Lecture 18:

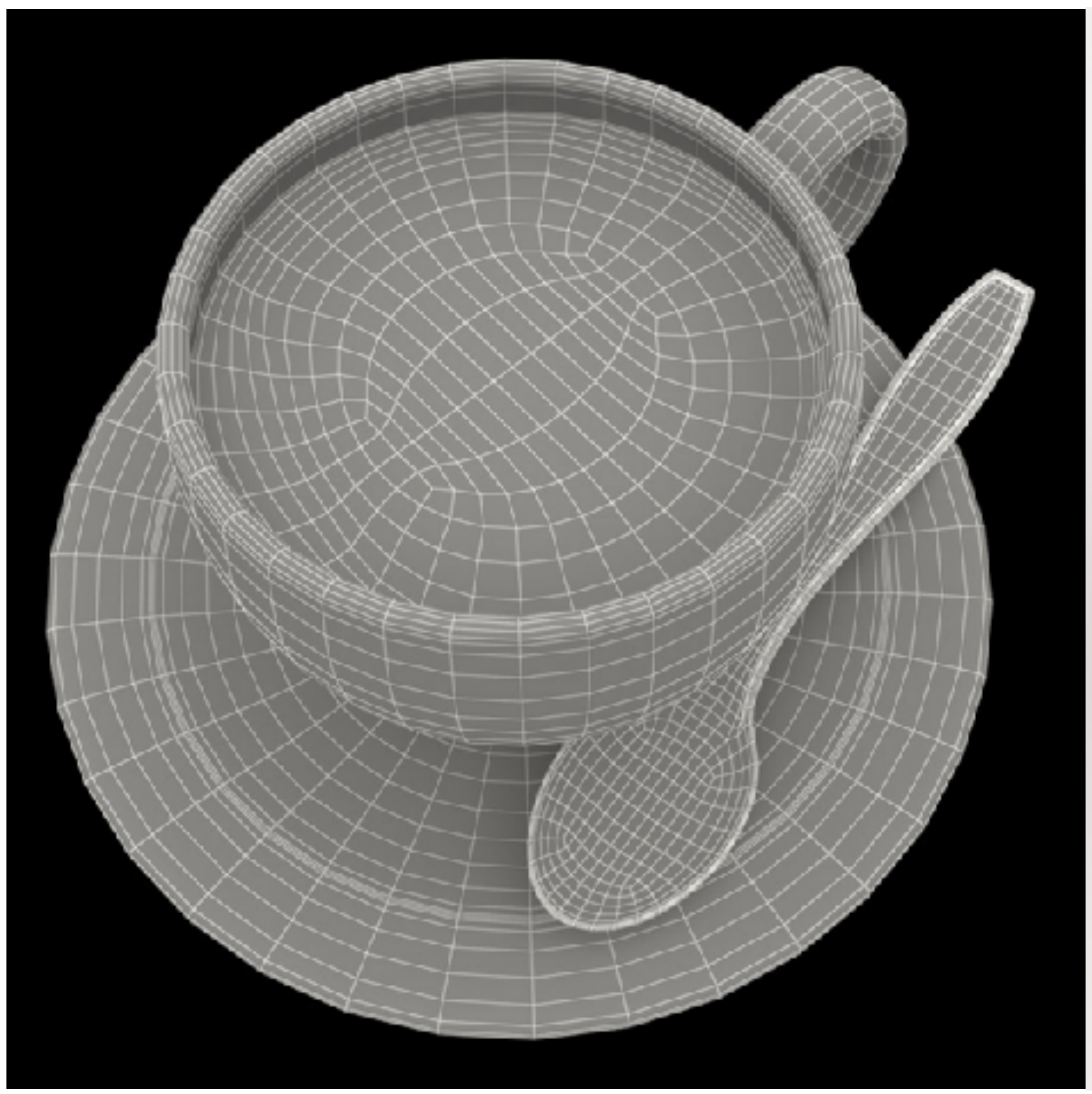
Introduction to Material Modeling

Computer Graphics and Imaging
UC Berkeley CS184/284A

The Appearance of Natural Materials

[Courtesy of Prof. Henrik Wann Jensen, UCSD]

What is Material in Computer Graphics?



3D coffee mug model

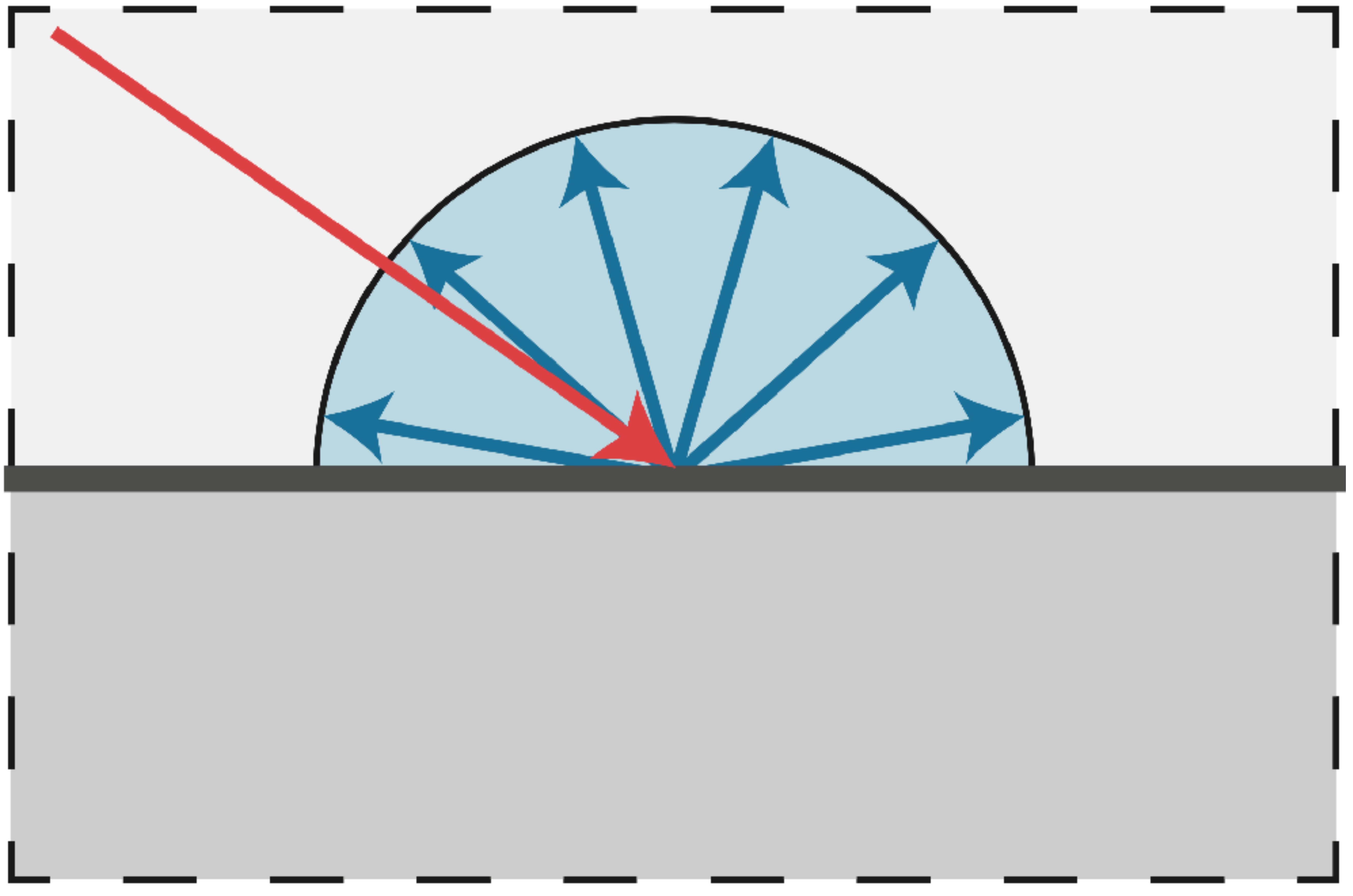
Rendered

Rendered

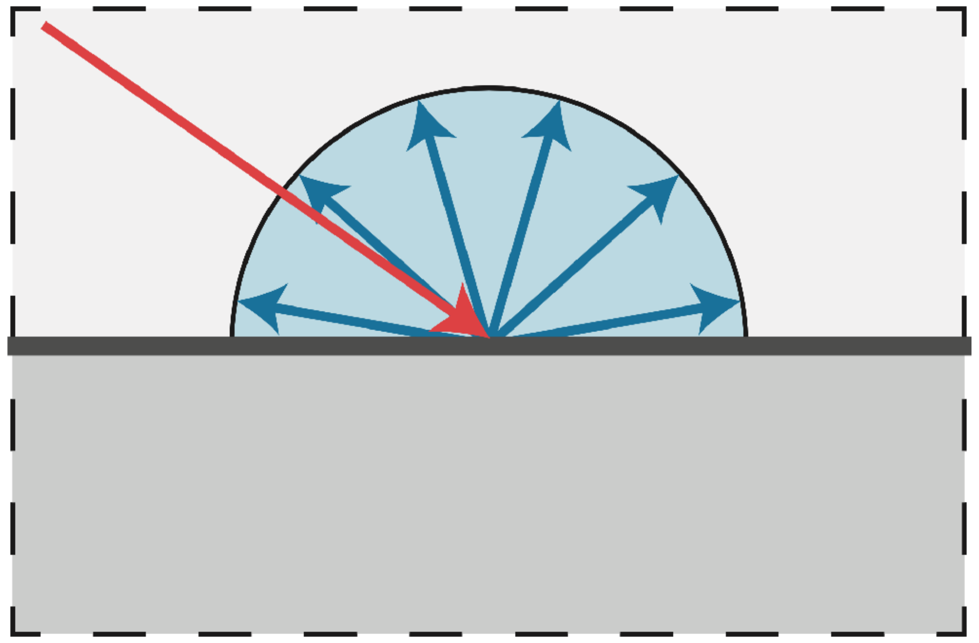
[From TurboSquid, created by artist 3dror]

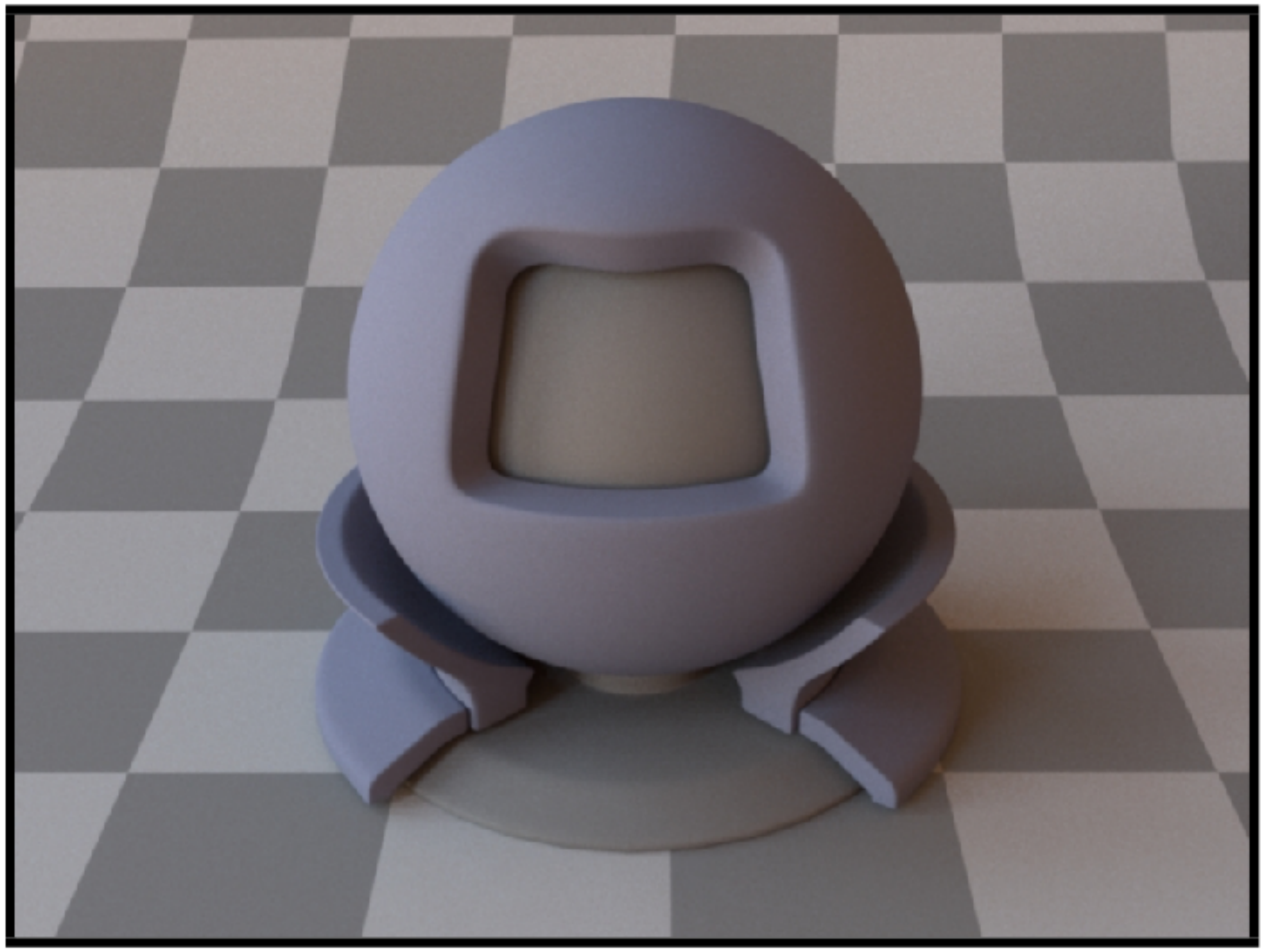
Material == BRDF

What is this material?

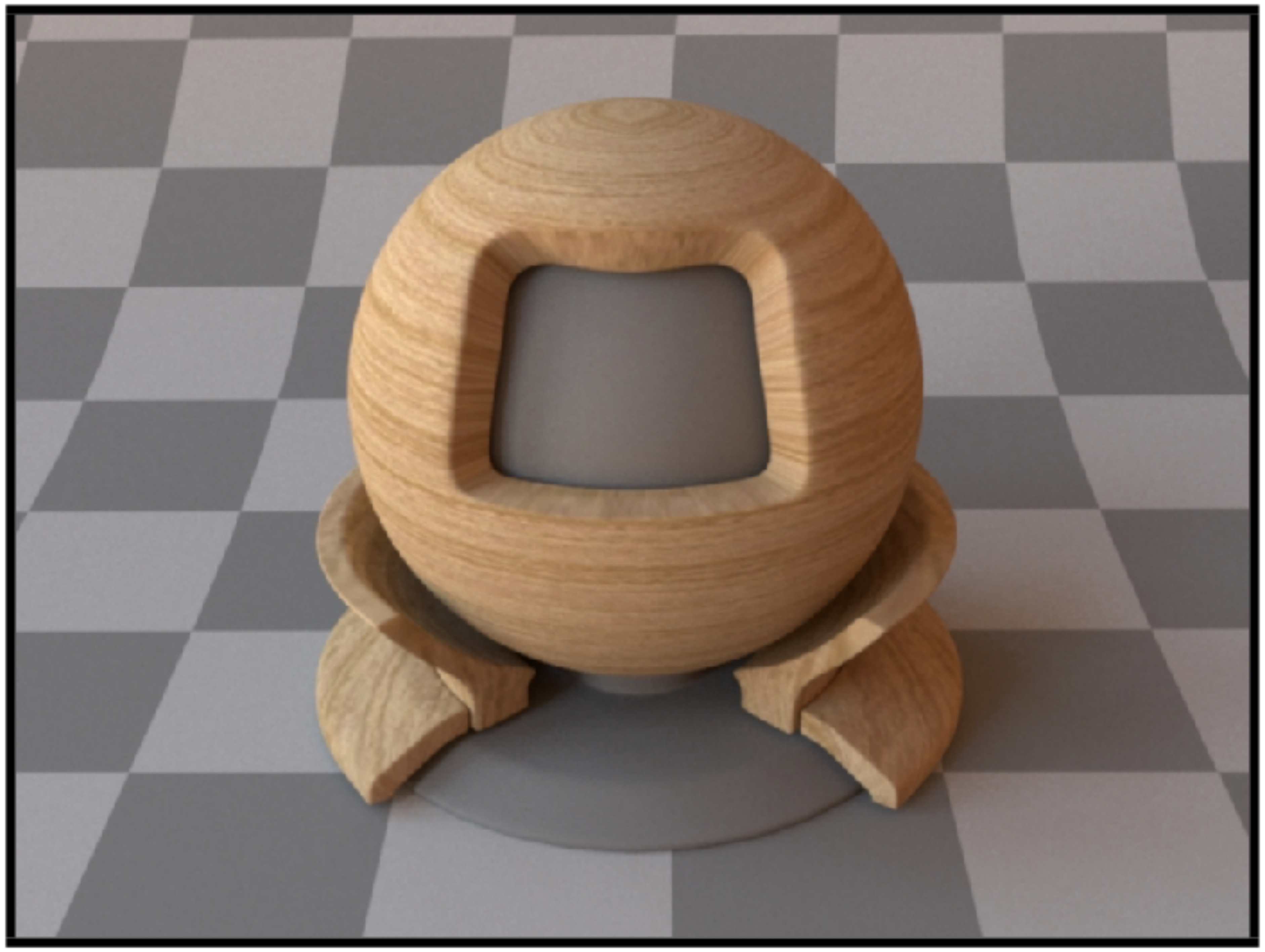


Diffuse / Lambertian Material (BRDF)





Uniform colored diffuse BRDF

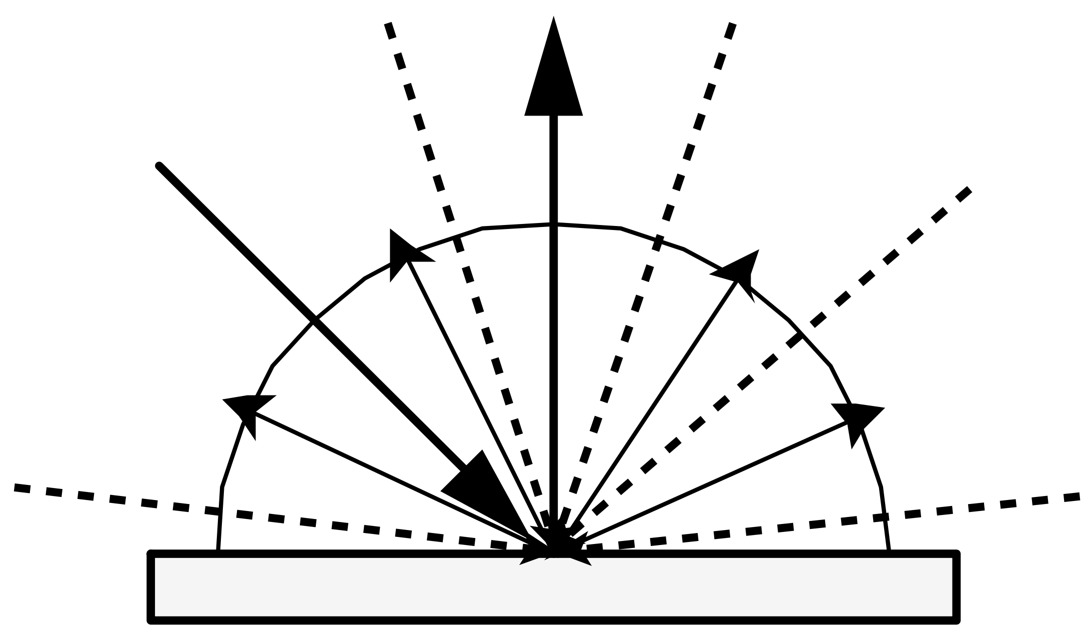


Textured diffuse BRDF

[Mitsuba renderer, Wenzel Jakob, 2010]

Diffuse / Lambertian Material

Light is equally reflected in each output direction



$$f_r = c$$

Suppose the incident lighting is uniform:

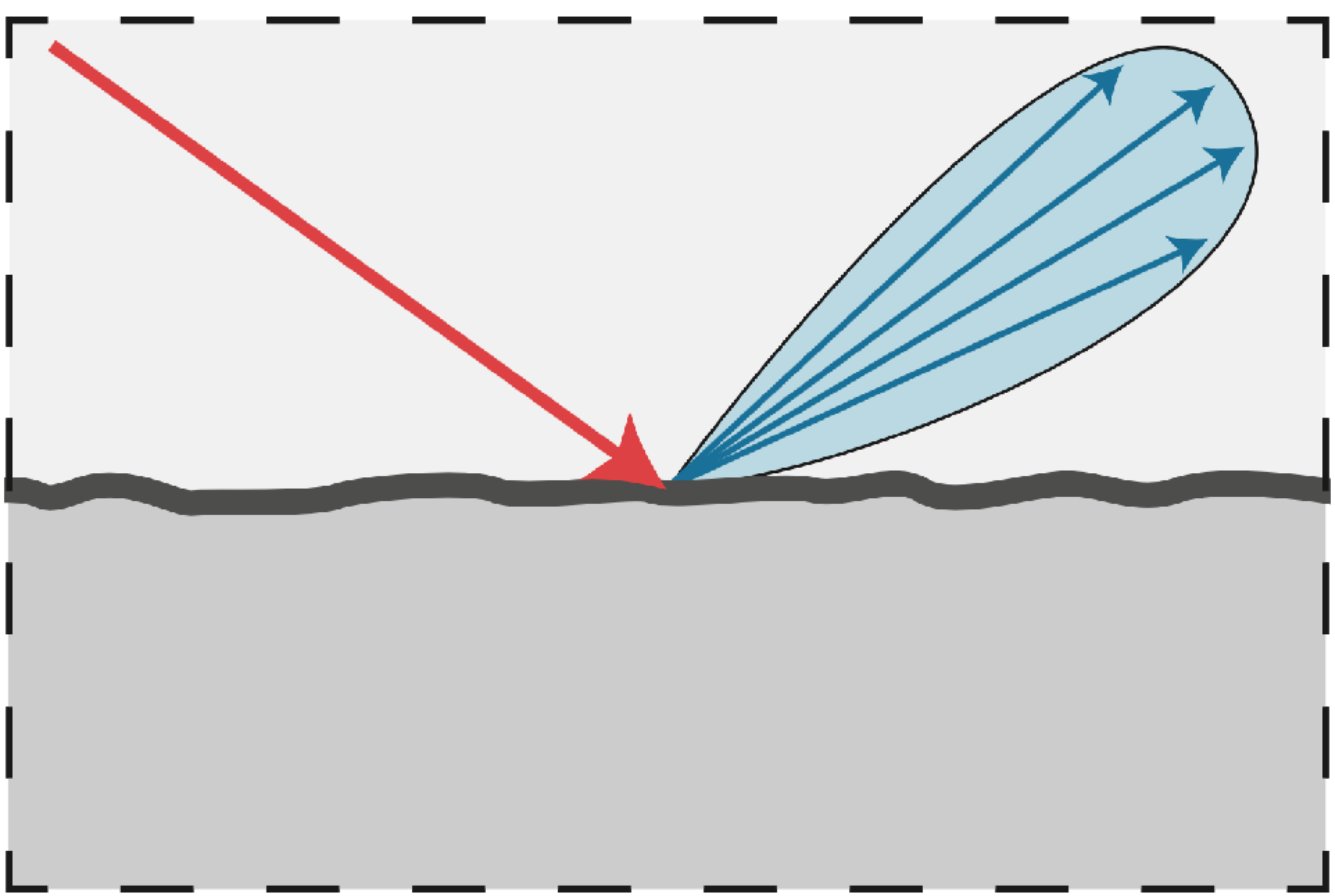
$$L_o(\omega_o) = \int_{H^2} f_r L_i(\omega_i) \cos\theta_i \, \mathrm{d}\omega_i$$

$$= f_r L_i \int_{H^2} \cancel{(\omega_i)} \cos\theta_i \, \mathrm{d}\omega_i$$

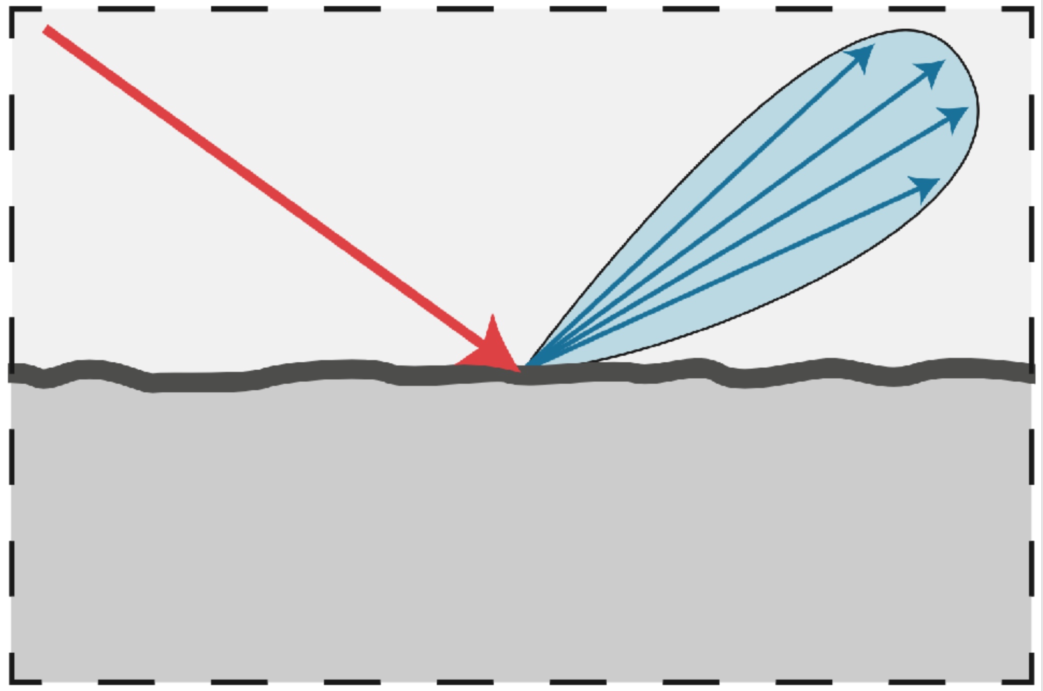
$$= \pi f_r L_i$$

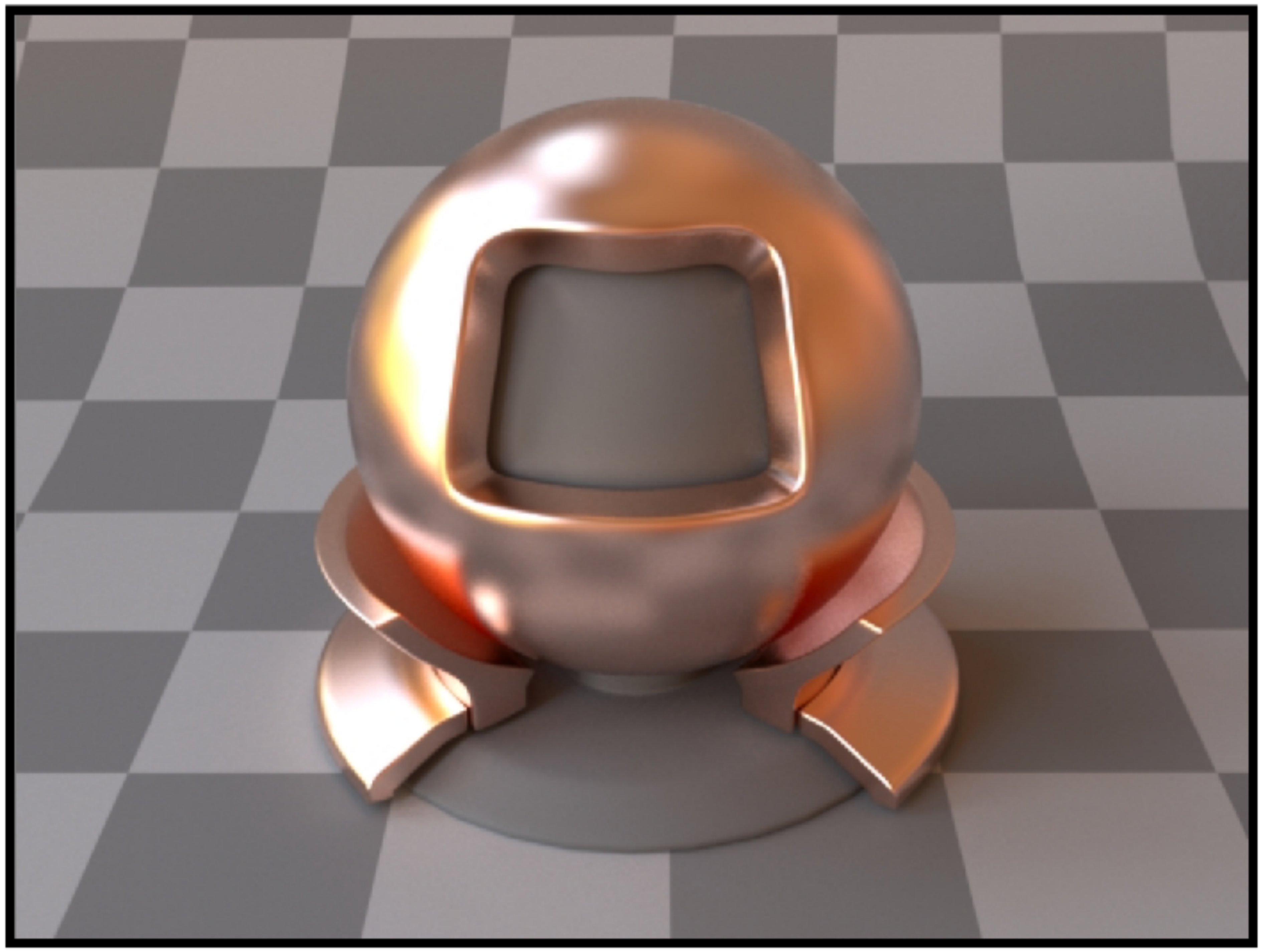
$$f_r = \frac{\rho}{\pi}$$ — albedo (color)

What is this material?

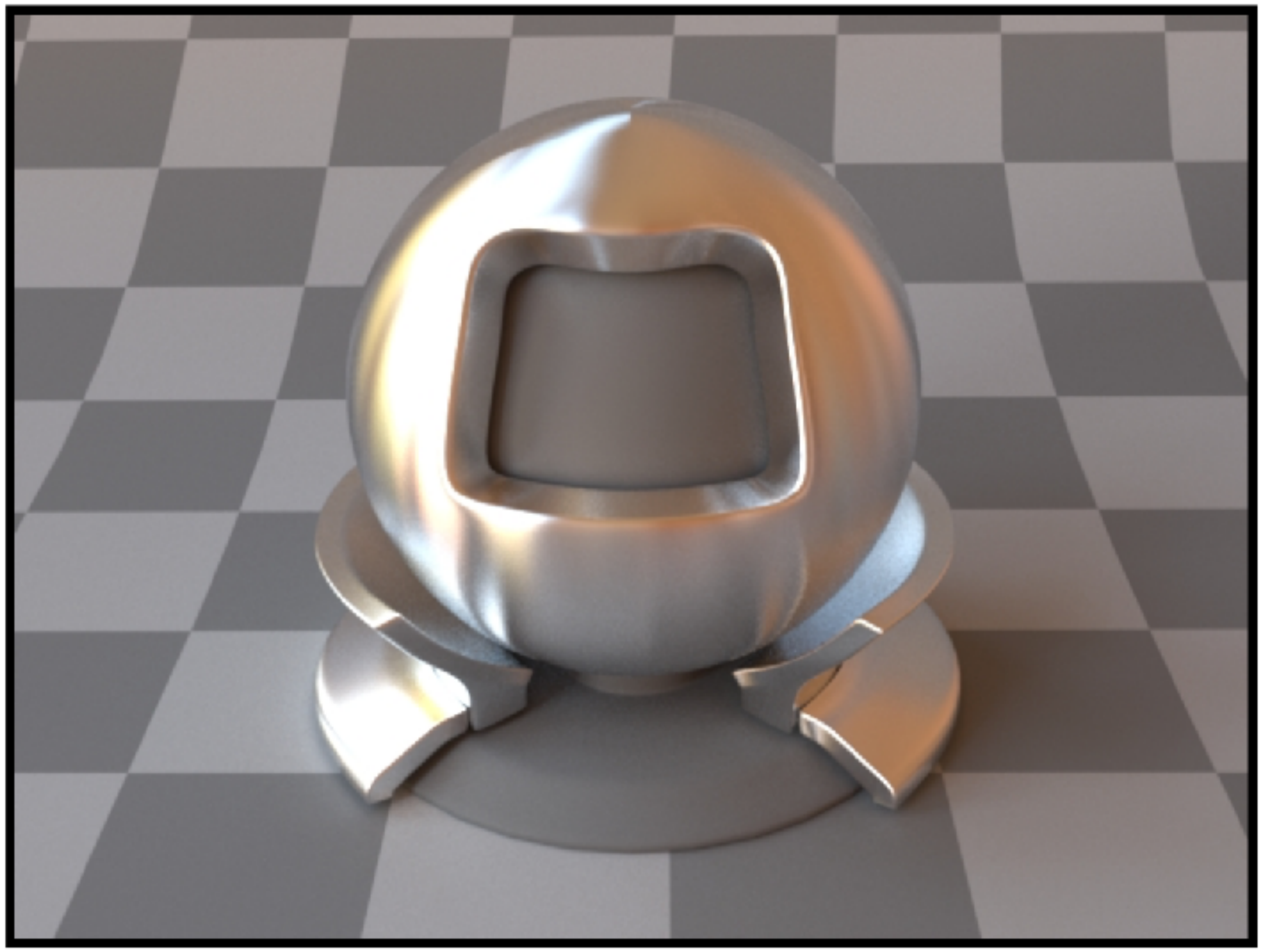


Glossy material (BRDF)





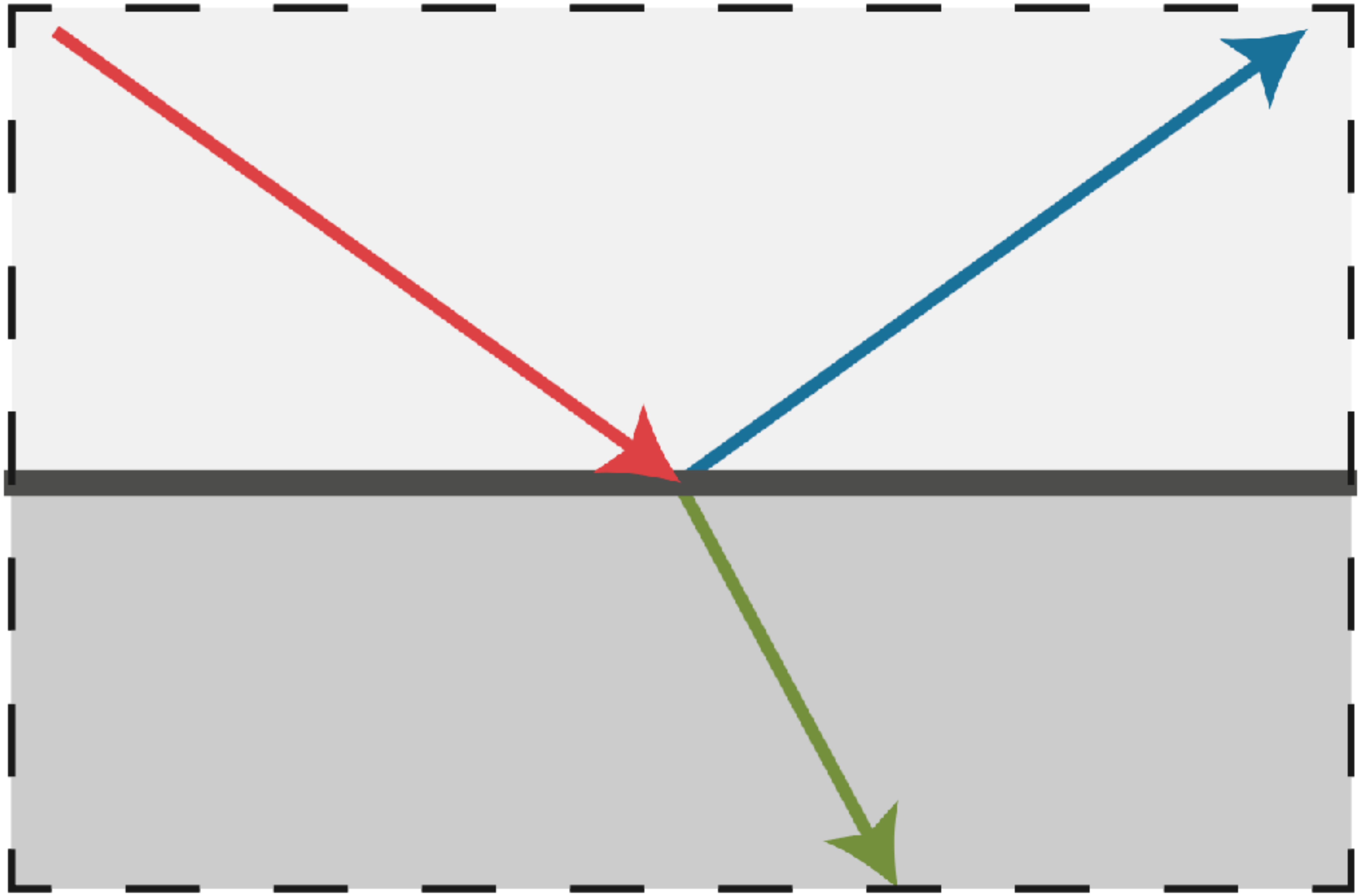
Copper



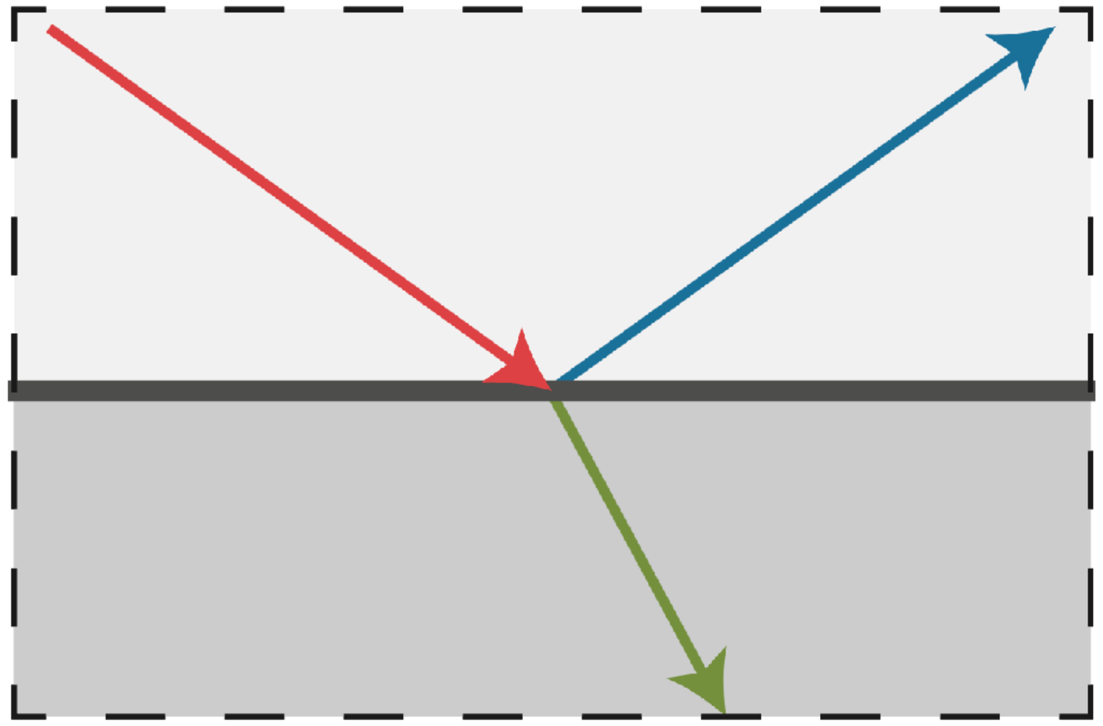
Aluminum

[Mitsuba renderer, Wenzel Jakob, 2010]

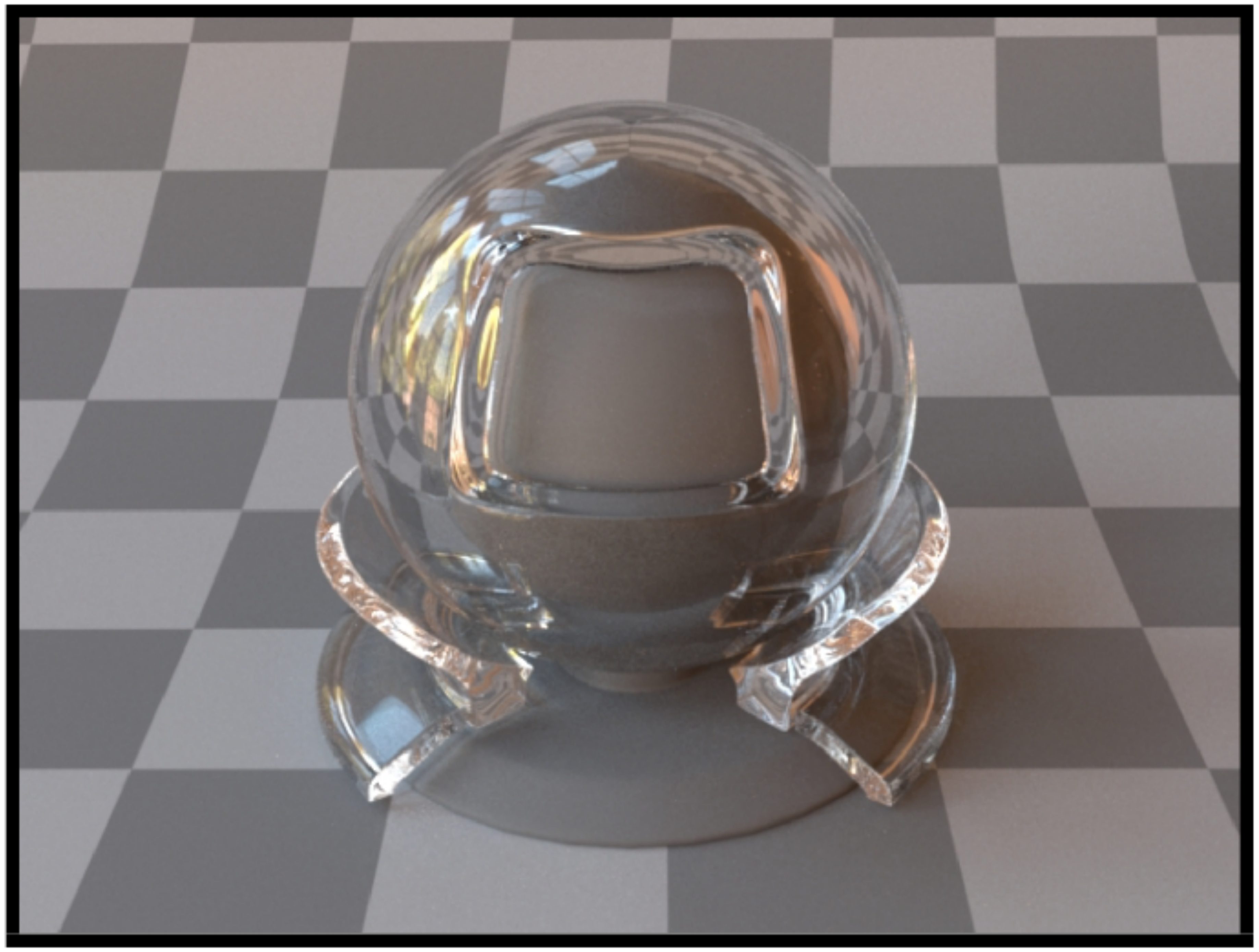
What is this material?



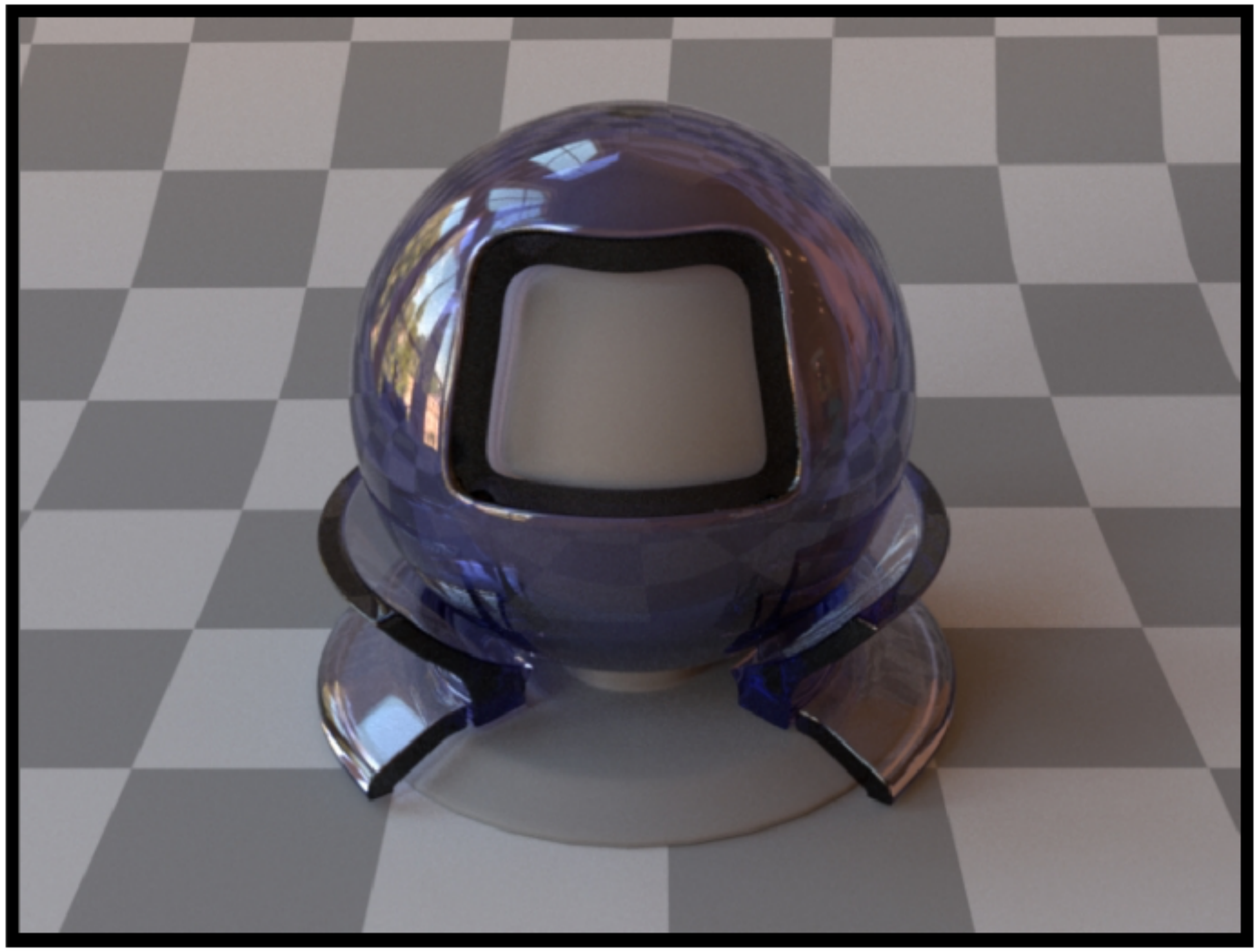
Ideal reflective / refractive material (BSDF*)



[Mitsuba renderer, Wenzel Jakob, 2010]

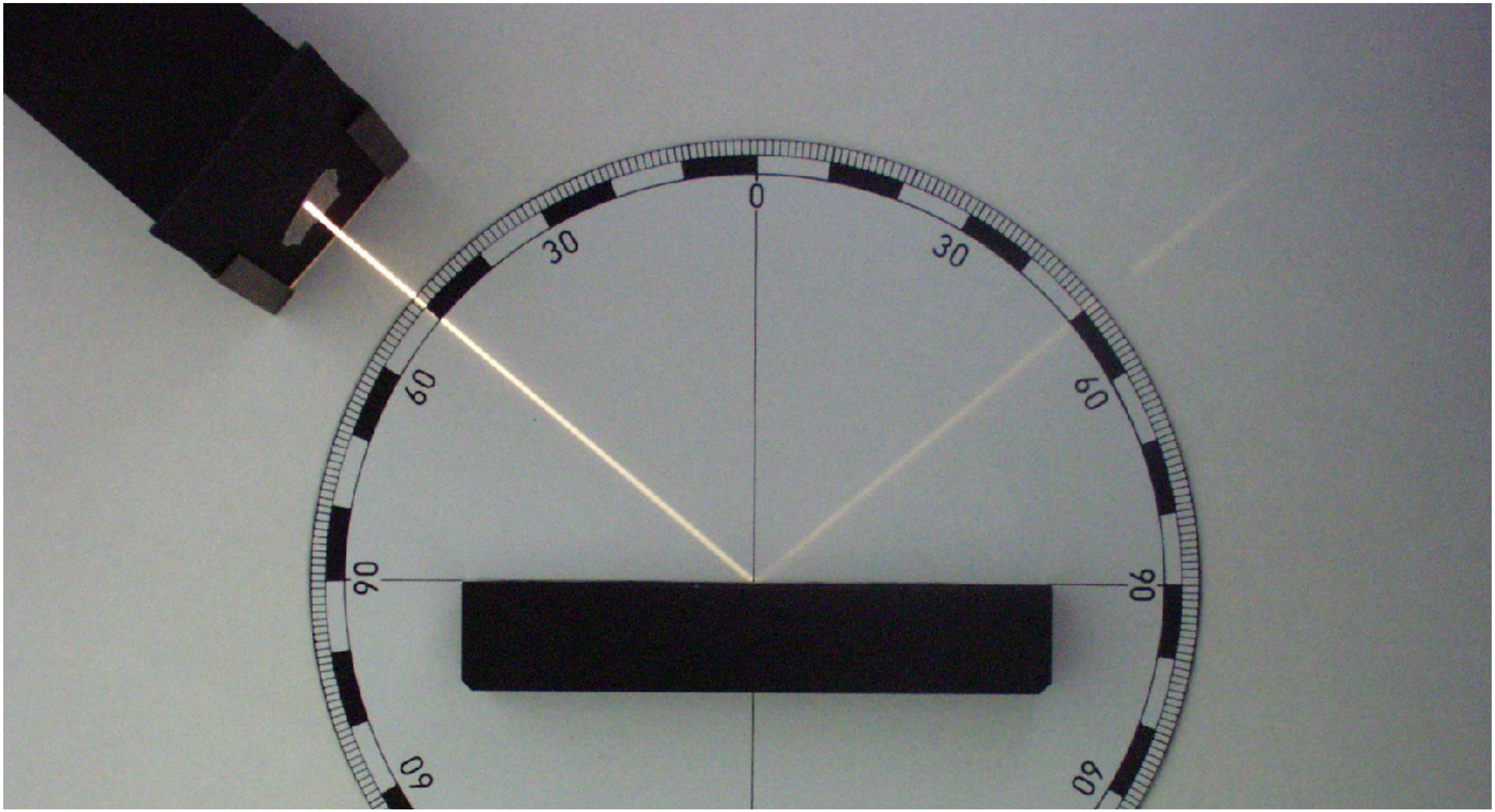


Air <-> water interface



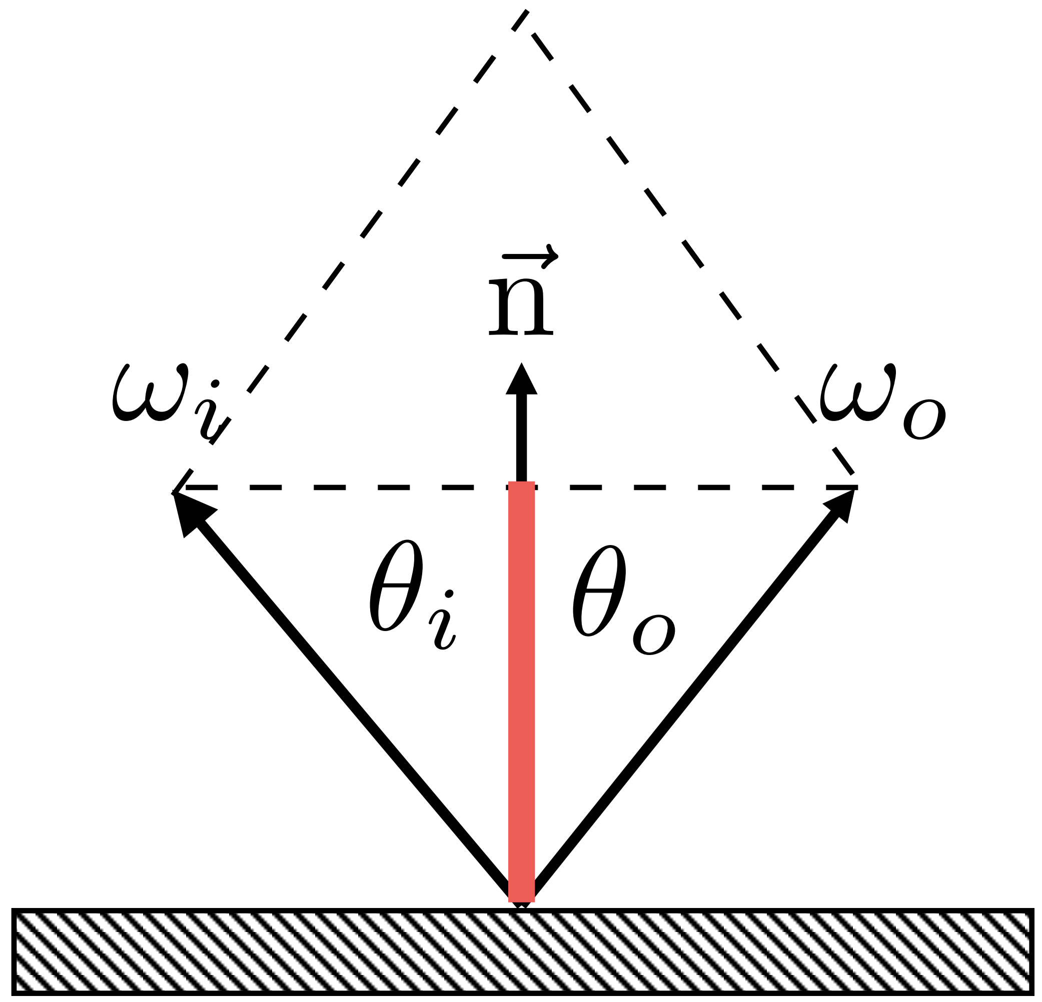
Air <-> glass interface
(with absorption)

Perfect Specular Reflection



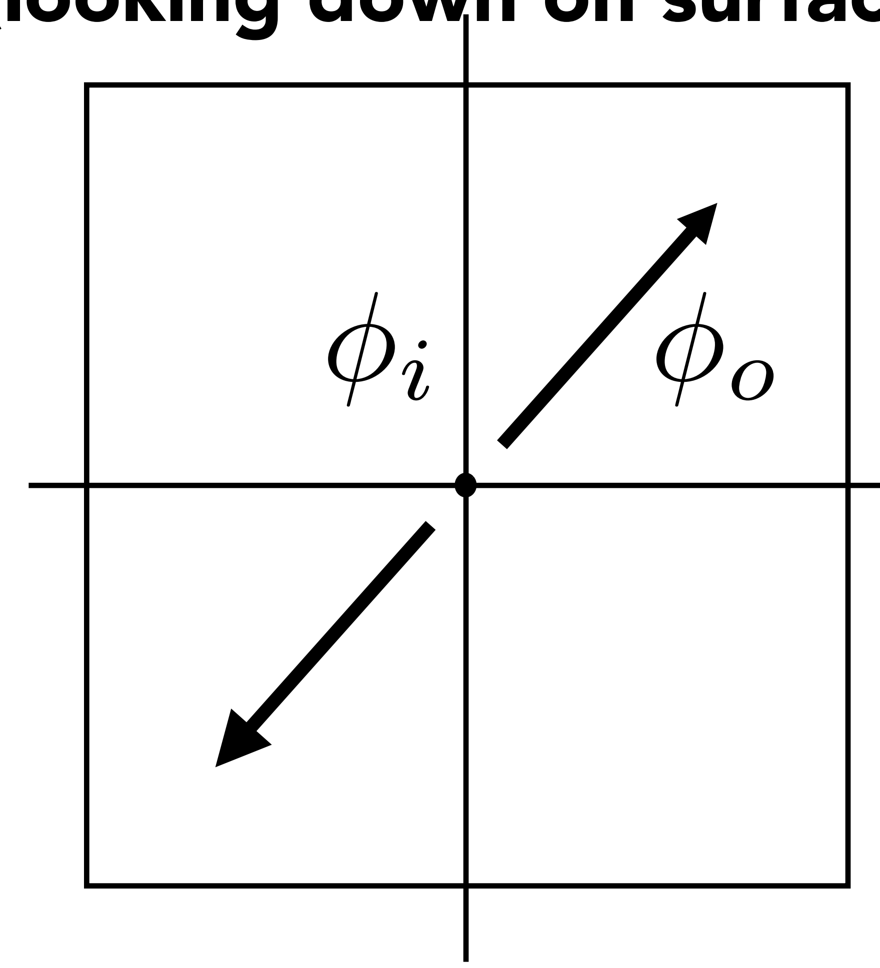
[Zátonyi Sándor]

Perfect Specular Reflection



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

Top-down view
(looking down on surface)

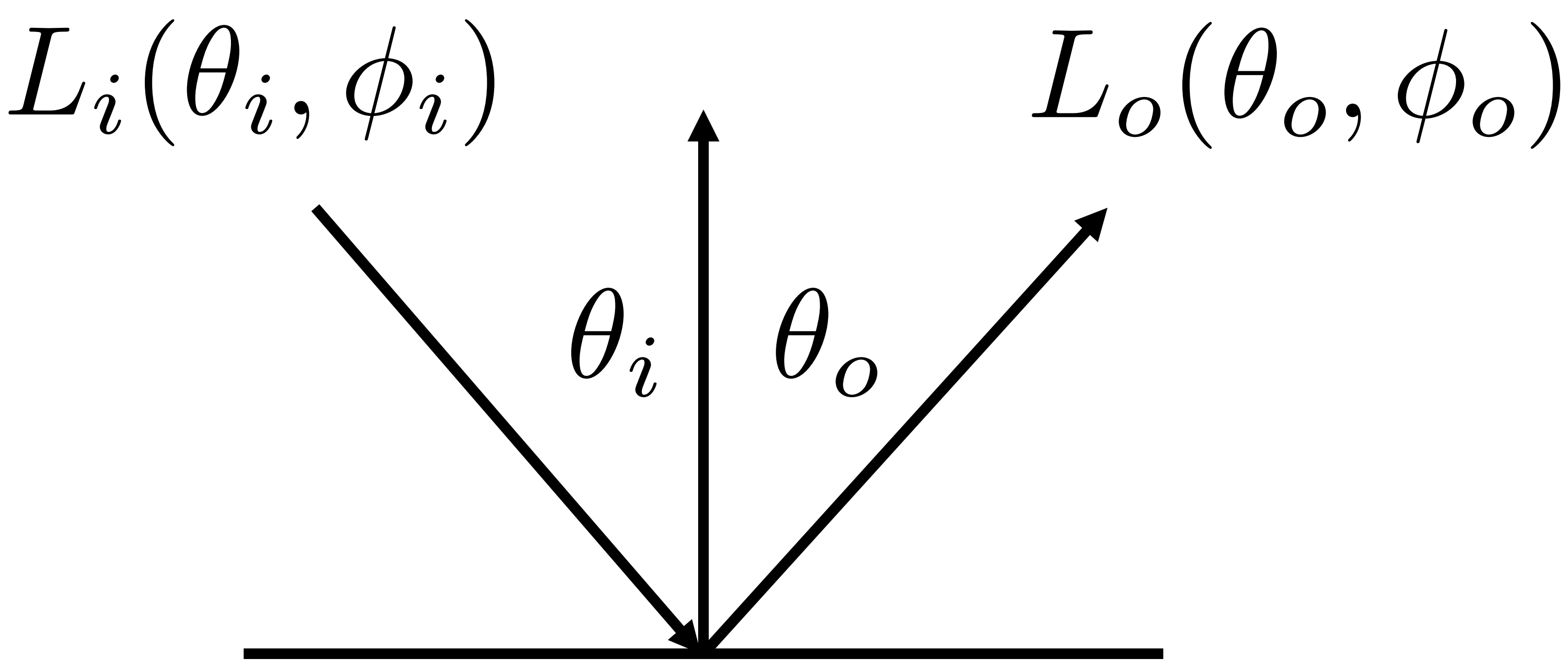


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Perfect Specular Reflection BRDF



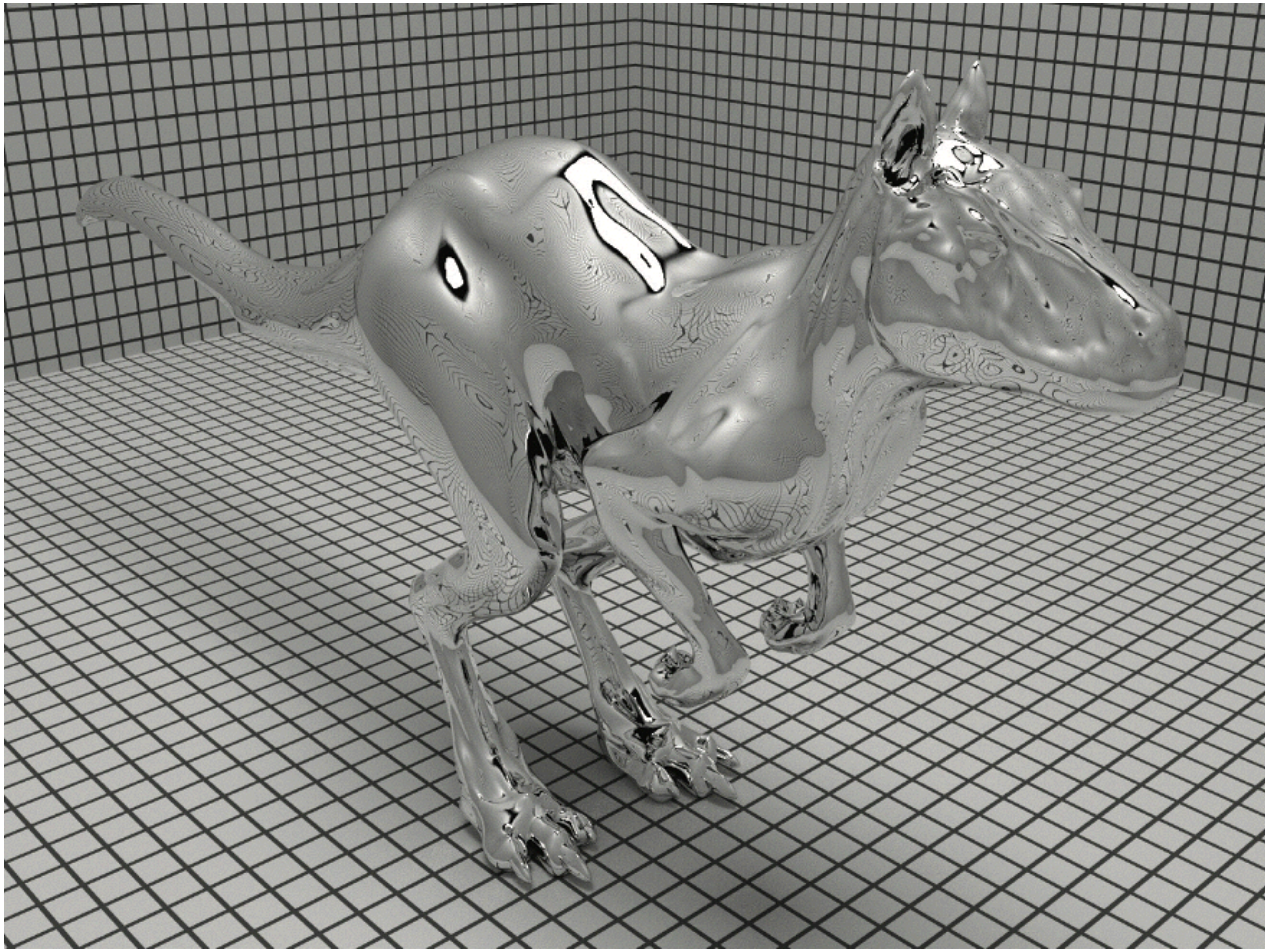
$$L_o(\theta_o, \phi_o) = L_i(\theta_i, \phi_i \pm \pi)$$

$$f_r(\theta_i, \phi_i; \theta_o, \phi_o) = \frac{\delta(\cos\theta_i - \cos\theta_o)}{\boxed{\cos\theta_i}} \delta(\phi_i - \phi_o \pm \pi)$$

- **Why cosθ_i?**

$$\begin{aligned} L_o(\theta_o, \phi_o) &= \int f_r(\theta_i, \phi_i; \theta_o, \phi_o)\, L_i(\theta_i, \phi_i)\, \boxed{\cos\theta_i}\, \mathrm{d}\cos\theta_i\, \mathrm{d}\phi_i \\ &= \int \frac{\delta(\cos\theta_i - \cos\theta_o)}{\cos\theta_i} \delta(\phi_i - \phi_o \pm \pi)\, L_i(\theta_i, \phi_i)\, \cos\theta_i\, \mathrm{d}\cos\theta_i\, \mathrm{d}\phi_i \\ &= L_i(\theta_r, \phi_r \pm \pi) \end{aligned}$$

Perfect Specular Reflection BRDF



PBRT

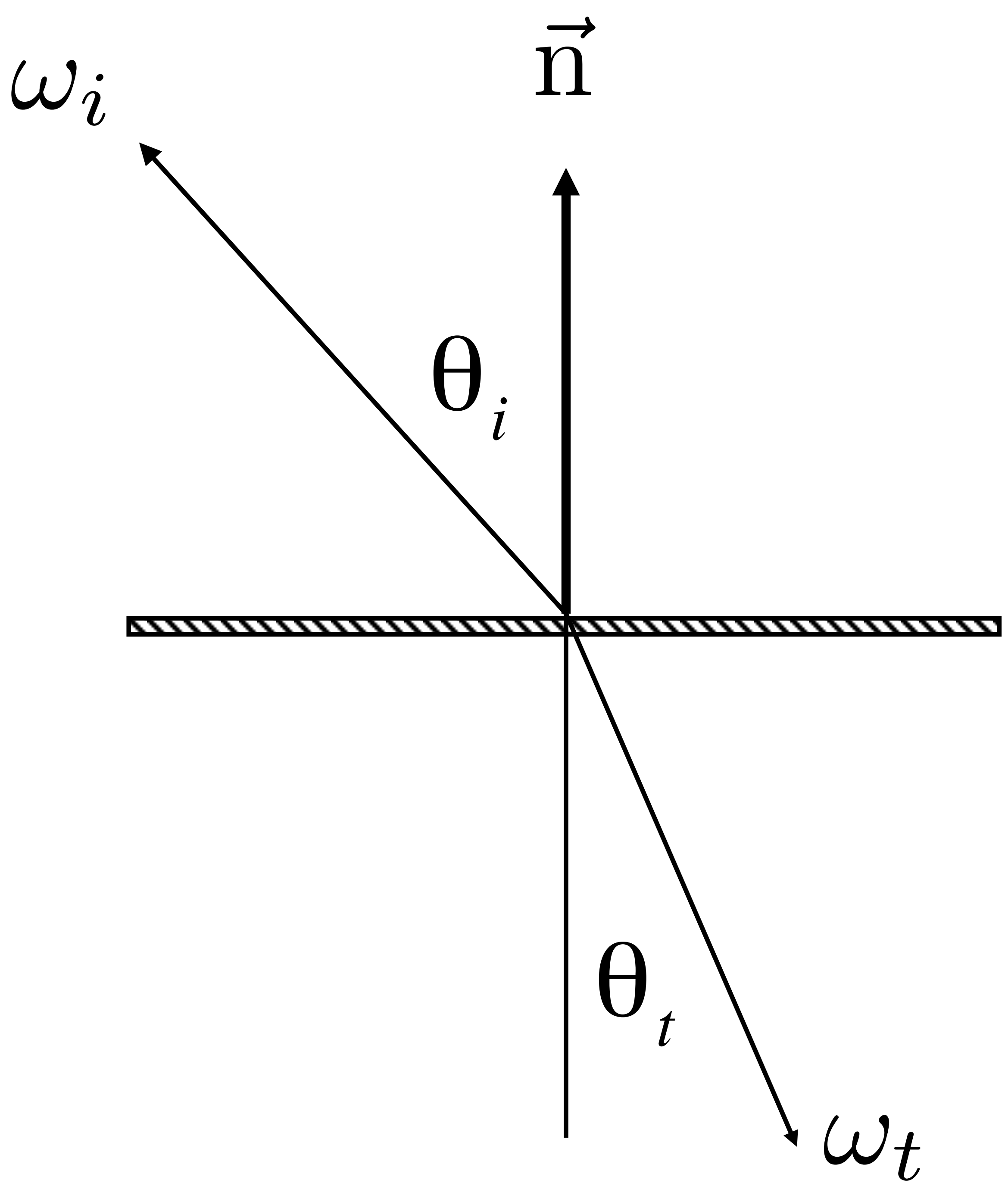
Specular Refraction

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

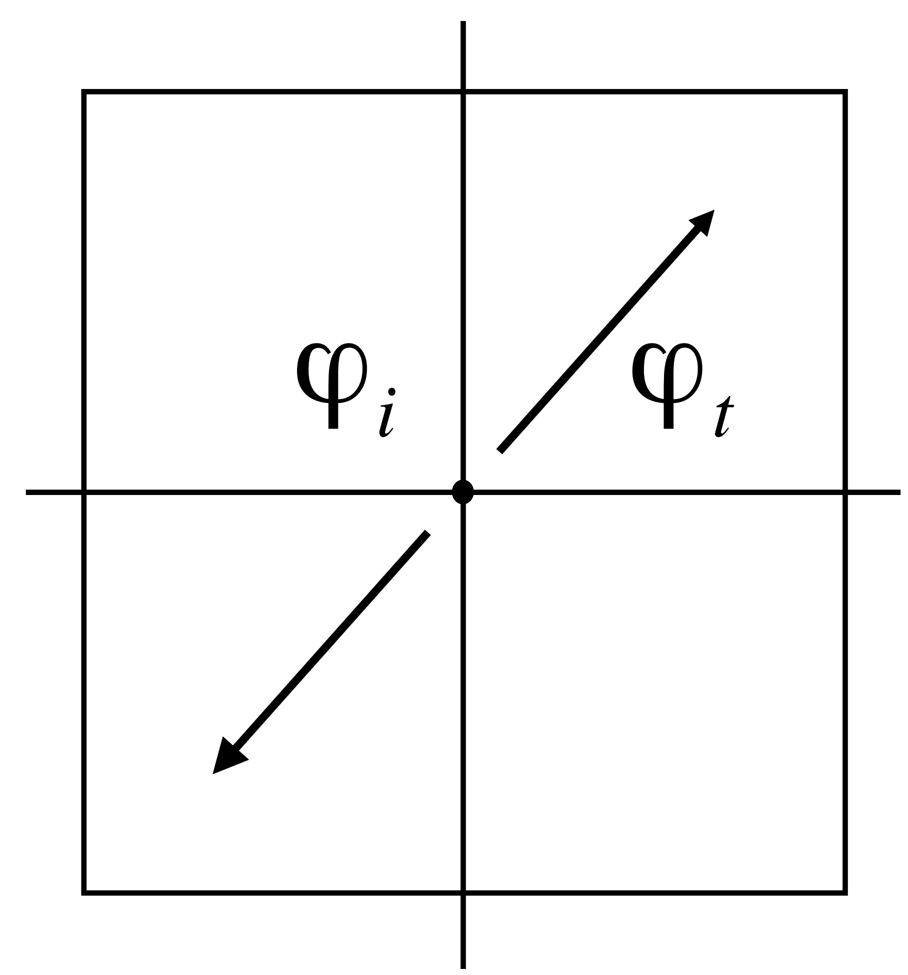
Light refracts when it enters a new medium.

Snell's Law

Transmitted angle depends on
- index of refraction (IOR) for incident ray
- index of refraction (IOR) for exiting ray



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

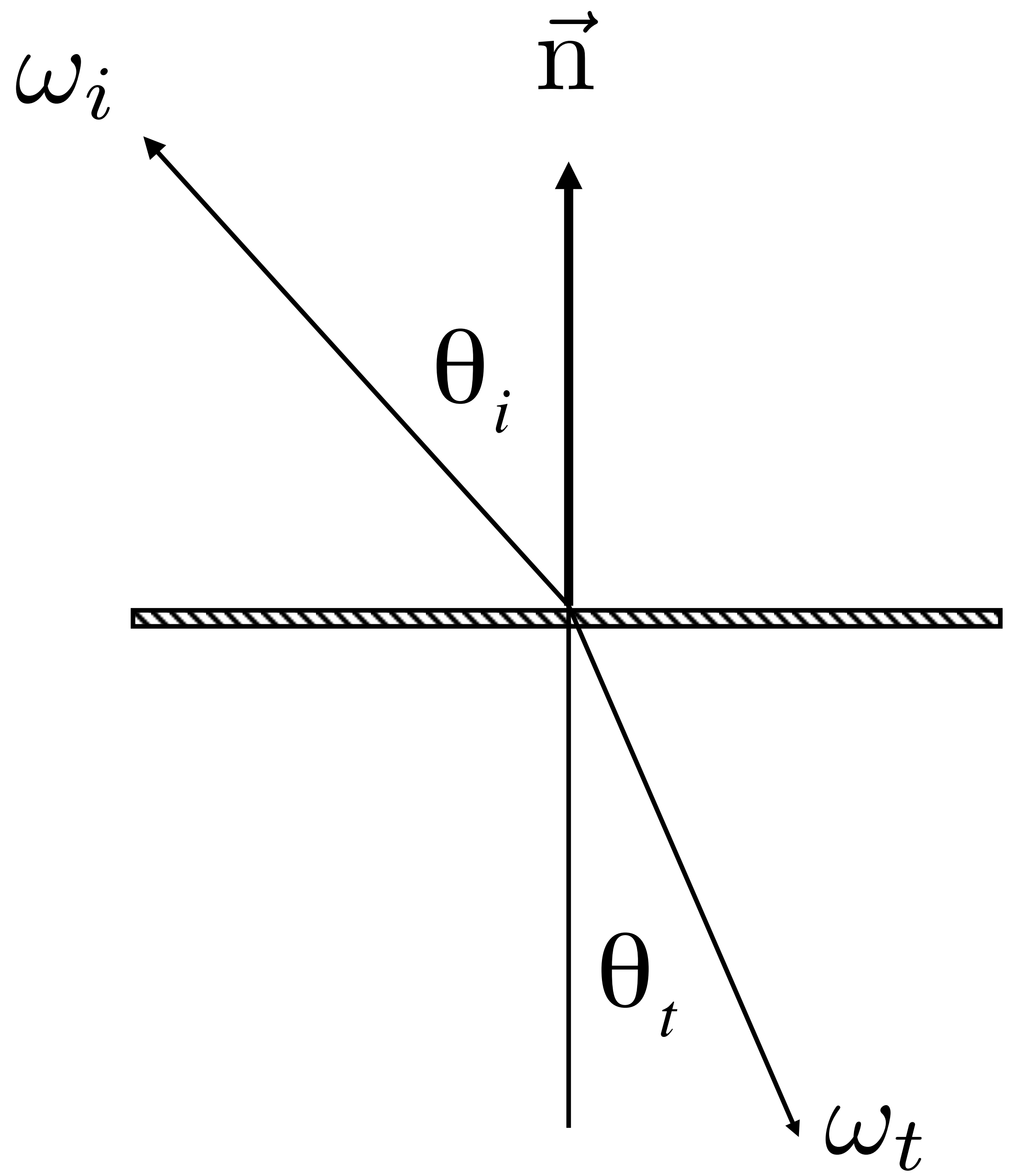


$$\varphi_t = \varphi_i \pm \pi$$

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:

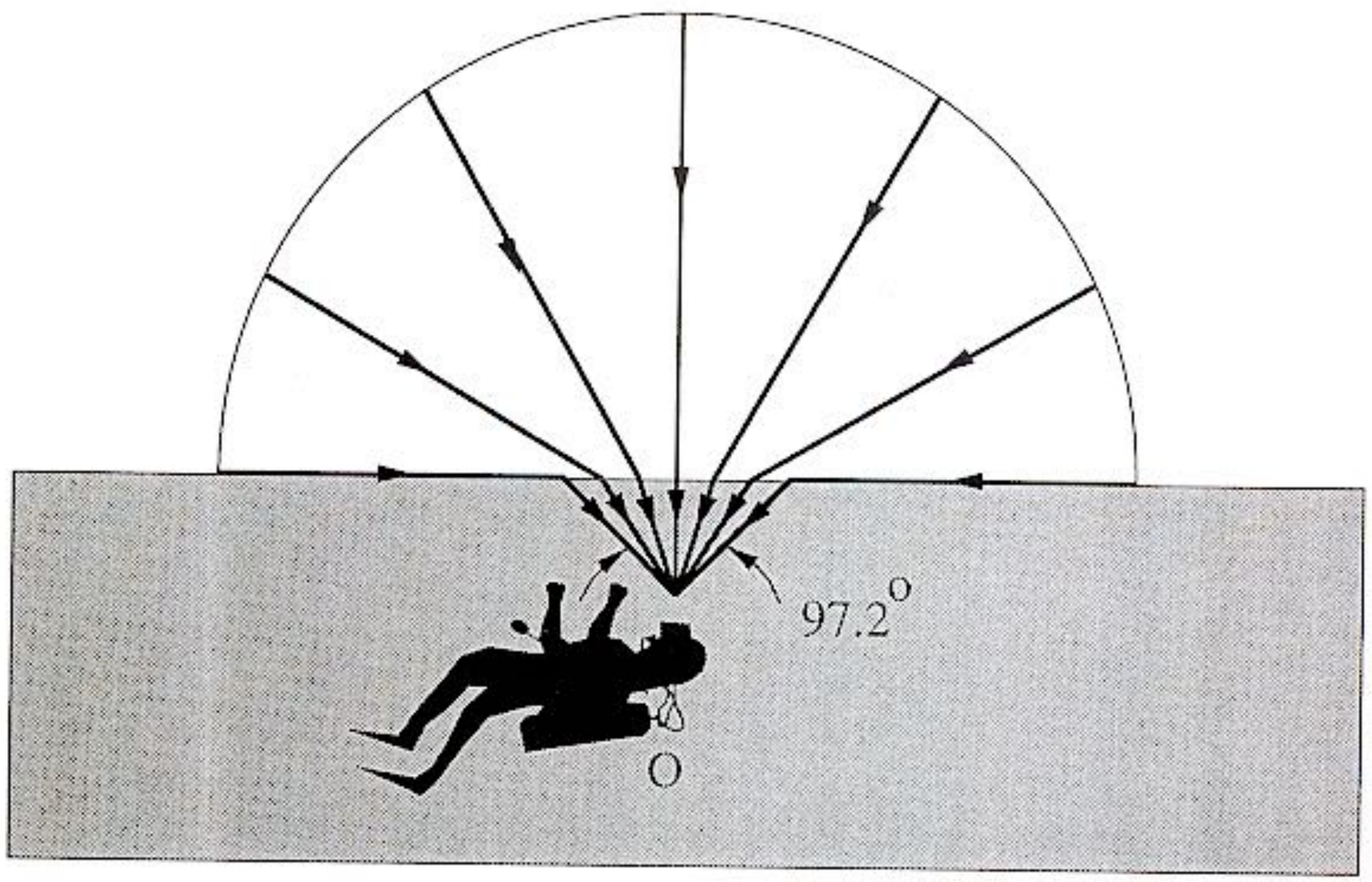
$$1-\left(\frac{\eta_i}{\eta_t}\right)^2 (1-\cos^2\theta_i) < 0$$

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

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

Snell's Window/Circle

Total internal reflection



[Livingston and Lynch]

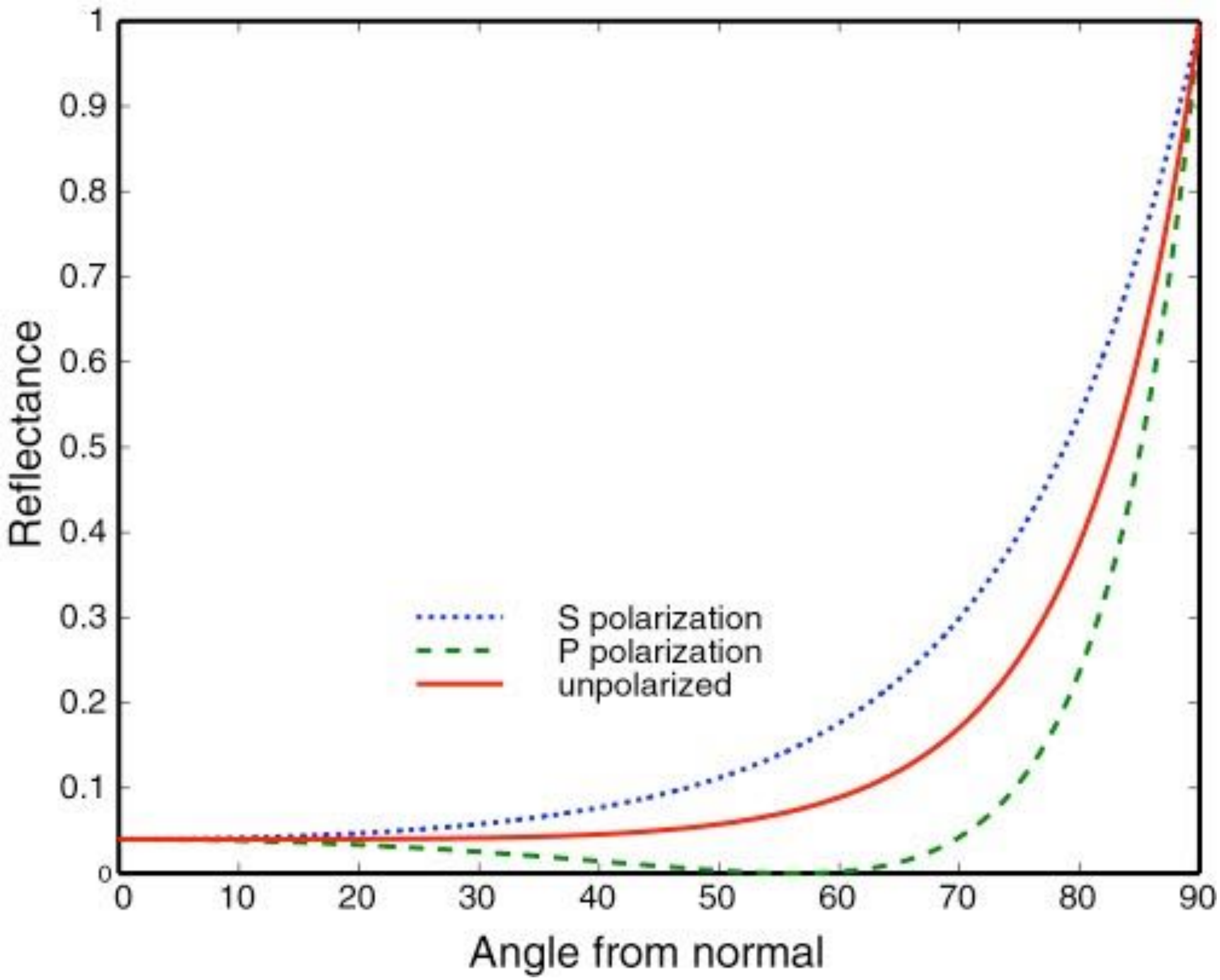
Fresnel Reflection / Term

Reflectance depends on incident angle (and polarization of light)

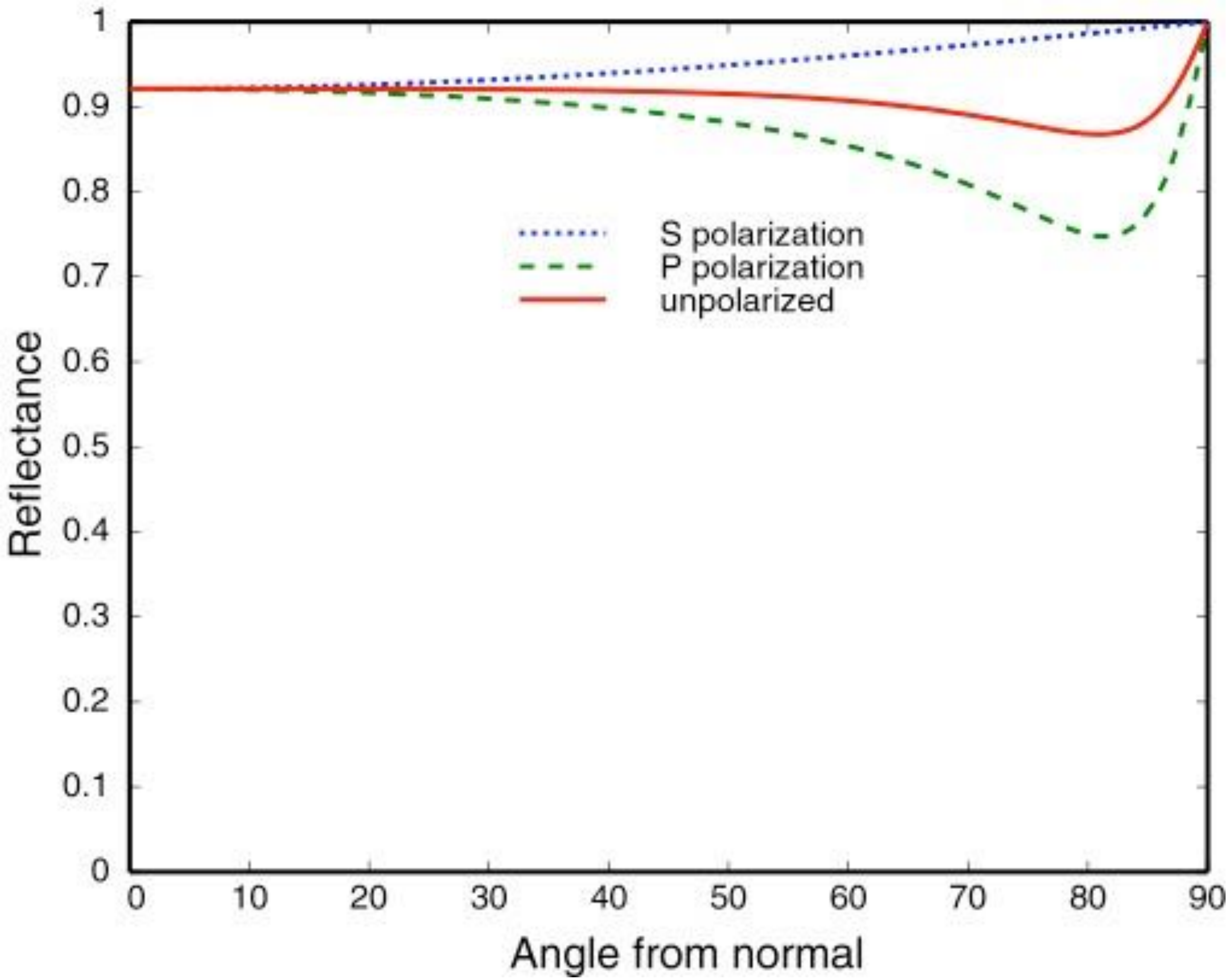
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

Fresnel Term (Dielectric, η =1.5)



Fresnel Term (Conductor)



Microfacet Material

Microfacet Reflection

https://twitter.com/Cmdr_Hadfield/status/318986491063828480/photo/1

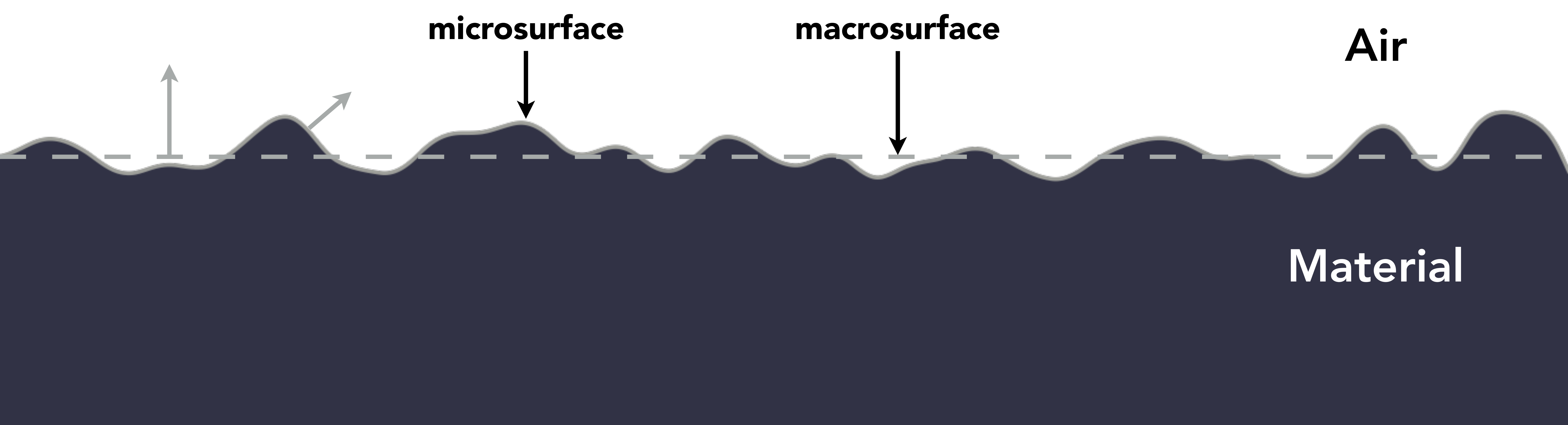
Microfacet Theory

Rough surface

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

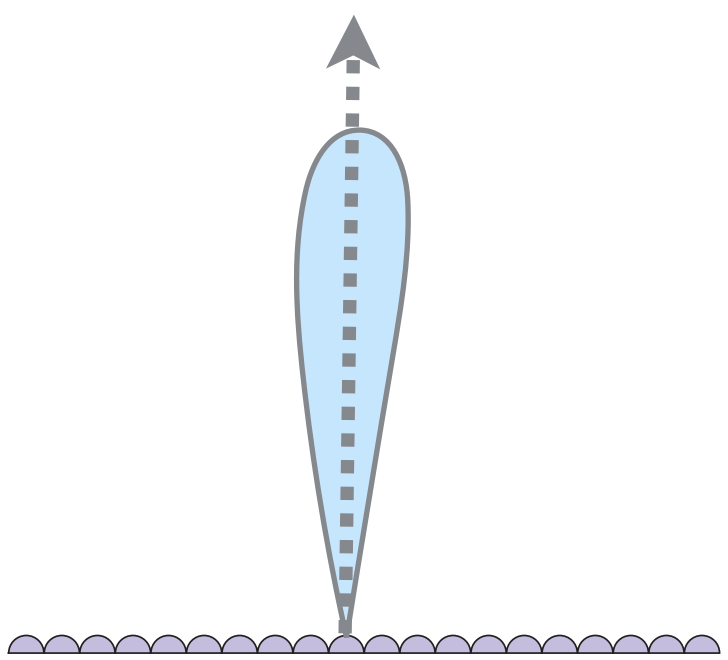
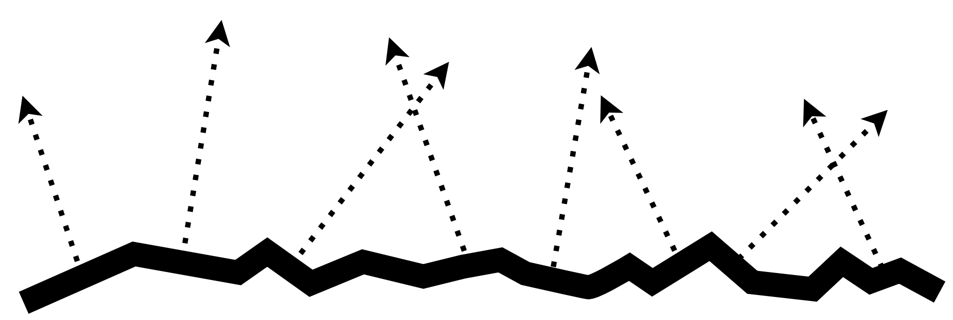
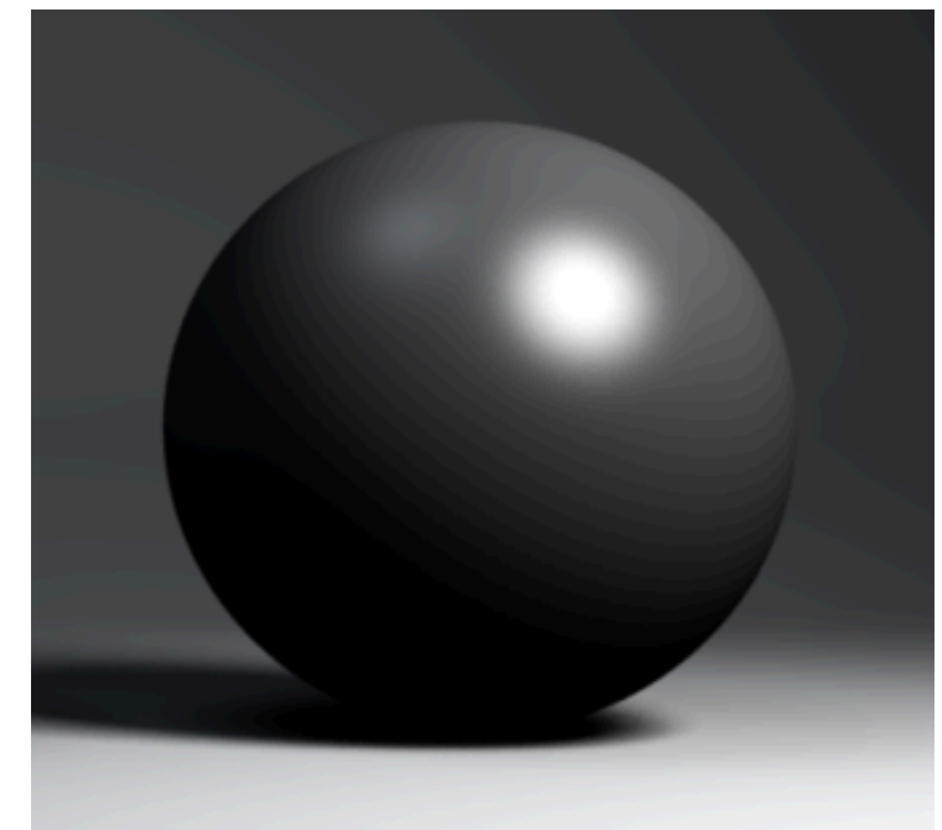
Individual elements of surface act like mirrors

- Known as Microfacets
- Each microfacet has its own normal

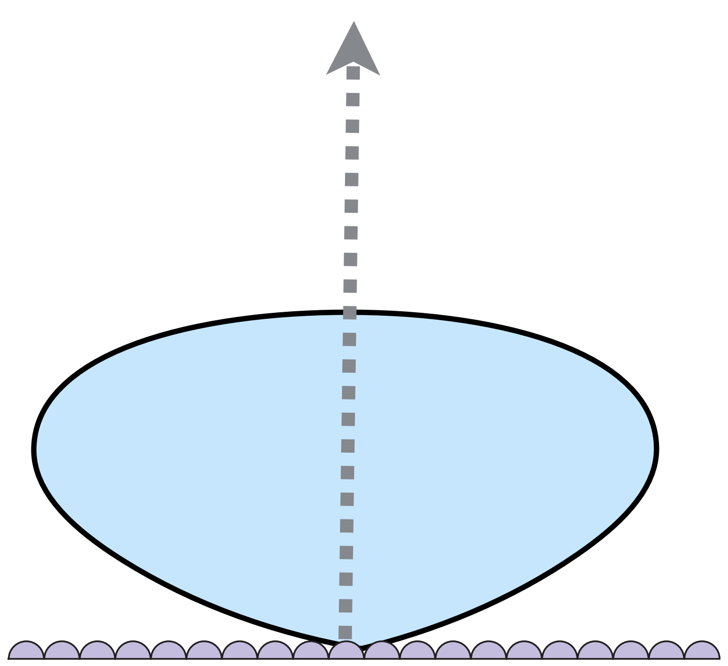
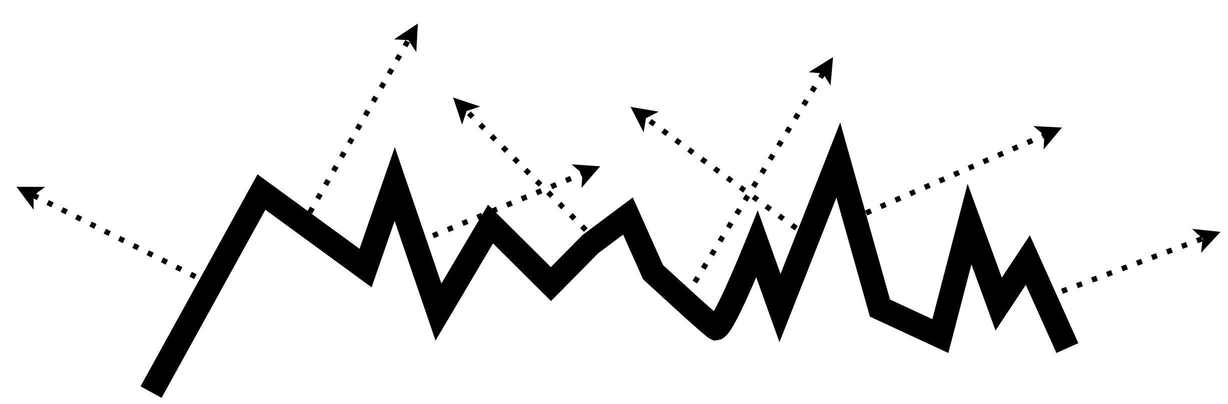
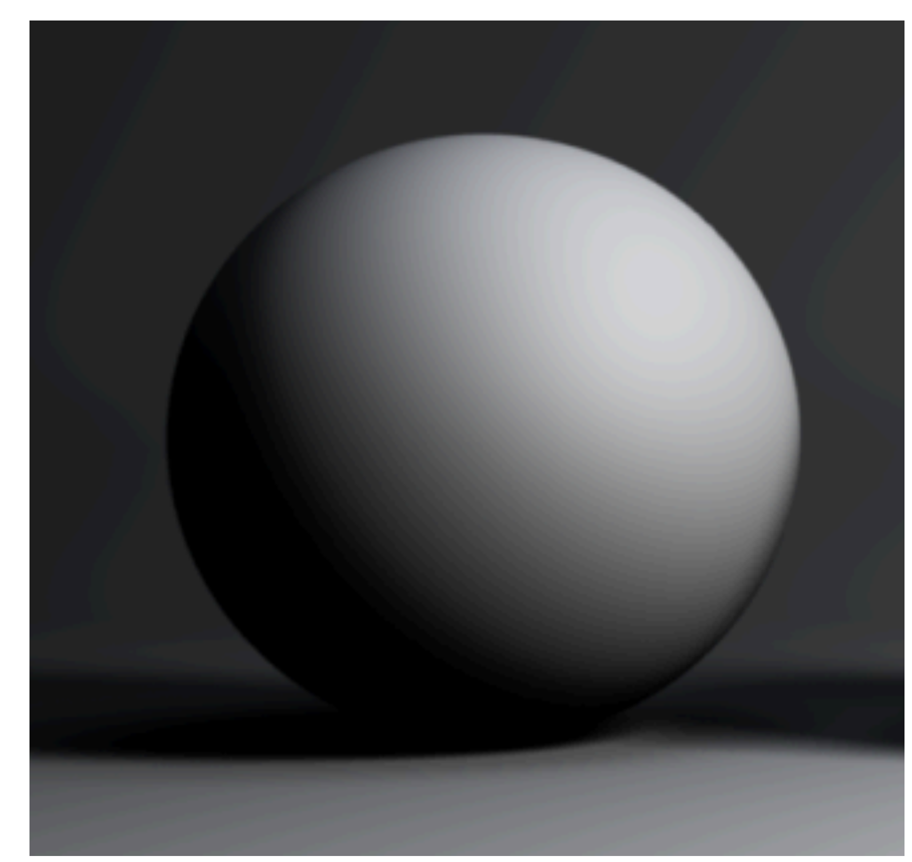


Microfacet BRDF

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

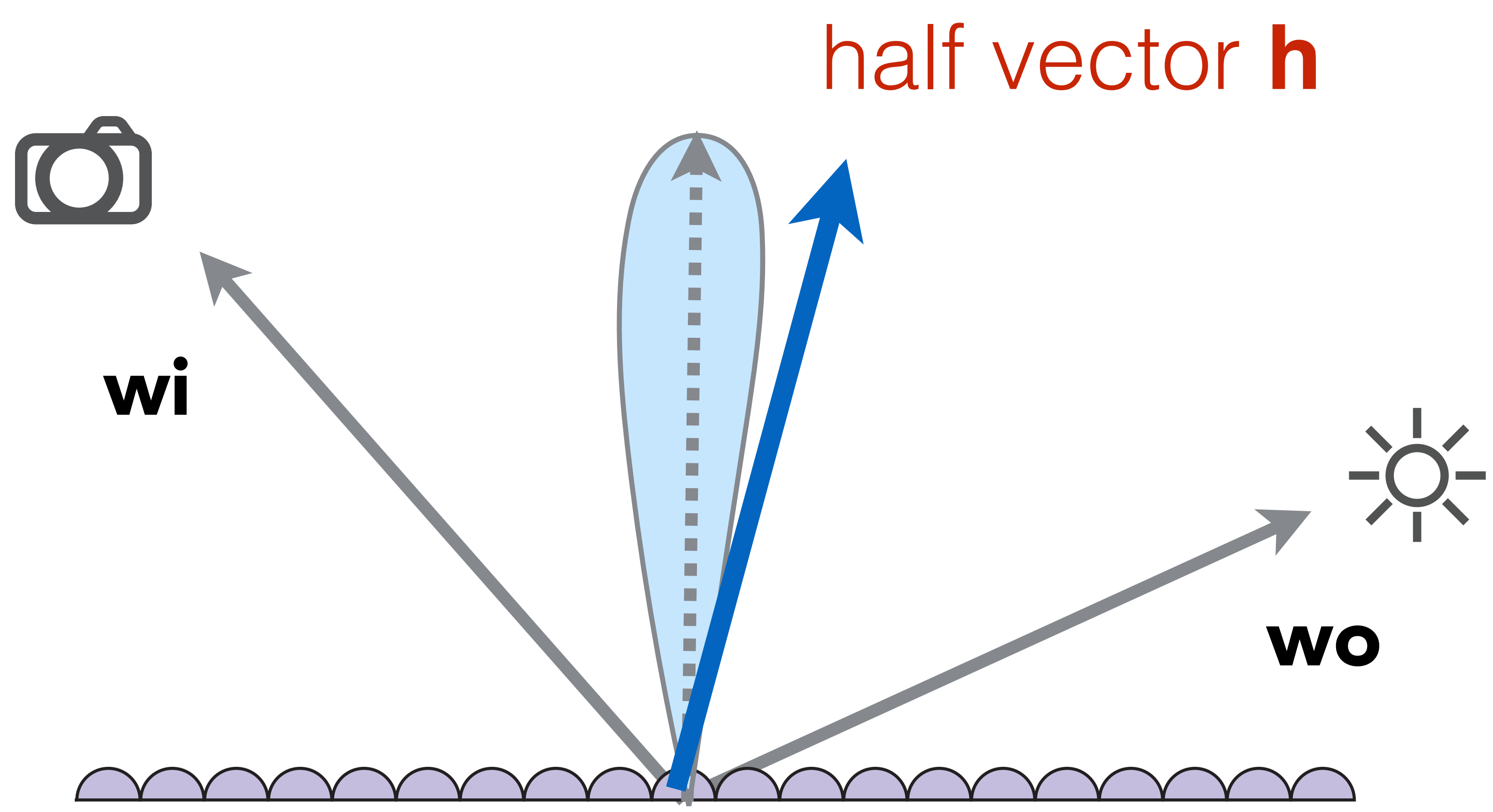




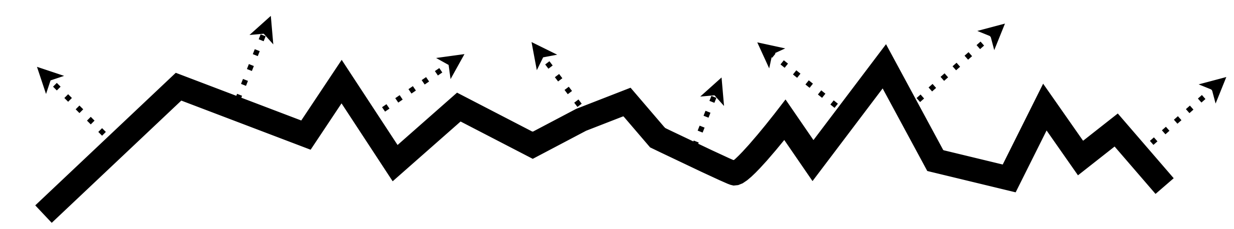
  - Spread <==> diffuse

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)

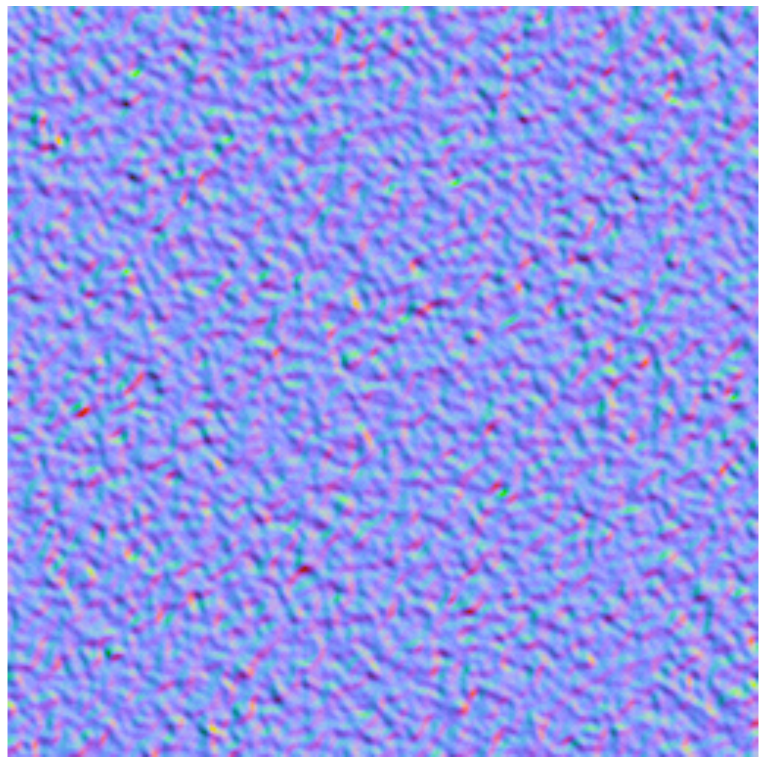
- So far, Point light + Metal = Round / Elliptical highlight
- What can we see inside an elevator?

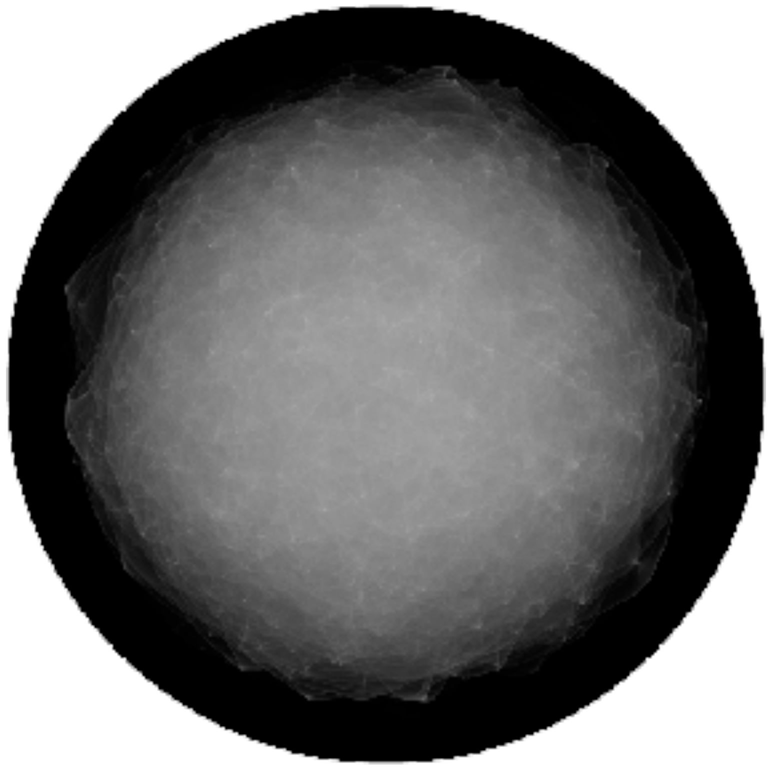
Inside an elevator

Isotropic / Anisotropic Materials (BRDFs)

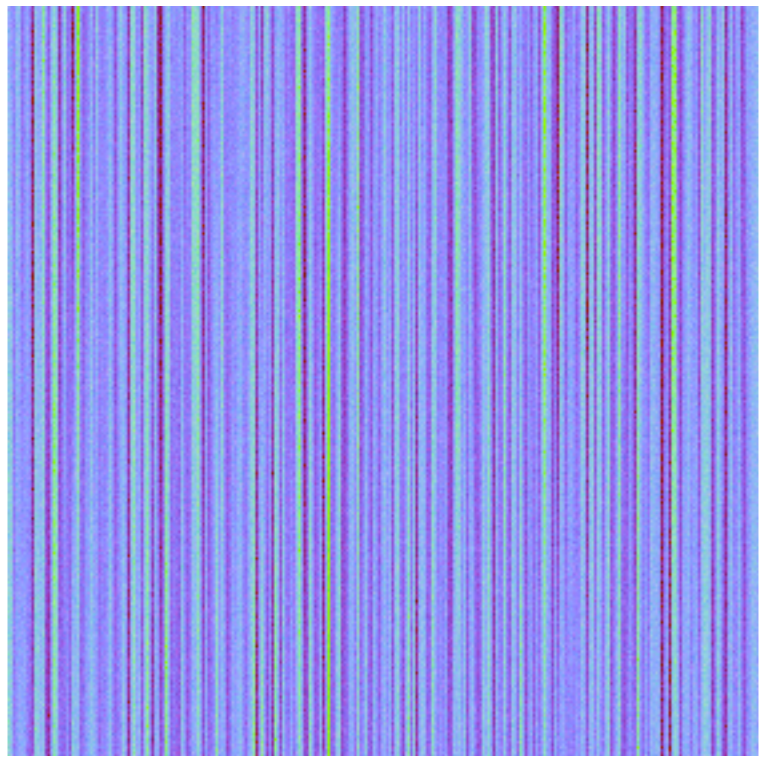
- Key: directionality of underlying surface

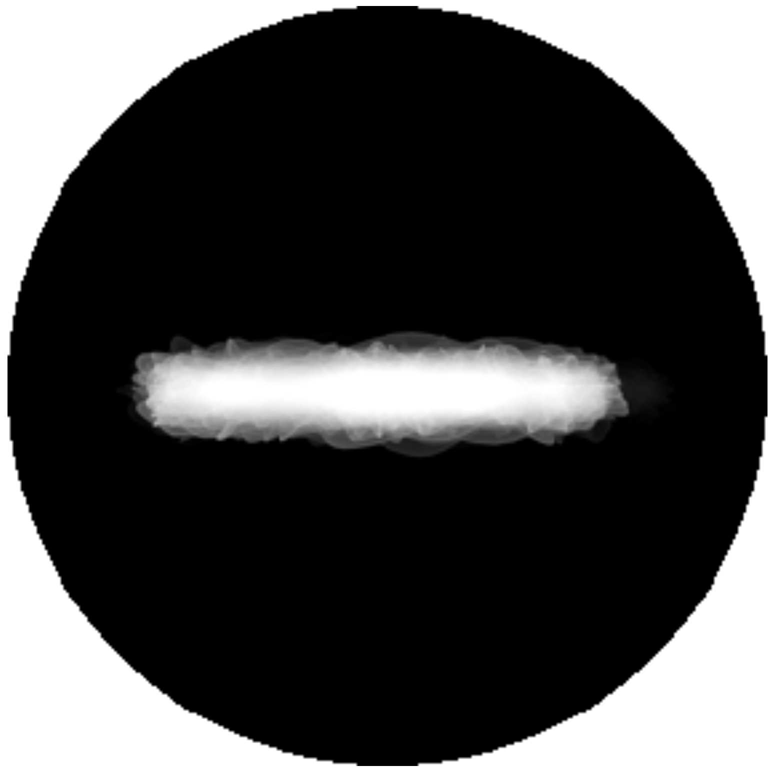
Isotropic





Anisotropic





Surface (normals)

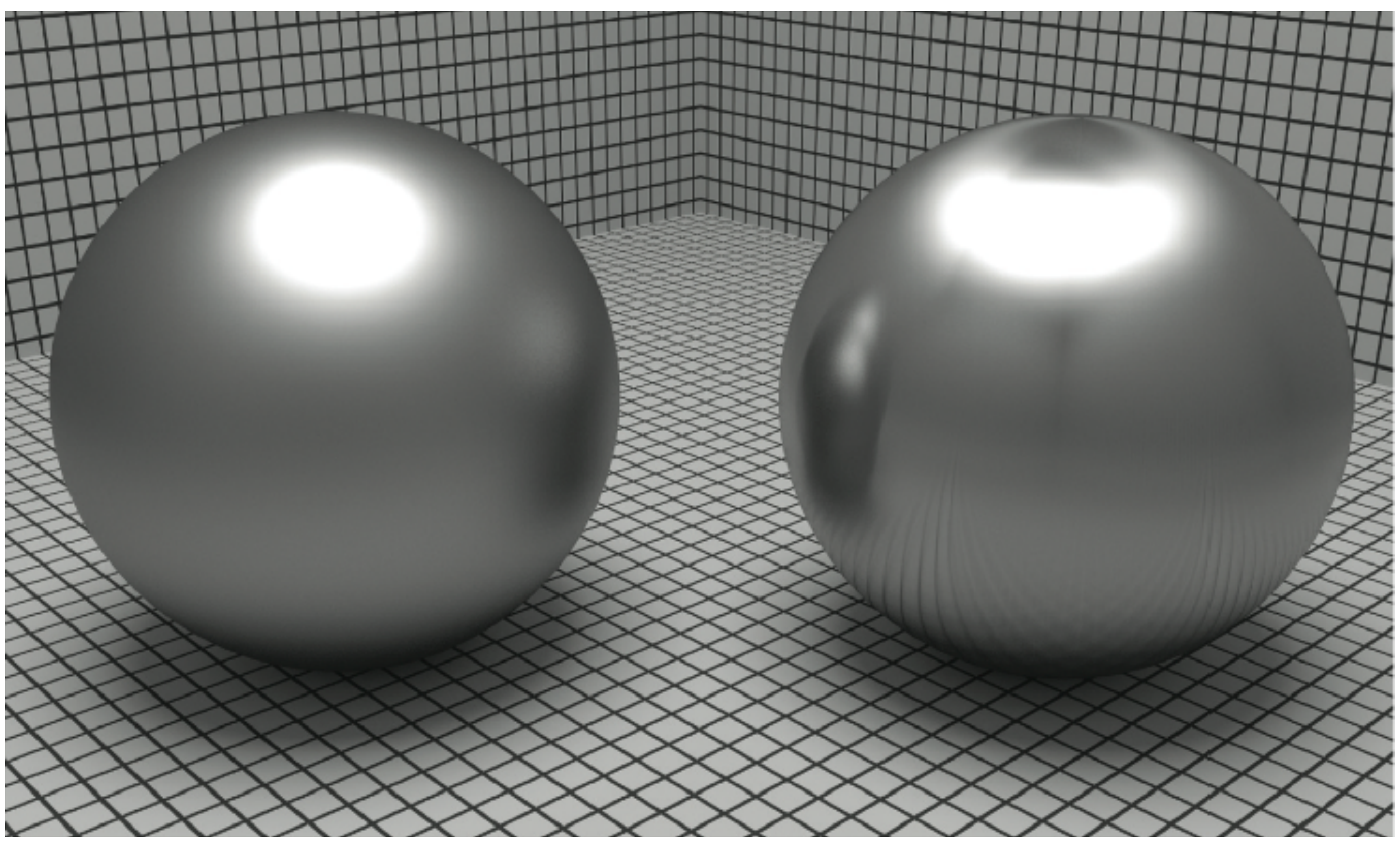
BRDF (fix wi, vary wo)

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



Isotropic vs Anisotropic Reflection

Isotropic

Anisotropic

Anisotropic BRDF: Brushed Metal

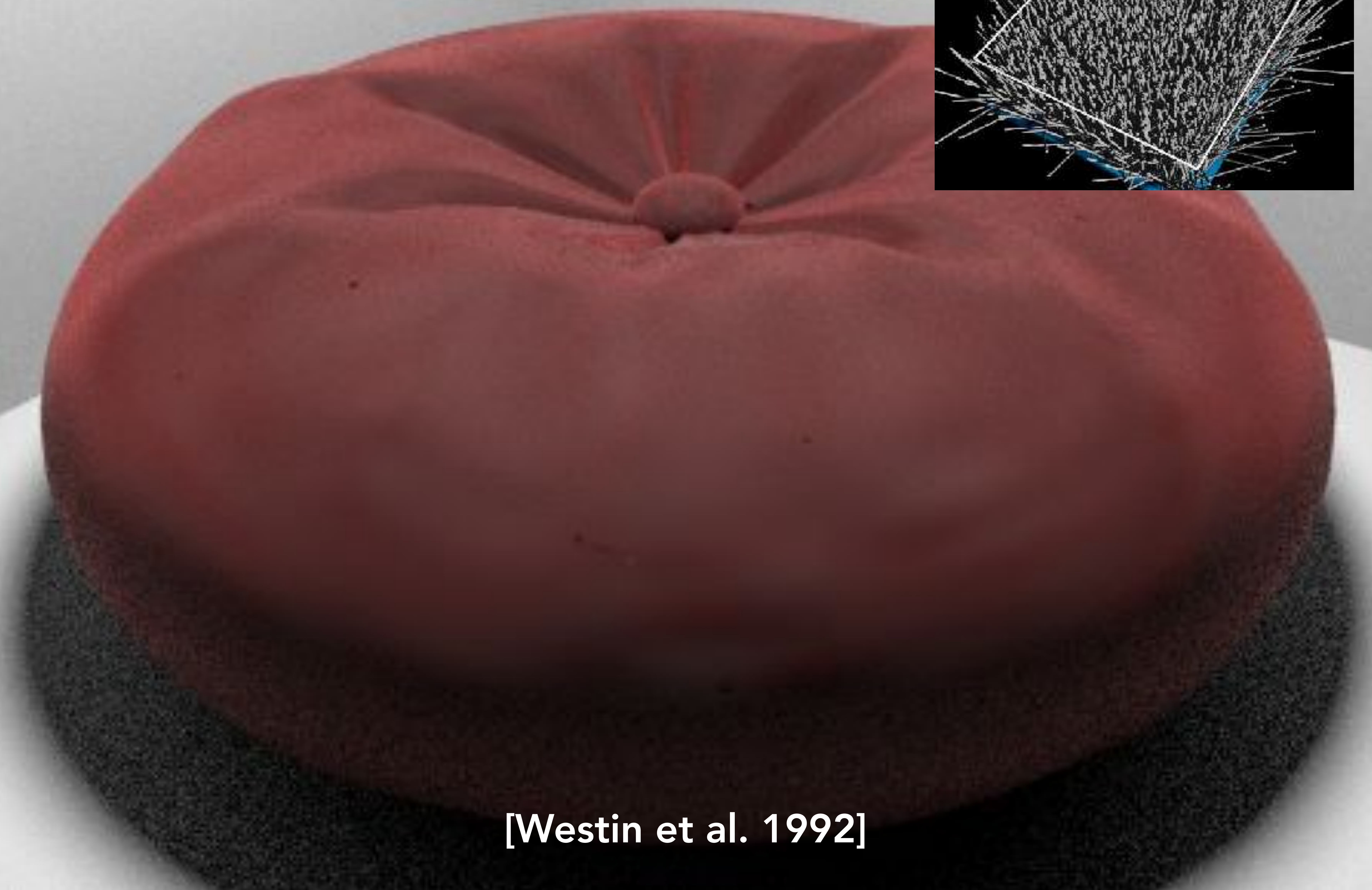
- How is the pan brushed?

[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]

Things to Remember

Materials (BRDFs)

- Diffuse, Glossy, ideal specular
- Fresnel reflection / Fresnel term
- Microfacet BRDFs
- Anisotropic BRDFs

Acknowledgments

Thanks to Matt Pharr, Pat Hanrahan, Kayvon Fatahalian and LingQi Yan for these slides.