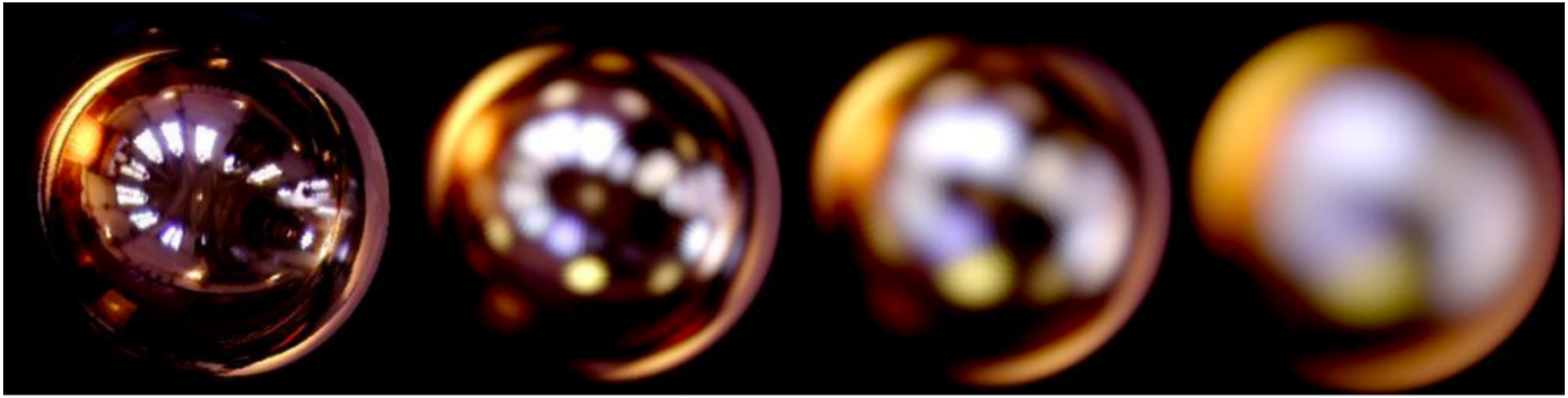
CS 87/187, Spring 2016

Rendering Algorithms

Appearance Modeling: Microfacet BRDFs

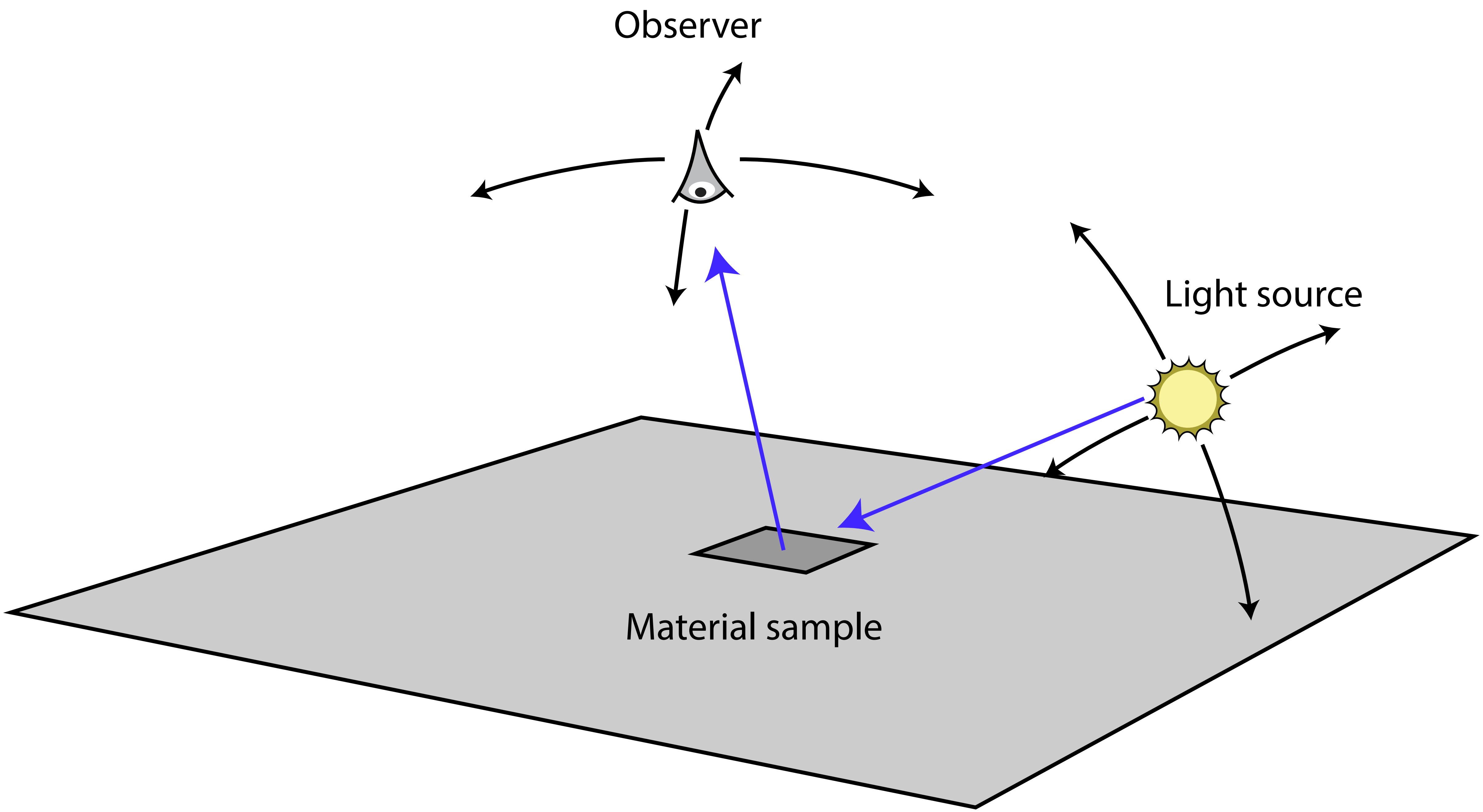


Prof. Wojciech Jarosz
wojciech.k.jarosz@dartmouth.edu

(with slide improvements from Jan Novák)

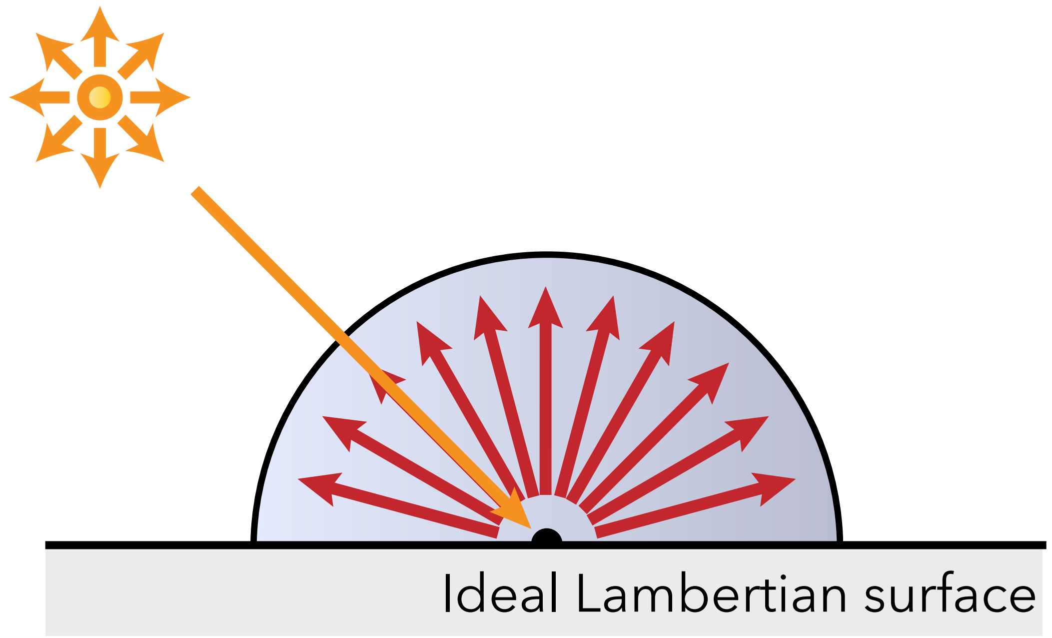
Dartmouth

Characterizing Materials

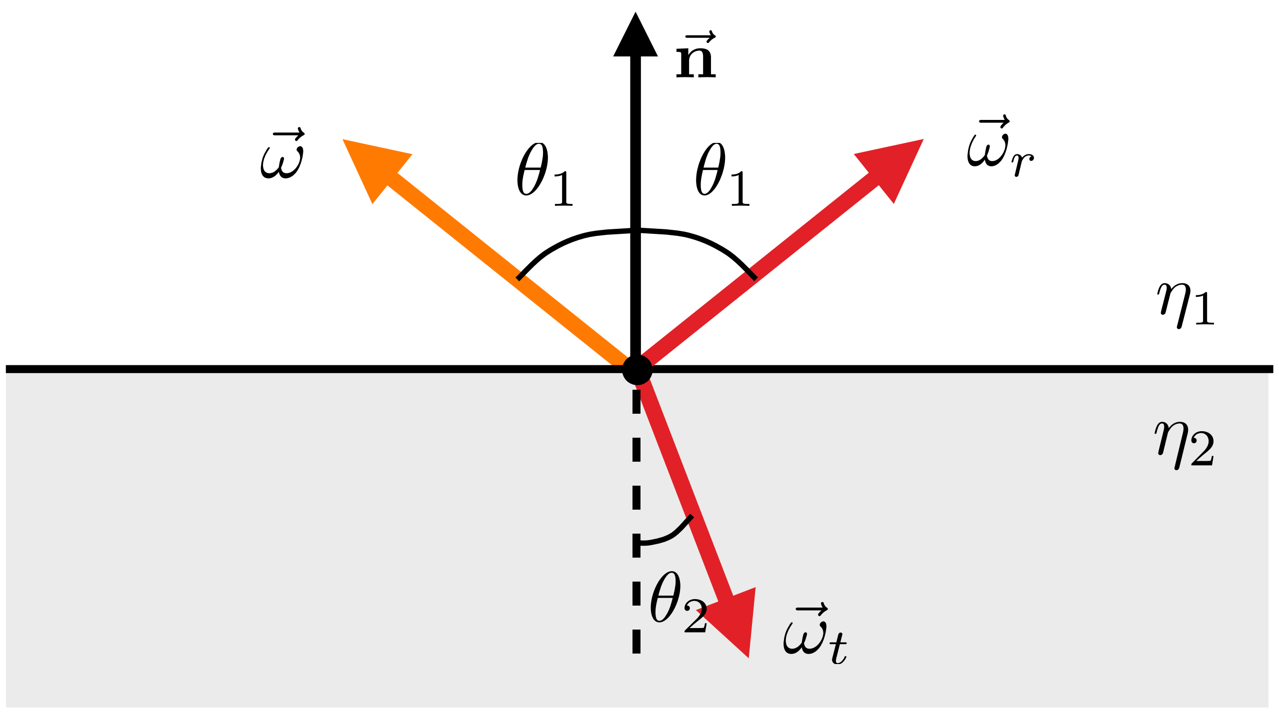


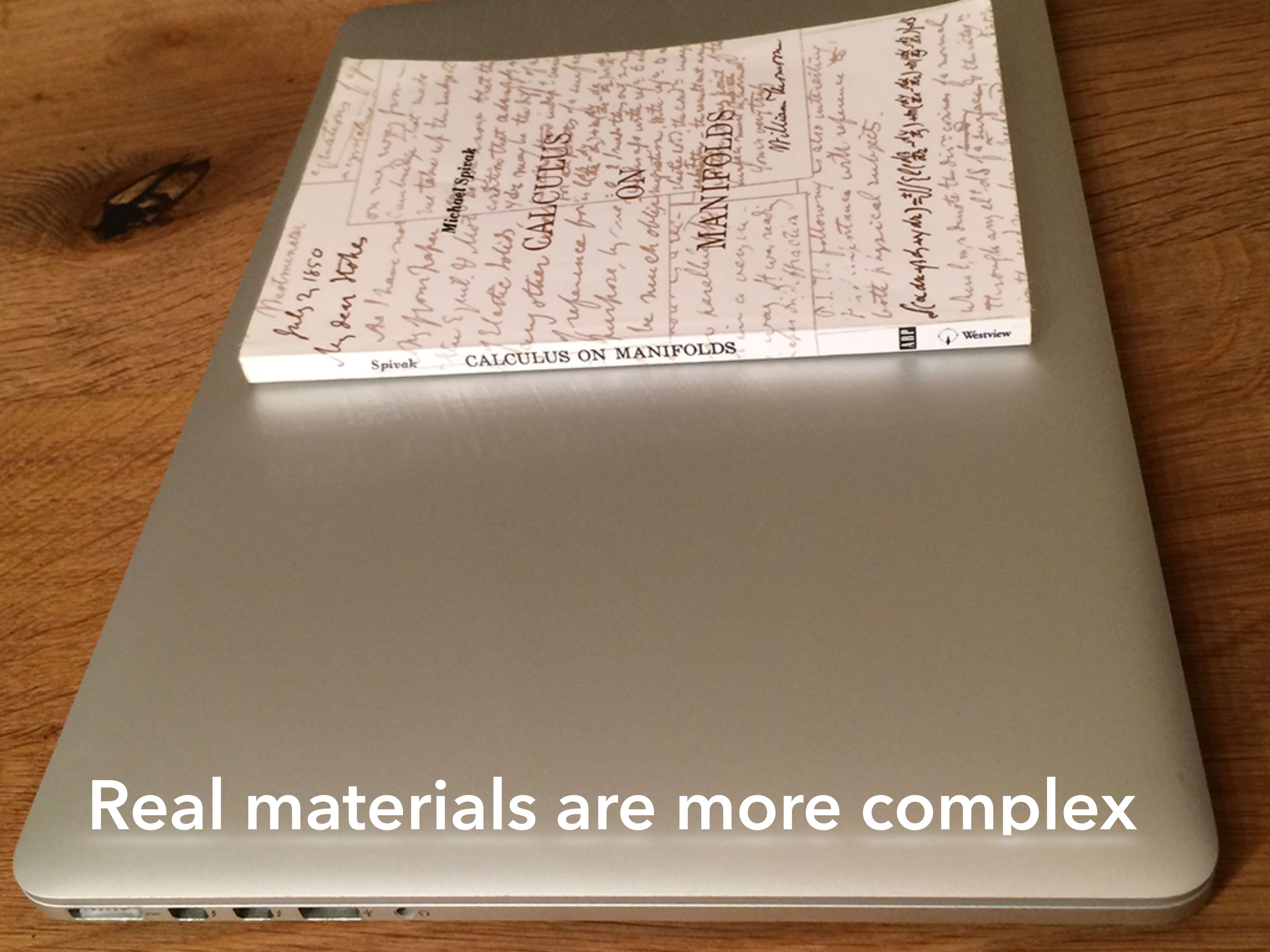
So Far: Idealized BRDF Models

- Diffuse



- Specular Reflection and Refraction





Real materials are more complex

Conductors vs. Dielectrics

Copper

Iron

Glass

Ethanol

Gold

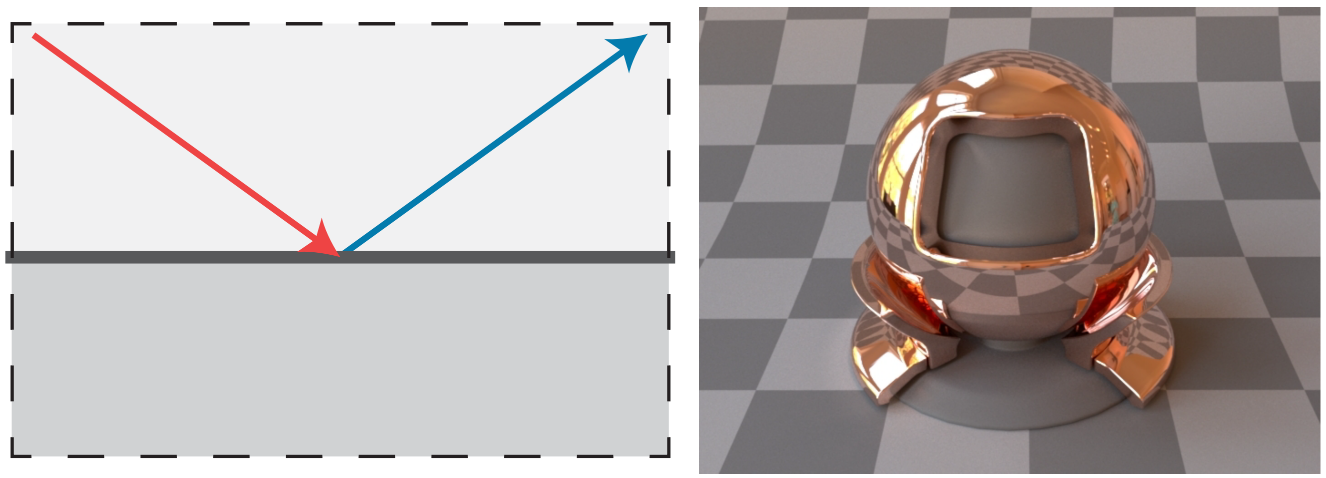
Mercury

Water

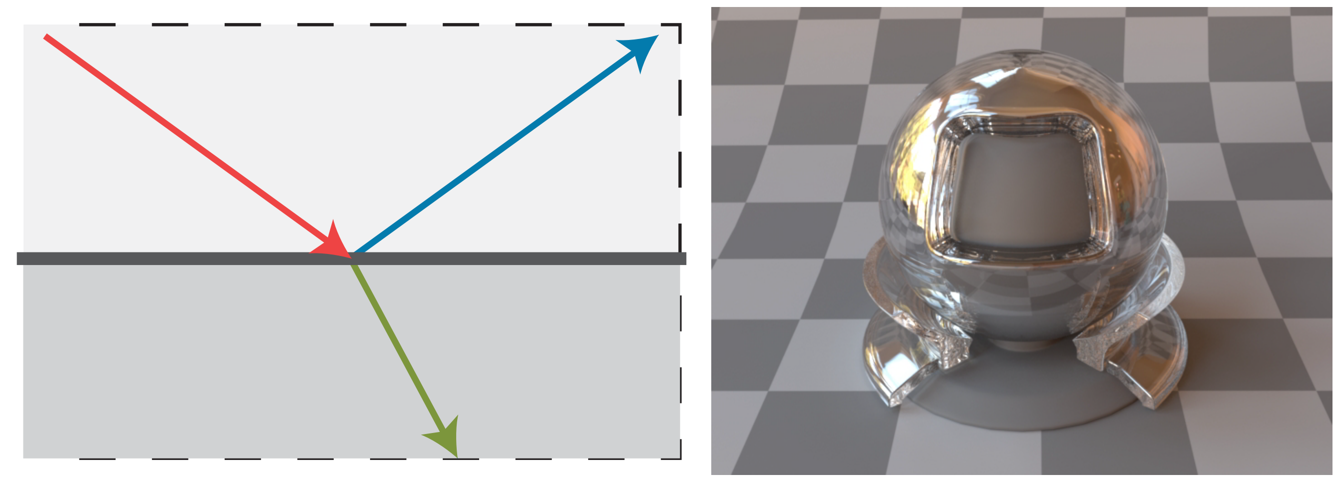
Air

Image credits: Wikipedia Commons

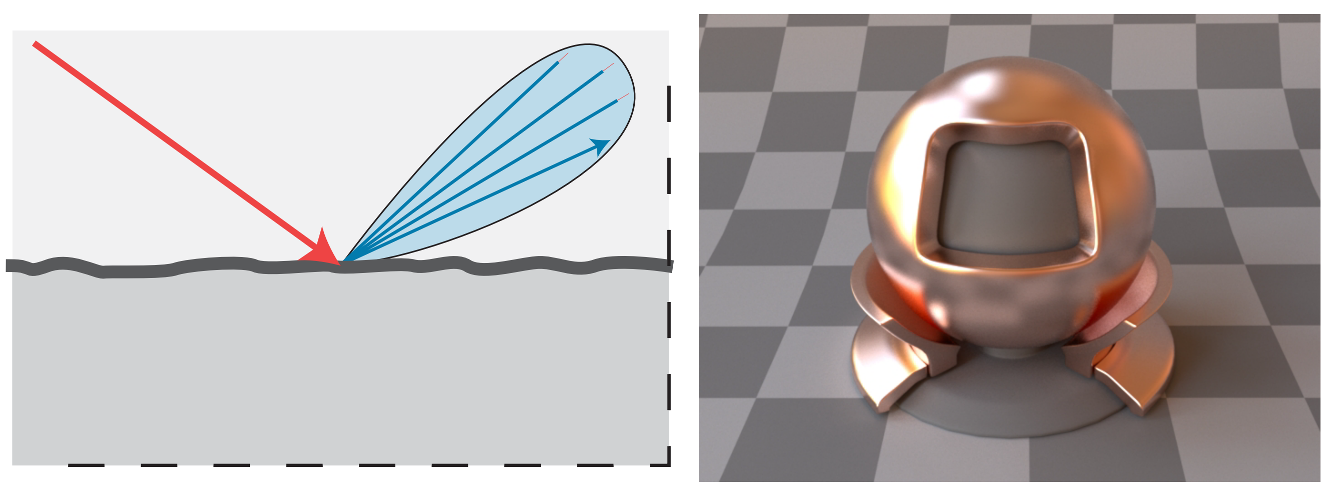
Conductors vs. Dielectrics



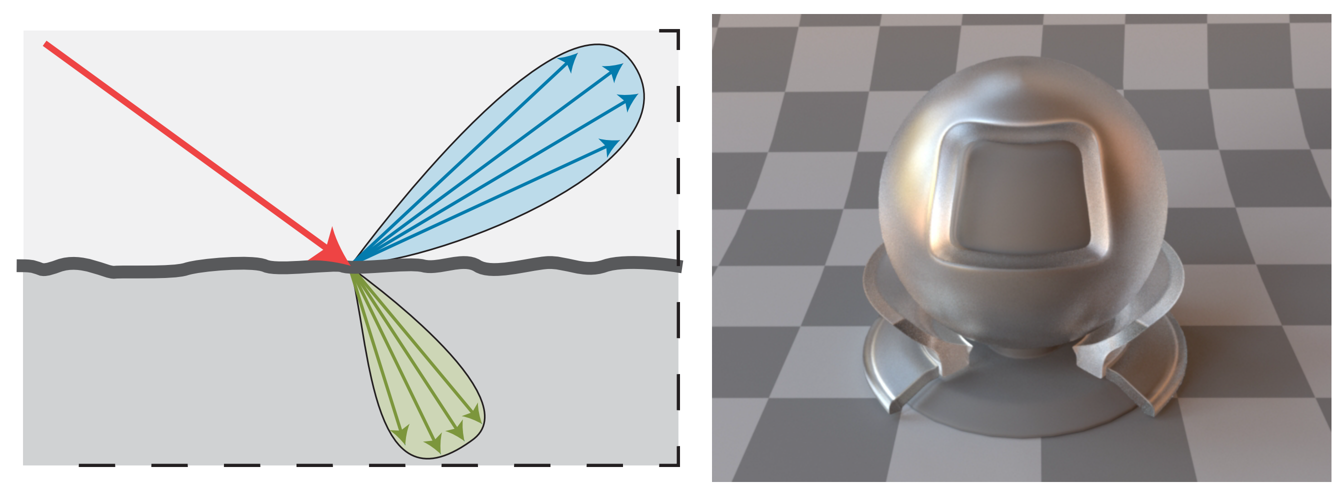
Smooth conducting material



Smooth dielectric material



Rough conducting material



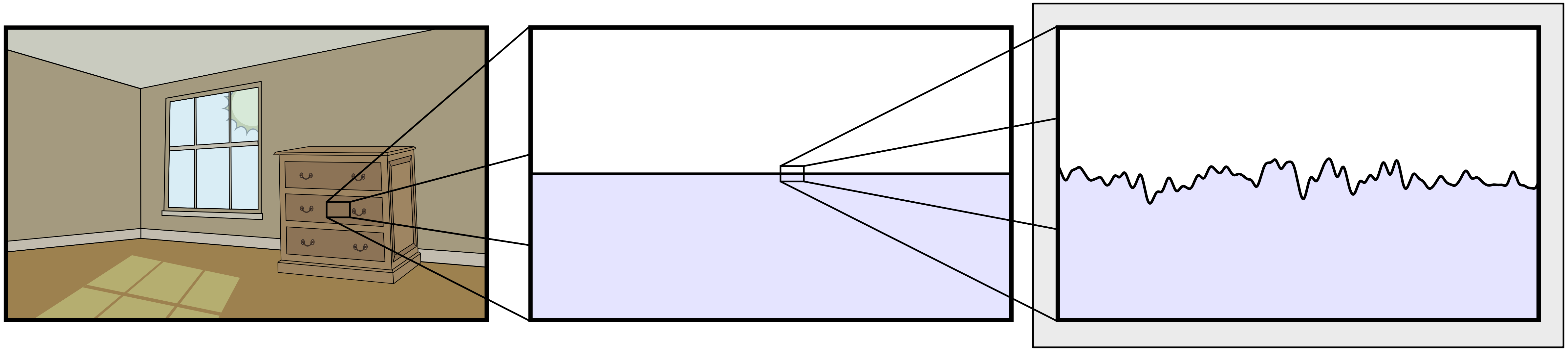
Rough dielectric material

Today’s Menu

- Statistical physics concepts
- More complex surface scattering
- Light interaction with rough surfaces
- Data-driven reflectance

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

BRDF History

- 1970s: Empirical models
  - Phong's illumination model
- 1980s:
  - Physically based models
  - Microfacet models (e.g. Cook-Torrance model)
- 1990s:
  - Physically-based appearance models of specific effects (materials, weathering, dust, etc)
- 2000s:
  - Measurement & acquisition of static materials/lights (wood, translucence, etc)

Rough Surfaces

- Many surfaces are not perfectly smooth
- Phong came up with an empirical model to account for this
- Simple
- Fast to evaluate

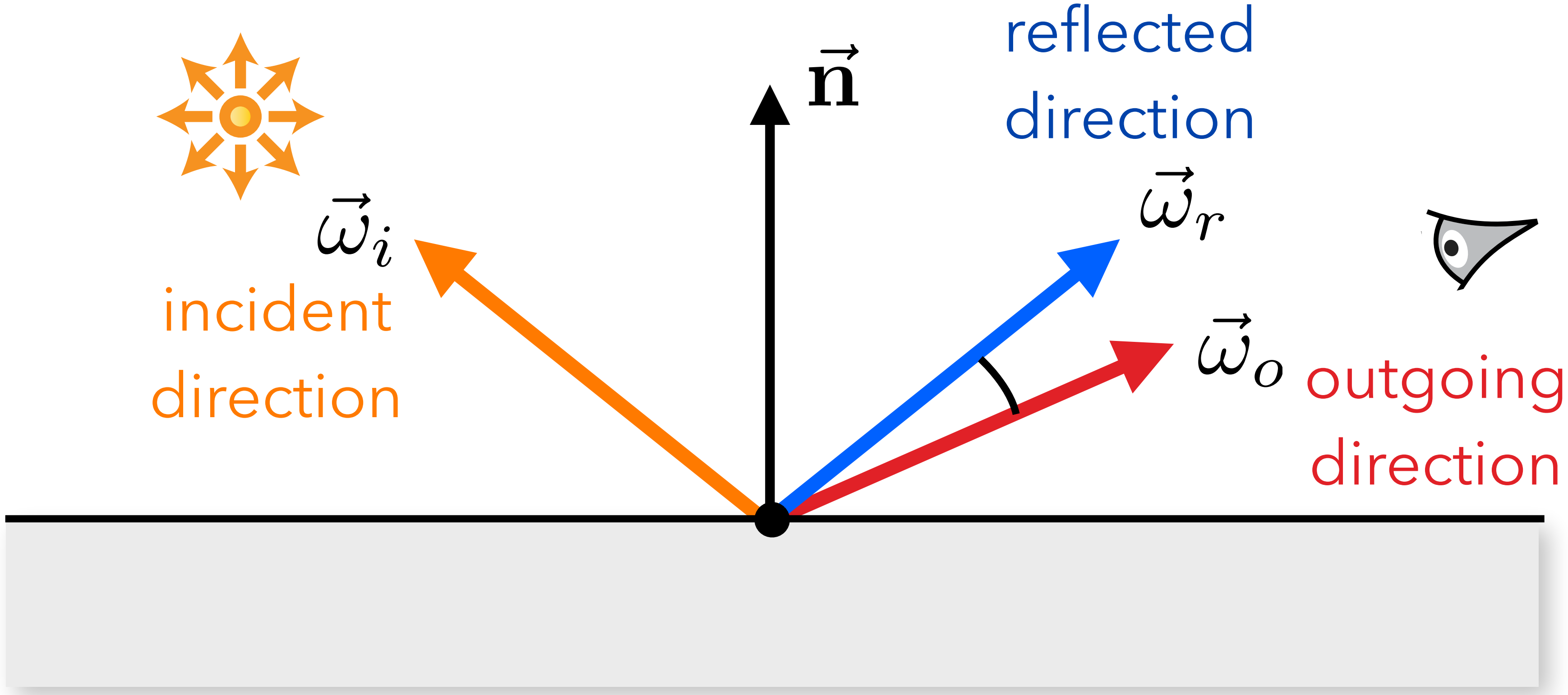
"In trying to improve the quality of the synthetic images, we do not expect to be able to display the object exactly as it would appear in reality, with texture, overcast shadows, etc. We hope only to **display an image that approximates the real object closely** enough to provide a certain degree of realism." – Bui Tuong Phong, 1975

Normalized Phong

- Normalized exponentiated cosine lobe:

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

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



Demo

500px user Sinan SOLMAZ

Normalized Phong

- Normalized exponentiated cosine lobe:

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

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

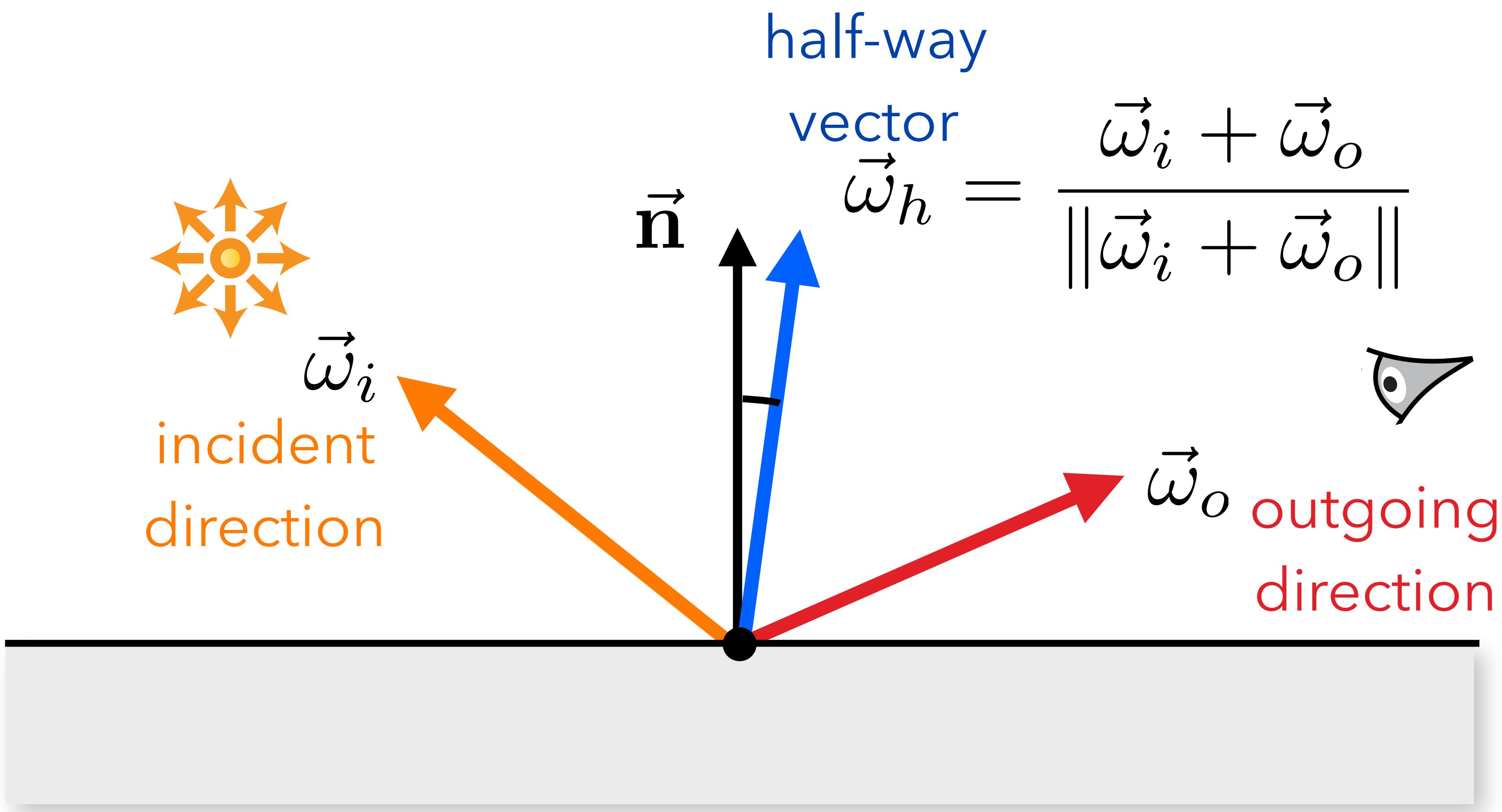
- Interpretation
  - blur reflection rays in a cone about mirror direction
  - perfect mirror reflection of a blurred light

Blinn-Phong

- "Blur" normals instead of reflection directions

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

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



Demo

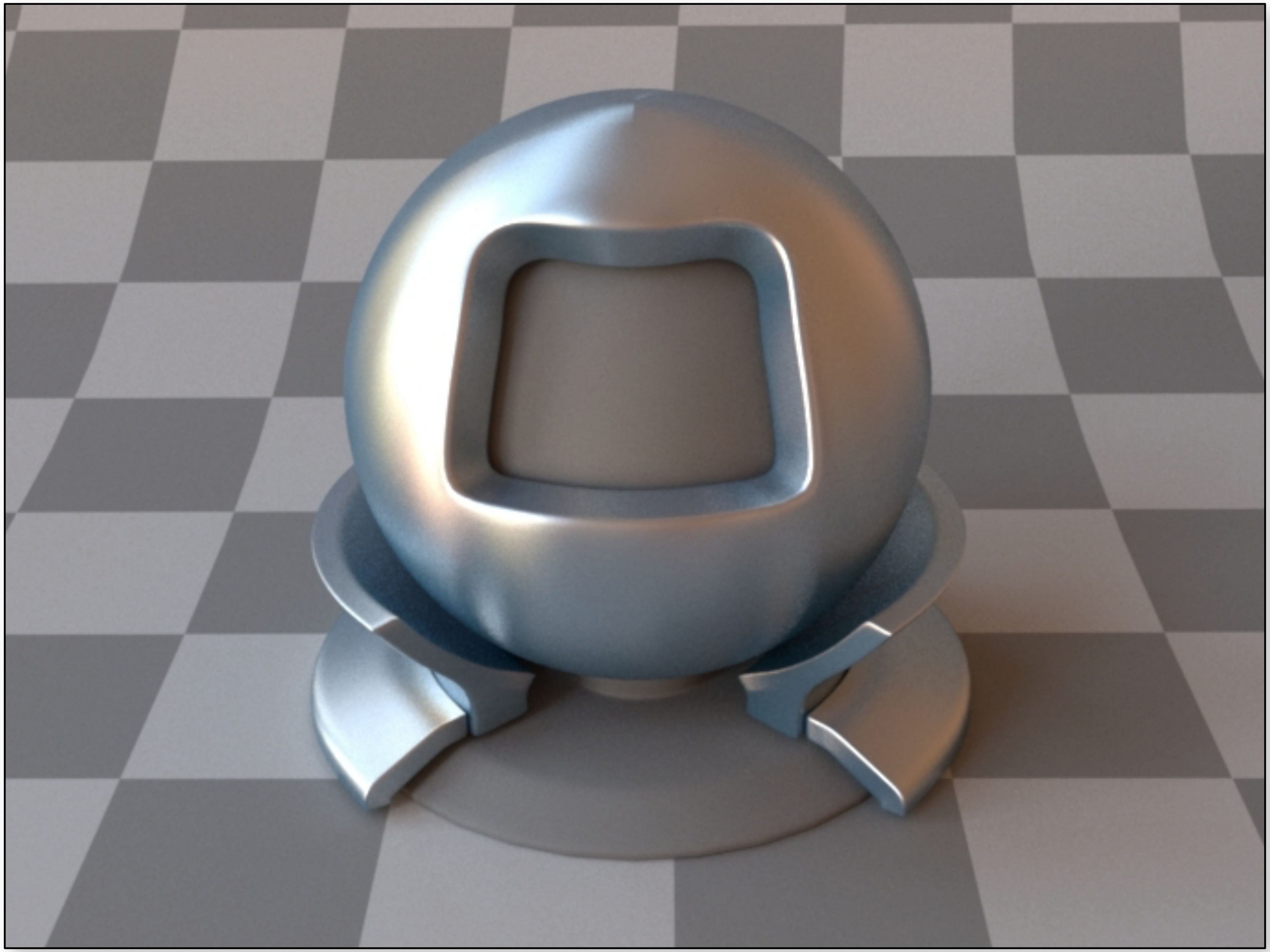
Visual Break (Ocean Sunset)

Visual Break (Ocean Sunset)

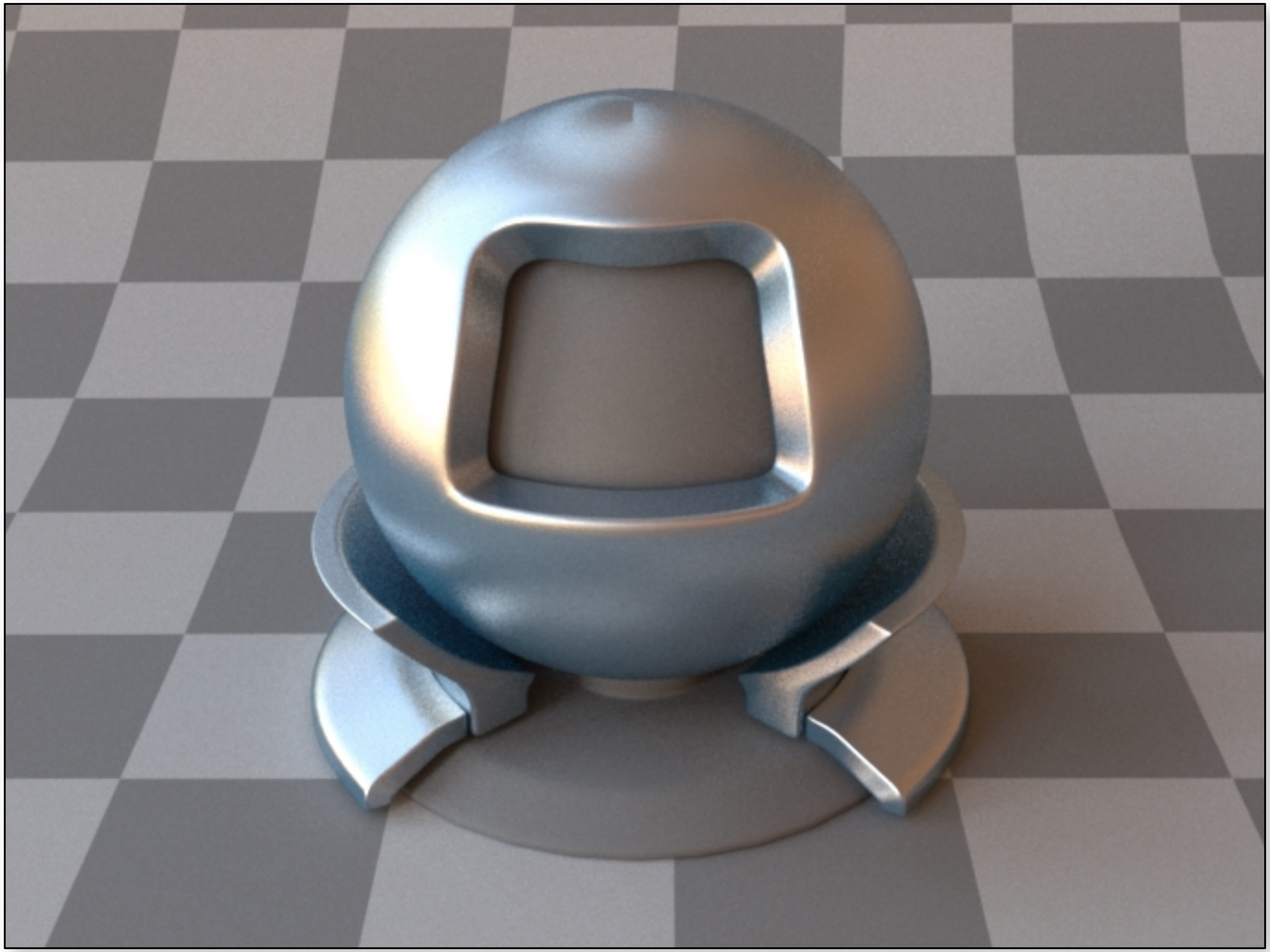
Ward model

- Gaussian blur distribution over half vector slopes
- Original version had issues with energy conservation and singularities; several modified variants exist

Anisotropic Ward



Anisotropic Ward



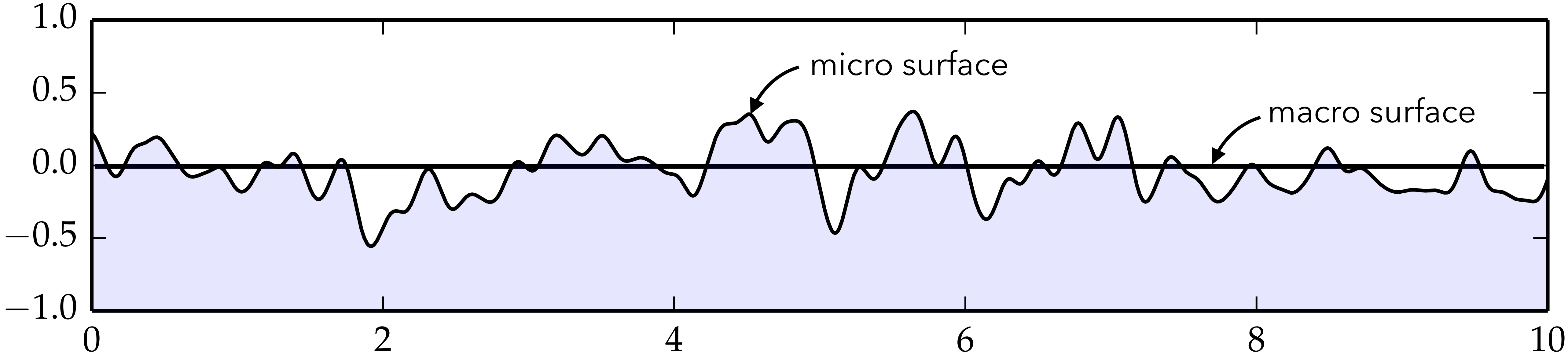
Rough Surfaces

- Empirical glossy models have limitations:
  - not physically-based
  - (often) not reciprocal
  - not energy-preserving (can be normalized)
  - (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

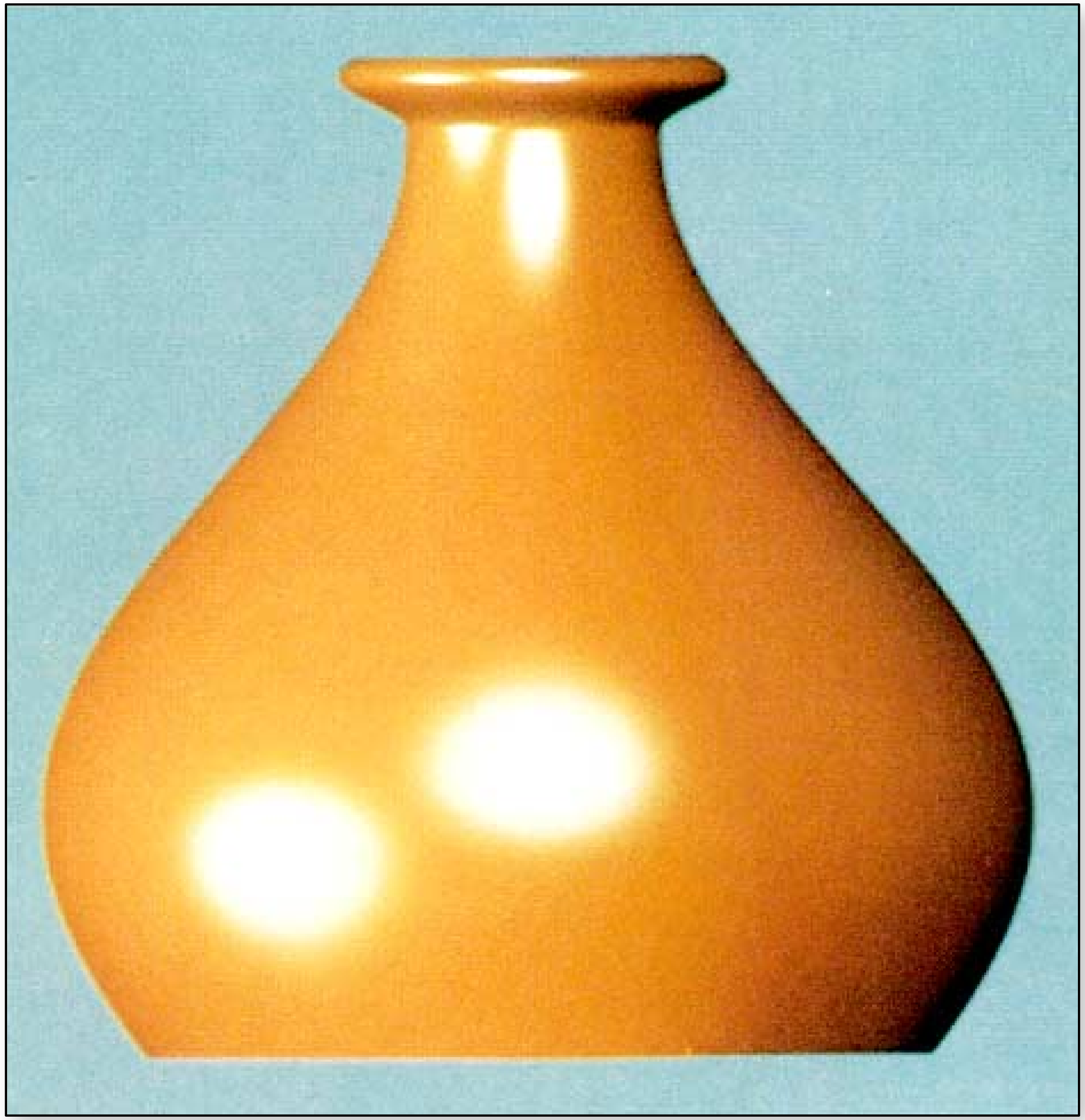
- Assume surface consists of tiny facets
- Assume that the differential area being viewed/illuminated is relatively large compared to the size of microfacets
- A facet can be perfectly specular or diffuse



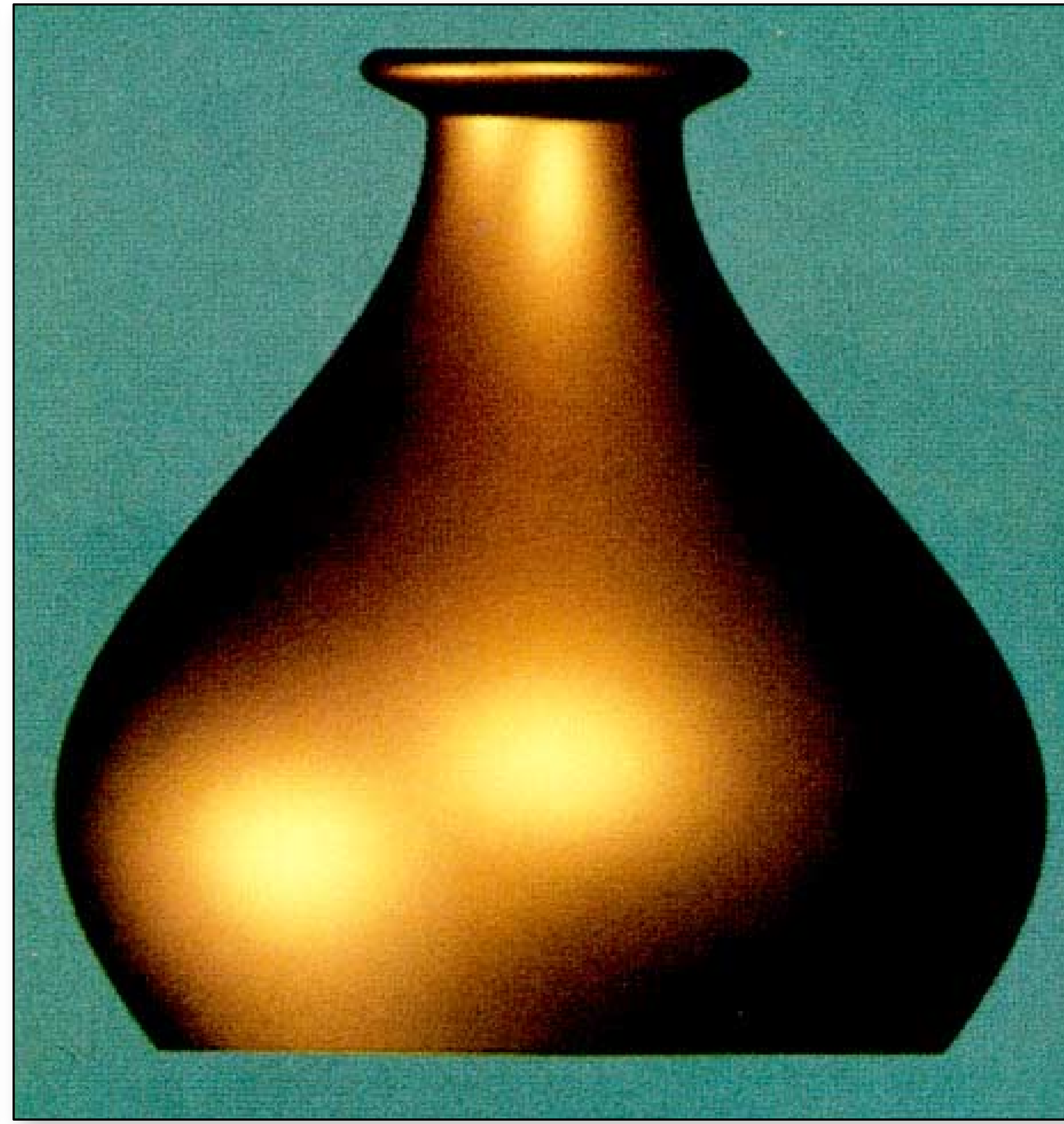
Torrance-Sparrow Model

- 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

source: Cook-T

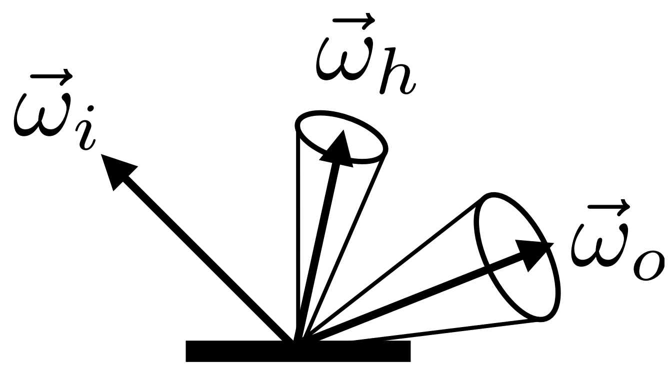
General Microfacet Model

Fresnel coefficient

Microfacet distribution

Shadowing/ masking

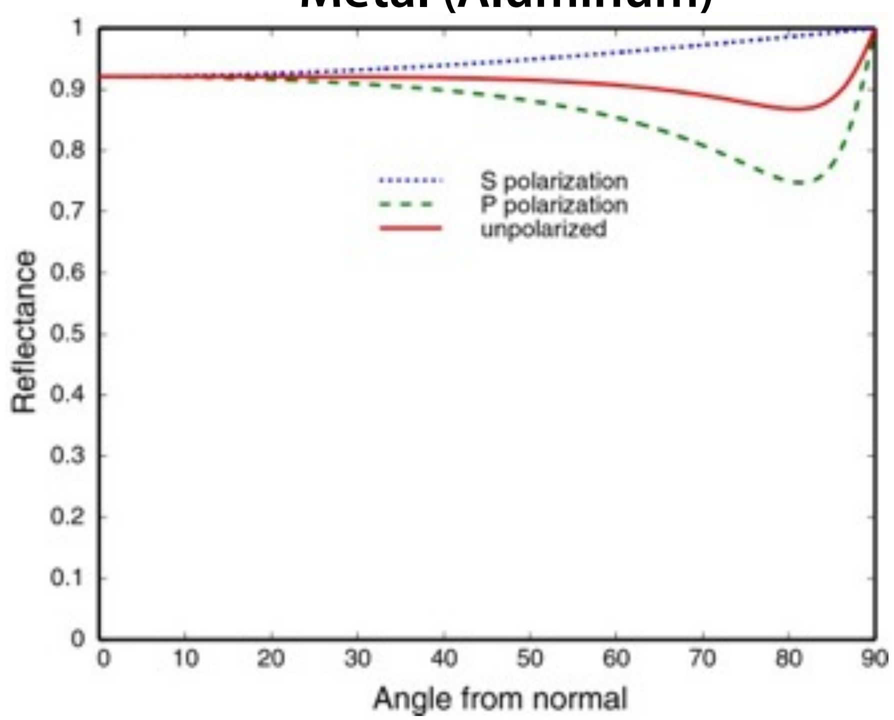
$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4\left|(\vec{\omega}_i \cdot \mathbf{n})(\vec{\omega}_o \cdot \mathbf{n})\right|}$$



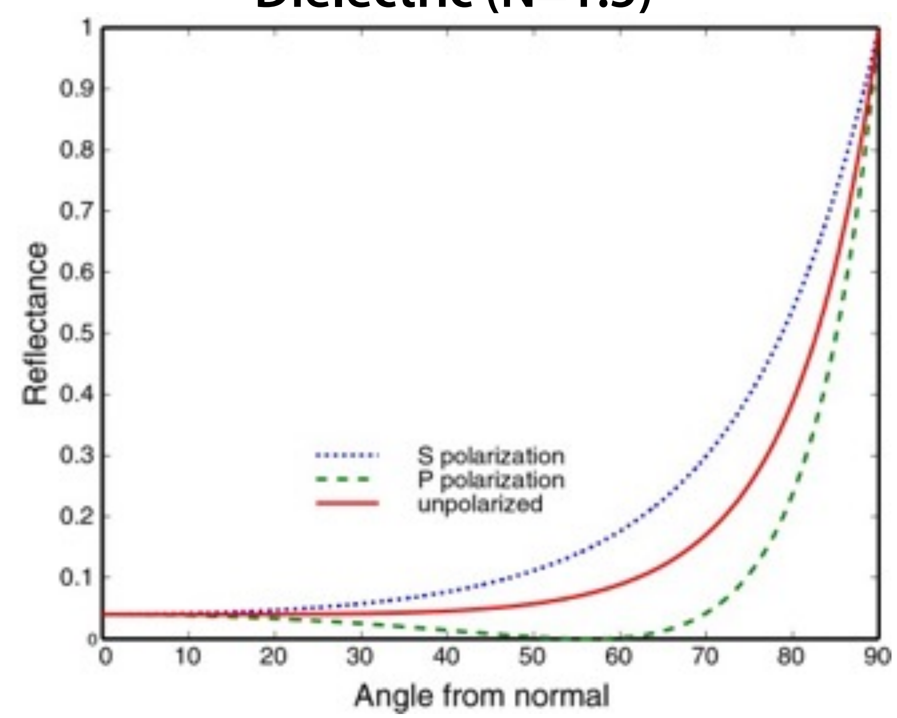
$$\vec{\omega}_h = \frac{\vec{\omega}_i + \vec{\omega}_o}{\|\vec{\omega}_i + \vec{\omega}_o\|}$$

Fresnel Term

Metal (Aluminum)



Dielectric (N=1.5)



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

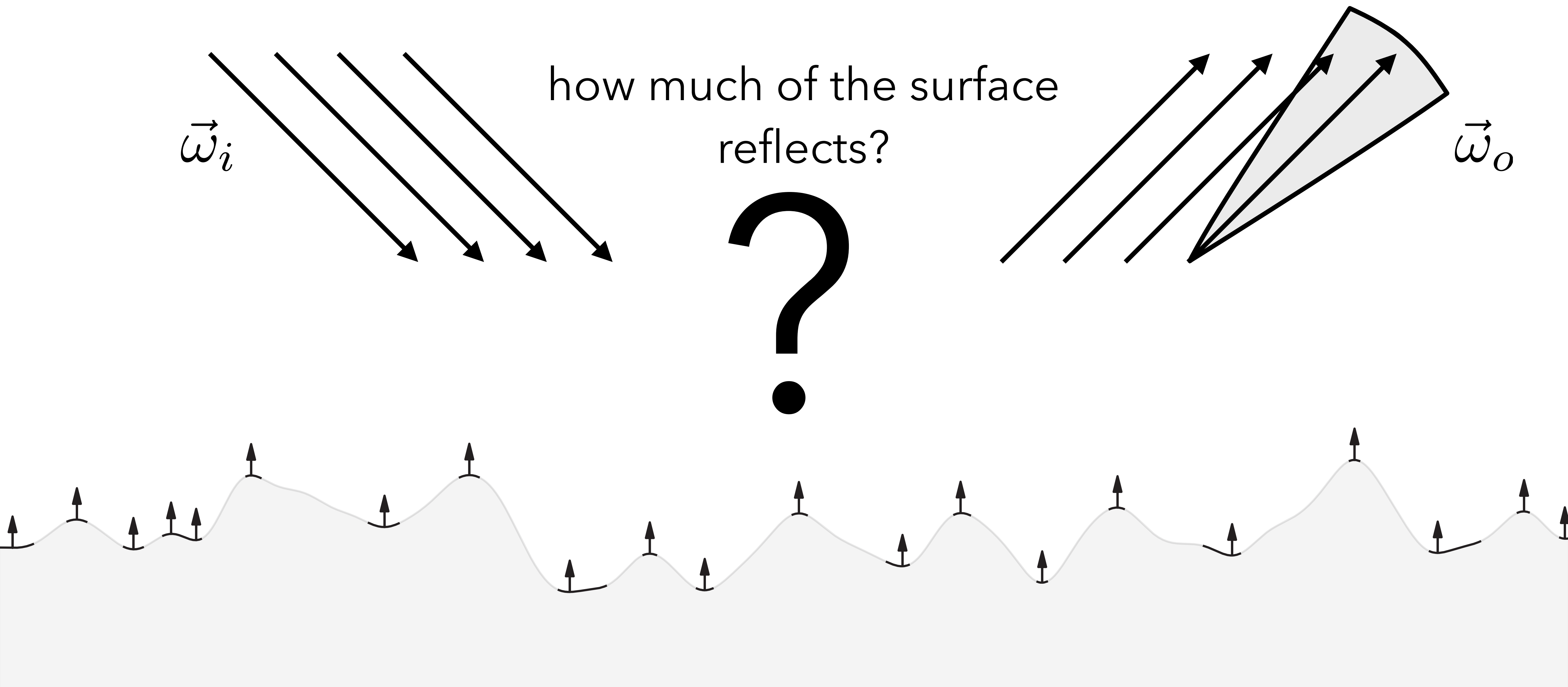
Glass	**n=1.5 F(0)=0.04**
Diamond	**n=2.4 F(0)=0.15**

General Microfacet Model

Microfacet
distribution

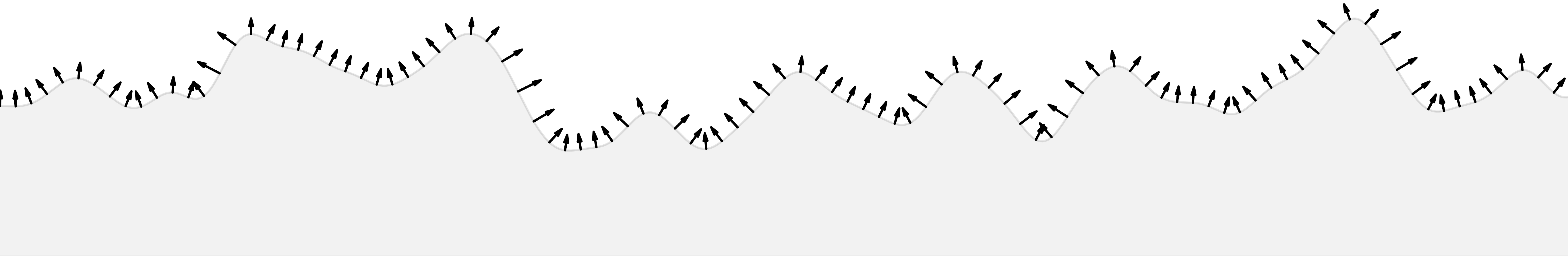
$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot \boxed{D(\vec{\omega}_h)} \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4\left|(\vec{\omega}_i \cdot \mathbf{\vec{n}})(\vec{\omega}_o \cdot \mathbf{\vec{n}})\right|}$$

Microfacet Distribution



Microfacet Distribution

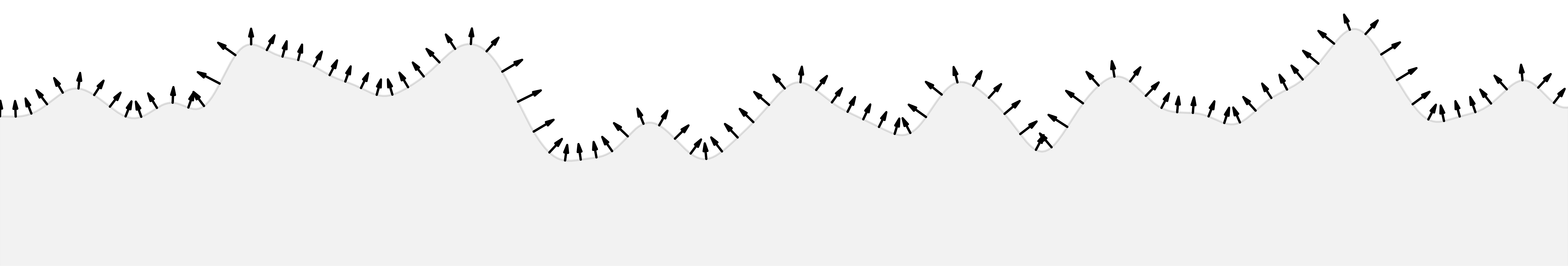
- What fraction of the surface participates in the reflection?
  - Answer 1: difficult to say (need an actual microsurface to compute this, tedious…)
  - Answer 2: solve using principles of statistical physics



Microfacet Distribution

- Fraction of microfacets facing each direction
- Probability density function over *projected* solid angle (must be normalized):

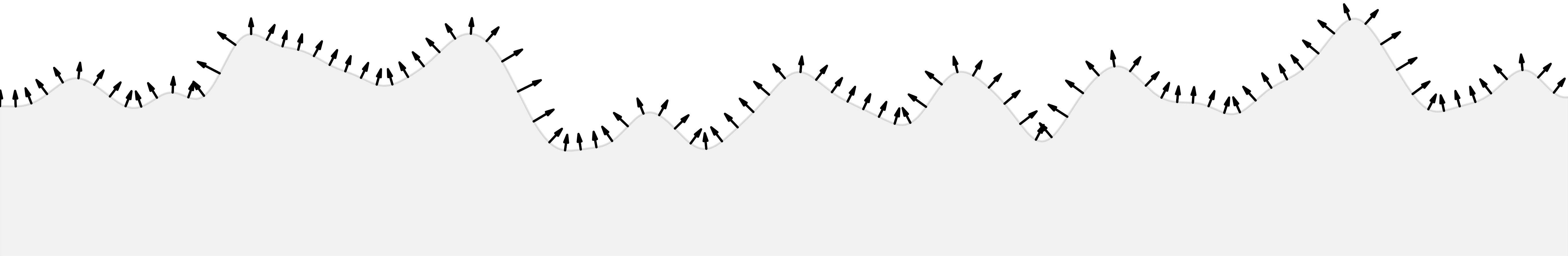
$$\int_{H^2} D(\vec{\omega}_h) \cos\theta_h \,\mathrm{d}\vec{\omega}_h = 1$$



The Beckmann Distribution

- The slopes follow a Gaussian distribution
- Let's express slope distribution wrt. directions
  - Slope of θ_h is $\tan\theta_h$

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



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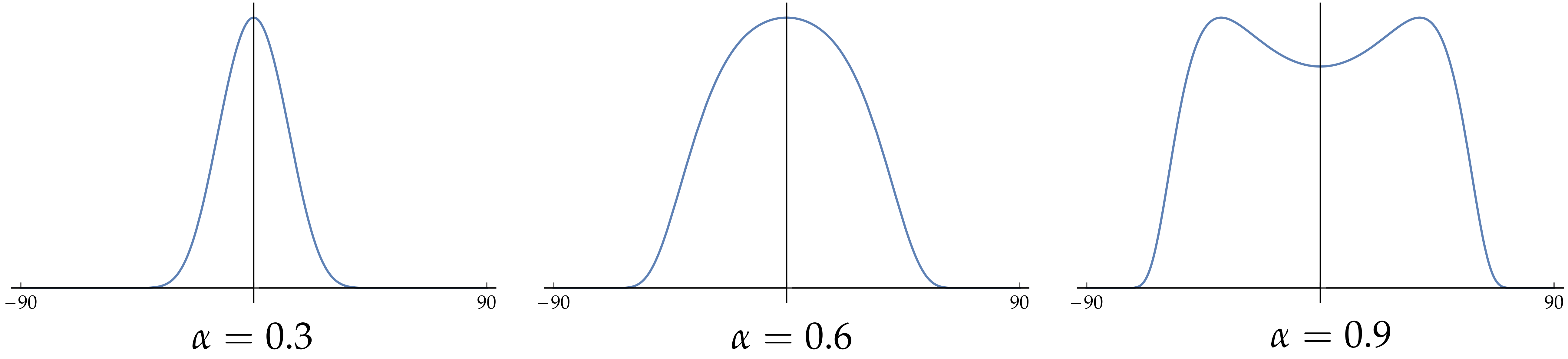
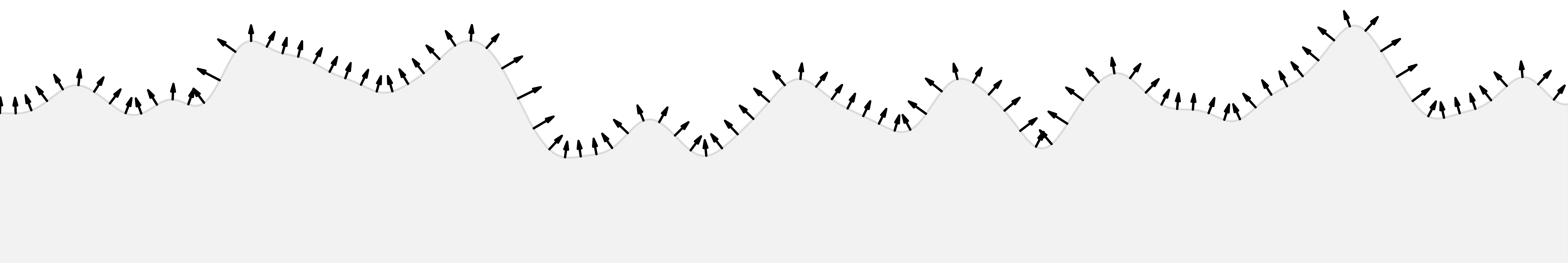


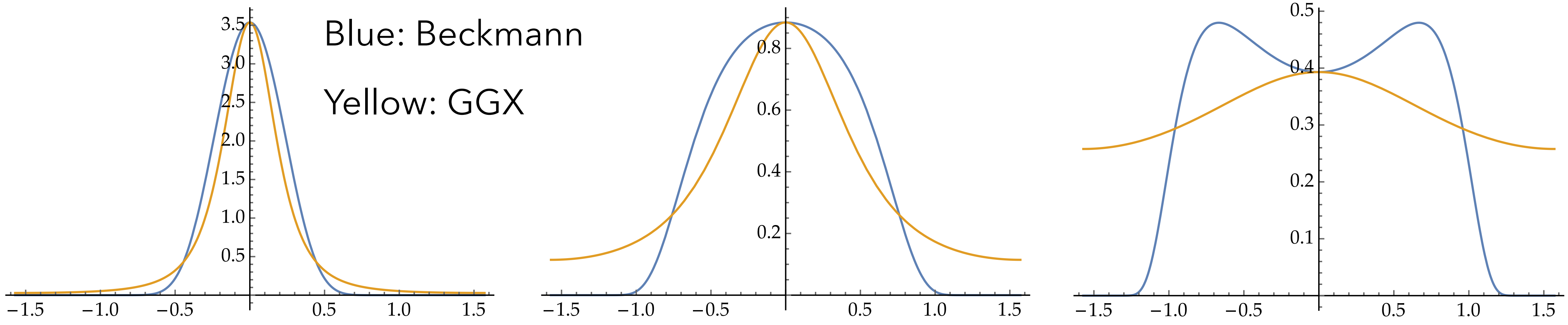


Other Distributions

- 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 [PBRT2, Ch. 8]



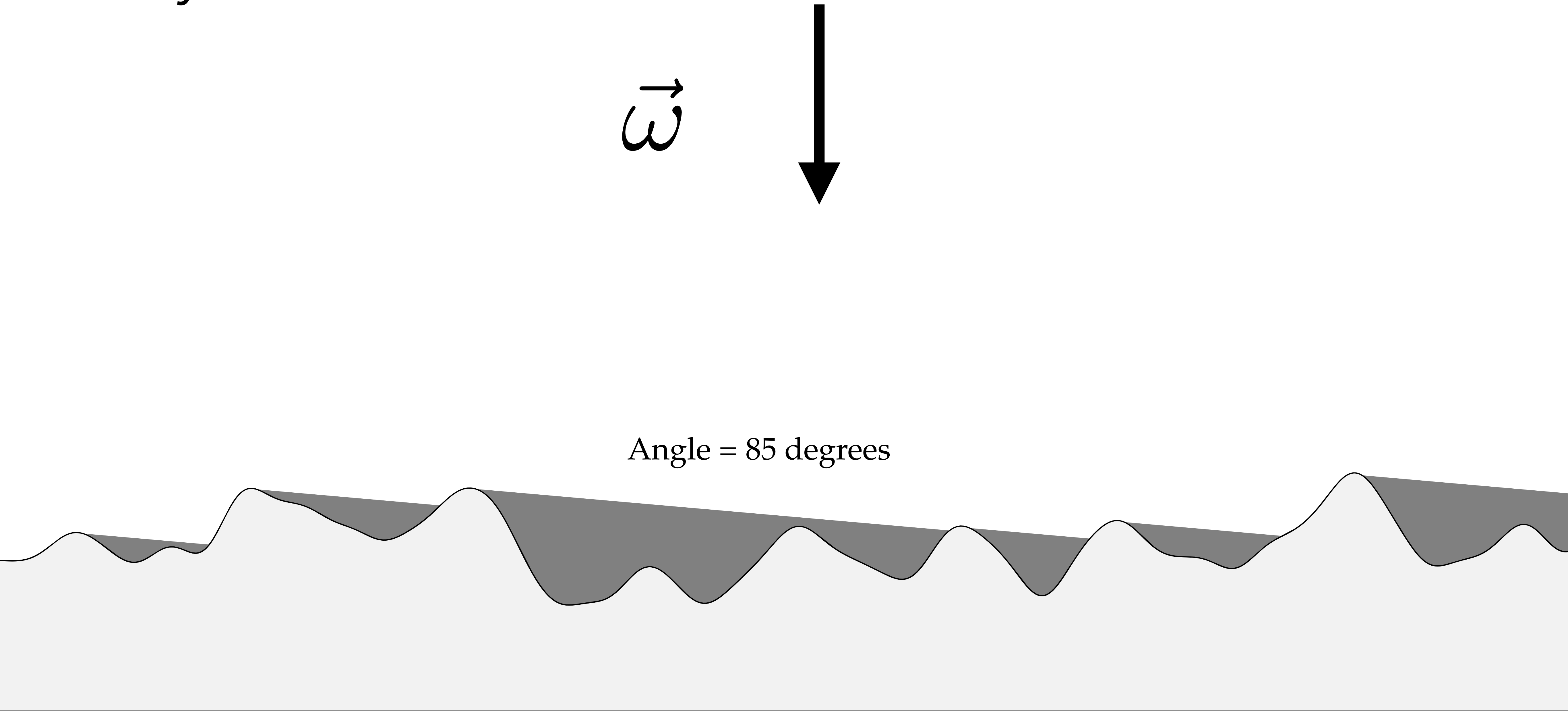
General Microfacet Model

Shadowing/
masking

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

Shadowing and Masking

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

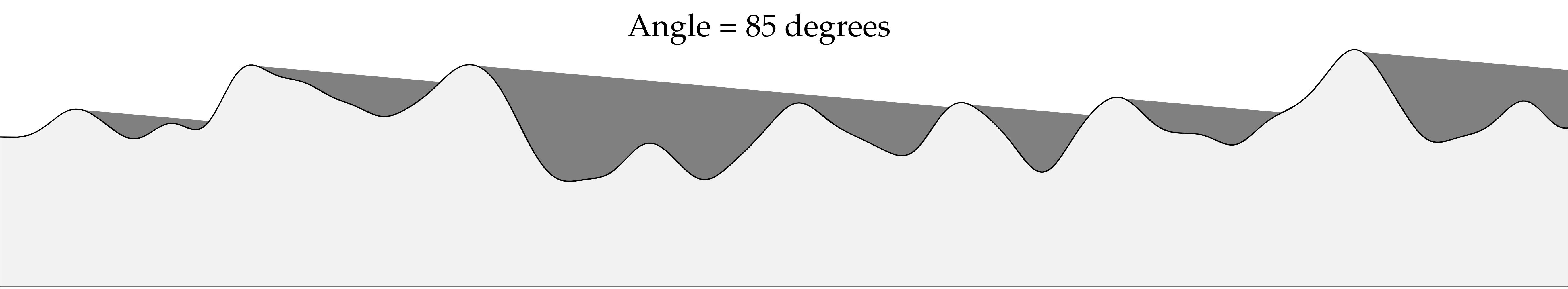


Shadowing and Masking

- Each microfacet distribution typically has its respective shadowing and masking term
- Beckman distribution:

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

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

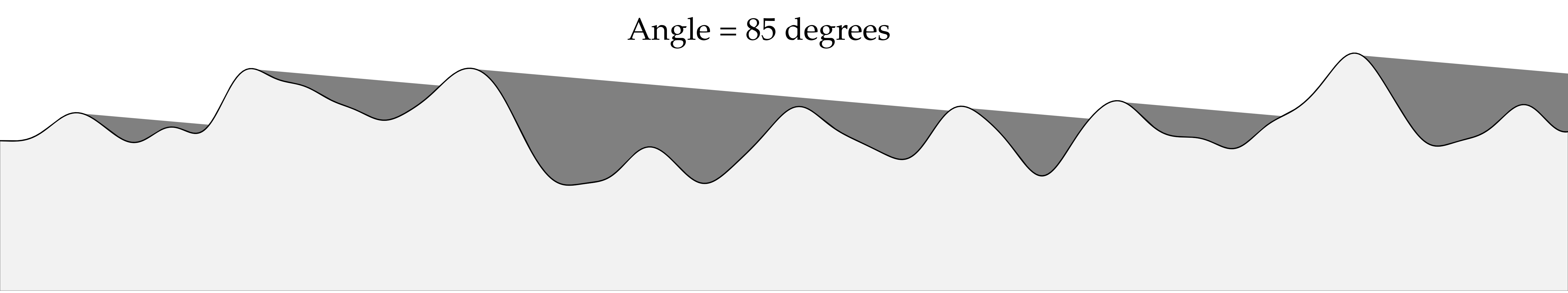


Shadowing and Masking

- Each microfacet distribution typically has its respective shadowing and masking term
- Beckman distribution (approximated):

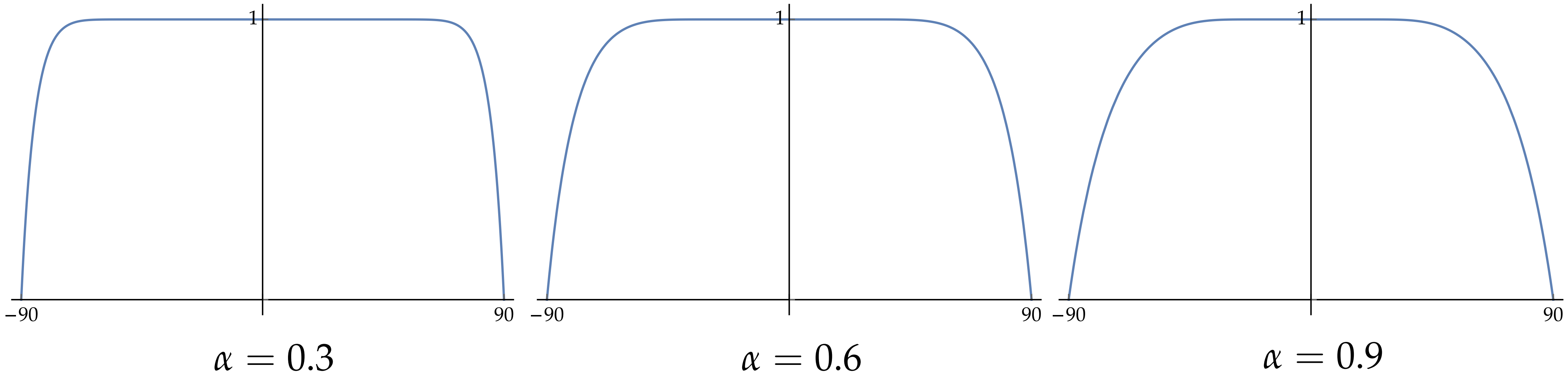
$$G(\vec{\omega}) \approx \begin{cases} \frac{3.535s+2.181s^2}{1+2.276s+2.577s^2}, & s < 1.6 \\ 1, & \text{otherwise} \end{cases}$$

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

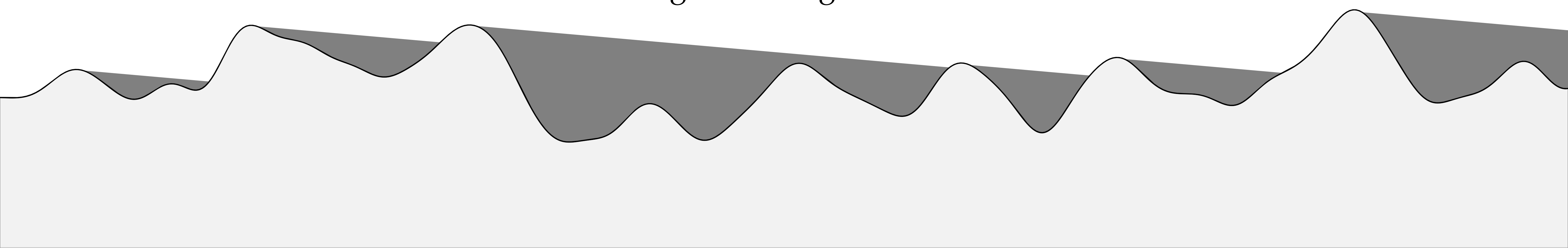


Shadowing and Masking

- Each microfacet distribution typically has its respective shadowing and masking term
- Beckman distribution (approximated):



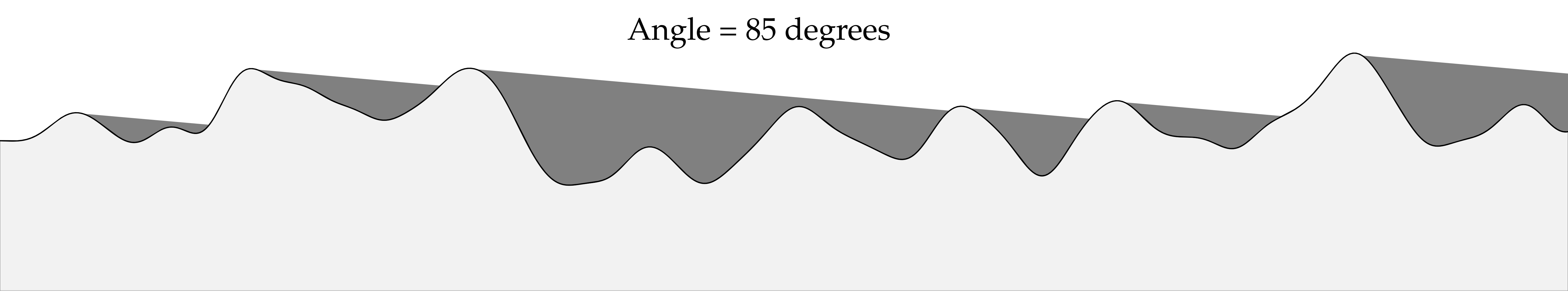
Angle = 85 degrees



Shadowing and Masking

- Each microfacet distribution typically has its respective shadowing and masking term
- Torrance-Sparrow (Blinn):

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

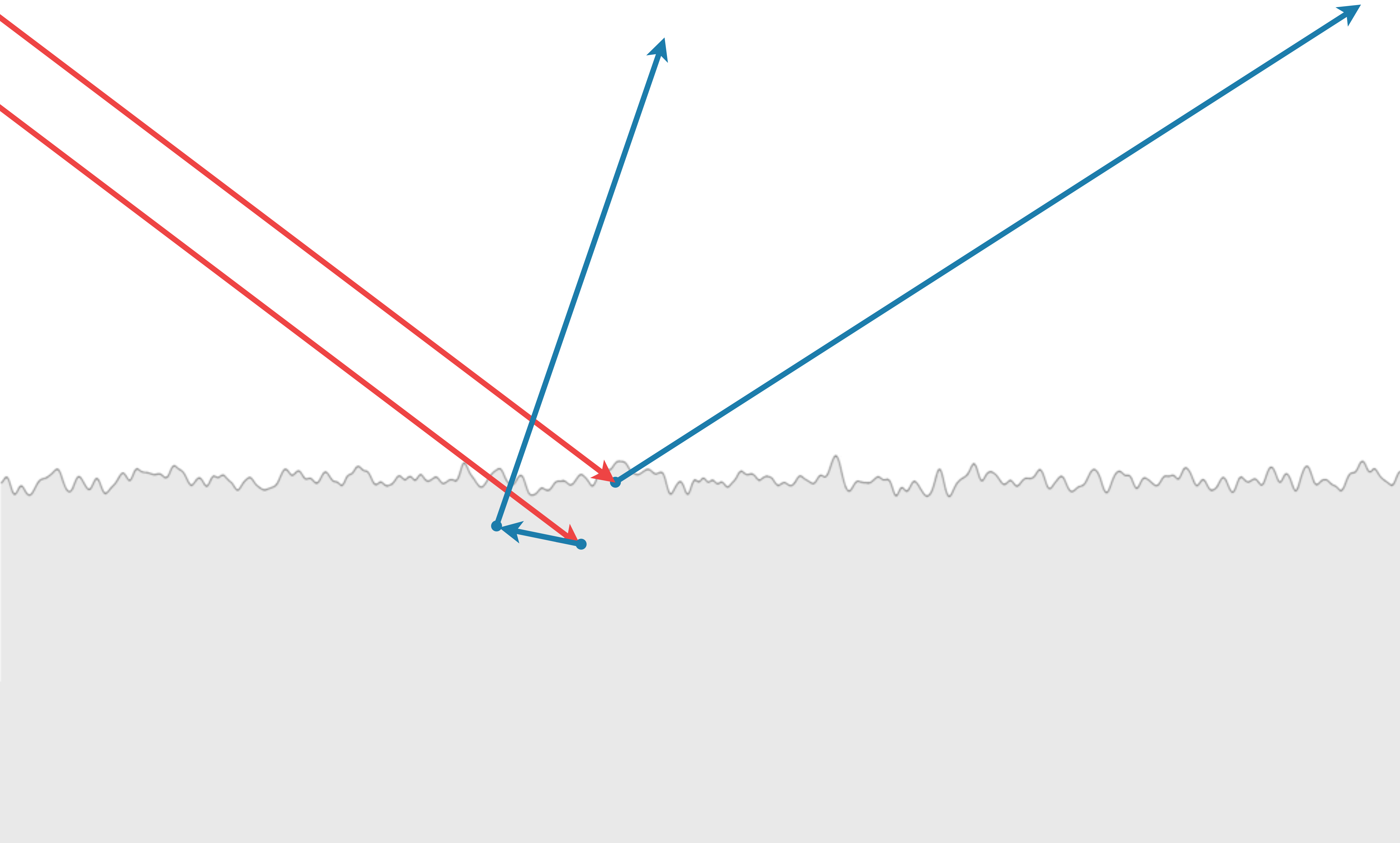


General Microfacet Model

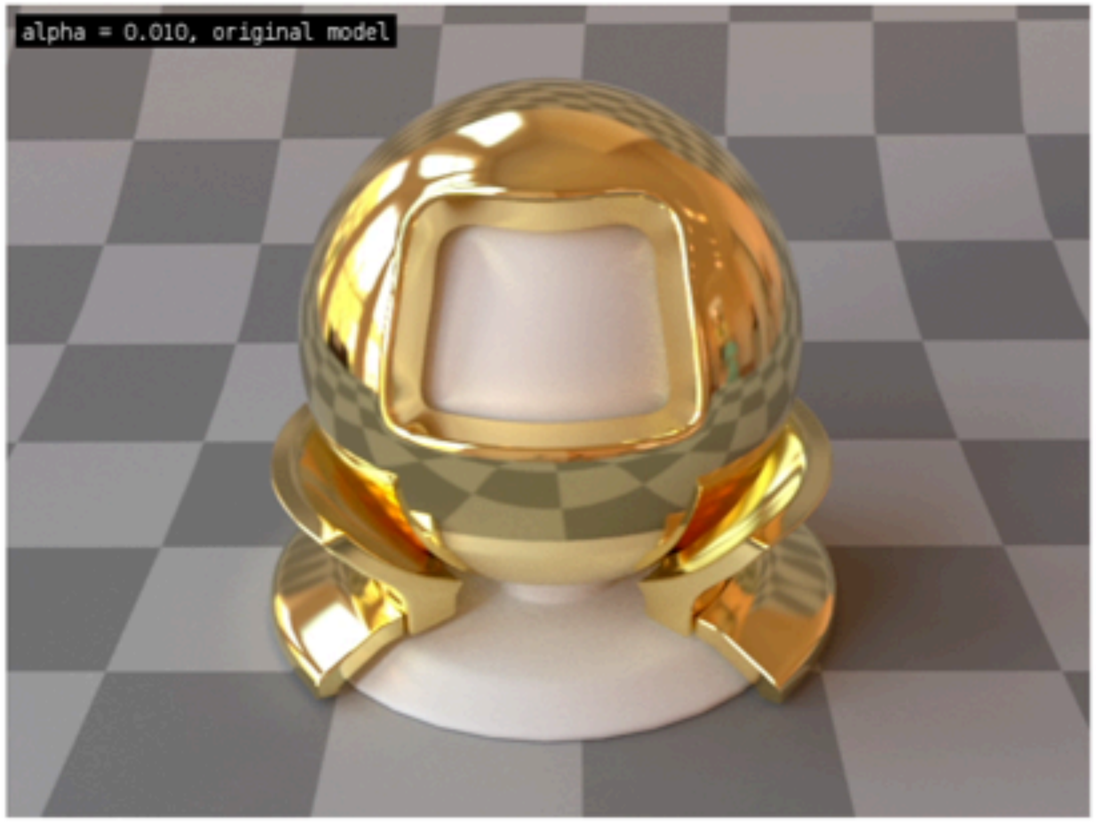
$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{F(\vec{\omega}_h, \vec{\omega}_o) \cdot D(\vec{\omega}_h) \cdot G(\vec{\omega}_i, \vec{\omega}_o)}{4|(\vec{\omega}_i \cdot \vec{\mathbf{n}})(\vec{\omega}_o \cdot \vec{\mathbf{n}})|}$$

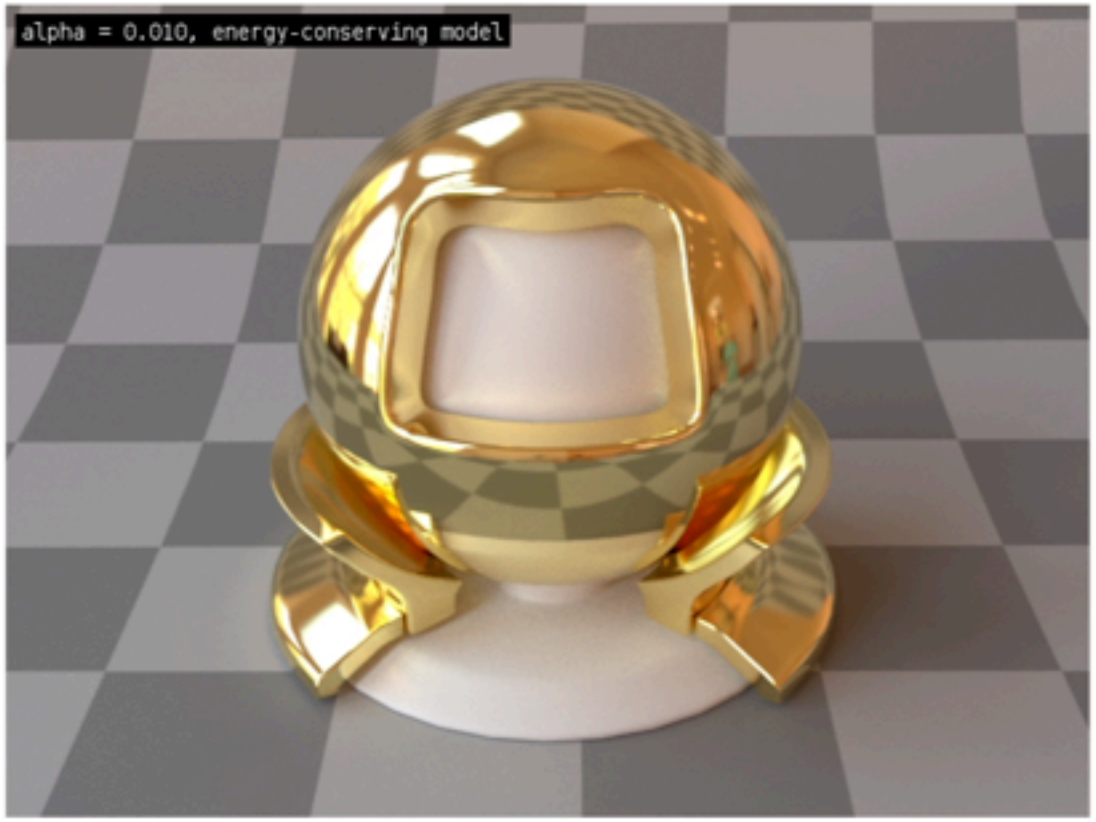
- Denominator: correction term coming from energy conservation, Jacobians, etc.
  - see [Walter et al., EGSR 2007] for more detail

Energy Loss Issue



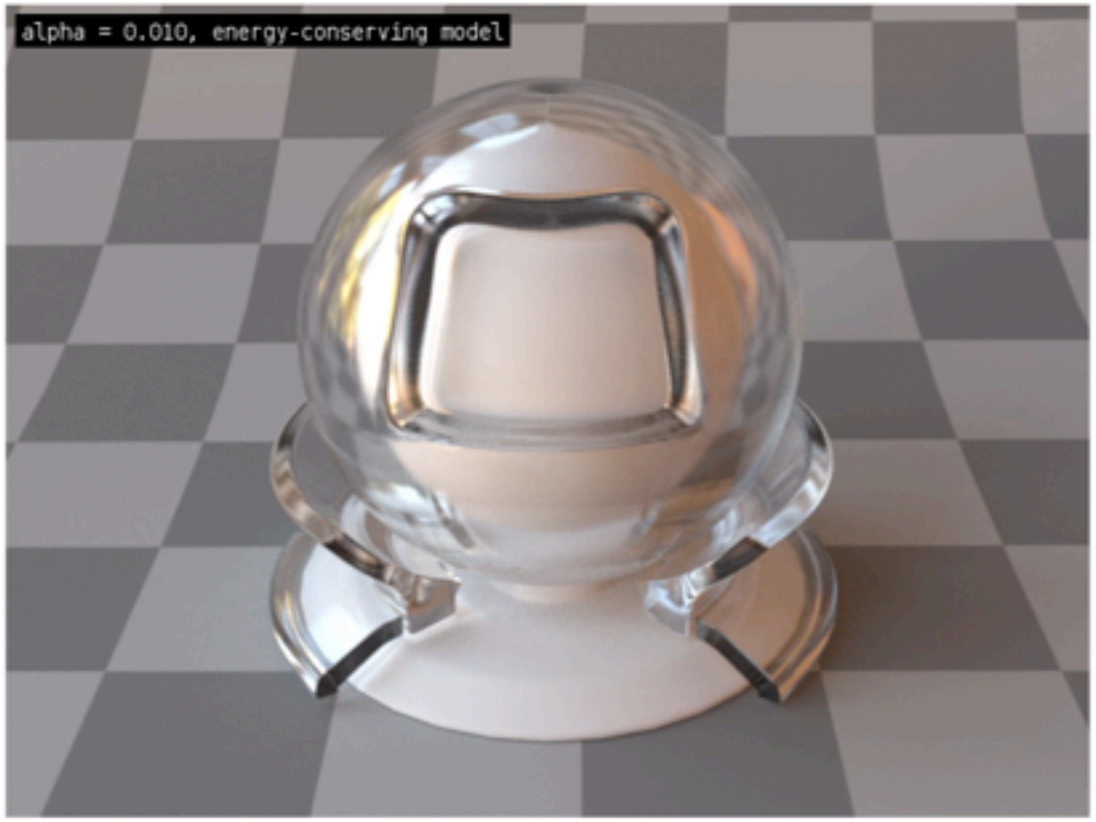
Energy Loss Issue - Conductor





Increasing roughness α = 0.01 .. 2.0

Energy Loss Issue - Dielectric



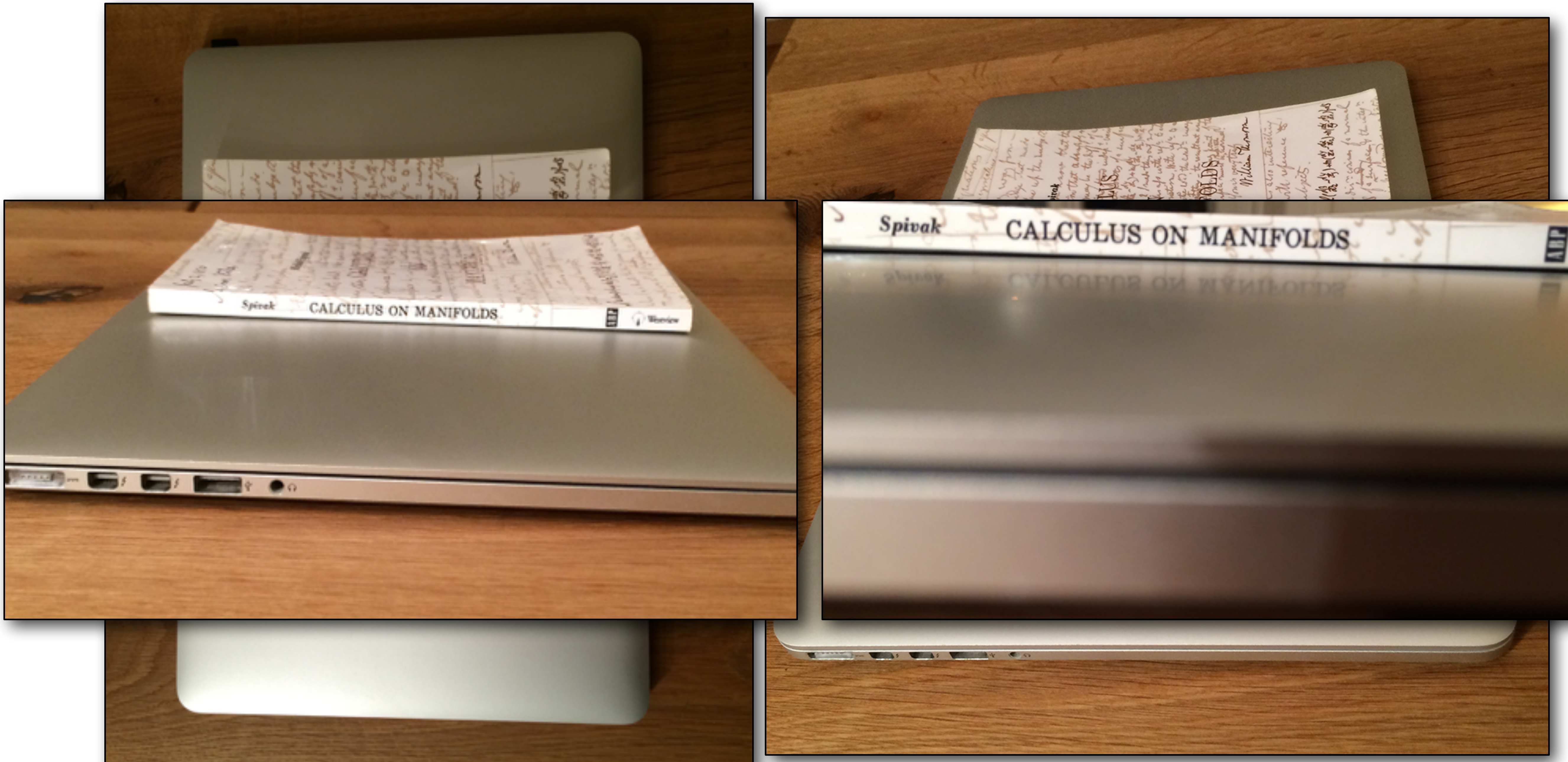
Increasing roughness α = 0.01 .. 2.0

GGX and Beckmann

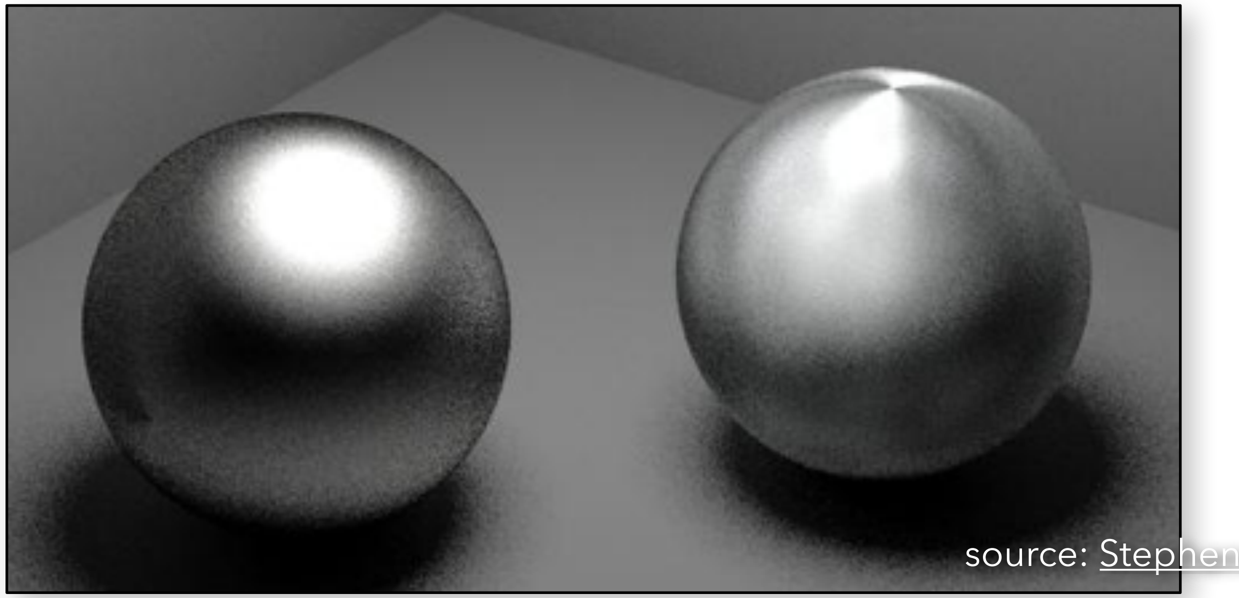
anti-glare (Beckman, $\alpha_b = 0.023$) ground (GGX, $\alpha_g = 0.394$) etched (GGX, $\alpha_g = 0.553$)

Walter et al. 07

Interesting grazing angle behavior

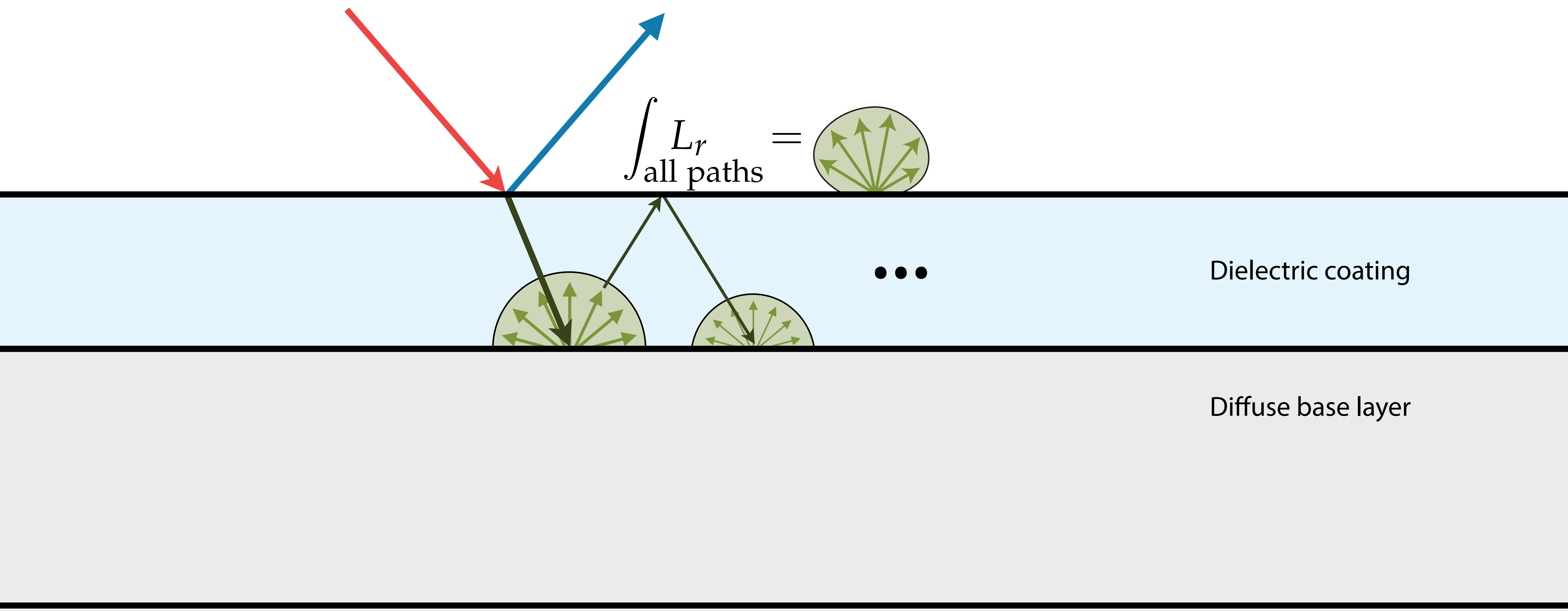


Extension: Anisotropic Reflection

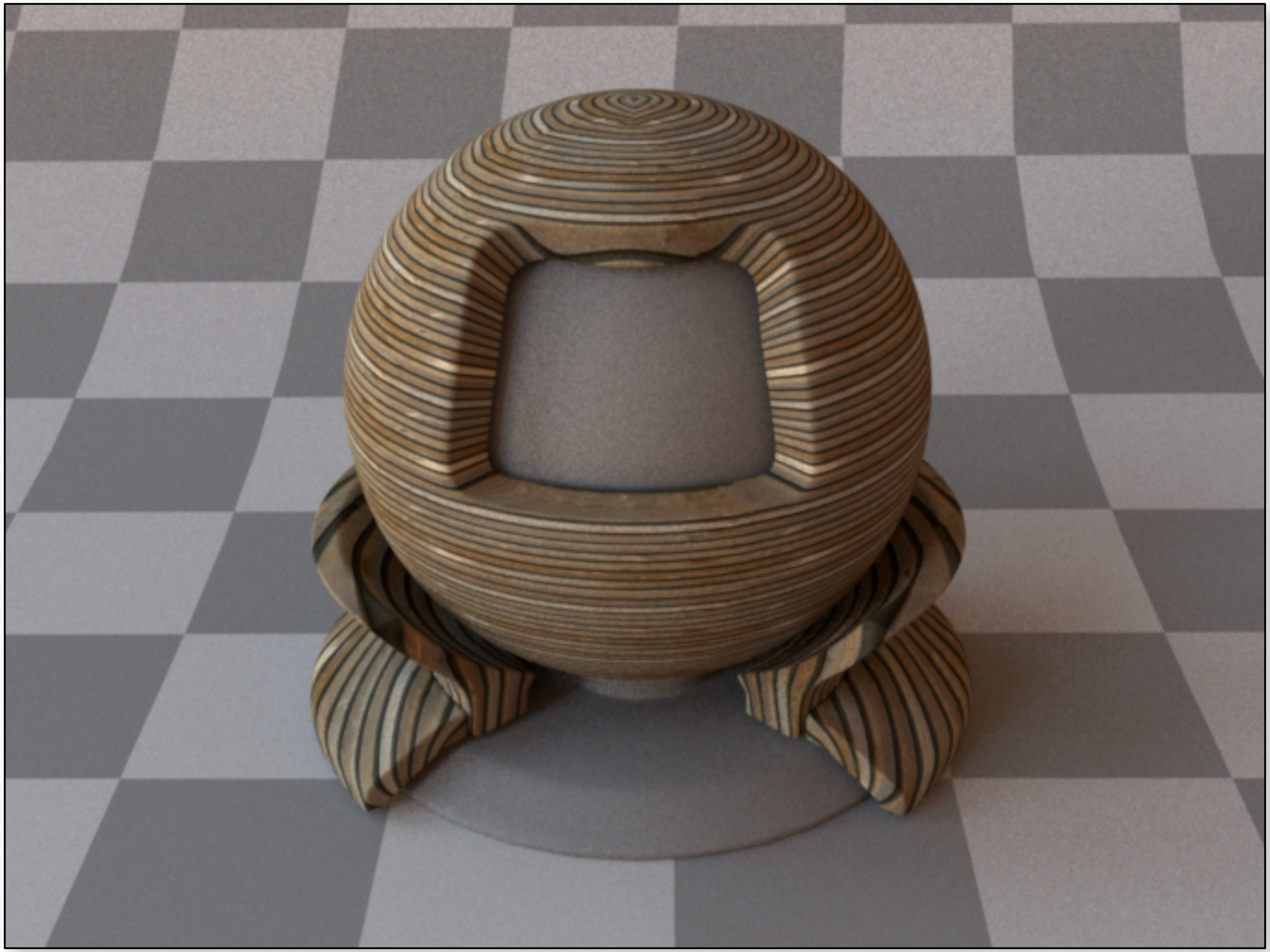


Extension: smooth/rough plastics

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

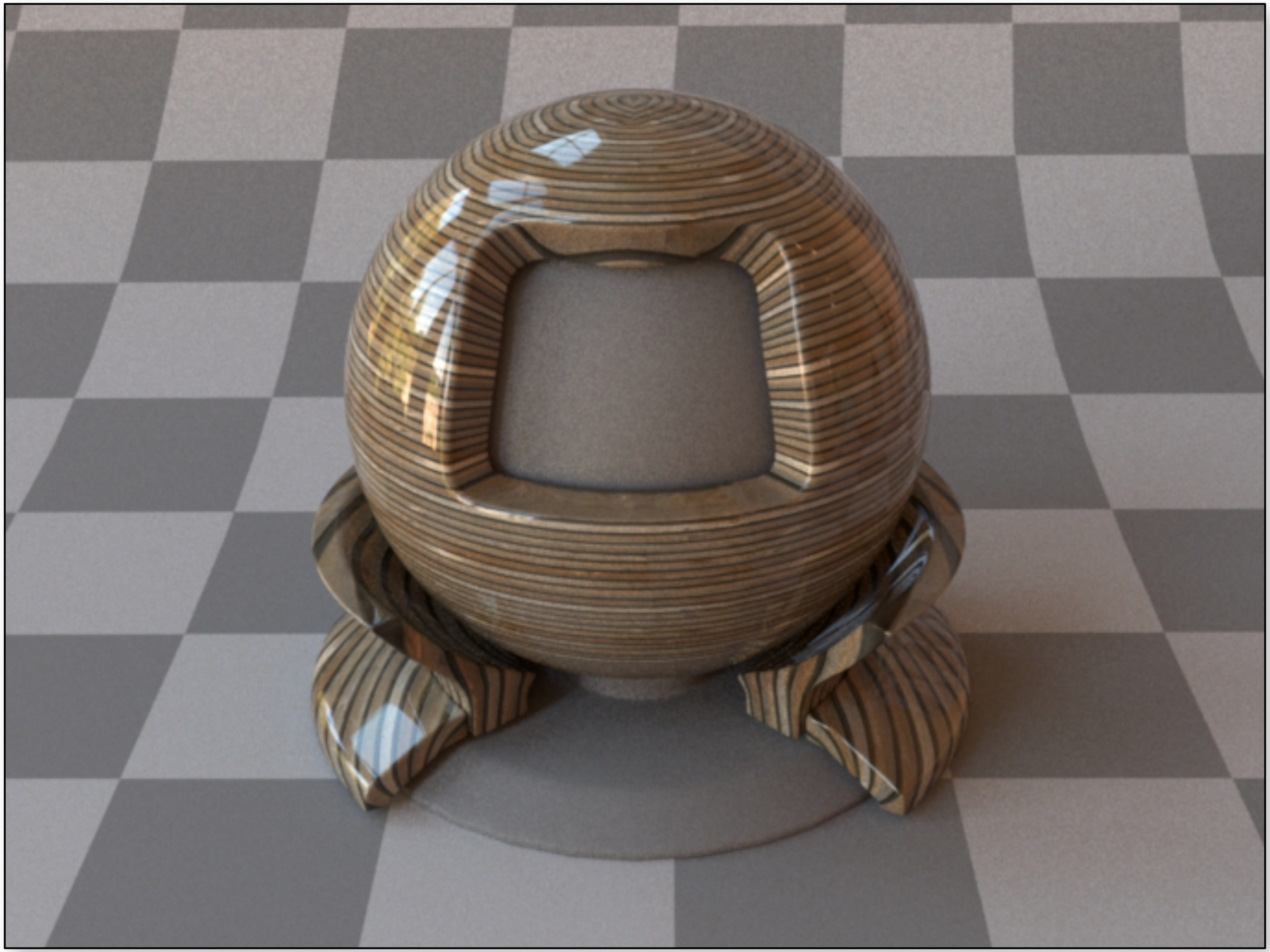


Smooth Diffuse



source: Wenz

Smooth Plastic

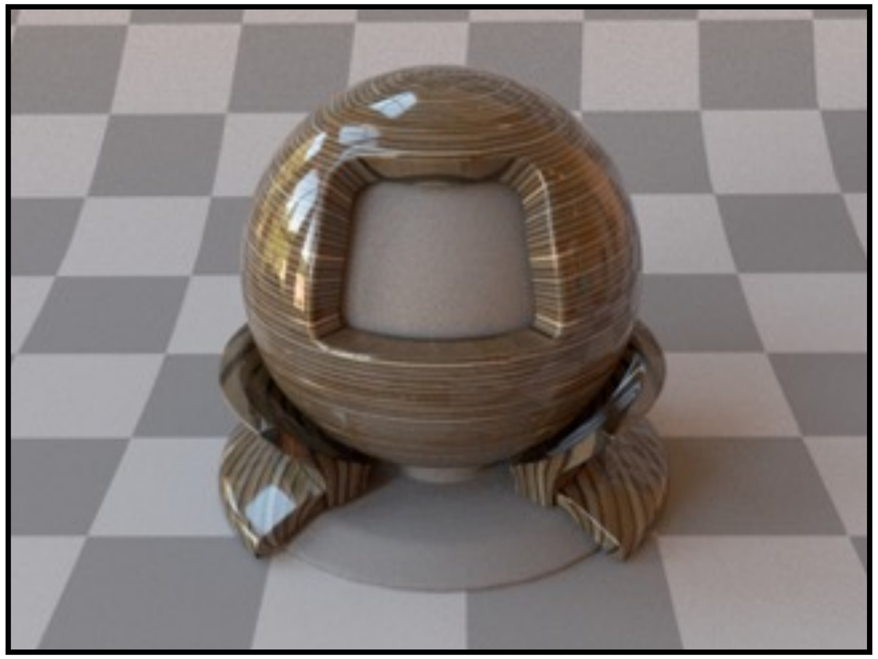


source: Wenz

Smooth Plastic

Plain diffuse material

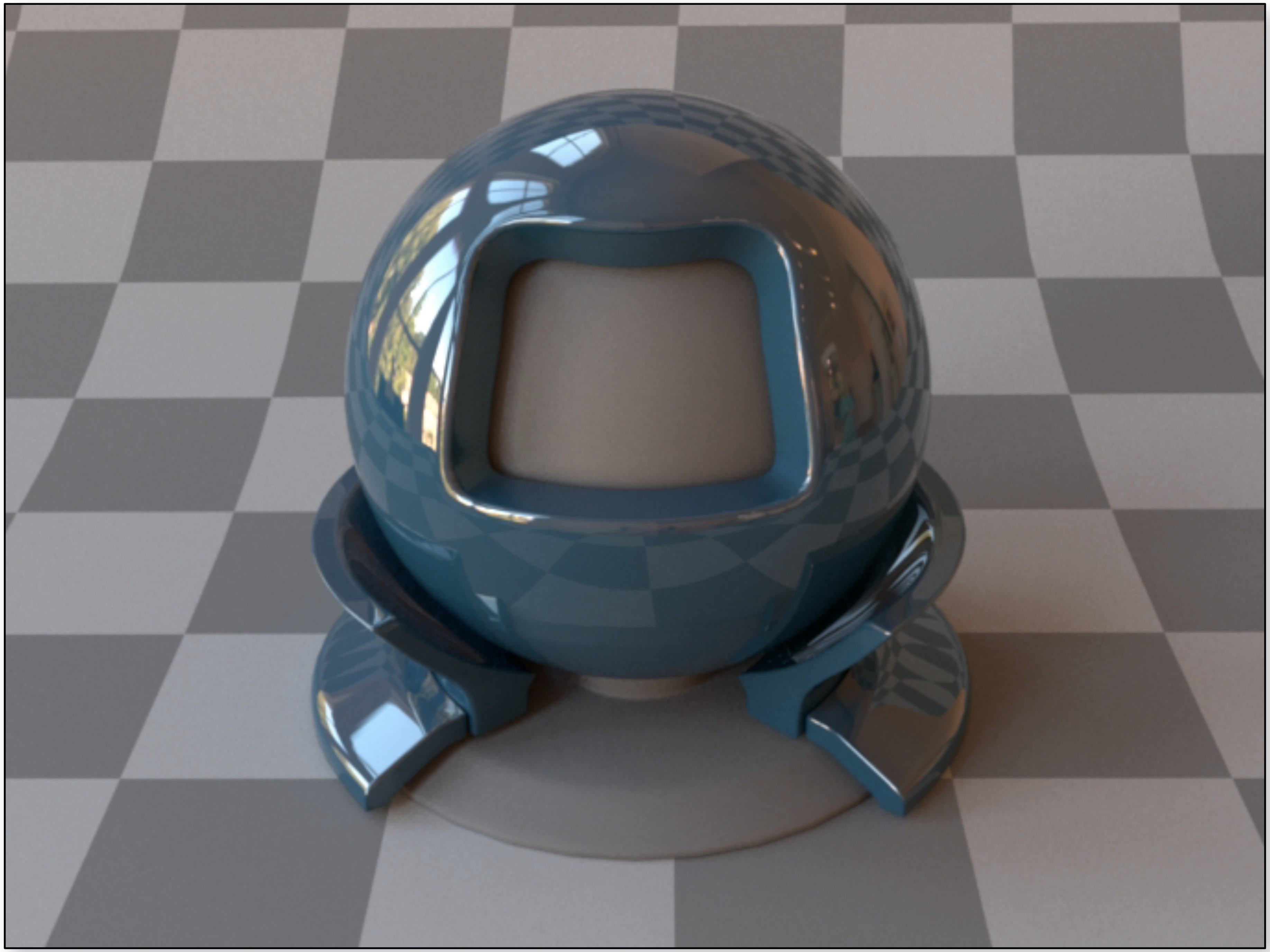
Naïve addition of diffuse + specular (*incorrect*)



Specular-matte (**correct**)

source: Wenze

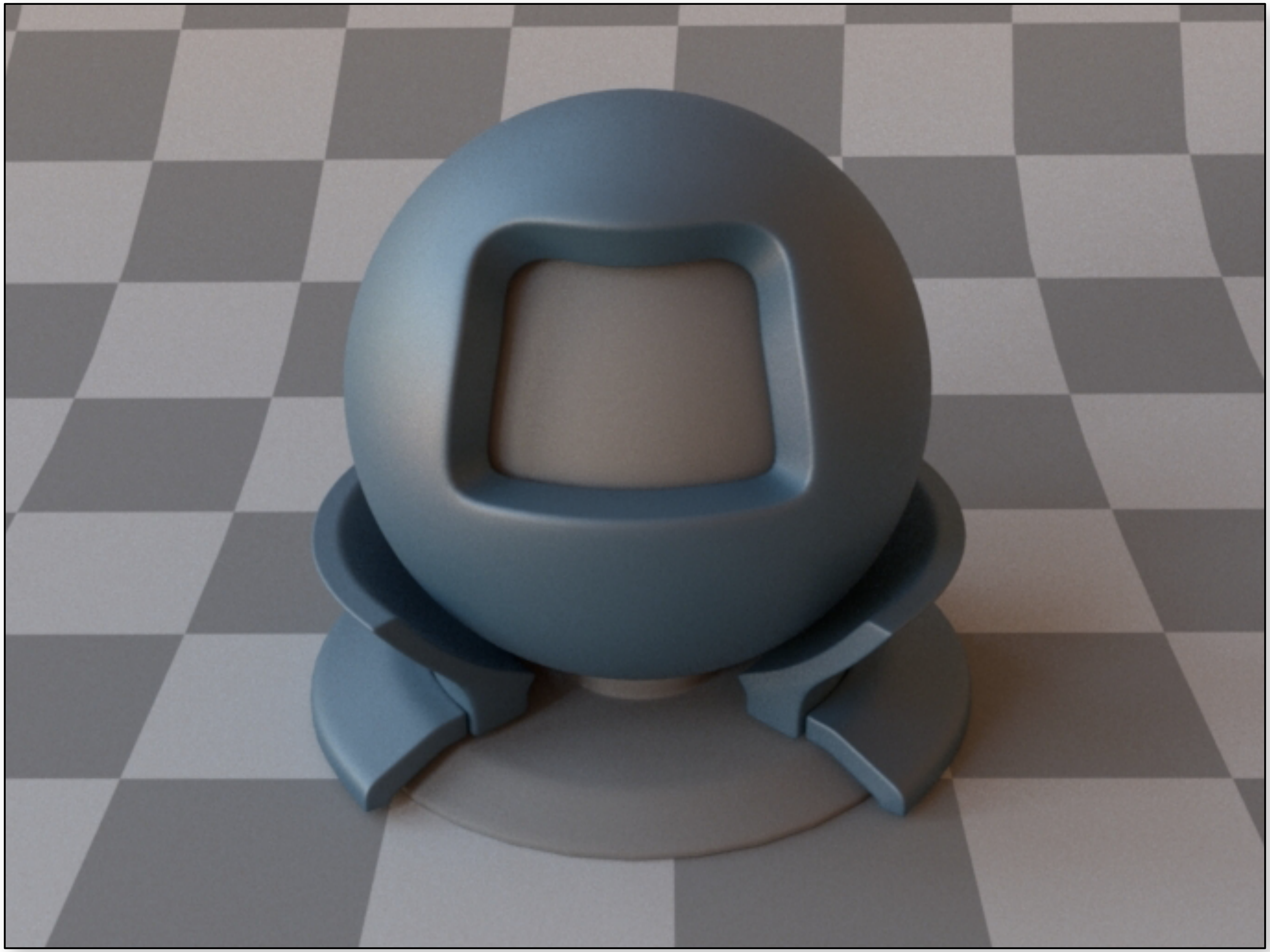
Smooth Plastic



Smooth dielectric varnish on top of diffuse surface

source: Wenz

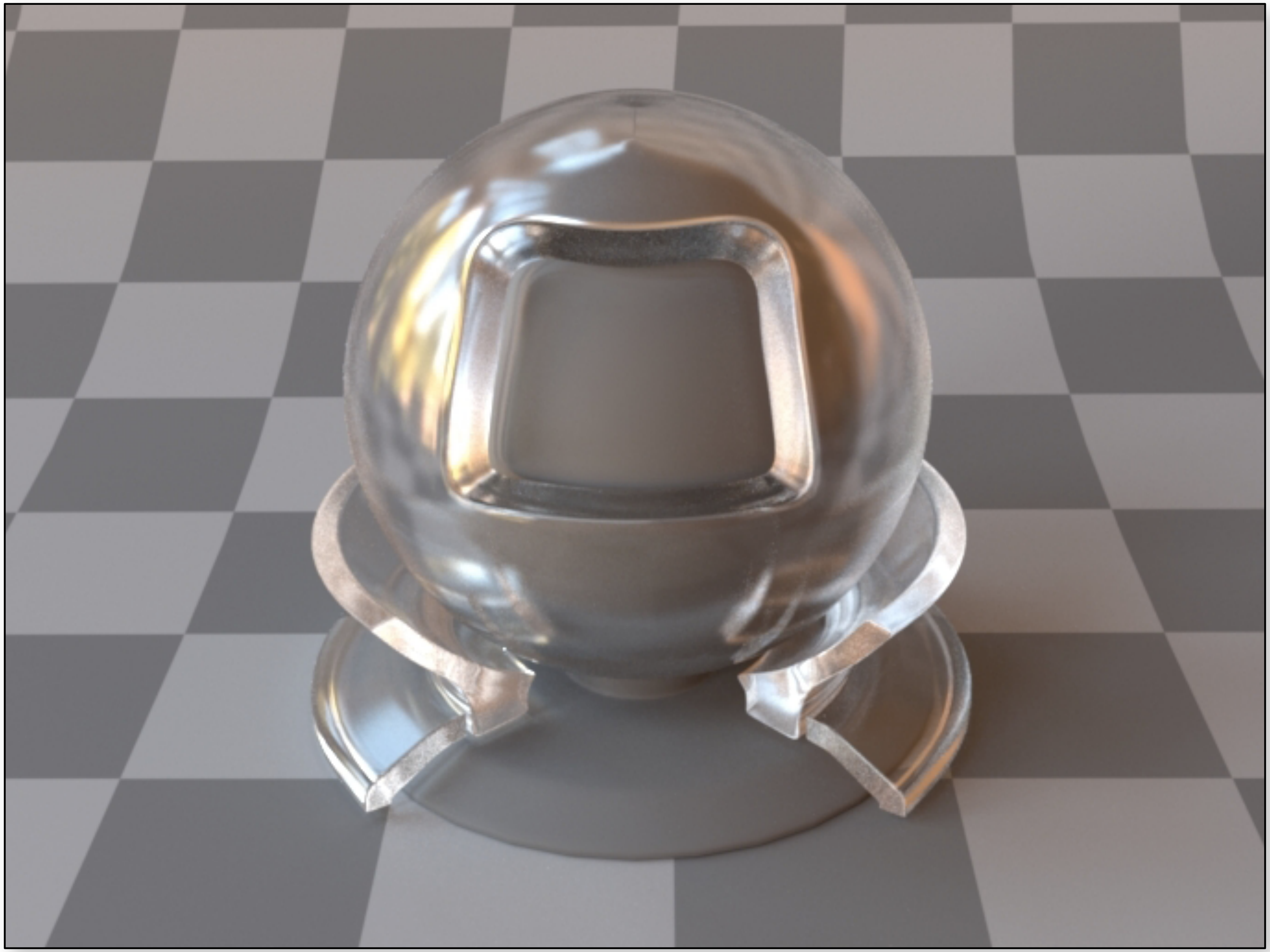
Rough Plastic



Rough dielectric varnish on top of diffuse surface

source: Wenz

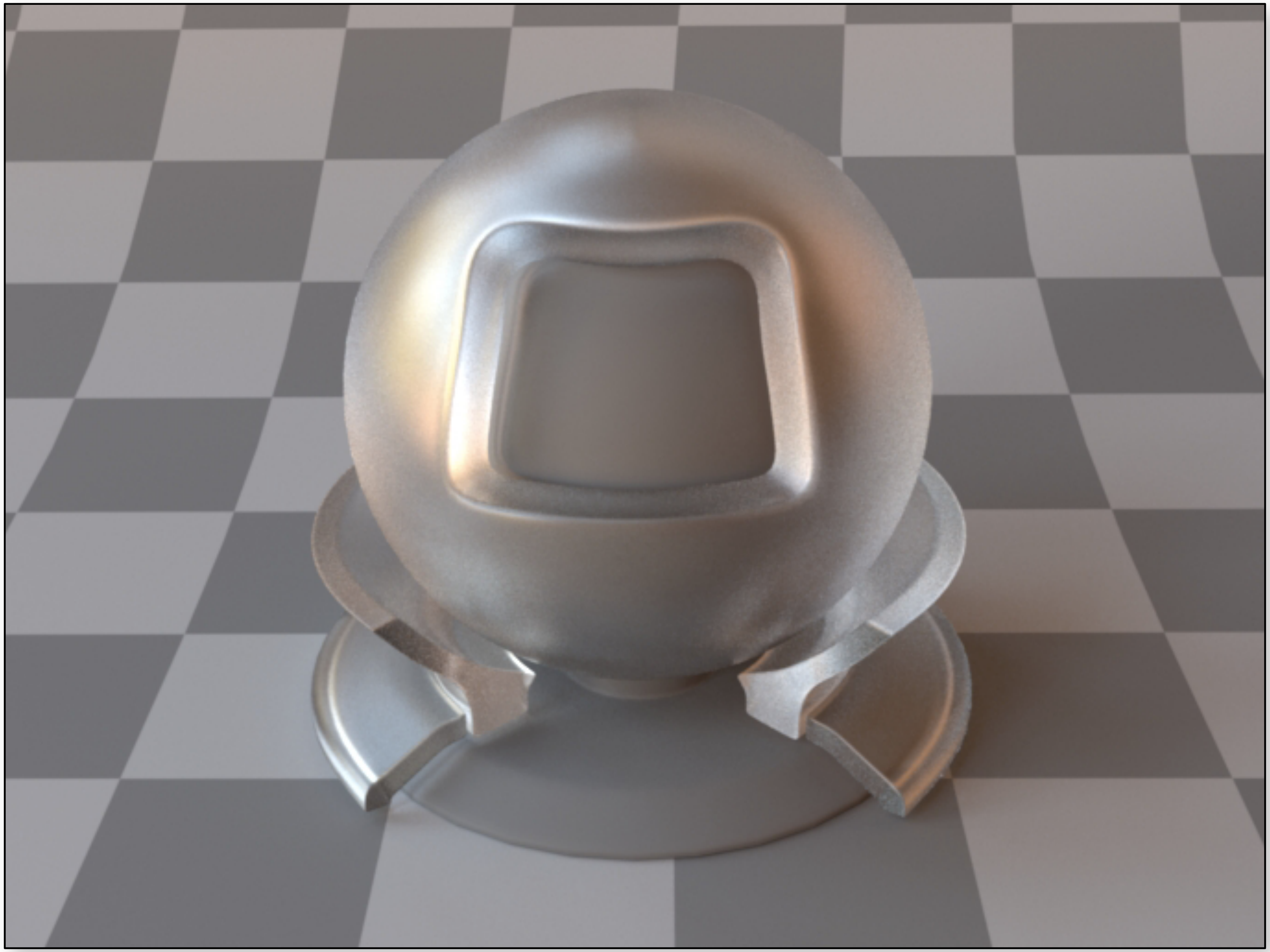
Rough Dielectric



Anti-glare glass ($m = 0.02$)

source: Wenze

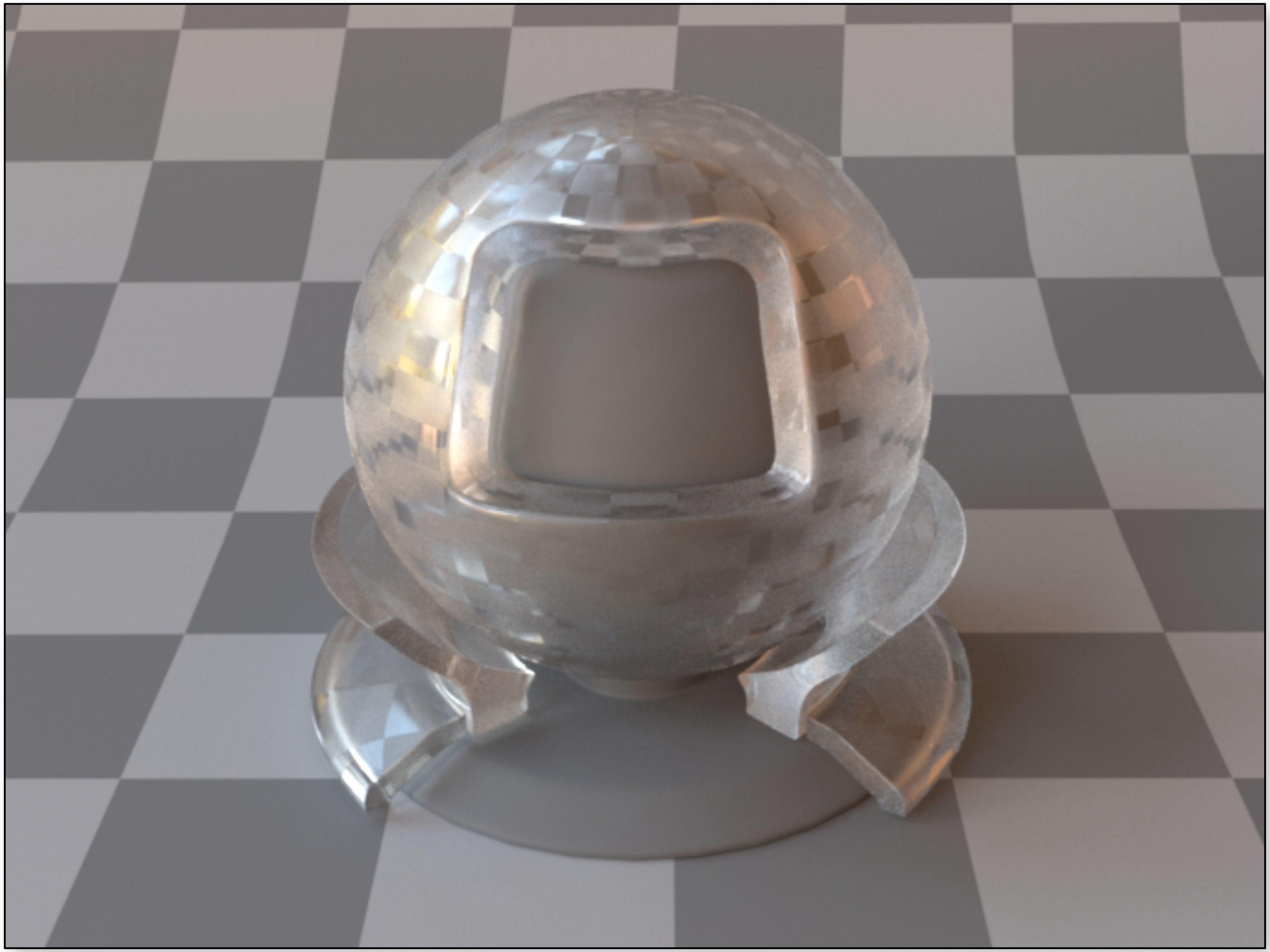
Rough Dielectric



Rough glass ($m = 0.1$)

source: Wenz

Rough Dielectric



Textured roughness

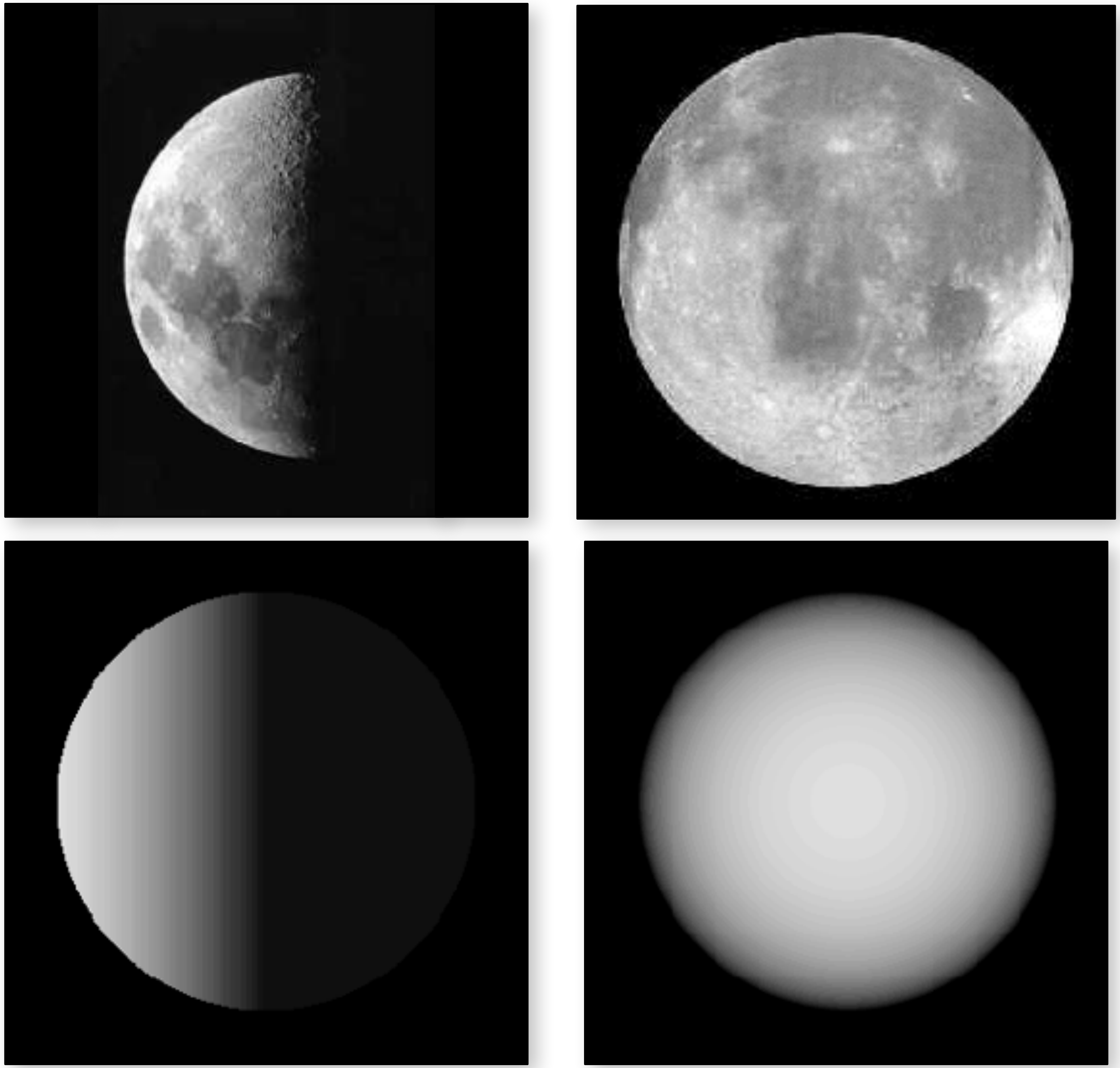
source: Wenz

Frosted Glass Dragon

source: Henrik W

Visual Break

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

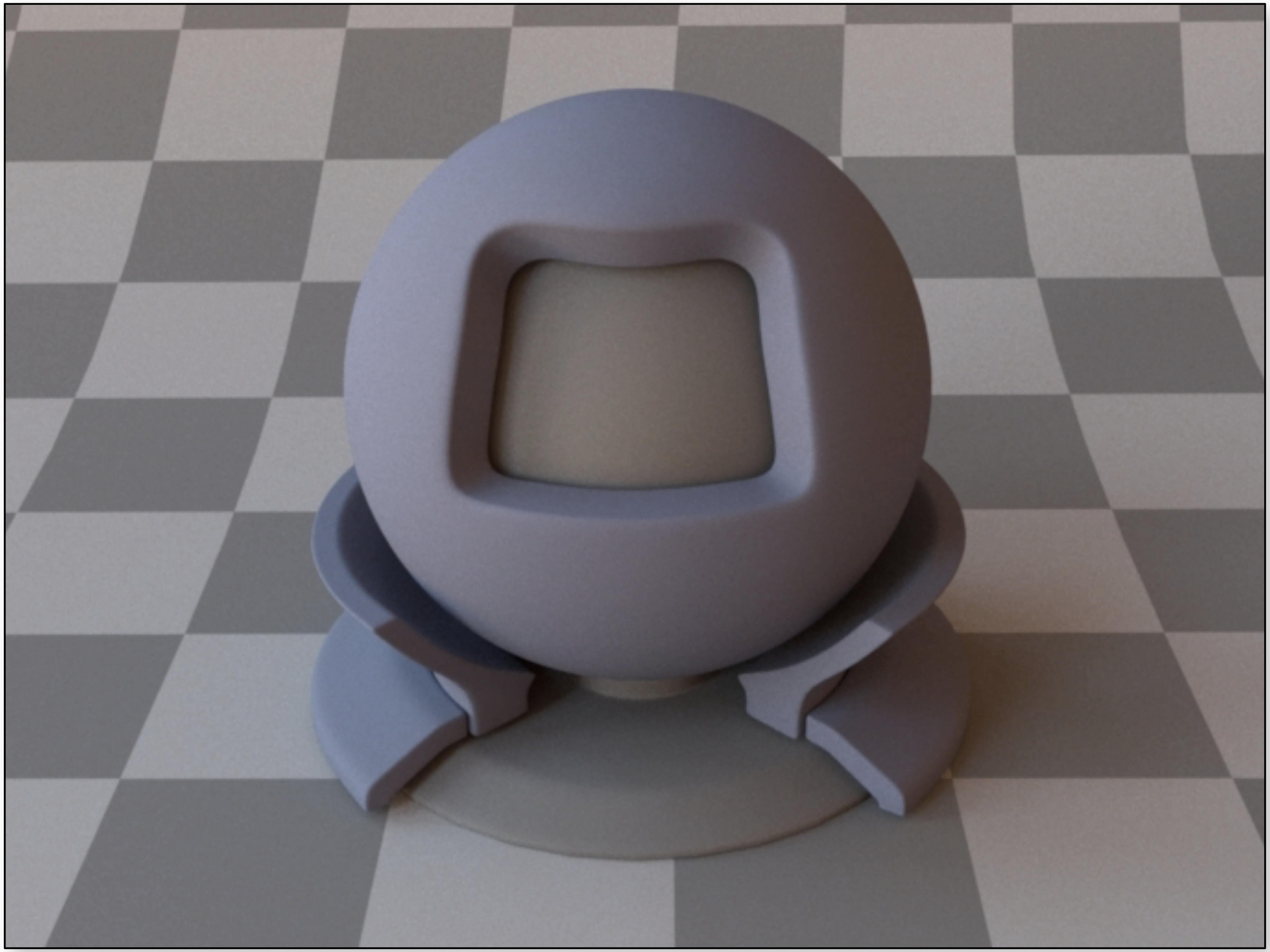
$$f_r(\vec{\omega}_o, \vec{\omega}_i) = \frac{\rho}{\pi}\left(A + B\ \max(0, \cos(\phi_i - \phi_o)) \sin\alpha \tan\beta\right)$$

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

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

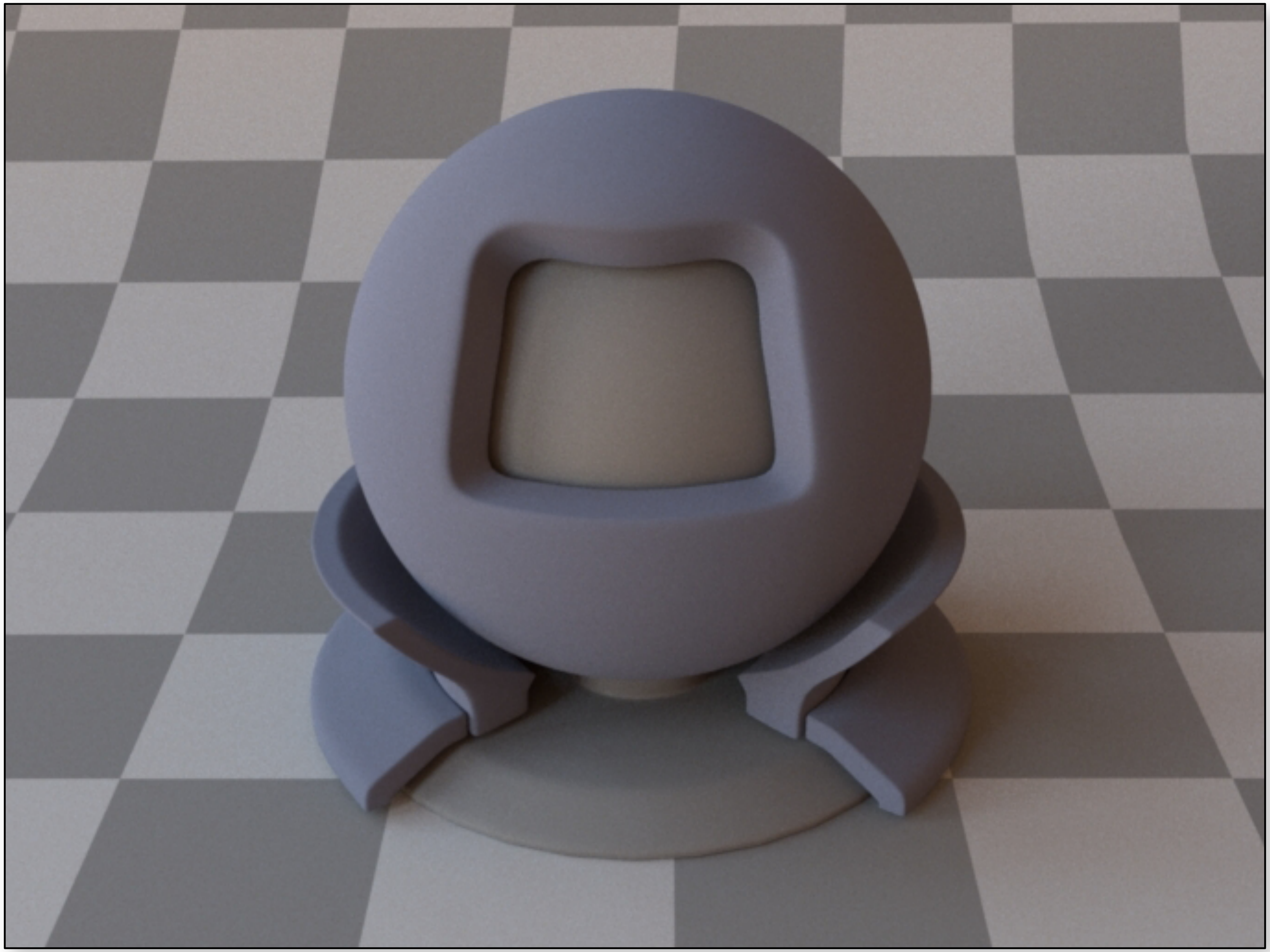
- Ideal Lambertian is just a special case (σ = 0)

Smooth Diffuse



source: Wenz

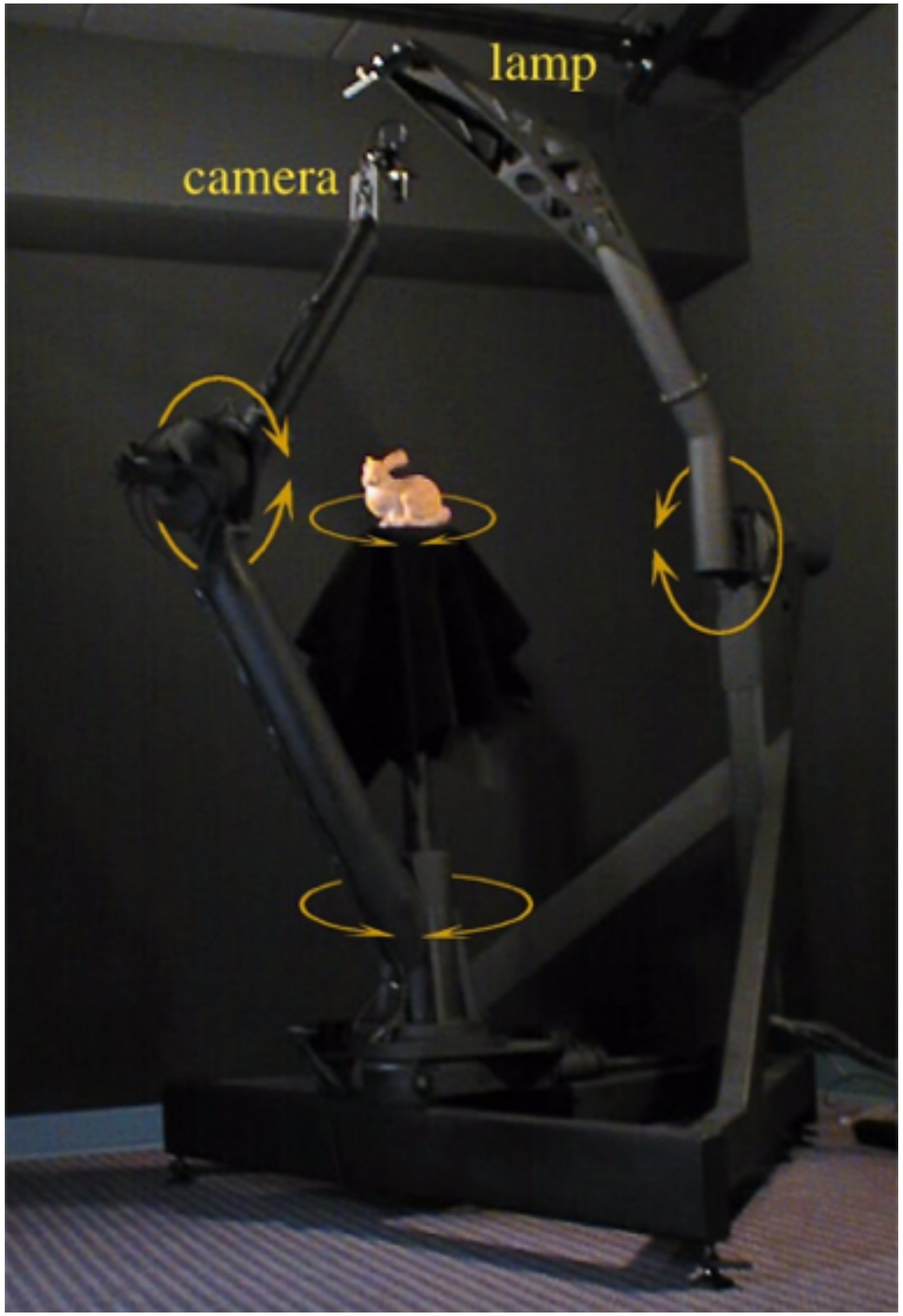
Rough Diffuse



source: Wenz

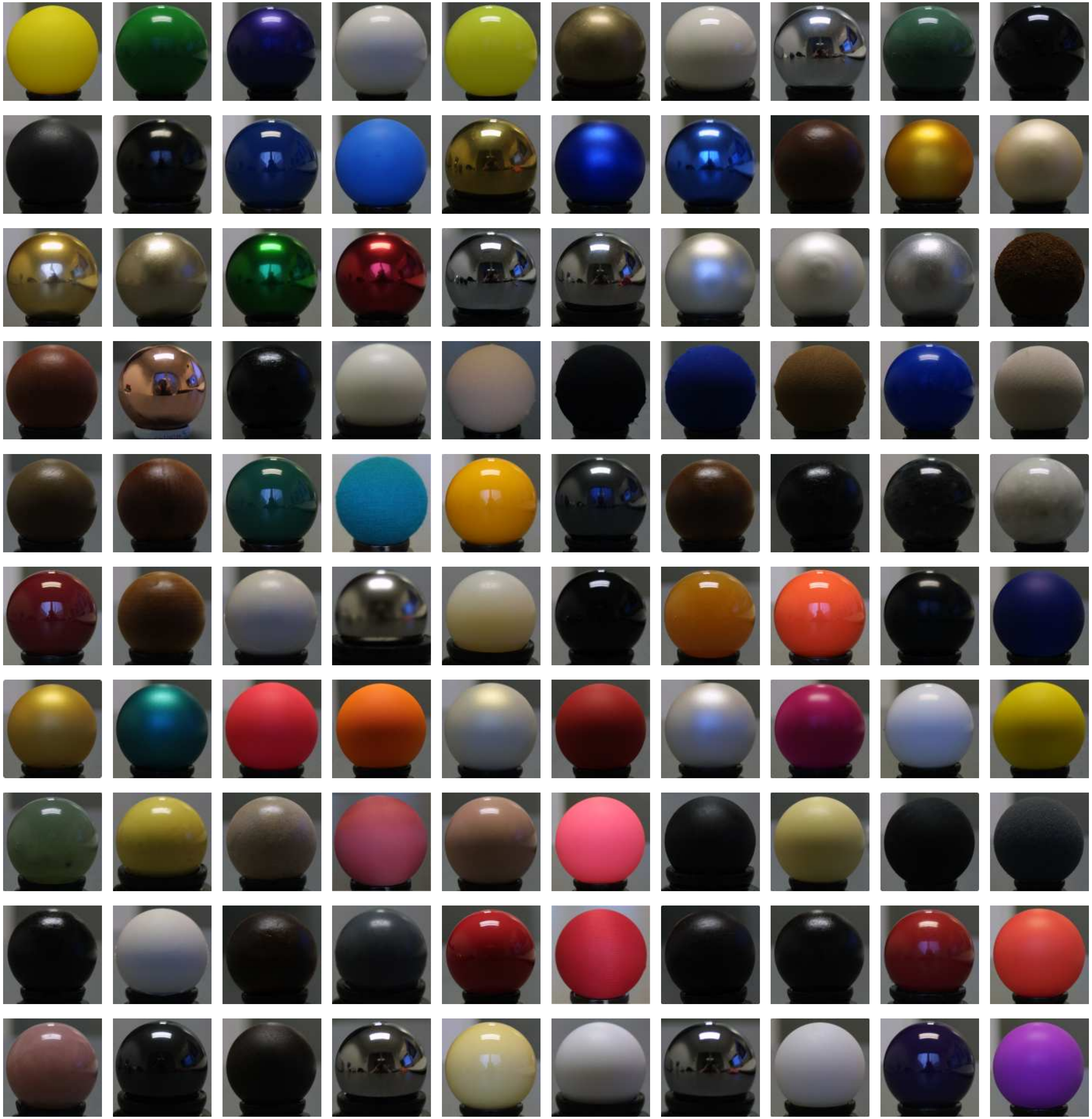
Data-Driven BRDFs

Spherical gantry



Measuring BRDFs

source: Matusik



Nickel

source: Matusik

Hematite

source: Matusik

Gold Paint

source: Matusik

Pink Fabric

source: Matusik

BRDF Editing/Navigation

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

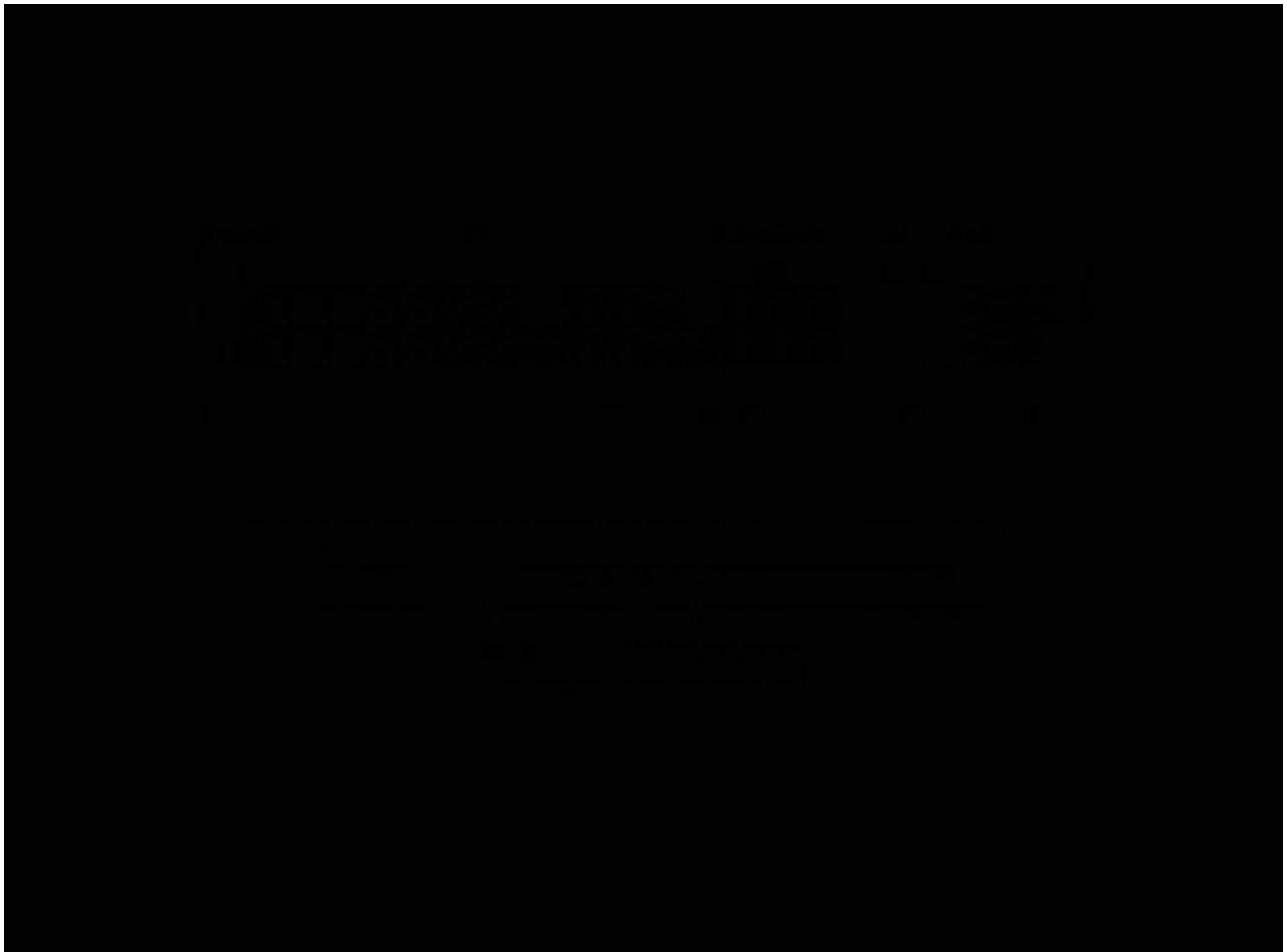
The MERL Database

- "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/

Spatially-Varying BRDFs

- Wood [Marschner et al. 2005]



Reading

- PBRT Chapter 8, and 14.5

Next Time

- Monte Carlo for image synthesis
- Motion blur, environment lighting