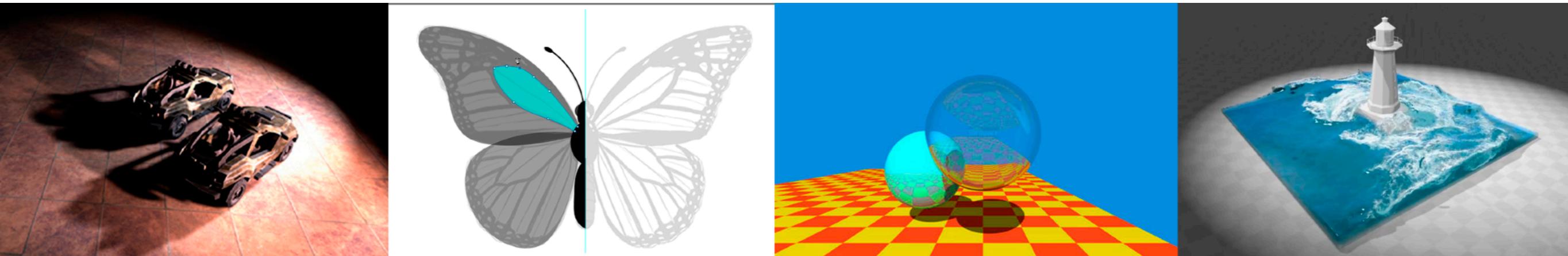


Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 17: Materials and Appearances



Announcements

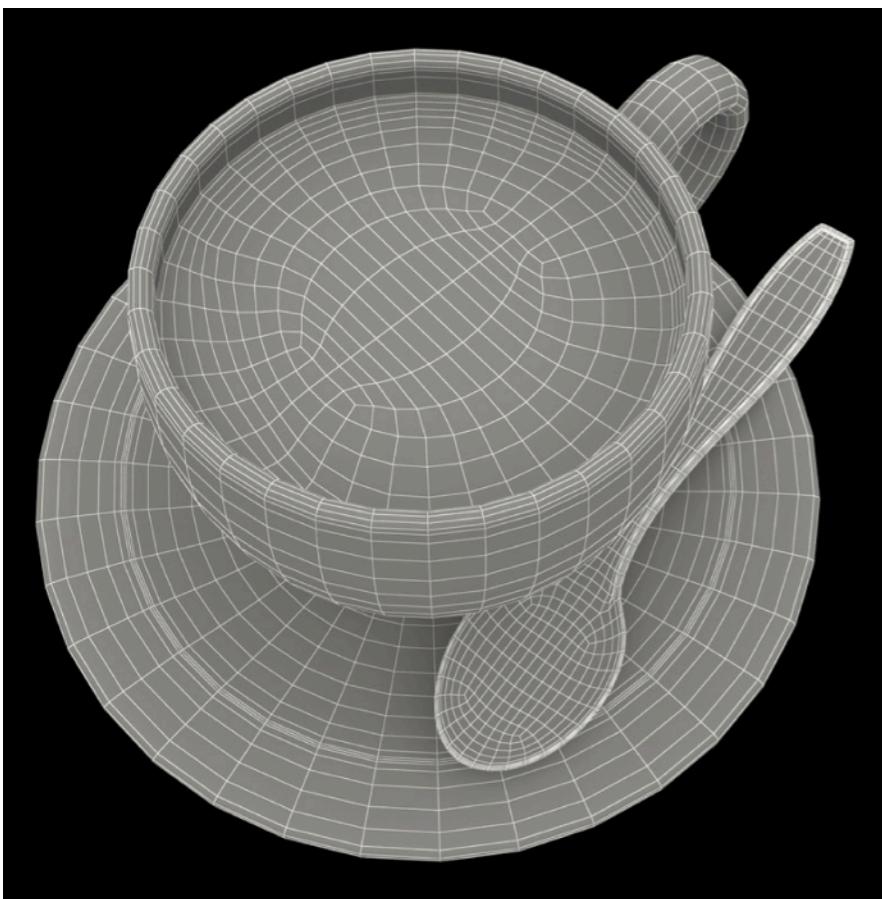
- Homework 6: 82 submissions so far (note: 1.5 weeks for it)
- New assignment on path tracing has been worked out!
 - Followed the pseudocode in the last lecture as much as possible
 - Will be released this Friday
- Final project ideas: to be released soon
- From today: the lectures will be much easier!

The Appearance of Natural Materials



[Courtesy of Prof. Henrik Wann Jensen, UCSD]

What is Material in Computer Graphics?



3D coffee mug model



Rendered

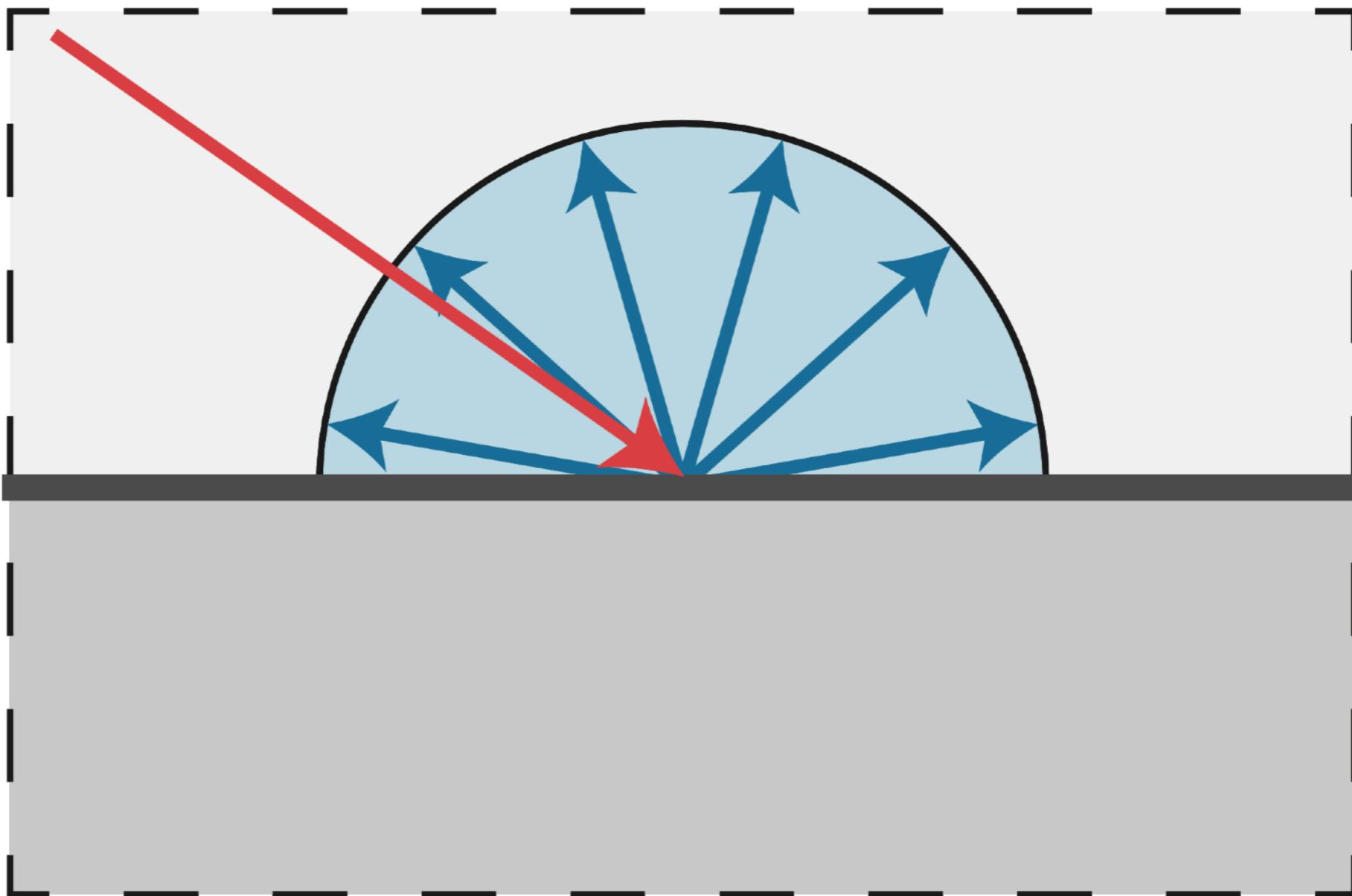


Rendered

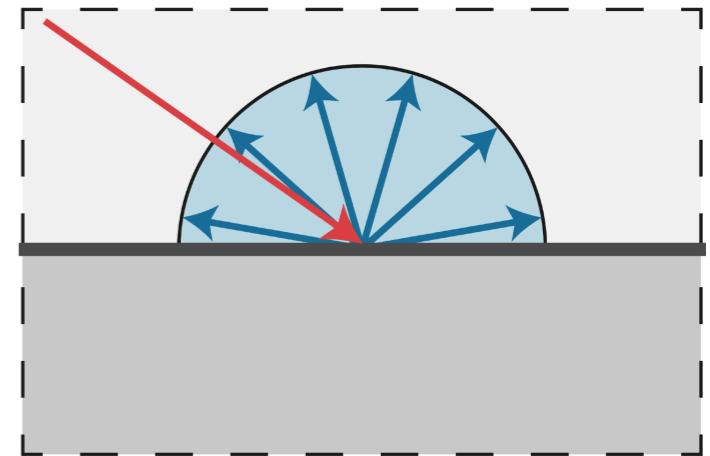
[From TurboSquid, created by artist 3dror]

Material == BRDF

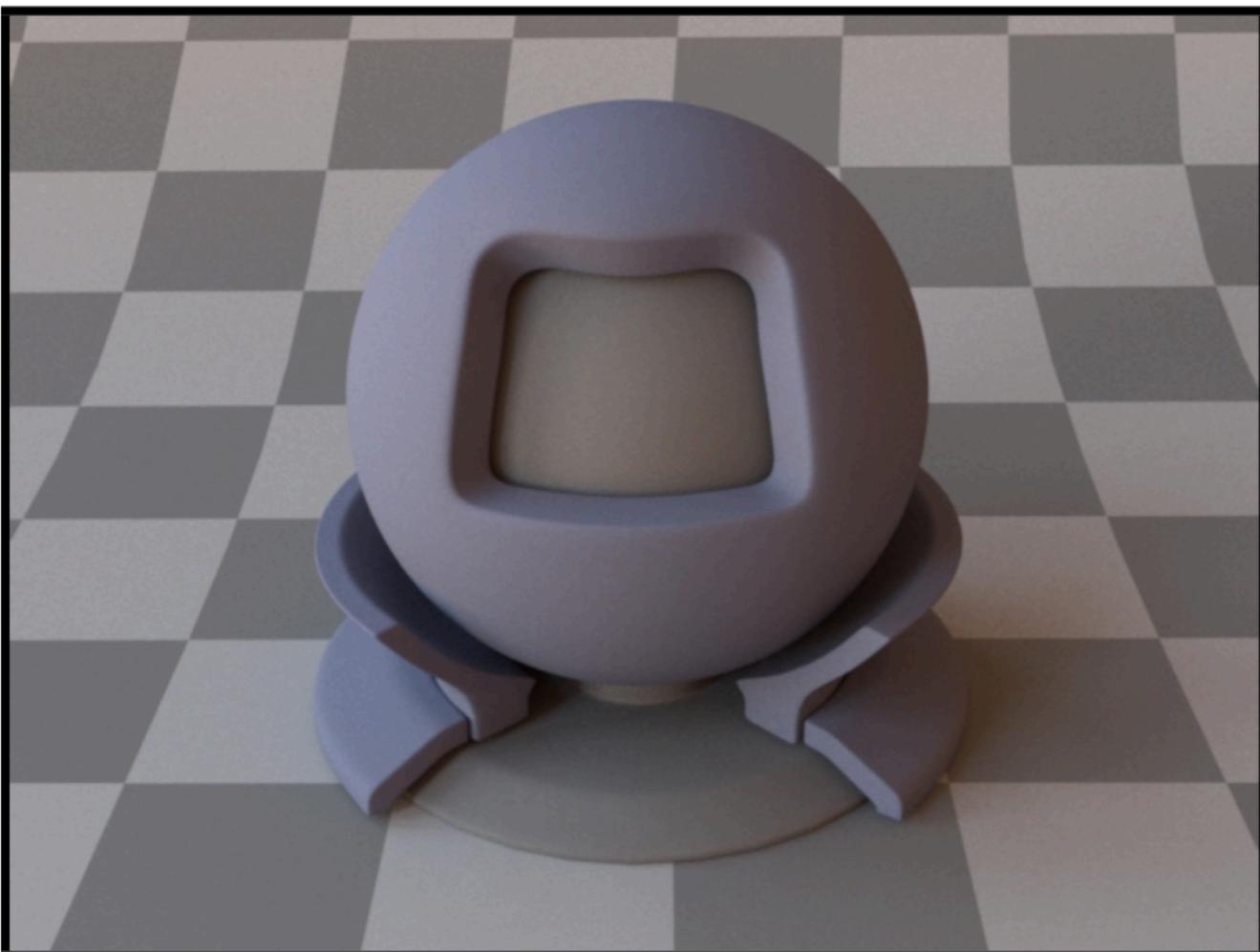
What is this material?



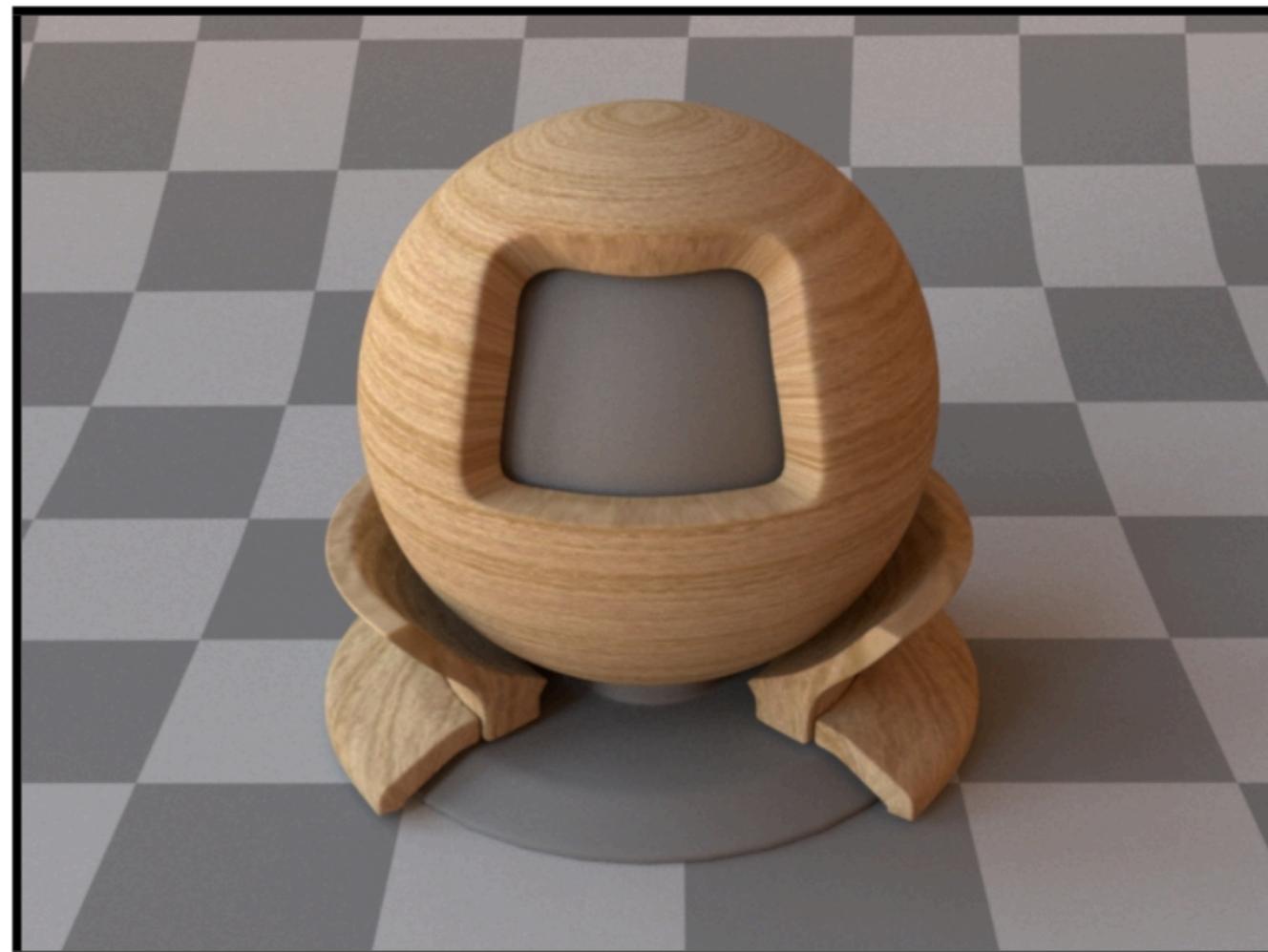
Diffuse / Lambertian Material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]



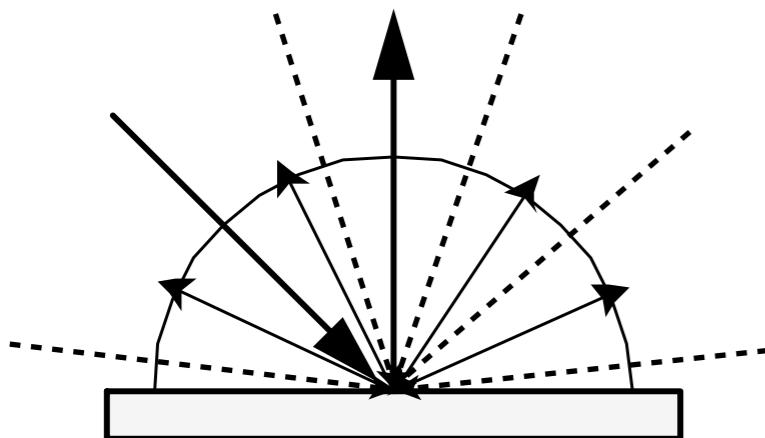
Uniform colored diffuse BRDF



Textured diffuse BRDF

Diffuse / Lambertian Material

Light is equally reflected in each output direction



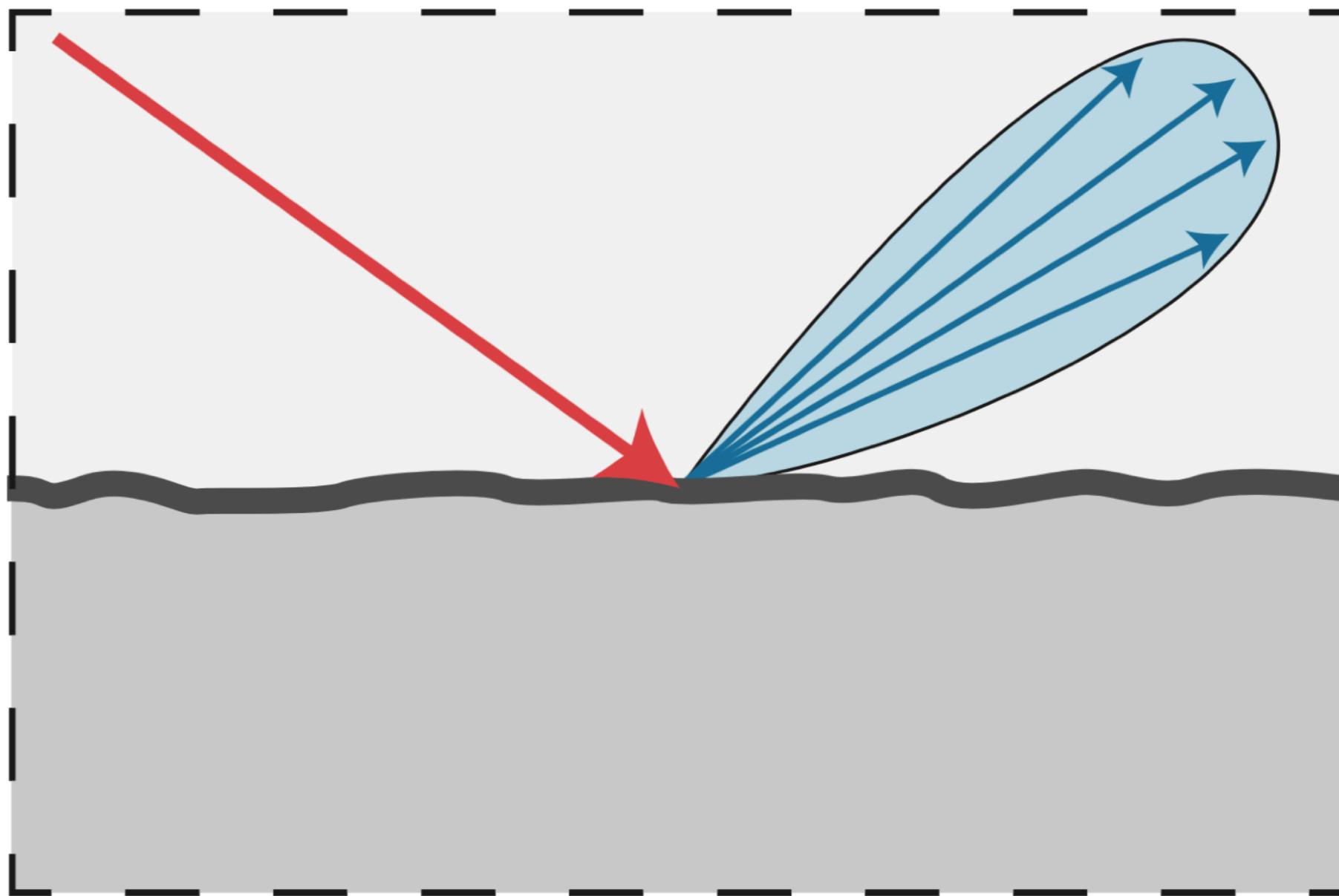
$$f_r = c$$

Suppose the incident lighting is **uniform**:

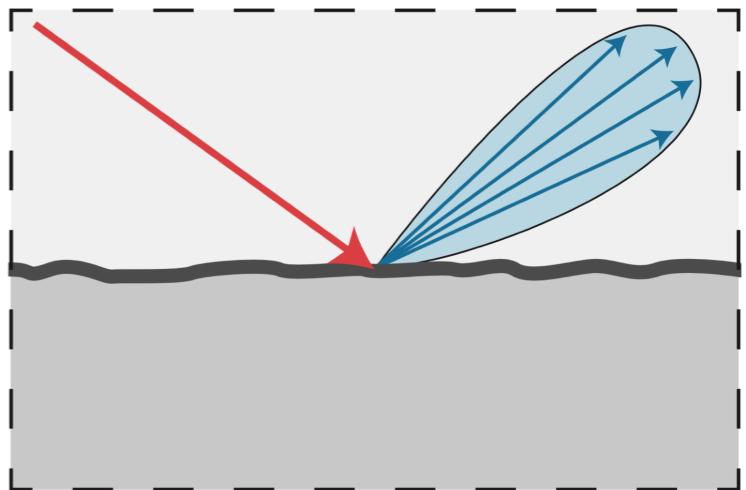
$$\begin{aligned} L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos \theta_i d\omega_i \\ &= f_r L_i \int_{H^2} (\omega_i) \cos \theta_i d\omega_i \\ &= \pi f_r L_i \end{aligned}$$

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

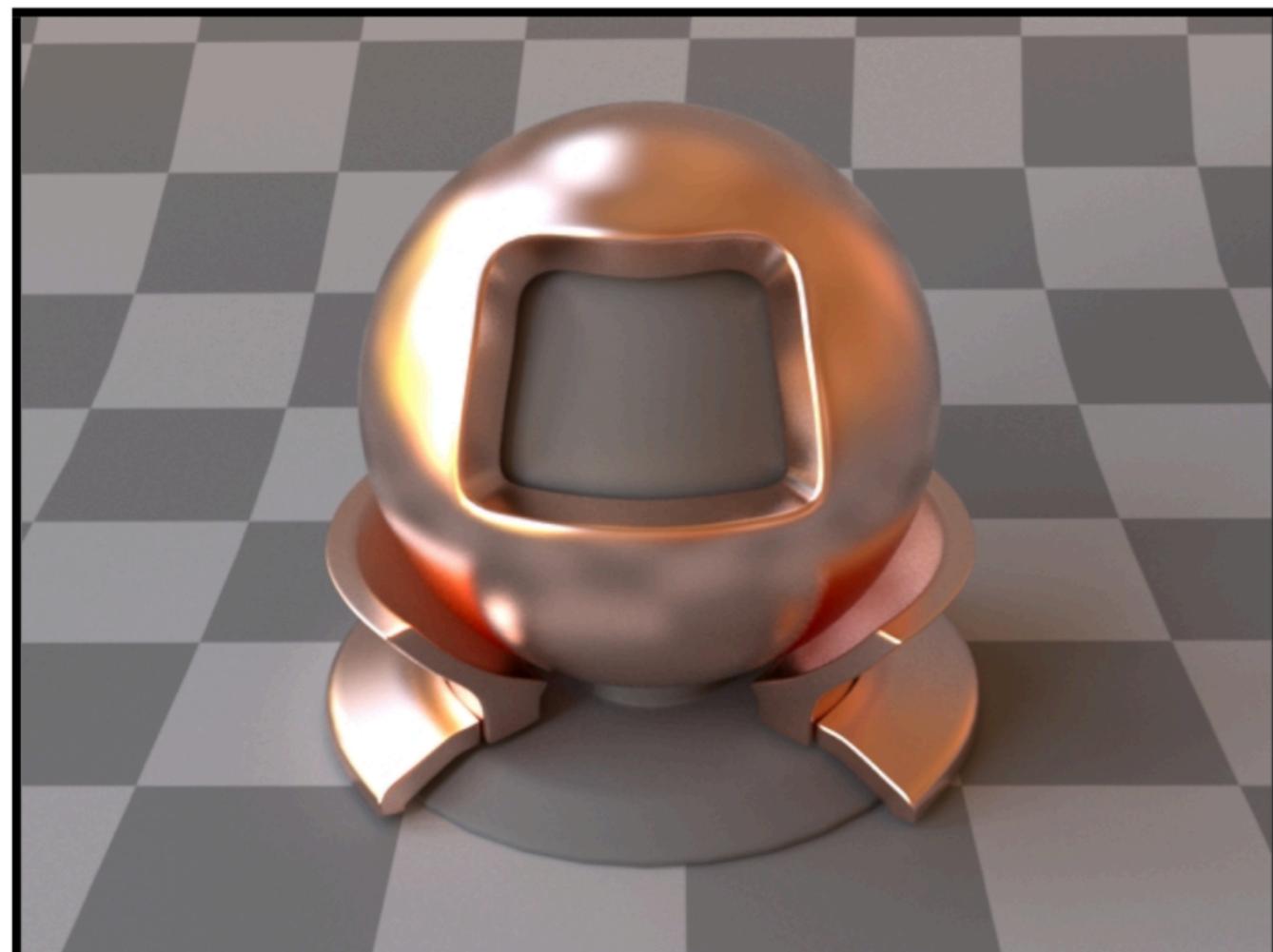
What is this material?



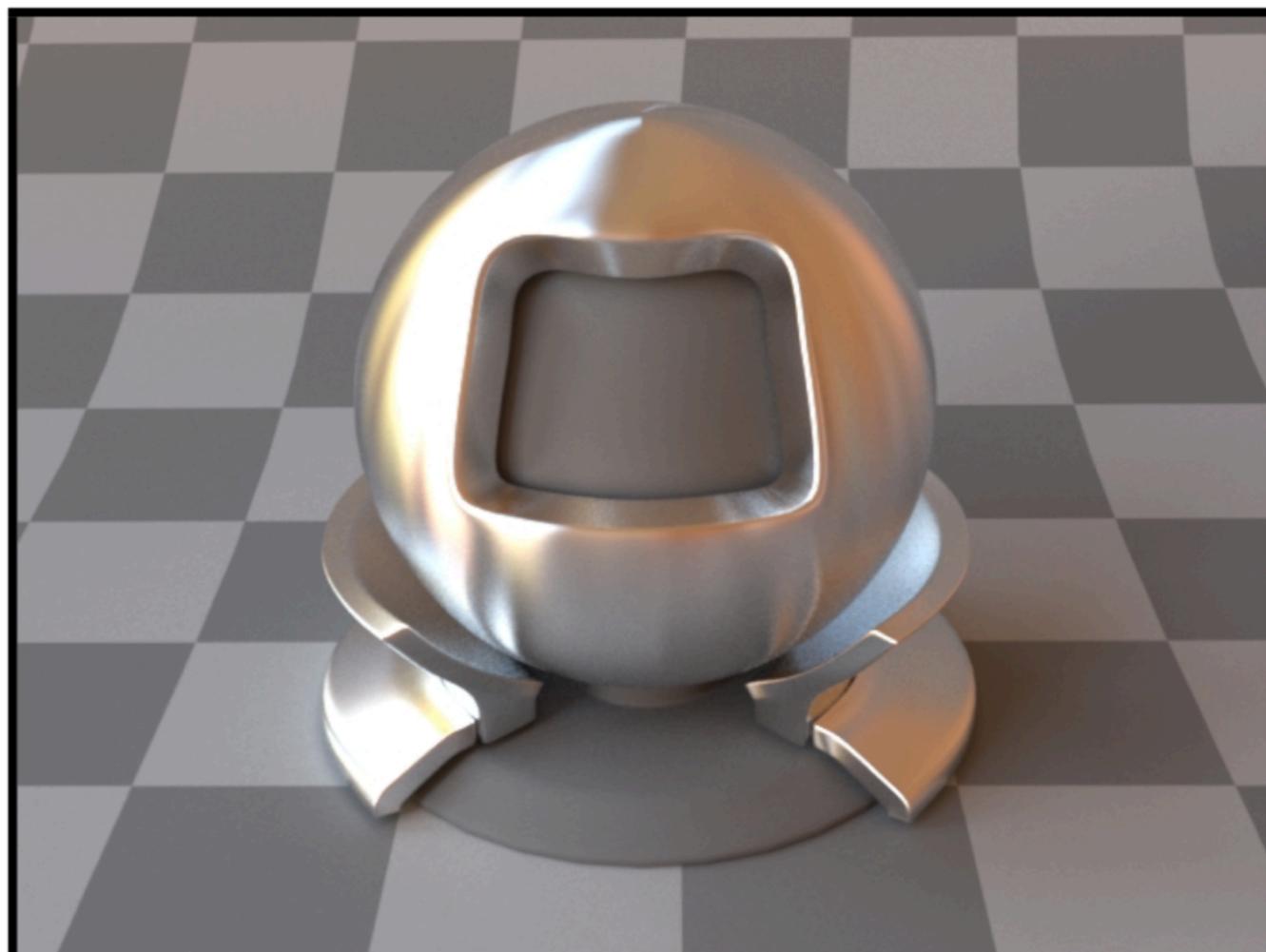
Glossy material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]

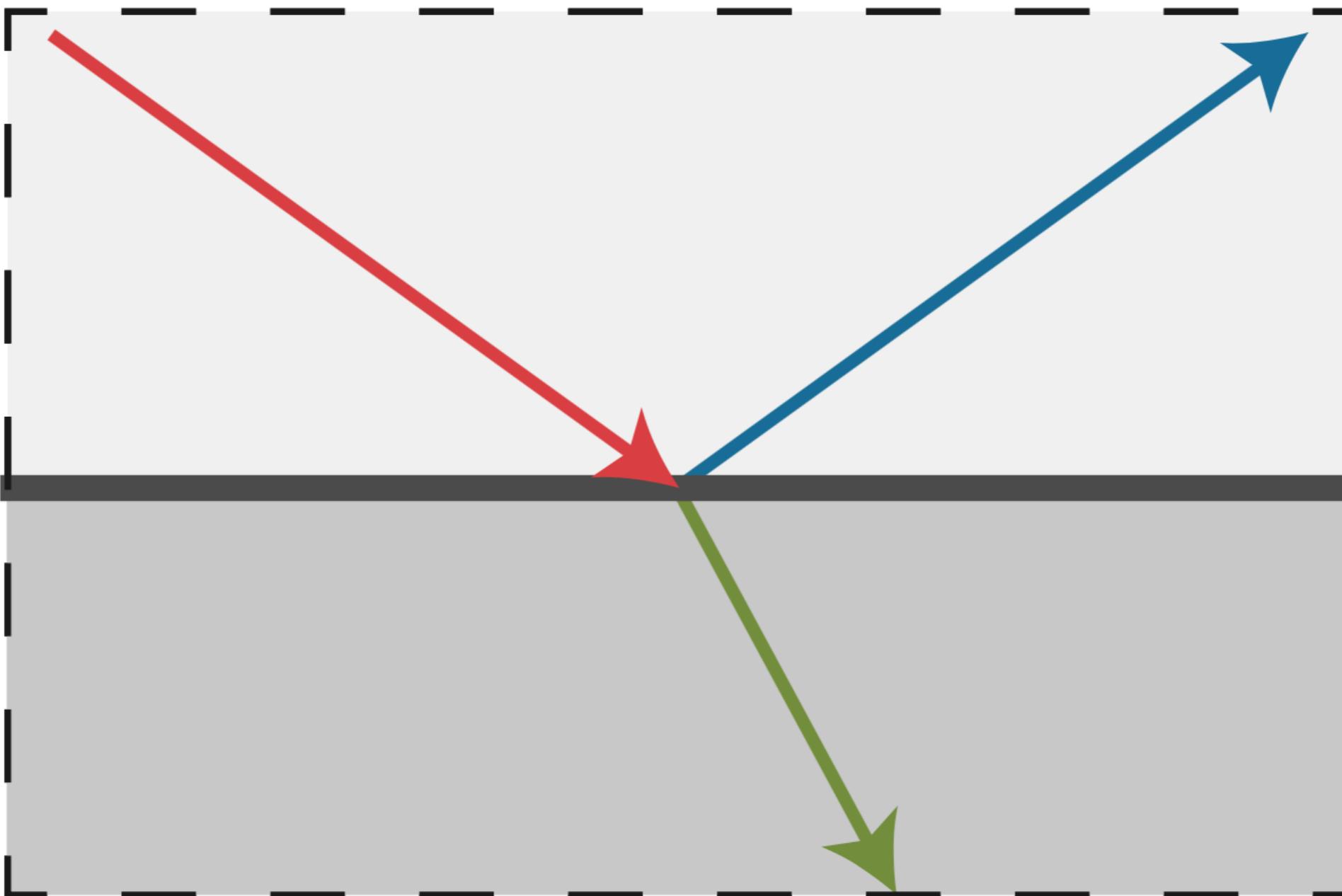


Copper



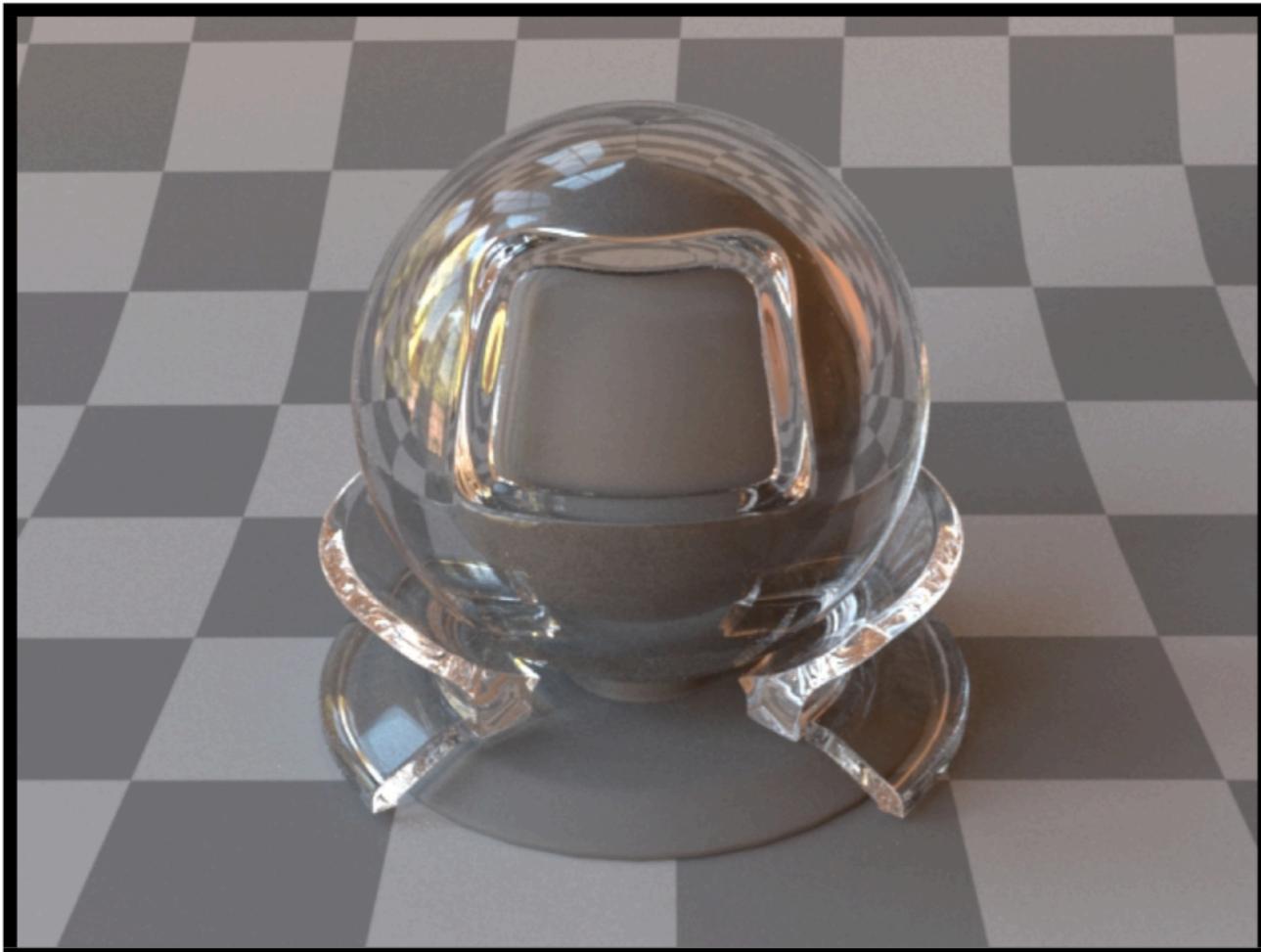
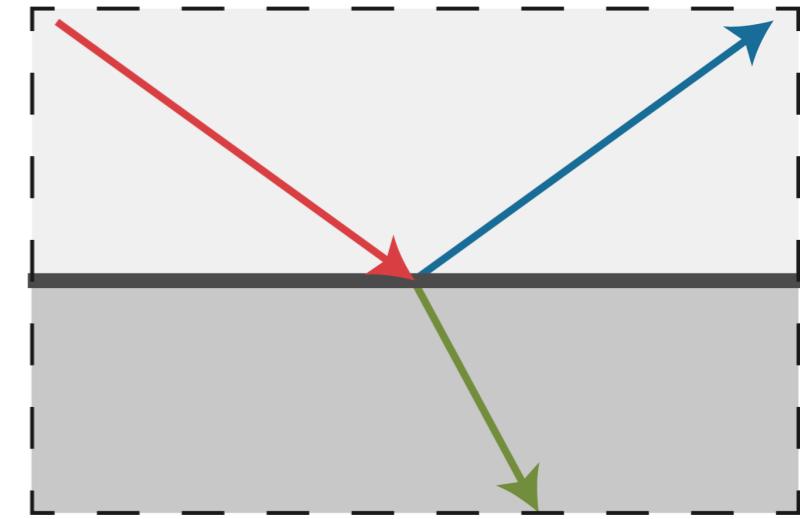
Aluminum

What is this material?

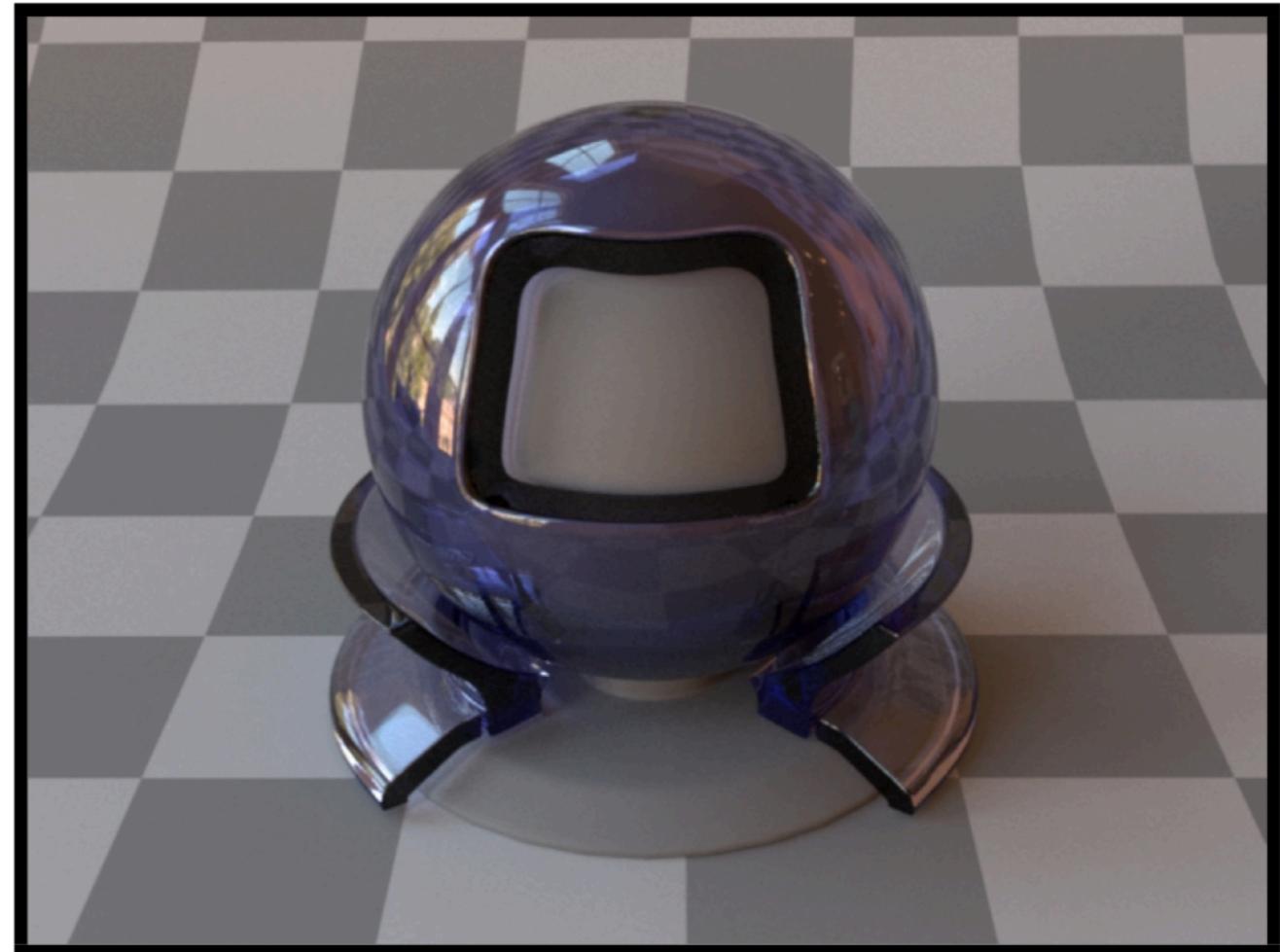


Ideal reflective / refractive material (BSDF*)

[Mitsuba renderer, Wenzel Jakob, 2010]

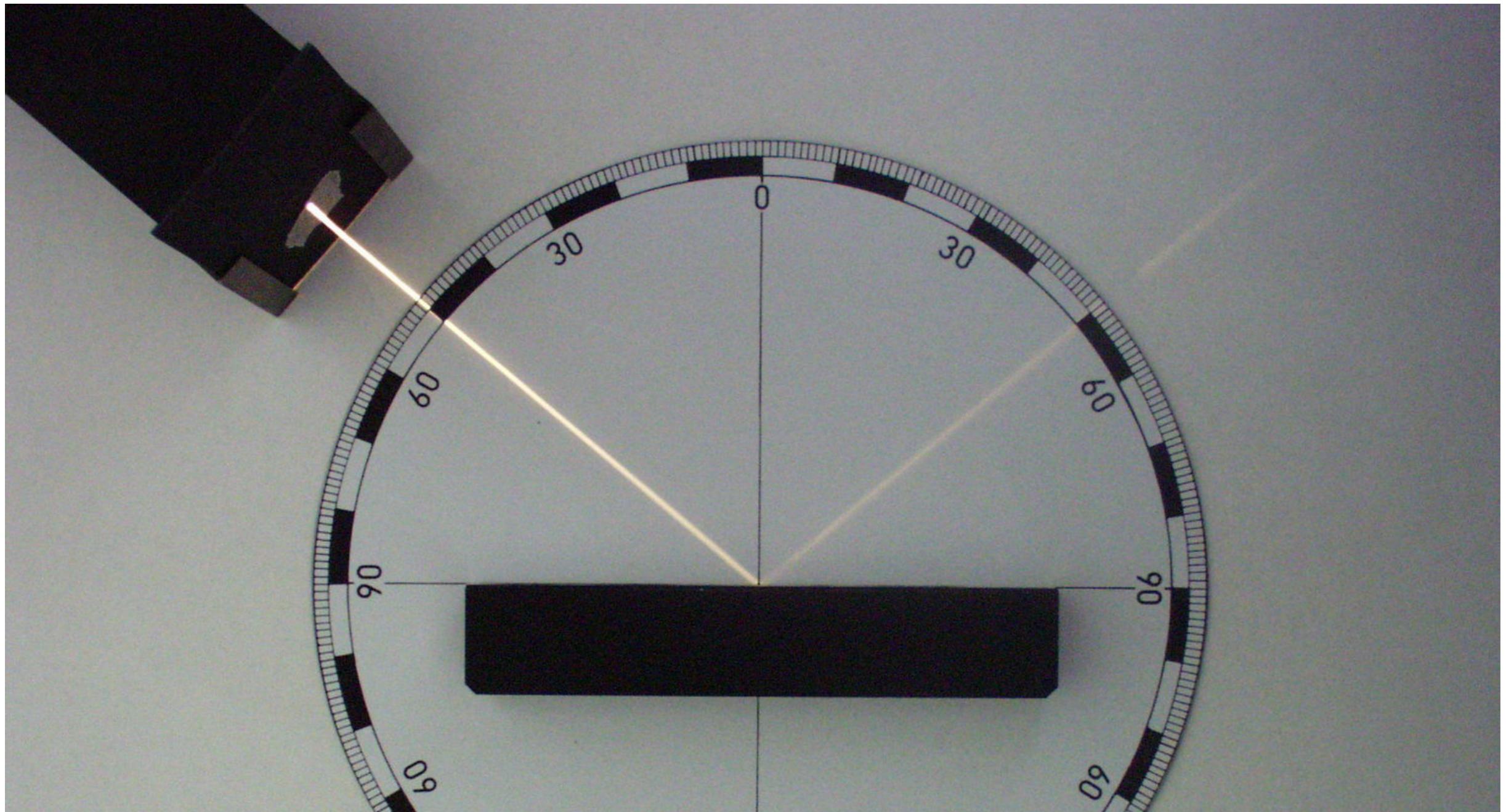


Air <-> water interface



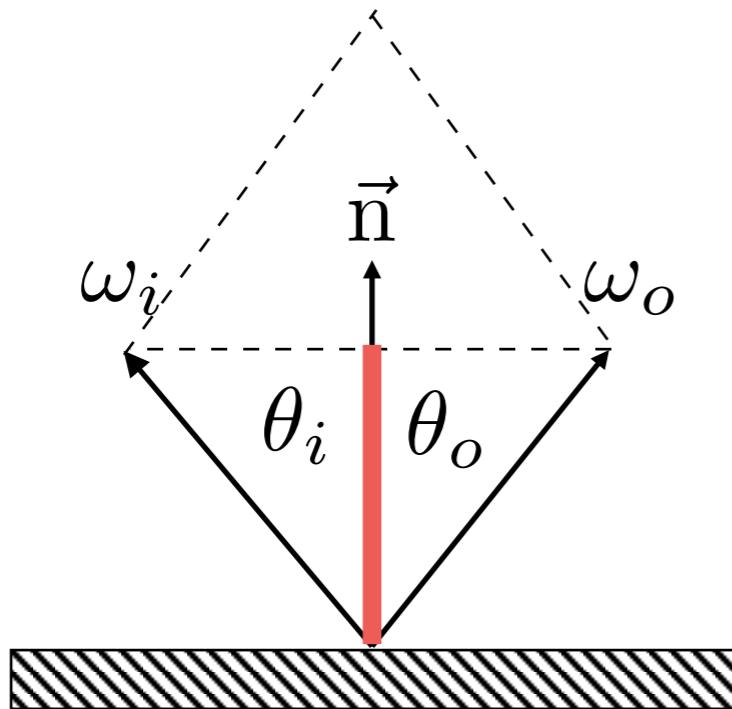
Air <-> glass interface
(with absorption)

Perfect Specular Reflection

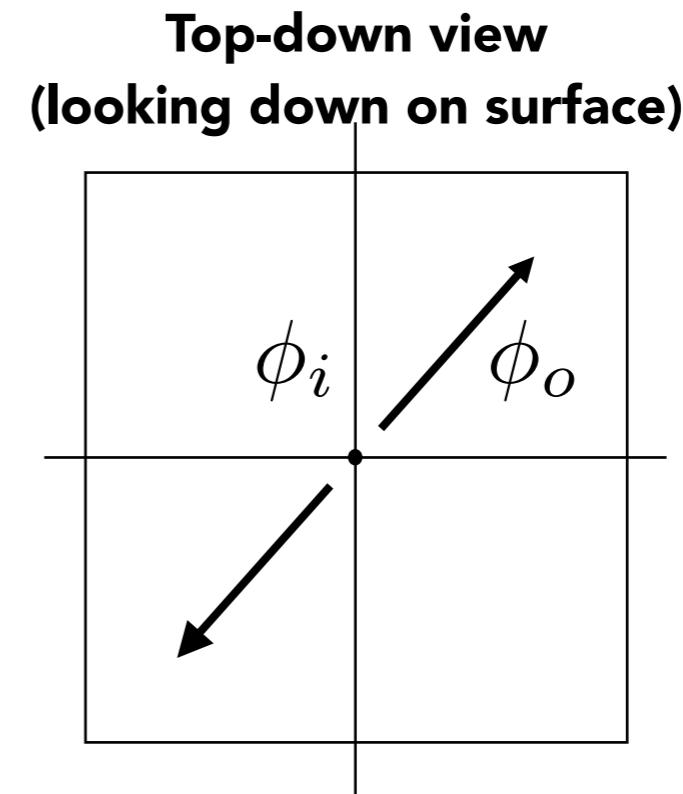


[Zátonyi Sándor]

Perfect Specular Reflection



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

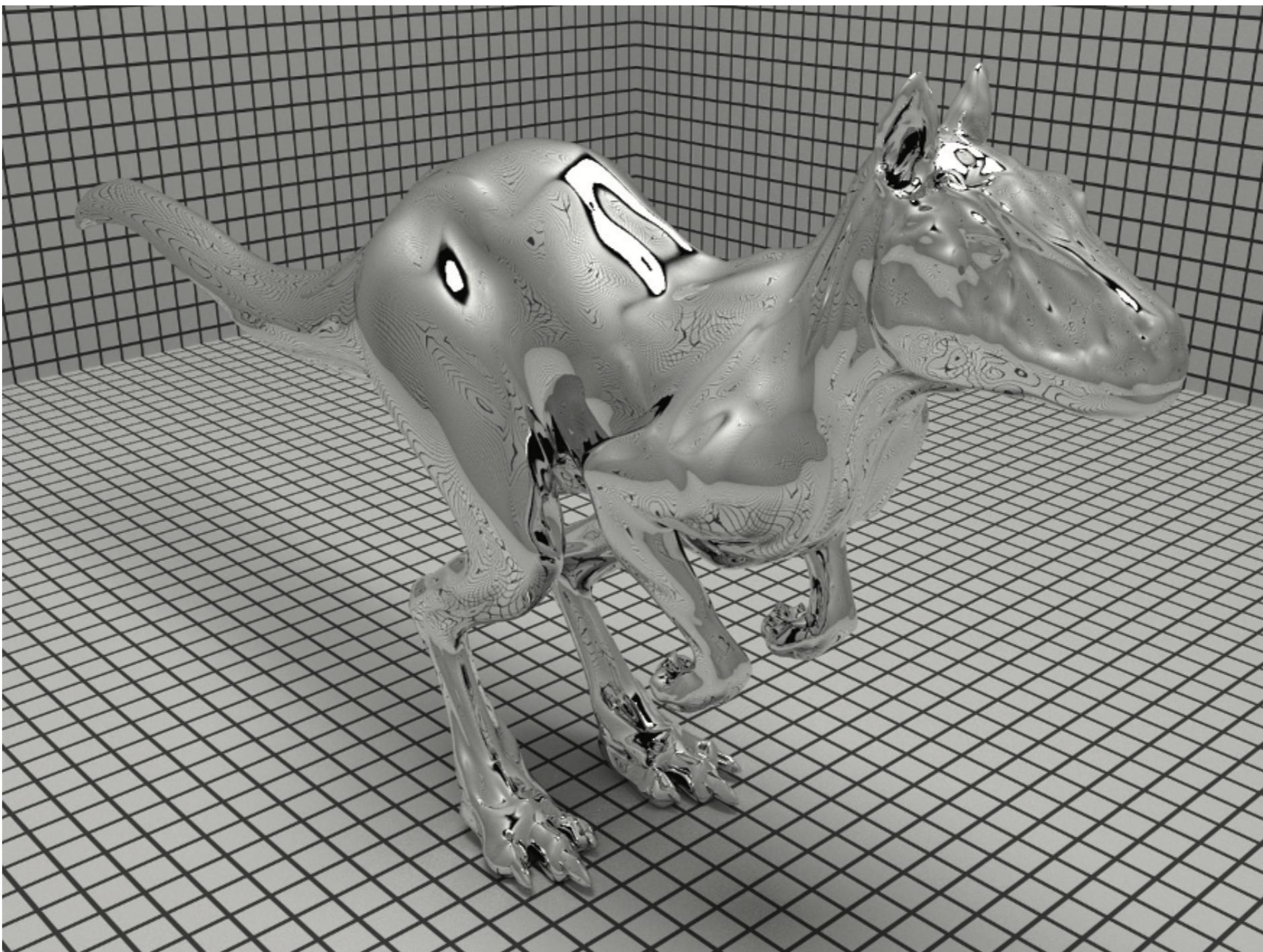


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Perfect Specular Reflection BRDF

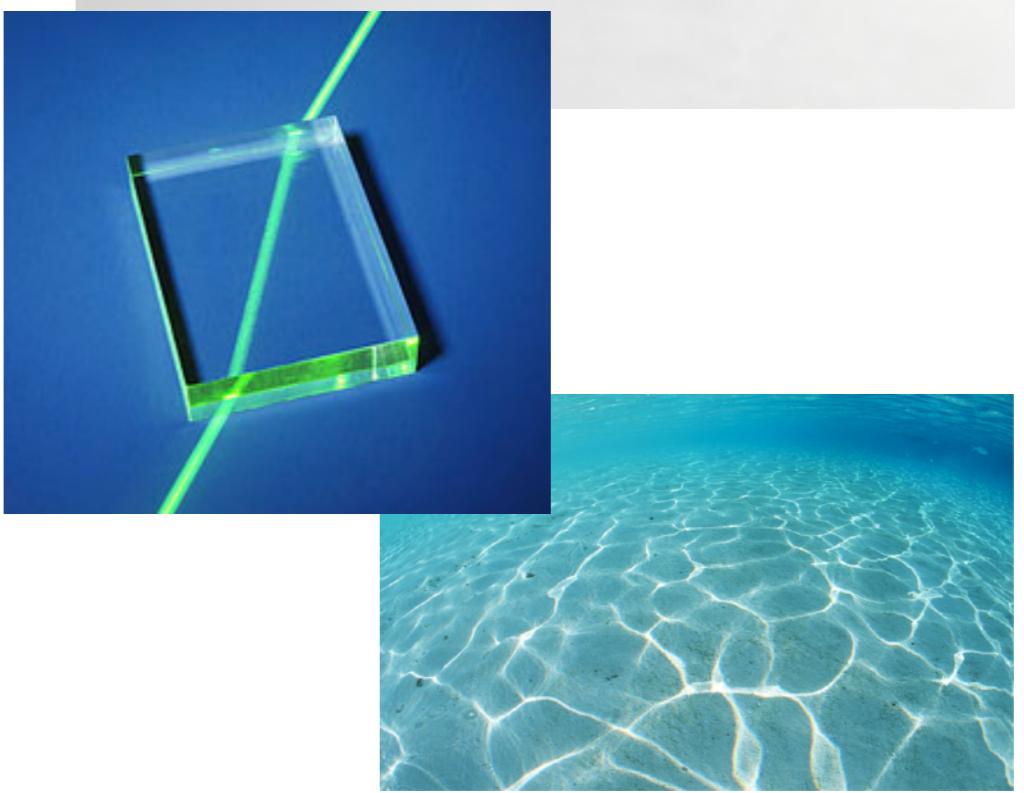


PBRT

Specular Refraction

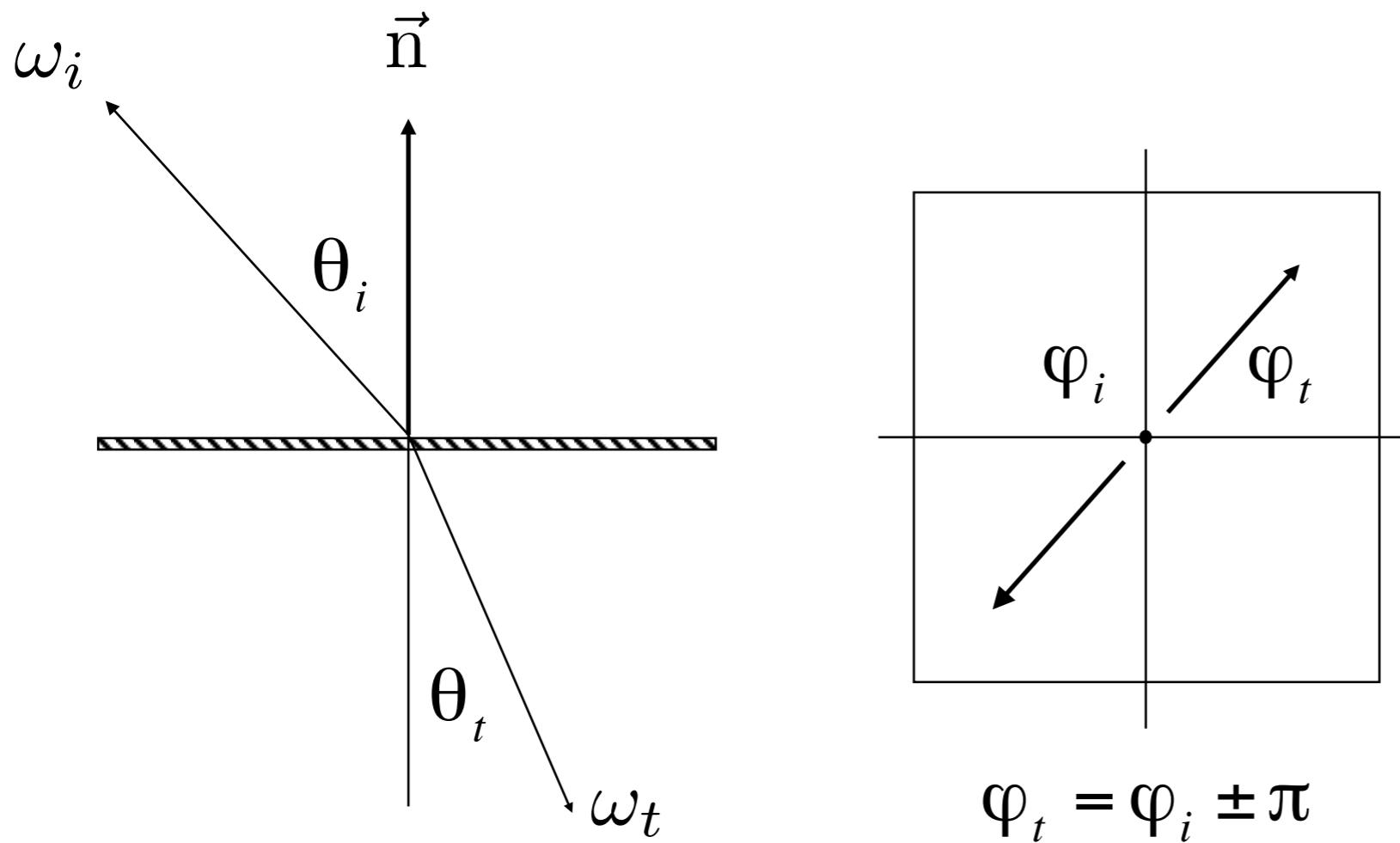
In addition to reflecting off surface, light may be transmitted through surface.

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

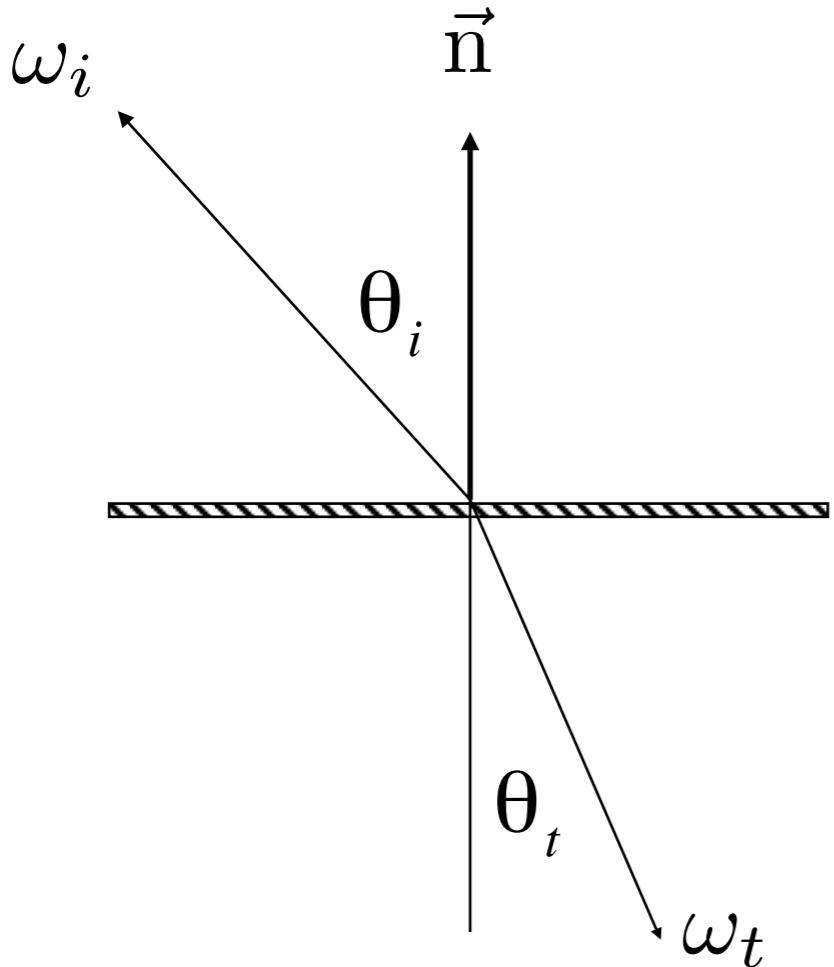


$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

Medium	η^*
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



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

$$\cos \theta_t = \sqrt{1 - \sin^2 \theta_t}$$

$$= \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 \sin^2 \theta_i}$$

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

Total internal reflection:

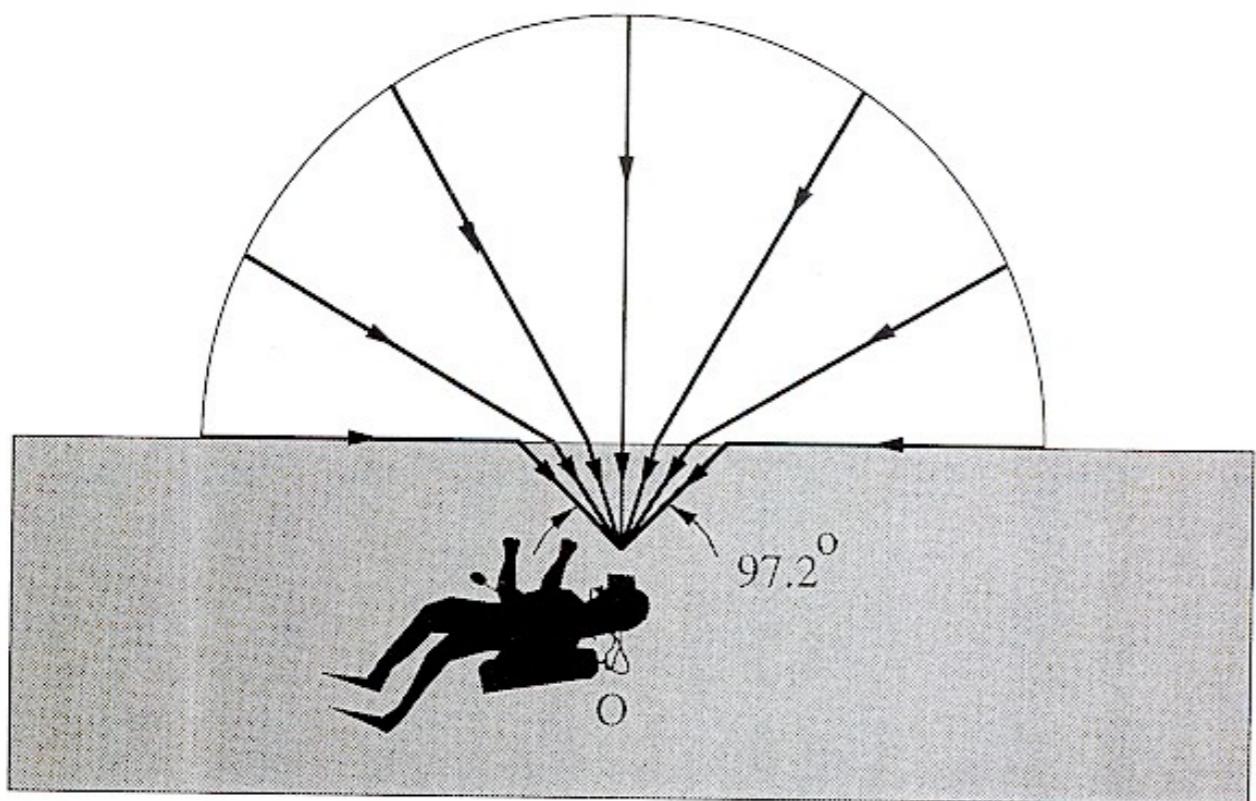
$$1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2 \theta_i) < 0$$

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)

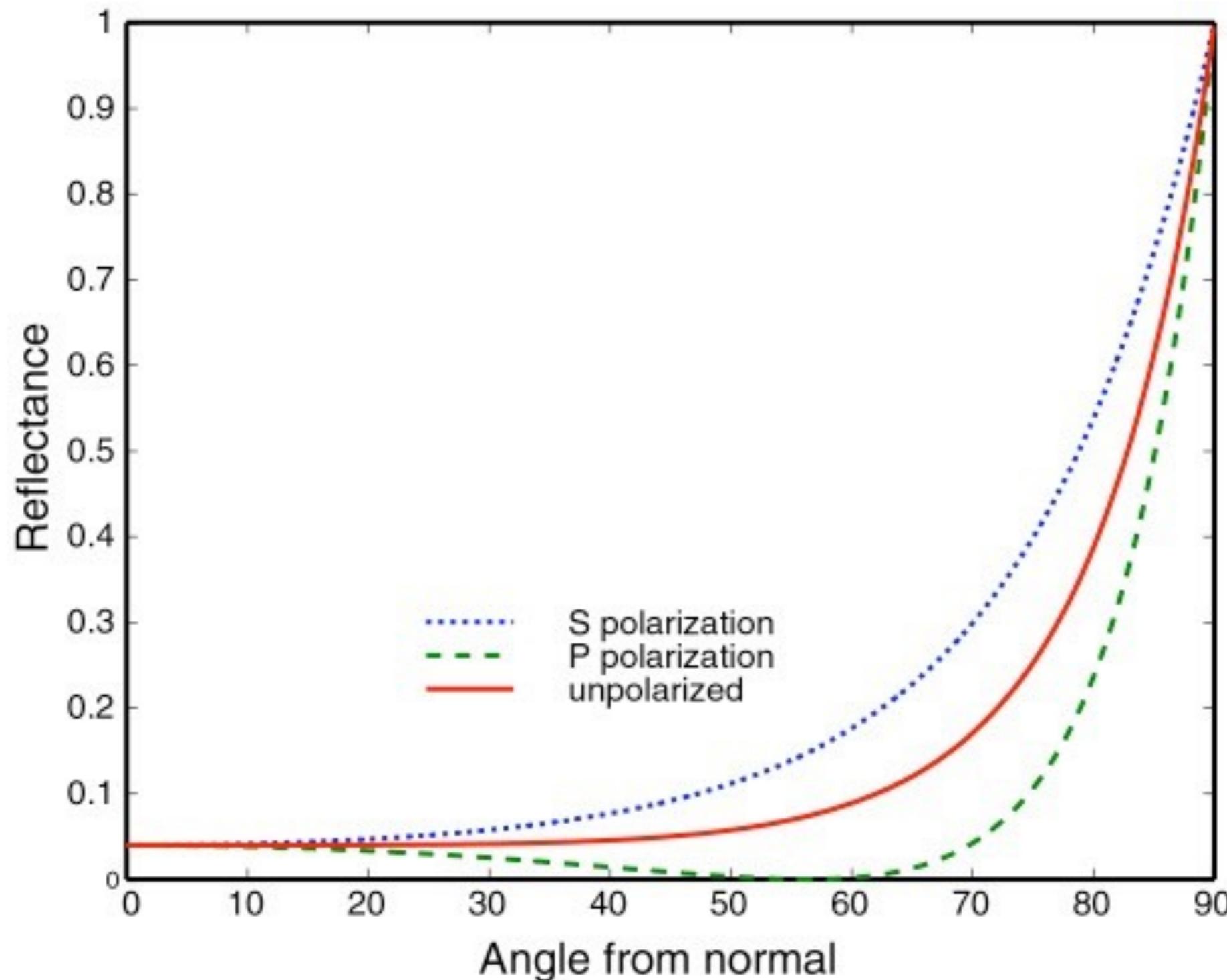
Reflectance depends on incident angle (and polarization of light)



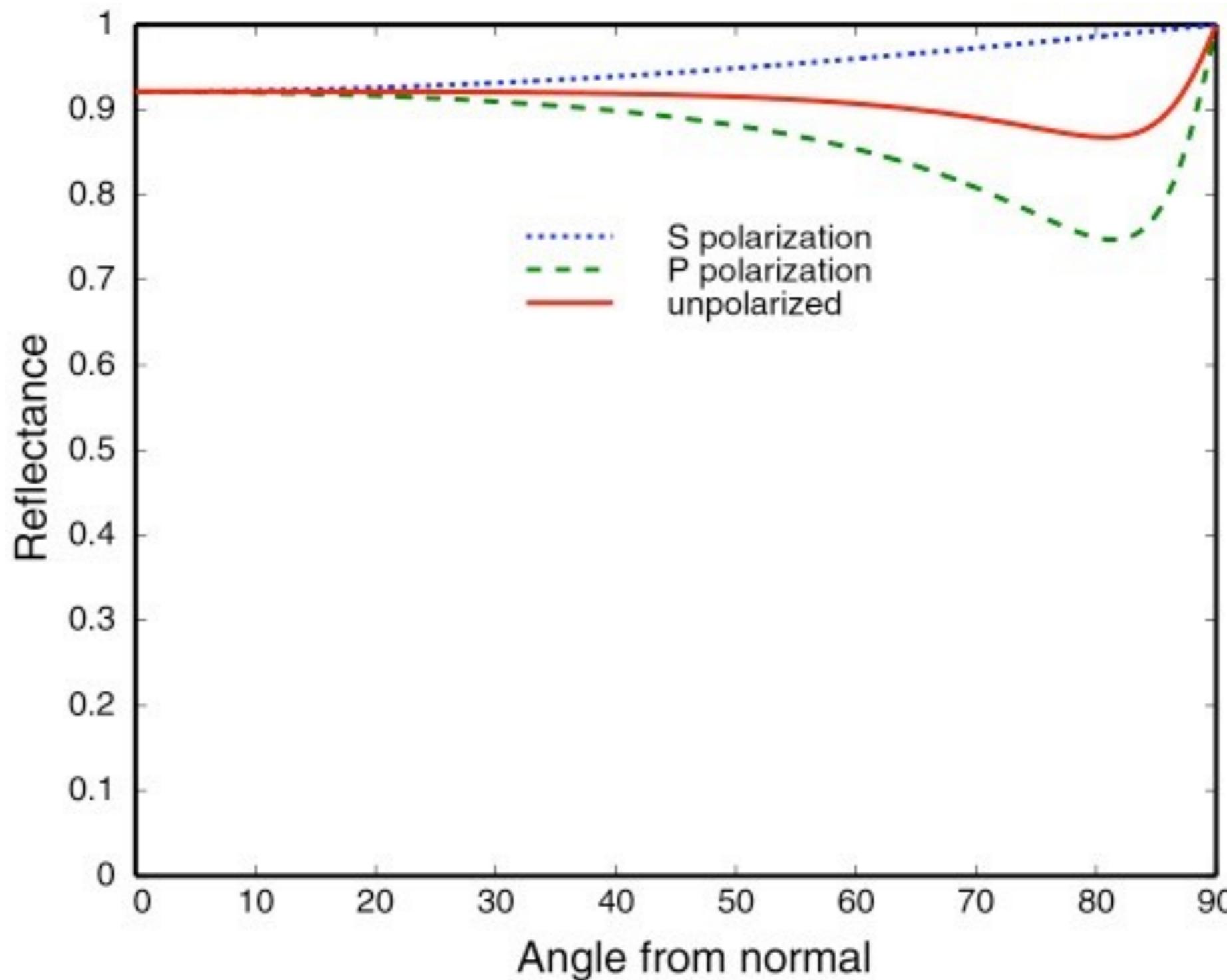
This example: reflectance increases with grazing angle

[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

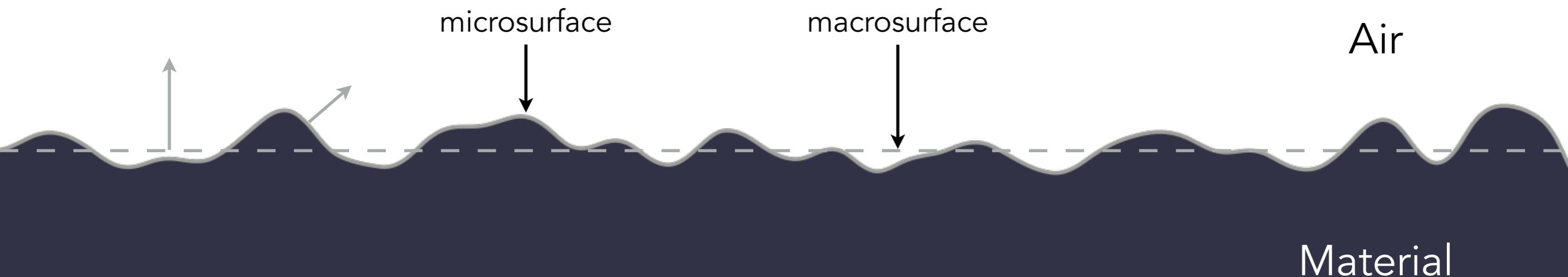
Microfacet Theory

Rough surface

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

Individual elements of surface act like **mirrors**

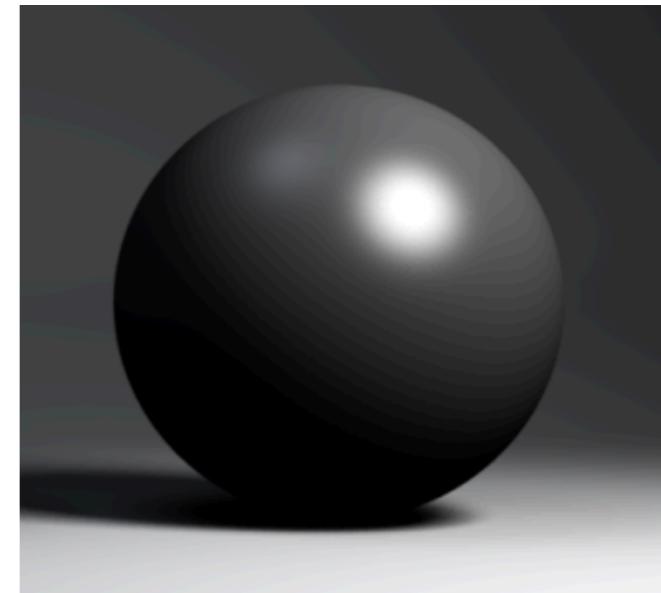
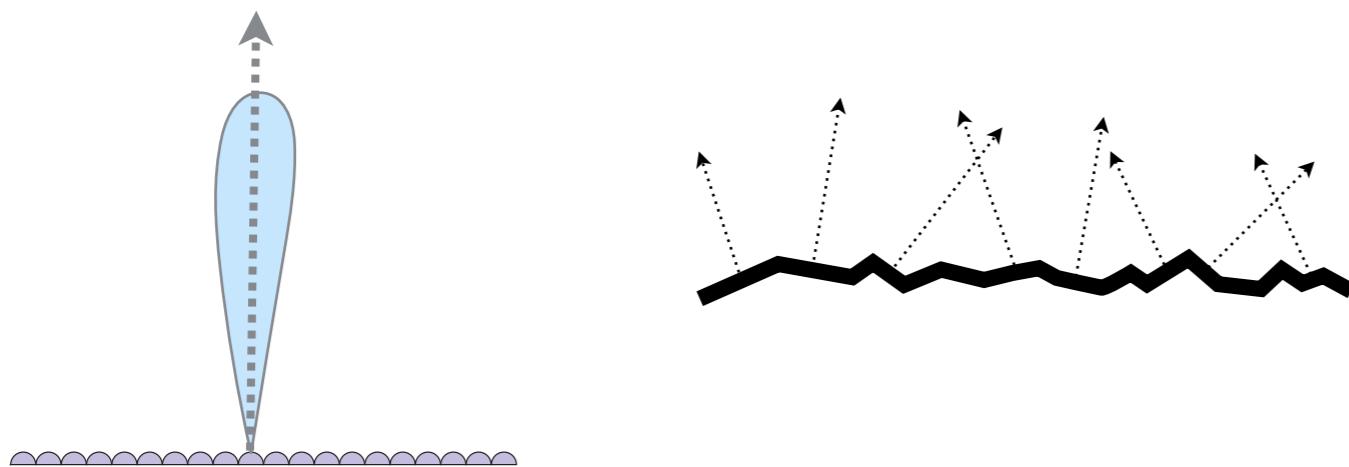
- Known as Microfacets
- Each microfacet has its own normal



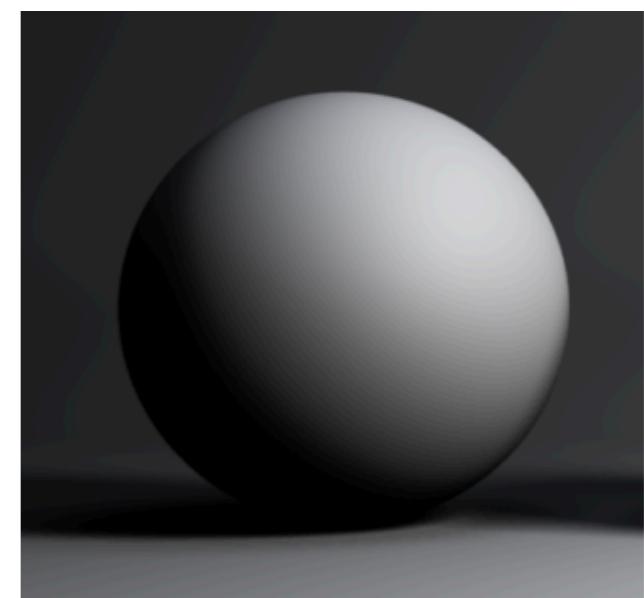
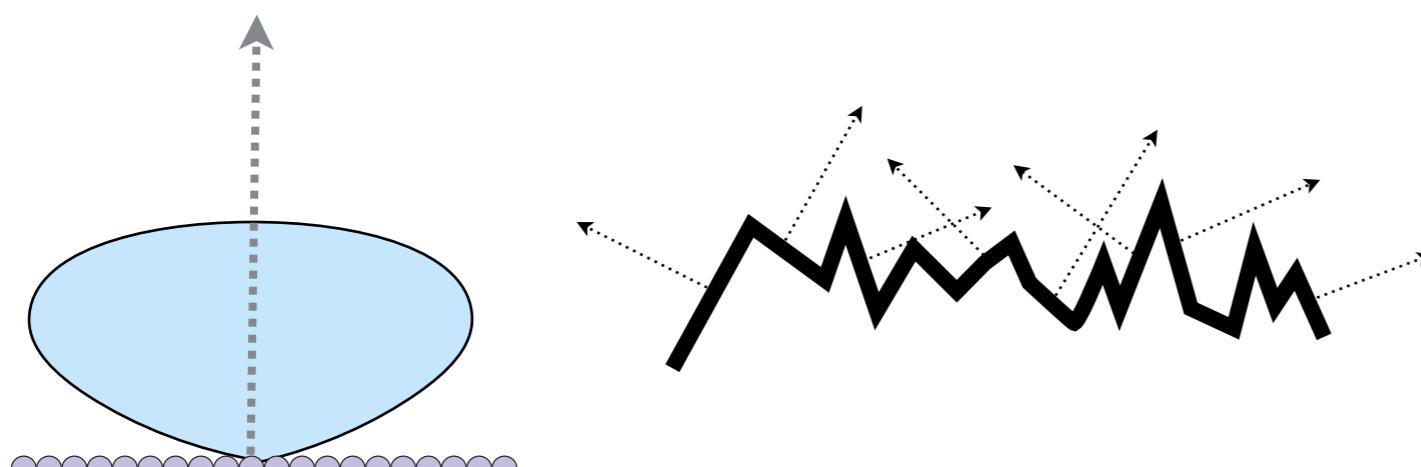
Microfacet BRDF

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

- Concentrated \Leftrightarrow glossy

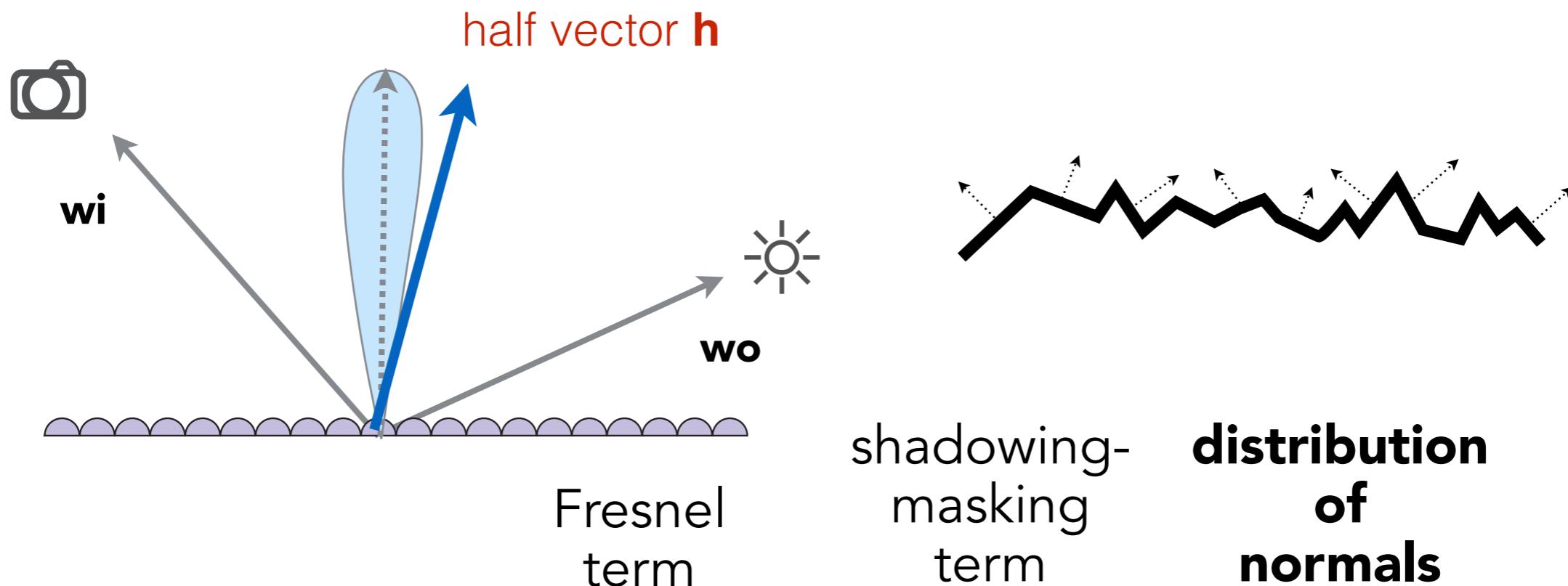


- Spread \Leftrightarrow diffuse



Microfacet BRDF

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



$$f(\mathbf{i}, \mathbf{o}) = \frac{\mathbf{F}(\mathbf{i}, \mathbf{h})\mathbf{G}(\mathbf{i}, \mathbf{o}, \mathbf{h})\mathbf{D}(\mathbf{h})}{4(n, \mathbf{i})(n, \mathbf{o})}$$

Microfacet BRDF: Examples



[Autodesk Fusion 360]

Isotropic / Anisotropic Materials (BRDFs)



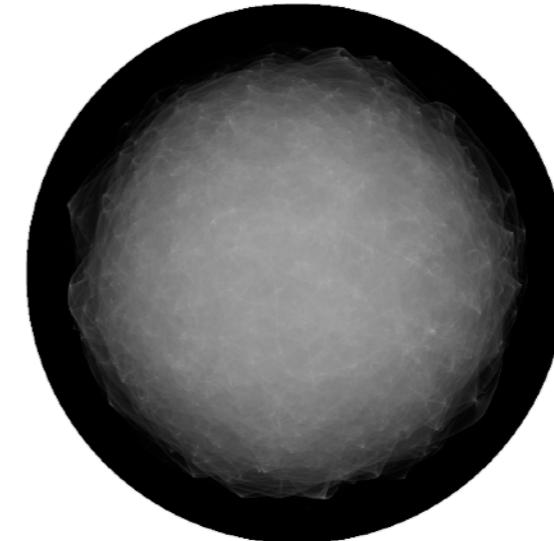
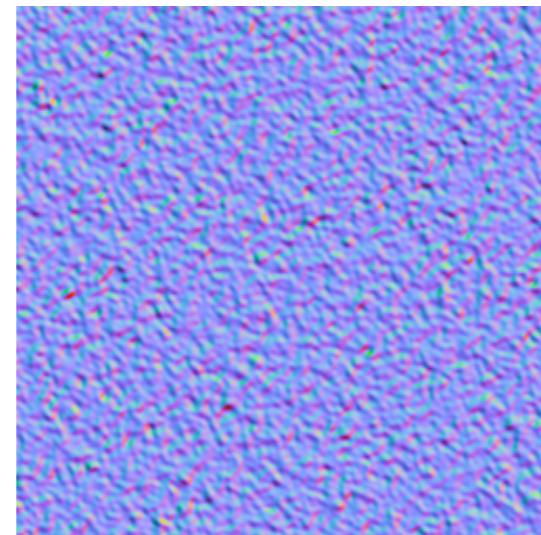
Inside an elevator

Slide courtesy of Prof. Ren Ng, UC Berkeley

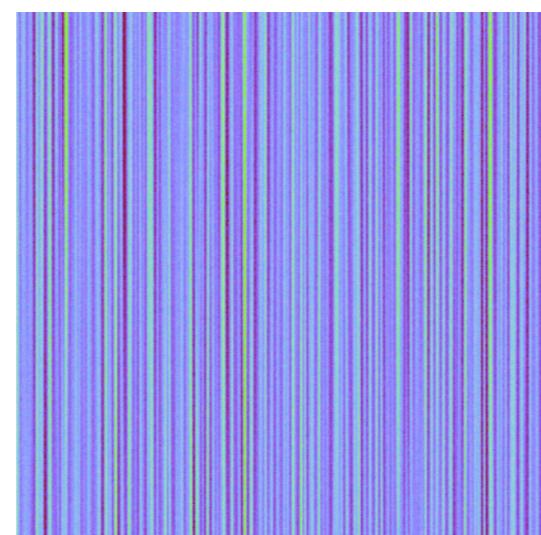
Isotropic / Anisotropic Materials (BRDFs)

- Key: **directionality** of underlying surface

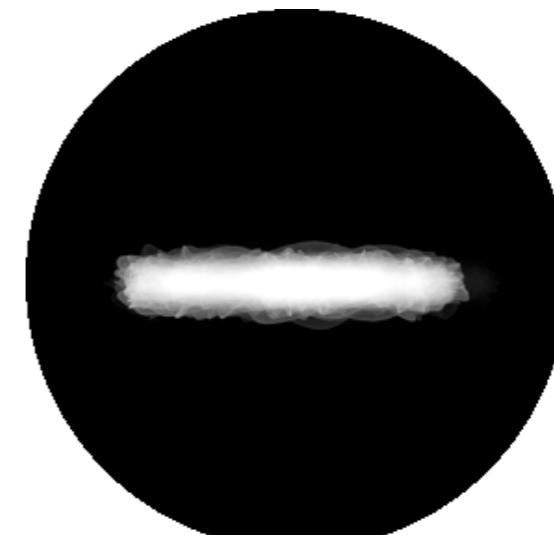
Isotropic



Anisotropic



Surface (normals)



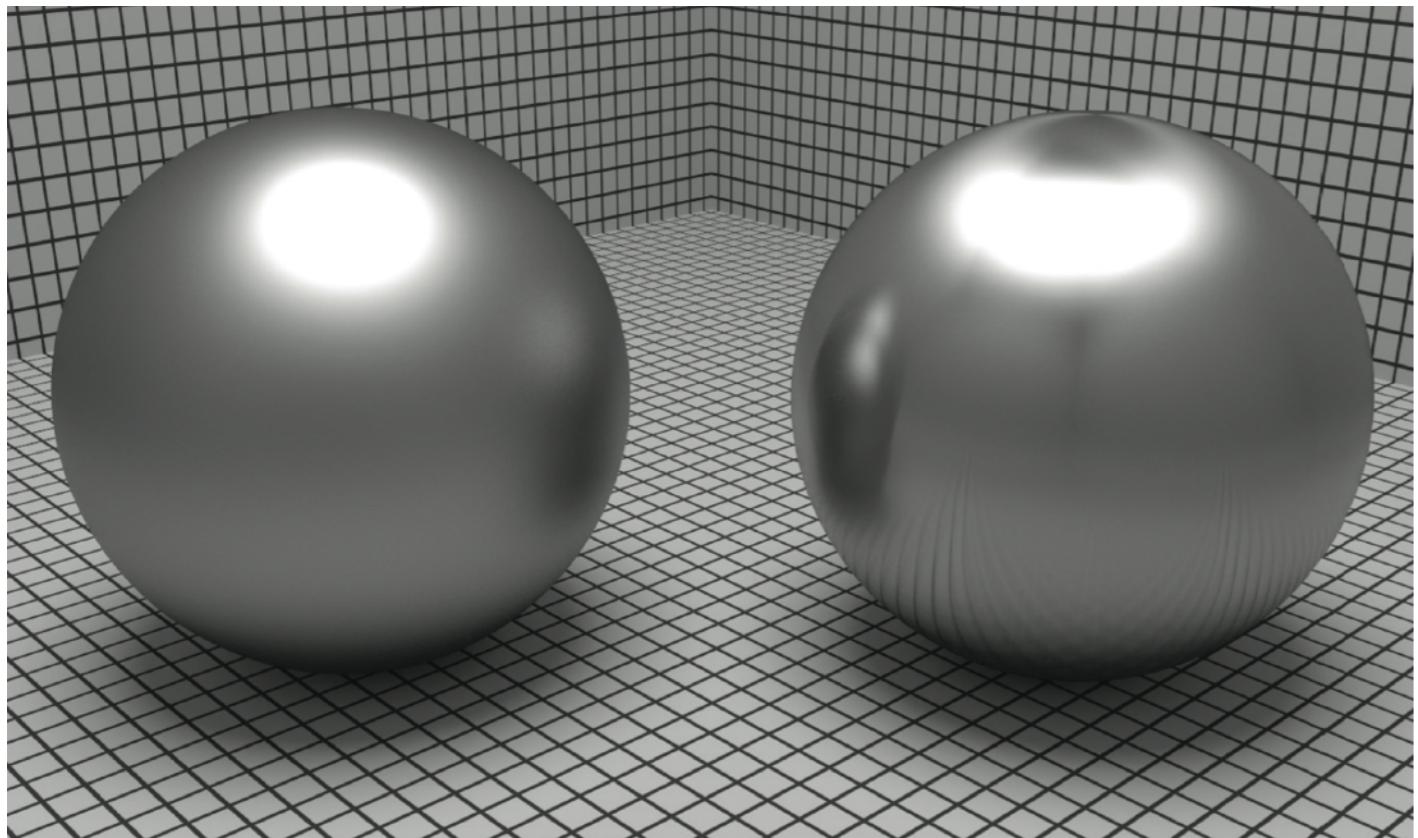
BRDF (fix w_i , vary w_o)

Anisotropic BRDFs

Reflection depends on azimuthal angle ϕ

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

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



Anisotropic BRDF: Brushed Metal

- How is the pan brushed?



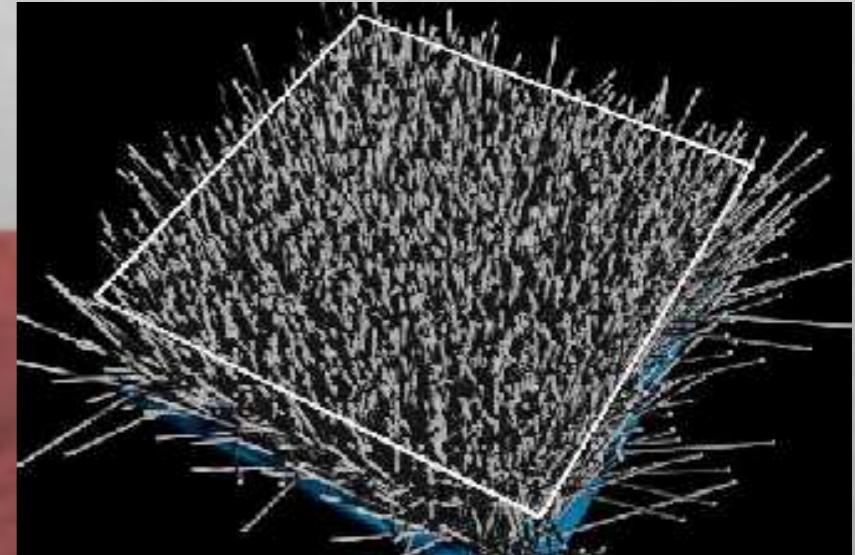
[VRay renderer]

Anisotropic BRDF: Nylon



[Westin et al. 1992]

Anisotropic BRDF: Velvet



[Westin et al. 1992]

Anisotropic BRDF: Velvet



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

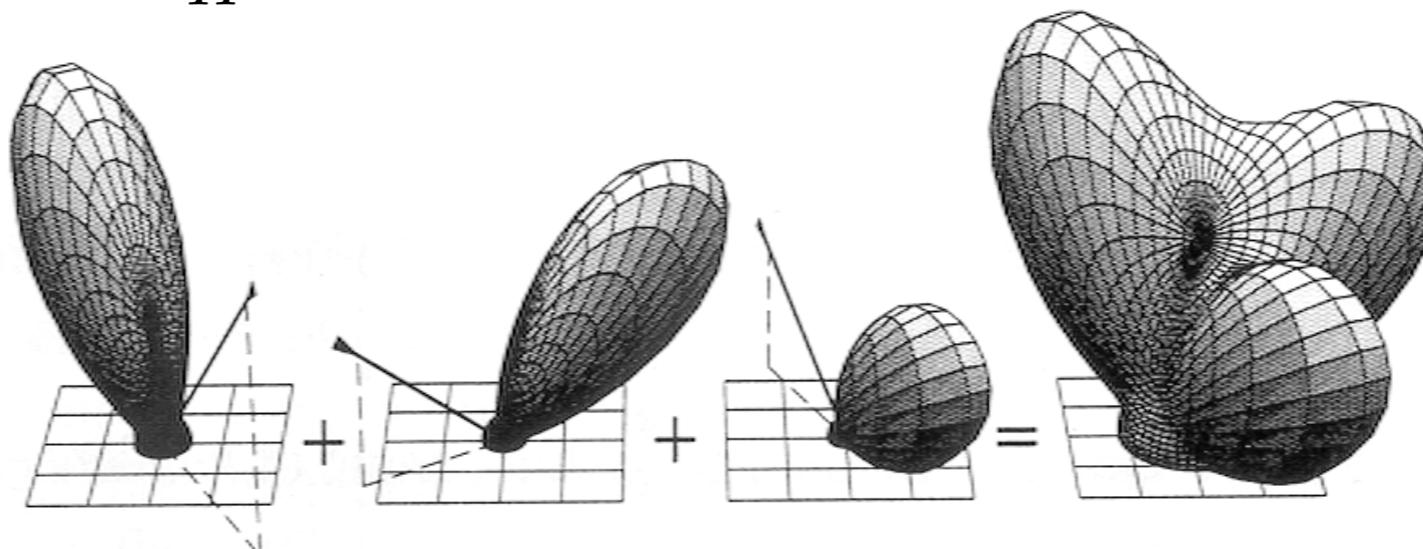
Properties of BRDFs

- Non-negativity

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

- Linearity

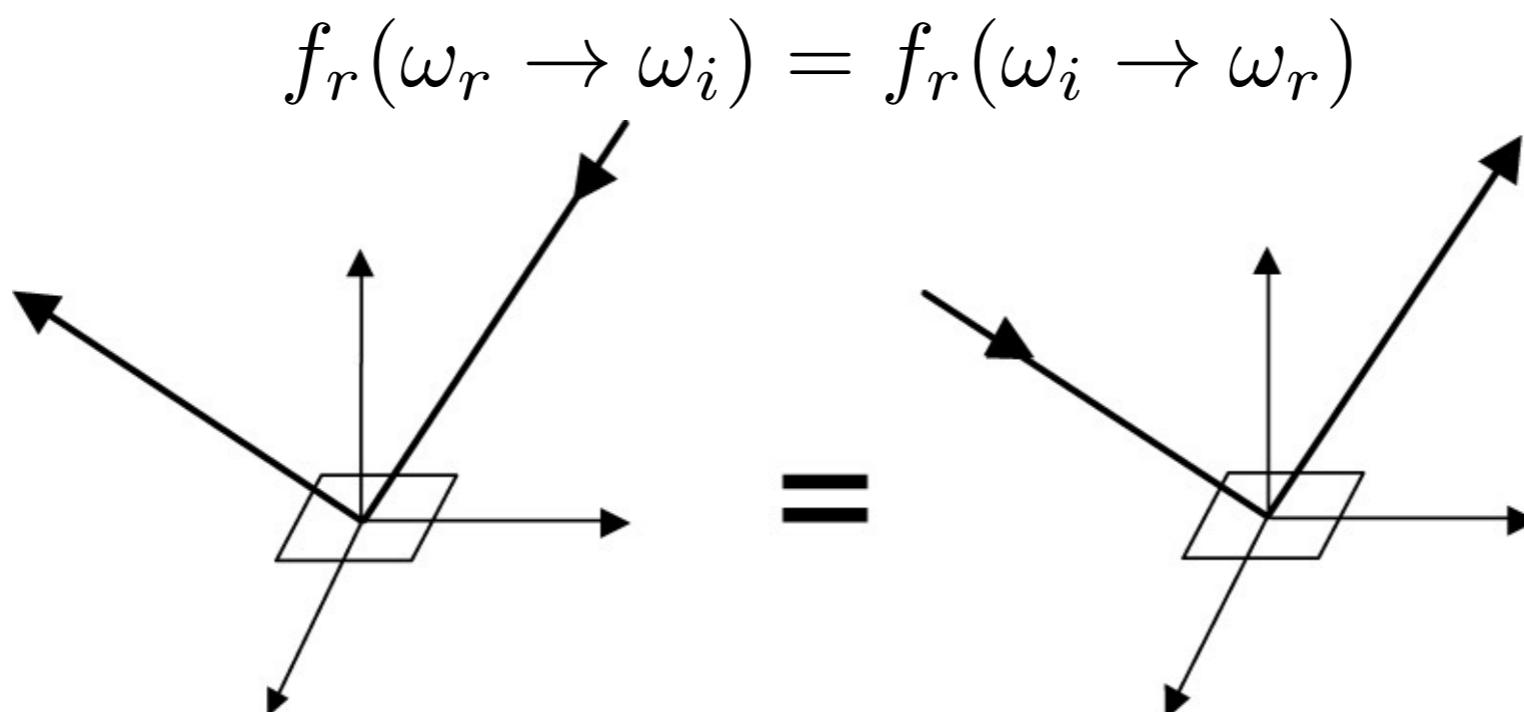
$$L_r(p, \omega_r) = \int_{H^2} f_r(p, \omega_i \rightarrow \omega_r) L_i(p, \omega_i) \cos \theta_i d\omega_i$$



[Sillion et al. 1990]

Properties of BRDFs

- Reciprocity principle



- Energy conservation

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

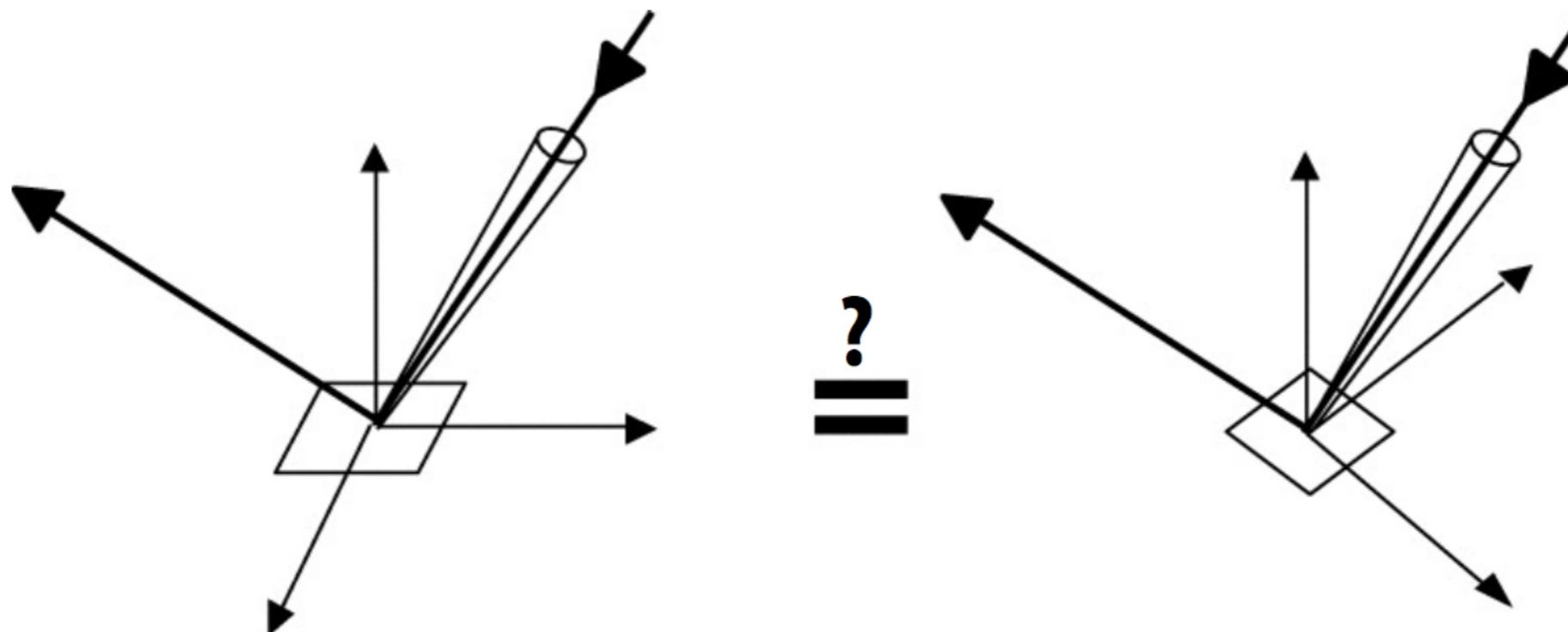
Properties of BRDFs

- 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:

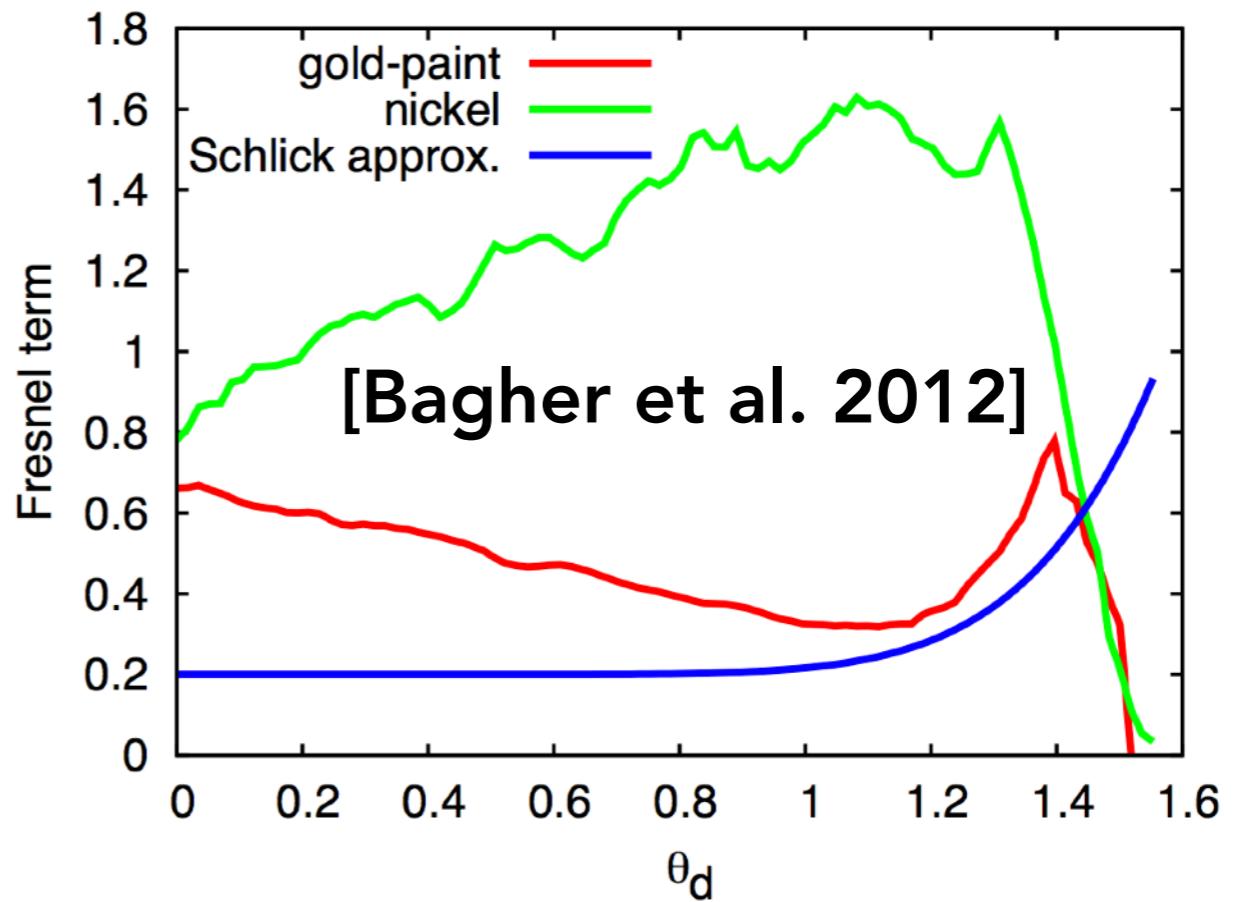
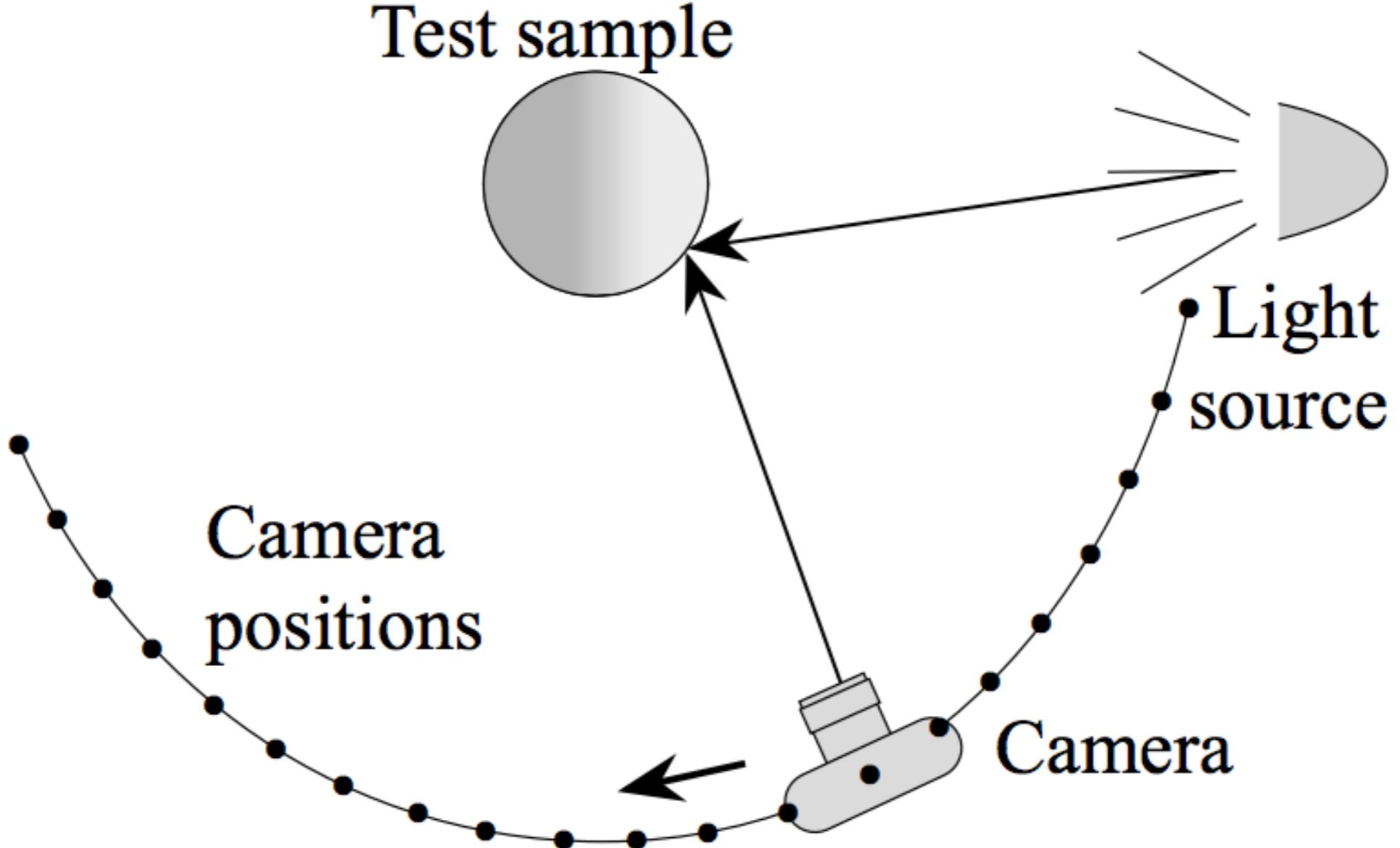
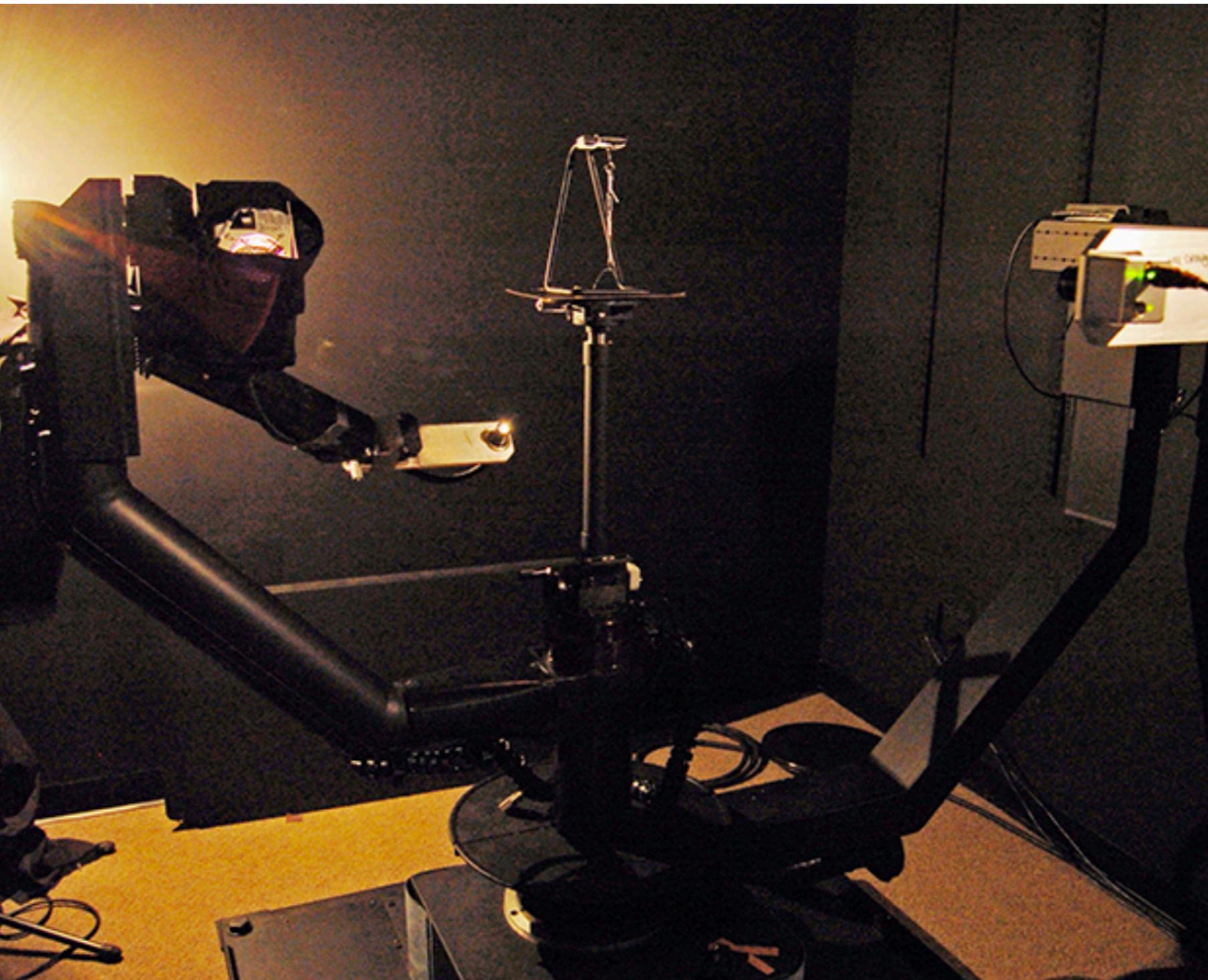


Image-Based BRDF Measurement



[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

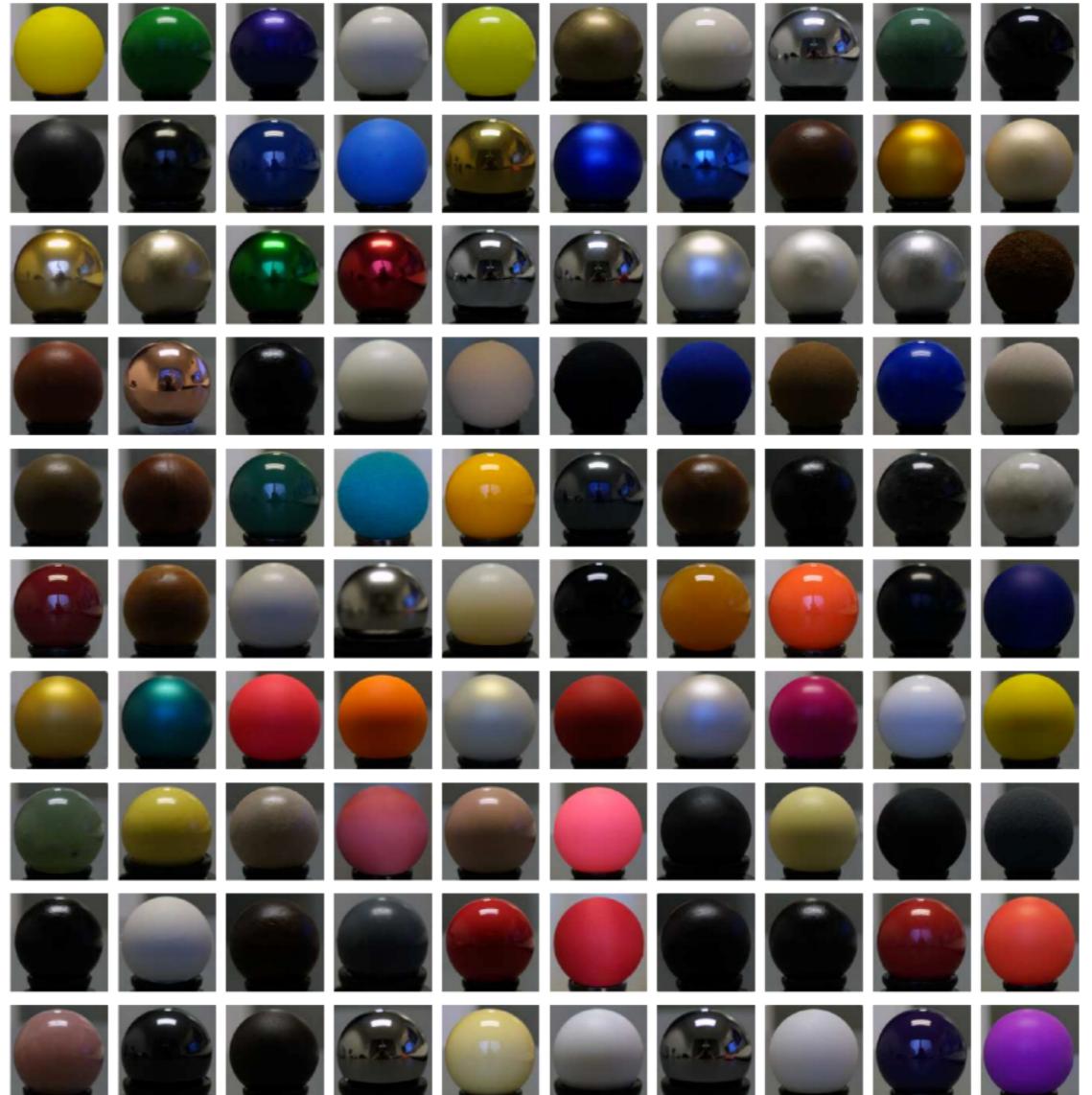
Tabular Representation

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!)