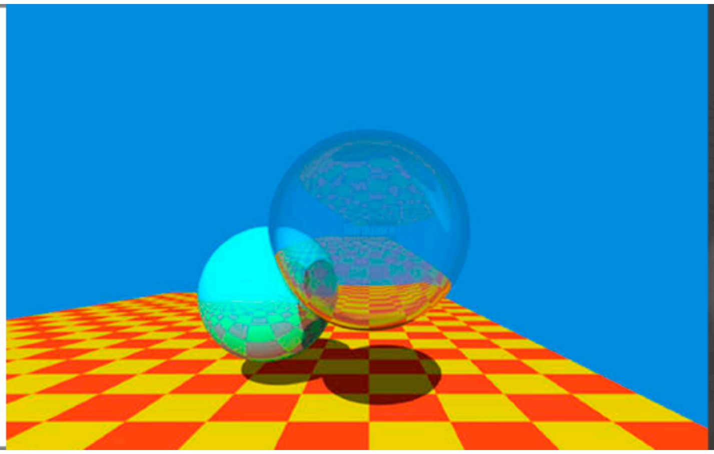
Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 17:

Materials and Appearances





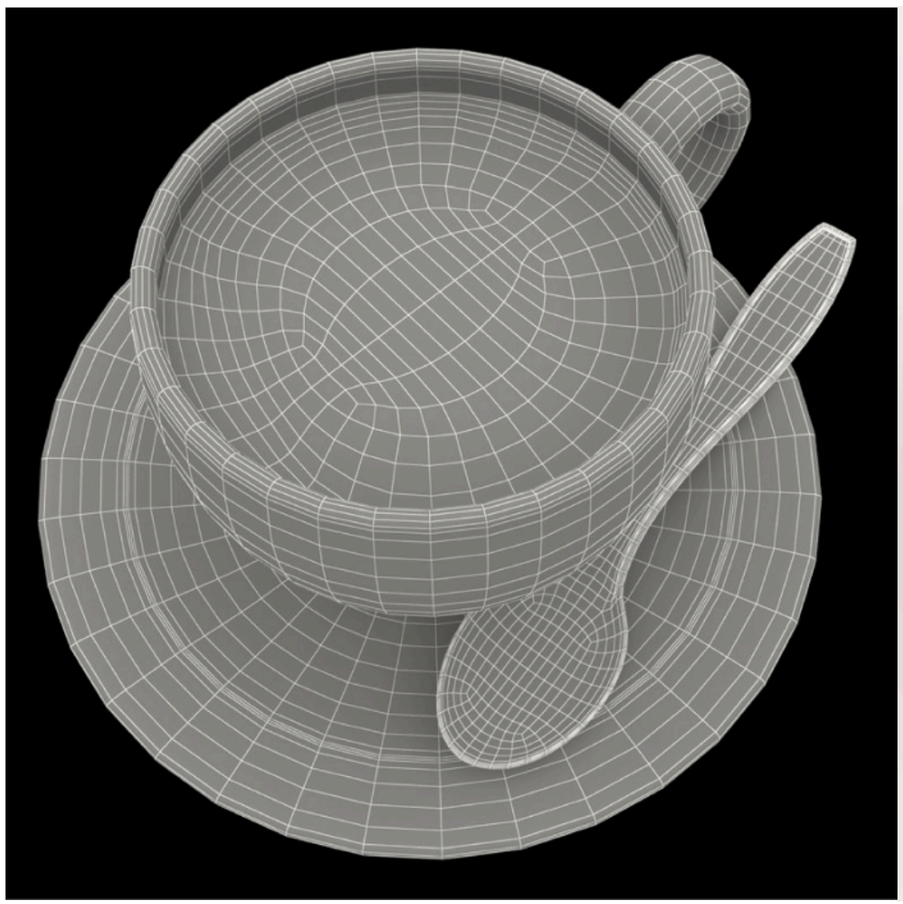

Announcements

- 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

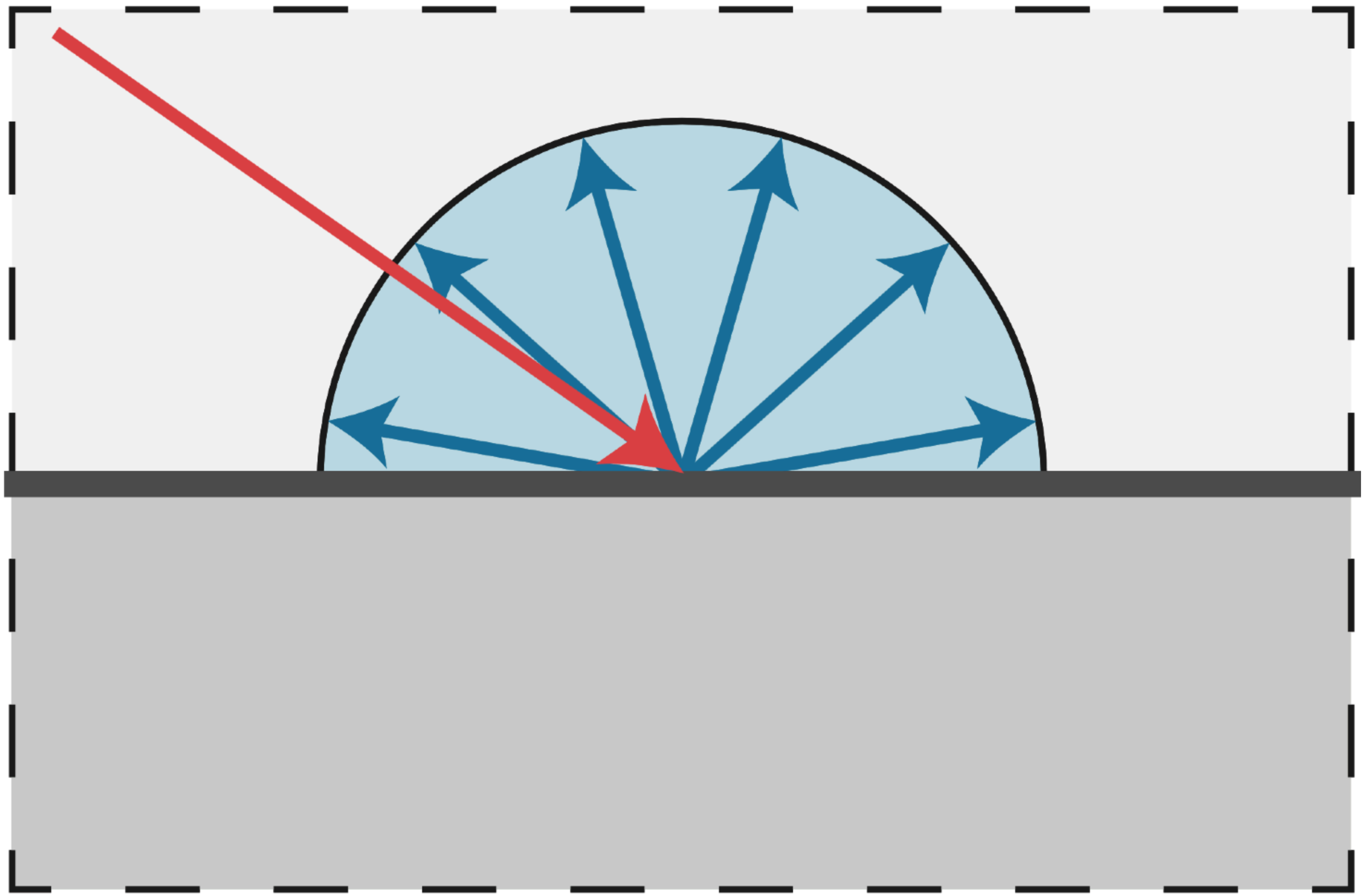
Rendered

Rendered

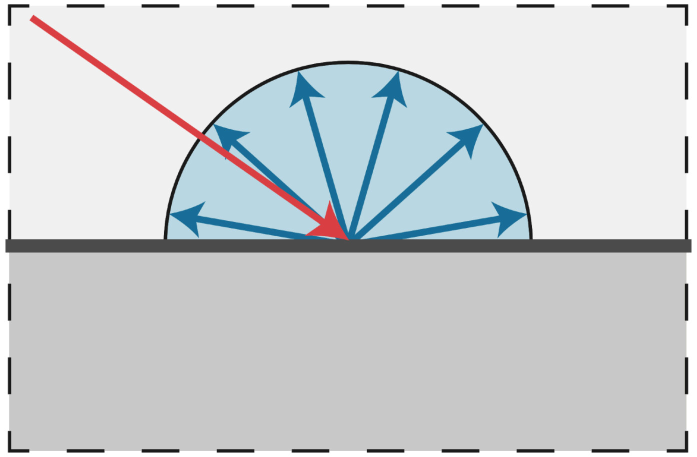
[From TurboSquid, created by artist 3dror]

Material == BRDF

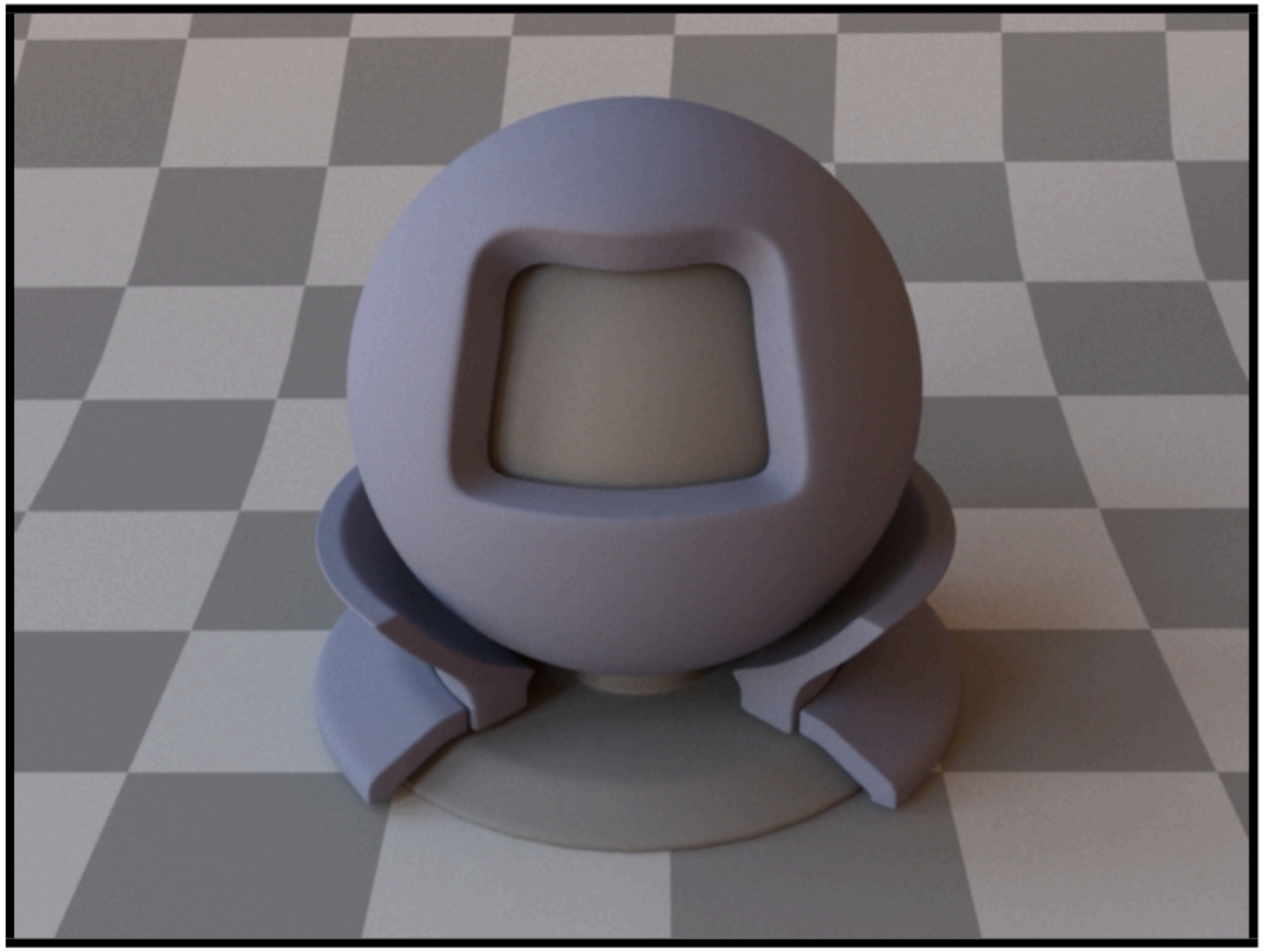
What is this material?



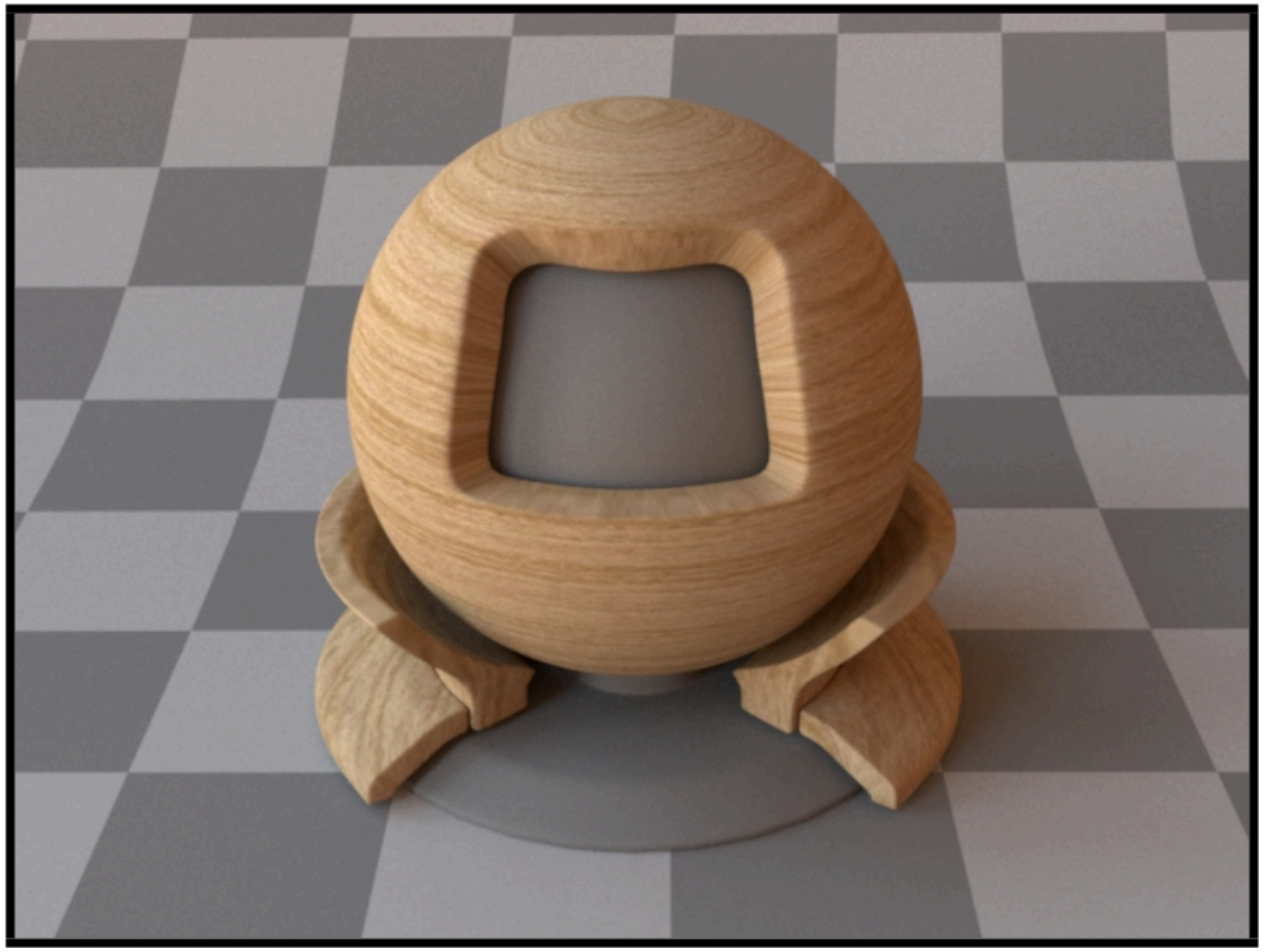
Diffuse / Lambertian Material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]



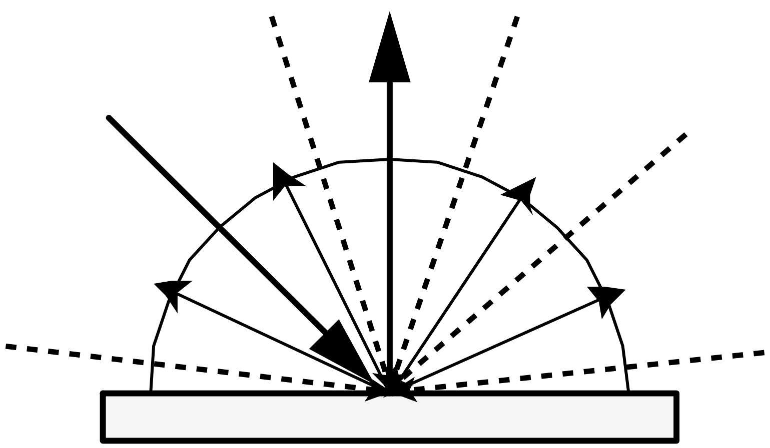
Uniform colored diffuse BRDF



Textured diffuse BRDF

Diffuse / Lambertian Material

Light is equally reflected in each output direction



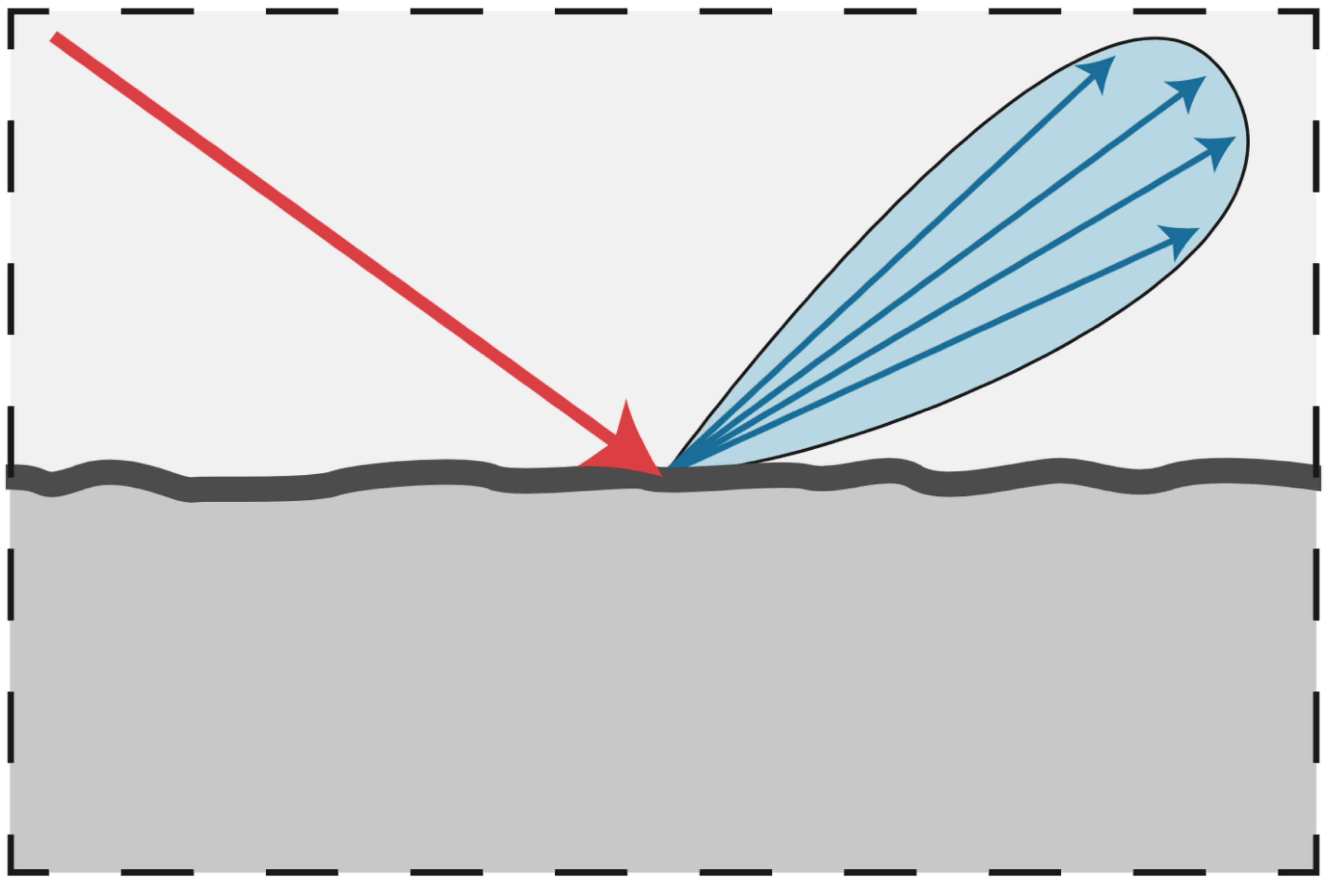
$f_r = c$

Suppose the incident lighting is uniform:

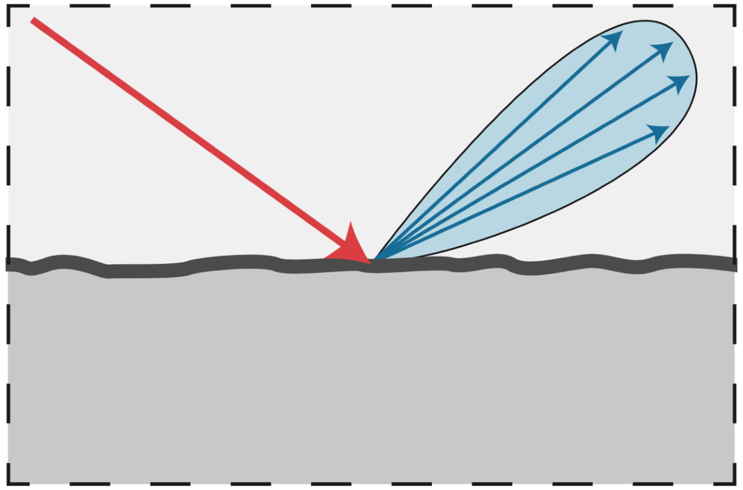
$$
\begin{aligned}
L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos\theta_i \, \mathrm{d}\omega_i \\
&= f_r L_i \int_{H^2} \cancel{(\omega_i)} \cos\theta_i \, \mathrm{d}\omega_i \\
&= \pi f_r L_i
\end{aligned}
$$

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

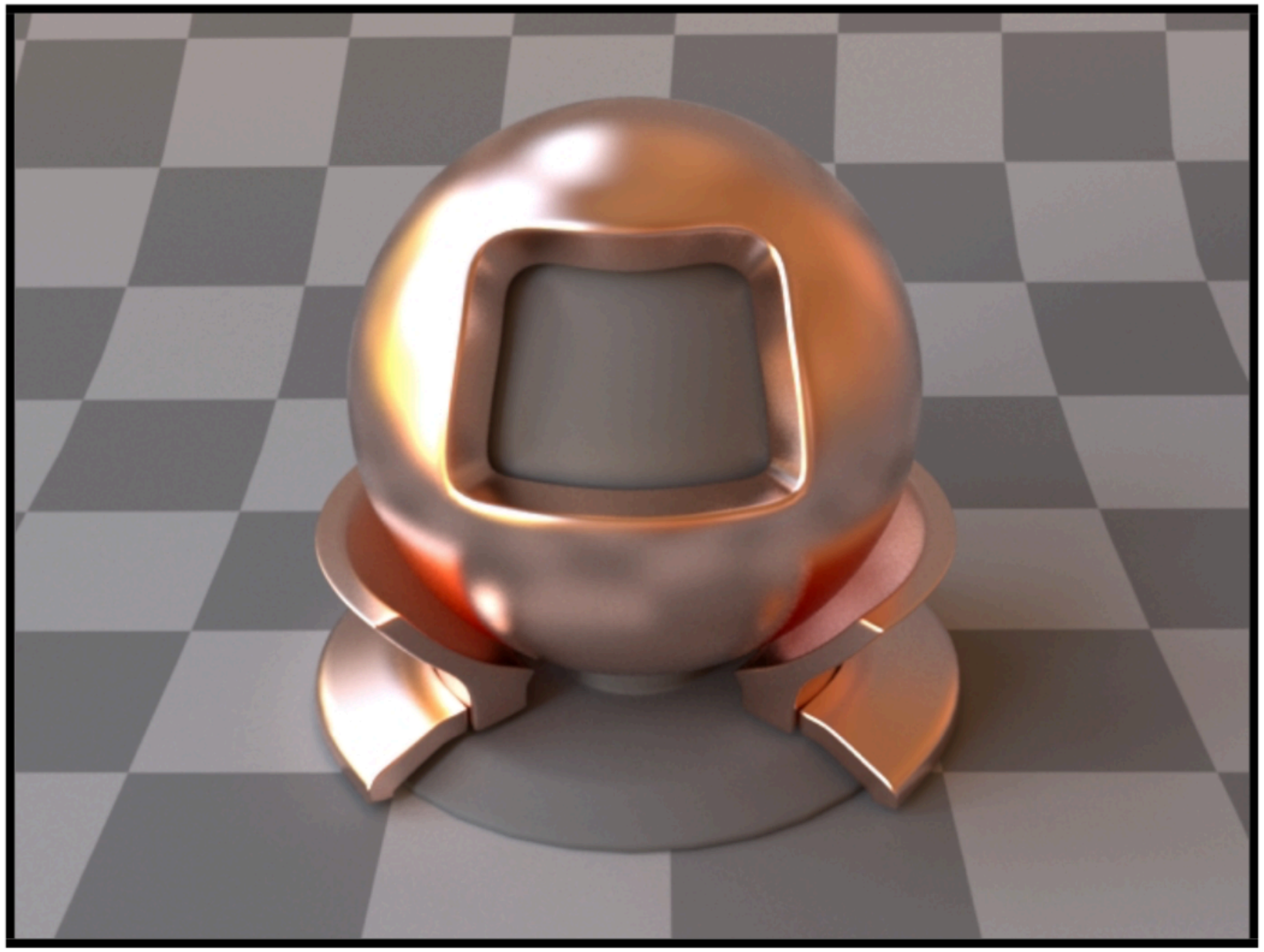
What is this material?



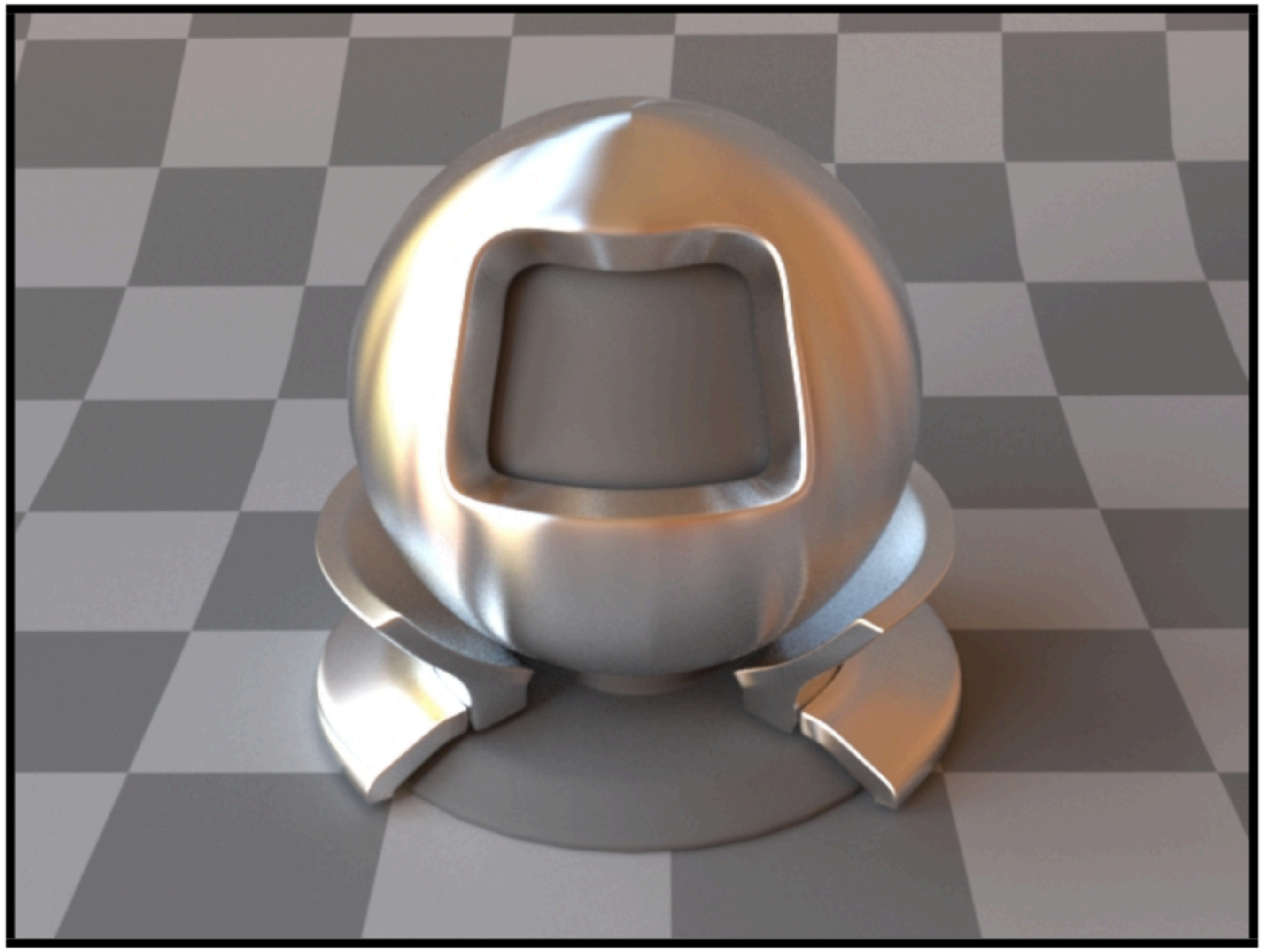
Glossy material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]

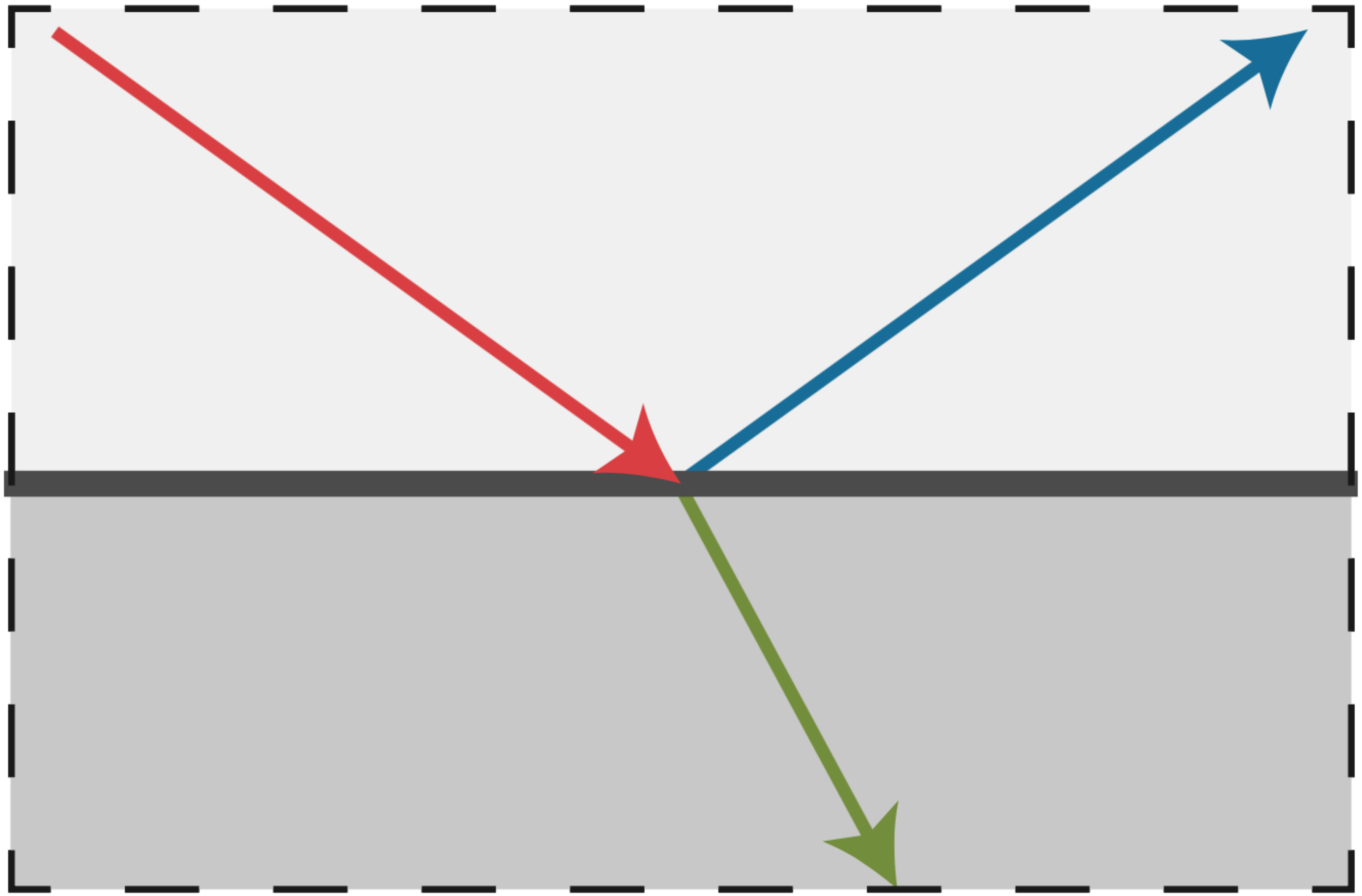


Copper

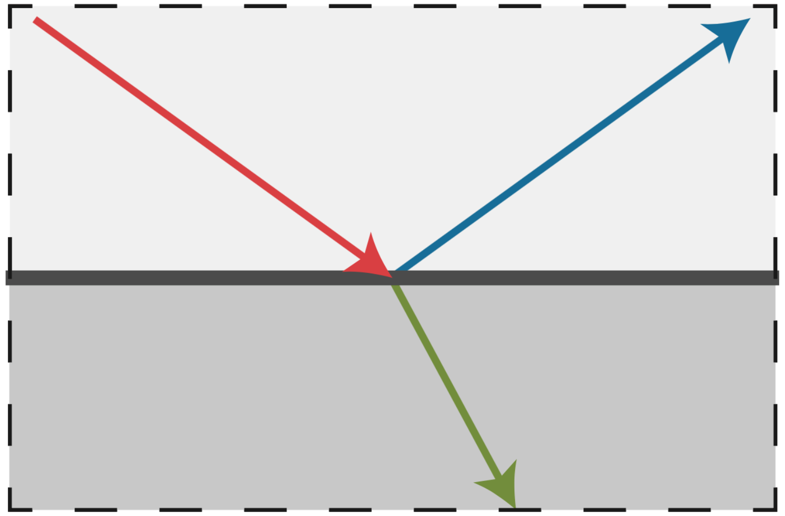


Aluminum

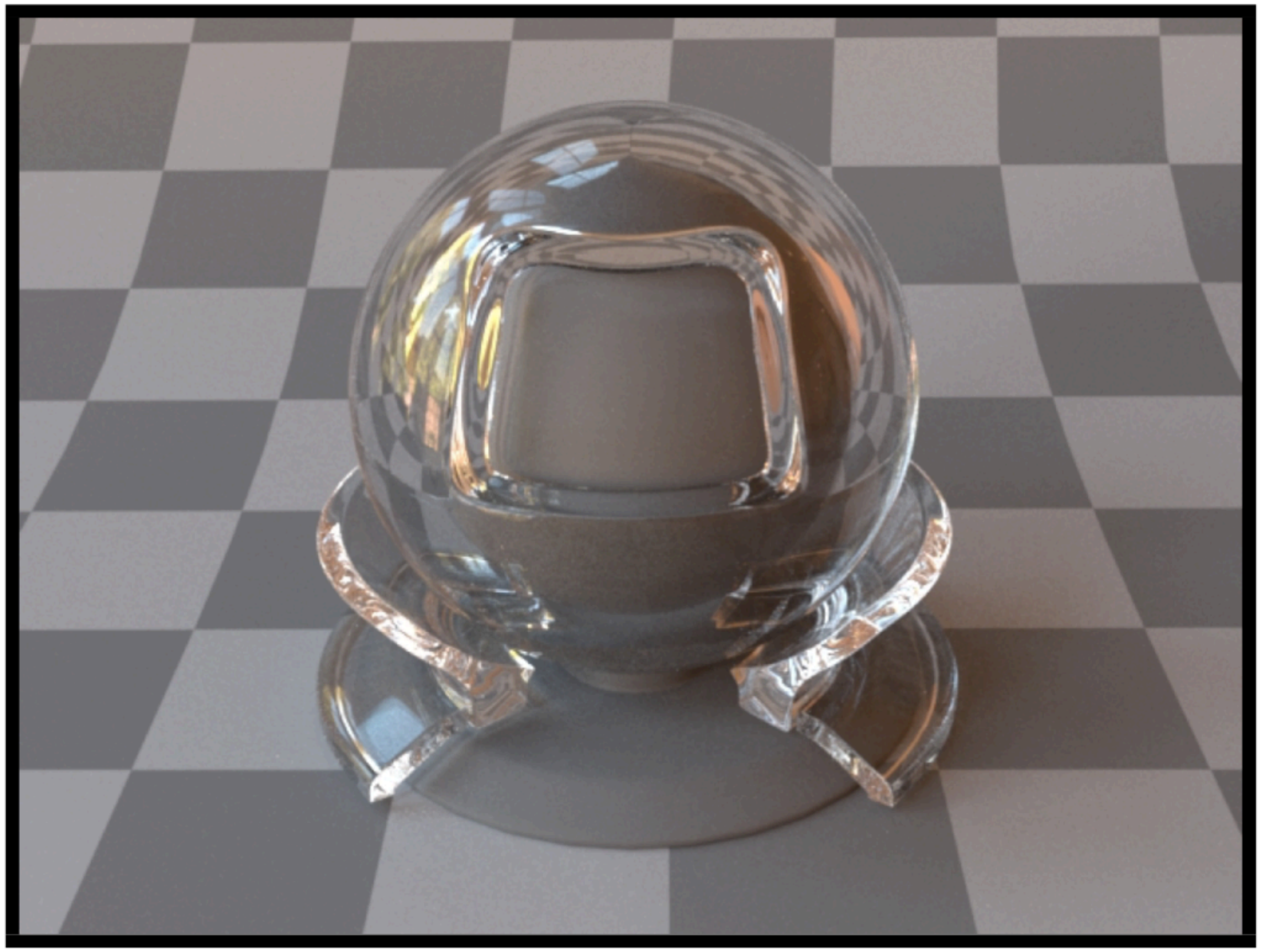
What is this material?



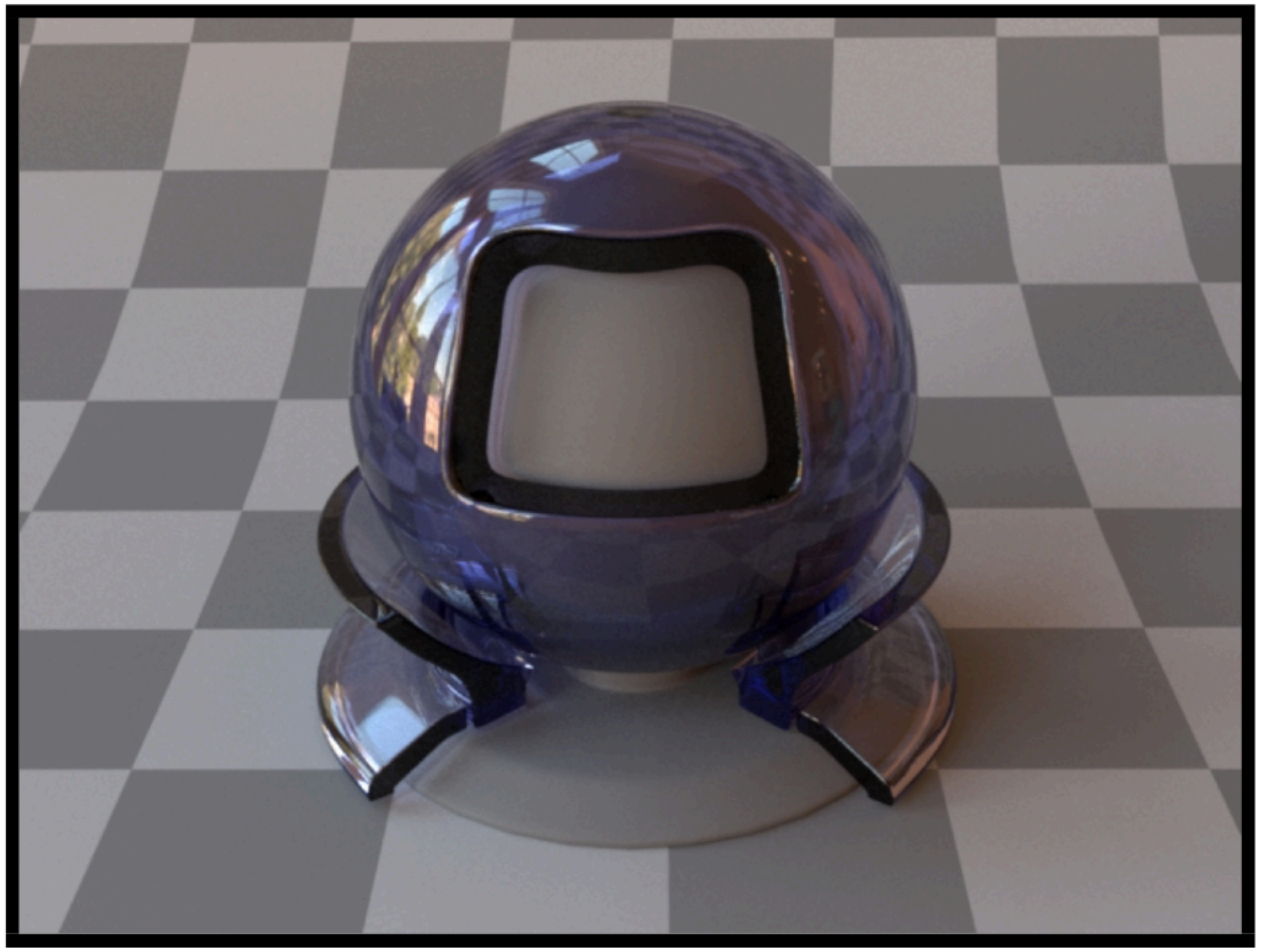
Ideal reflective / refractive material (BSDF*)



[Mitsuba renderer, Wenzel Jakob, 2010]

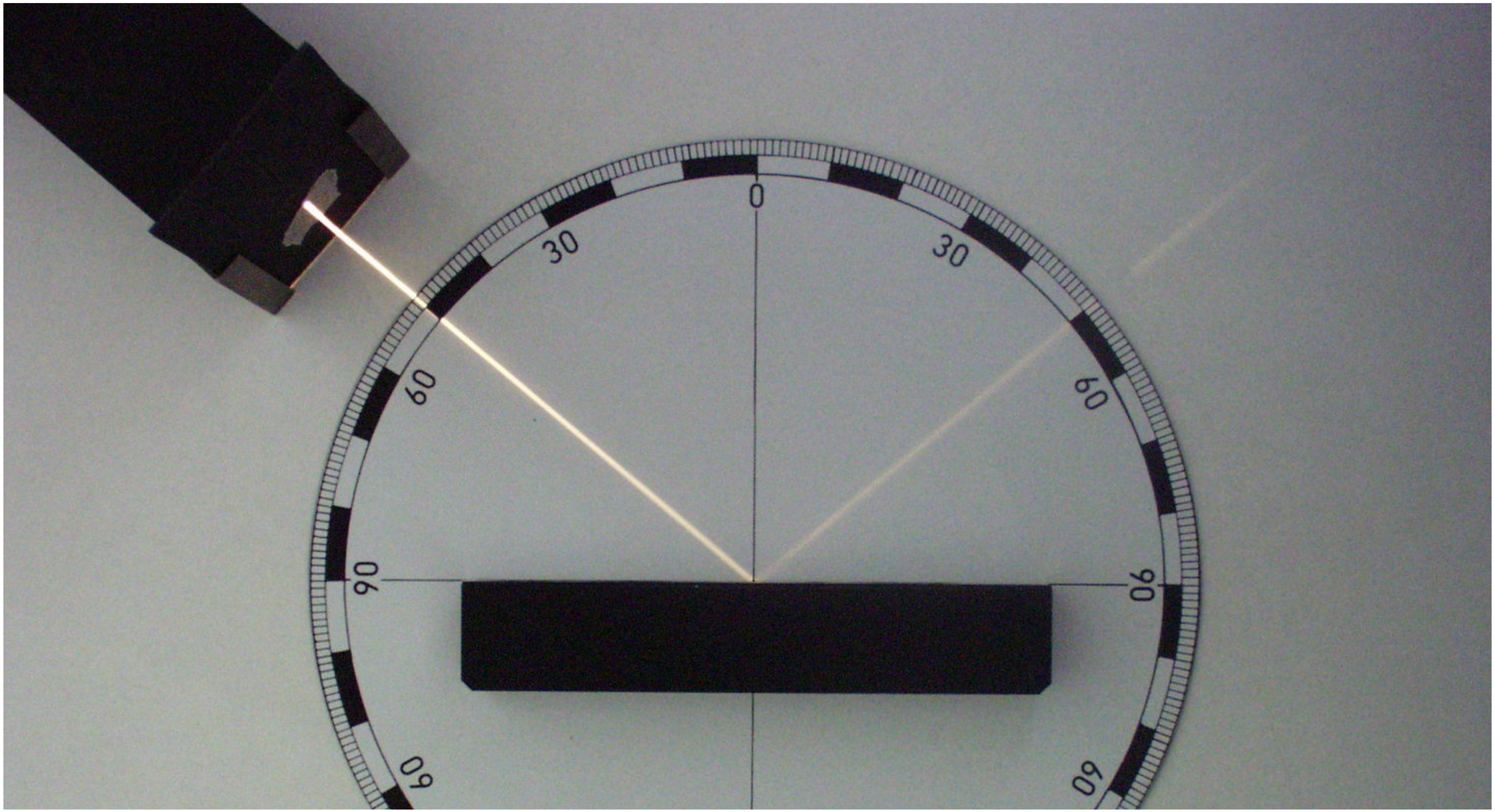


Air <-> water interface



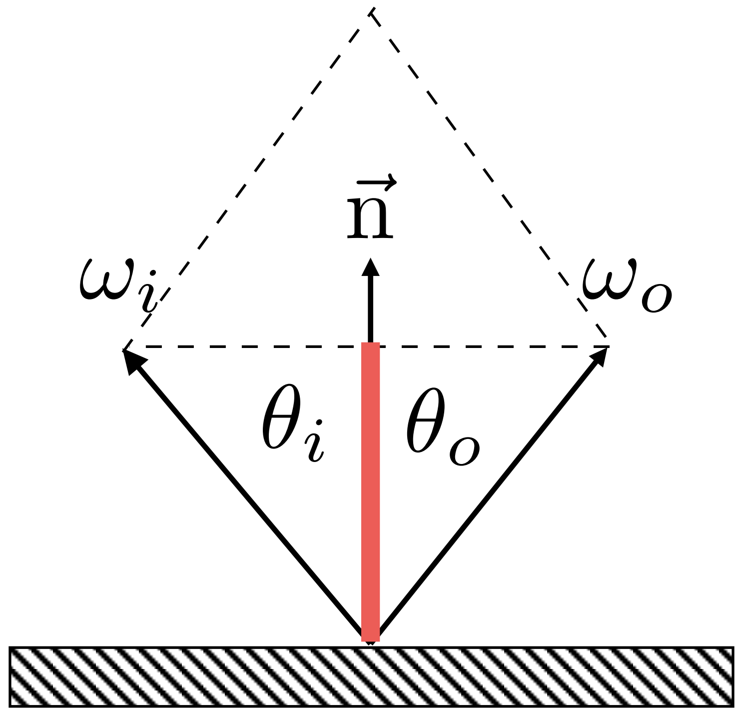
Air <-> glass interface
(with absorption)

Perfect Specular Reflection



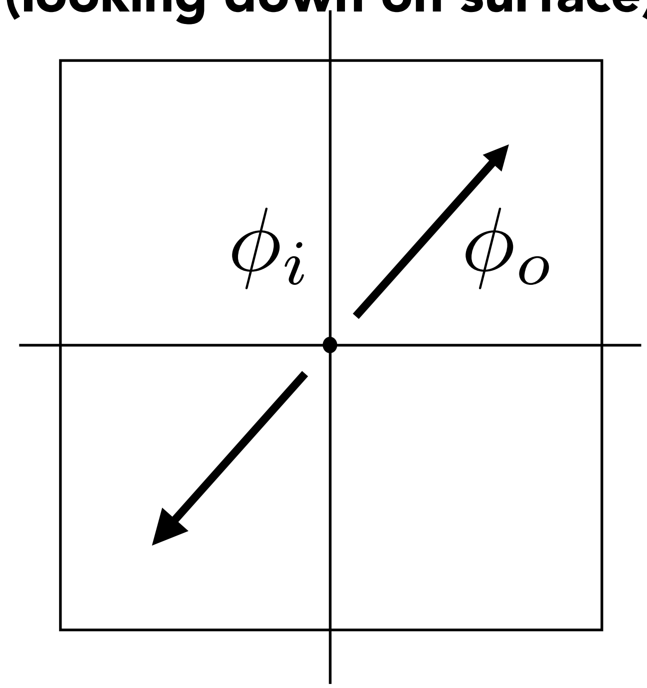
[Zátonyi Sándor]

Perfect Specular Reflection



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

Top-down view
(looking down on surface)

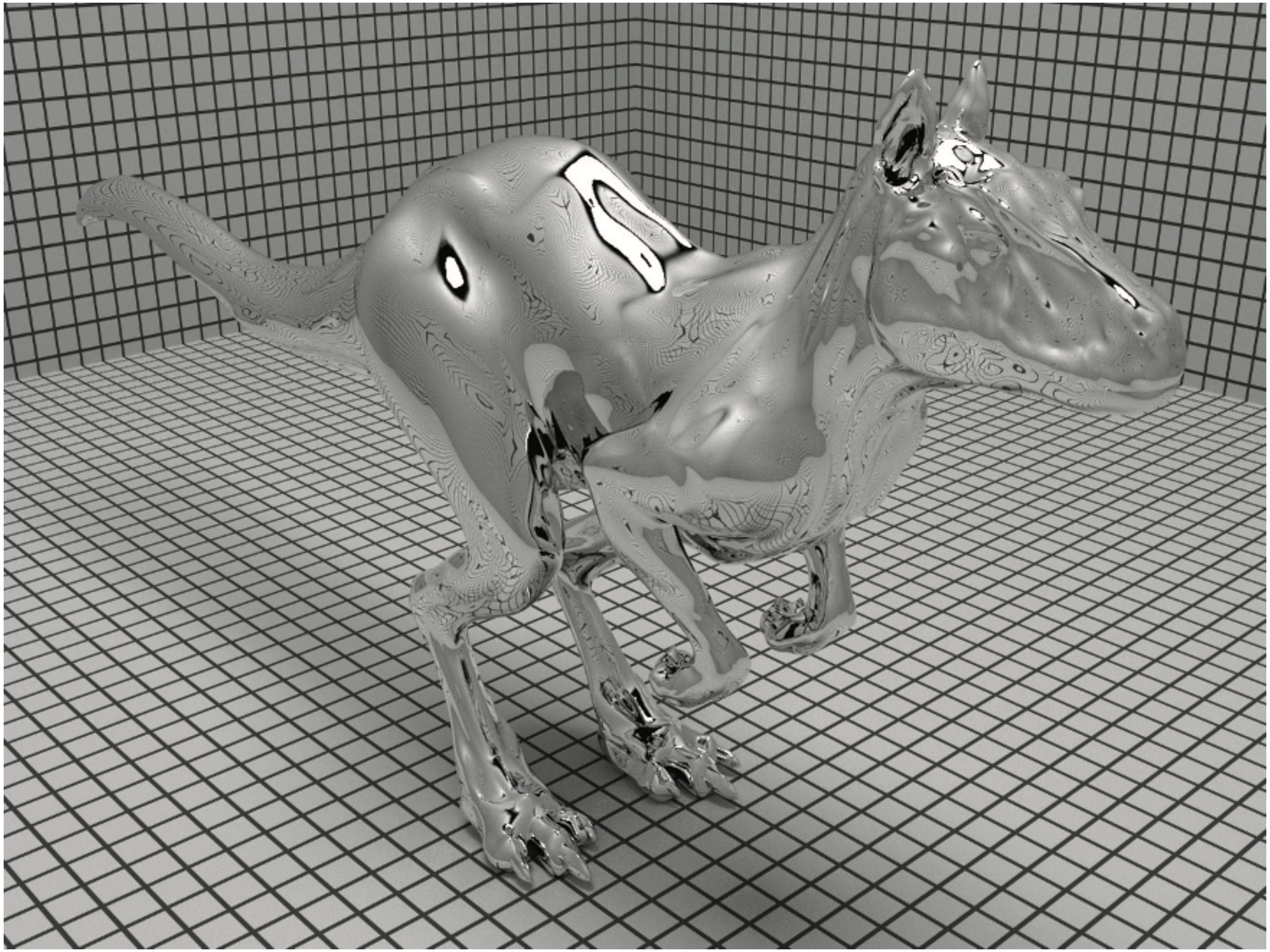


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Perfect Specular Reflection BRDF

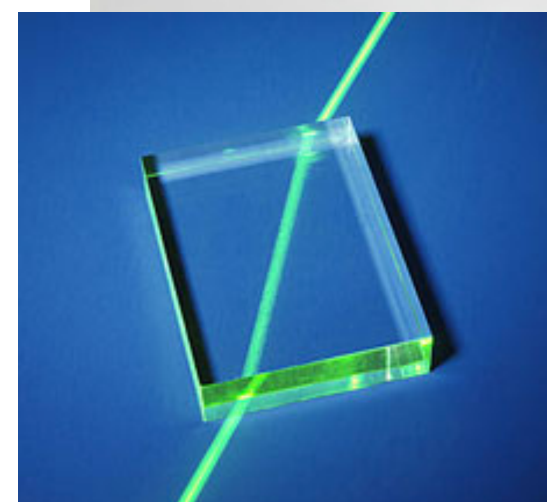


PBRT

Specular Refraction

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

Light refracts when it enters a new medium.

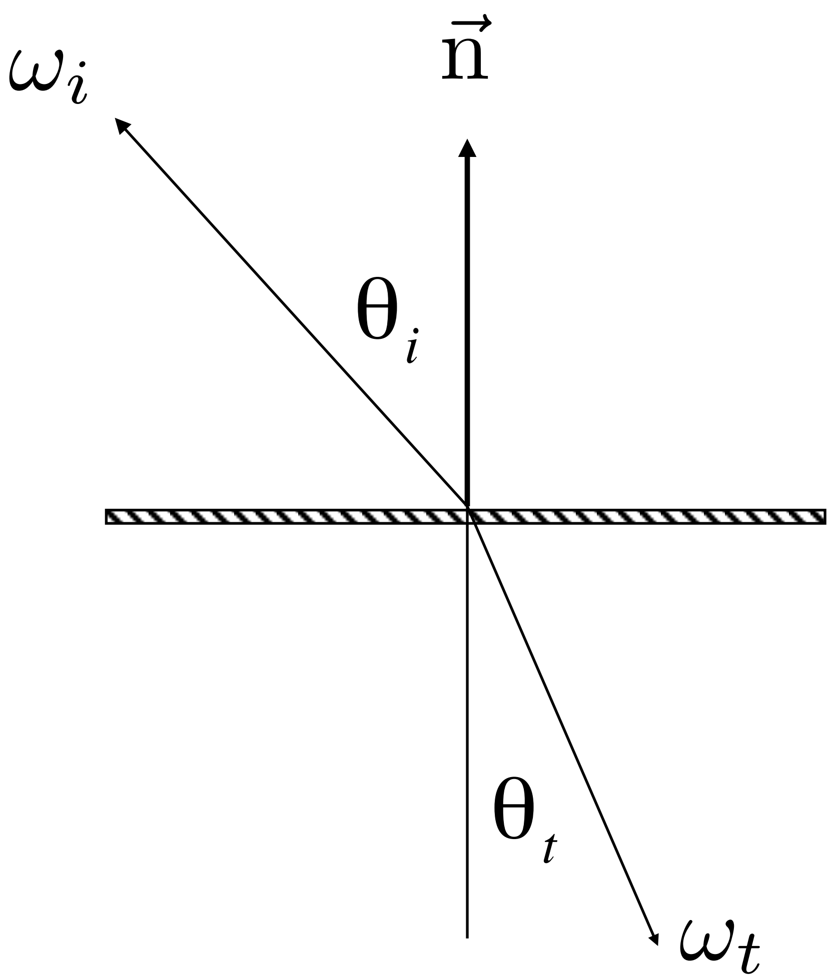


Snell's Law

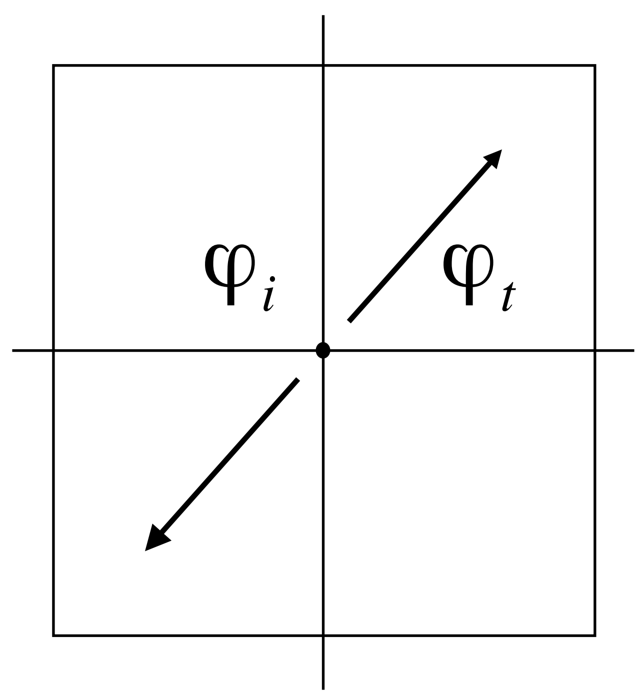
Transmitted angle depends on

index of refraction (IOR) for incident ray

index of refraction (IOR) for exiting ray



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

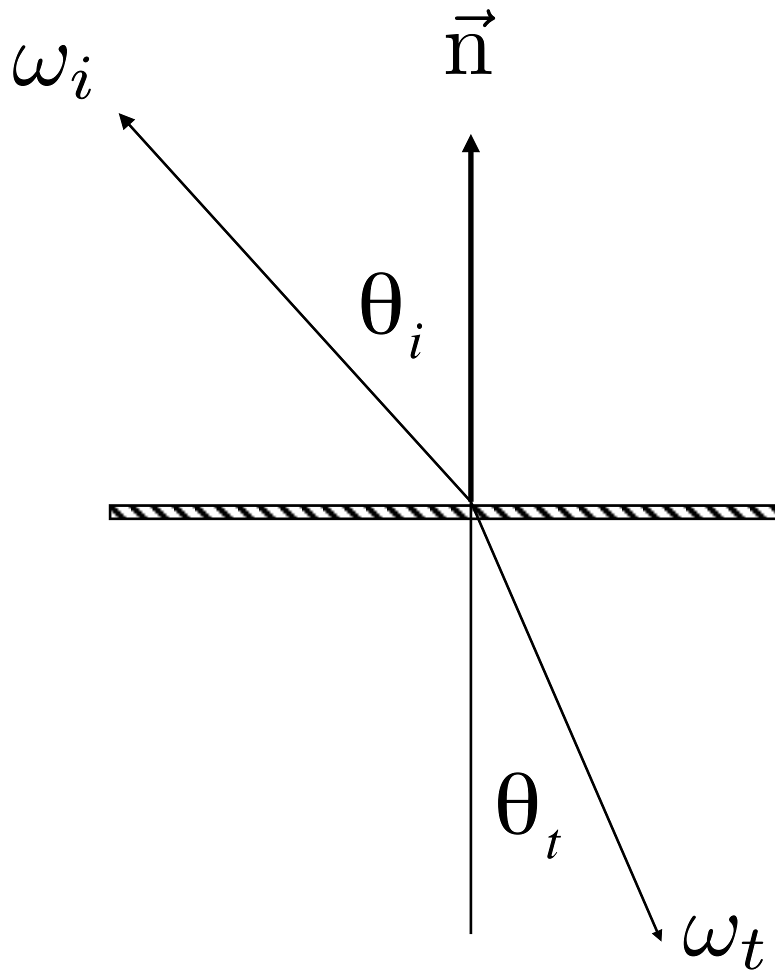


$$\varphi_t = \varphi_i \pm \pi$$

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



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

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

Total internal reflection:

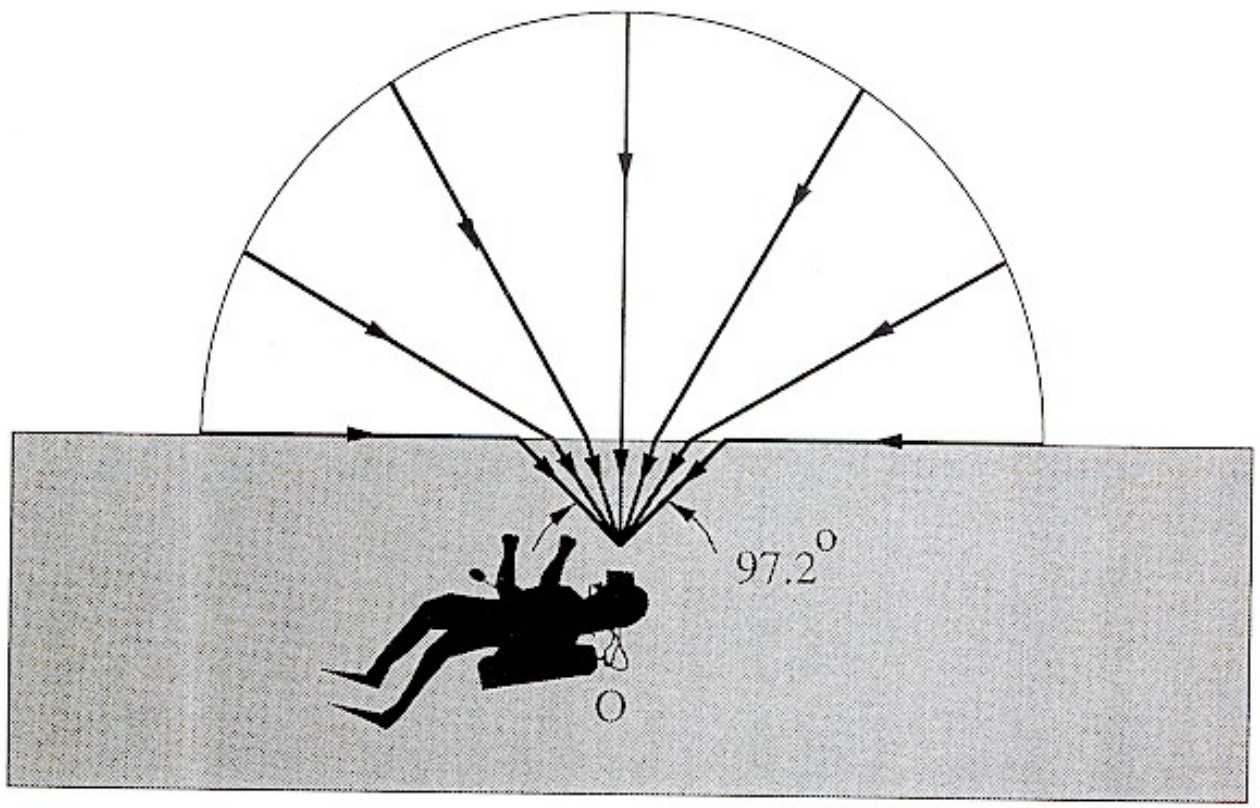
$$1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2\theta_i) < 0$$

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

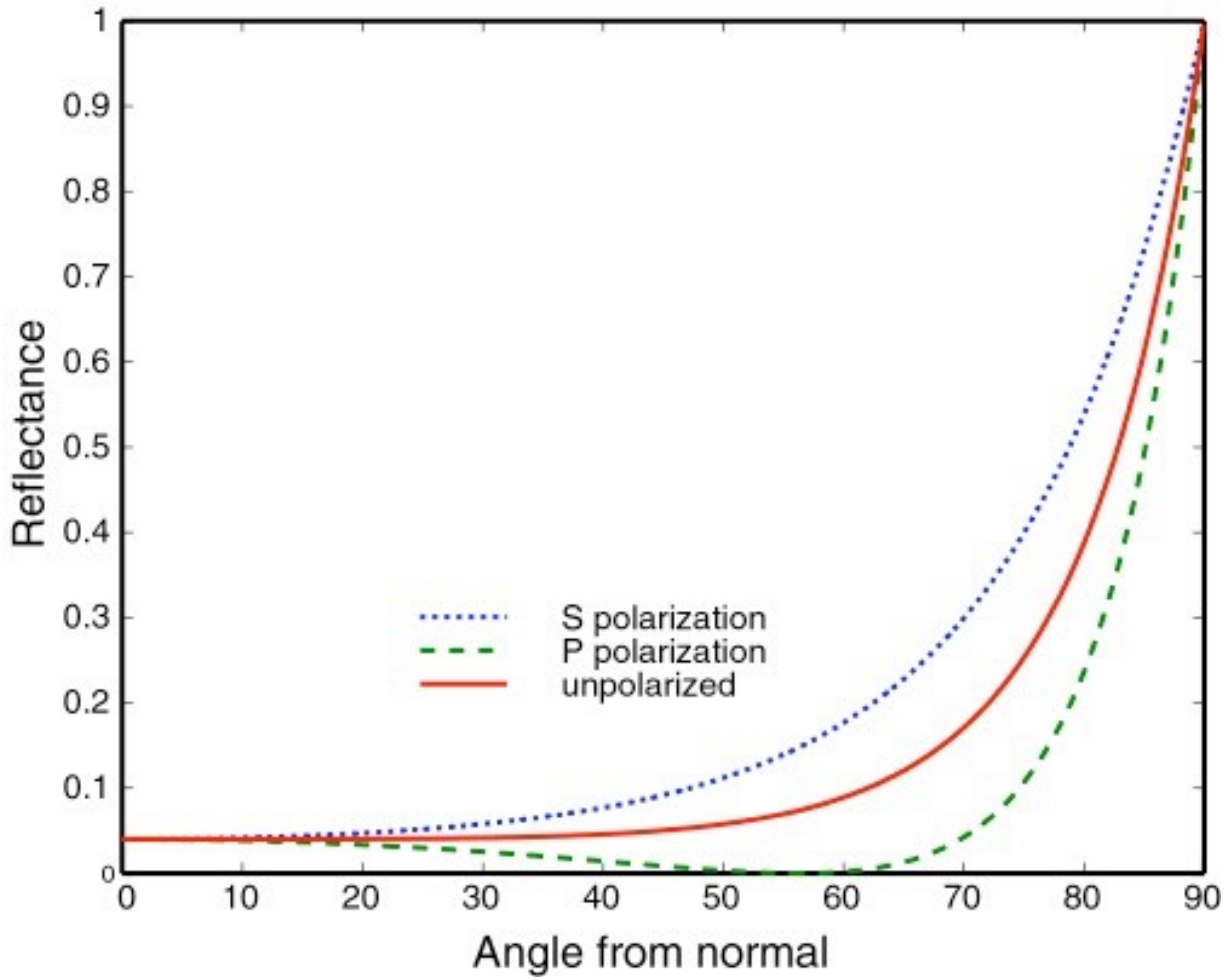
(菲涅耳项)

Reflectance depends on incident angle (and polarization of light)

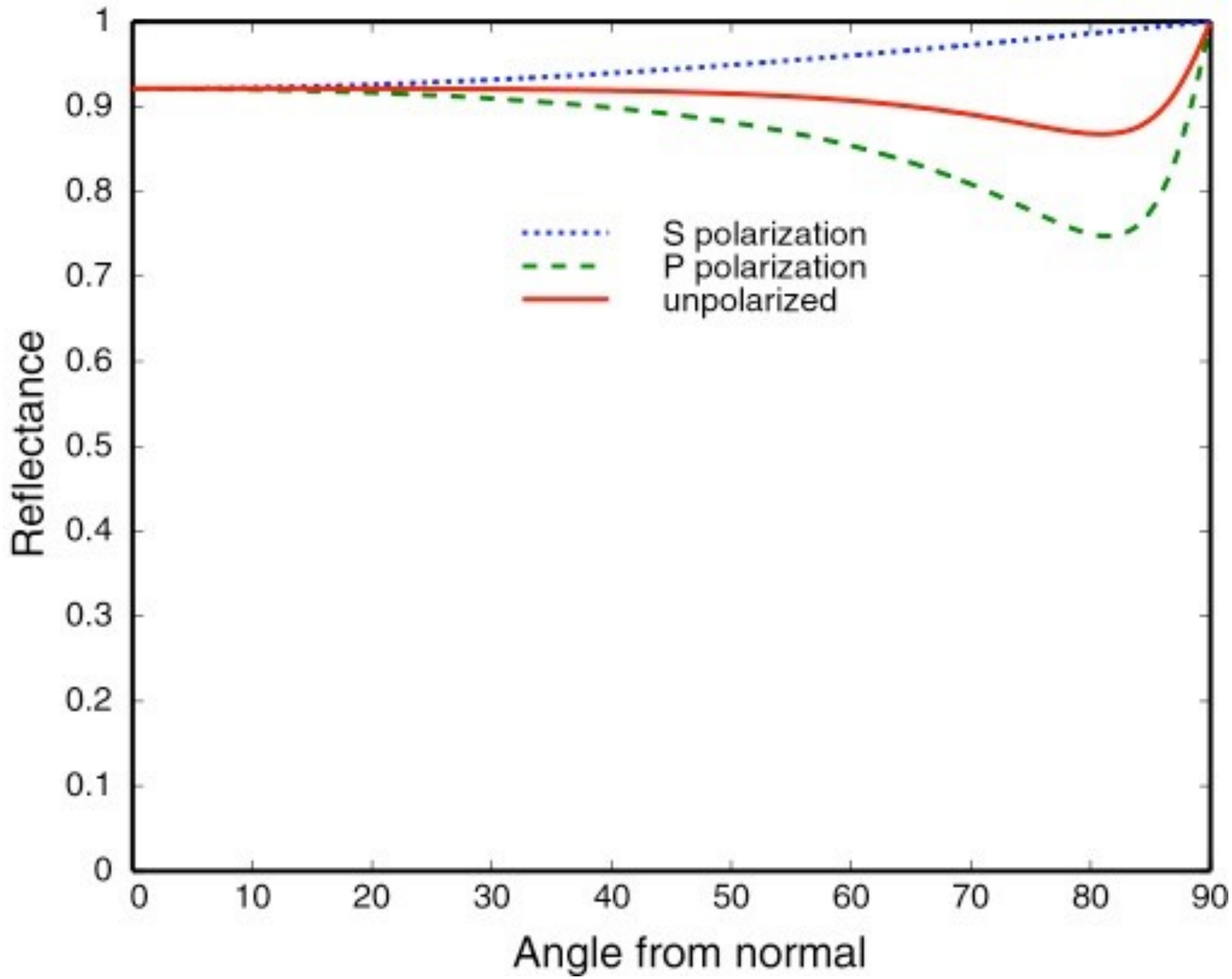
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

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



Fresnel Term (Conductor)



Fresnel Term — Formulae

Accurate: need to consider polarization

$$R_{\mathrm{s}} = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \cos\theta_{\mathrm{t}}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \cos\theta_{\mathrm{t}}} \right|^2 = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}} \right|^2,$$

$$R_{\mathrm{p}} = \left| \frac{n_1 \cos\theta_{\mathrm{t}} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \cos\theta_{\mathrm{t}} + n_2 \cos\theta_{\mathrm{i}}} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} + n_2 \cos\theta_{\mathrm{i}}} \right|^2.$$

$$R_{\mathrm{eff}} = \frac{1}{2}\left(R_{\mathrm{s}} + R_{\mathrm{p}}\right).$$

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

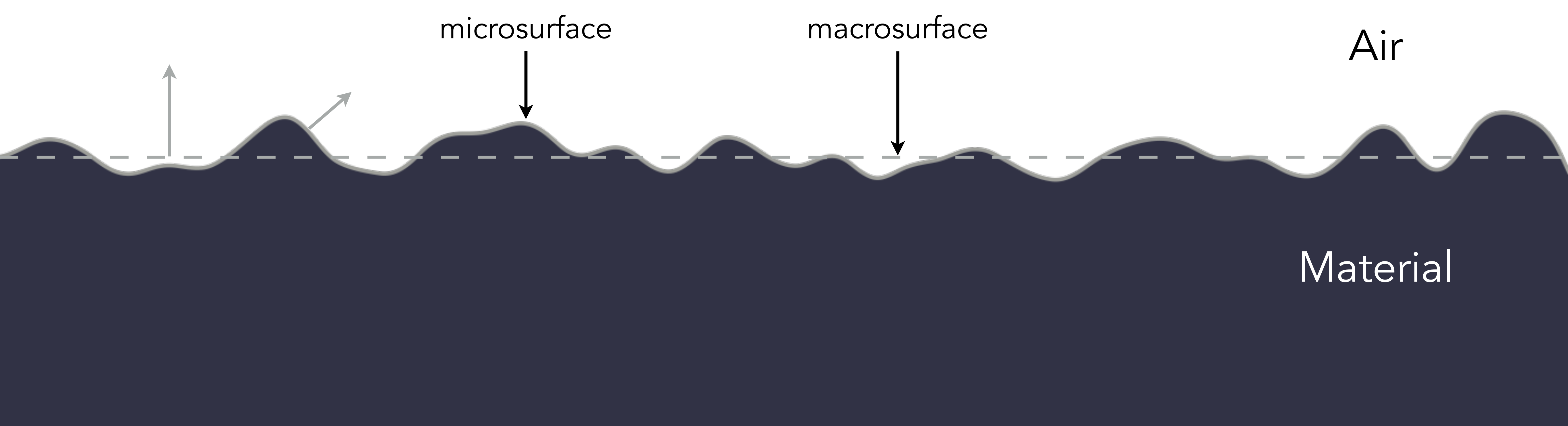
Microfacet Theory

Rough surface

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

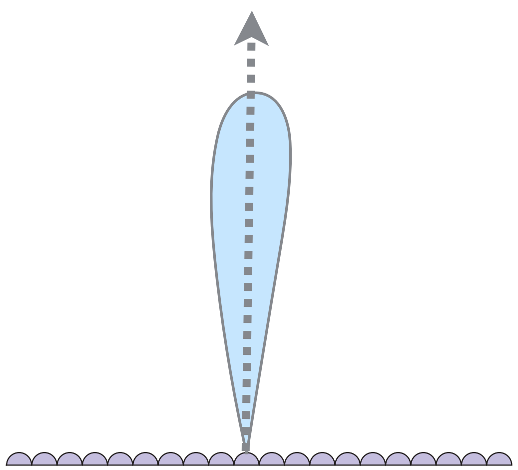
Individual elements of surface act like mirrors

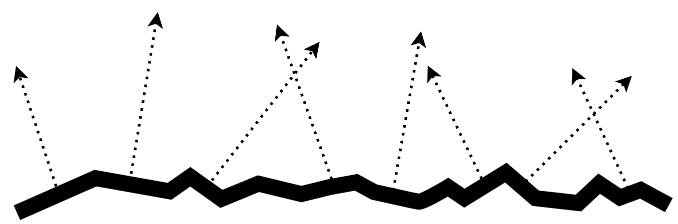
- Known as Microfacets
- Each microfacet has its own normal

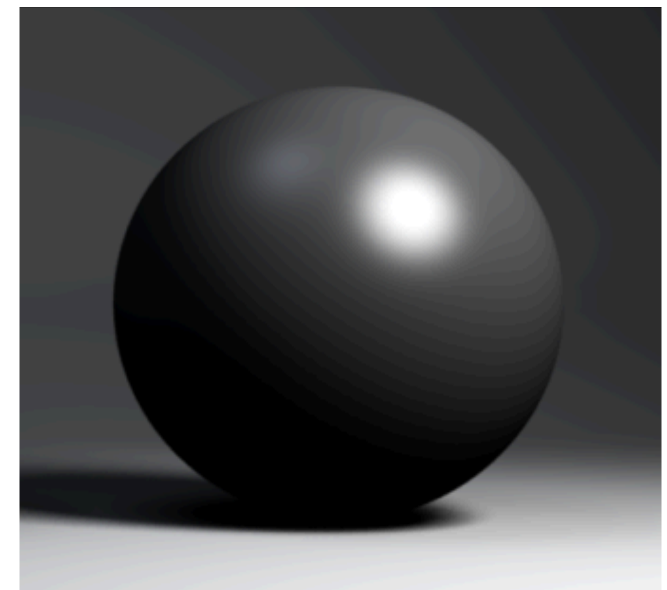


Microfacet BRDF

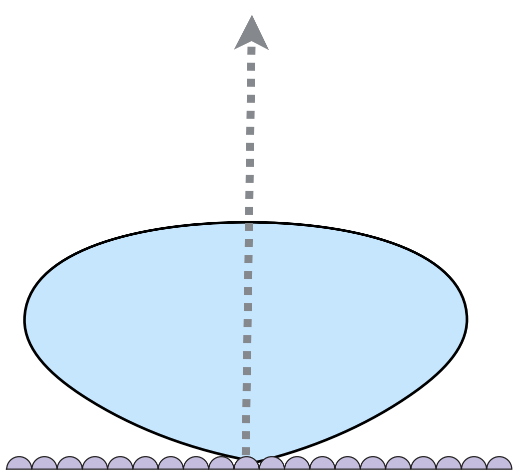
- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

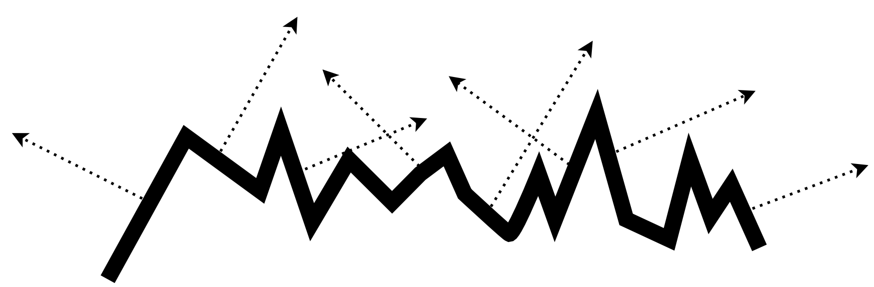


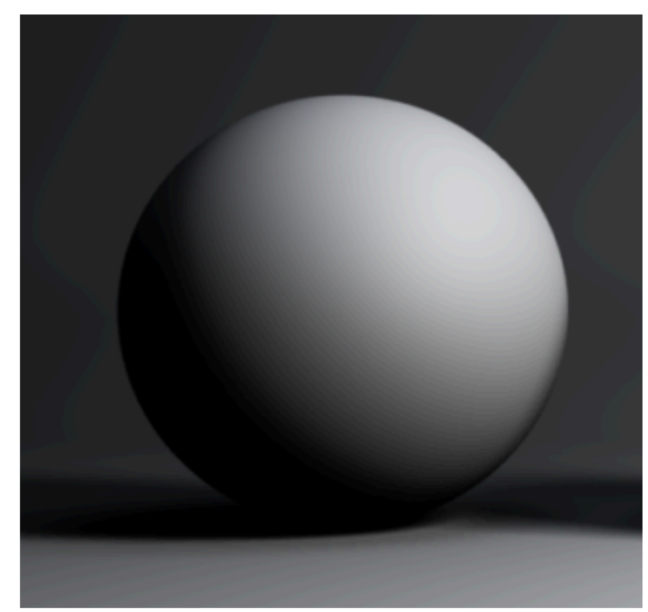




  - Spread <==> diffuse

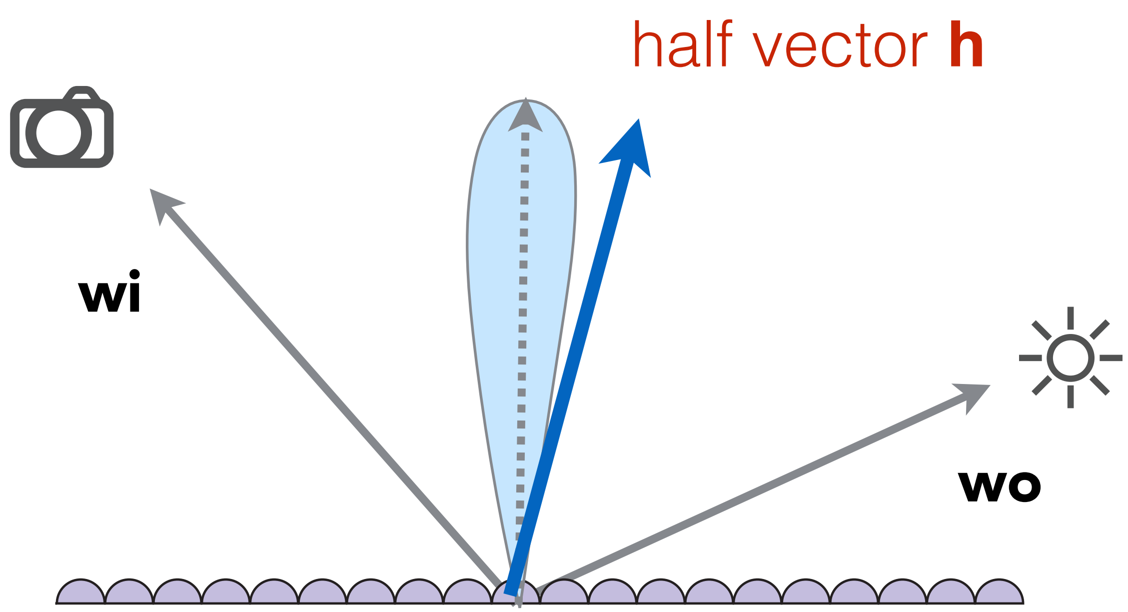


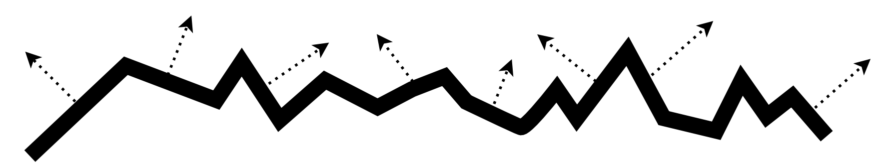




Microfacet BRDF

- What kind of microfacets reflect wi to wo?
  (hint: microfacets are mirrors)





Fresnel term

shadowing-masking term

distribution of normals

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

Microfacet BRDF: Examples

[Autodesk Fusion 360]

Isotropic / Anisotropic Materials (BRDFs)

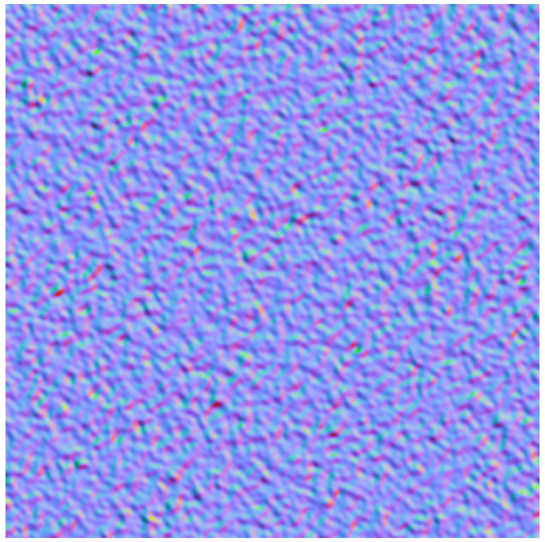
Inside an elevator

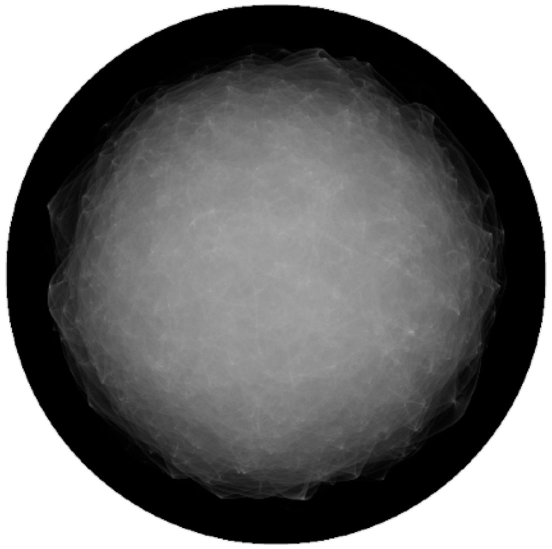
Slide courtesy of Prof. Ren Ng, UC Berkeley

Isotropic / Anisotropic Materials (BRDFs)

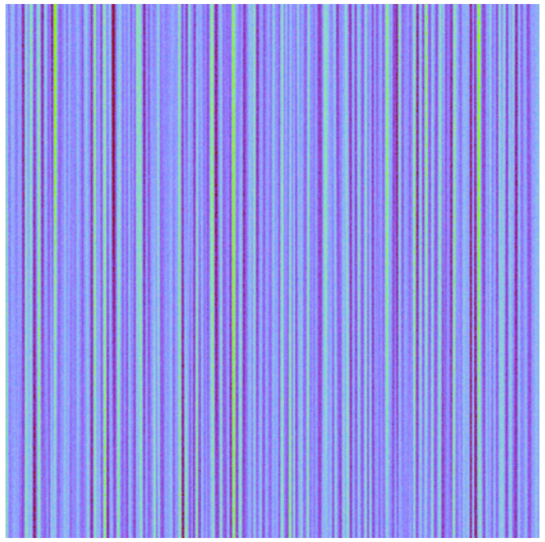
- Key: directionality of underlying surface

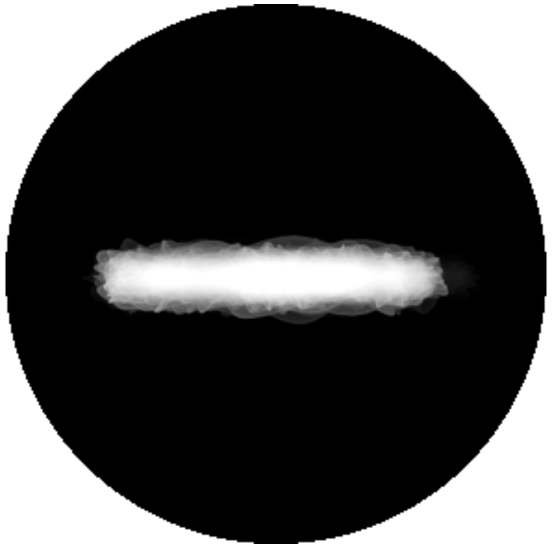
Isotropic





Anisotropic





Surface (normals)

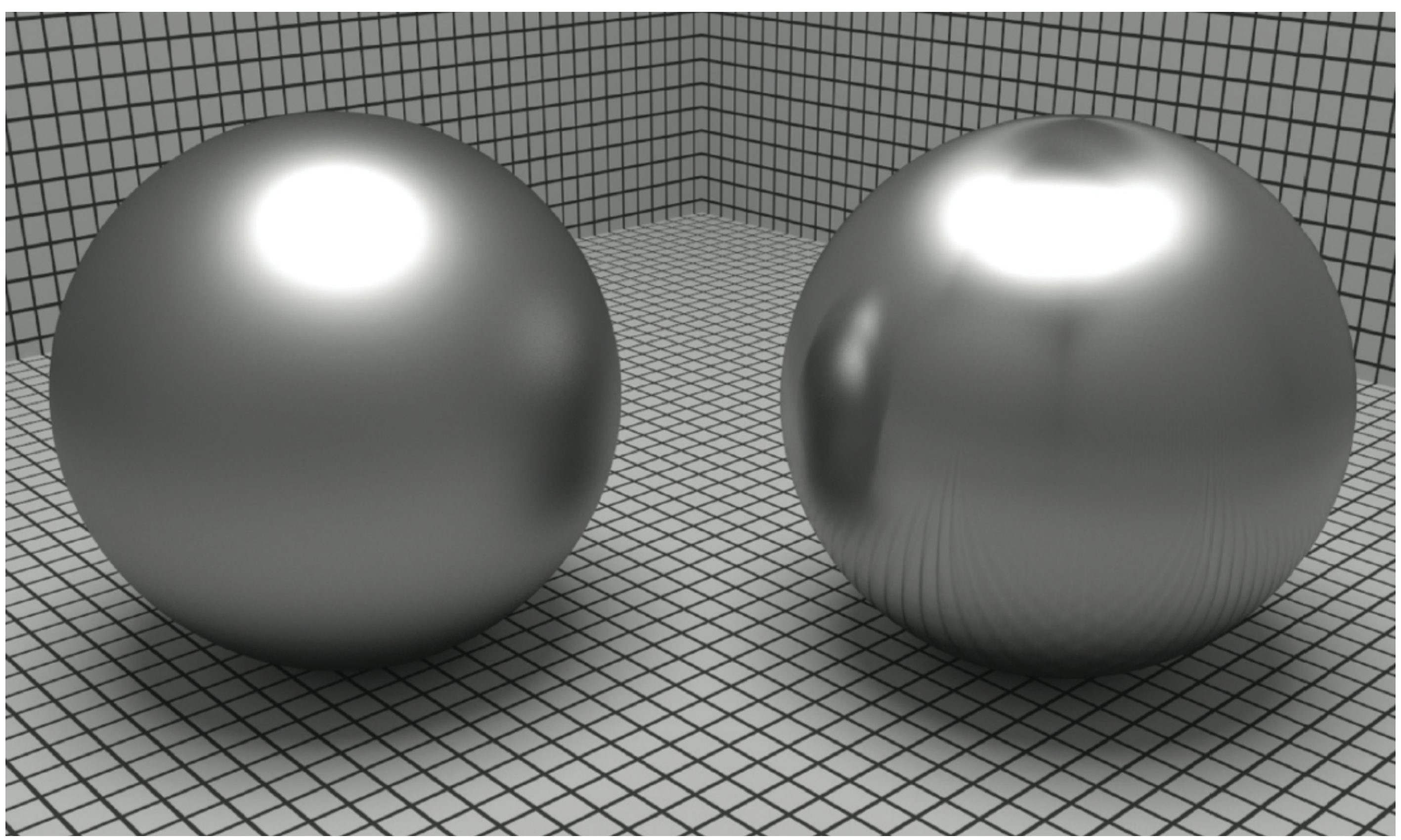
BRDF (fix wi, vary wo)

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

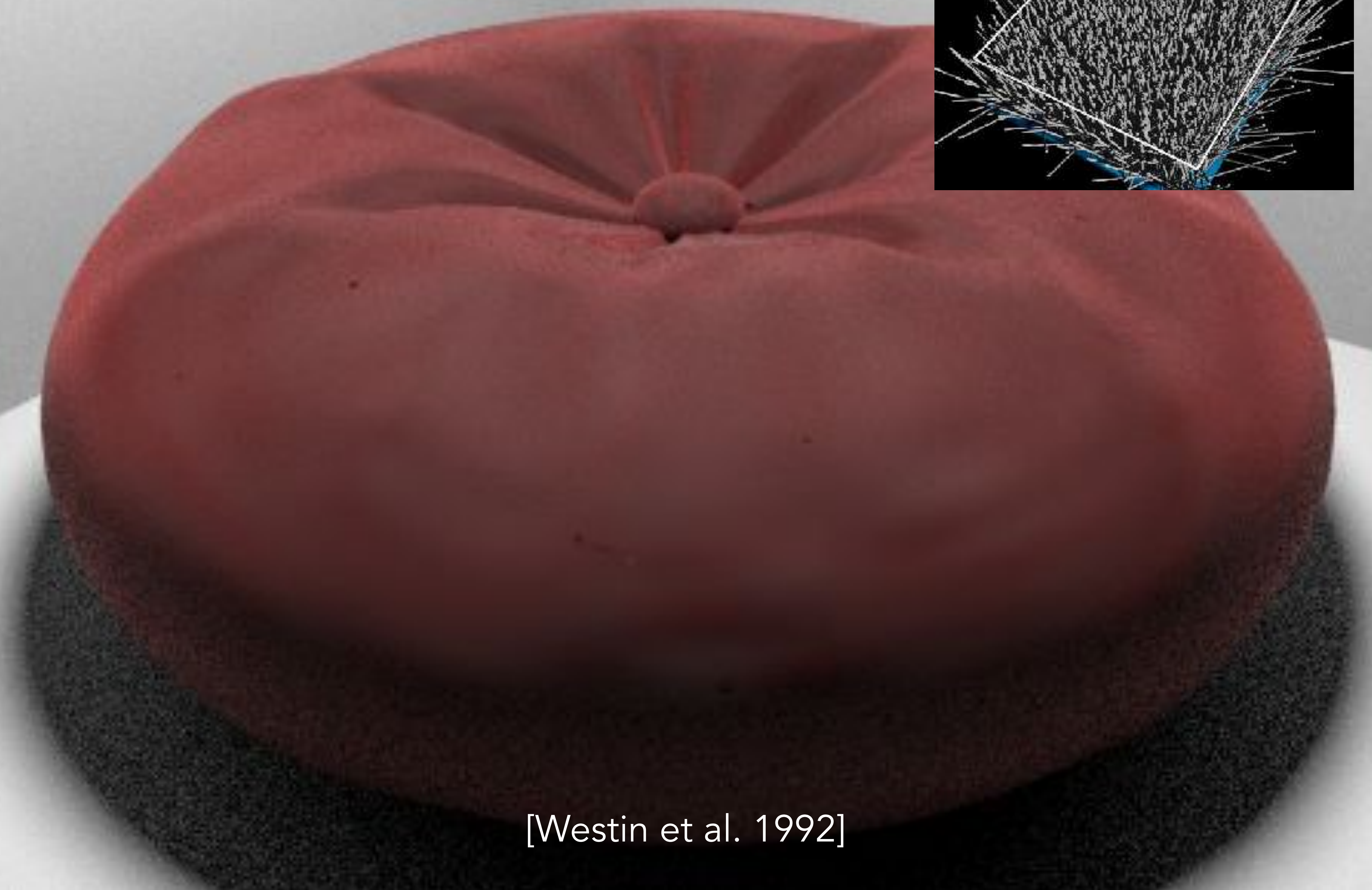
- How is the pan brushed?

[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]

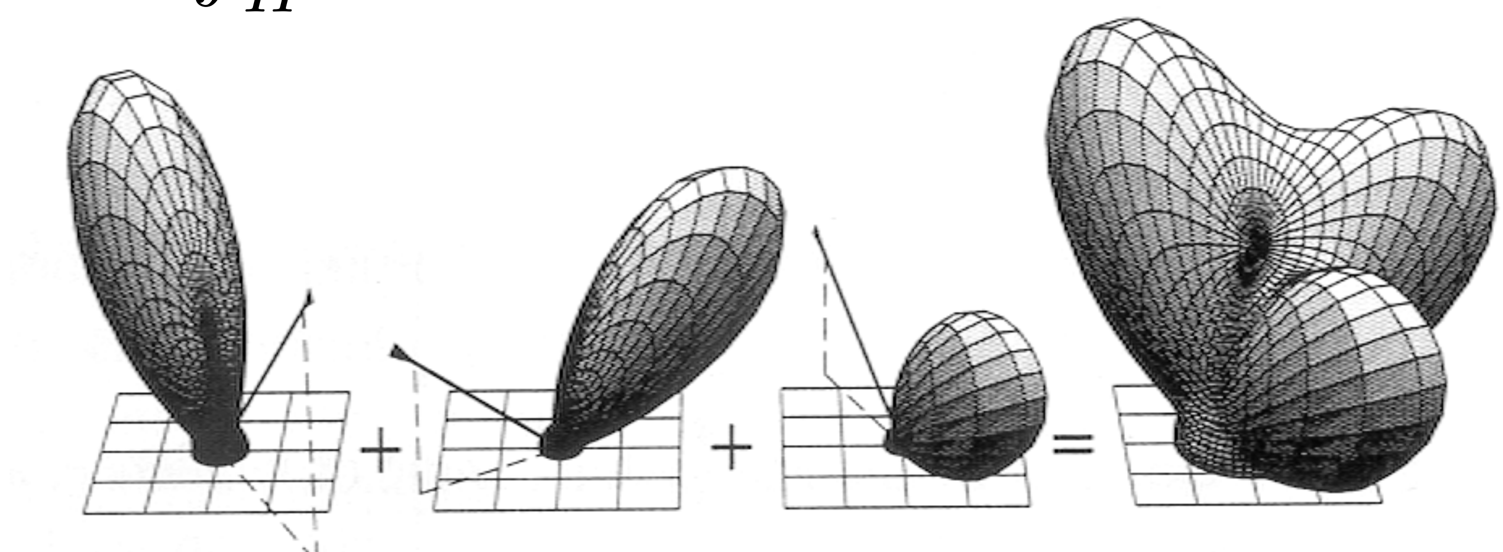
Properties of BRDFs

- Non-negativity

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

- Linearity

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

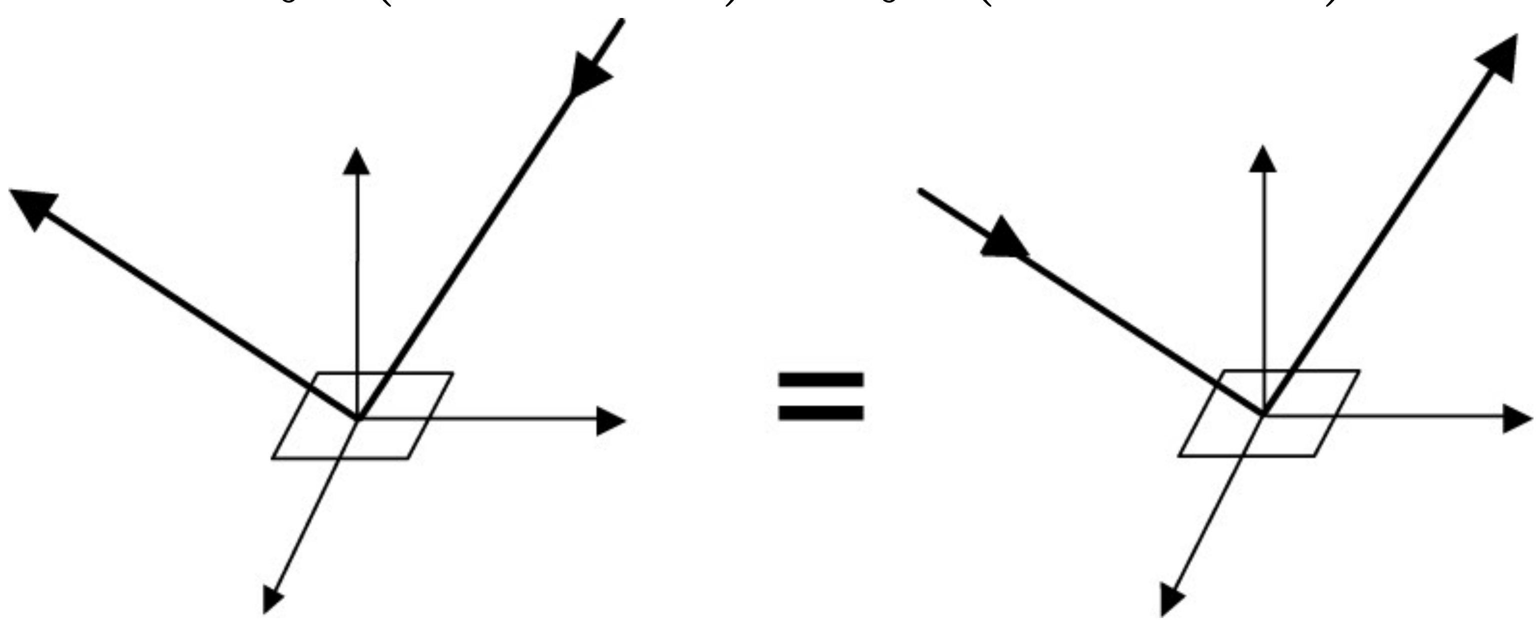


[Sillion et al. 1990]

Properties of BRDFs

- Reciprocity principle

$$f_r(\omega_r \to \omega_i) = f_r(\omega_i \to \omega_r)$$



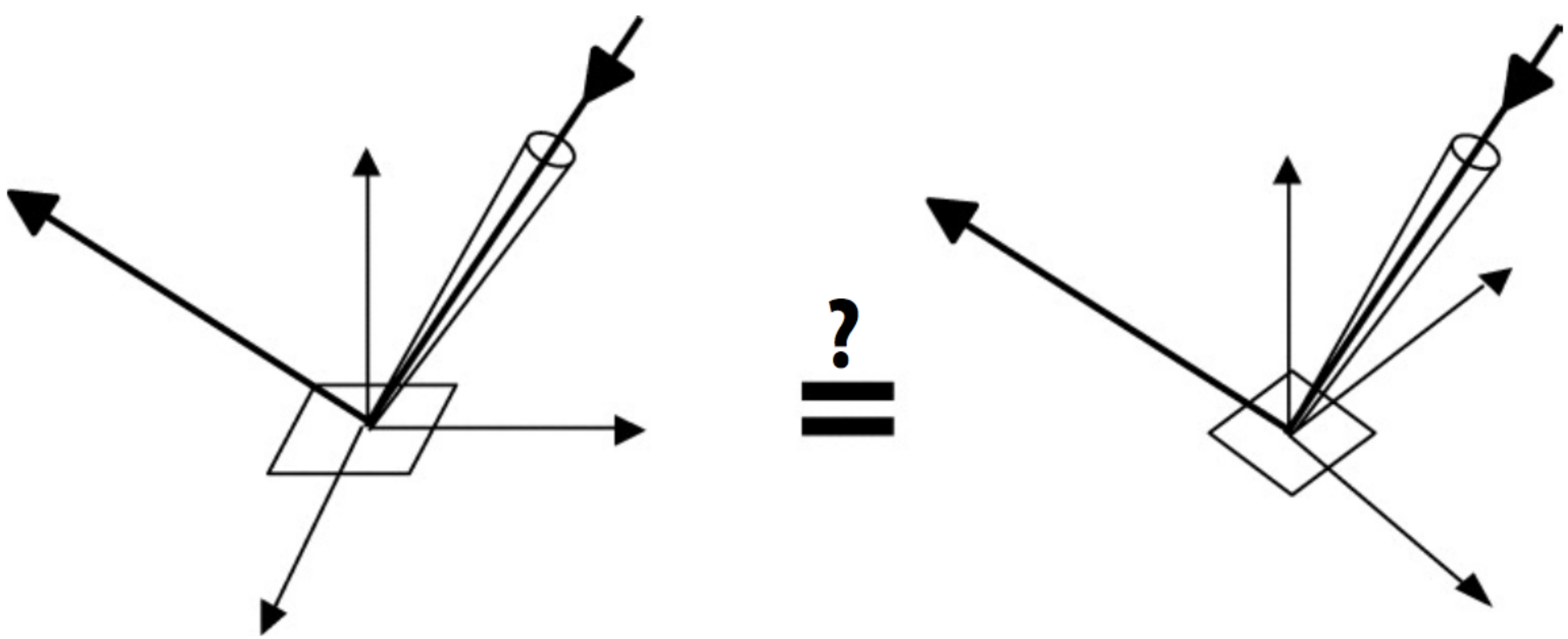
- Energy conservation

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

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:

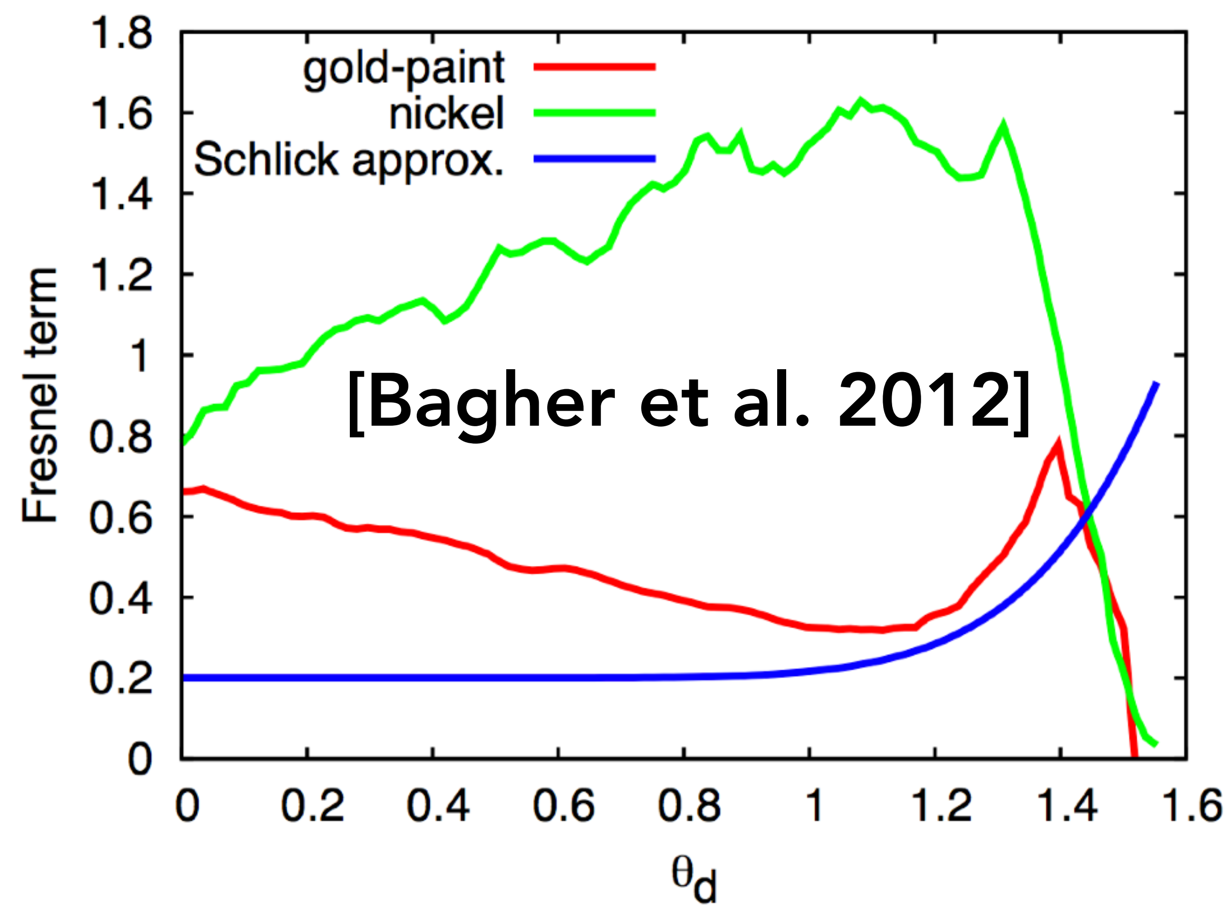
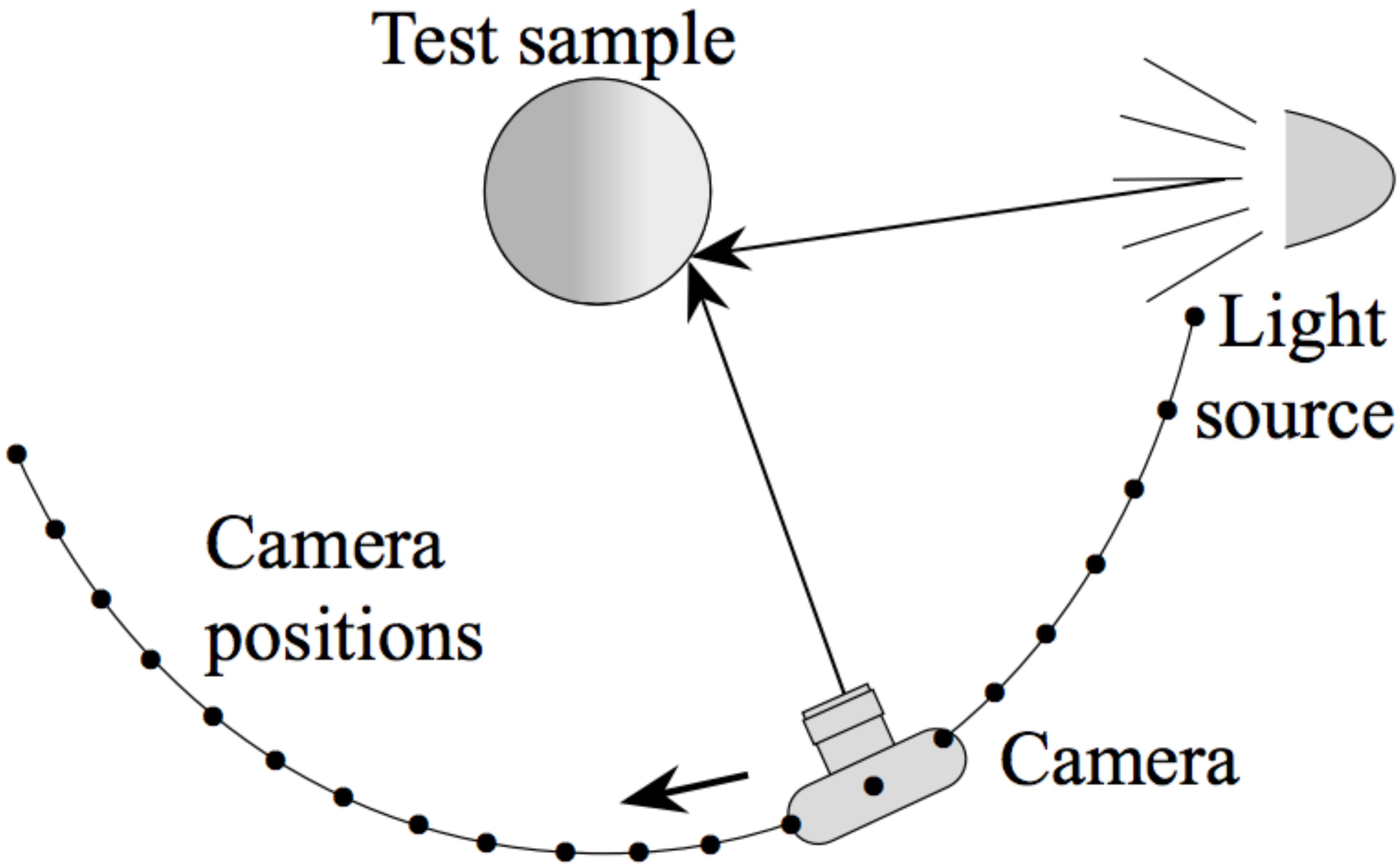
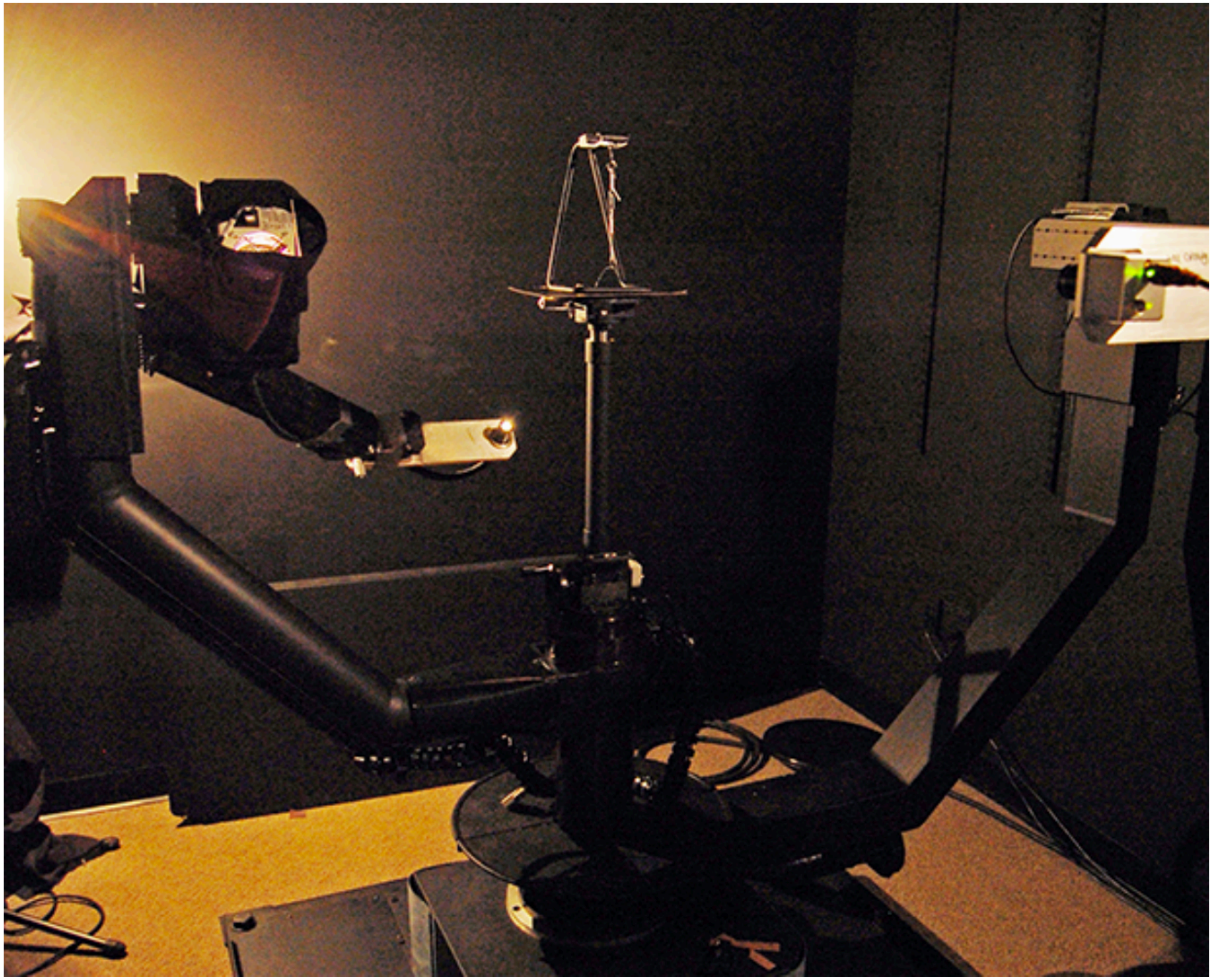


Image-Based BRDF Measurement



[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

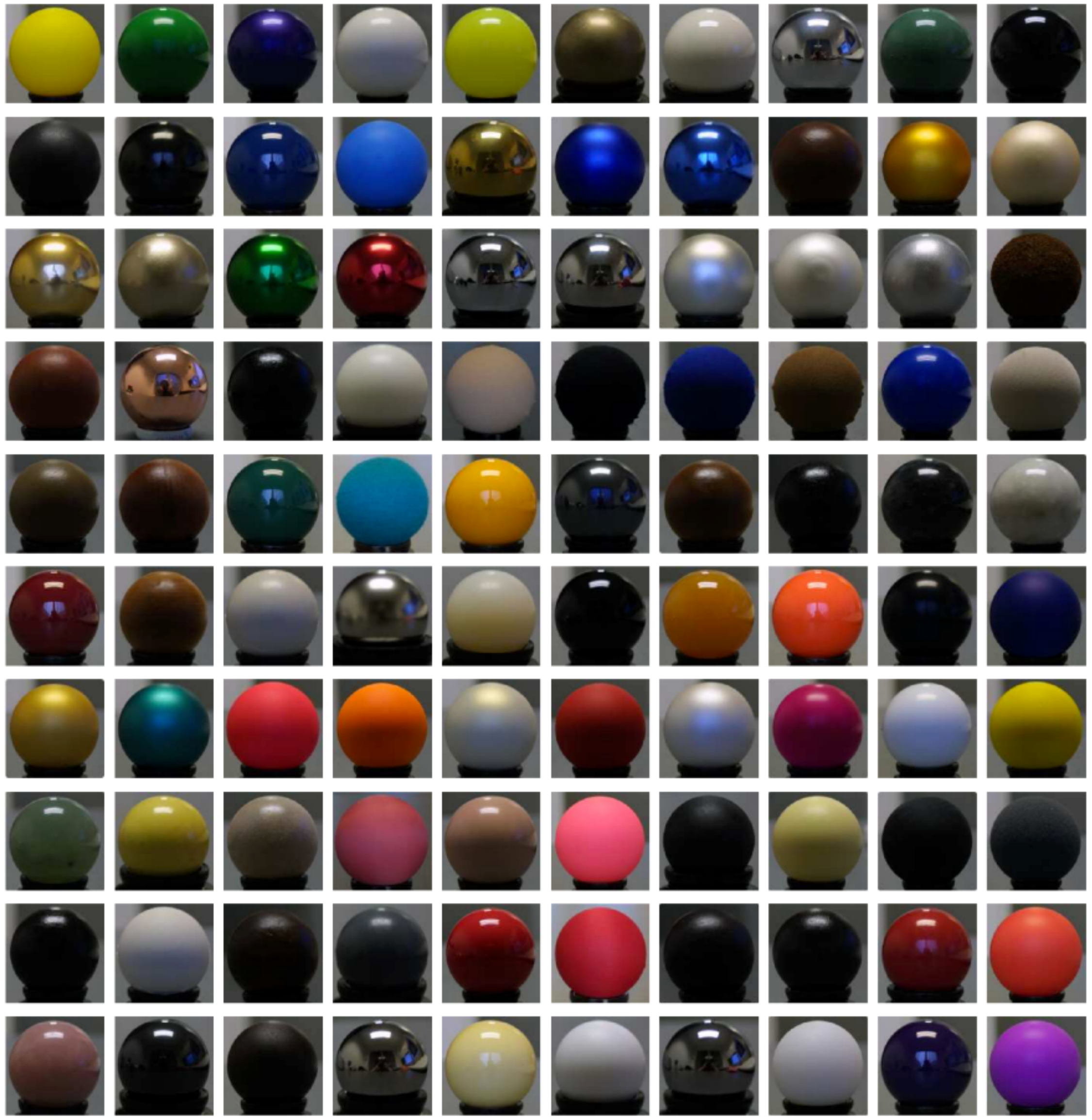
Tabular Representation

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!)