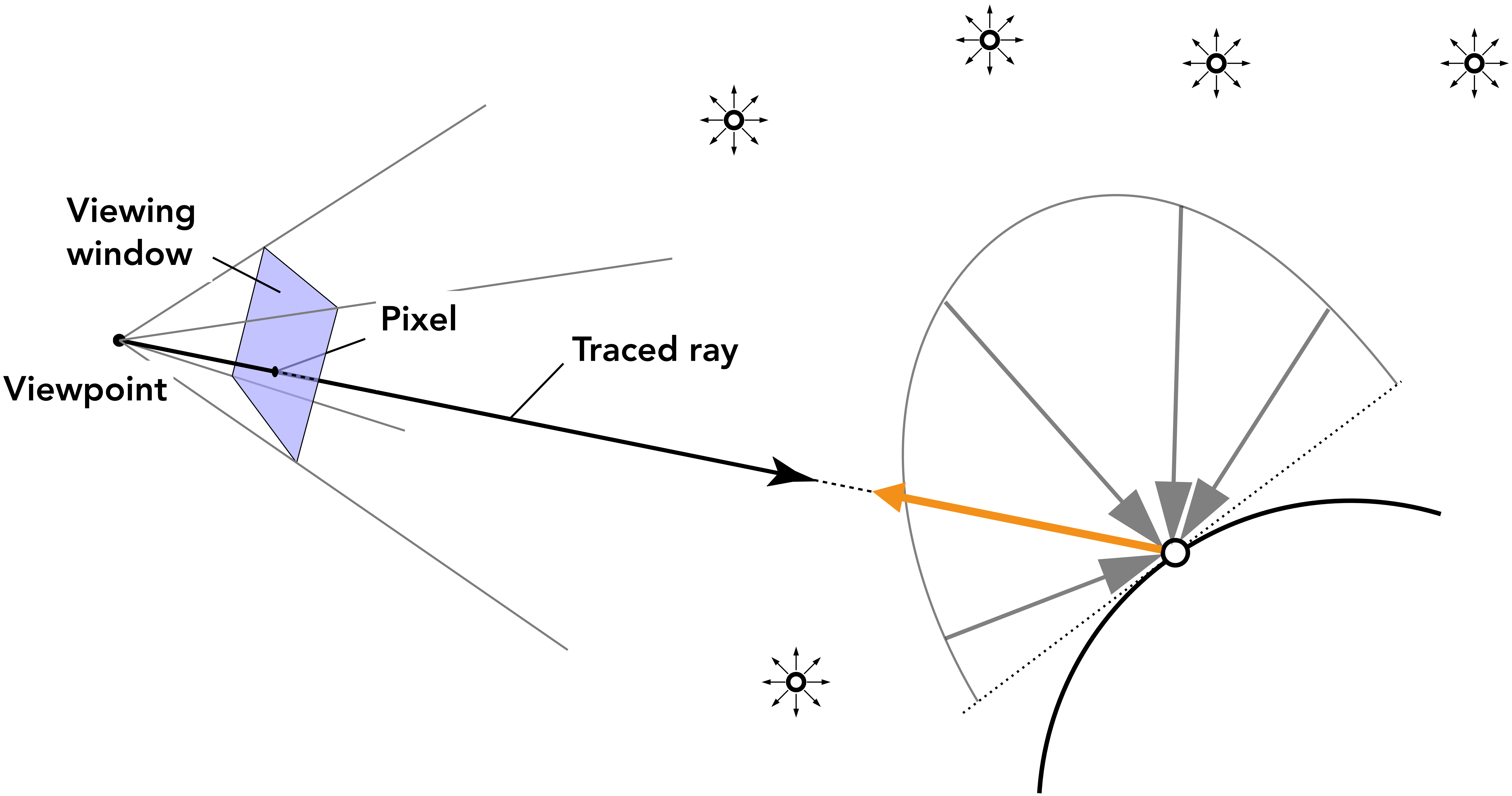
Lecture 14:

Material Modeling

Computer Graphics and Imaging
UC Berkeley CS184/284A

Ray Tracer Samples Radiance Along A Ray



(For opaque surfaces)

The light entering the pixel is the sum total of the light ***reflected off*** the surface into the ray's (reverse) direction

Reflection

(as opposed to **transmission, absorption, emission**)

Definition: *reflection* is the process by which light incident on a surface interacts with the surface, such that it leaves on the incident (same) side, without change in frequency

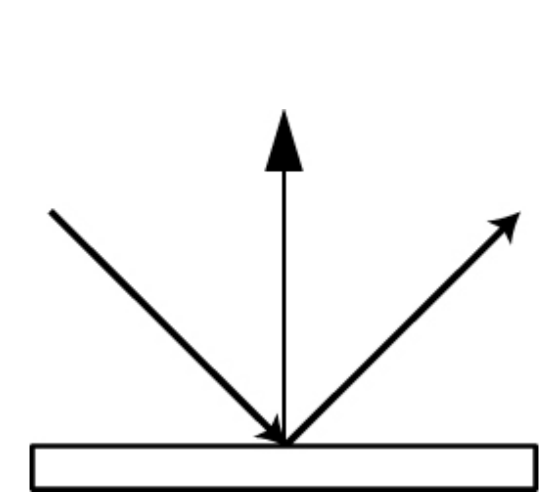
Properties

- **Color spectrum distribution** (later)
- **Polarization** (not covered in this course)
- **<u>Spatioangular distribution</u>** (today)

Types of Reflection Functions

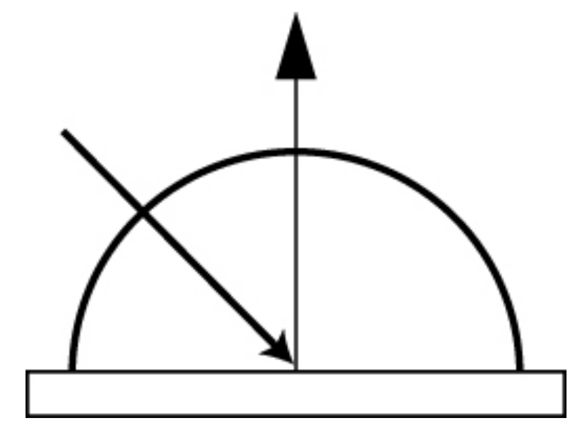
Ideal specular

- Perfect mirror reflection



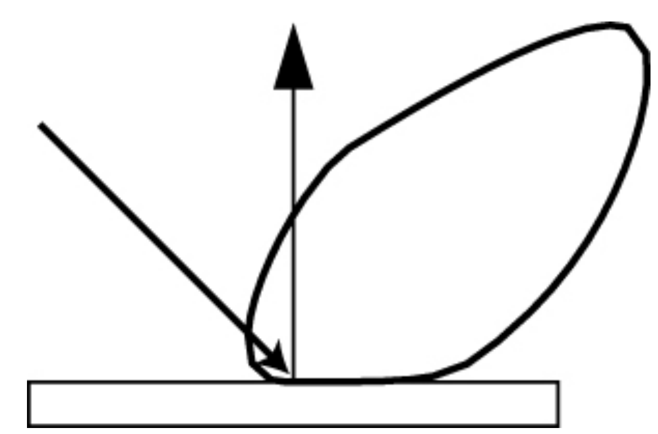
Ideal diffuse

- Equal reflection in all directions



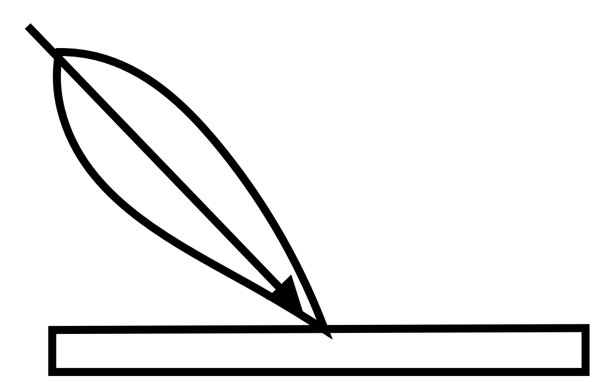

Glossy specular

- Majority of light reflected near mirror direction



Retro-reflective

- Light reflected back towards light source

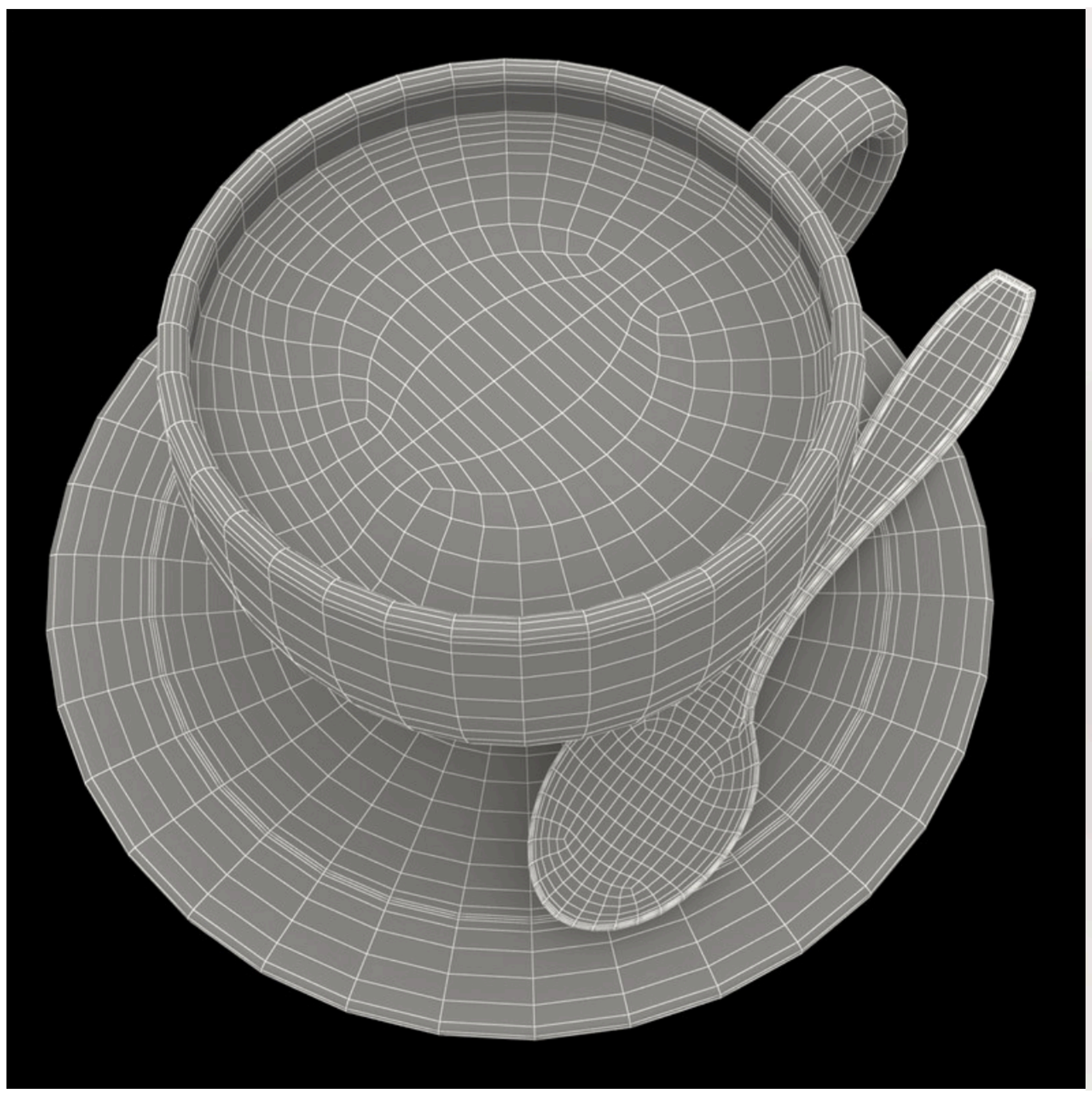



Diagrams illustrate how light from incoming direction is reflected in various outgoing directions.

The Appearance of Natural Materials

[Courtesy of Prof. Henrik Wann Jensen, UCSD]

What is Material in Computer Graphics?

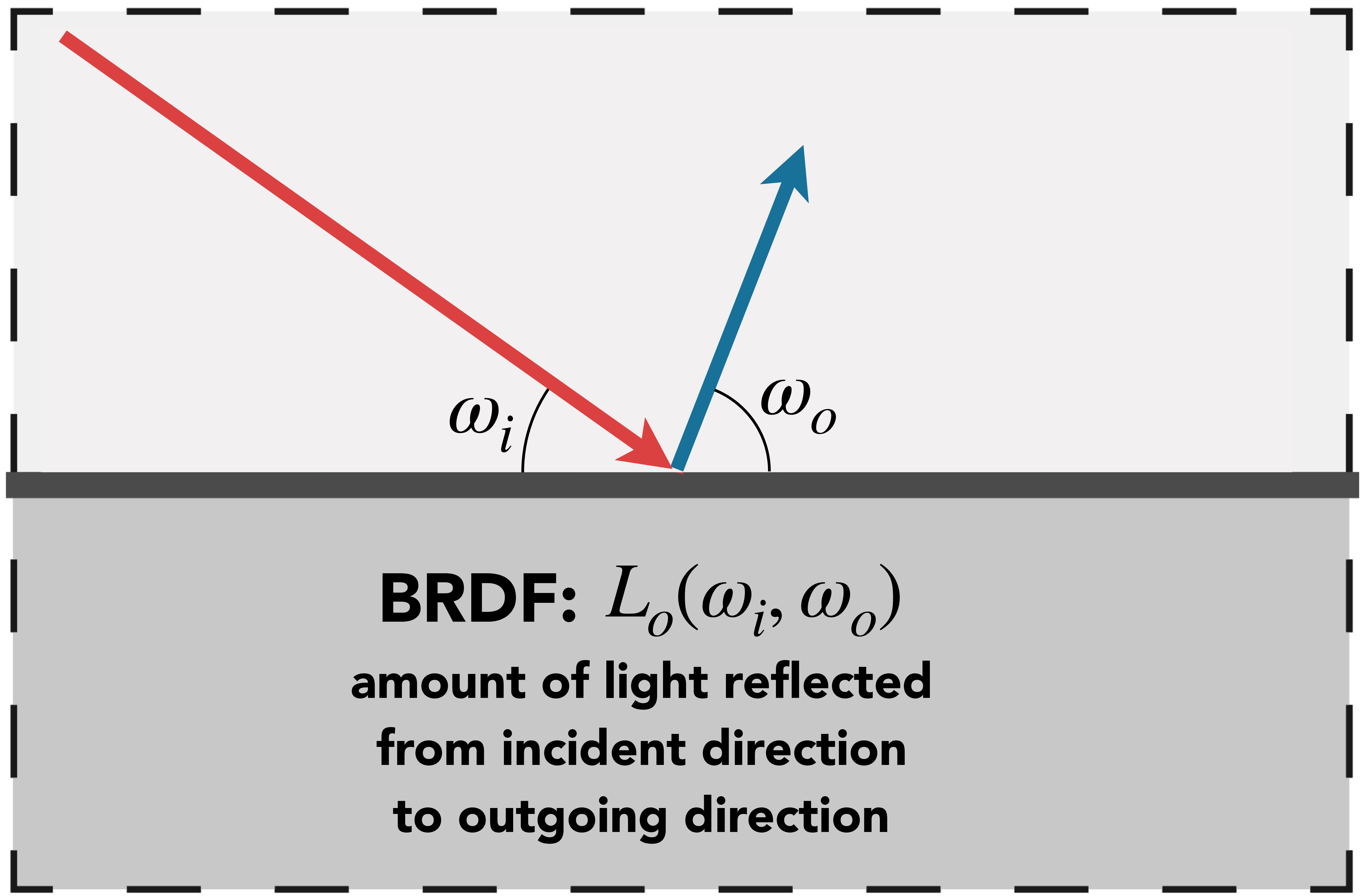


3D coffee mug model | Rendered | Rendered

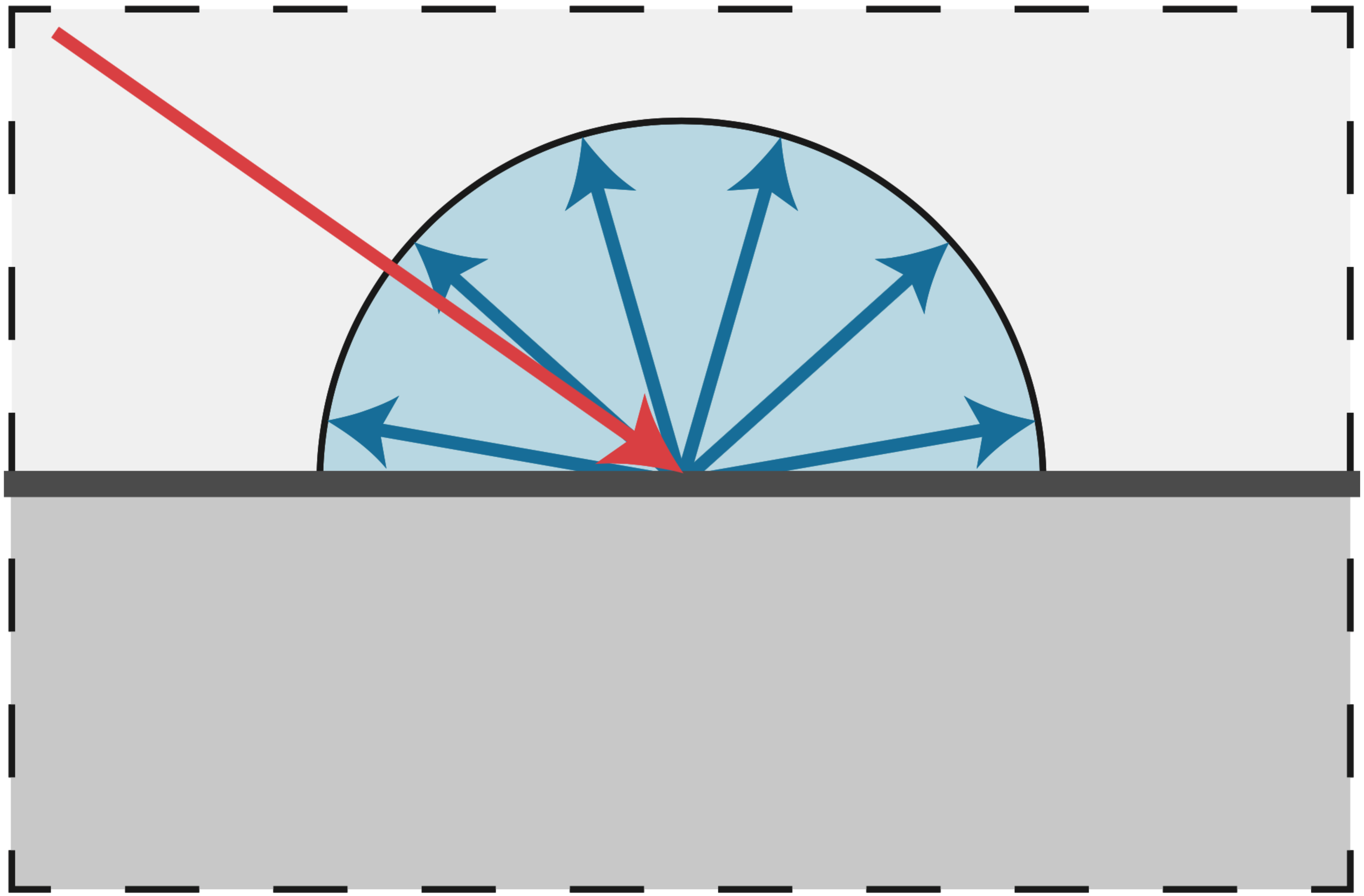
[From TurboSquid, created by artist 3dror]

Material == BRDF

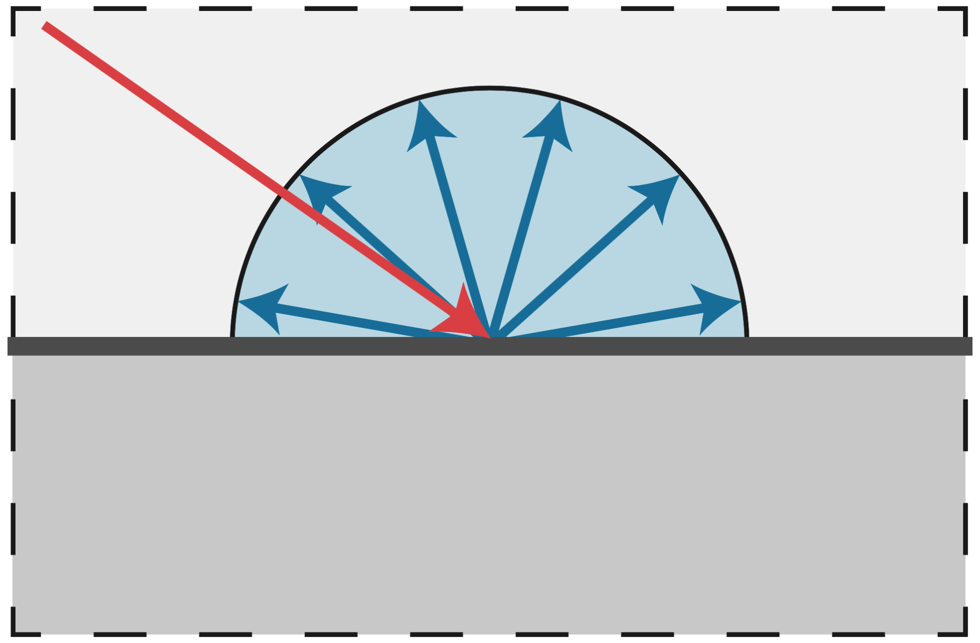
BRDF: Bidirectional Reflection Distribution Function

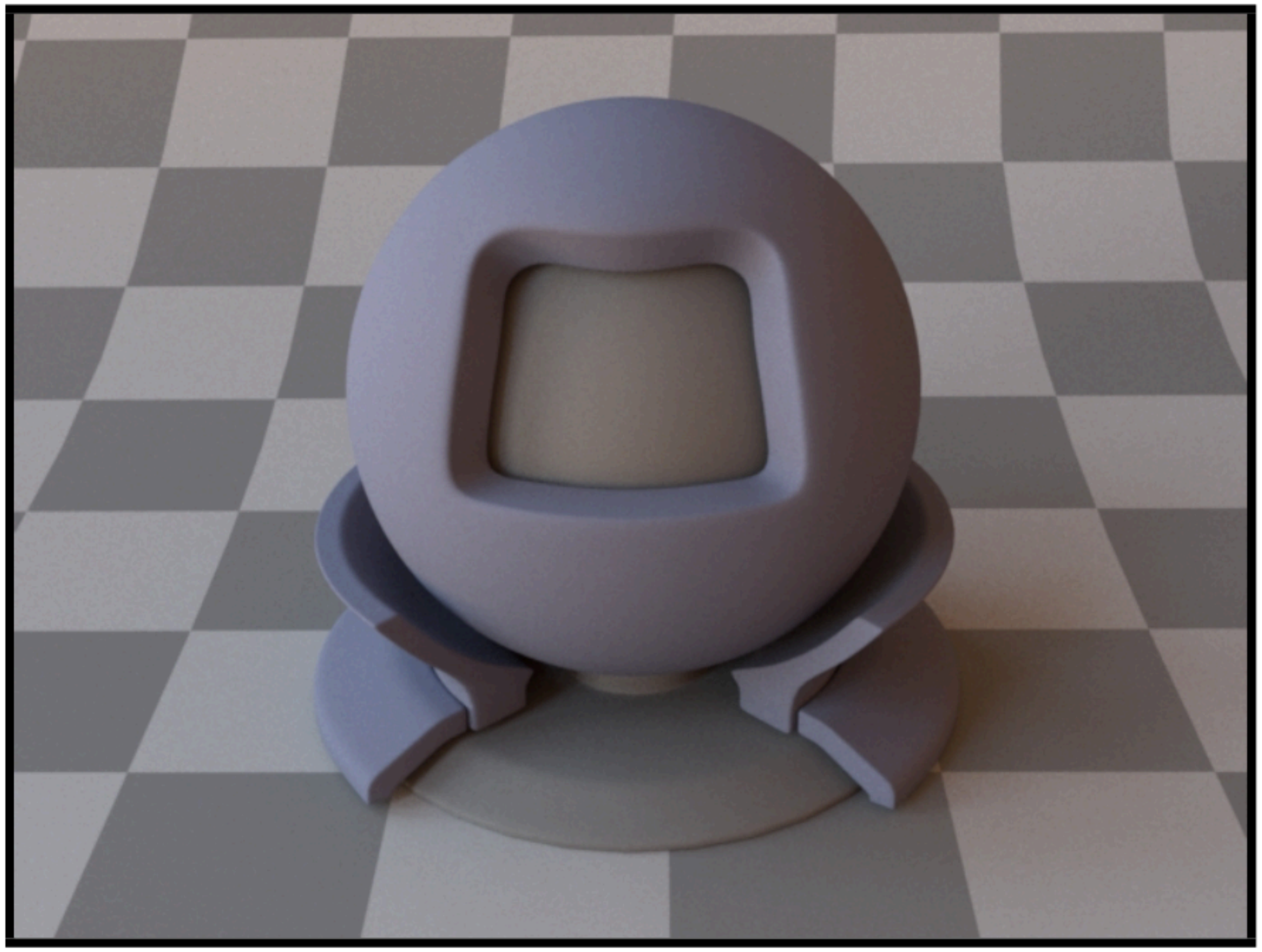


What is this material?

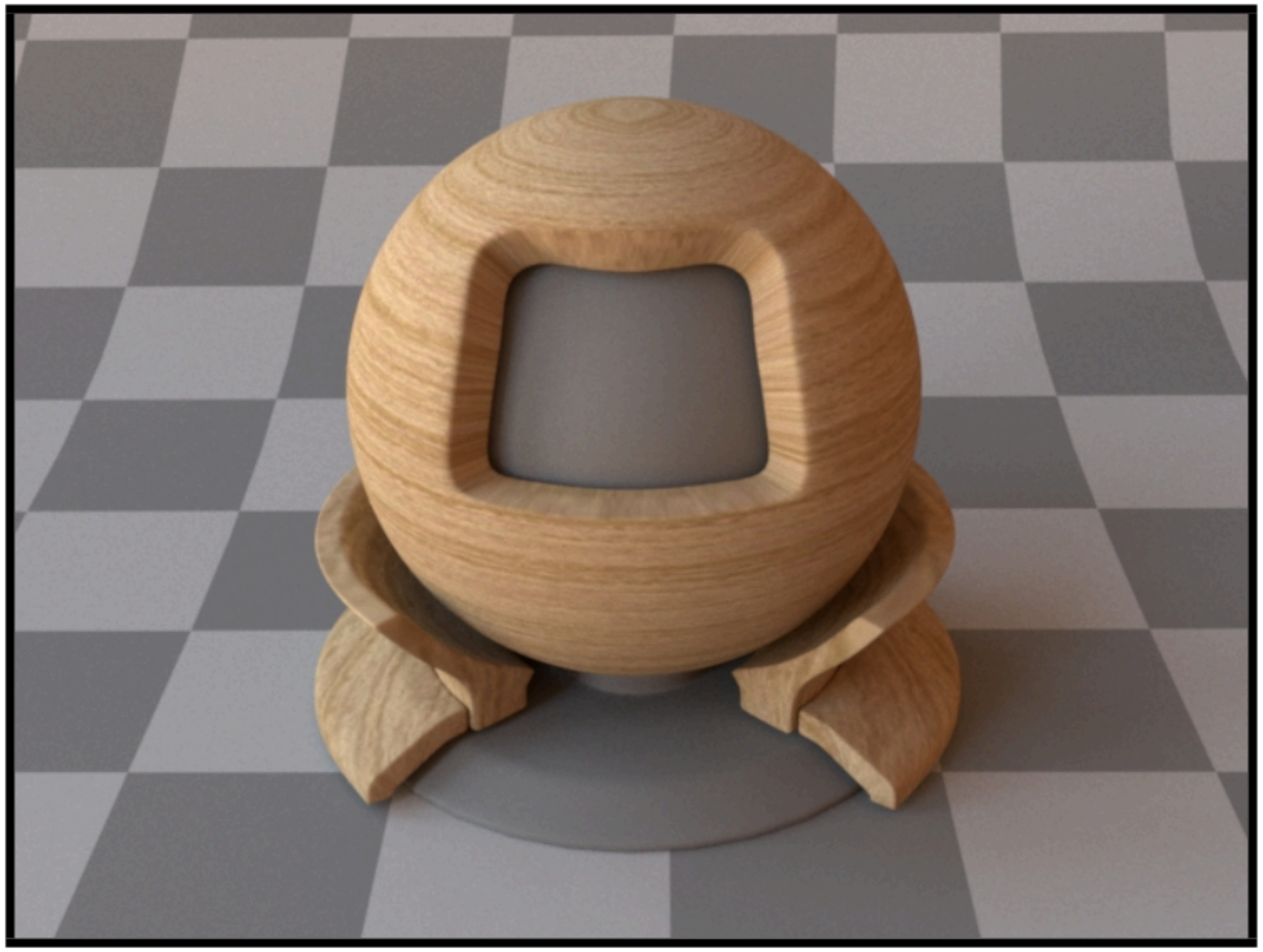


Diffuse / Lambertian Material (BRDF)





Uniform colored diffuse BRDF

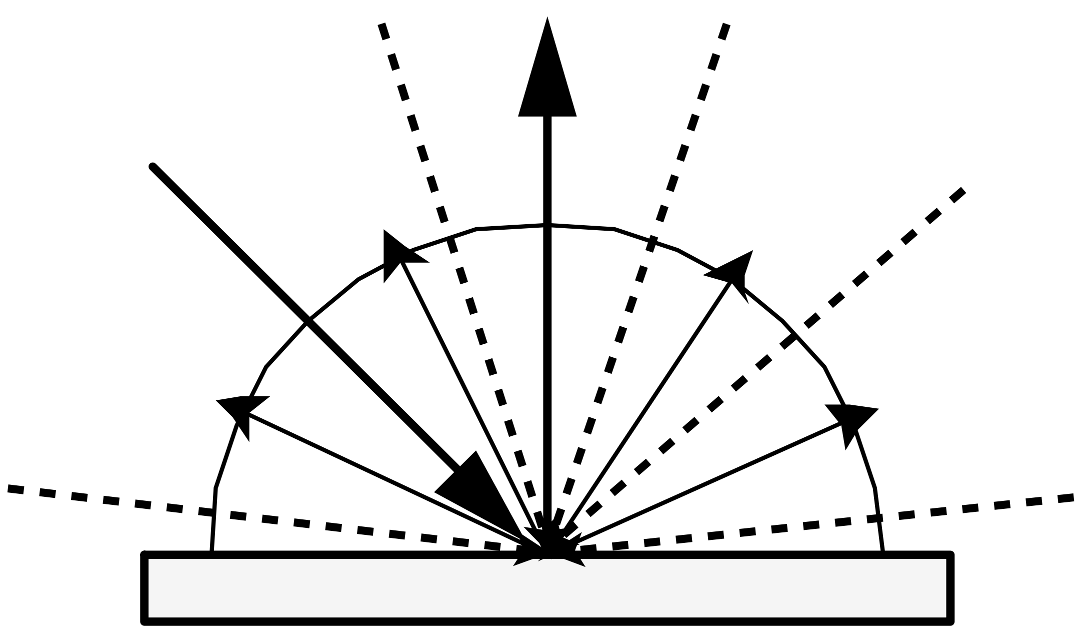


Textured diffuse BRDF

[Mitsuba renderer, Wenzel Jakob, 2010]

Diffuse / Lambertian Material

Light is equally reflected in each output direction



$$f_r = c$$

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

Suppose the incident lighting is uniform:

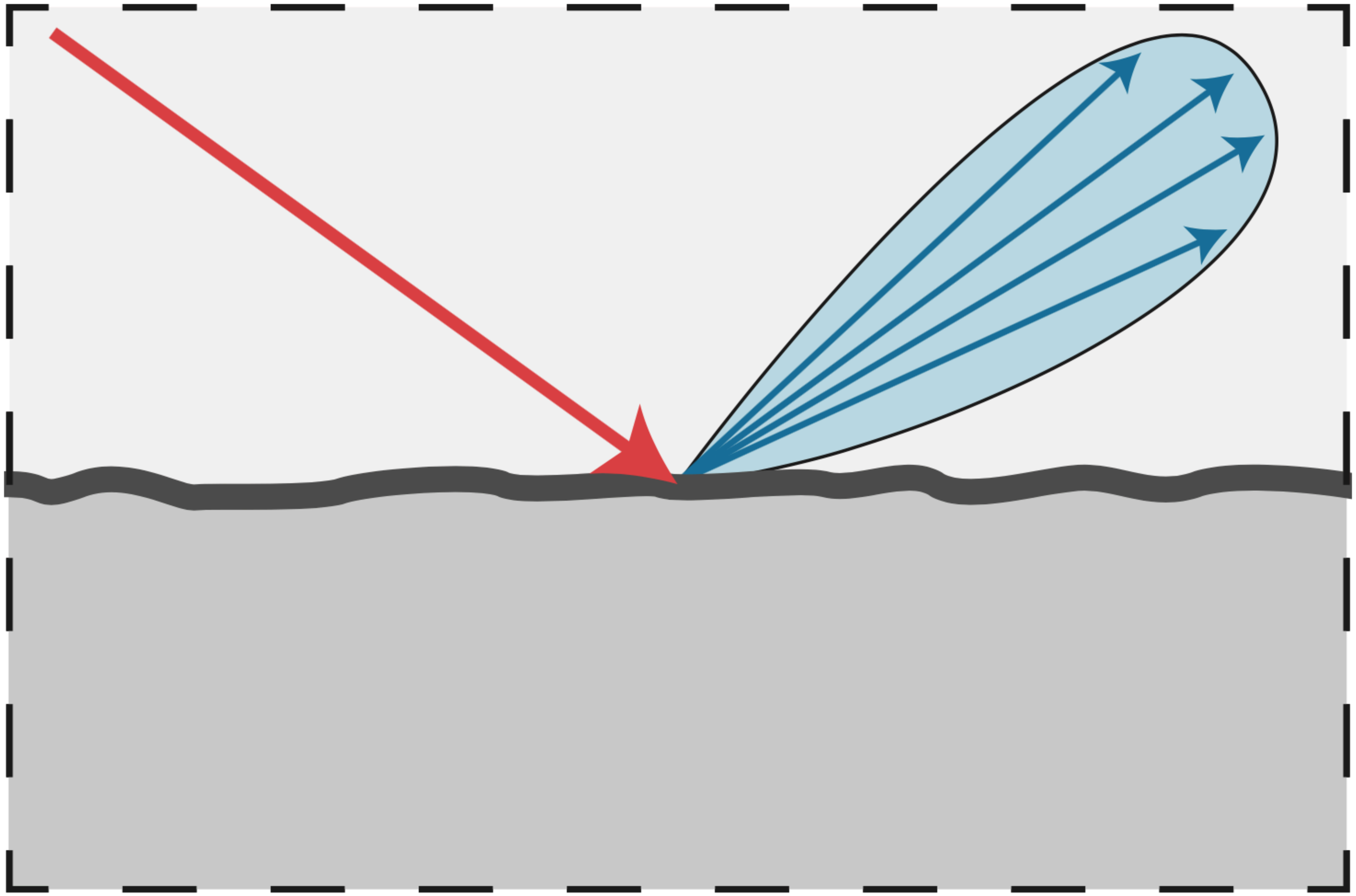
$$= f_r L_i \int_{H^2} \cancel{(\omega_i)} \cos\theta_i \, \mathrm{d}\omega_i$$

$$= \pi f_r L_i$$

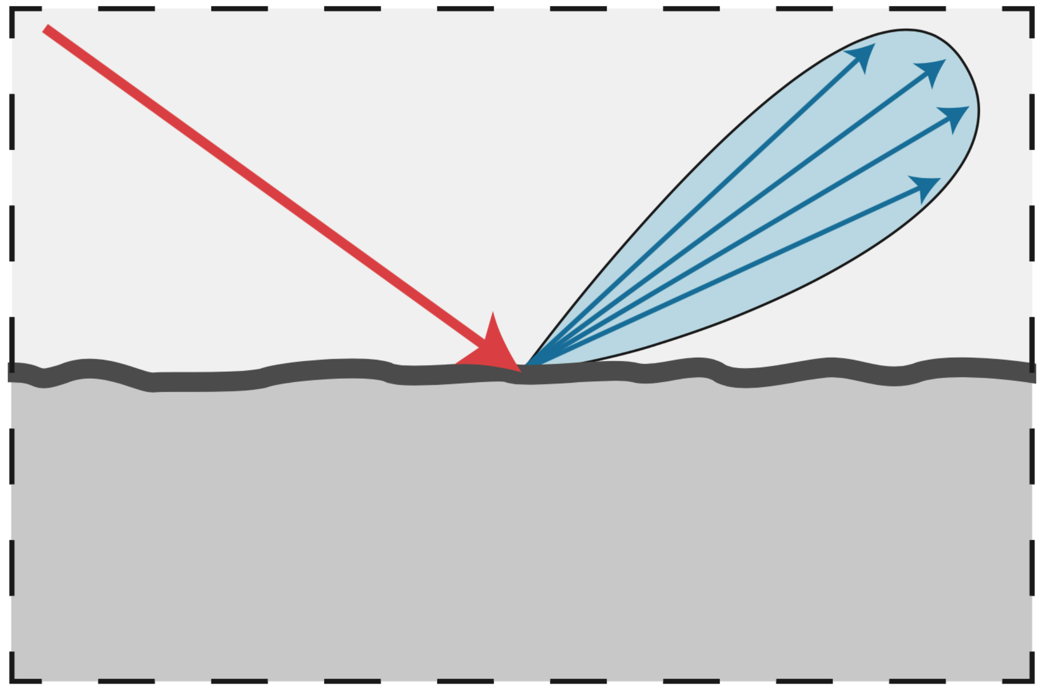
$$f_r = \frac{\rho}{\pi}$$ (albedo — "color")

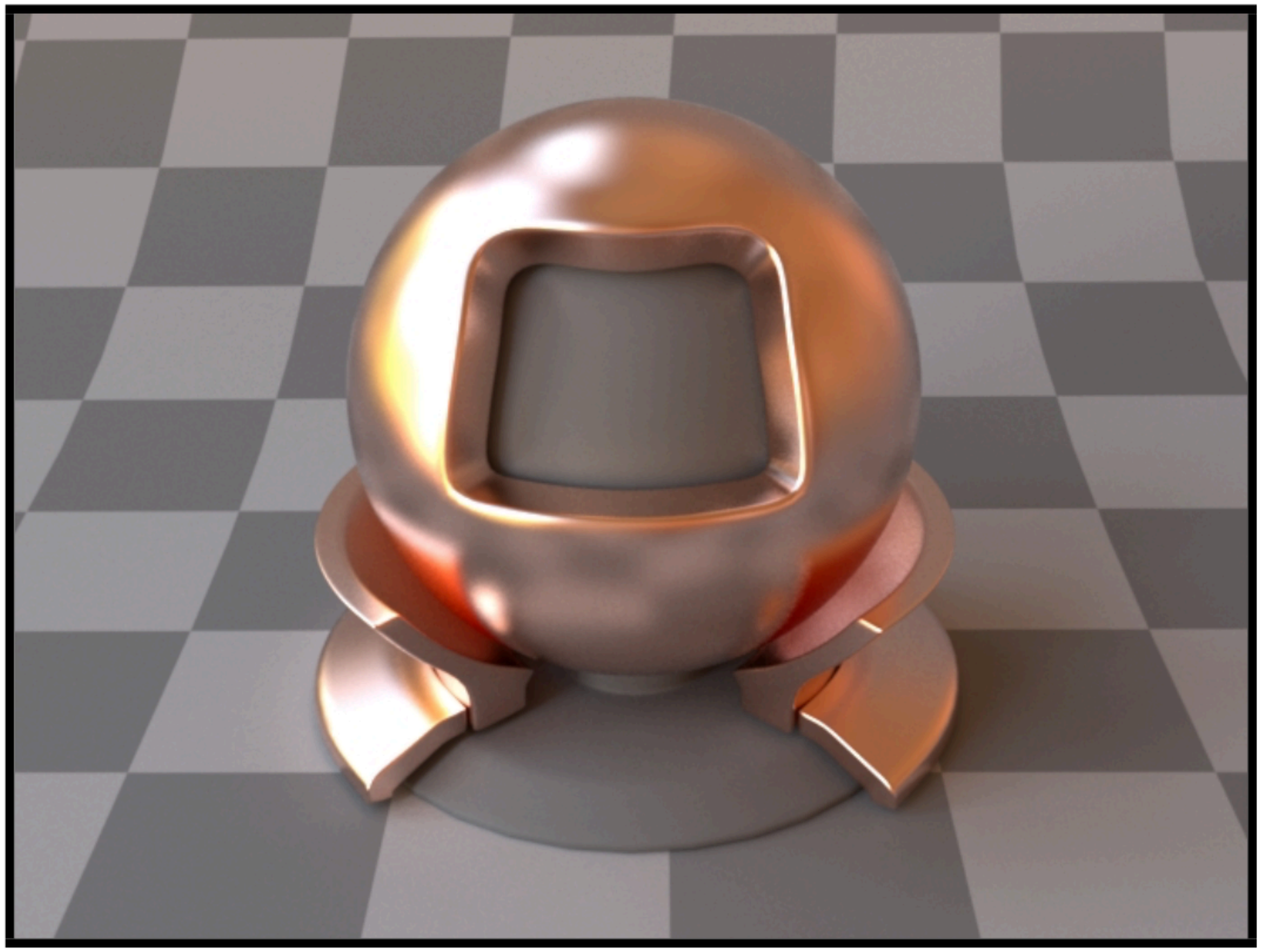
isn't it conceptually simpler to explain this in terms of conservation of energy over all outbound directions?

What is this material?

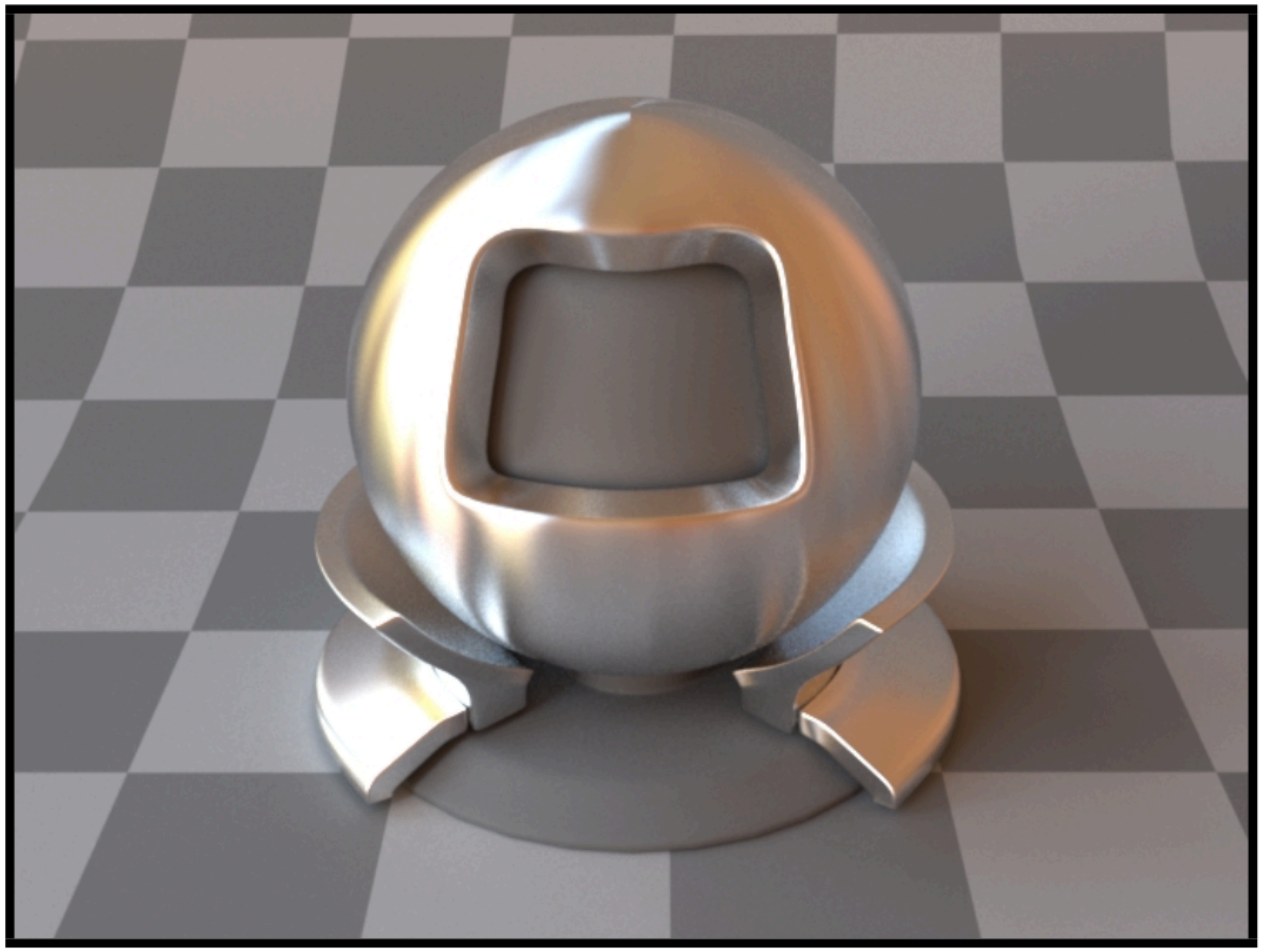


Glossy material (BRDF)





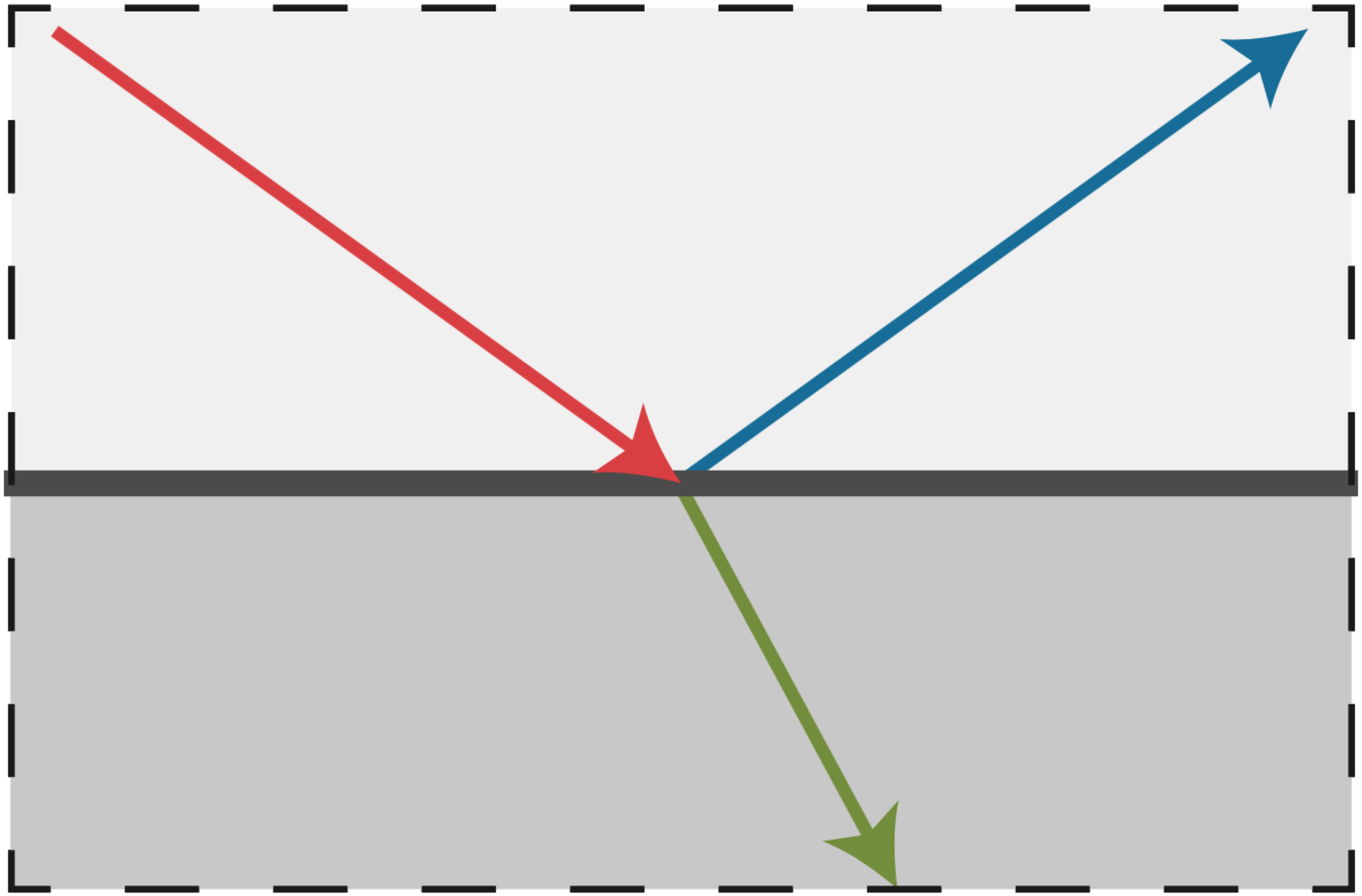
Copper



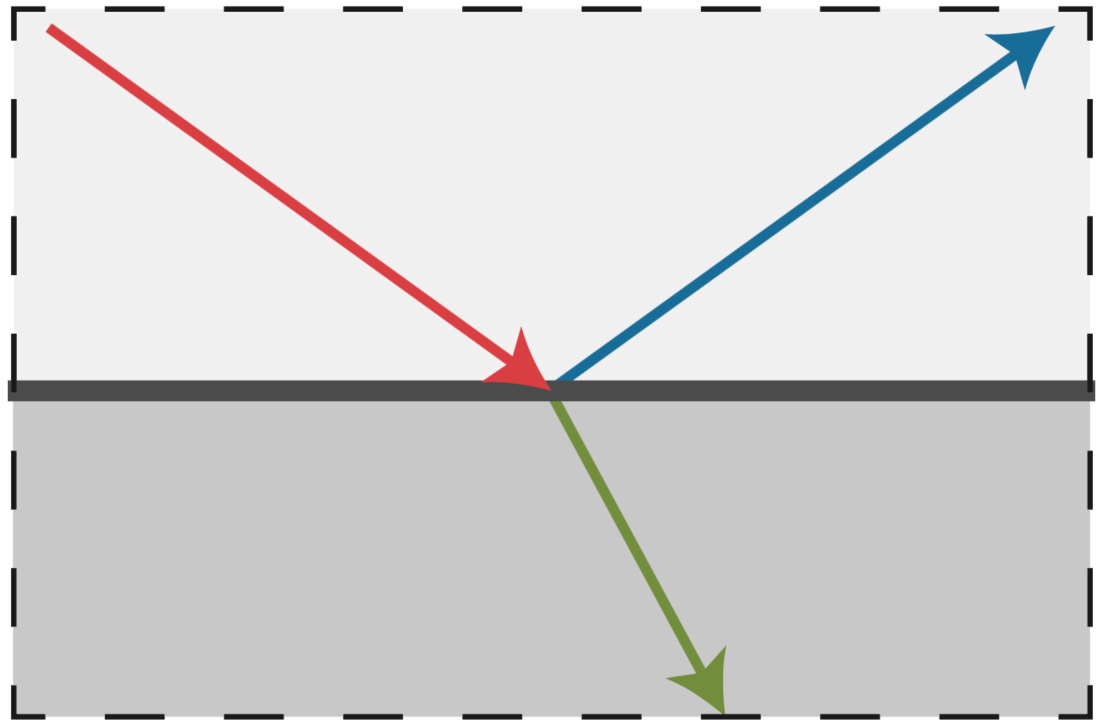
Aluminum

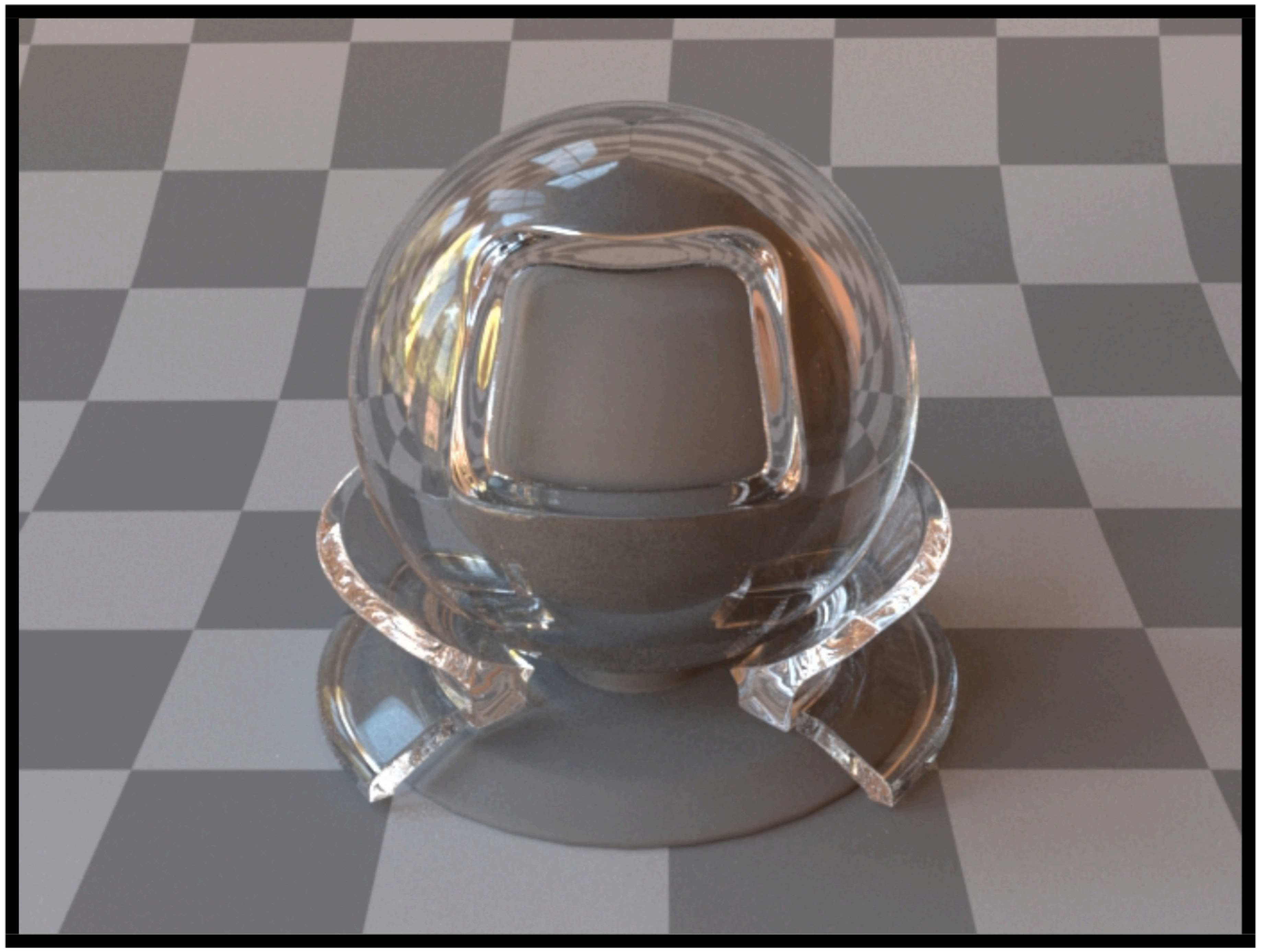
[Mitsuba renderer, Wenzel Jakob, 2010]

What is this material?

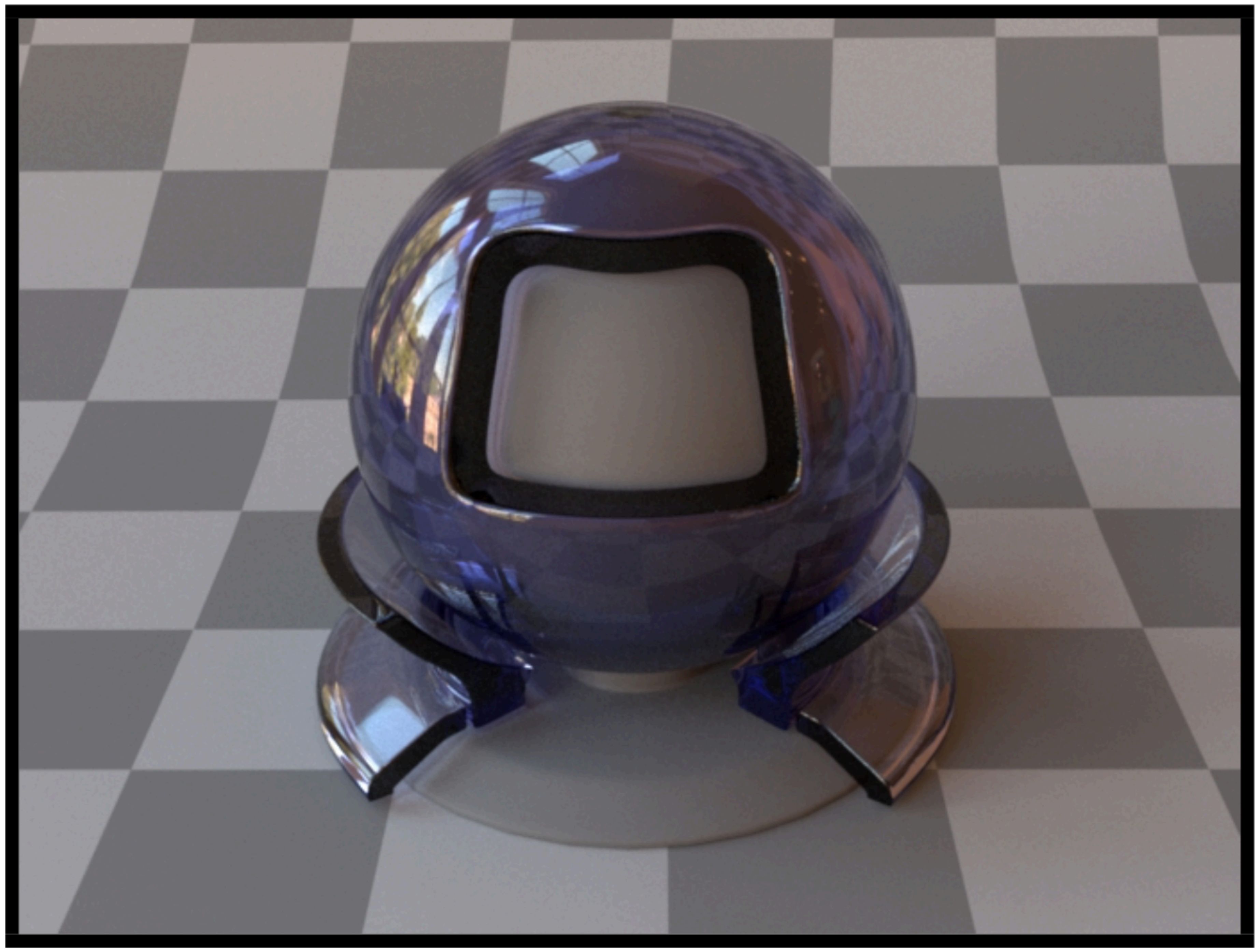


Ideal reflective / refractive material (BSDF*)





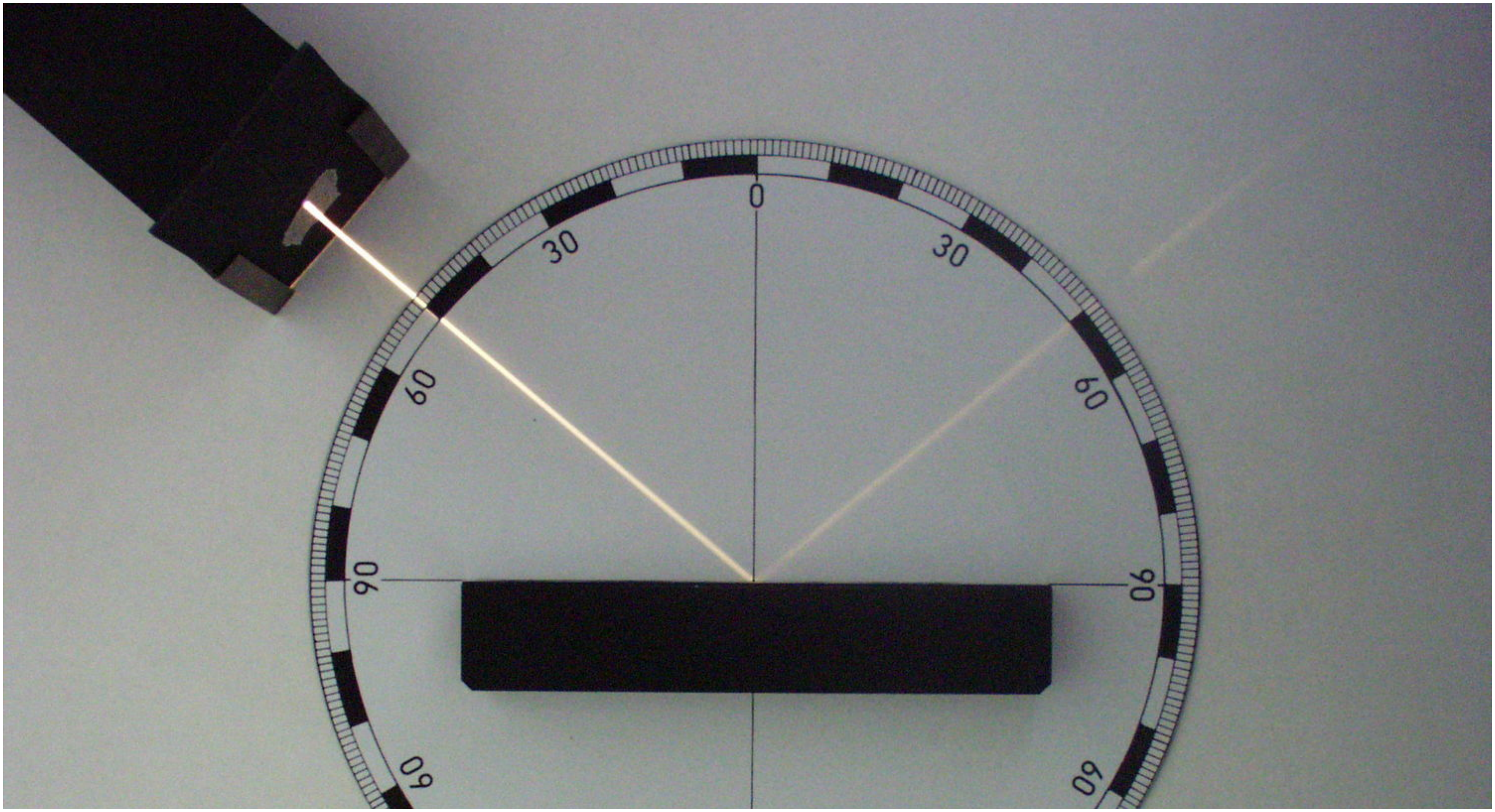
Air ↔ water interface



Air ↔ glass interface (with absorption)

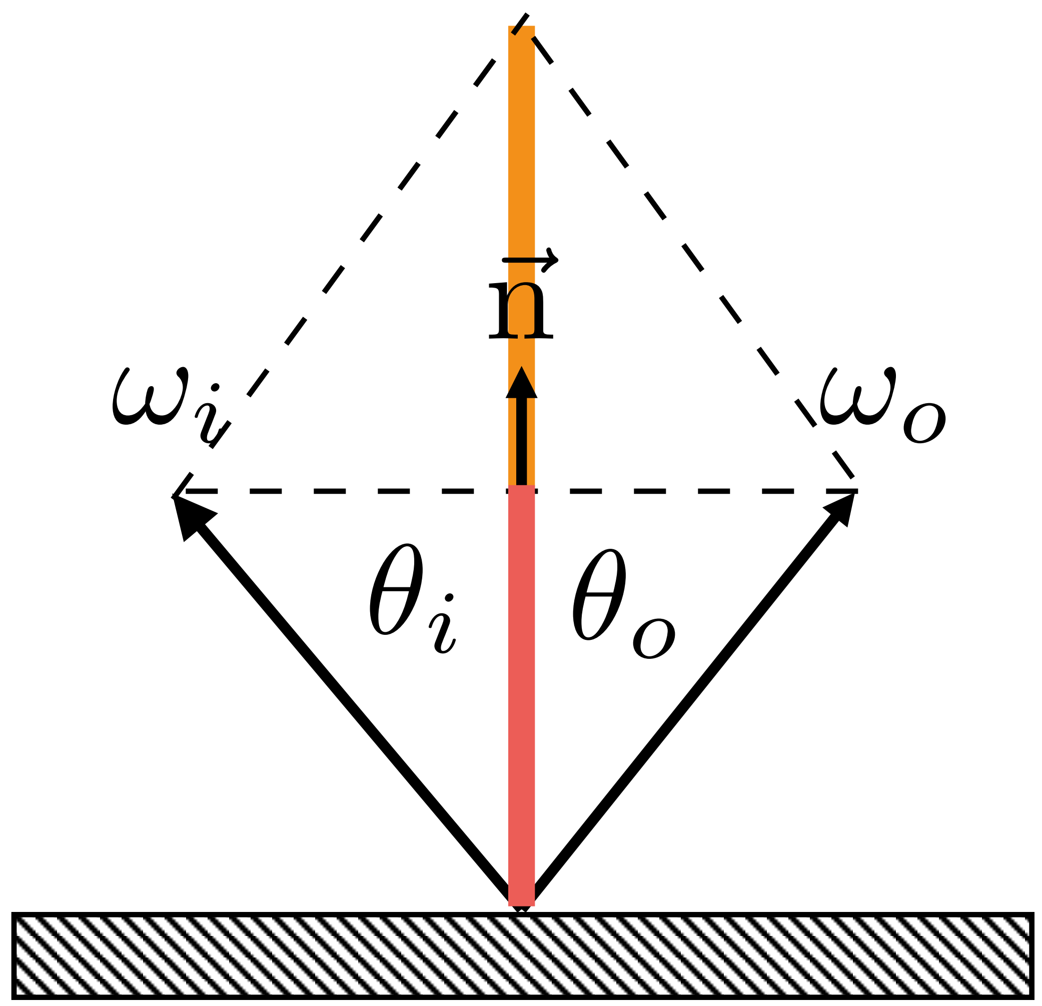
[Mitsuba renderer, Wenzel Jakob, 2010]

Perfect Specular Reflection



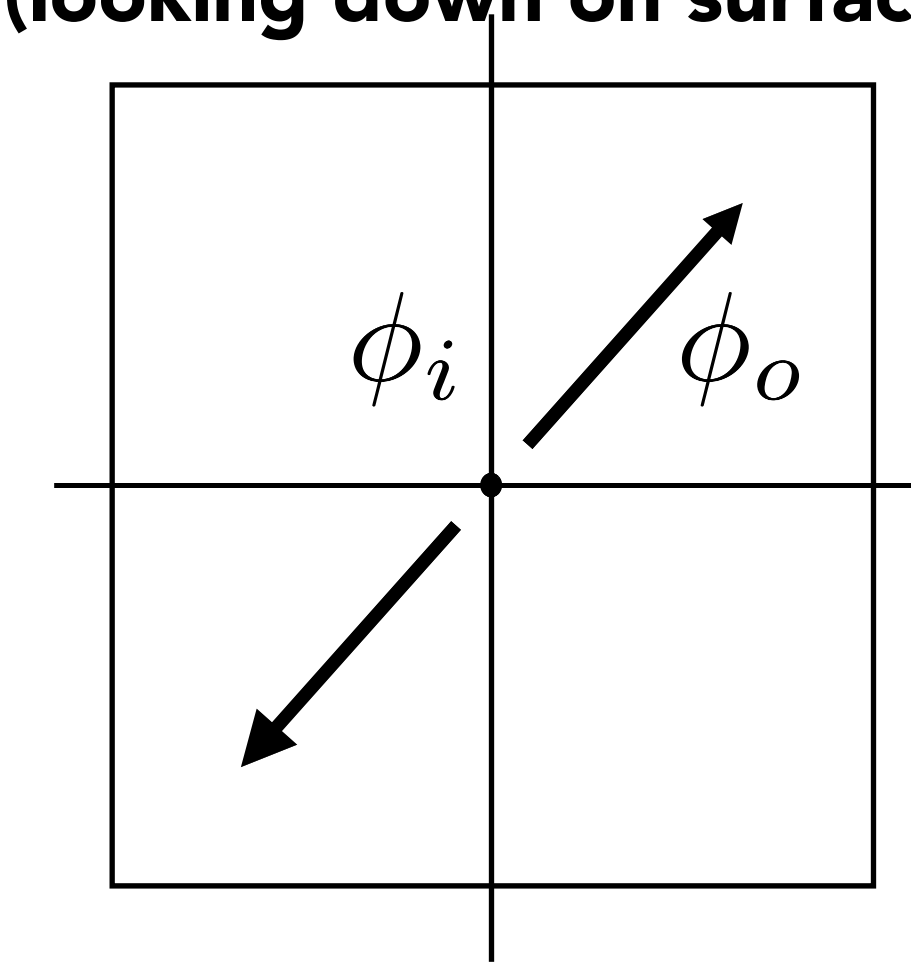
[Zátonyi Sándor]

Perfect Specular Reflection



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

Top-down view
(looking down on surface)

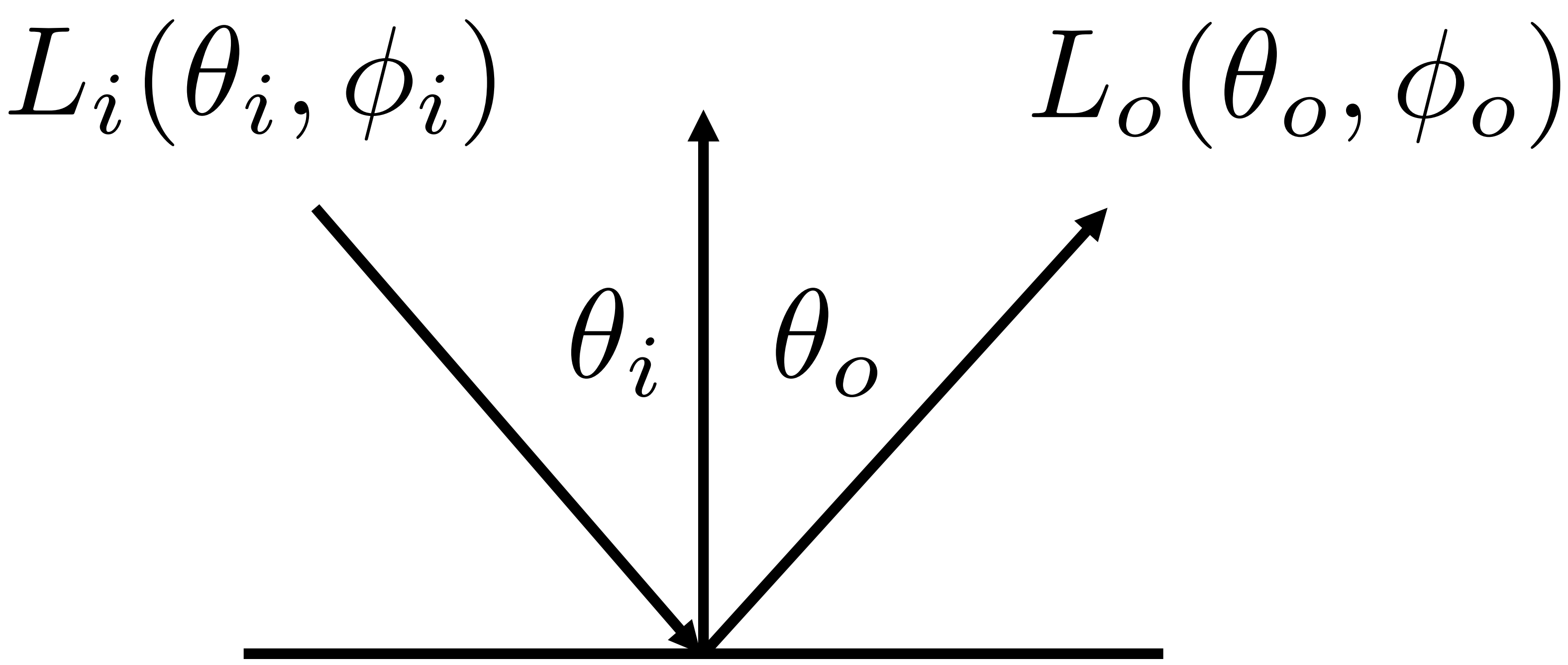


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Perfect Specular Reflection BRDF



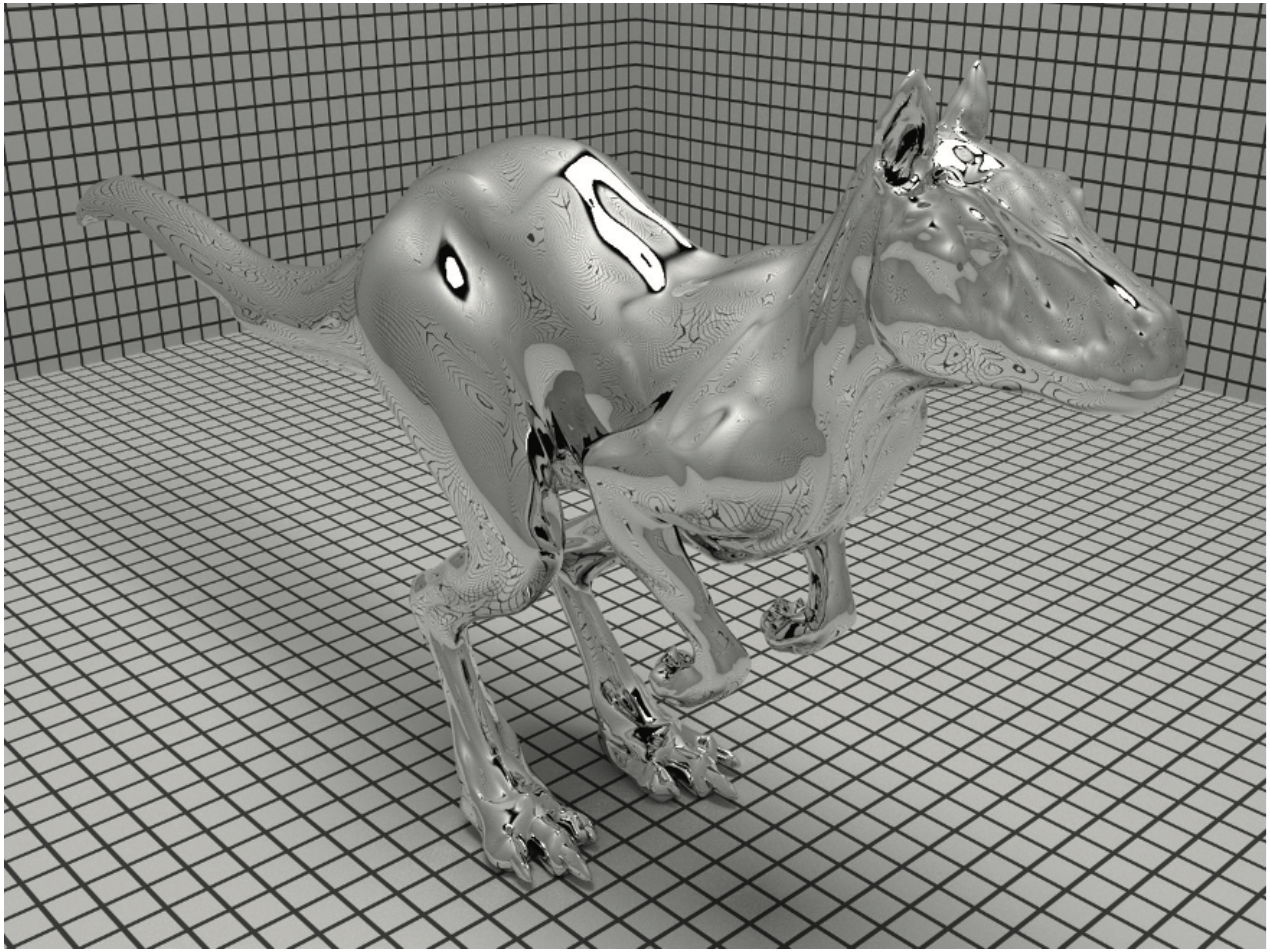
$$L_o(\theta_o, \phi_o) = L_i(\theta_i, \phi_i \pm \pi)$$

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

- **Why $\cos\theta_i$?**

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

Perfect Specular Reflection BRDF

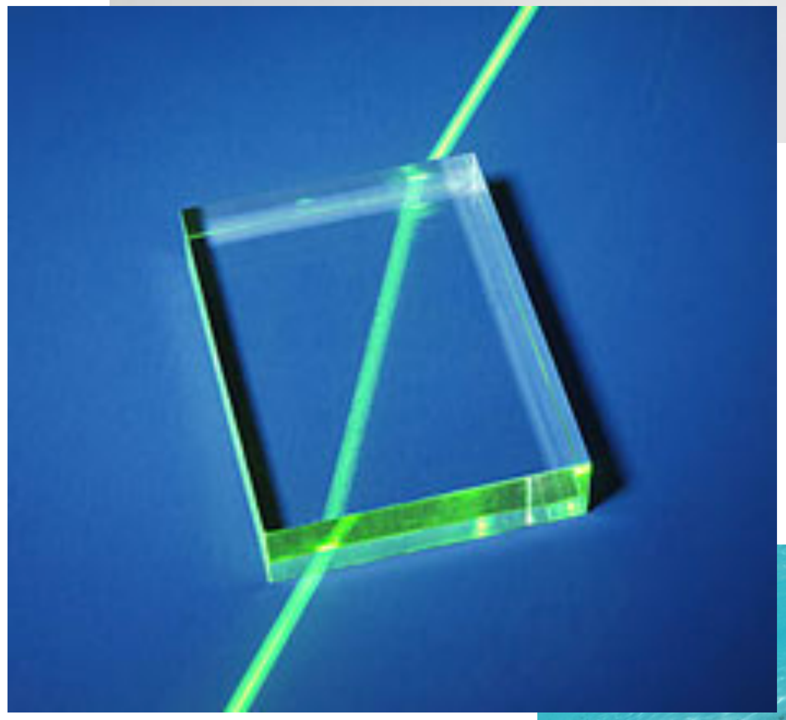


PBRT

Specular Refraction

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

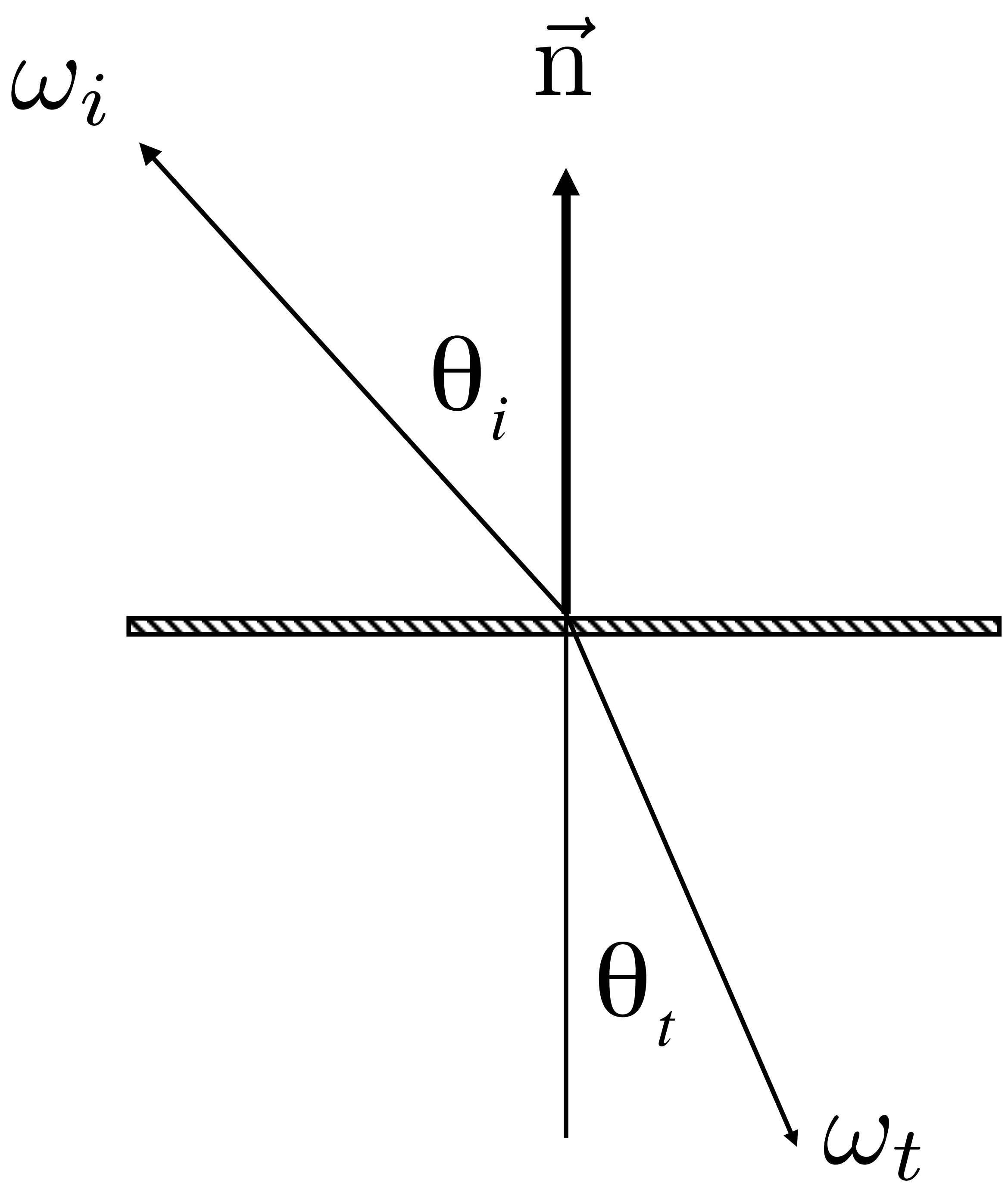
Light refracts when it enters a new medium.



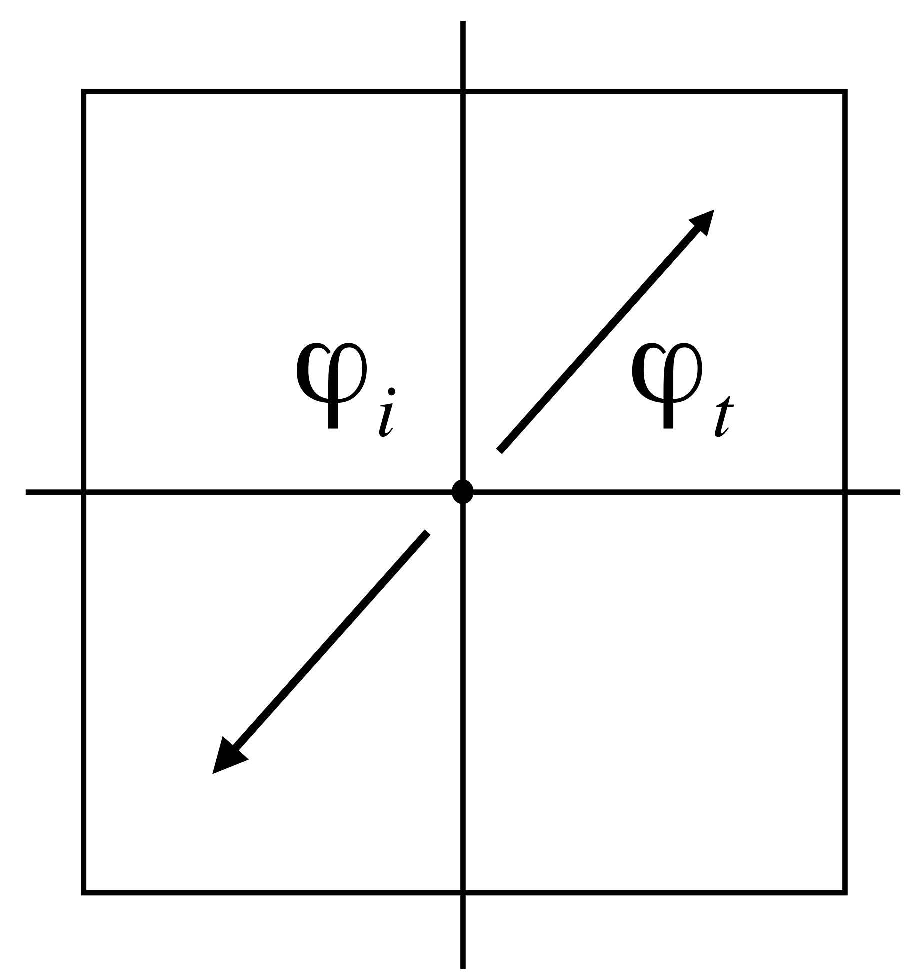
Snell's Law

Transmitted angle depends on

- index of refraction (IOR) for incident ray
- index of refraction (IOR) for exiting ray



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

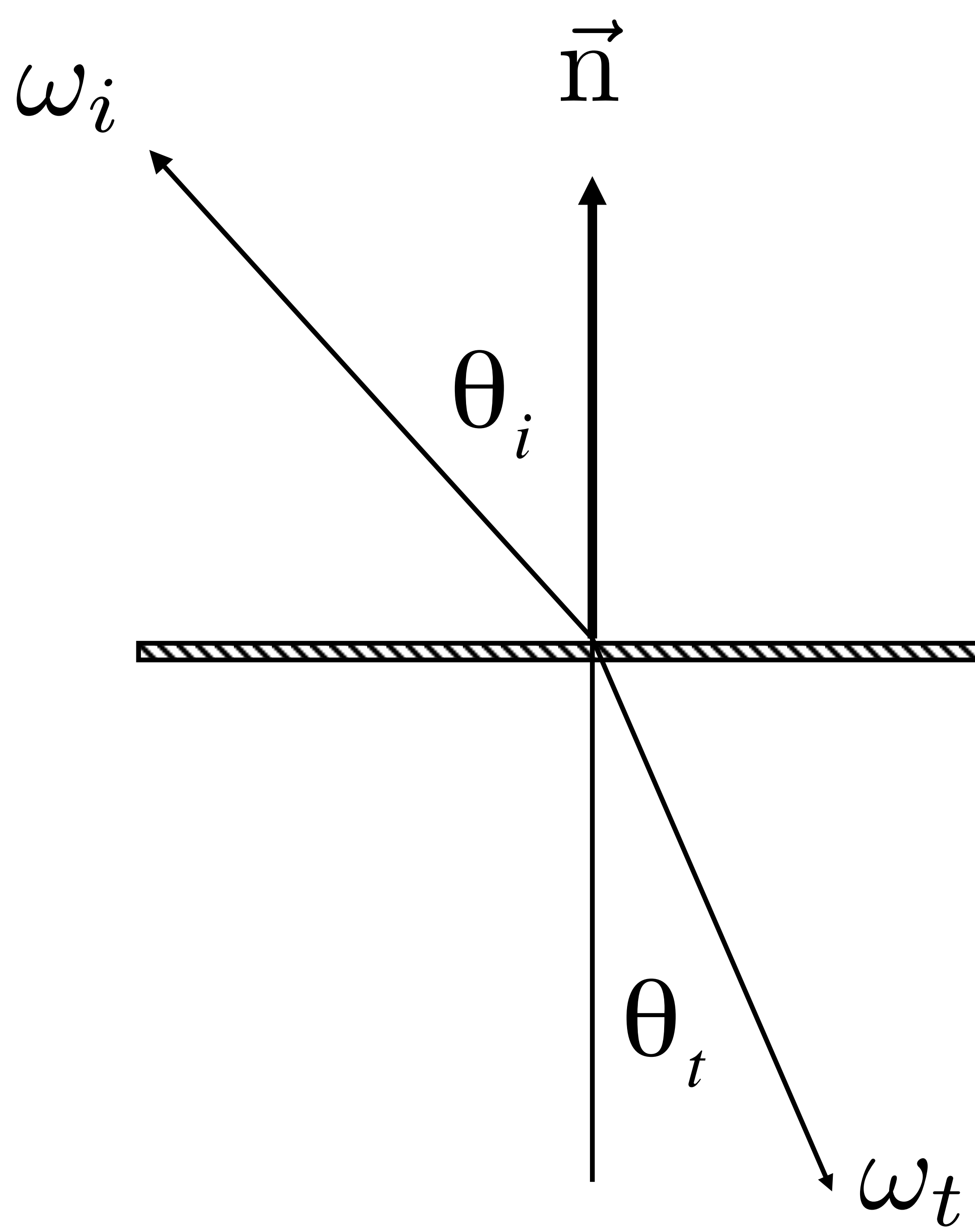


$$\varphi_t = \varphi_i \pm \pi$$

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:

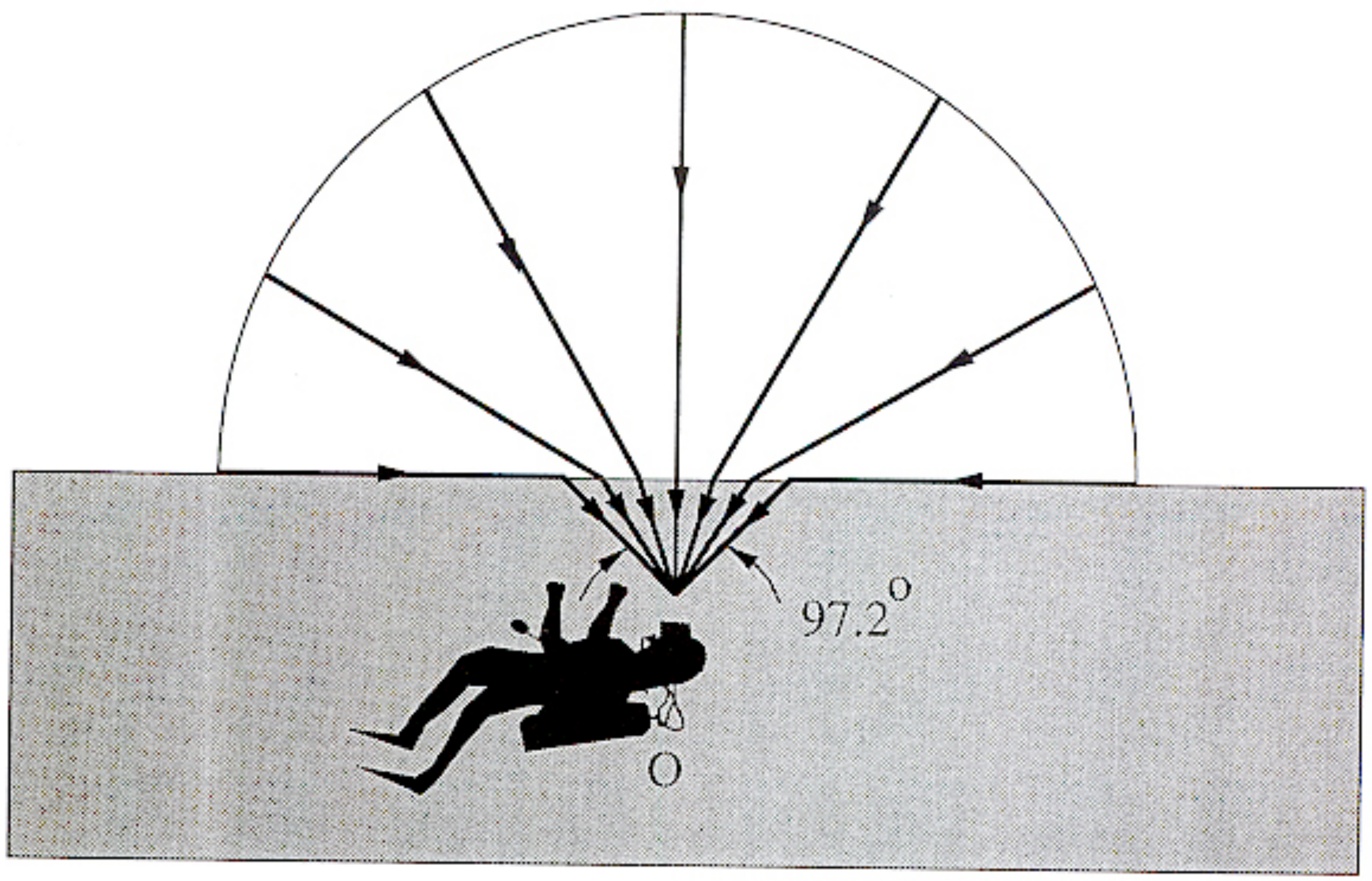
$$1-\left(\frac{\eta_i}{\eta_t}\right)^2 (1-\cos^2\theta_i) < 0$$

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

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

Snell's Window/Circle

Total internal reflection



[Livingston and Lynch]

Attendance Time

If you are seated in class, go to this form and sign in:

- https://tinyurl.com/184lecture

Notes:

- Time-stamp will be taken when you submit form.
  Do it now, won't count later.
- Don't tell friends outside class to fill it out now,
  because we will audit at some point in semester.
- Failing audit will have large negative consequence.
  You don't need to, because you have an alternative!

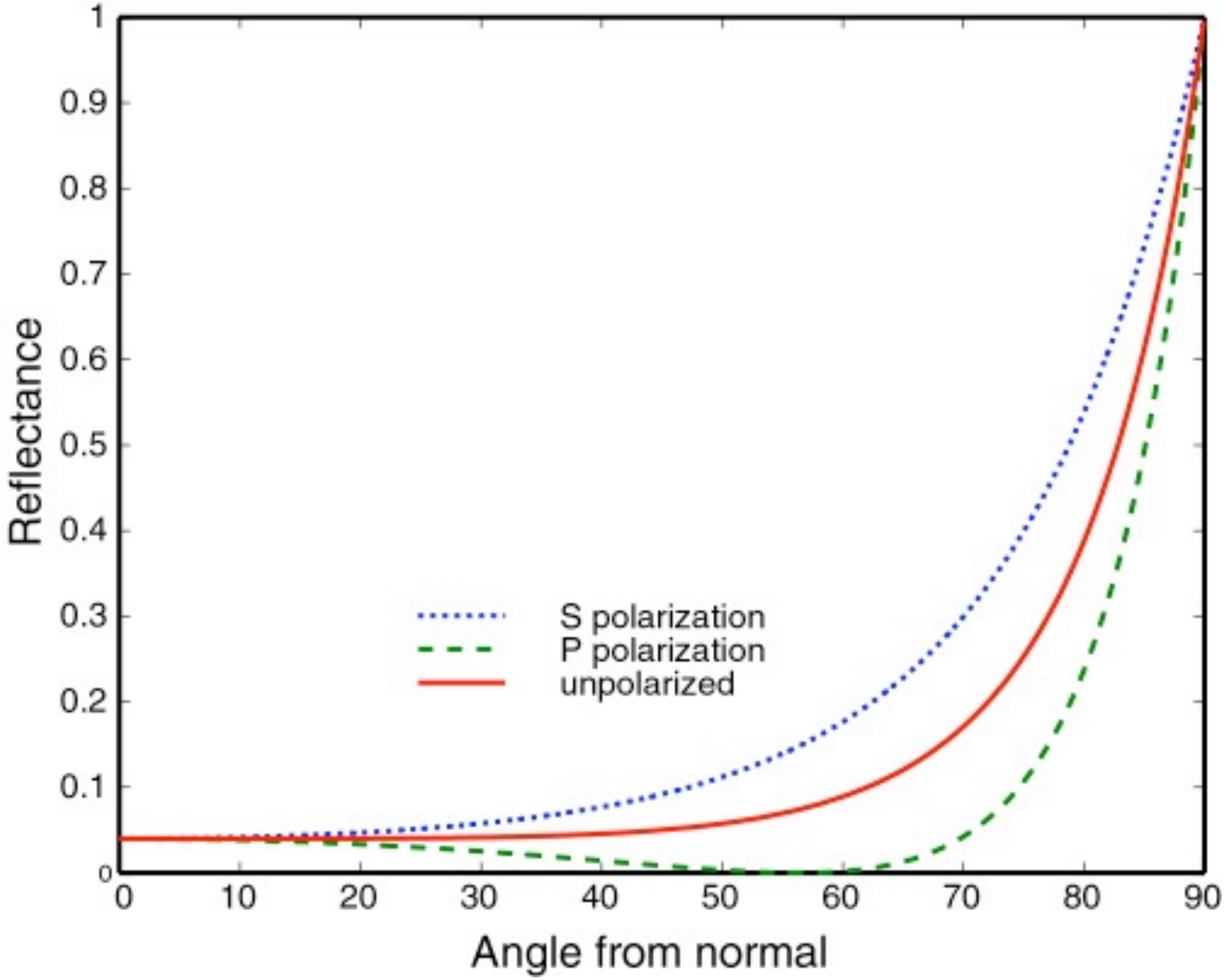
Fresnel Reflection / Term

Reflectance depends on incident angle (and polarization of light)

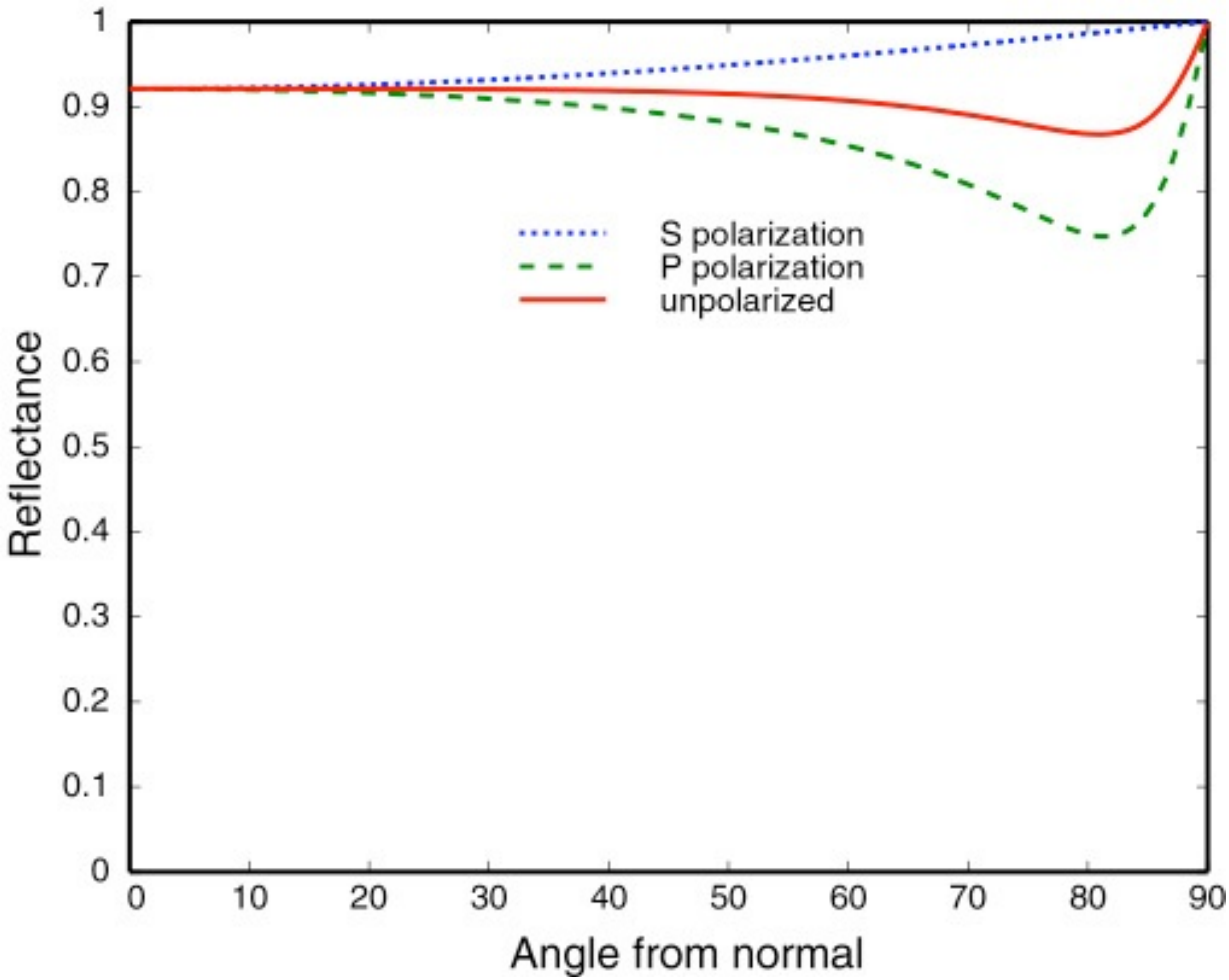
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

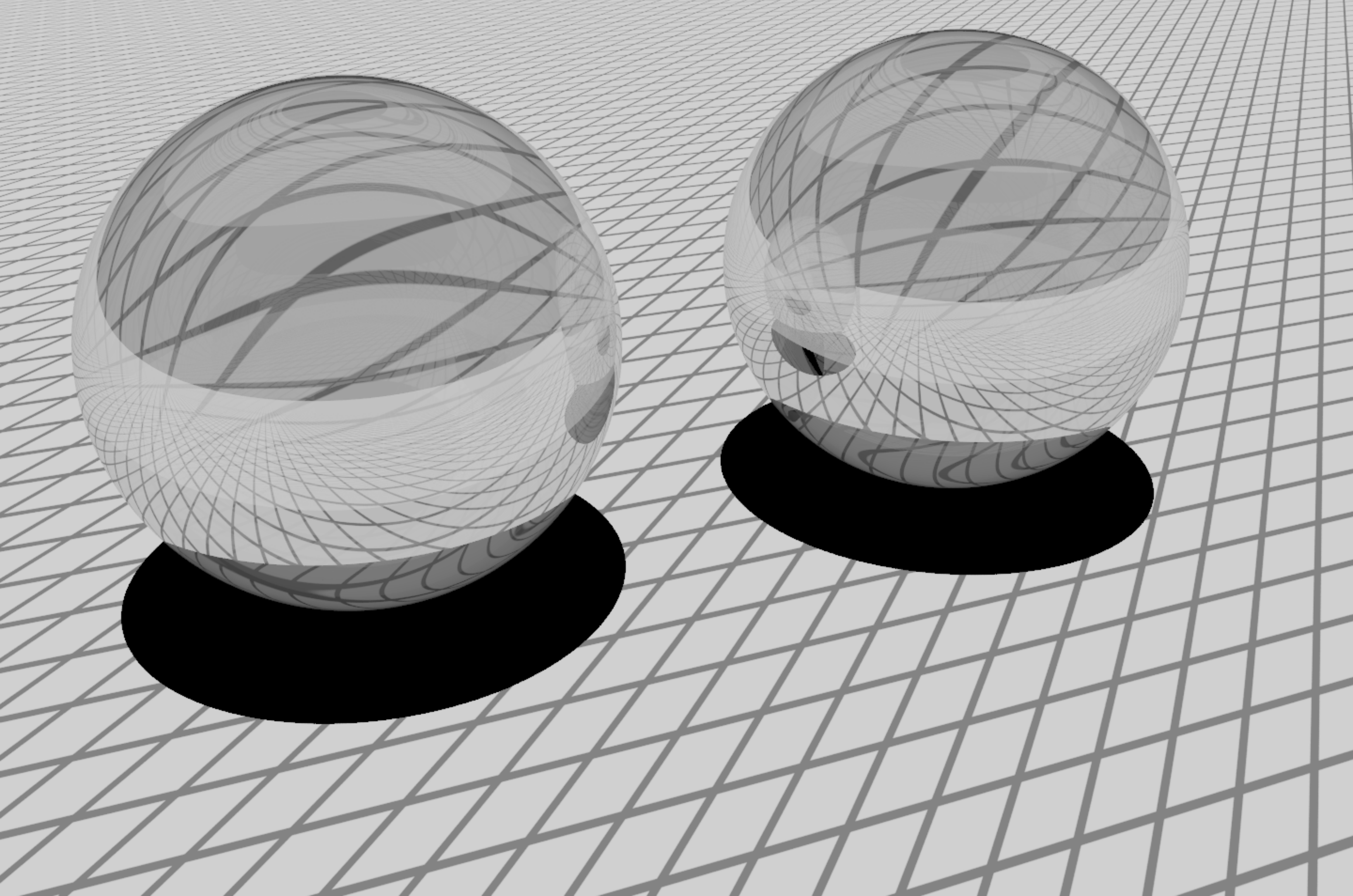
Fresnel Term (Dielectric, η =1.5)



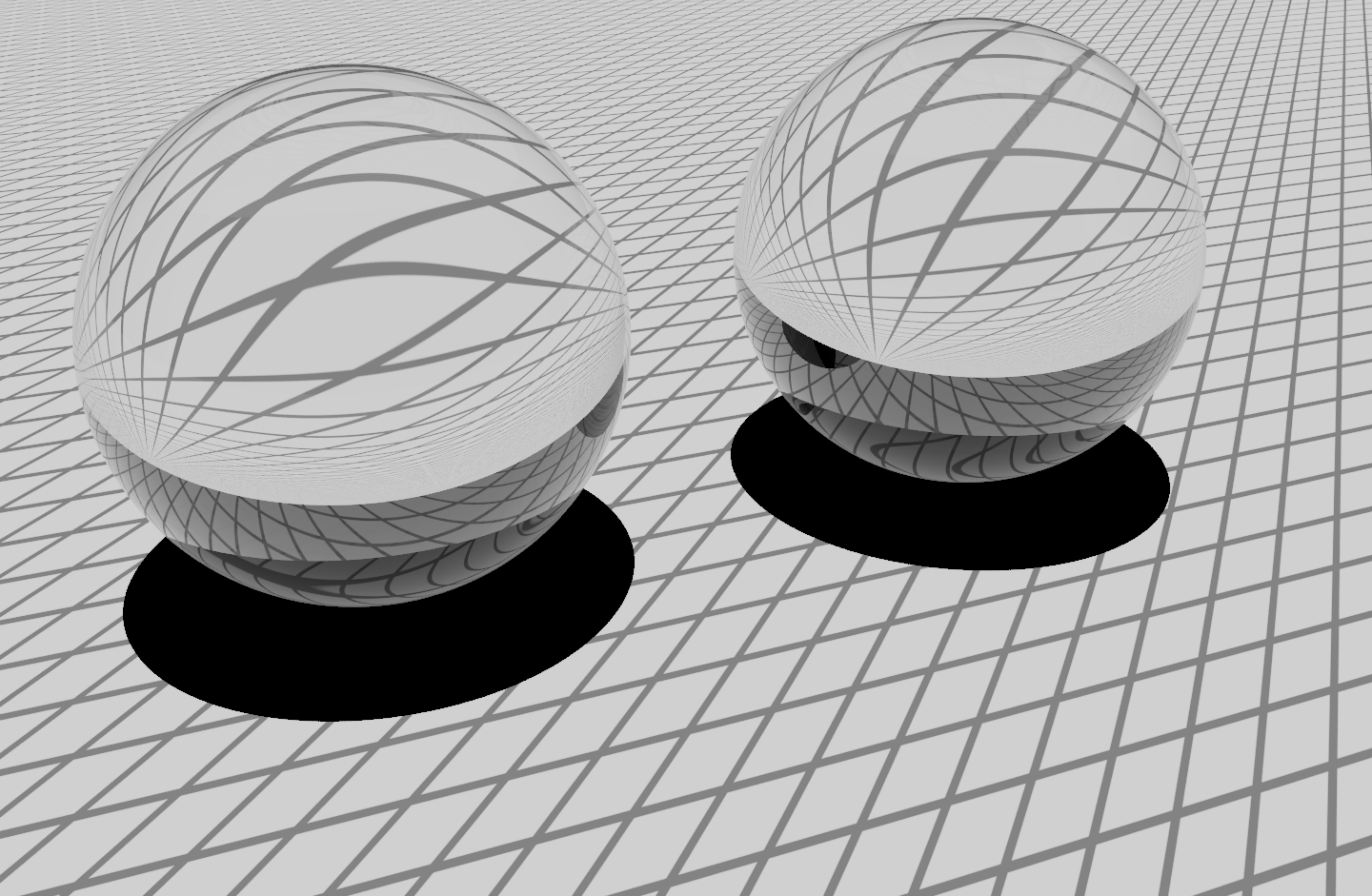
Fresnel Term (Conductor)



Without Fresnel (Fixed Reflectance/Transmission)



Glass with Fresnel Reflection/Transmission



Microfacet Material

Microfacet Reflection

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

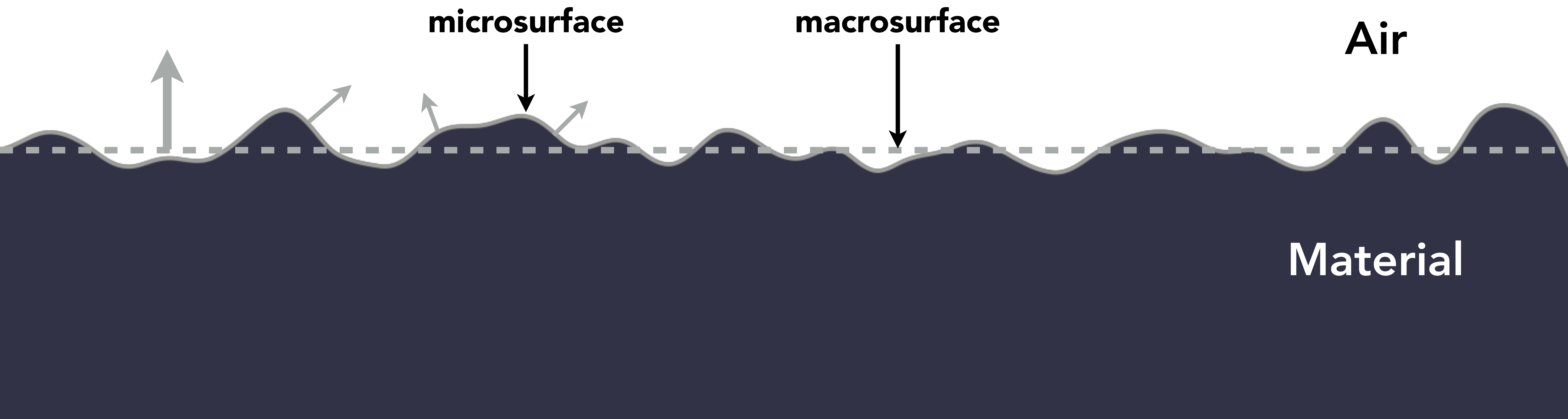
Microfacet Theory

Rough surface

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

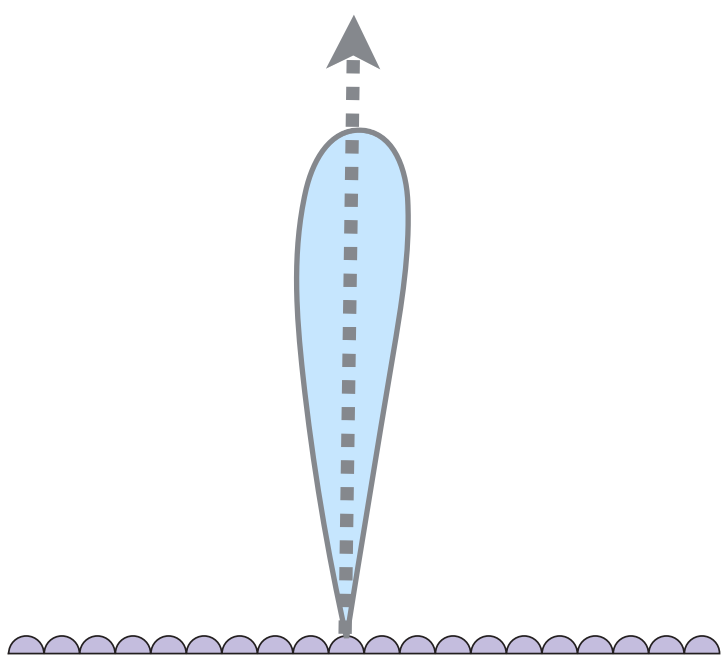
Individual elements of surface act like mirrors

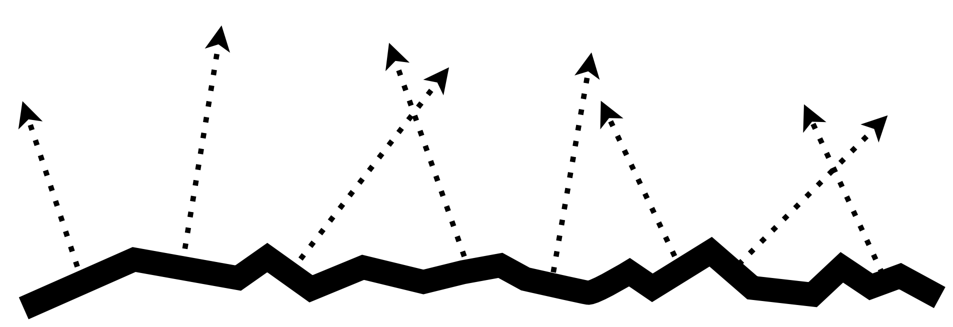
- Known as Microfacets
- Each microfacet has its own normal

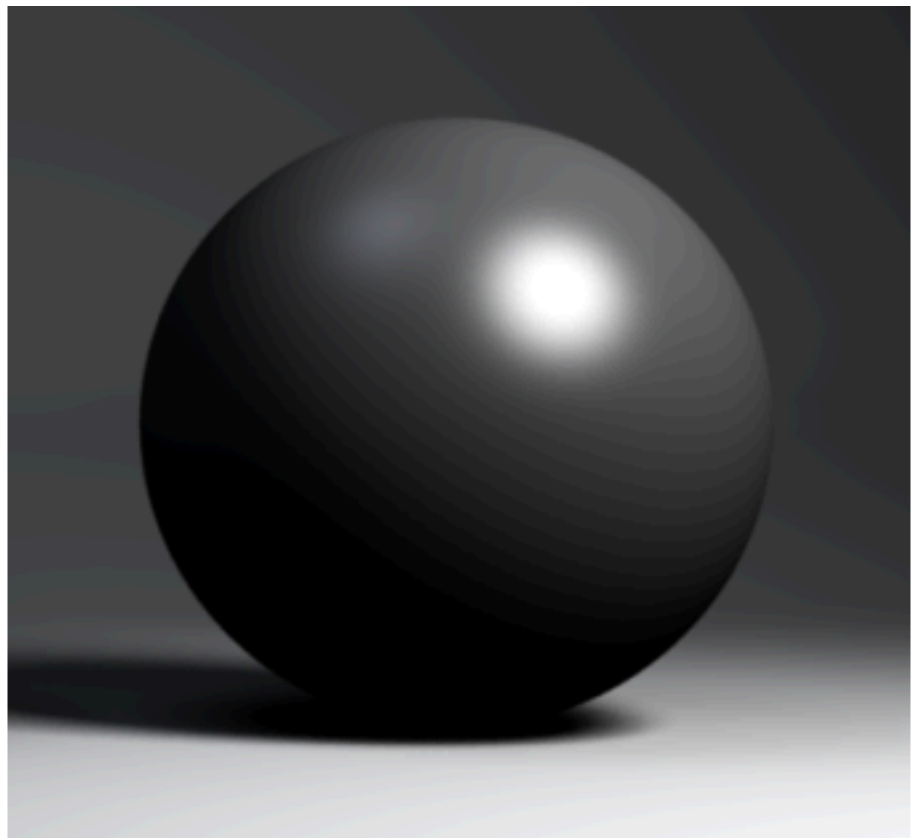


Microfacet BRDF

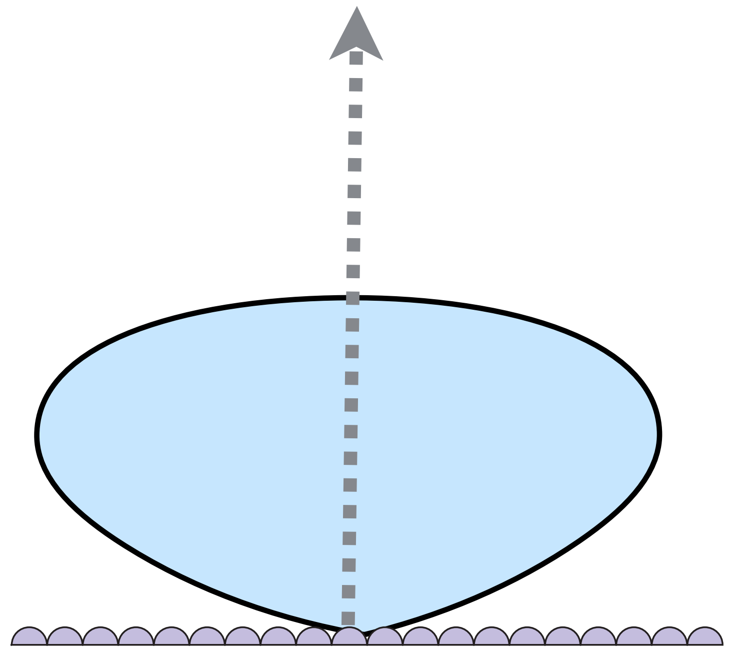
- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

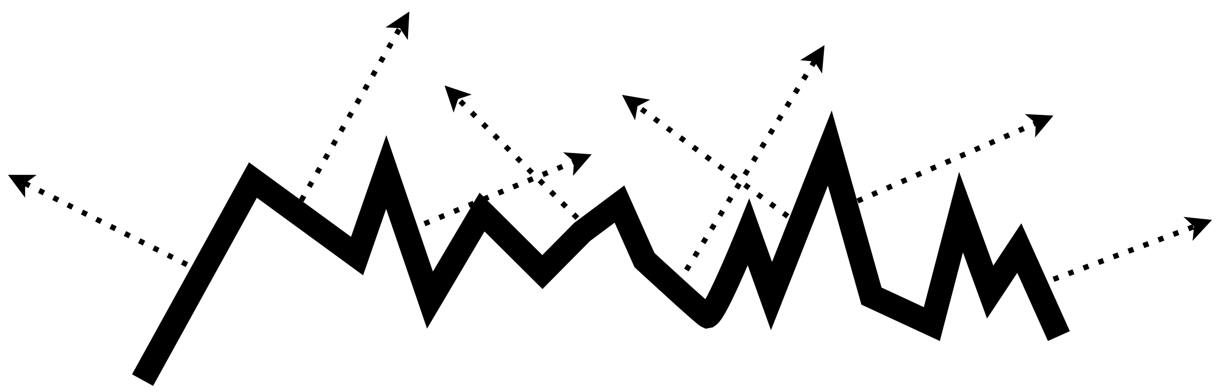


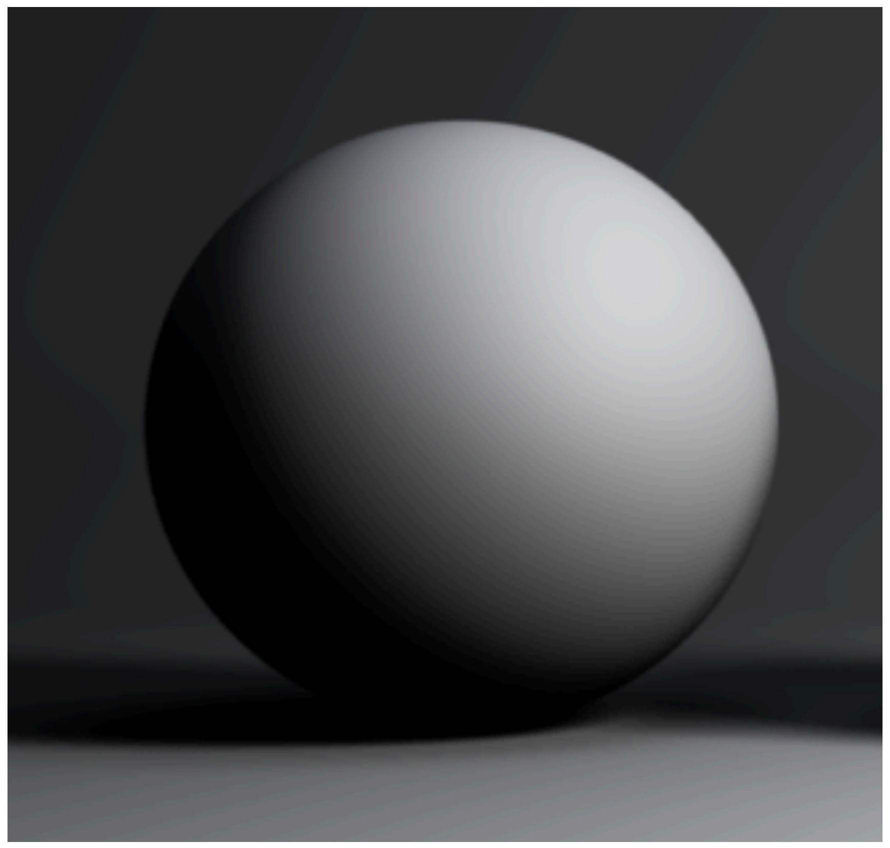




  - Spread <==> diffuse

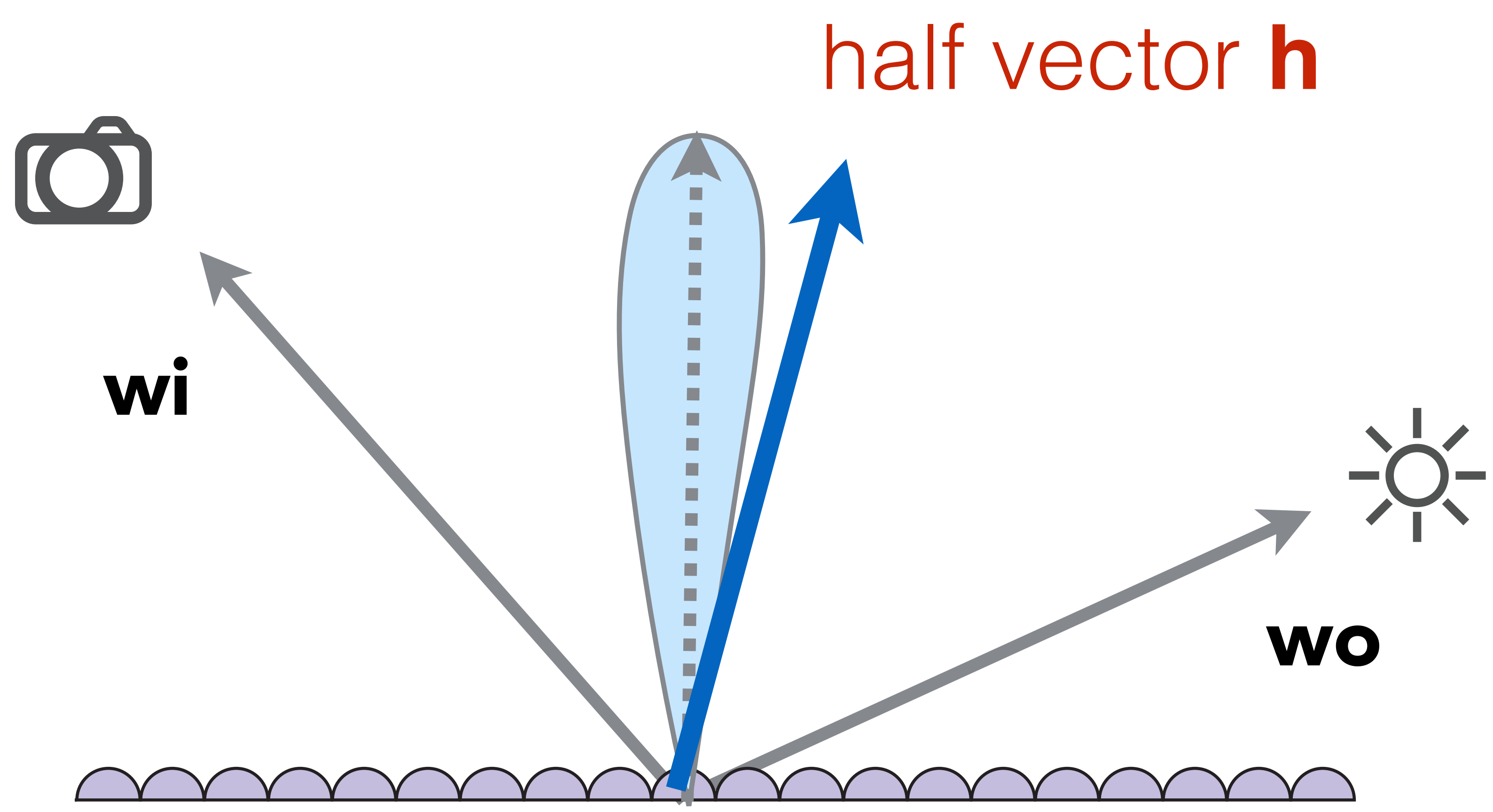


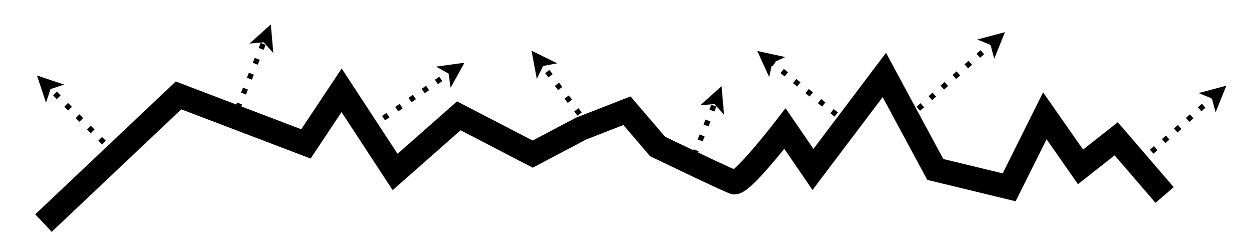




Microfacet BRDF

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





Fresnel term | shadowing-masking term | **distribution of normals**

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

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?

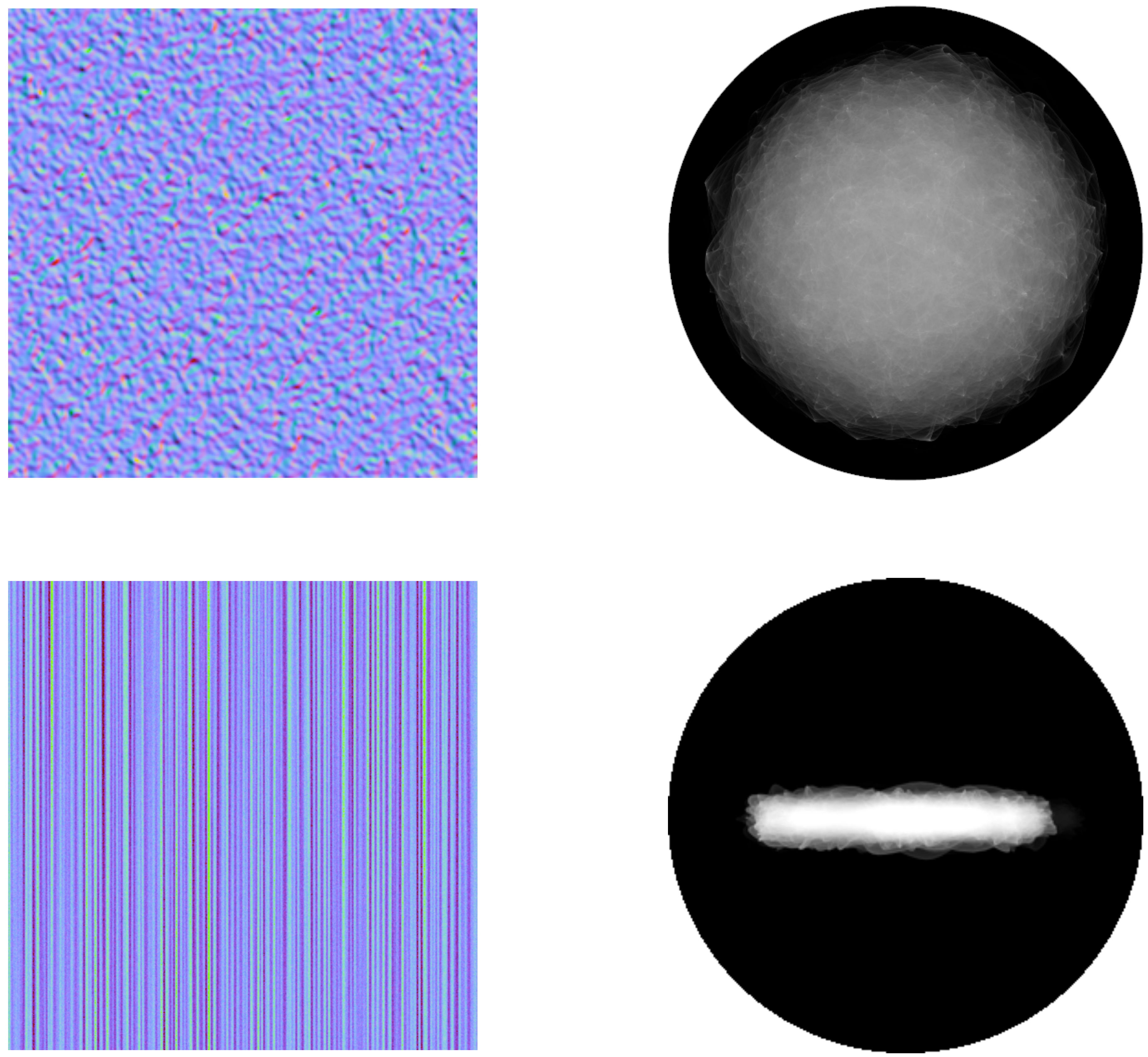
Inside an elevator

Isotropic / Anisotropic Materials (BRDFs)

- Key: directionality of underlying surface

Isotropic

Anisotropic



Surface (normals)

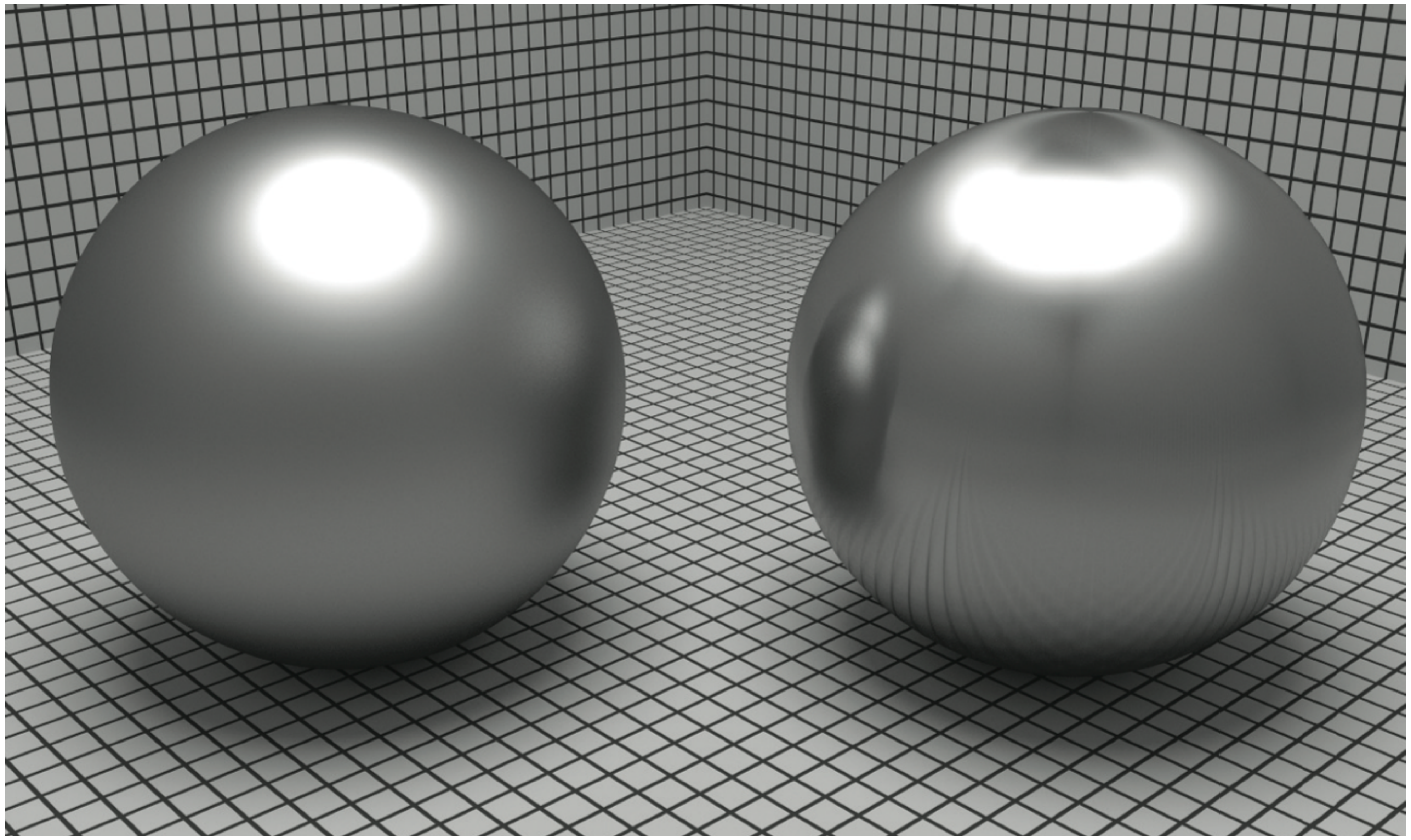
BRDF (fix wi, vary wo)

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



Anisotropic BRDF: Brushed Metal

- How is the pan brushed?

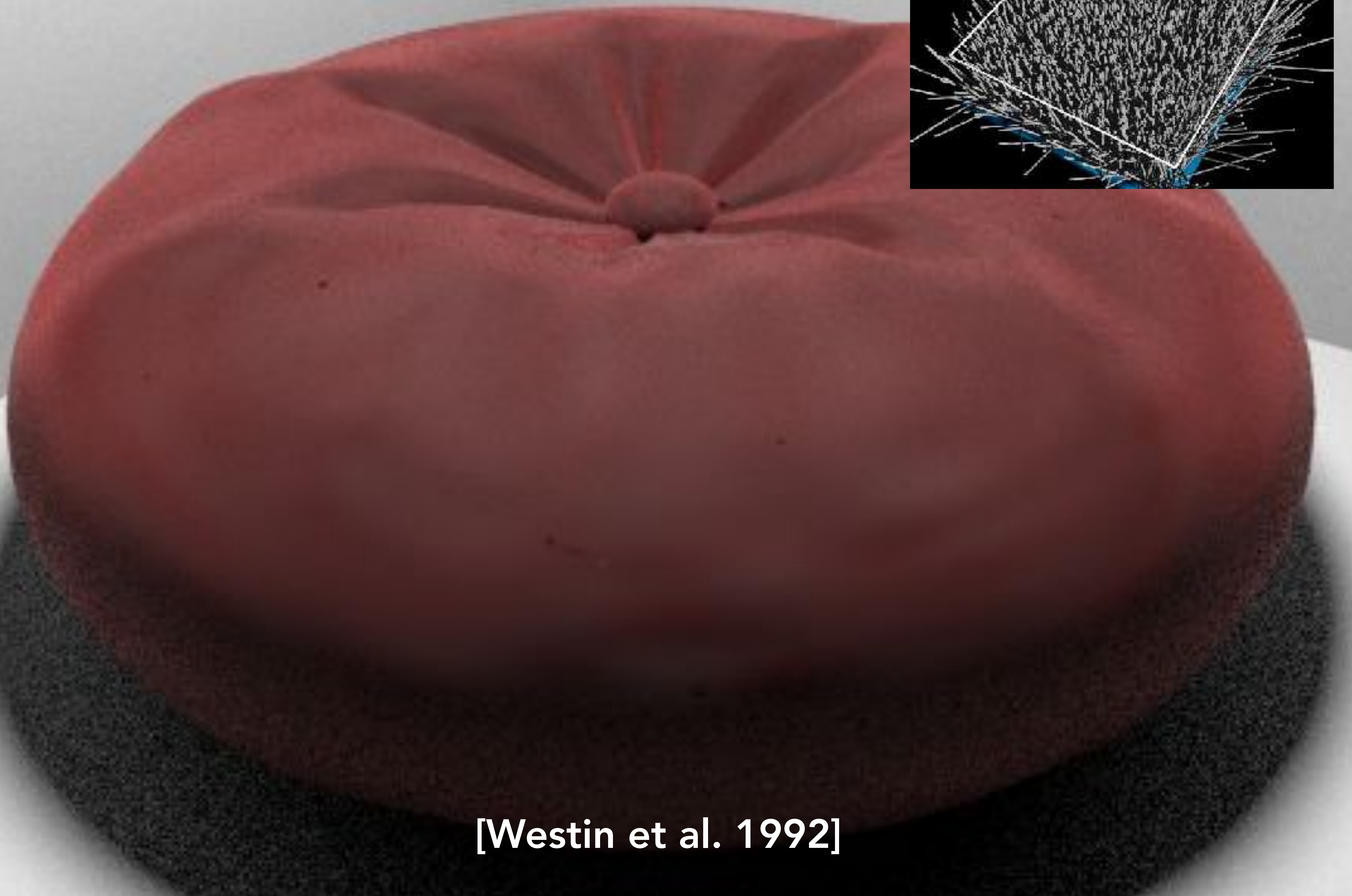
[VRay renderer]

Jonathan Ragan-Kelley & Ren Ng

Anisotropic BRDF: Nylon

[Westin et al. 1992]

Anisotropic BRDF: Velvet



[Westin et al. 1992]

Anisotropic BRDF: Velvet

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

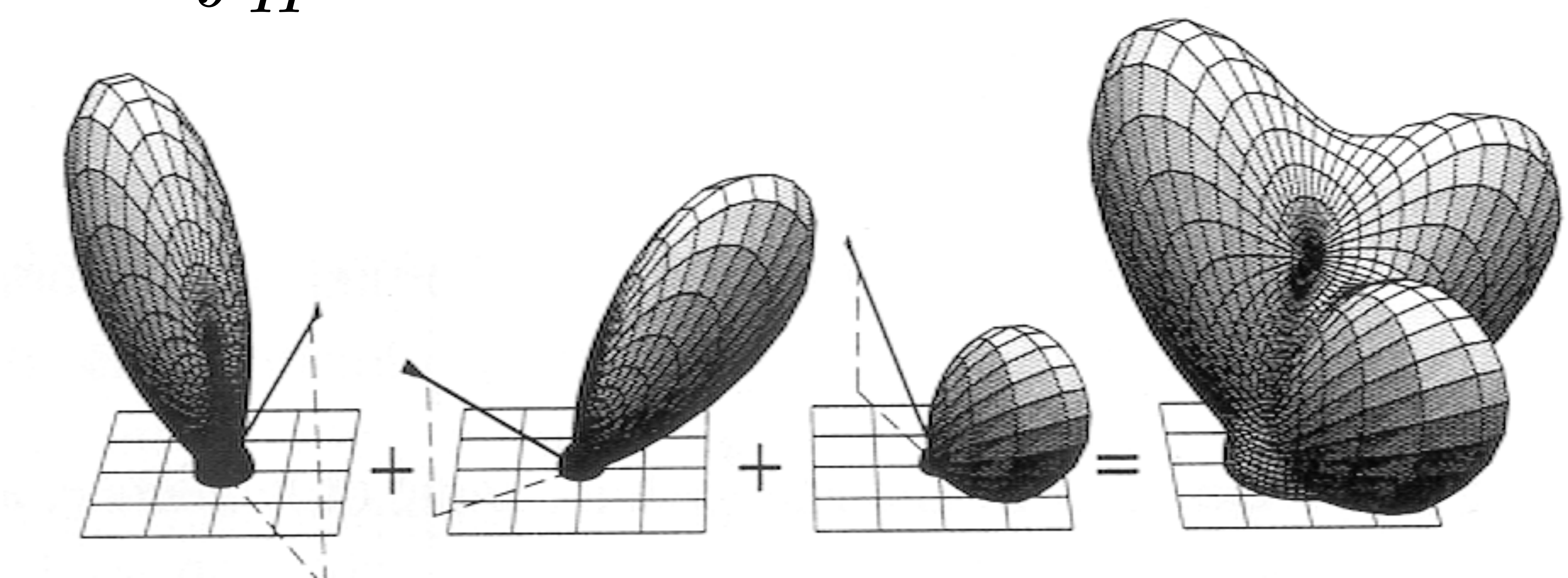
Properties of BRDFs

- **Non-negativity**

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

- **Linearity**

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

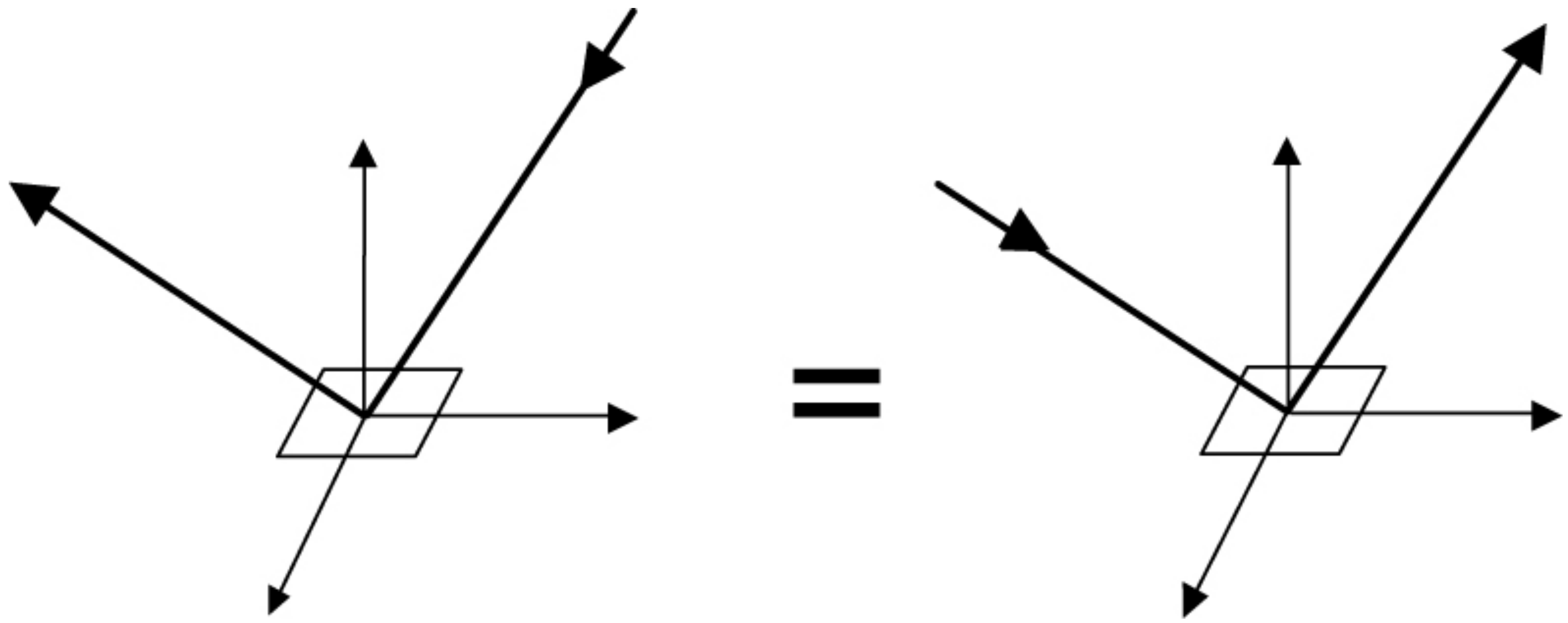


[Sillion et al. 1990]

Properties of BRDFs

- Reciprocity

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



- Energy conservation

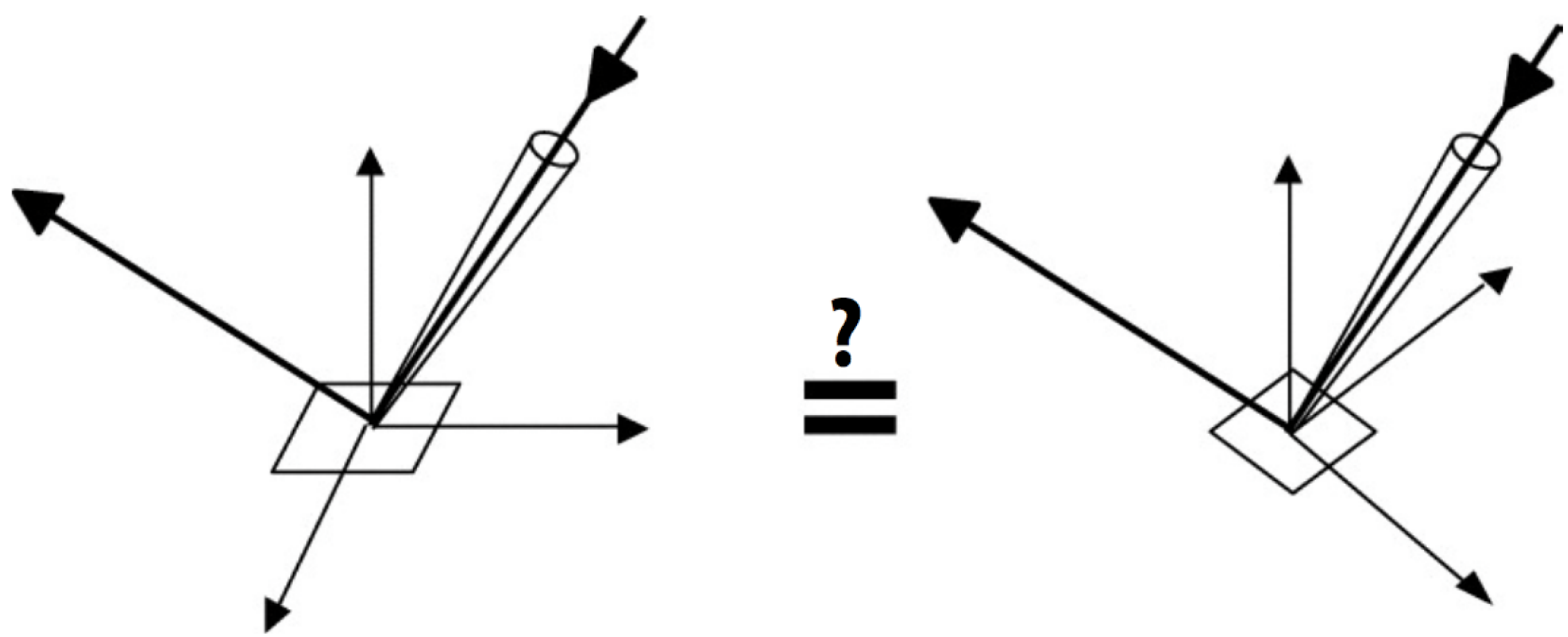
$$\forall \omega_r \int_{H^2} f_r(\omega_i \to \omega_r)\, \cos\theta_i \, \mathrm{d}\omega_i \leq 1$$

Jonathan Ragan-Kelley & Ren Ng

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:

[Bagher et al. 2012]

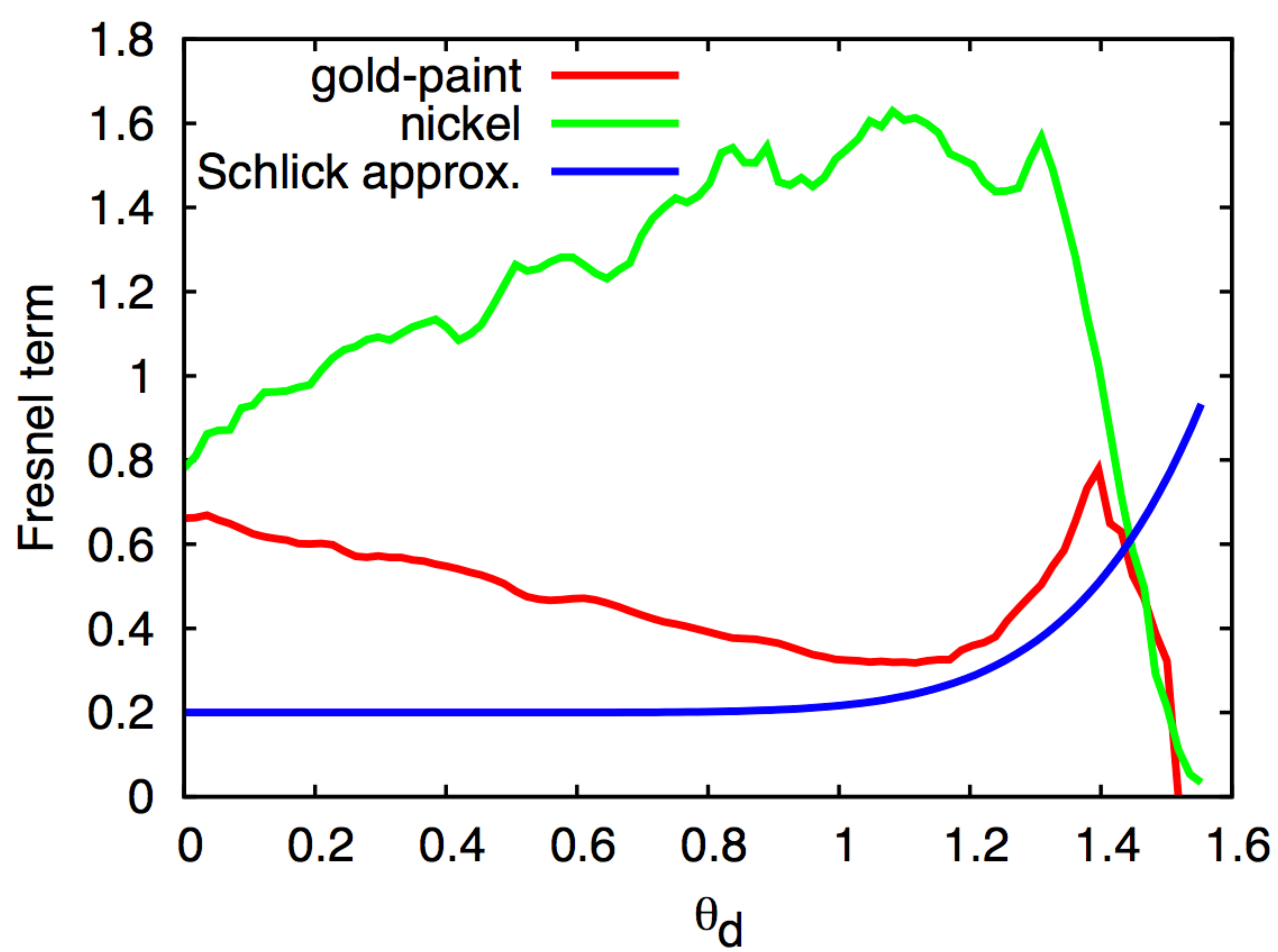
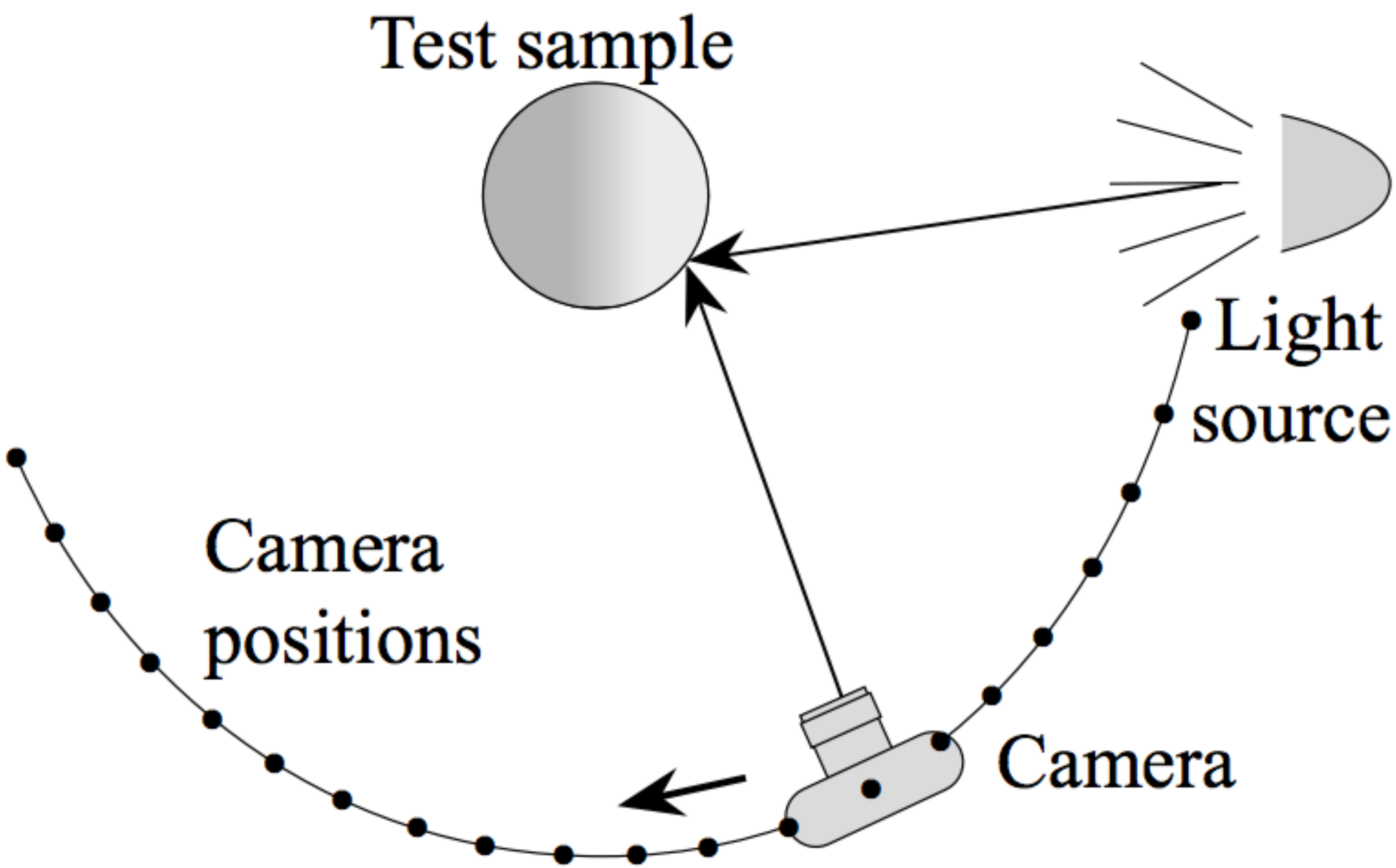
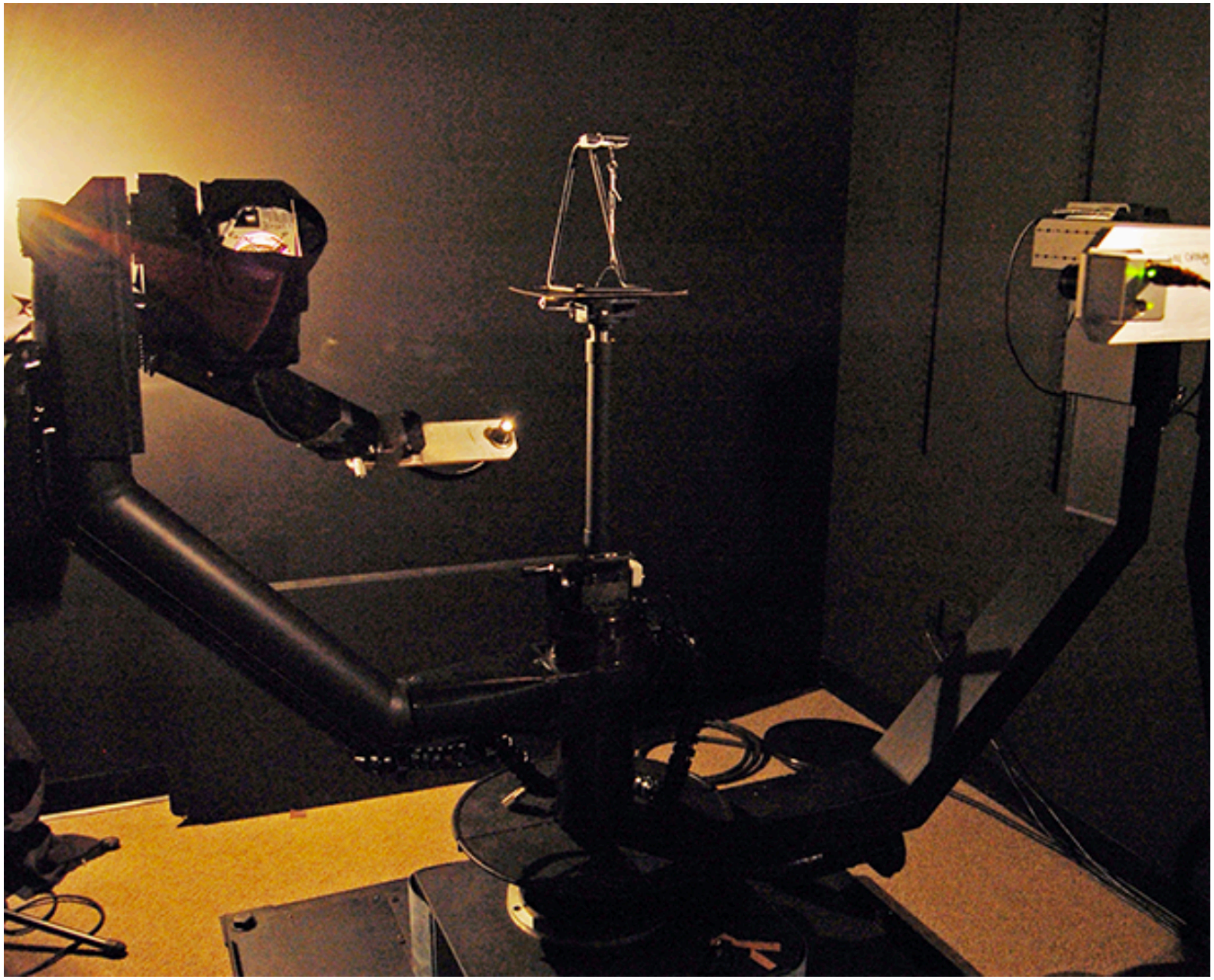


Image-Based BRDF Measurement



[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

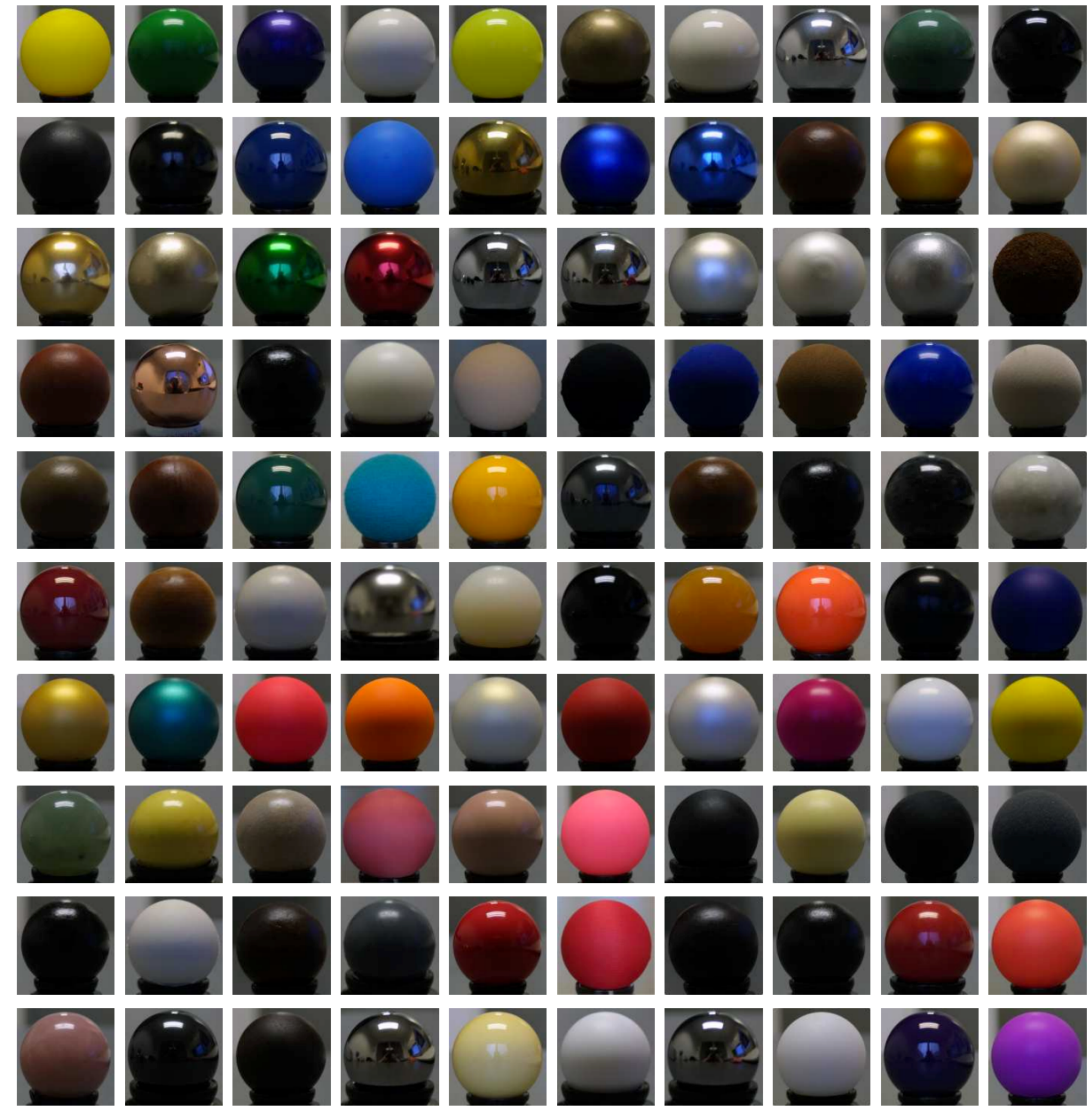
Tabular Representation

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

Advanced Appearance Models

Translucent Materials: Jade

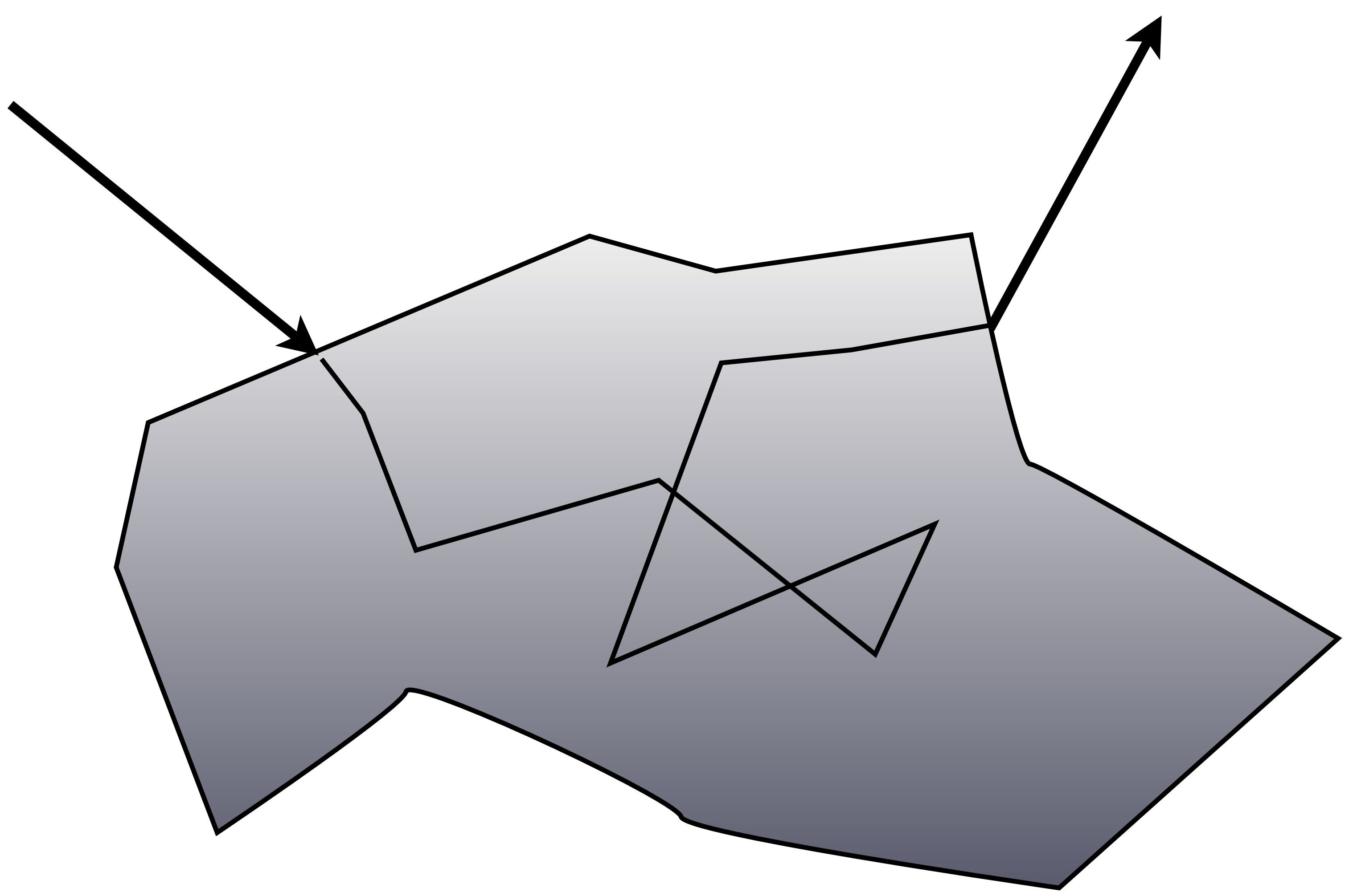
Translucent Materials: Skin

Translucent Materials: Leaves

Subsurface Scattering

Visual characteristics of many surfaces caused by light entering at different points than it exits

- Violates a fundamental assumption of the BRDF



[Jensen et al 2001]

[Donner et al 2008]

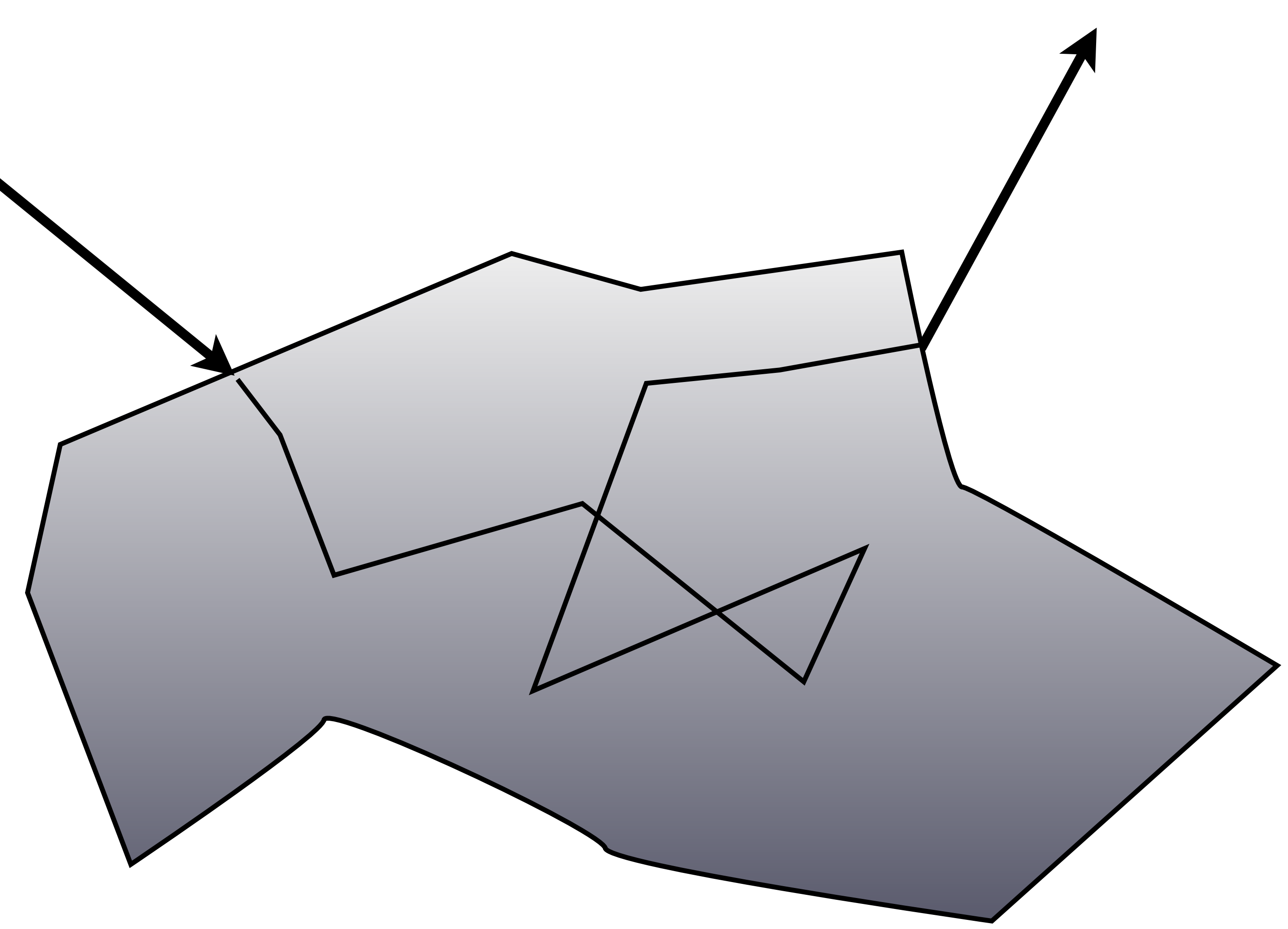
Scattering Functions

- **Generalization of BRDF; describes exitant radiance at one point due to incident differential irradiance at another point:**

$$S(x_i, \omega_i, x_o, \omega_o)$$

- **Generalization of reflection equation integrates over all points on the surface and all directions (!)**

$$L(x_o, \omega_o) = \int_A \int_{H^2} S(x_i, \omega_i, x_o, \omega_o)\, L_i(x_i, \omega_i) \cos\theta_i \,\mathrm{d}\omega_i \,\mathrm{d}A$$

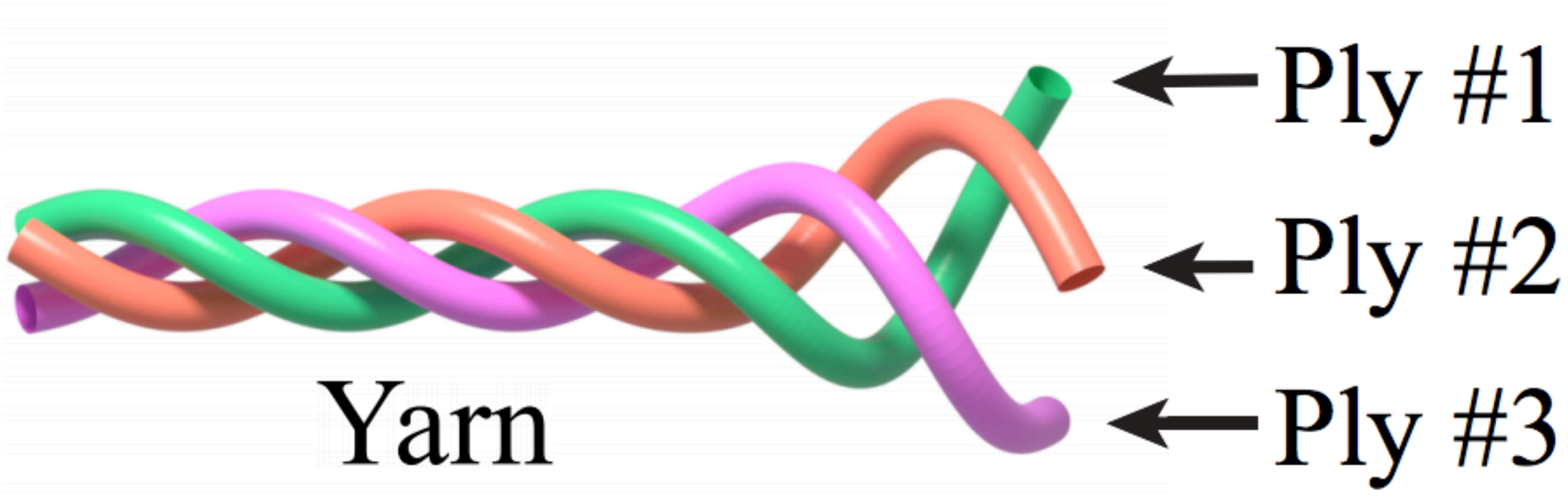


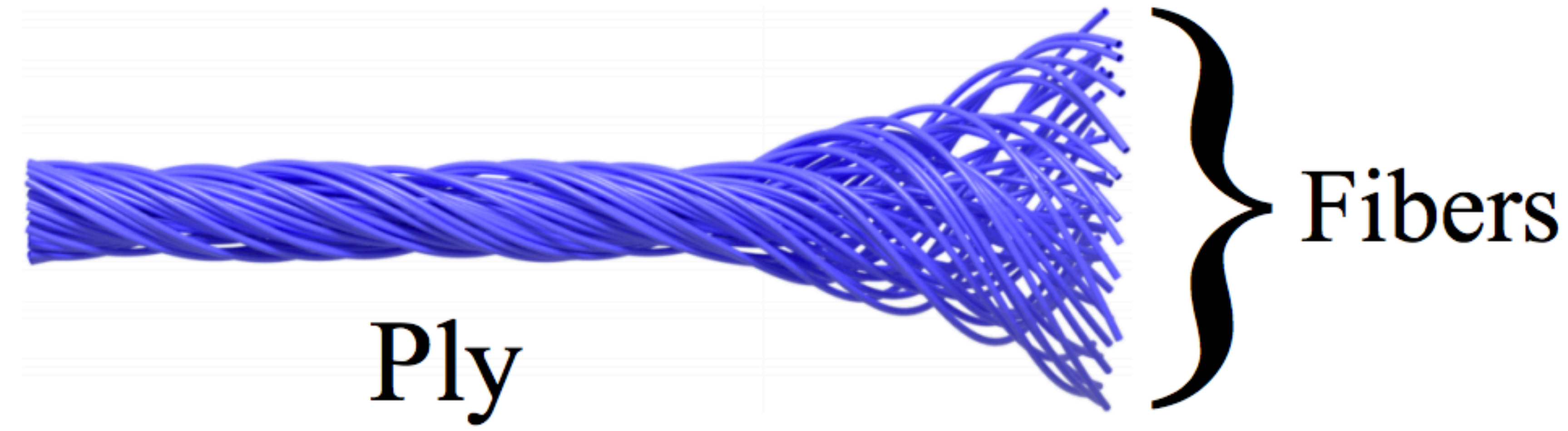
BRDF

BSSRDF

Cloth

- A collection of twisted fibers!
- Two levels of twist

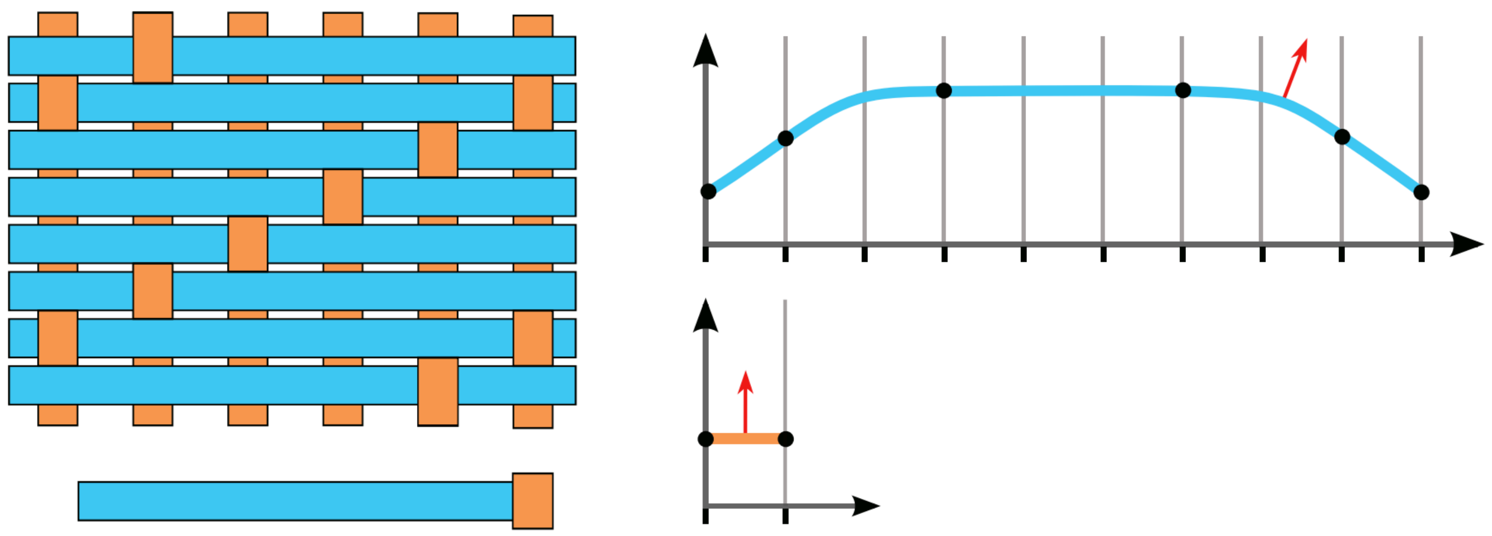


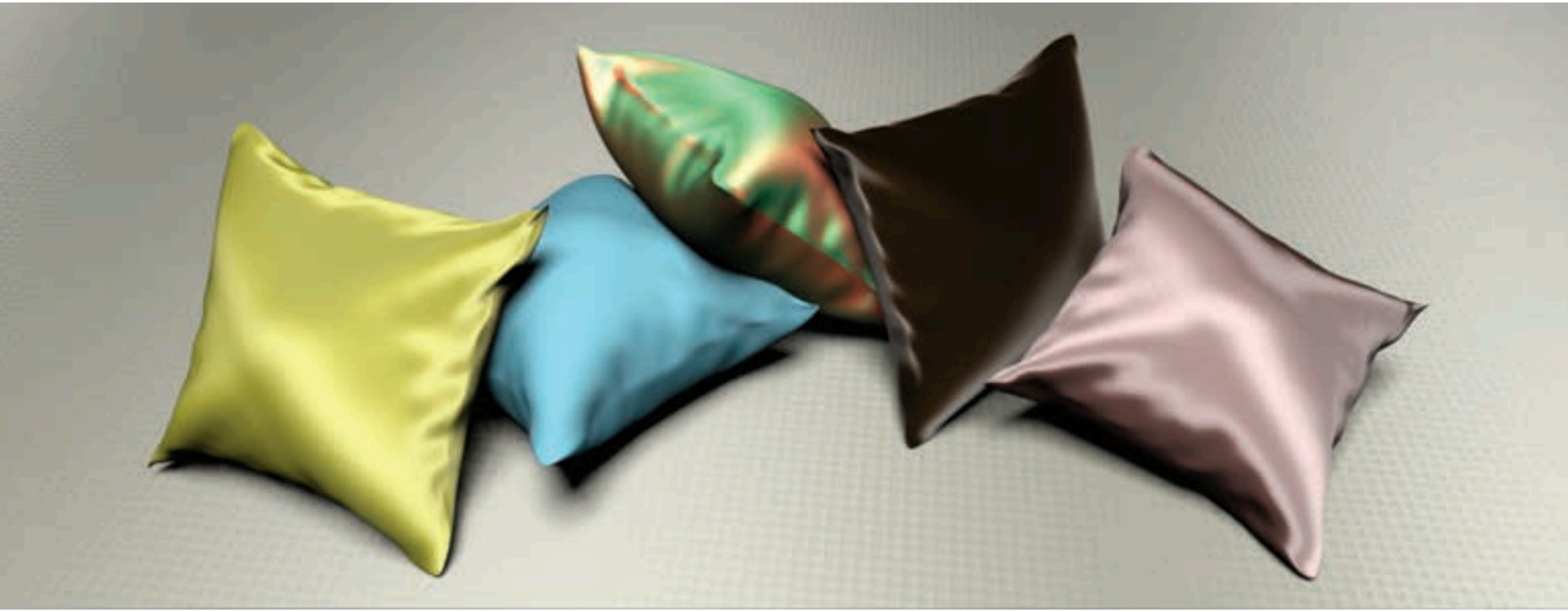


- Woven or knitted

Cloth: Render as Surface

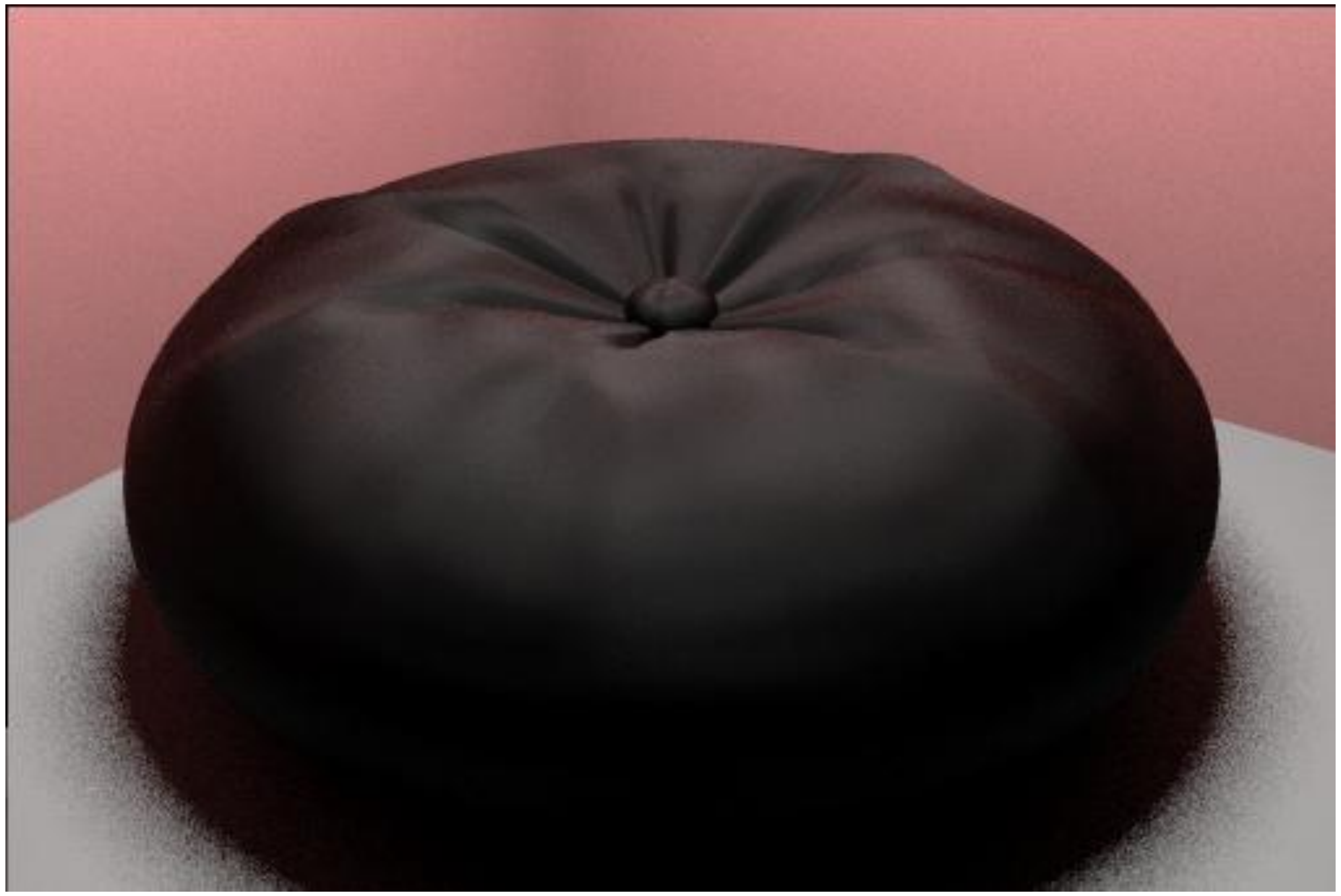
- Given the weaving pattern, calculate the overall behavior
- Render using a BRDF

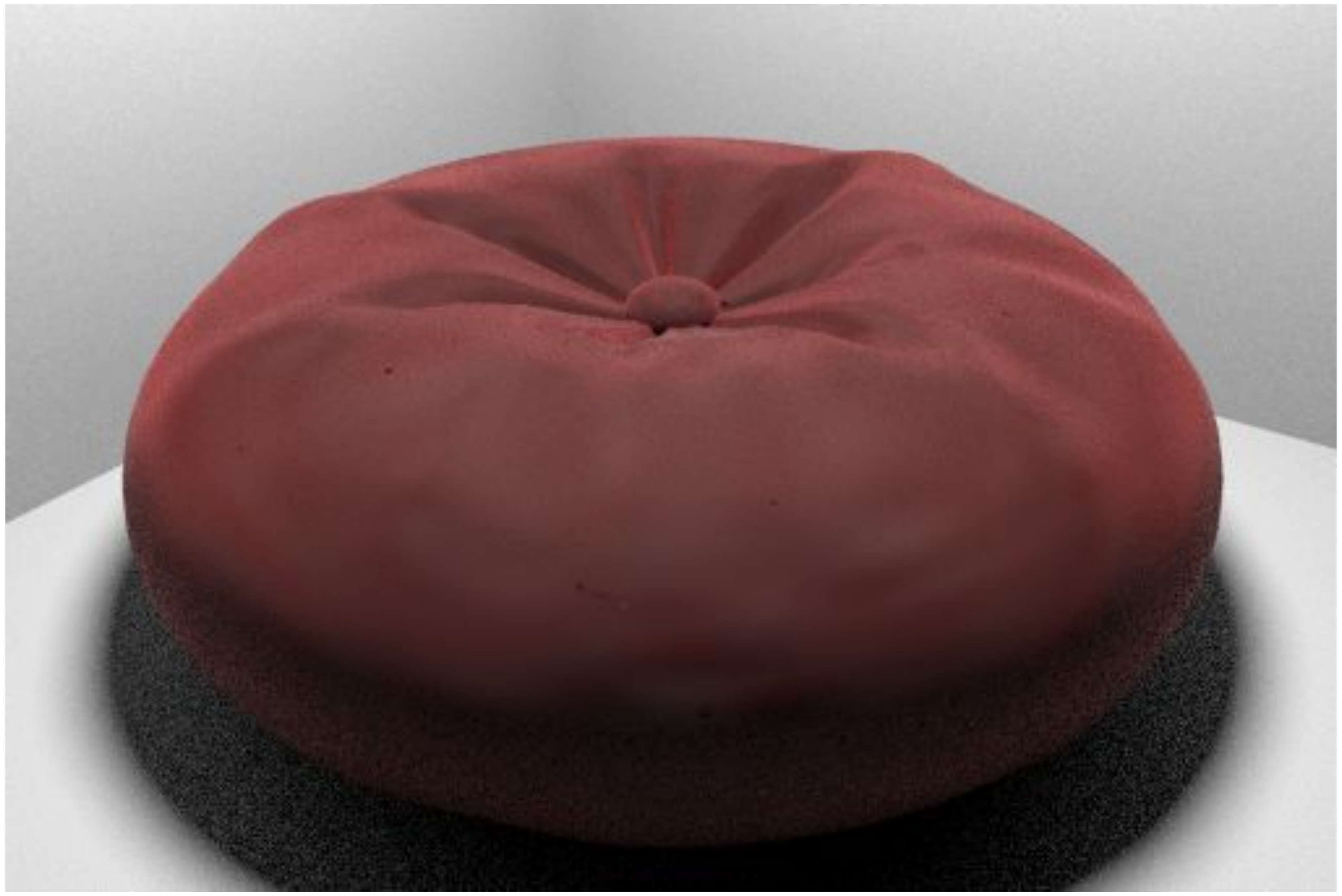


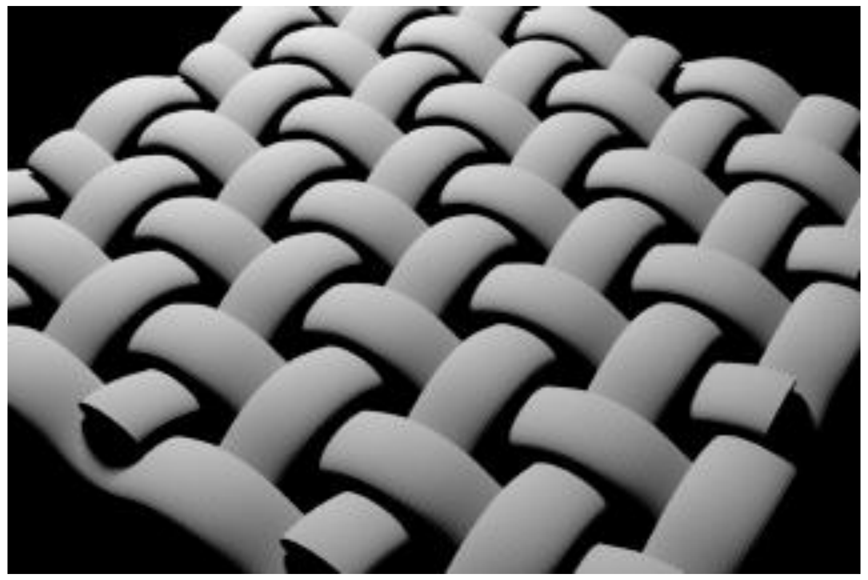


[Sadeghi et al. 2013]

Render as Surface — Limitation

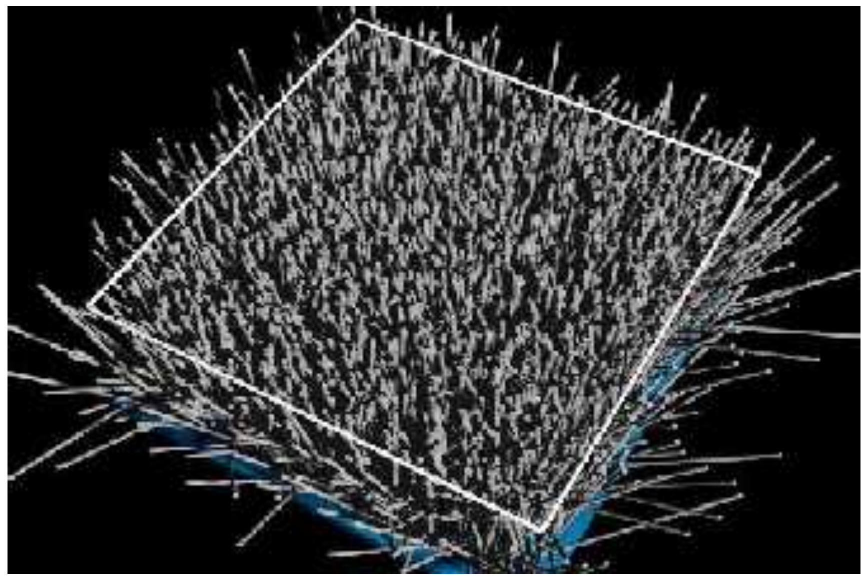






[Westin et al. 1992]

✓



✗

Cloth: Render as Participating Media

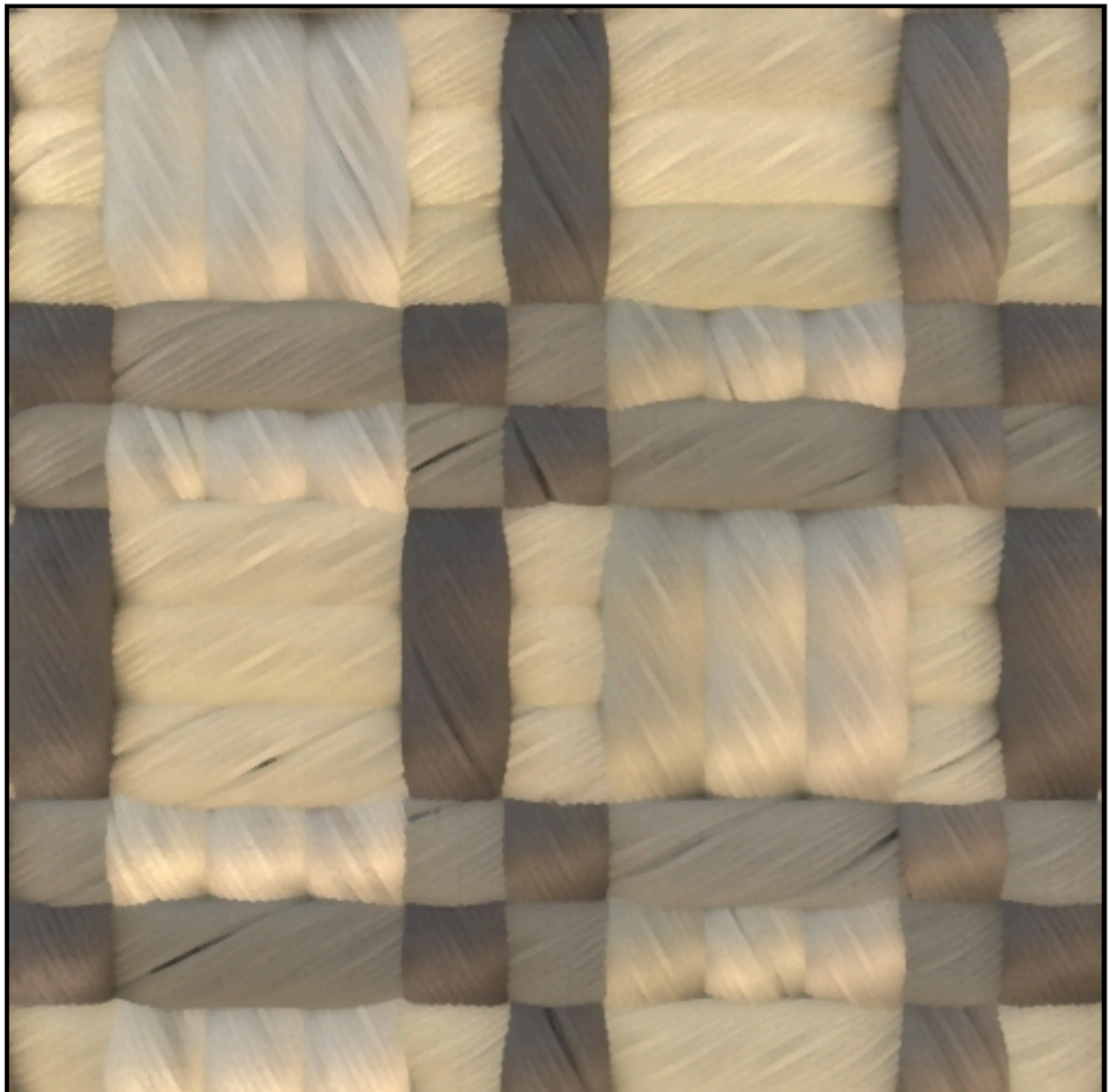
- Properties of individual fibers & their distribution -> scattering parameters
- Render as a participating medium

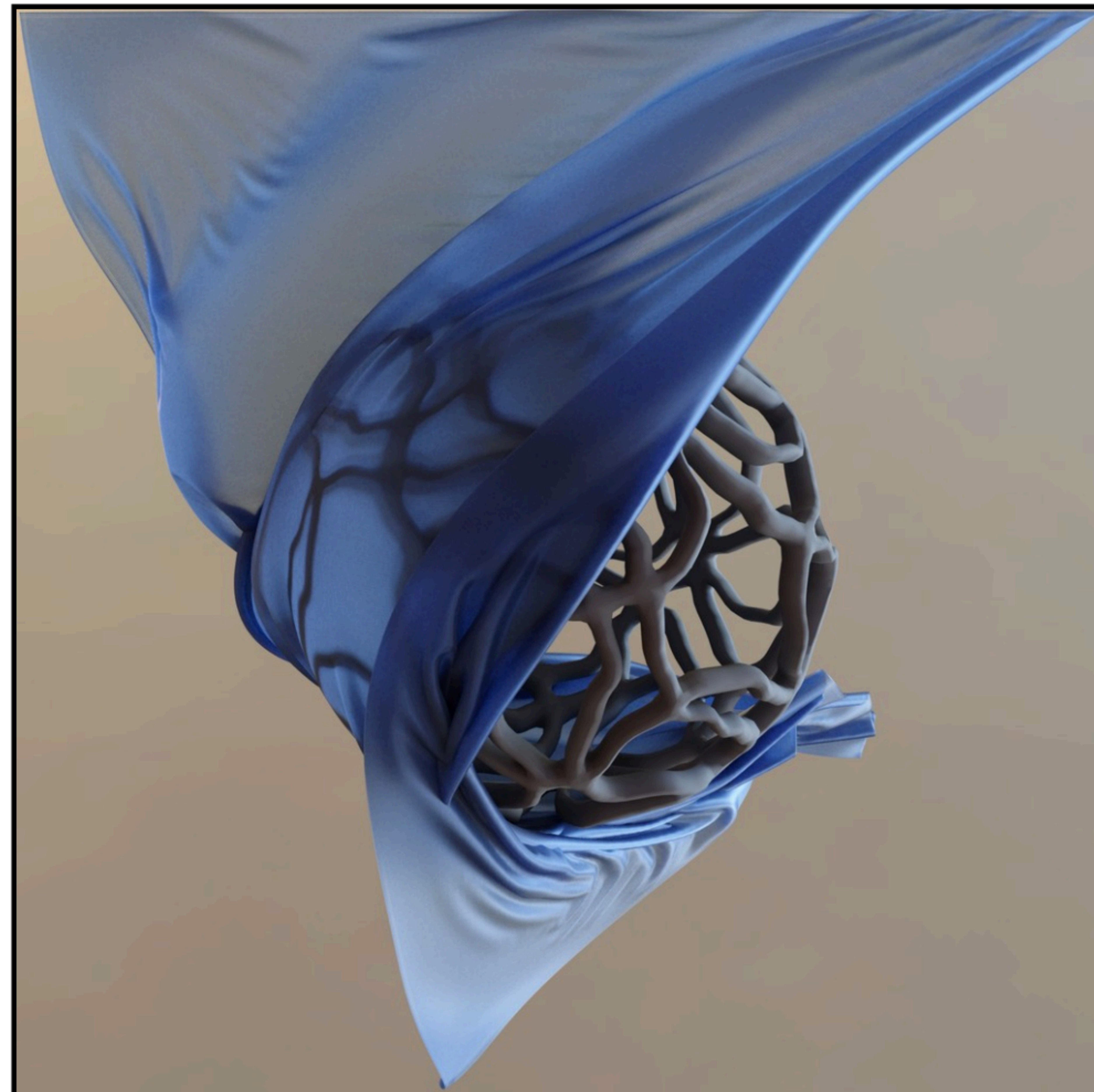
[Jakob et al. 2010]

[Schroder et al. 2011]

Cloth: Render as Actual Fibers

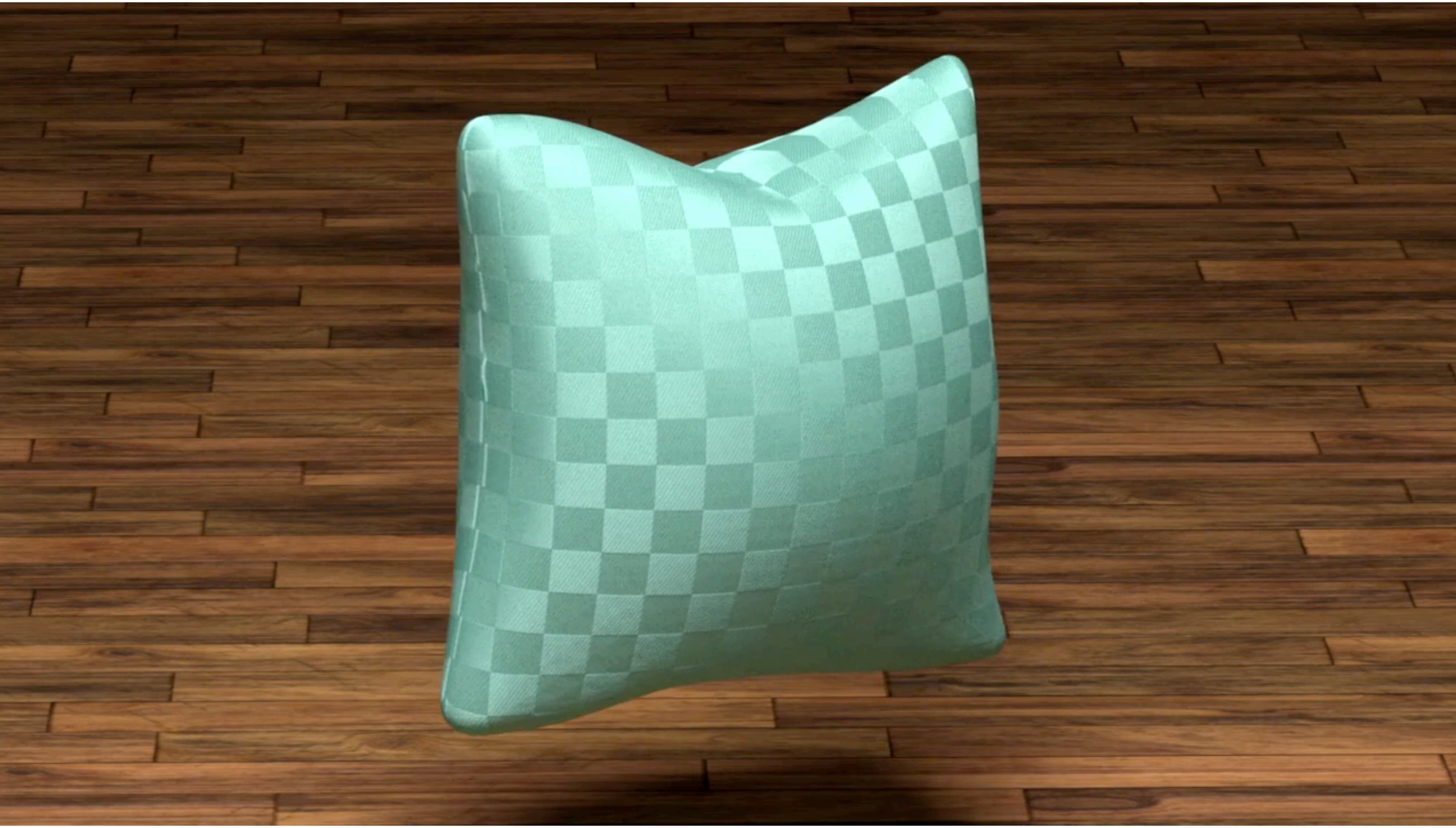
- Render every fiber explicitly!





[Kai Schroder]

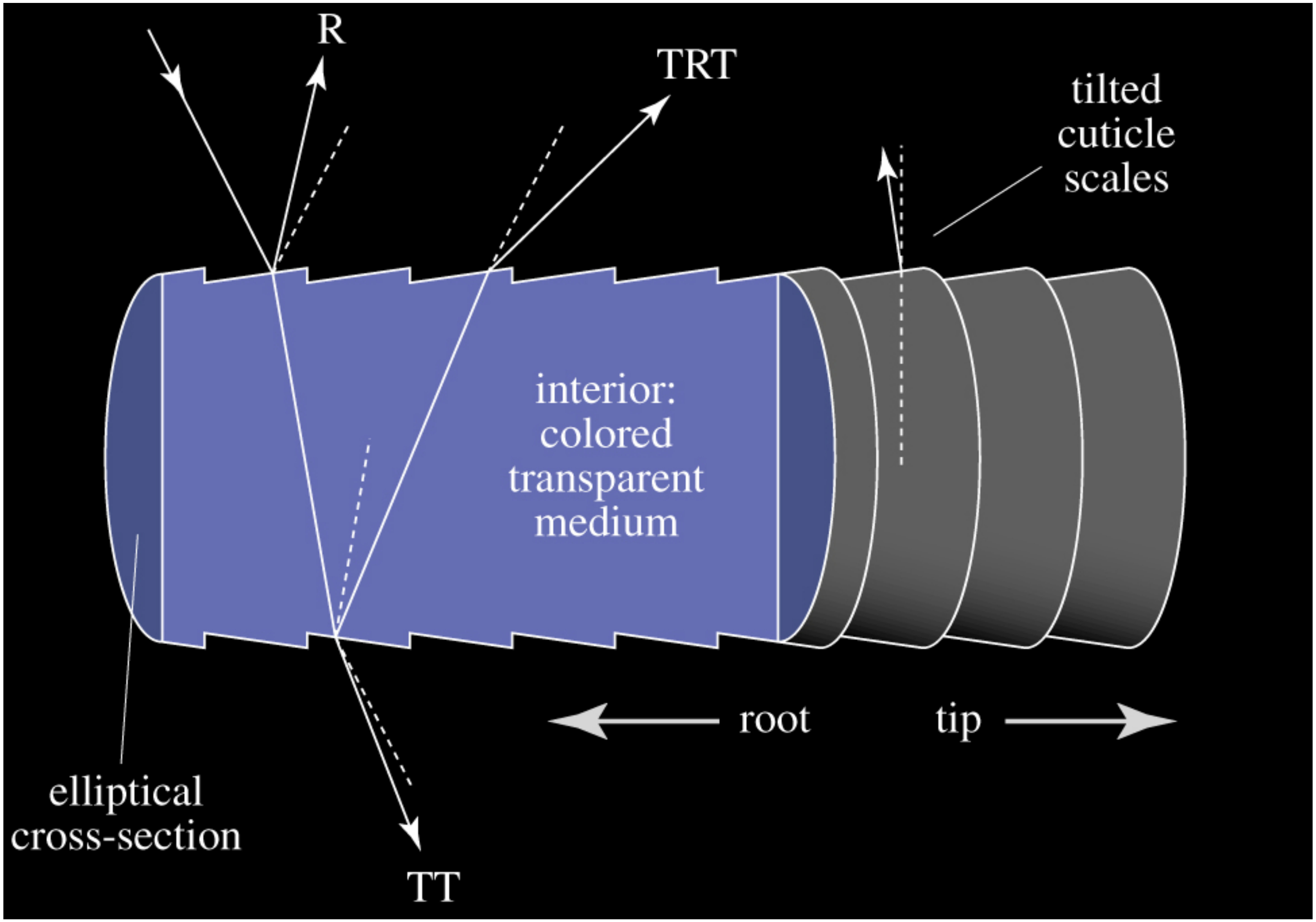
Cloth: Demo



[Shuang et al. 2012]

Hair Appearance

Fiber Model



[Marschner et al. 2003]




Things to Remember

Materials (BRDFs)

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

Acknowledgments

Thanks to Matt Pharr, Pat Hanrahan, Kayvon Fatahalian, and Ling-Qi Yan for these slides.