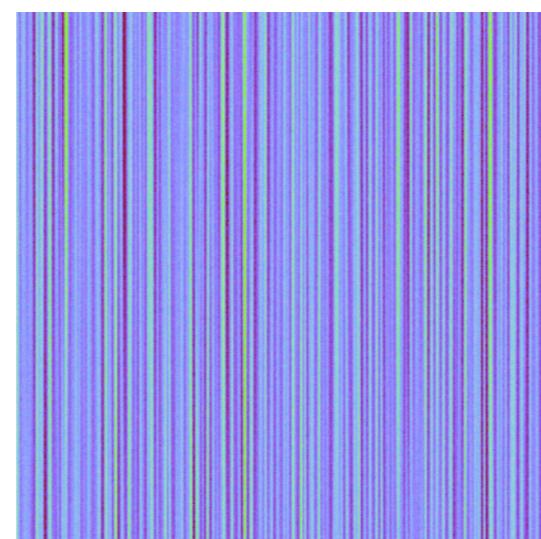
# Isotropic / Anisotropic Materials (BRDFs)

- Key: **directionality** of underlying surface

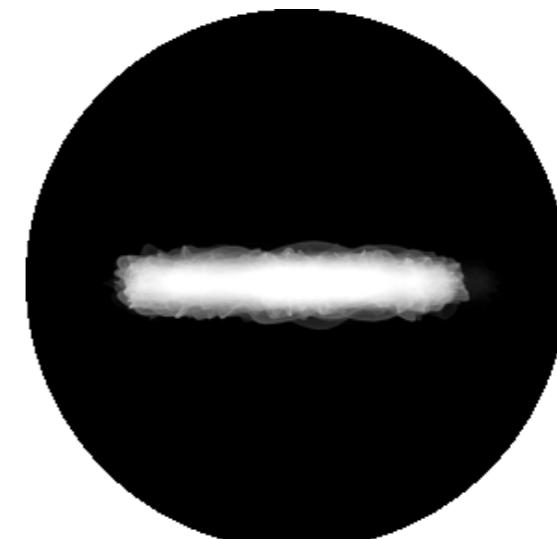
Isotropic



Anisotropic



Surface (normals)



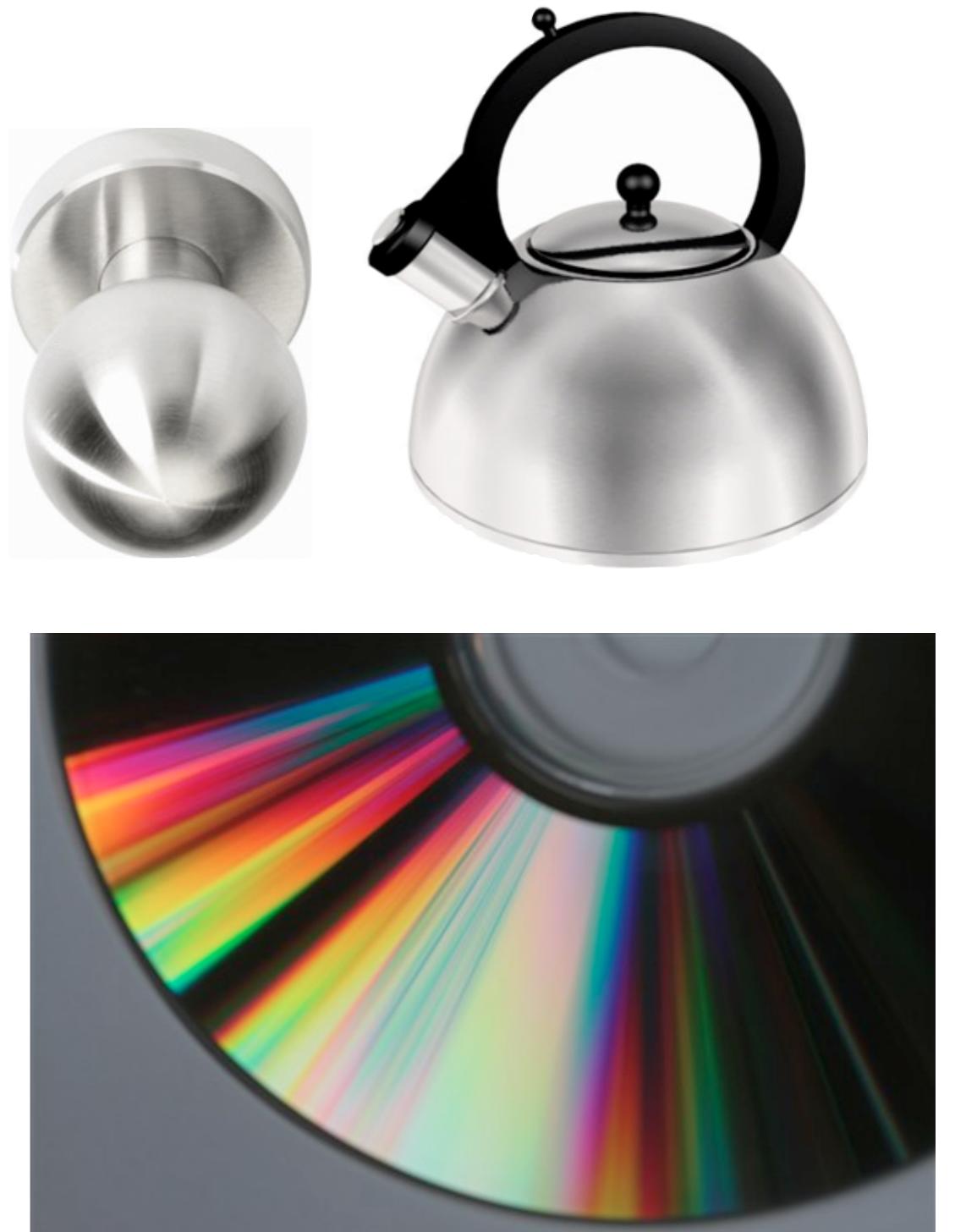
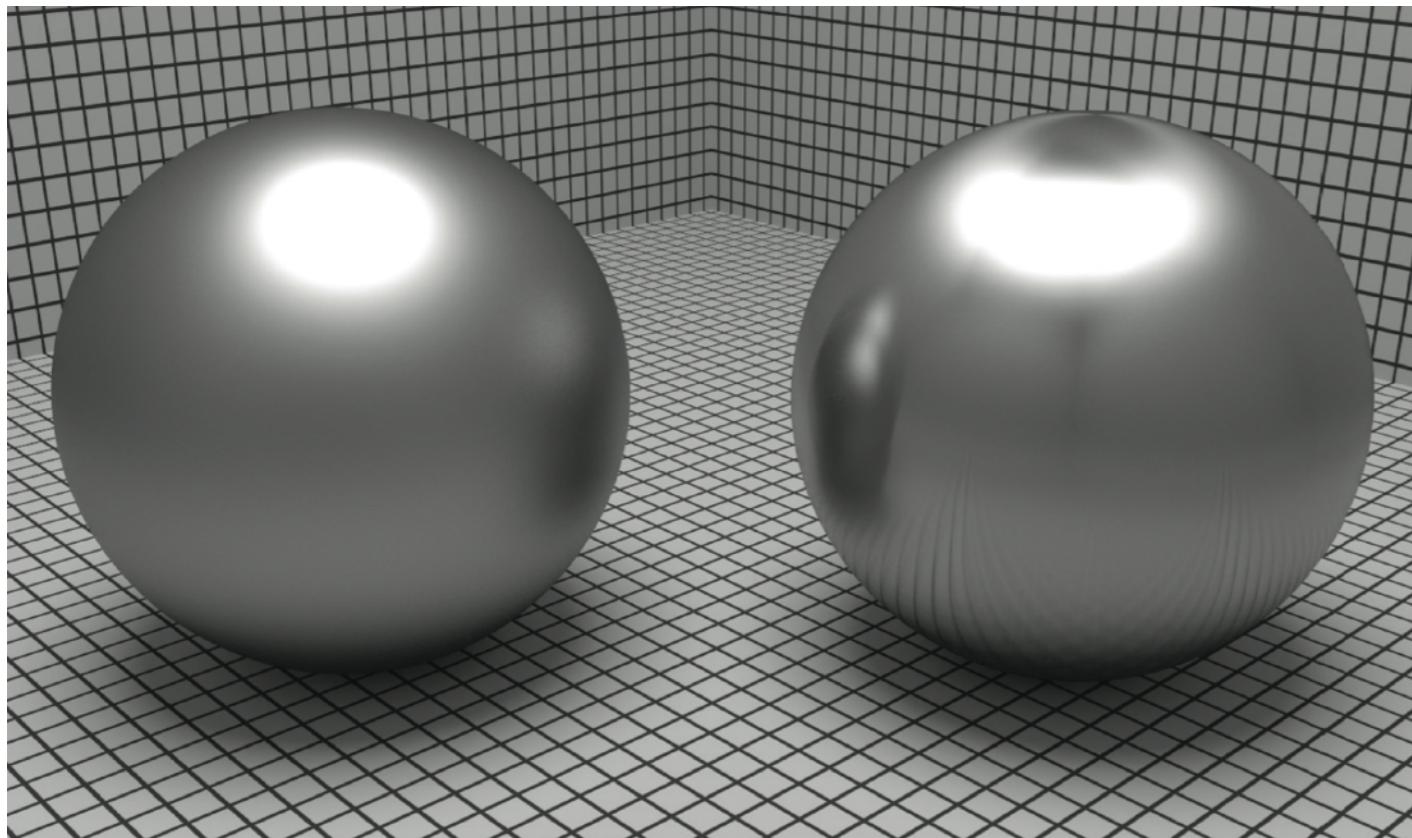
BRDF (fix  $w_i$ , vary  $w_o$ )

# Anisotropic BRDFs

Reflection depends on azimuthal angle  $\phi$

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) \neq f_r(\theta_i, \theta_r, \phi_r - \phi_i)$$

Results from oriented microstructure of surface, e.g., brushed metal



# Anisotropic BRDF: Brushed Metal

- How is the pan brushed?



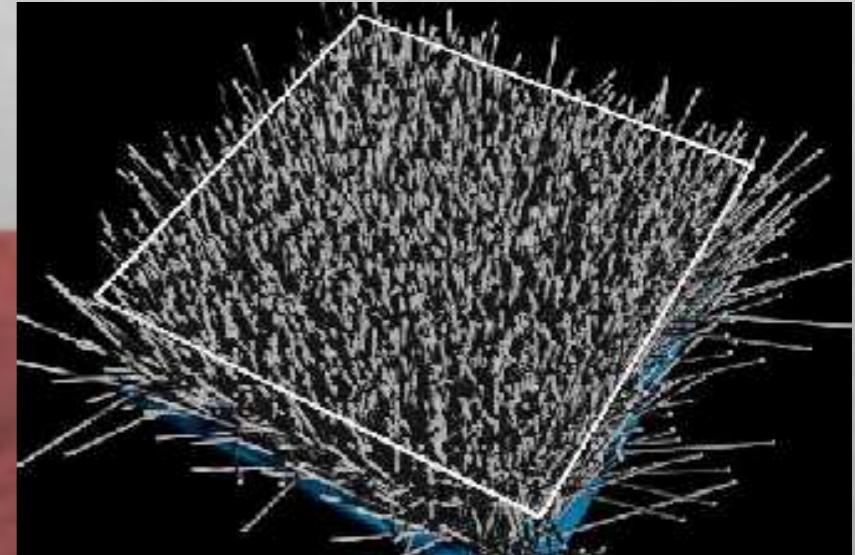
[VRay renderer]

# Anisotropic BRDF: Nylon



[Westin et al. 1992]

# Anisotropic BRDF: Velvet



[Westin et al. 1992]

# Anisotropic BRDF: Velvet



[<https://www.youtube.com/watch?v=2hjoW8TYTd4>]

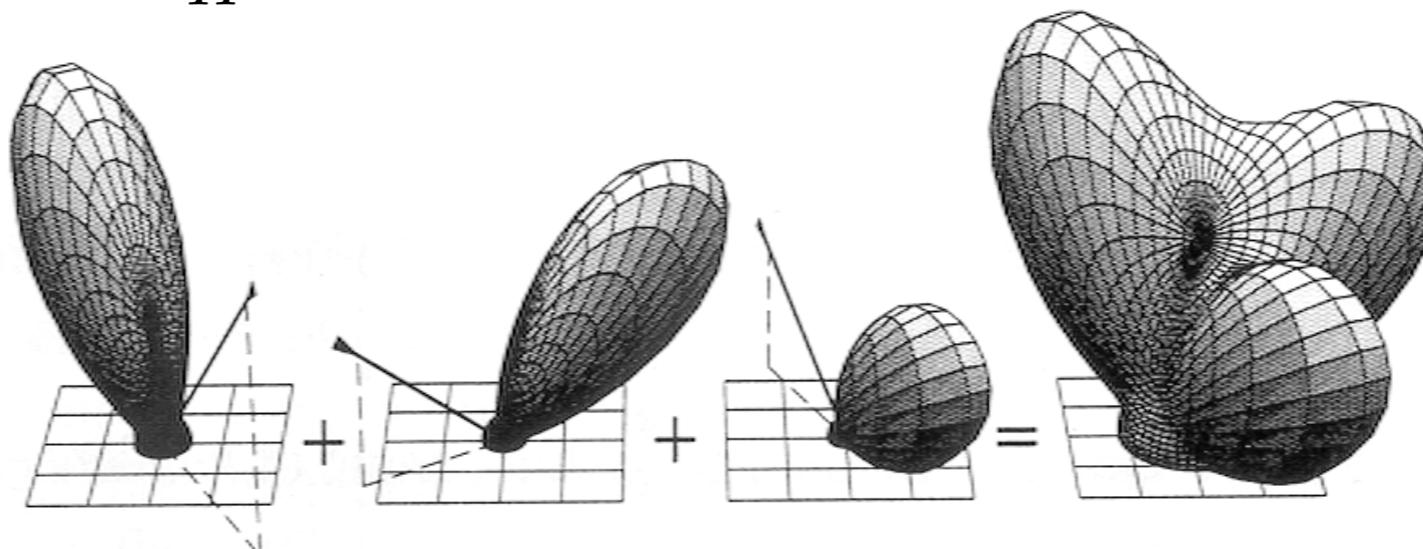
# Properties of BRDFs

- Non-negativity

$$f_r(\omega_i \rightarrow \omega_r) \geq 0$$

- Linearity

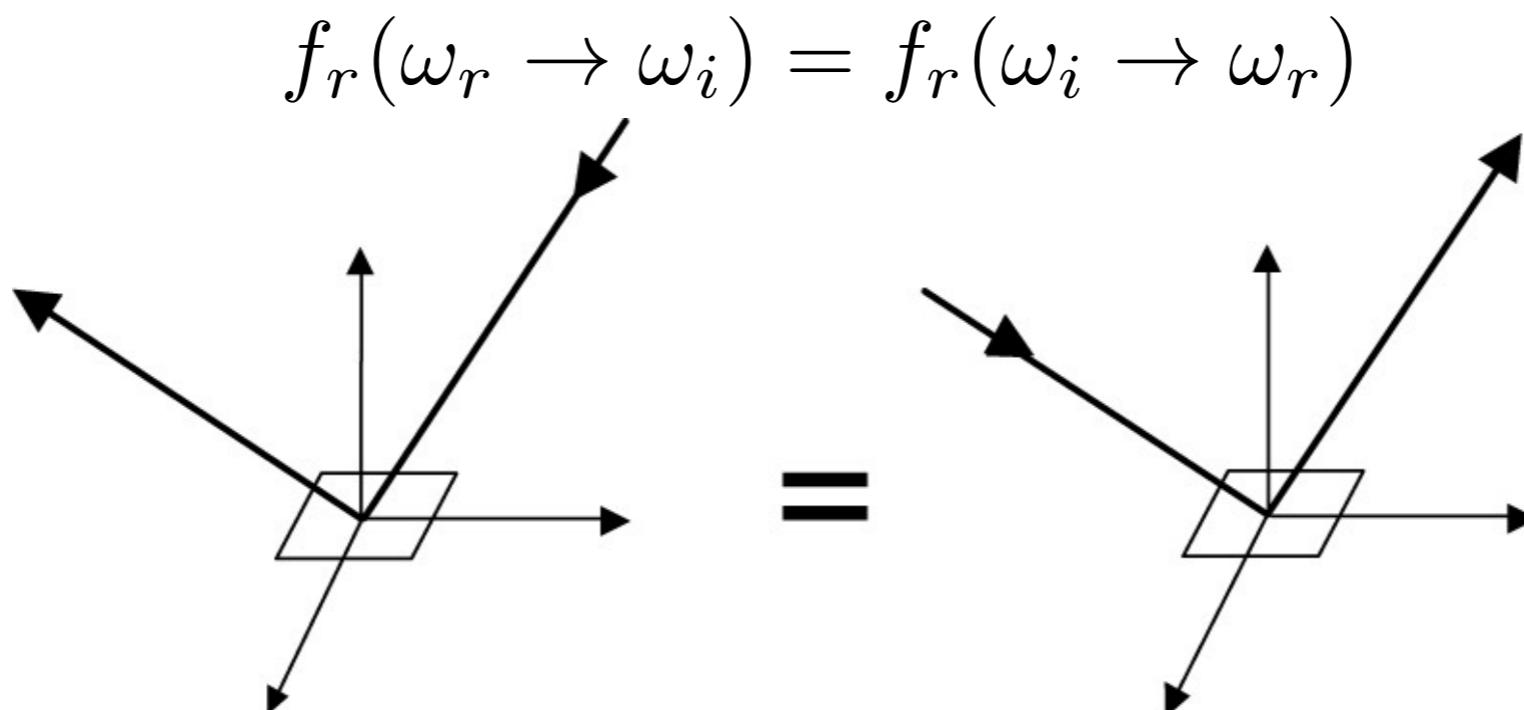
$$L_r(p, \omega_r) = \int_{H^2} f_r(p, \omega_i \rightarrow \omega_r) L_i(p, \omega_i) \cos \theta_i d\omega_i$$



[Sillion et al. 1990]

# Properties of BRDFs

- Reciprocity principle



- Energy conservation

$$\forall \omega_r \int_{H^2} f_r(\omega_i \rightarrow \omega_r) \cos \theta_i d\omega_i \leq 1$$

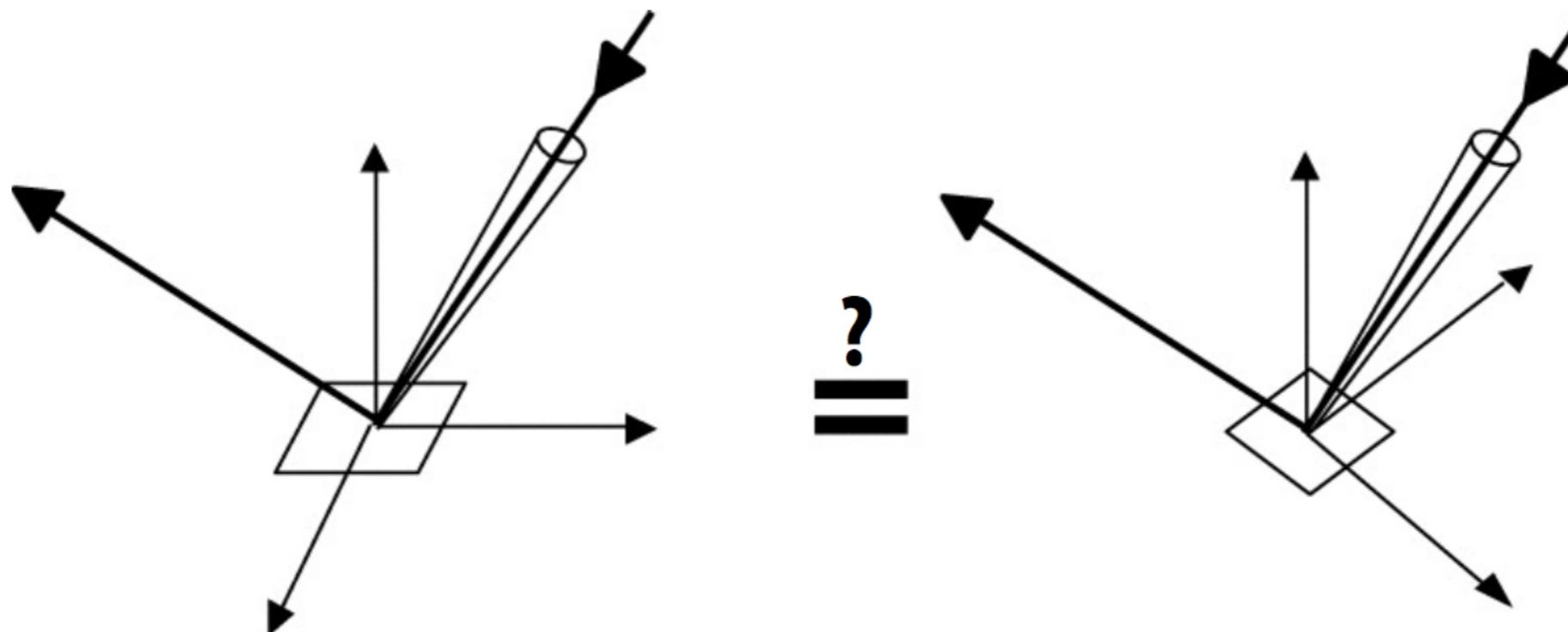
# Properties of BRDFs

- Isotropic vs. anisotropic

- If isotropic,  $f_r(\theta_i, \phi_i; \theta_r, \phi_r) = f_r(\theta_i, \theta_r, \phi_r - \phi_i)$

- Then, from reciprocity,

$$f_r(\theta_i, \theta_r, \phi_r - \phi_i) = f_r(\theta_r, \theta_i, \phi_i - \phi_r) = f_r(\theta_i, \theta_r, |\phi_r - \phi_i|)$$



# Measuring BRDFs

# Measuring BRDFs: Motivation

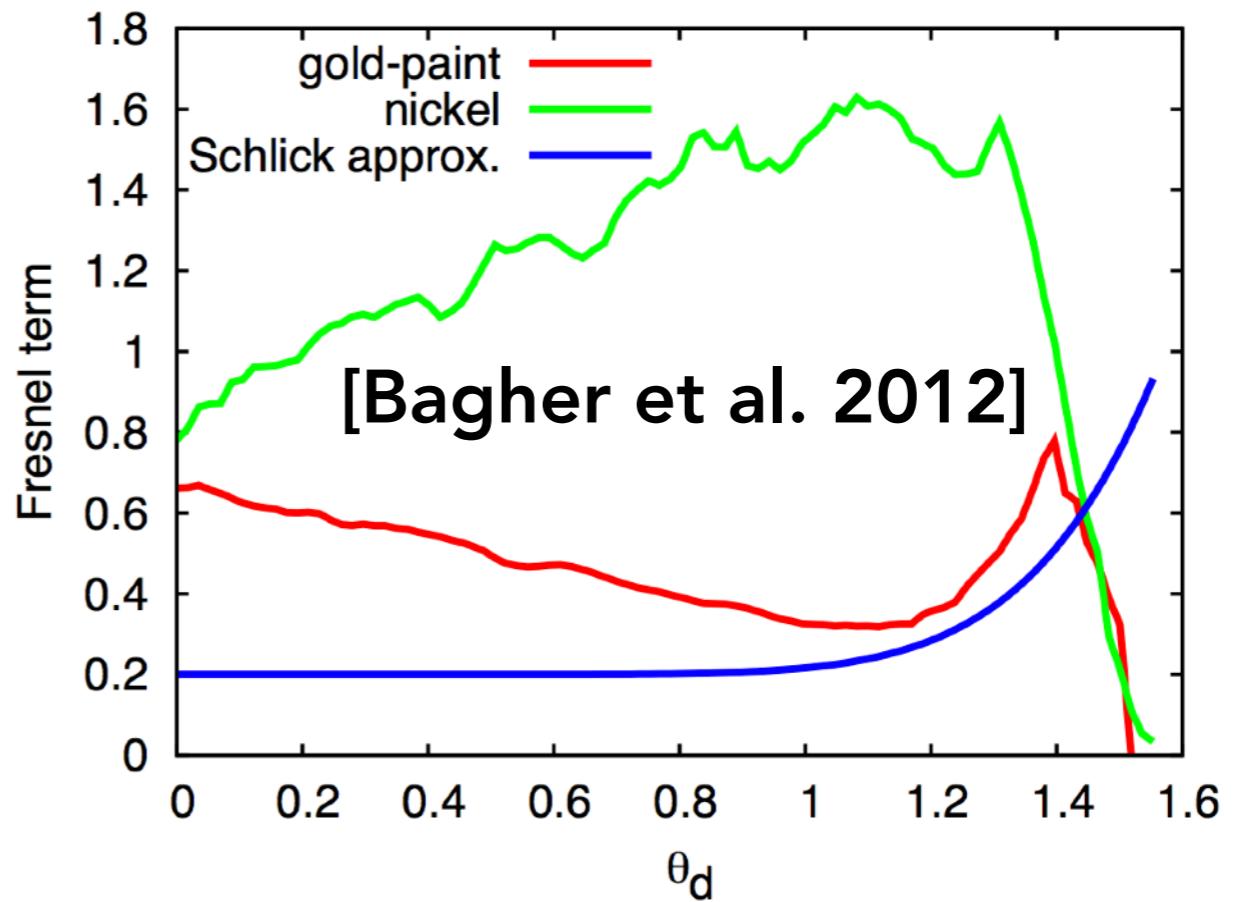
Avoid need to develop / derive models

- Automatically includes all of the scattering effects present

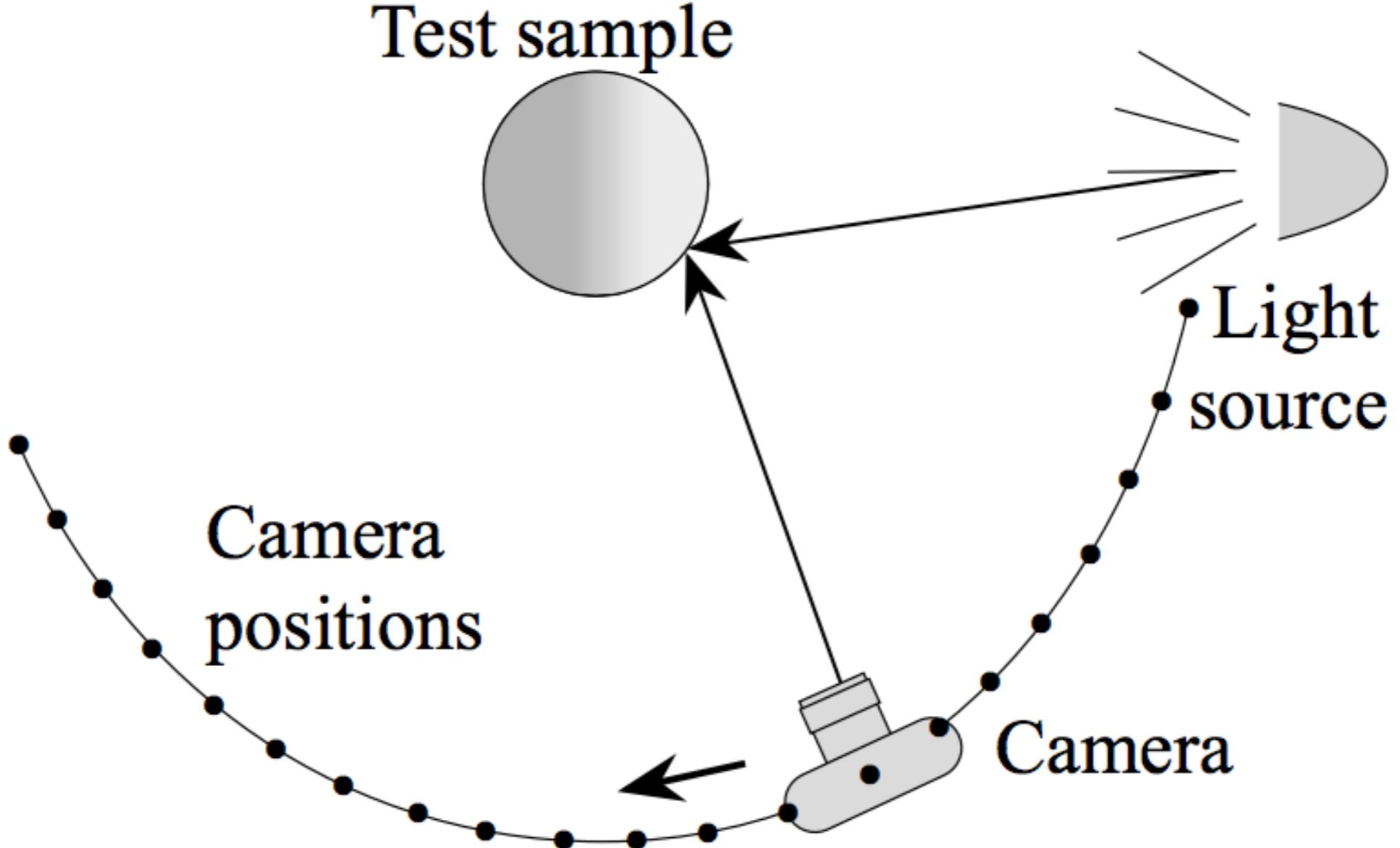
Can accurately render with real-world materials

- Useful for product design, special effects, ...

Theory vs. practice:

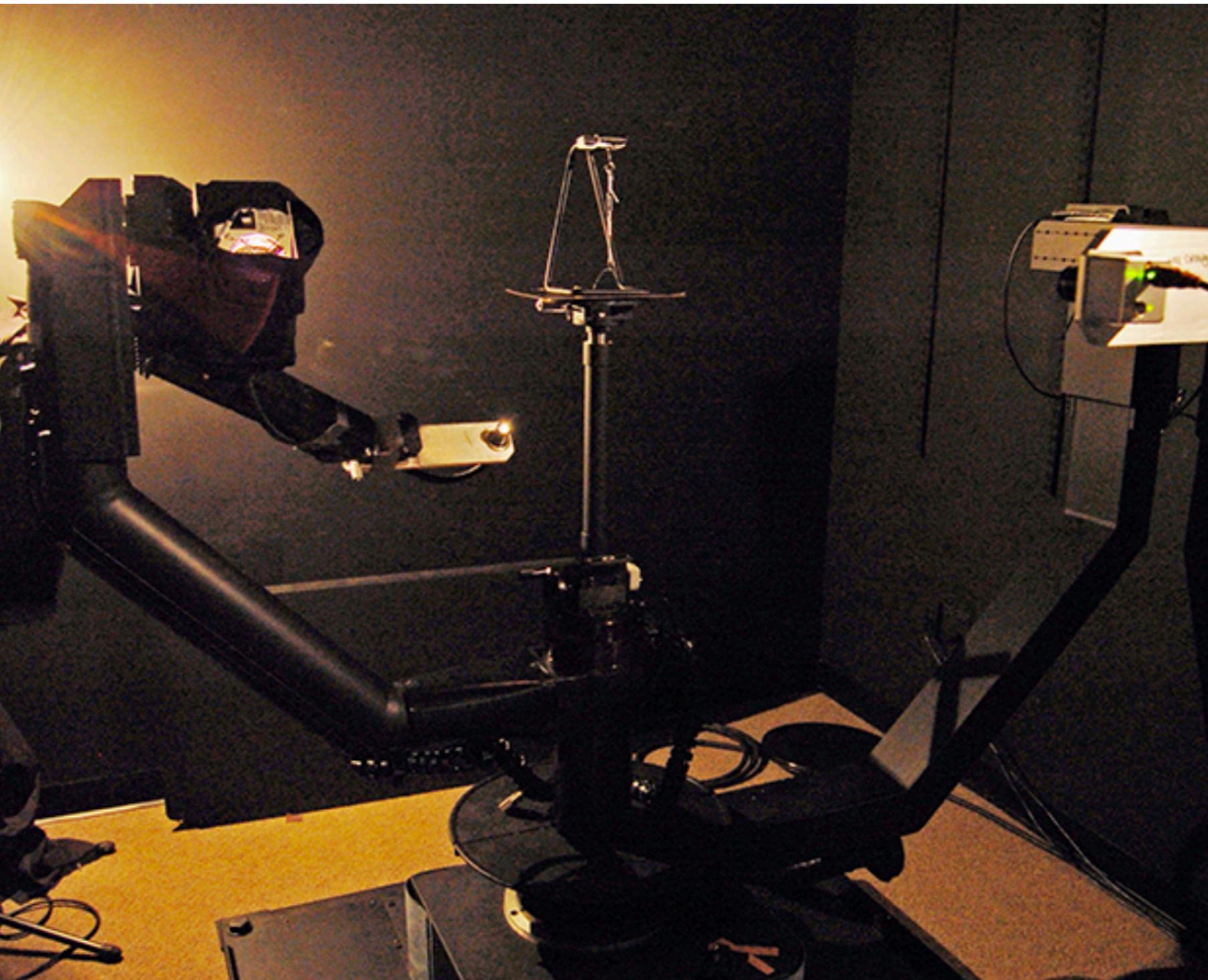


# Image-Based BRDF Measurement



[Marschner et al. 1999]

# Measuring BRDFs: gonioreflectometer



Spherical gantry at UCSD

# Measuring BRDFs

General approach:

```
foreach outgoing direction wo
    move light to illuminate surface with a thin beam from wo
    for each incoming direction wi
        move sensor to be at direction wi from surface
        measure incident radiance
```

Improving efficiency:

- Isotropic surfaces reduce dimensionality from 4D to 3D
- Reciprocity reduces # of measurements by half
- Clever optical systems...

# Challenges in Measuring BRDFs

- Accurate measurements at grazing angles
  - Important due to Fresnel effects
- Measuring with dense enough sampling to capture high frequency specularities
- Retro-reflection
- Spatially-varying reflectance, ...

# Representing Measured BRDFs

## Desirable qualities

- Compact representation
- Accurate representation of measured data
- Efficient evaluation for arbitrary pairs of directions
- Good distributions available for importance sampling

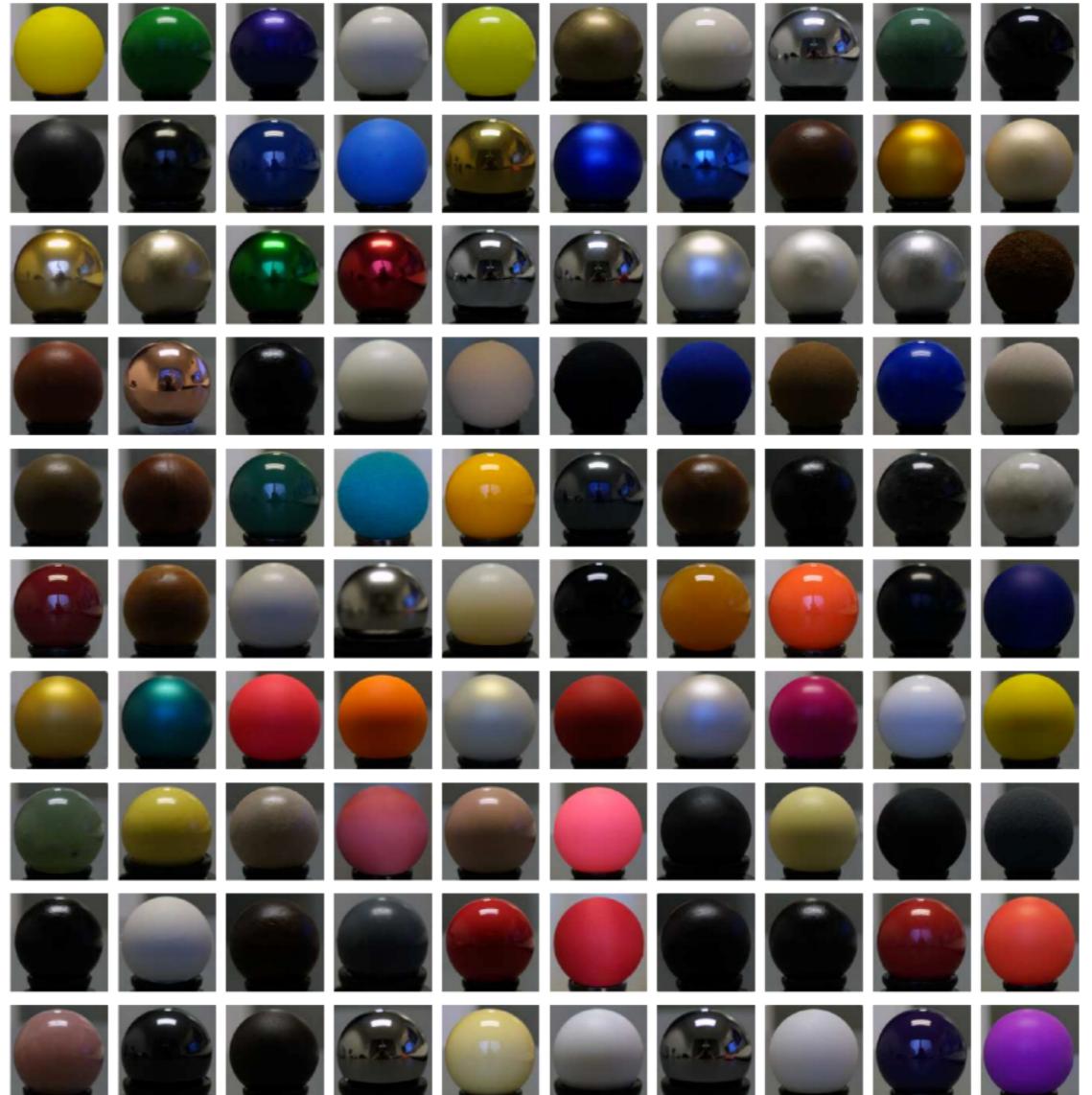
# Tabular Representation

Store regularly-spaced samples in  
 $(\theta_i, \theta_o, |\phi_i - \phi_o|)$

- Better: reparameterize angles to better match specularities

Generally need to resample measured values to table

Very high storage requirements



MERL BRDF Database  
[Matusik et al. 2004]  
90 \* 90 \* 180 measurements

# Thank you!

(And thank Prof. Ravi Ramamoorthi and Prof. Ren Ng for many of the slides!)