Modeling BRDFs

15-468, 15-668, 15-868
Physics-based Rendering
Spring 2021, Lecture 16

http://graphics.cs.cmu.edu/courses/15-468

Course announcements

- Programming assignment 4 posted, due Friday 4/9 at 23:59.
  - How many of you have looked at/started/finished it?
  - Any questions?
- Take-home quiz 6 posted.
- Gallery of scenes from PA2 posted.
- This week's reading group.
  - We'll cover the ReSTIR paper.

Graphics faculty candidate talk

- Speaker: **Mina Lukovic** (MIT)
- Title: **Transforming design and fabrication with computational discovery**

- Abstract: Recent advances in material science and computational fabrication provide promising opportunities for product design, mechanical and biomedical engineering, medical devices, robotics, architecture, art, and science. Engineered materials and personalized fabrication are revolutionizing manufacturing culture and having a significant impact on various scientific and industrial products. As new fabrication technologies emerge, effective computational tools are needed to fully exploit the potential of computational fabrication.

  In this talk, I argue that computer science and mathematical models are essential for advancing and accelerating design practices and harnessing the potential of novel fabrication technologies. My aim is to transform the design workflow with computational tools and artificial intelligence and change "what?" and "how?" we can fabricate. I will discuss how the insights from differential geometry can help us understand existing materials and create new materials with specific performance. I will further demonstrate how grammars and deep learning can be combined for the autonomous discovery of terrain-optimized robots. Finally, I will show a data-efficient machine learning algorithm for optimal experiment design. Although different in methodologies, all these projects follow the same design pipeline and tackle two critical challenges: (i) providing tools for inverse design and (ii) accelerating design and fabrication with sophisticated algorithms.

Overview of today's lecture

- BRDF modeling.
- Microfacet BRDFs.
- Data-driven BRDFs.

Slide credits

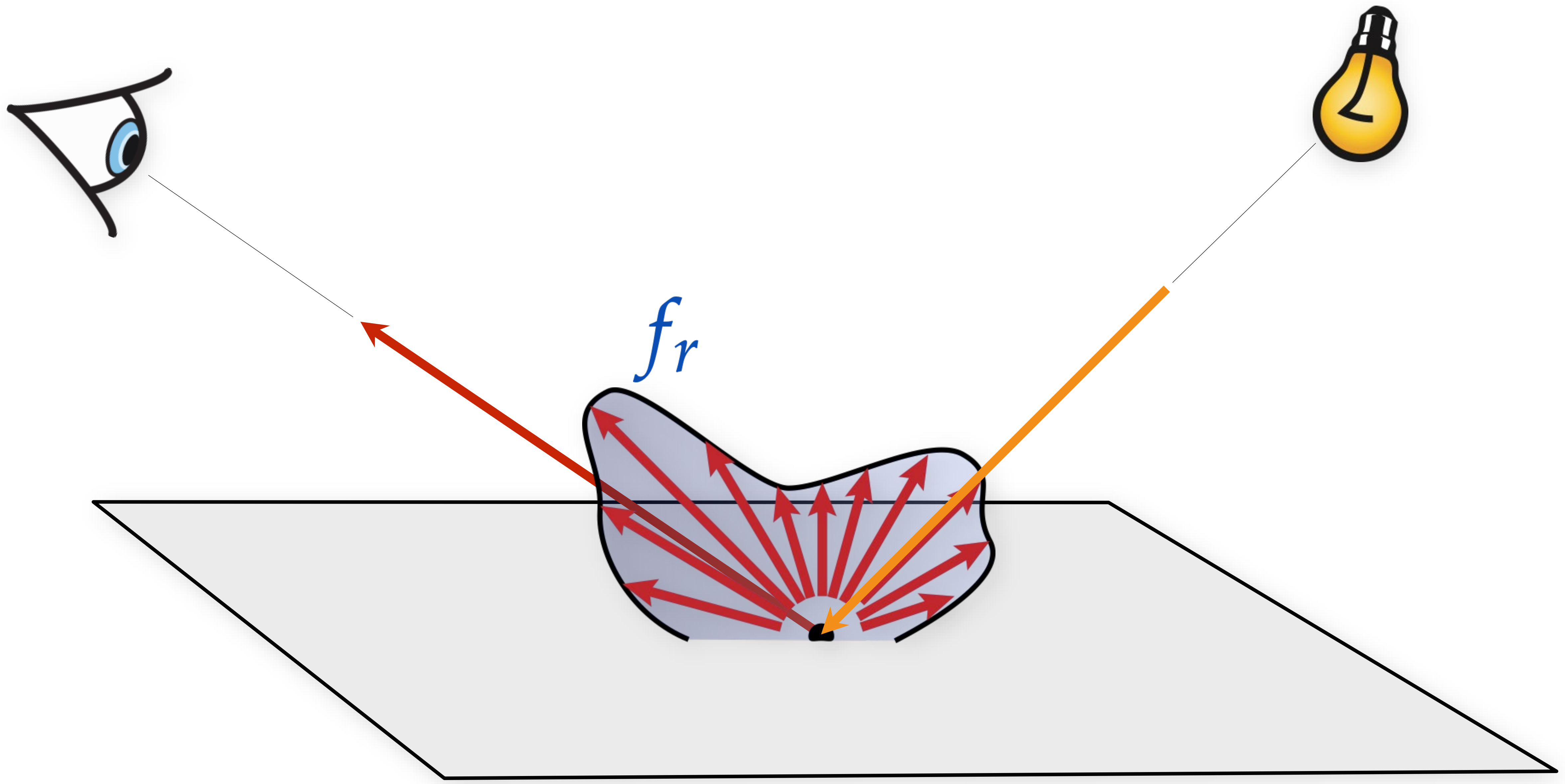
Most of these slides were directly adapted from:

- Wojciech Jarosz (Dartmouth).

The BRDF

Bidirectional **R**eflectance **D**istribution **F**unction

- how much light gets scattered from one direction into each other direction



BRDFs Properties

Real/physically-plausible BRDFs obey:

- Energy conservation

$$\int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) \cos\theta_i \, \mathrm{d}\vec{\omega}_i \leq 1, \quad \forall \vec{\omega}_r$$

- Helmholtz reciprocity

$$f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) = f_r(\mathbf{x}, \vec{\omega}_r, \vec{\omega}_i)$$

$$f_r(\mathbf{x}, \vec{\omega}_i \leftrightarrow \vec{\omega}_r)$$

Real materials are complex

Conductors vs. Dielectrics

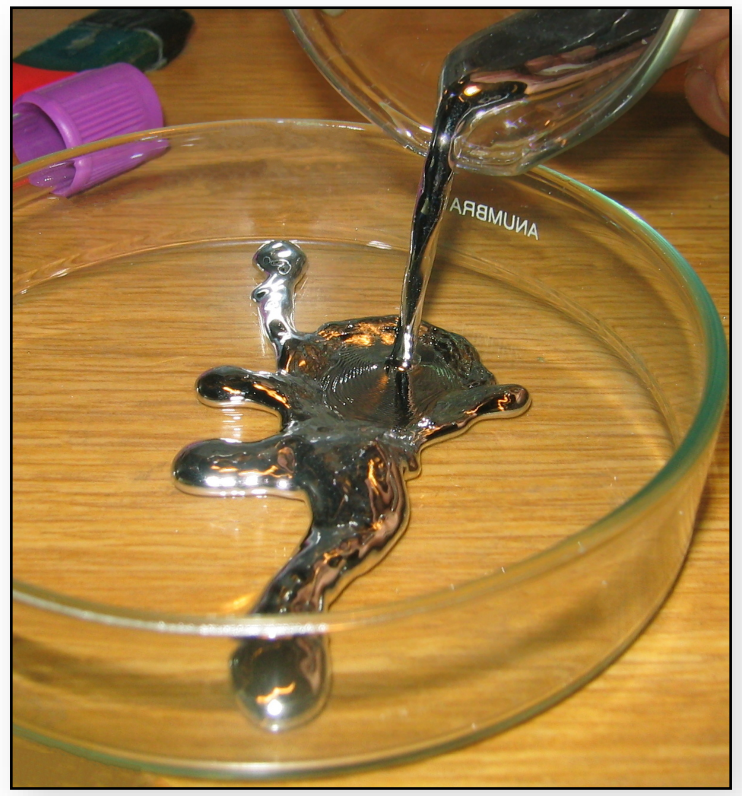
Copper

Iron

Glass

Ethanol

Gold



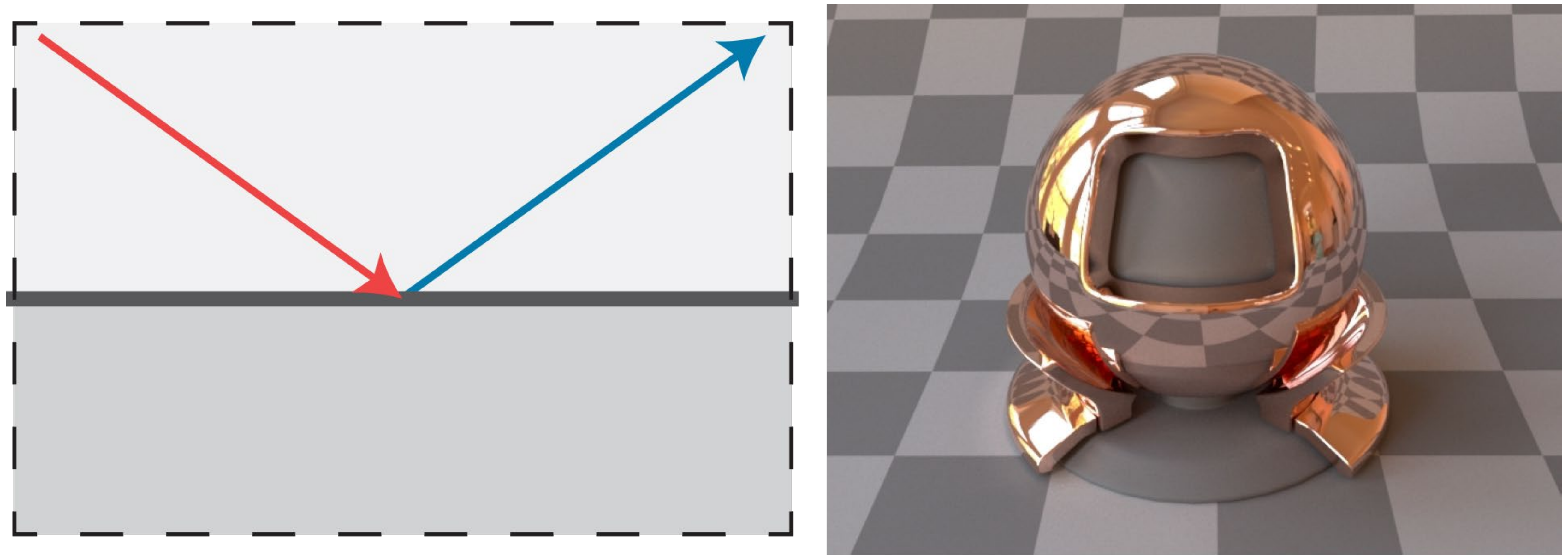
Mercury

Water

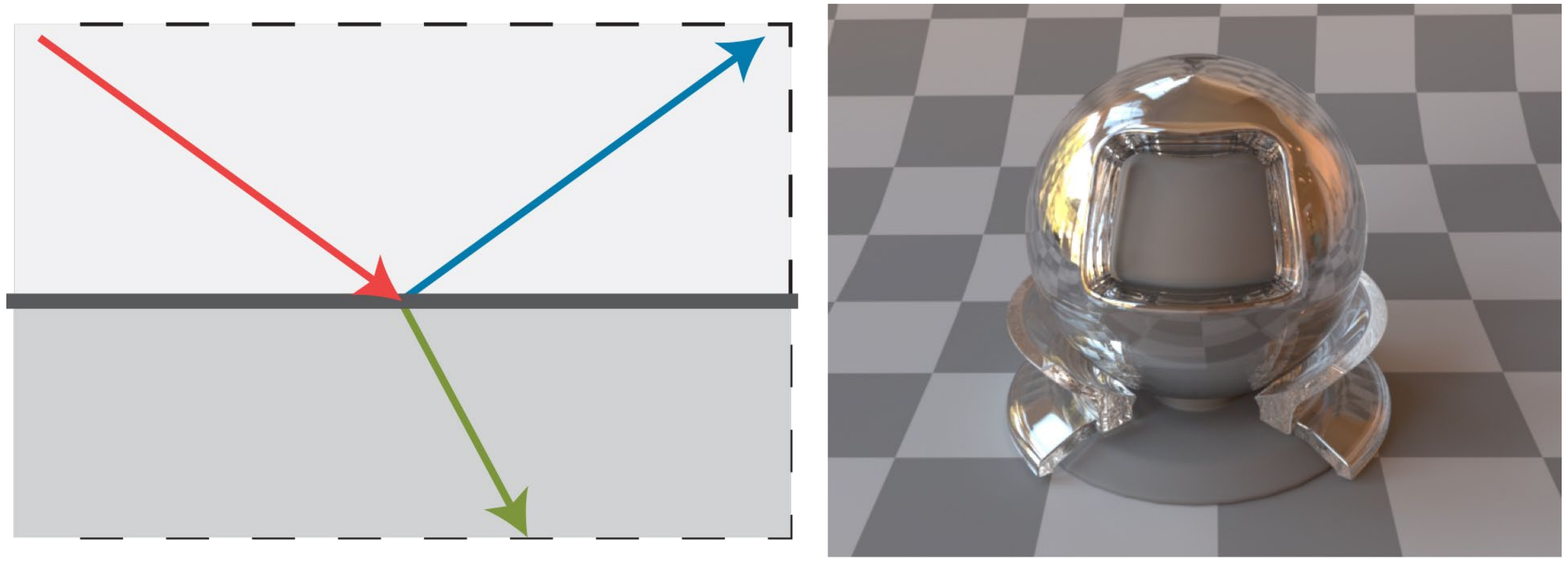
Air

Image credits: Wikipedia Commons

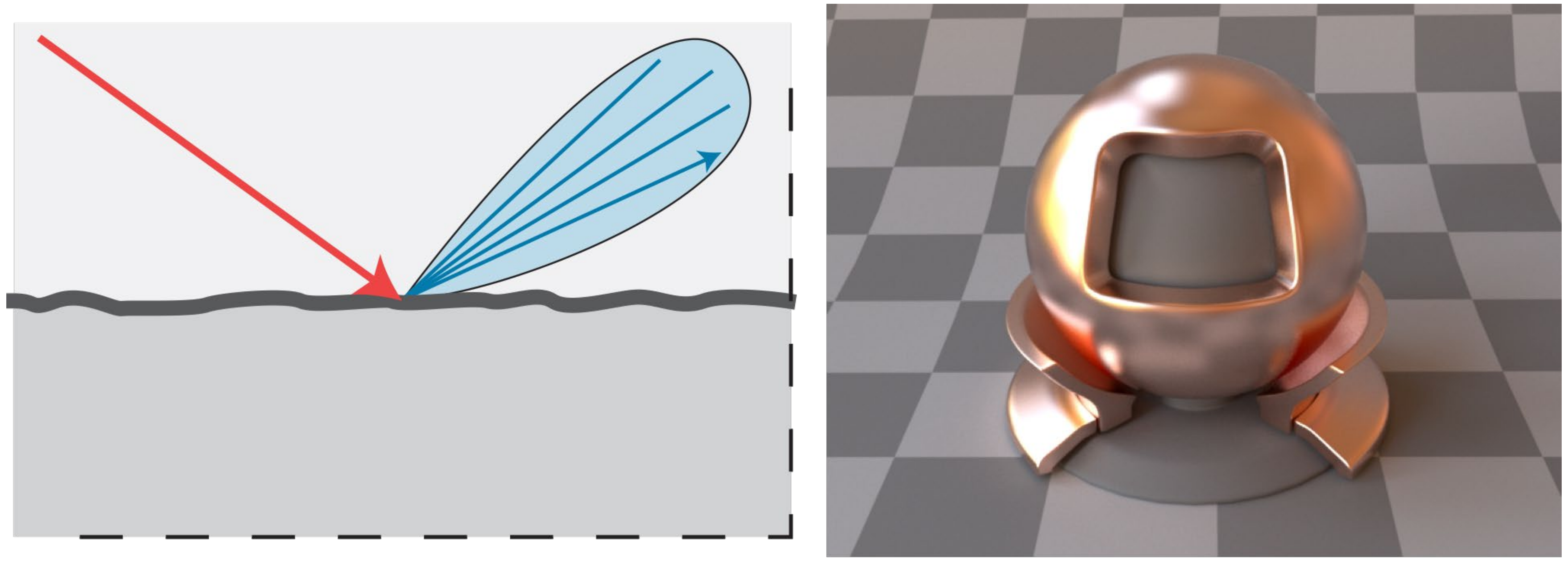
Conductors vs. Dielectrics



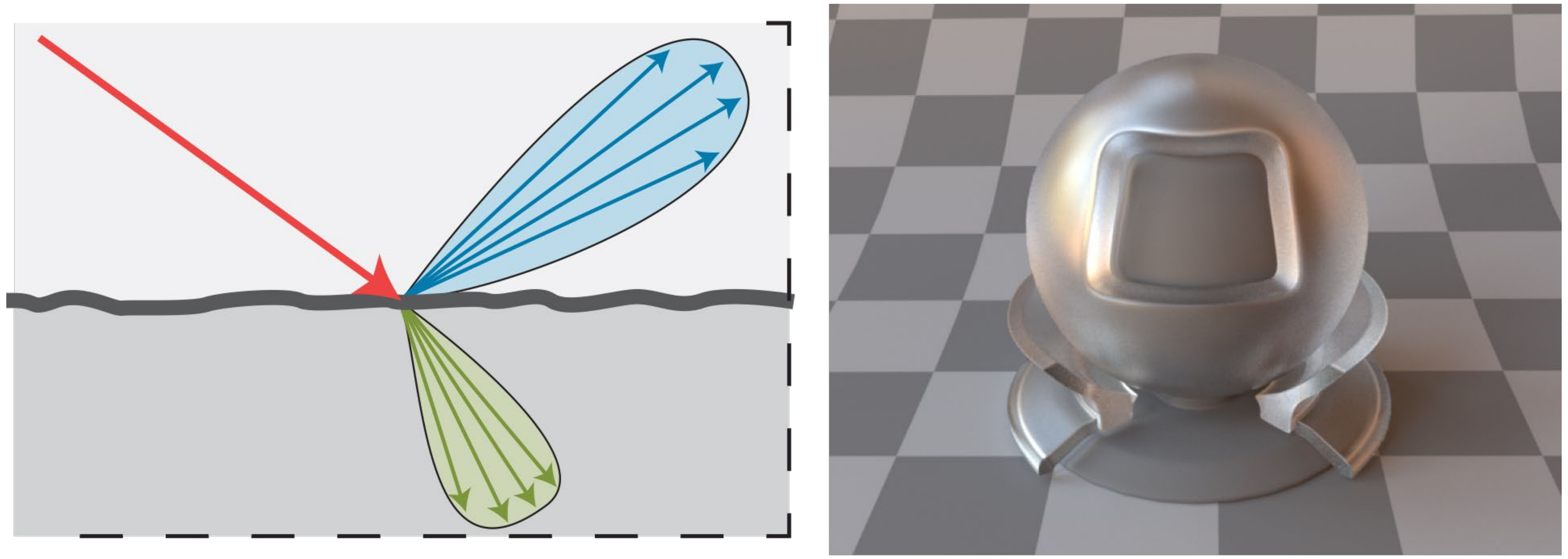
Smooth conducting material



Smooth dielectric material



Rough conducting material

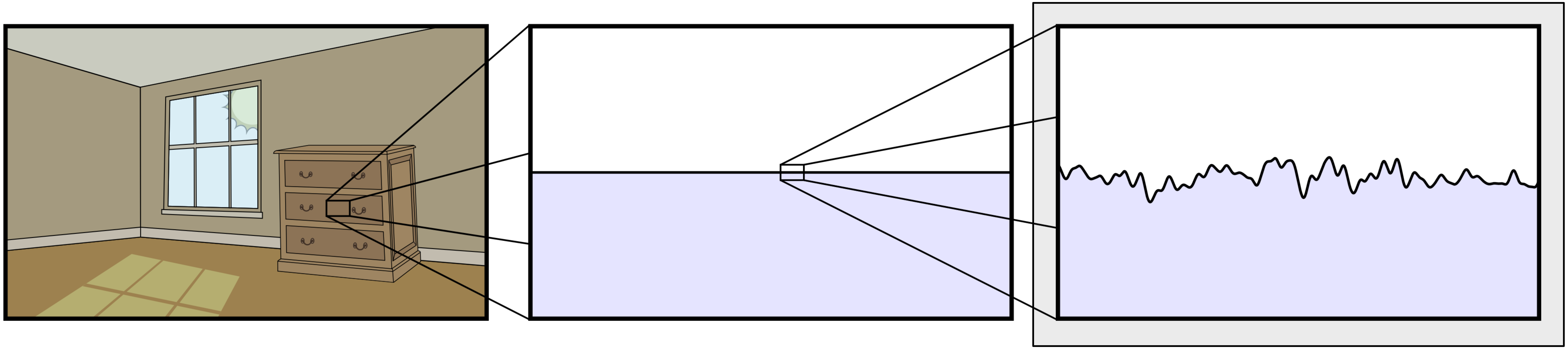


Rough dielectric material

Three Levels of Detail

Key idea:

- transition from individual interactions to statistical averages



Macro scale

Scene geometry

Meso scale

Detail at intermediate scales

(can have variations here too)

Micro scale

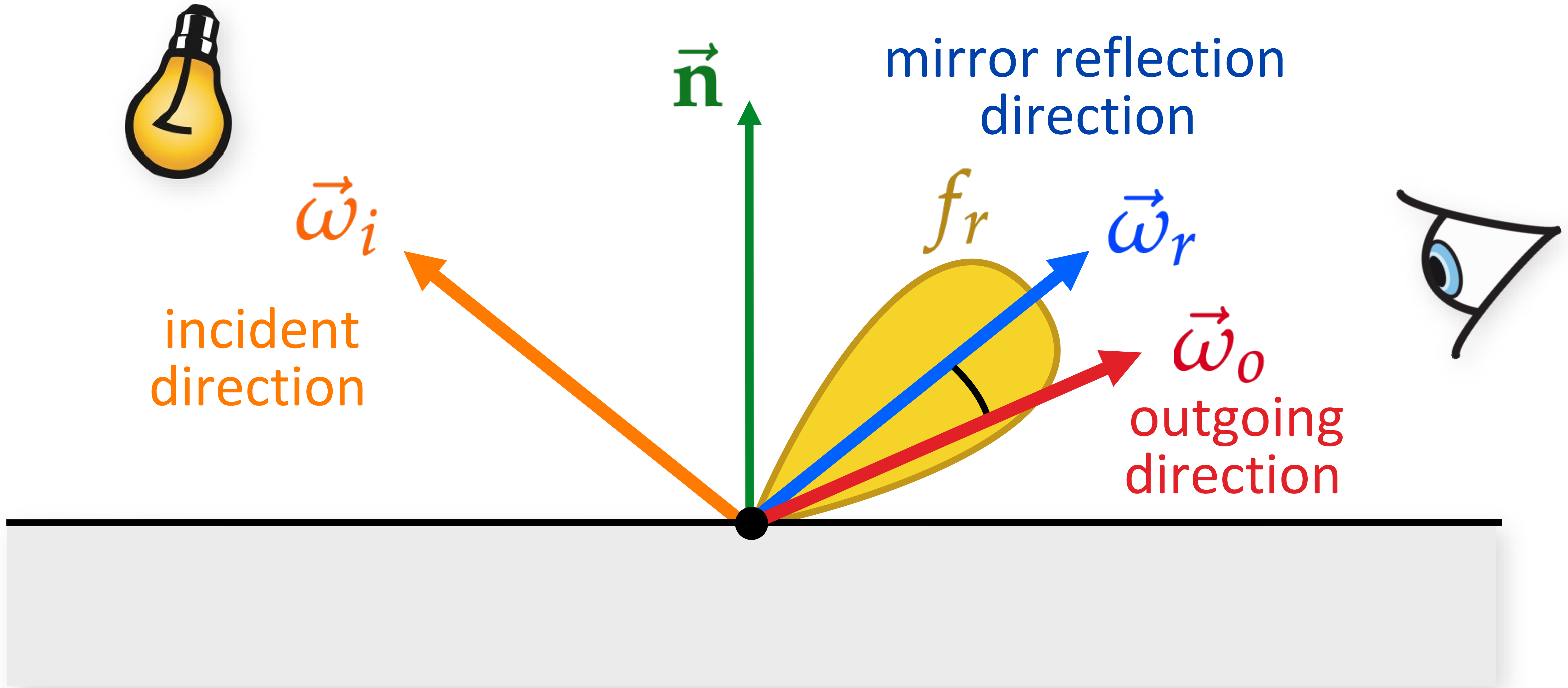
Roughness

Phong BRDF

Reflection direction distributed over an exponentiated cosine lobe:

$$f_r(\vec{\omega}_o, \vec{\omega}_i) = \frac{e+2}{2\pi}(\vec{\omega}_r \cdot \vec{\omega}_o)^e$$

$$\vec{\omega}_r = (2\vec{\mathbf{n}}(\vec{\mathbf{n}} \cdot \vec{\omega}_i) - \vec{\omega}_i)$$

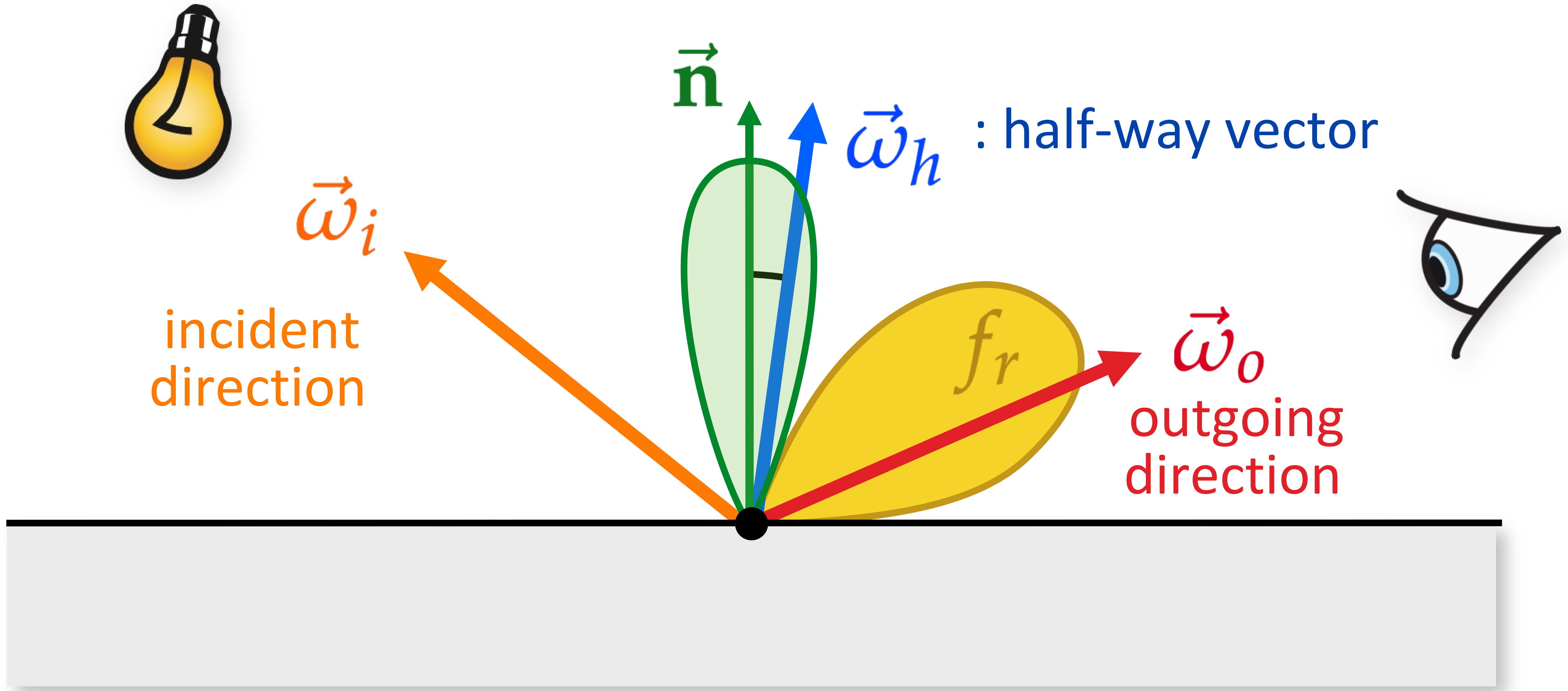


Blinn-Phong BRDF

Distribution of normals instead of reflection directions

$$f_r(\vec{\omega}_o, \vec{\omega}_i) = \frac{e+2}{2\pi}(\vec{\omega}_h \cdot \vec{\mathbf{n}})^e$$

$$\vec{\omega}_h = \frac{\vec{\omega}_i + \vec{\omega}_o}{\|\vec{\omega}_i + \vec{\omega}_o\|}$$



Ward model

Gaussian blur distribution over half vector slopes

Original version had issues with energy conservation and singularities; several modified variants exist

Rough Surfaces

Empirical glossy models have limitations:

- not physically-based
- (often) not reciprocal
- not energy-preserving (can be normalized)
  - many conflicting normalizations in the literature
- (often) no Fresnel effects
- cannot accurately model appearance of many glossy surfaces

Blinn-Phong was first step in the right direction

Can do better

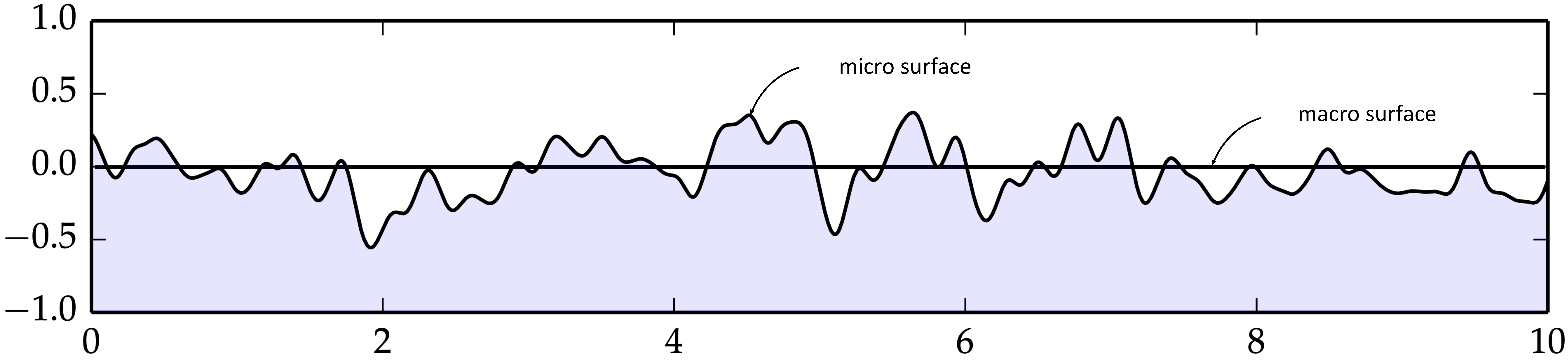
Microfacet Theory

Microfacet Theory

Assume surface consists of tiny facets

Assume that the differential area being viewed/illuminated is relatively large compared to the size of microfacets

A facet can be perfectly specular or diffuse



Torrance-Sparrow Model

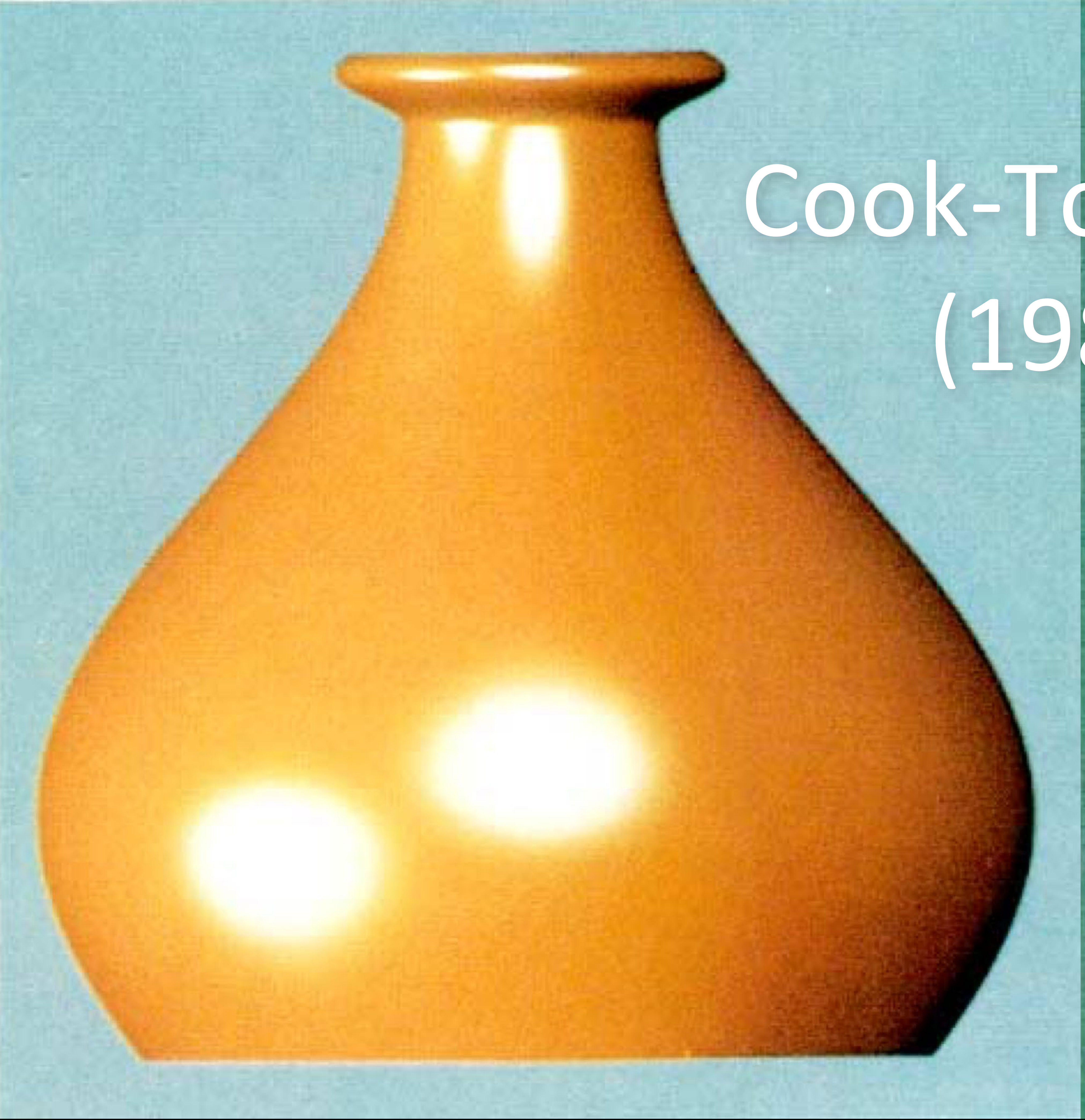
Developed by Torrance & Sparrow in 1967

- Originally used in the physics community
- Adapted by Cook & Torrance and Blinn for graphics
    - added ambient and diffuse terms

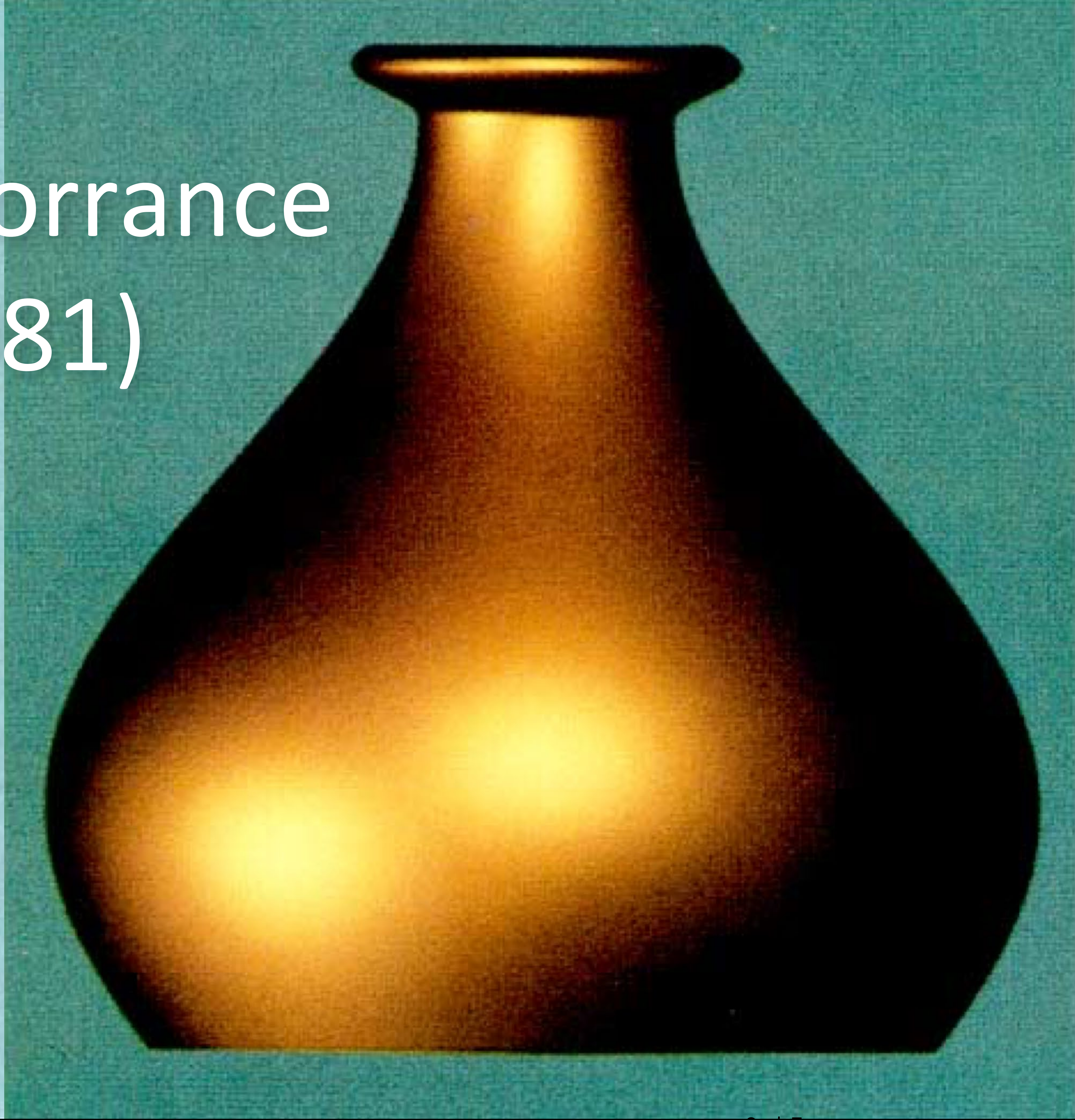
Explains off-specular peaks

Assumes surface is composed of many micro-grooves, each of which is a perfect mirror.

Cook-Torrance (1981)



Copper-colored plastic



Copper

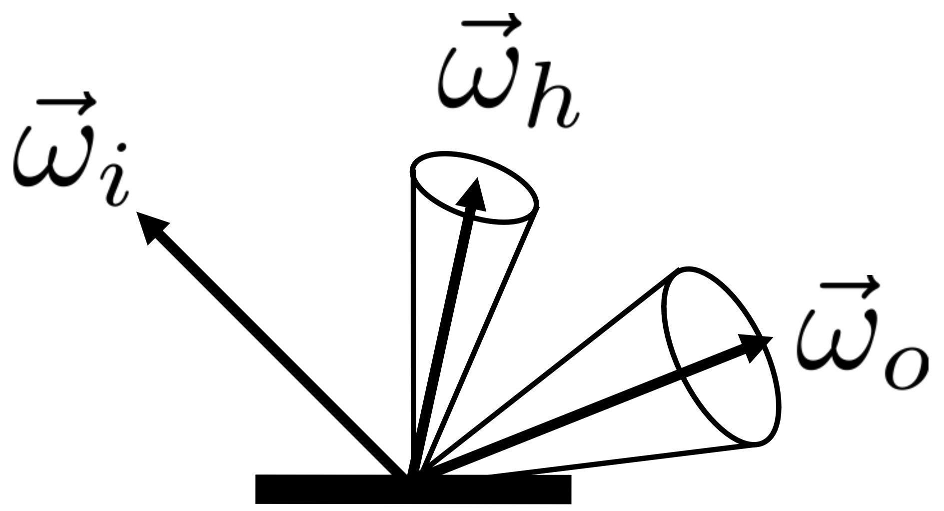
General Microfacet Model

Fresnel coefficient

Microfacet distribution

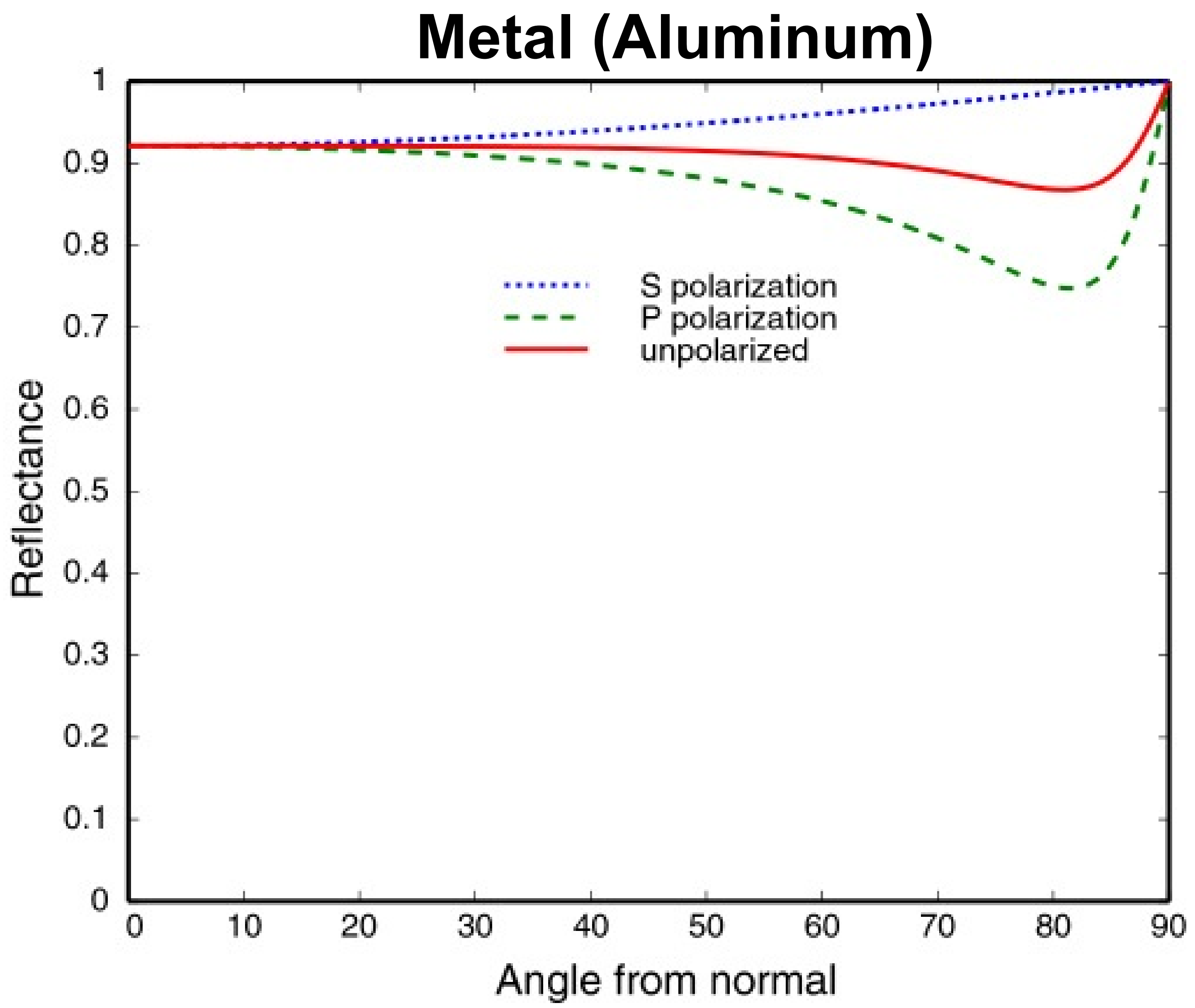
Shadowing/ masking

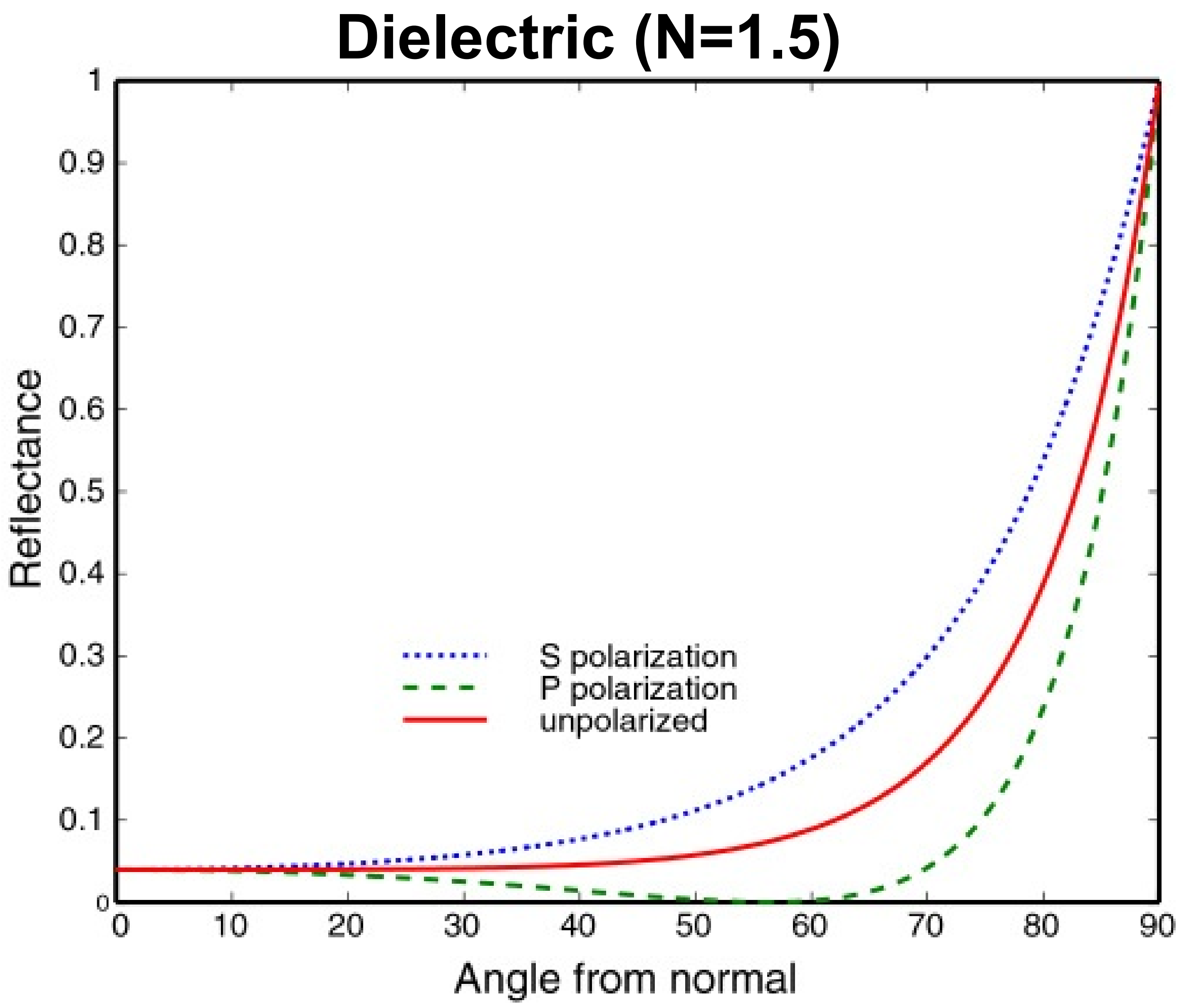
$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4|(\vec{\omega}_i \cdot \vec{\mathbf{n}})(\vec{\omega}_o \cdot \vec{\mathbf{n}})|}$$



$$\vec{\omega}_h = \frac{\vec{\omega}_i + \vec{\omega}_o}{||\vec{\omega}_i + \vec{\omega}_o||}$$

Fresnel Term





Gold	**F(0)=0.82**
Silver	**F(0)=0.95**

Glass	**n=1.5 F(0)=0.04**
Diamond	**n=2.4 F(0)=0.15**

General Microfacet Model

Microfacet
distribution

$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4|(\vec{\omega}_i \cdot \vec{\mathbf{n}})(\vec{\omega}_o \cdot \vec{\mathbf{n}})|}$$

Microfacet Distribution

Microfacet Distribution

What fraction of the surface participates in the reflection?

- Answer 1: difficult to say (need an actual microsurface to compute this, tedious...)
- Answer 2: solve using principles of statistical physics
  - Is there something general we can say about the surface when there are many bumps?

Microfacet Distribution

Fraction of microfacets facing each direction

Probability density function over *projected* solid angle (must be normalized):

$$\int_{H^2} D(\vec{\omega}_h) \cos\theta_h \, \mathrm{d}\vec{\omega}_h = 1$$

The Beckmann Distribution

The slopes follow a Gaussian distribution

Let’s express slope distribution wrt. directions

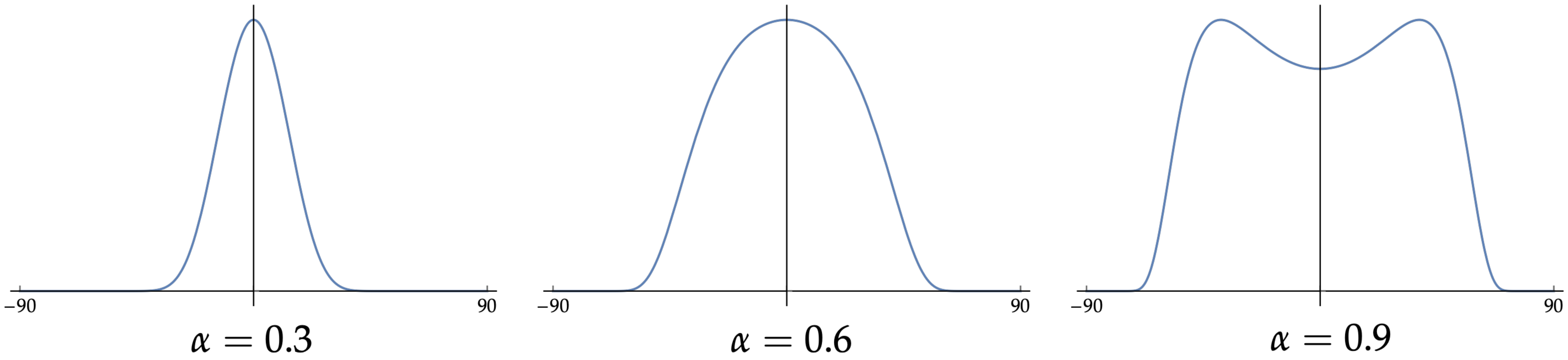
– Slope of θ_h is $\tan\theta_h$

$$D(\vec{\omega}_h) = \frac{1}{\pi\alpha^2\cos^4\theta_h}\, e^{-\frac{\tan^2\theta_h}{\alpha^2}}$$

The Beckmann Distribution

The slopes follow a Gaussian distribution

Let’s express slope distribution wrt. directions



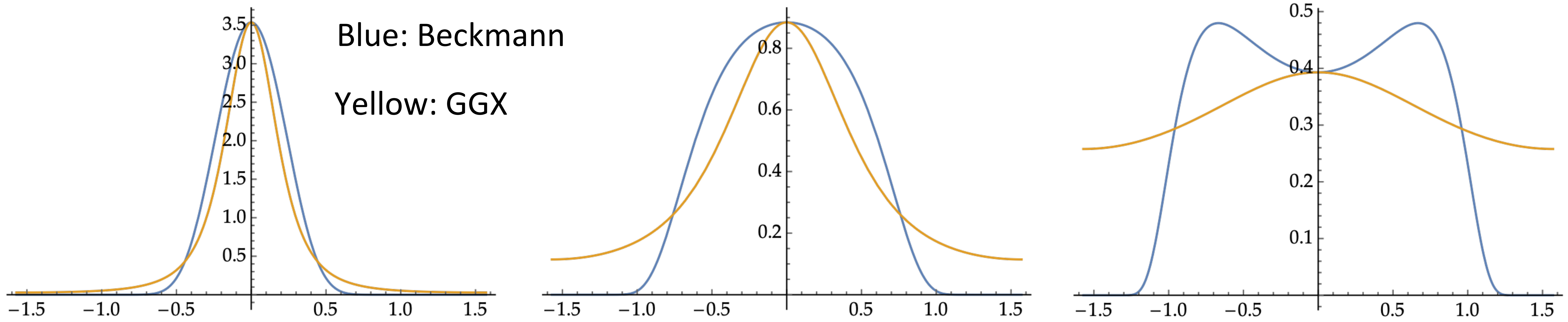
Other Distributions

The Blinn distribution:

$$D(\vec{\omega}_h) = \frac{e+2}{2\pi}(\vec{\omega}_h \cdot \vec{\mathbf{n}})^e$$

GGX distribution, see [Walter et al., EGSR 2007]

Anisotropic distributions, see [PBRTv2, Ch. 8]



General Microfacet Model

Shadowing/
masking

$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4|(\vec{\omega}_i \cdot \vec{\mathbf{n}})(\vec{\omega}_o \cdot \vec{\mathbf{n}})|}$$

Shadowing and Masking

Microfacets can be *shadowed* and/or *masked* by other microfacets

Shadowing and Masking

Each microfacet distribution typically has its respective shadowing and masking term

Beckman distribution:

$$G(\vec{\omega}) = \frac{2}{1 + \mathrm{erf}(s) + \frac{1}{s\sqrt{\pi}} e^{-s^2}} \qquad s = \frac{1}{\alpha \tan\theta}$$

$$G(\vec{\omega}_i, \vec{\omega}_o) = G(\vec{\omega}_i) \cdot G(\vec{\omega}_o)$$

Shadowing and Masking

Each microfacet distribution typically has its respective shadowing and masking term

Beckman distribution (approximated):

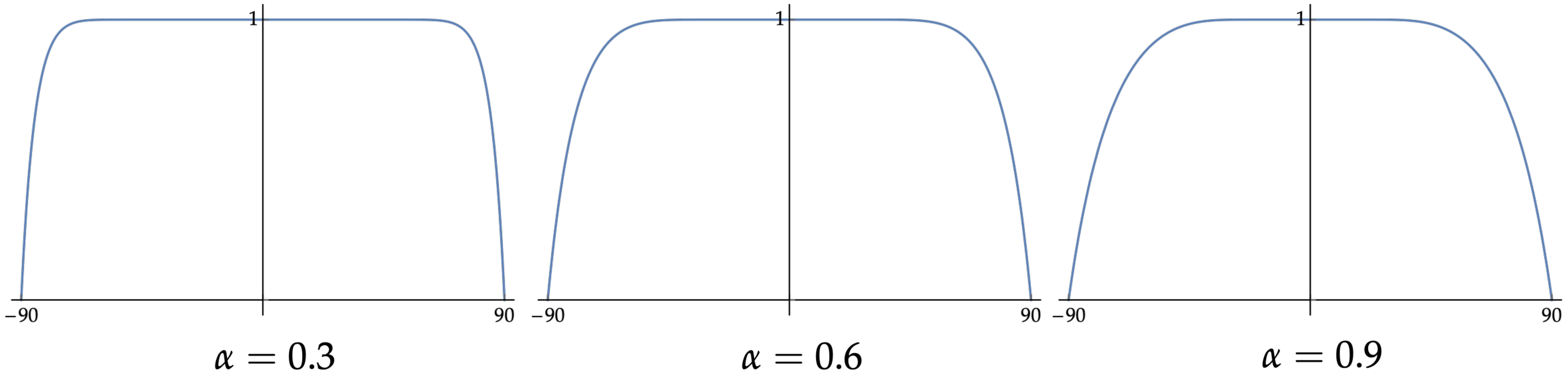
$$G(\vec{\omega}) \approx \begin{cases} \frac{3.535s+2.181s^2}{1+2.276s+2.577s^2}, & s < 1.6 \\ 1, & \text{otherwise} \end{cases}$$

$$G(\vec{\omega}_i, \vec{\omega}_o) = G(\vec{\omega}_i) \cdot G(\vec{\omega}_o)$$

Shadowing and Masking

Each microfacet distribution typically has its respective shadowing and masking term

Beckman distribution (approximated):



Shadowing and Masking

Each microfacet distribution typically has its respective shadowing and masking term

Torrance-Sparrow (Blinn):

$$G(\vec{\omega}_i, \vec{\omega}_o) = \min\left(1, \frac{2(\vec{\mathbf{n}} \cdot \vec{\omega}_h)(\vec{\mathbf{n}} \cdot \vec{\omega}_i)}{(\vec{\omega}_h \cdot \vec{\omega}_i)}, \frac{2(\vec{\mathbf{n}} \cdot \vec{\omega}_h)(\vec{\mathbf{n}} \cdot \vec{\omega}_o)}{(\vec{\omega}_h \cdot \vec{\omega}_o)}\right)$$

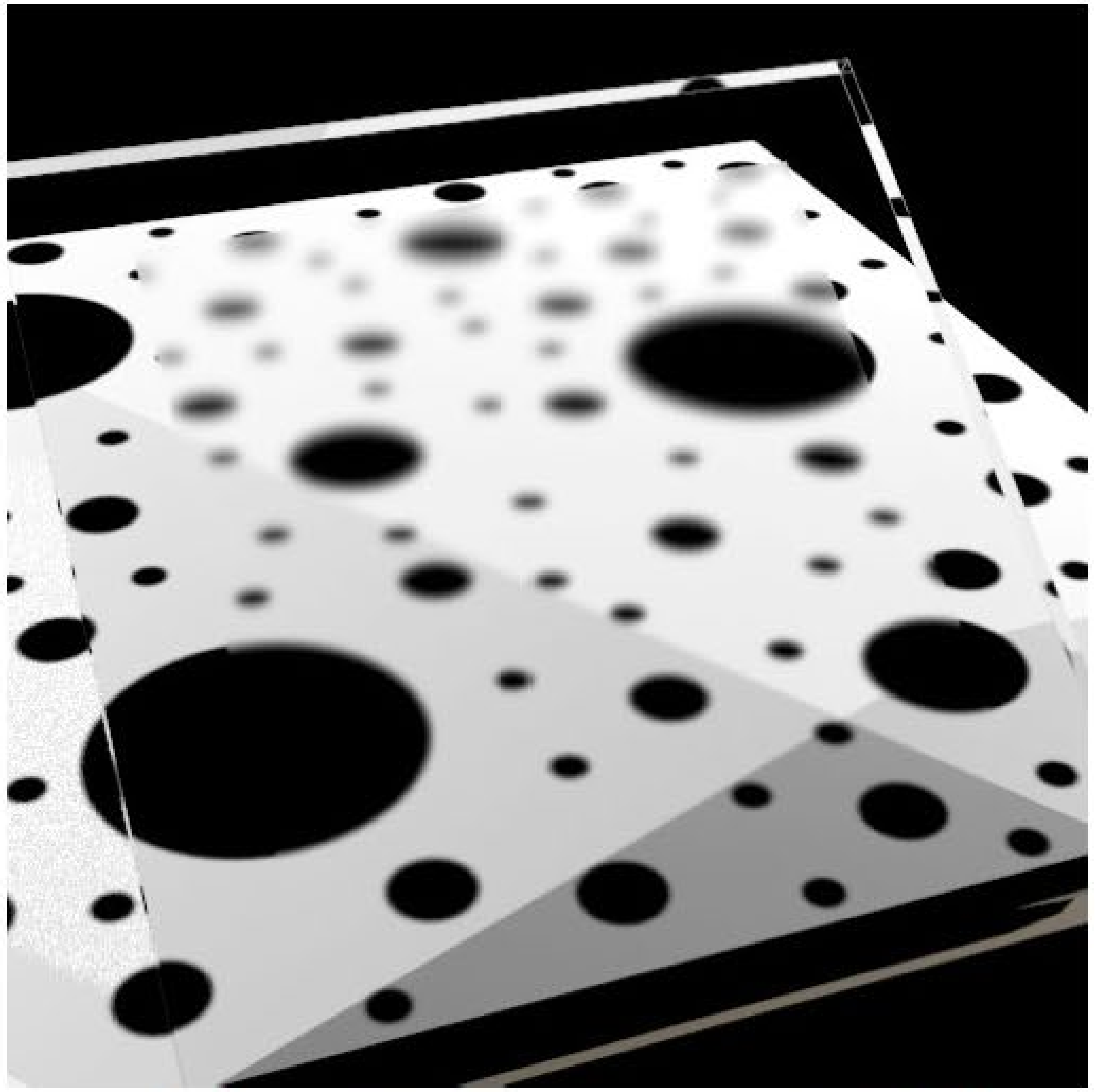
General Microfacet Model

$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4\left|(\vec{\omega}_i \cdot \vec{\mathbf{n}})(\vec{\omega}_o \cdot \vec{\mathbf{n}})\right|}$$

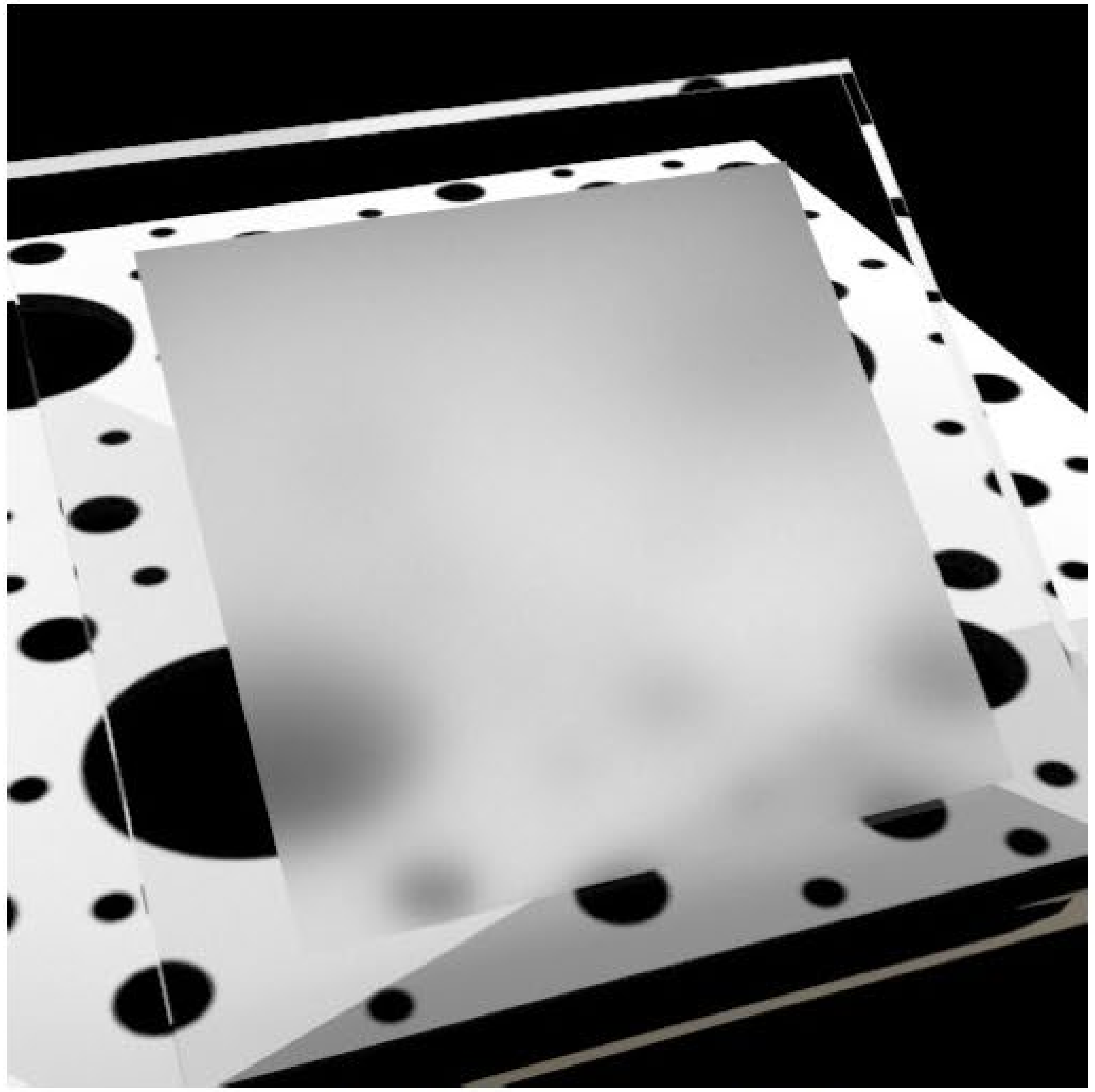
Denominator: correction term coming from energy conservation, Jacobians, etc.

- see PBR book and Walter et al. [EGSR 2007] for more detail

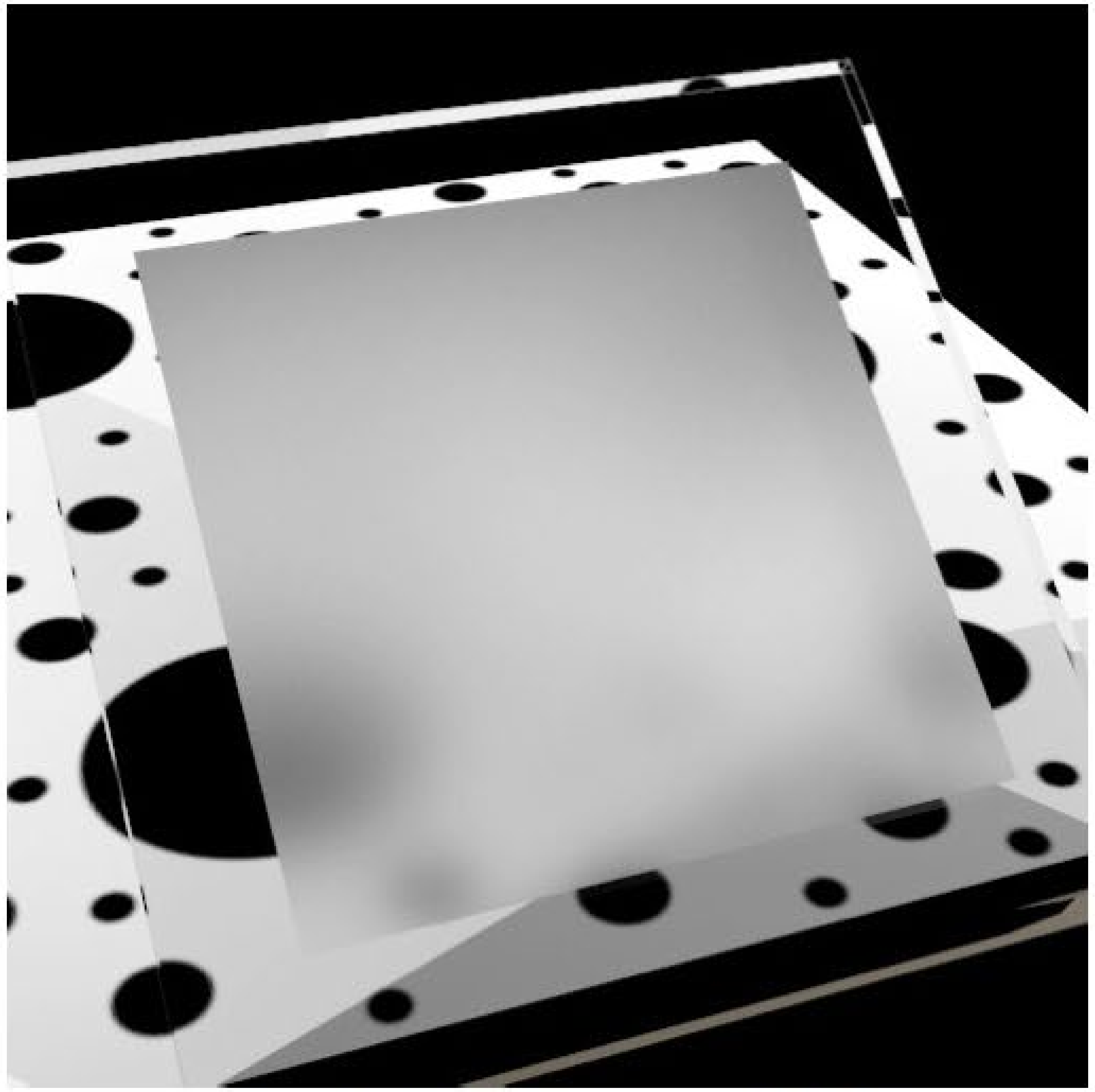
GGX and Beckmann



anti-glare (Beckman, $\alpha_b = 0.023$)



ground (GGX, $\alpha_g = 0.394$)



etched (GGX, $\alpha_g = 0.553$)

Walter et al. 07

Energy Loss Issue

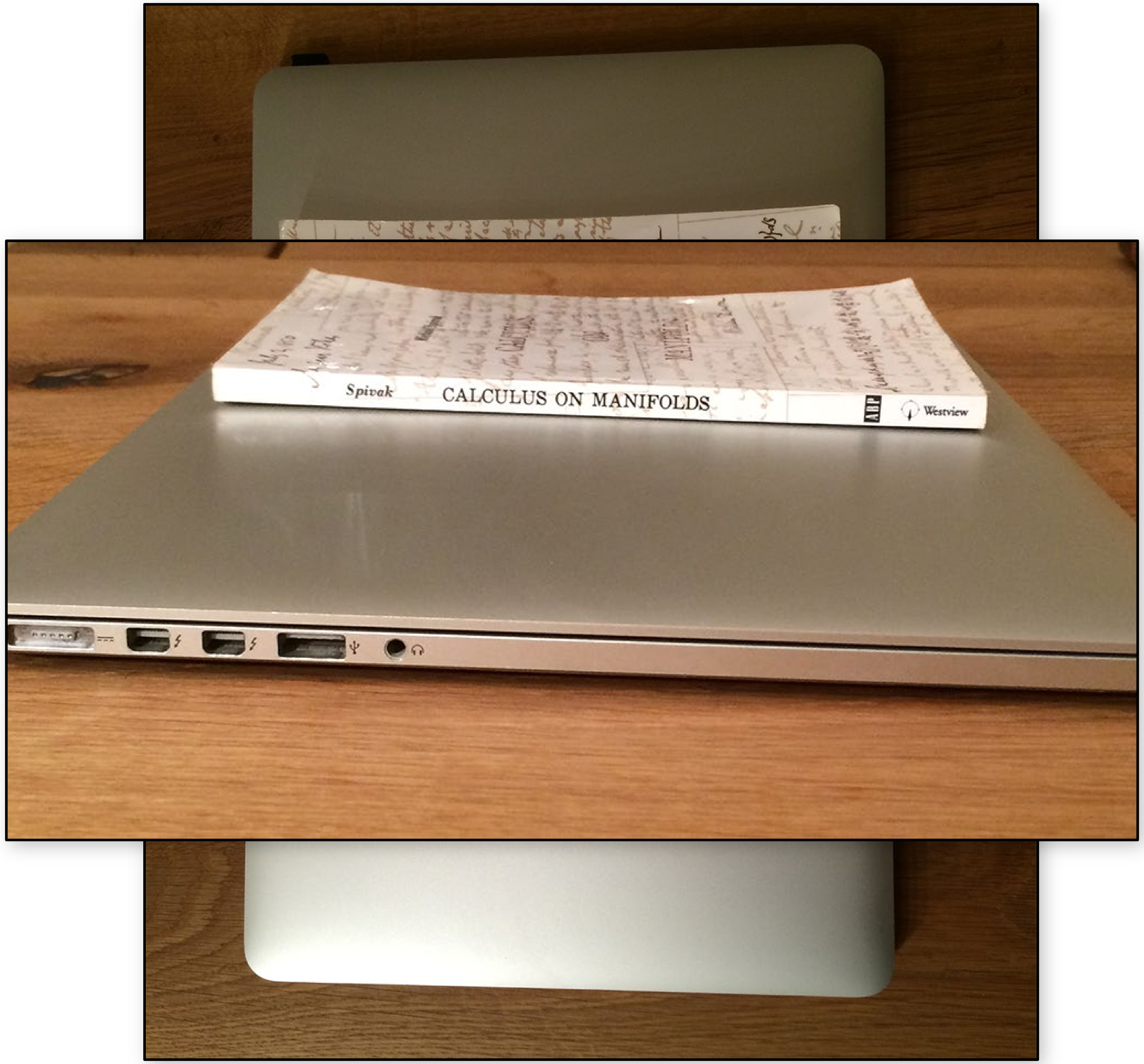
Energy Loss Issue - Conductor

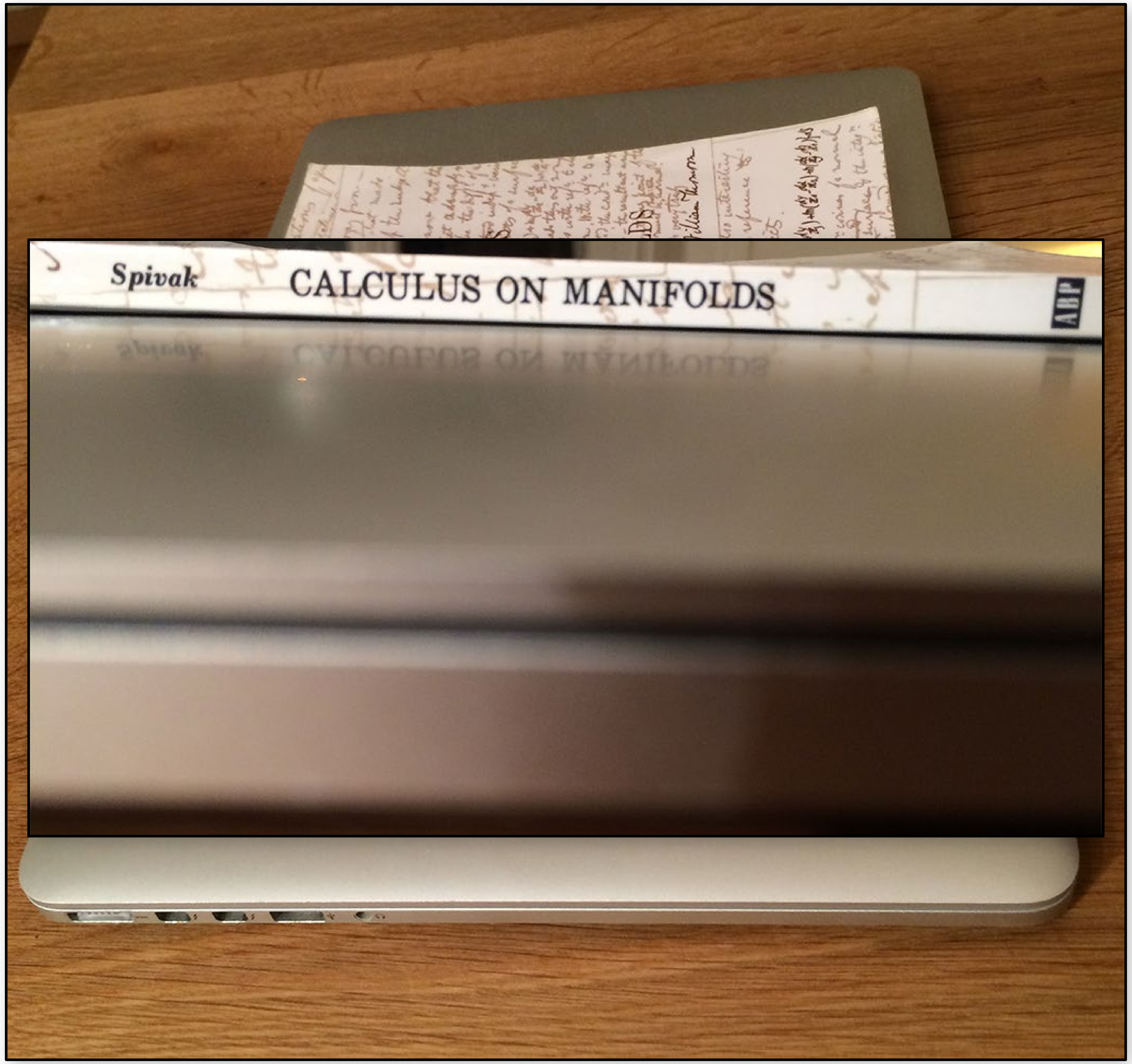
Increasing roughness $\alpha = 0.01 .. 2.0$

Energy Loss Issue - Dielectric

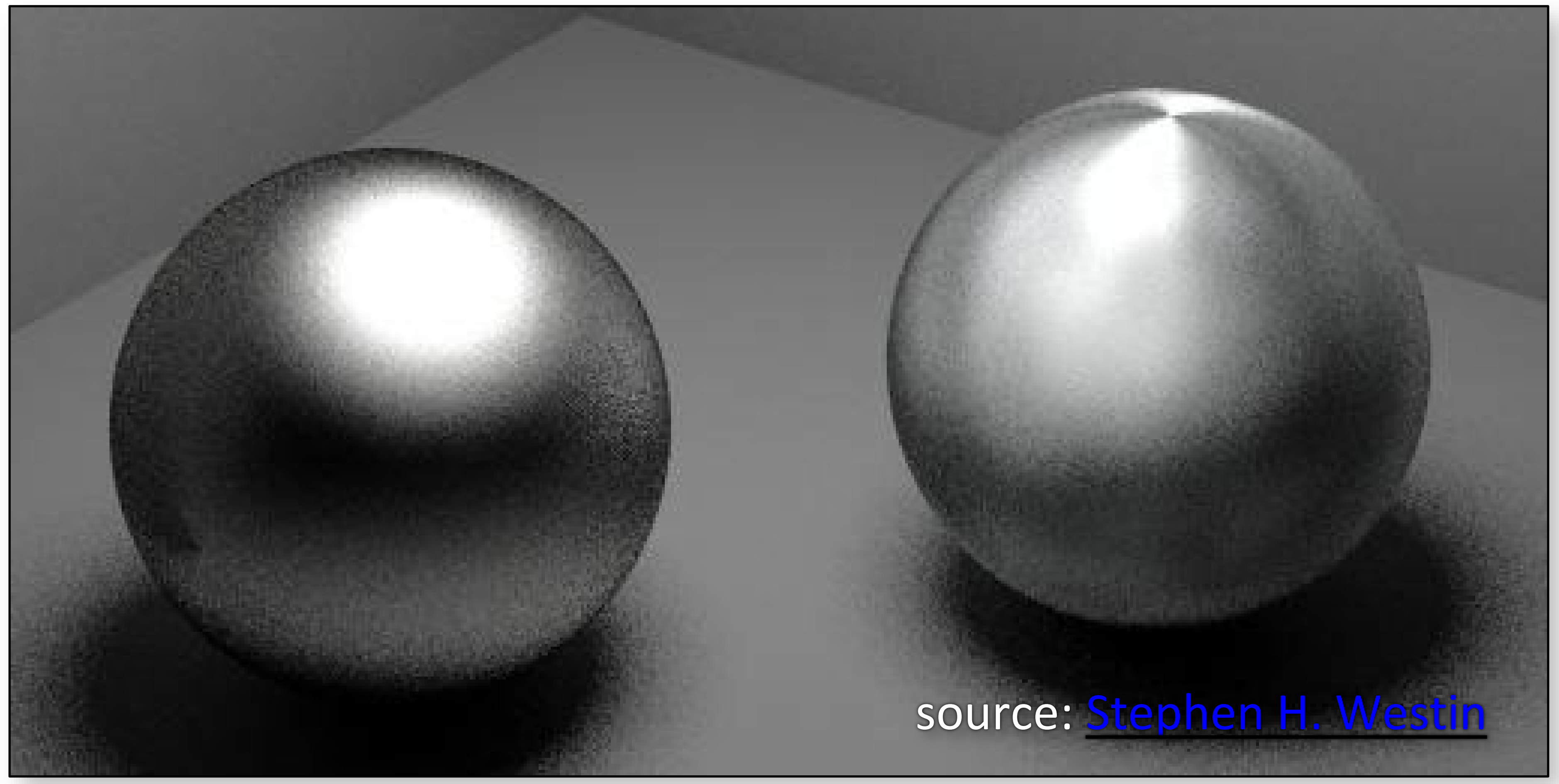
Increasing roughness α = 0.01 .. 2.0

Interesting grazing angle behavior





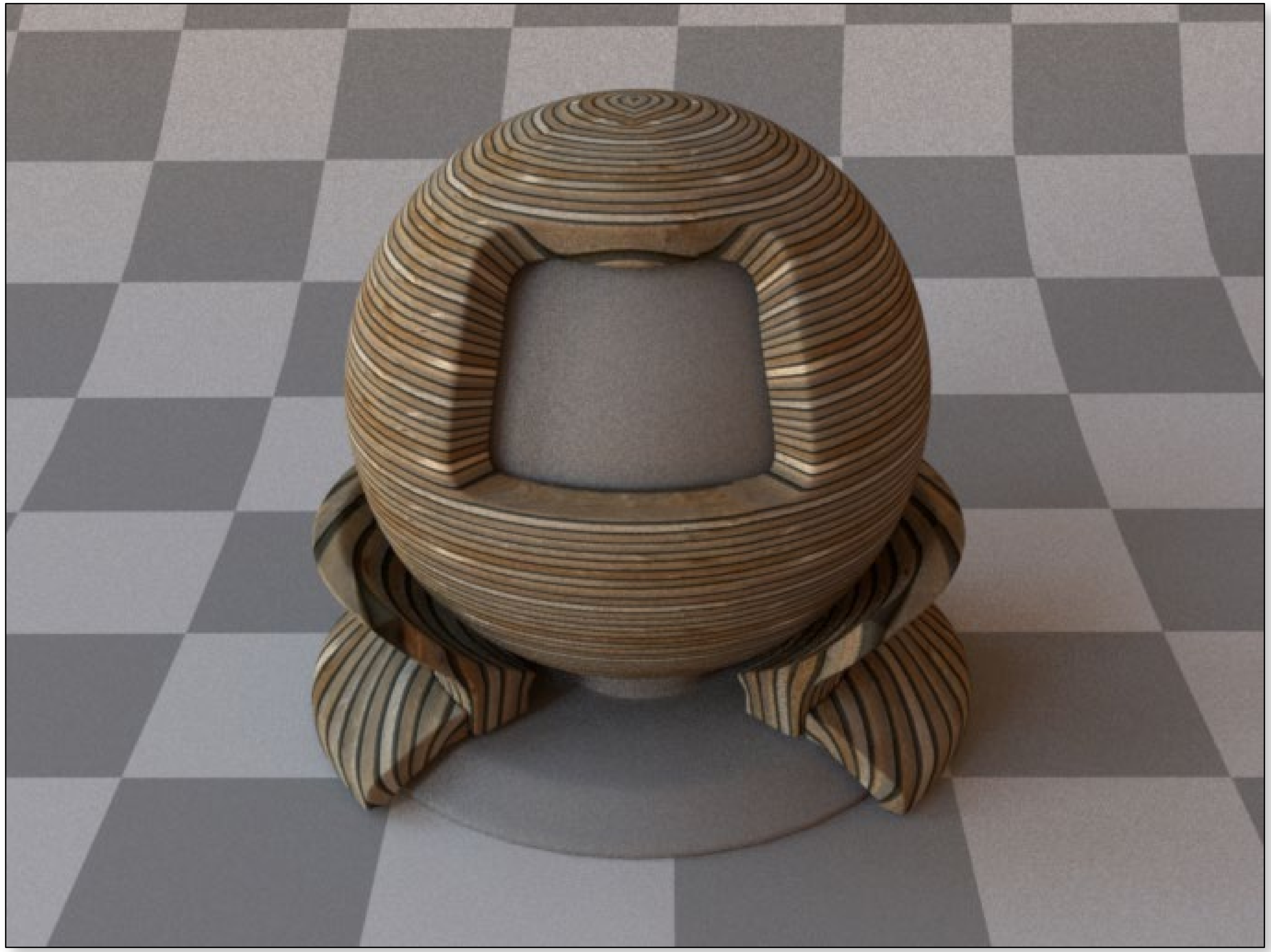
Extension: Anisotropic Reflection



Extension: layered materials

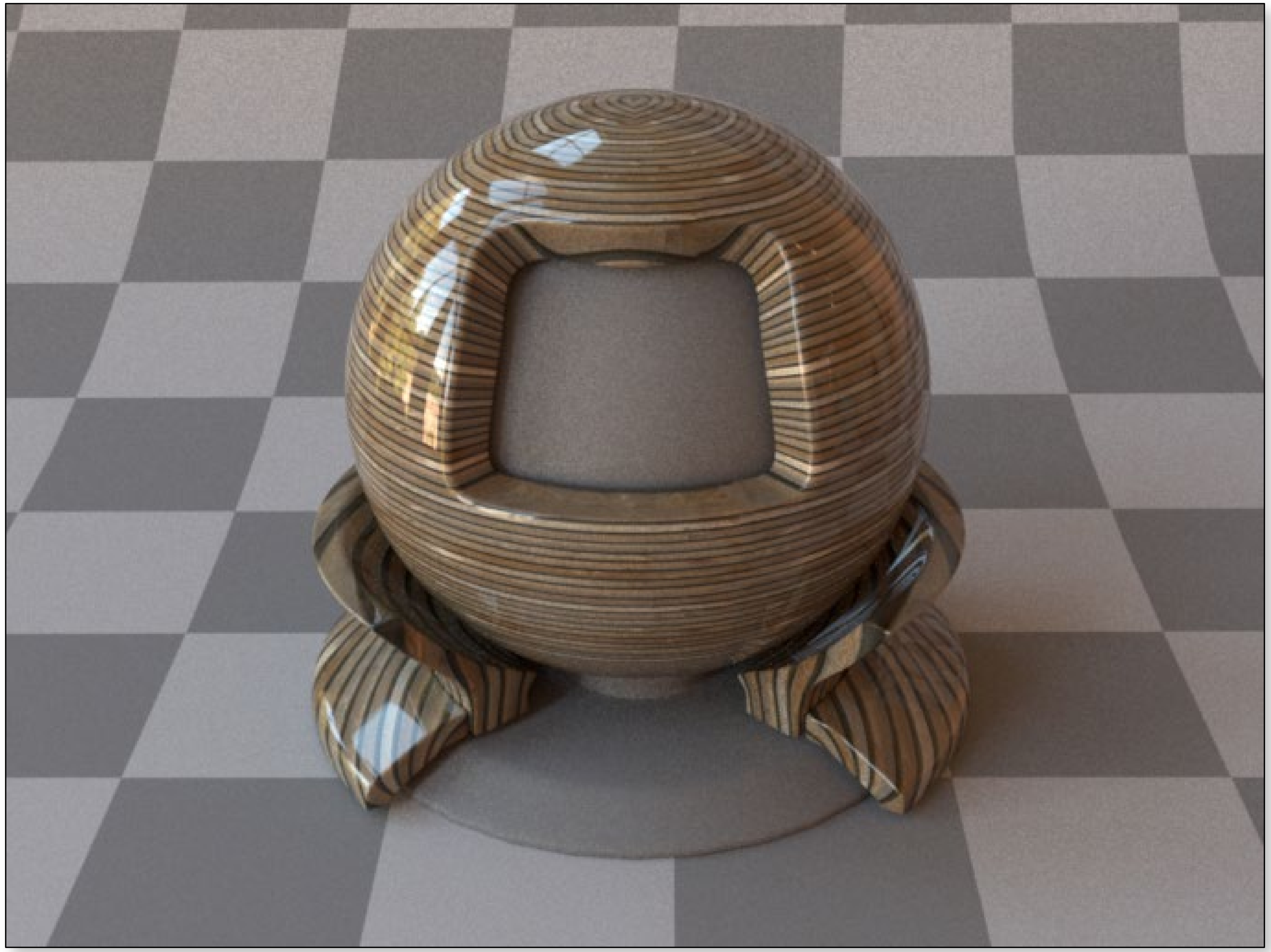
Diffuse base layer coated using a perfectly smooth dielectric (can do something similar with microfacets)

Smooth Diffuse



source: Wenzel Jakob

Smooth Plastic

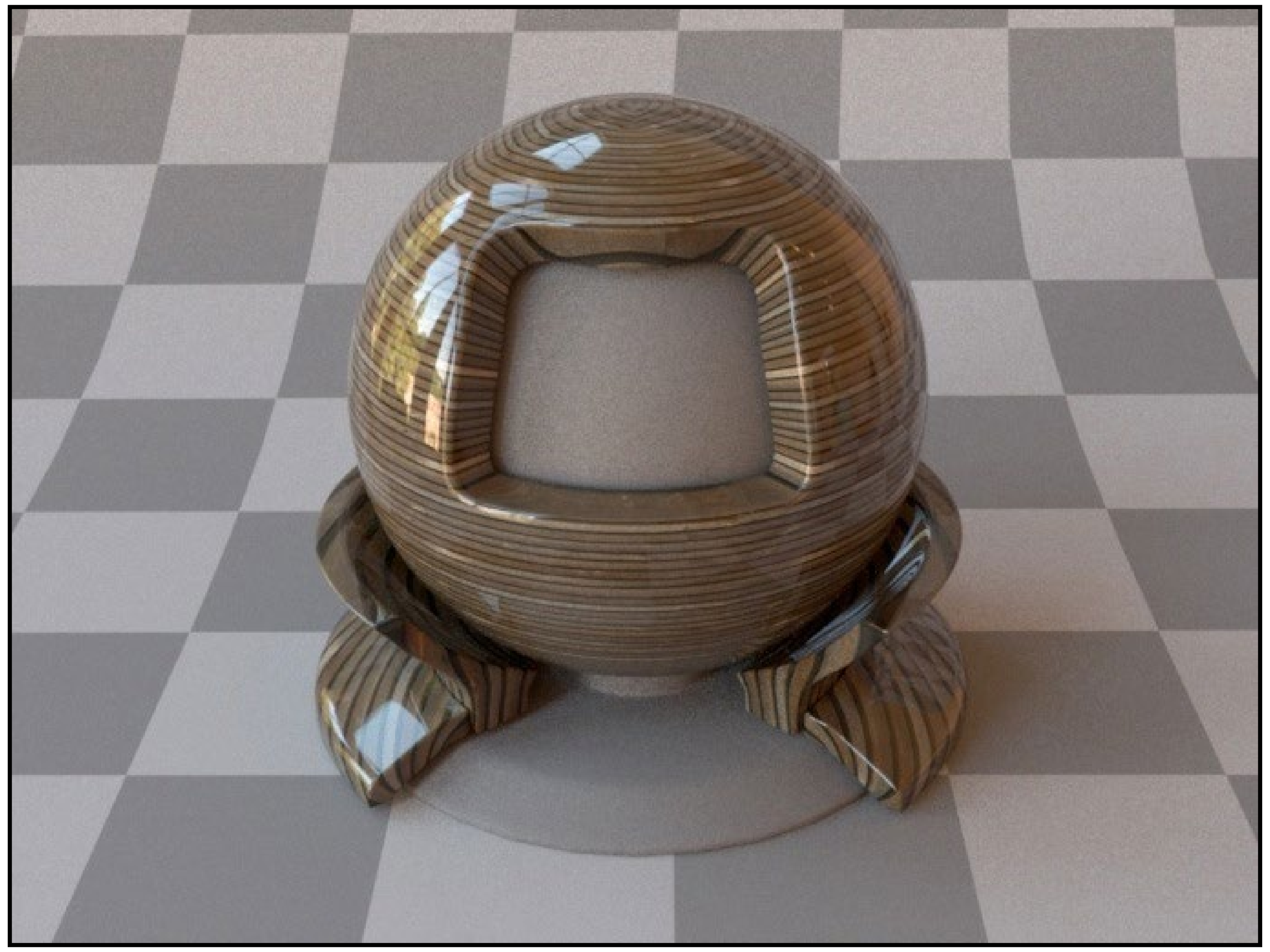


source: Wenzel Jakob

Smooth Plastic

Plain diffuse material

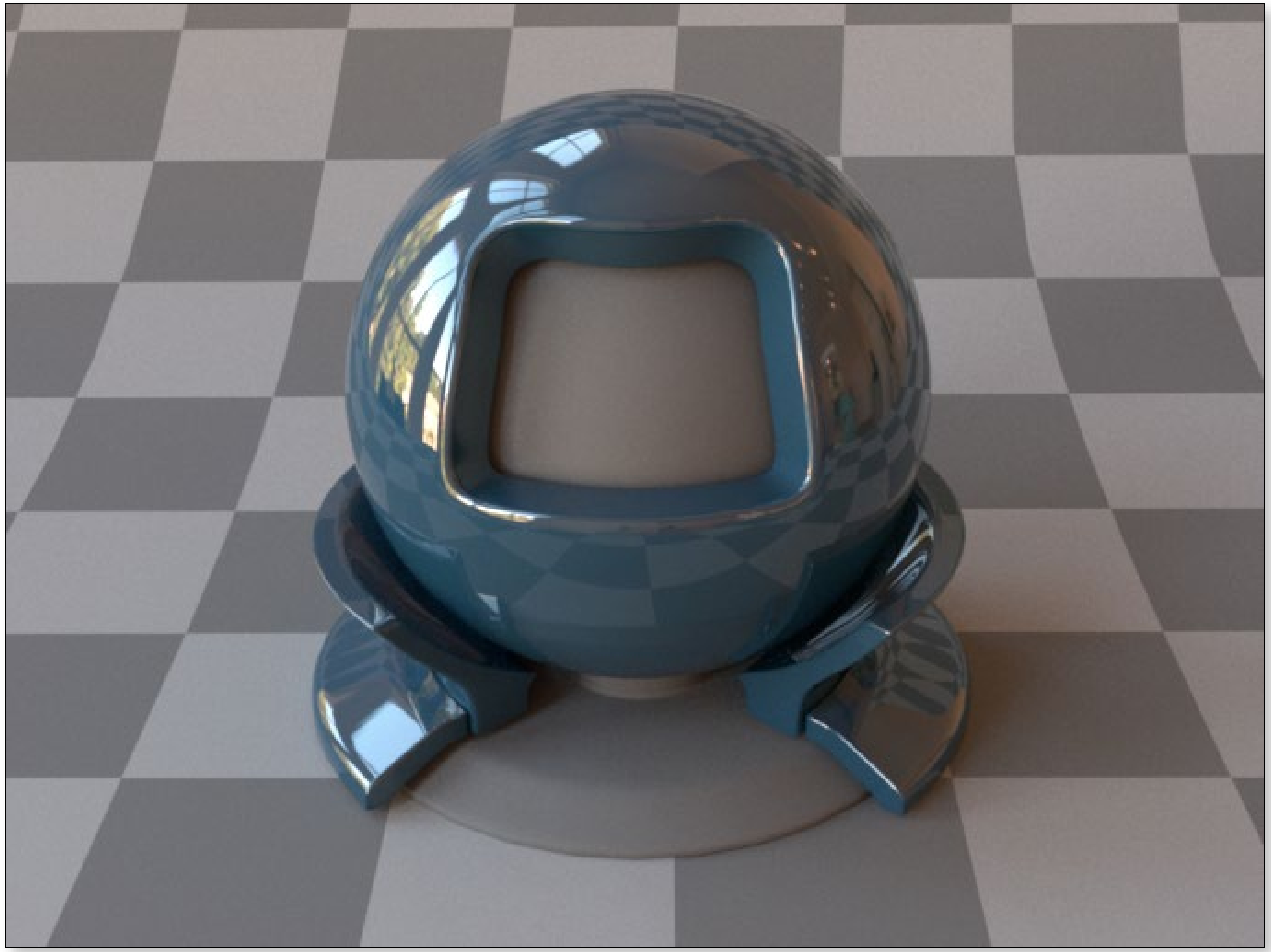
Naïve blend of diffuse + specular
(*incorrect*)



Specular-matte
(**correct**)

source: Wenzel Jakob

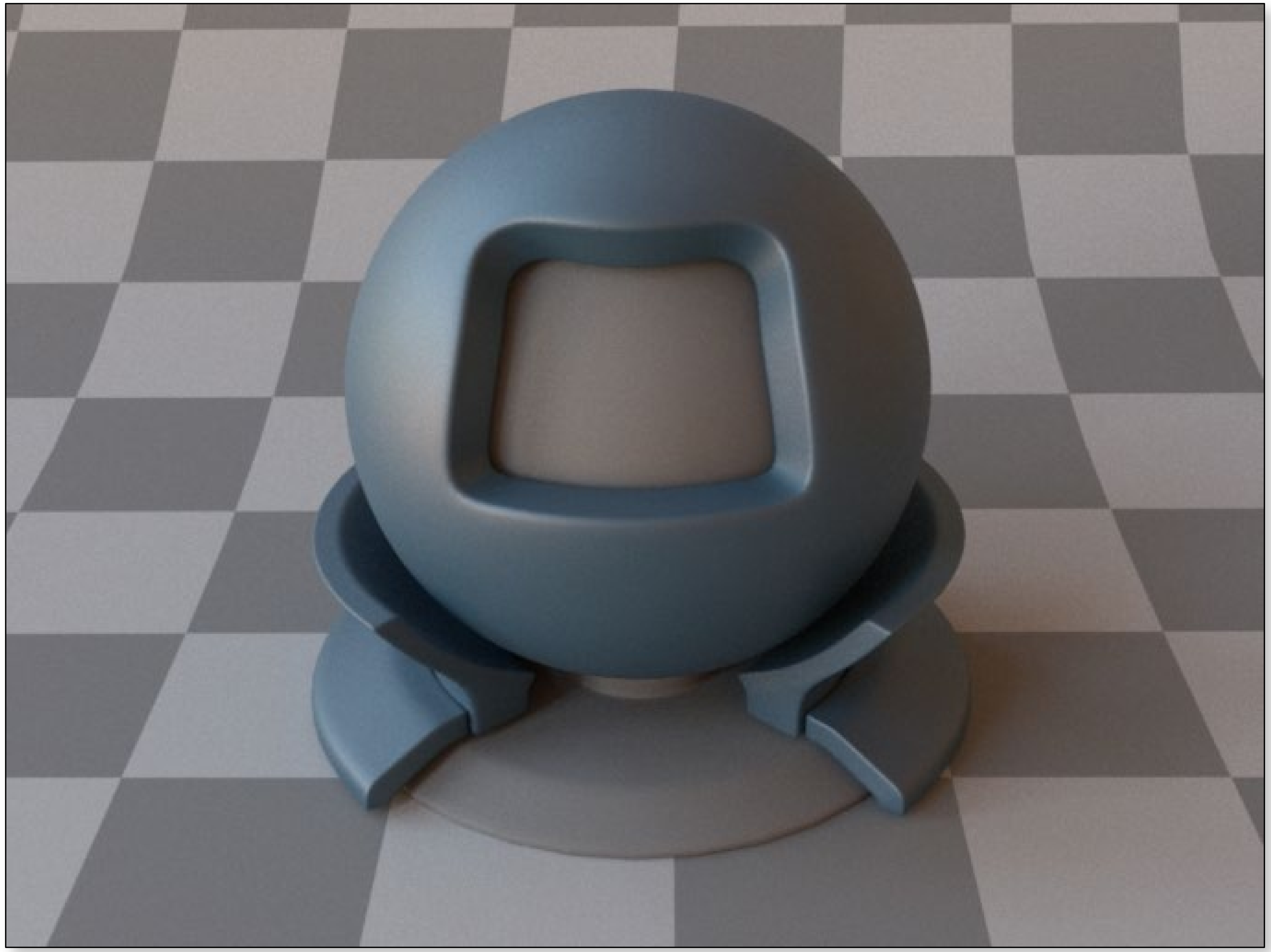
Smooth Plastic



Smooth dielectric varnish on top of diffuse surface

source: Wenzel Jakob

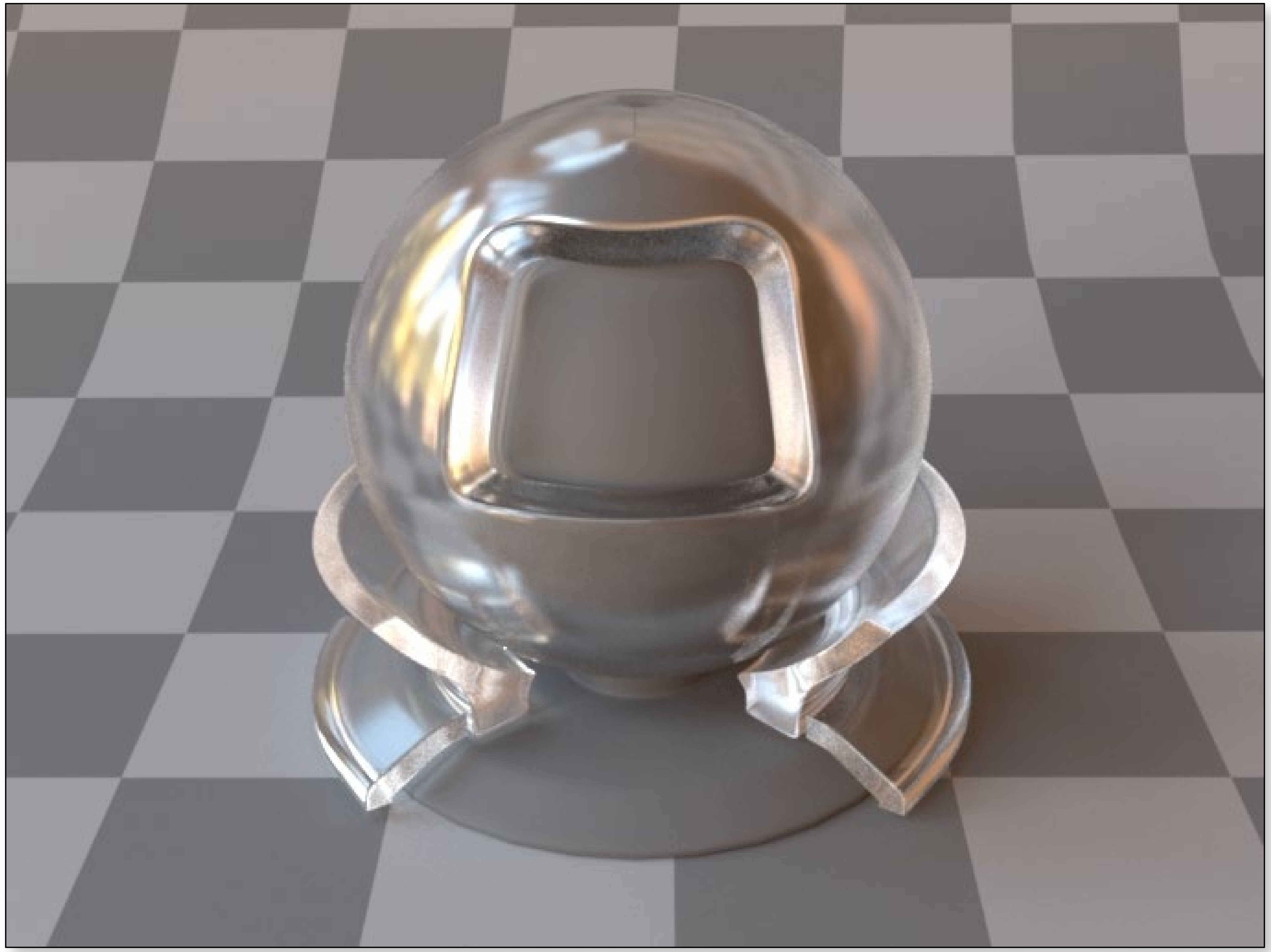
Rough Plastic



Rough dielectric varnish on top of diffuse surface

source: Wenzel Jakob

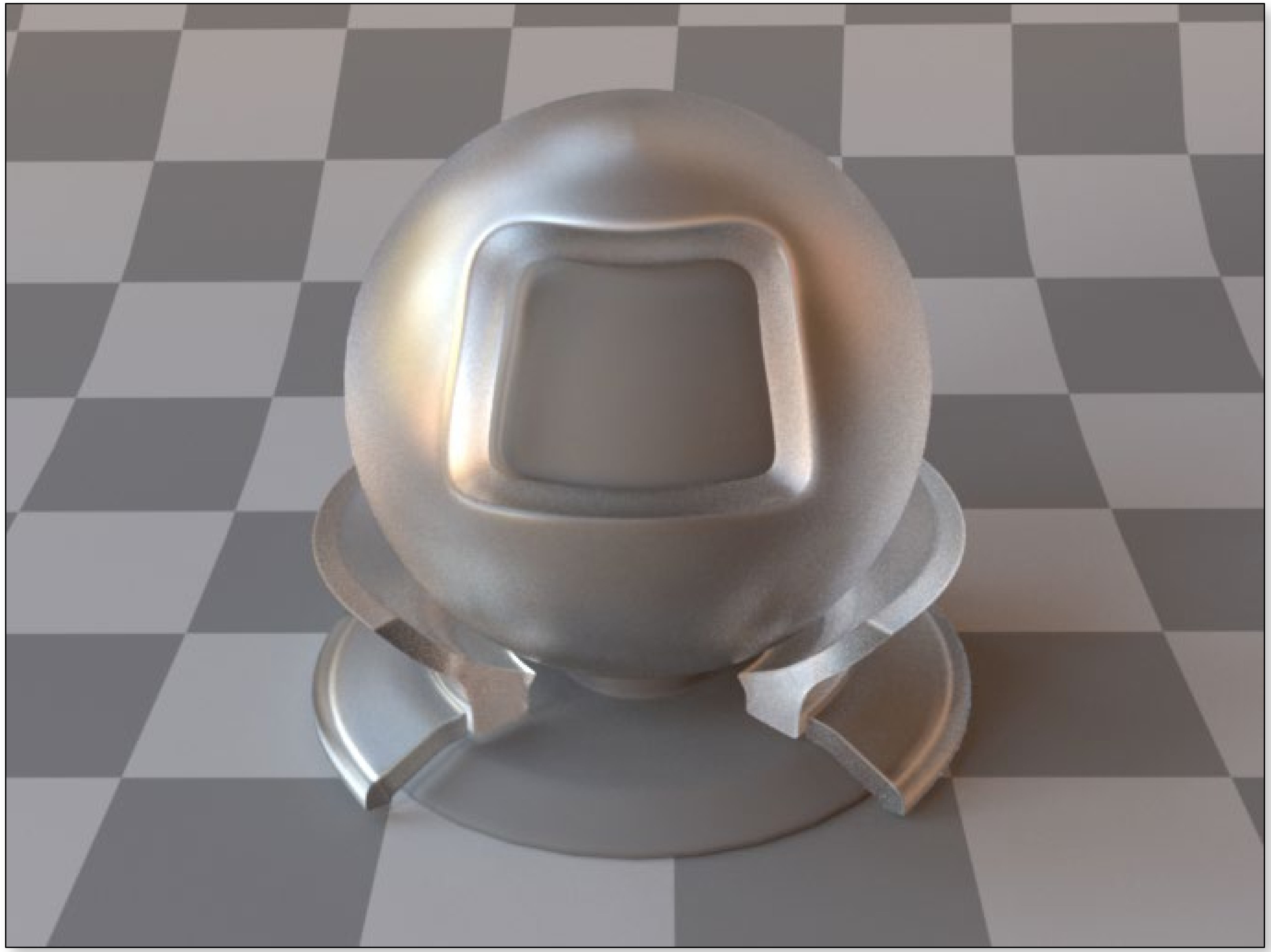
Rough Dielectric



Anti-glare glass ($m = 0.02$)

source: Wenzel Jakob

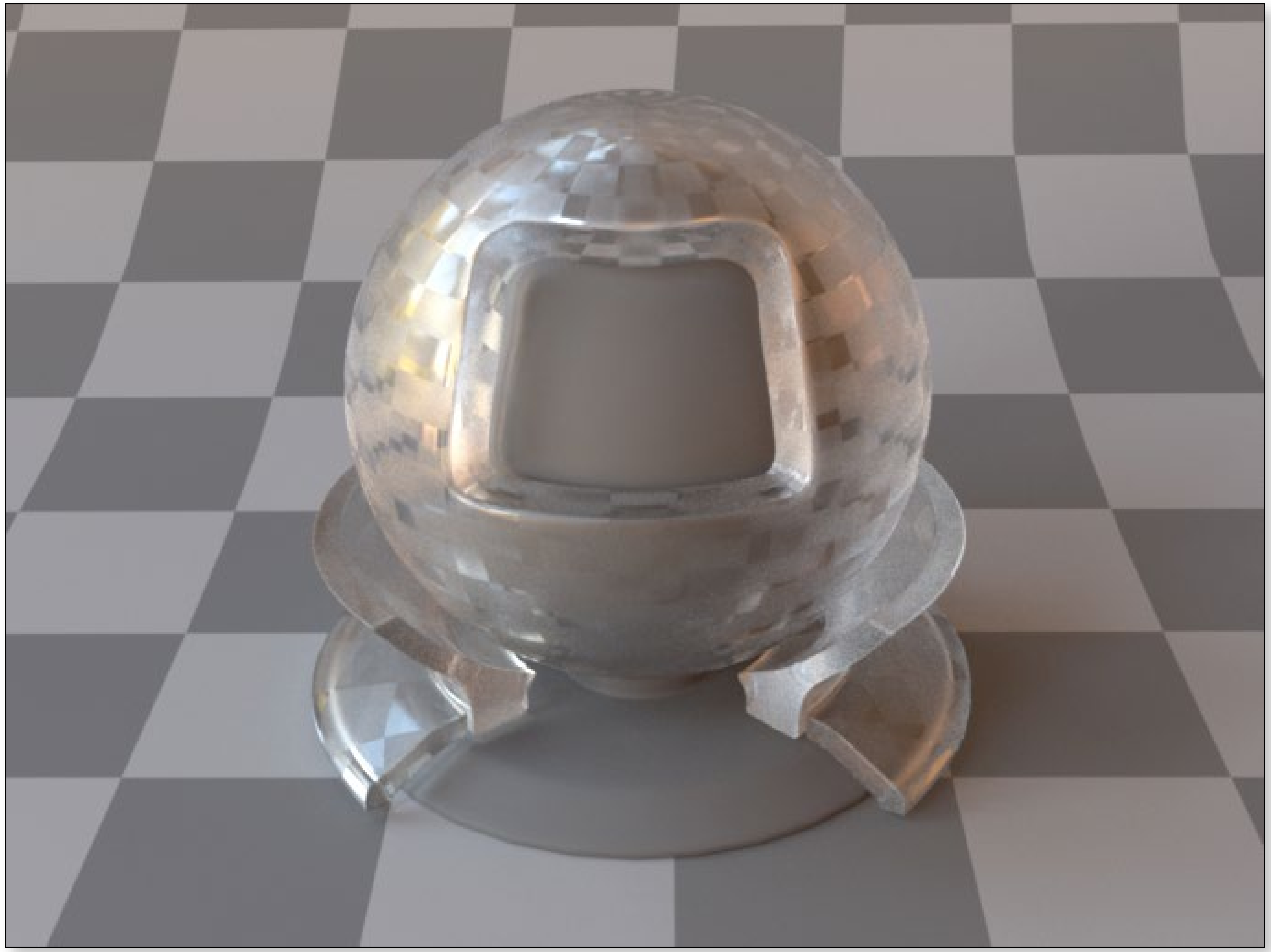
Rough Dielectric



Rough glass ($m = 0.1$)

source: Wenzel Jakob

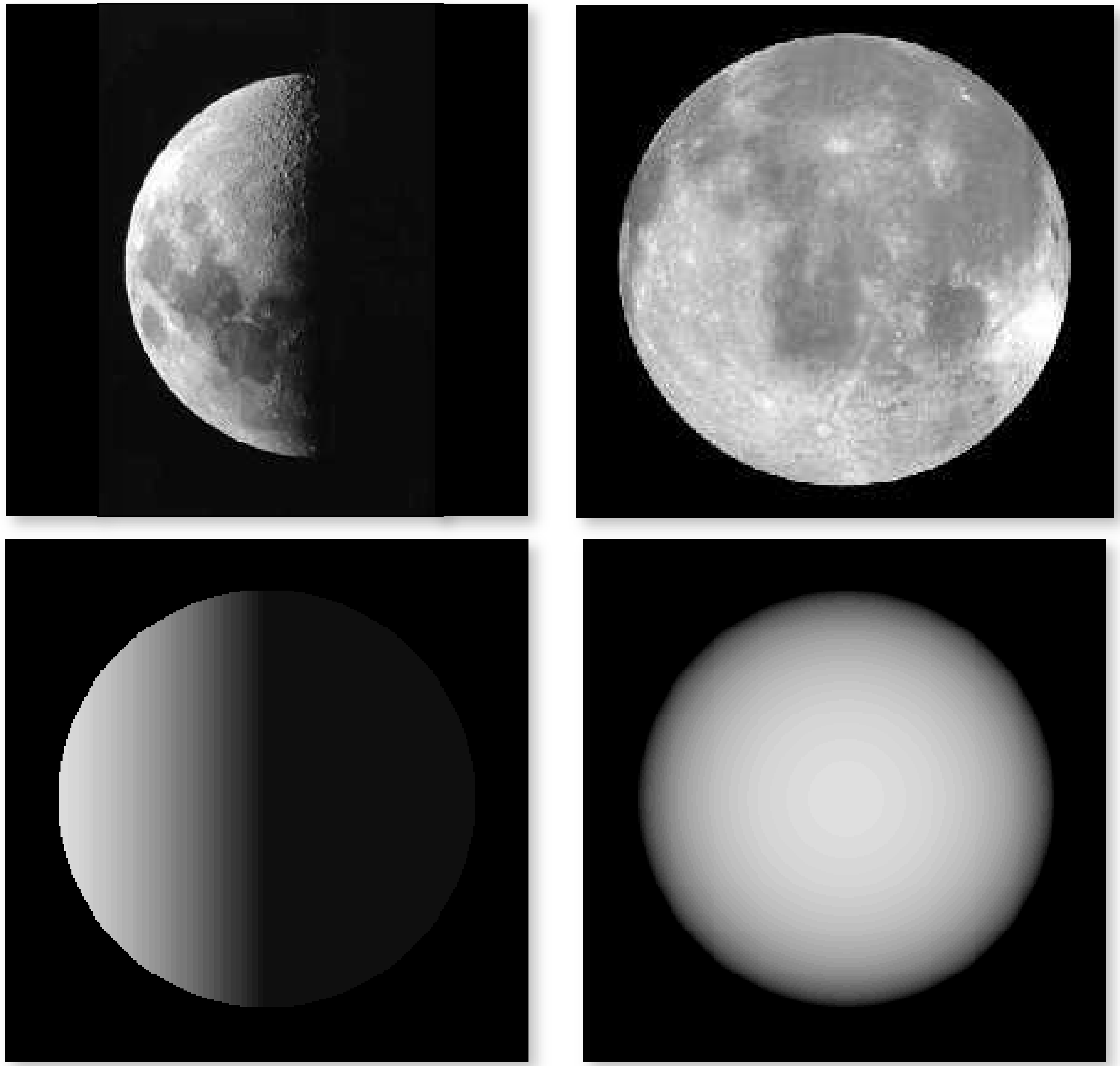
Rough Dielectric



Textured roughness

source: Wenzel Jakob

Why does the Moon have a flat appearance?



Lambertian sphere and Moon under similar illumination

The Oren-Nayar Model

Same concept as the microfacet models, but assumes that the facets are diffuse

Shadowing/masking + interreflections

No analytic solution; fitted approximation

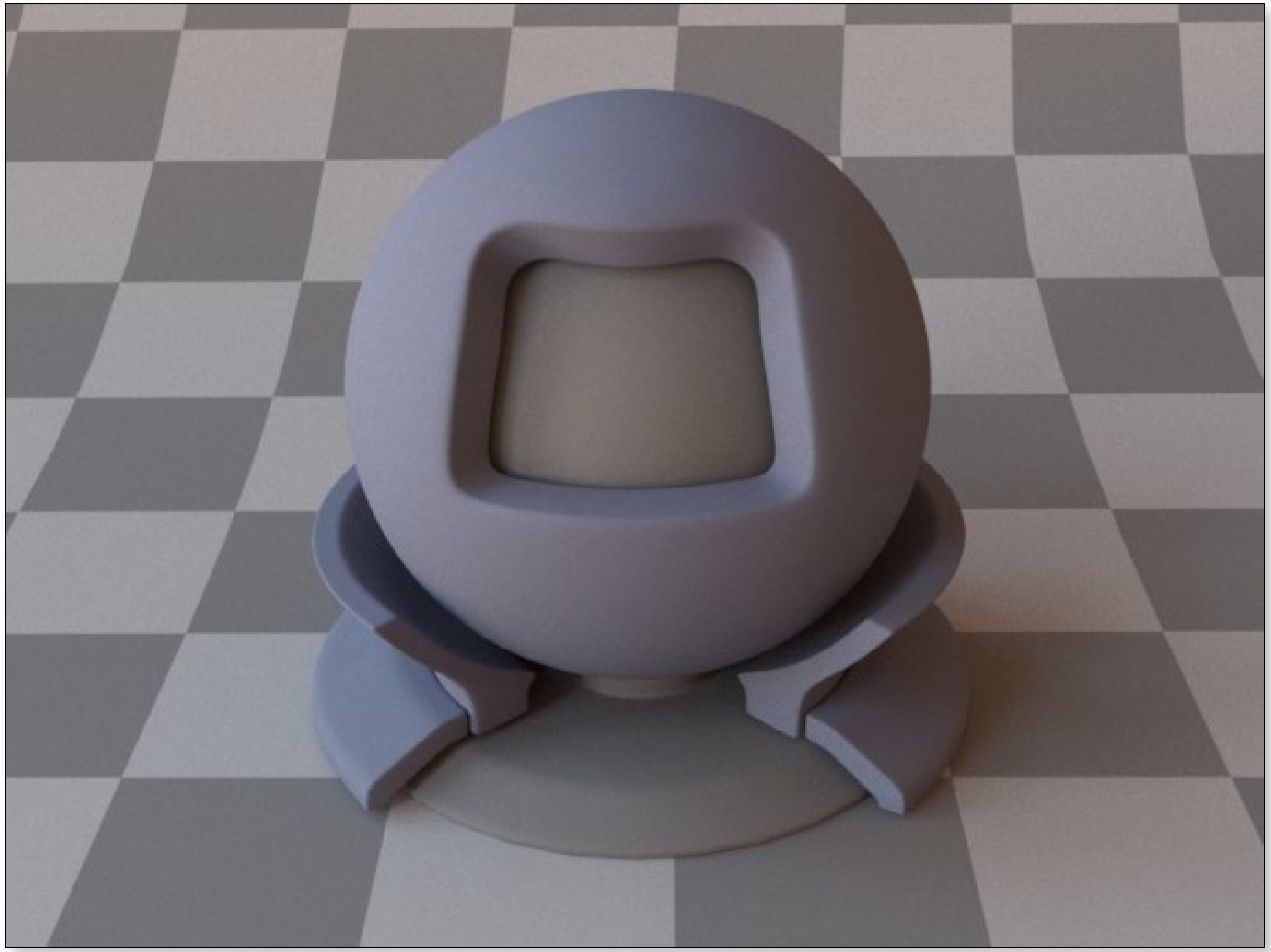
$$f_r(\vec{\omega}_o, \vec{\omega}_i) = \frac{\rho}{\pi}\left(A + B\ \max(0, \cos(\phi_i - \phi_o)) \sin\alpha \tan\beta\right)$$

$$A = 1 - \frac{\sigma^2}{2(\sigma^2 + 0.33)} \qquad B = \frac{0.45\sigma^2}{\sigma^2 + 0.09}$$

$$\alpha = \max(\theta_i, \theta_o) \qquad \beta = \min(\theta_i, \theta_o)$$

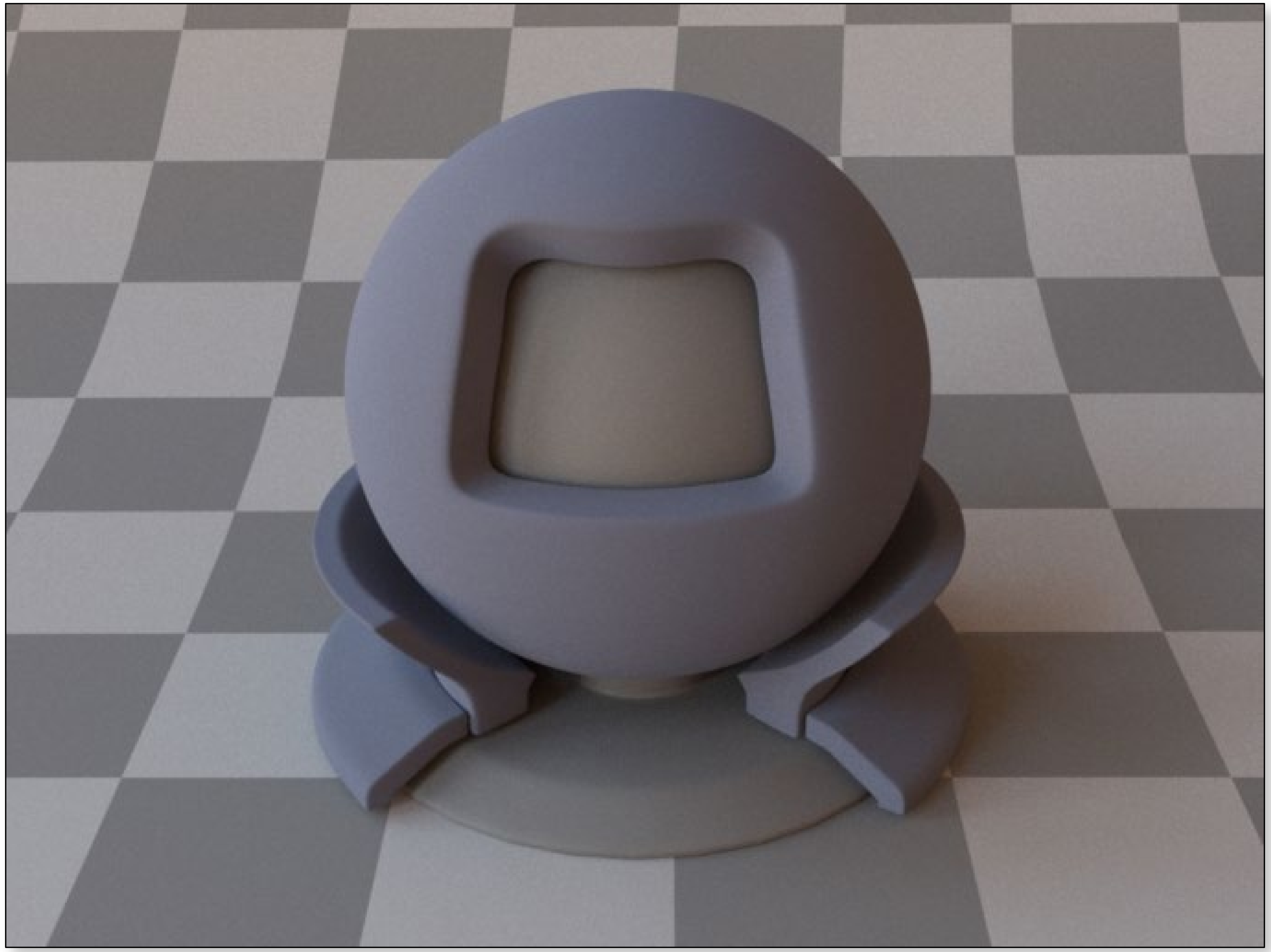
Ideal Lambertian is just a special case ($\sigma = 0$)

Smooth Diffuse



source: Wenzel Jakob

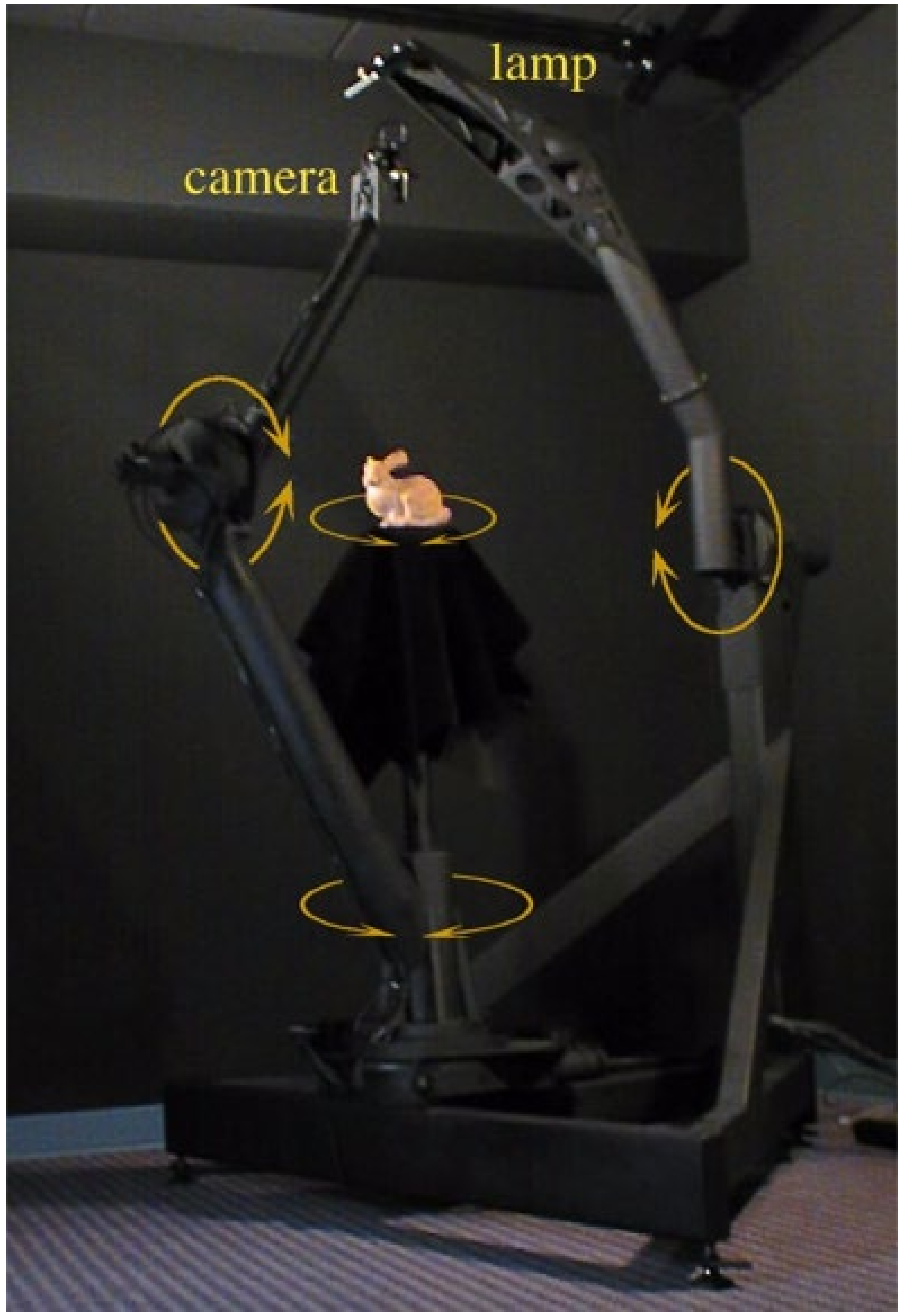
Rough Diffuse



source: Wenzel Jakob

Data-Driven BRDFs

Spherical gantry



Measuring BRDFs

source: Matusik et al. 2003

Nickel

source: Matusik et al. 2003

Hematite

source: Matusik et al. 2003

Gold Paint

source: Matusik et al. 2003

Pink Fabric

source: Matusik et al. 2003

BRDF Editing/Navigation

Given a large database, can mix/match and interpolate between BRDFs

The MERL Database

"A Data-Driven Reflectance Model"
Wojciech Matusik, Hanspeter Pfister, Matt Brand and Leonard McMillan.
ACM Transactions on Graphics 22, 3(2003), 759-769.

Download them and use them in your own renderer!

- http://www.merl.com/brdf/

Measuring and Modeling the Appearance of Wood

Stephen R. Marschner, Stephen H. Westin,
Adam Arbree, and Jonathan T. Moon

Cornell University

Reading

PBRTv3 Chapter 8, and 14.1