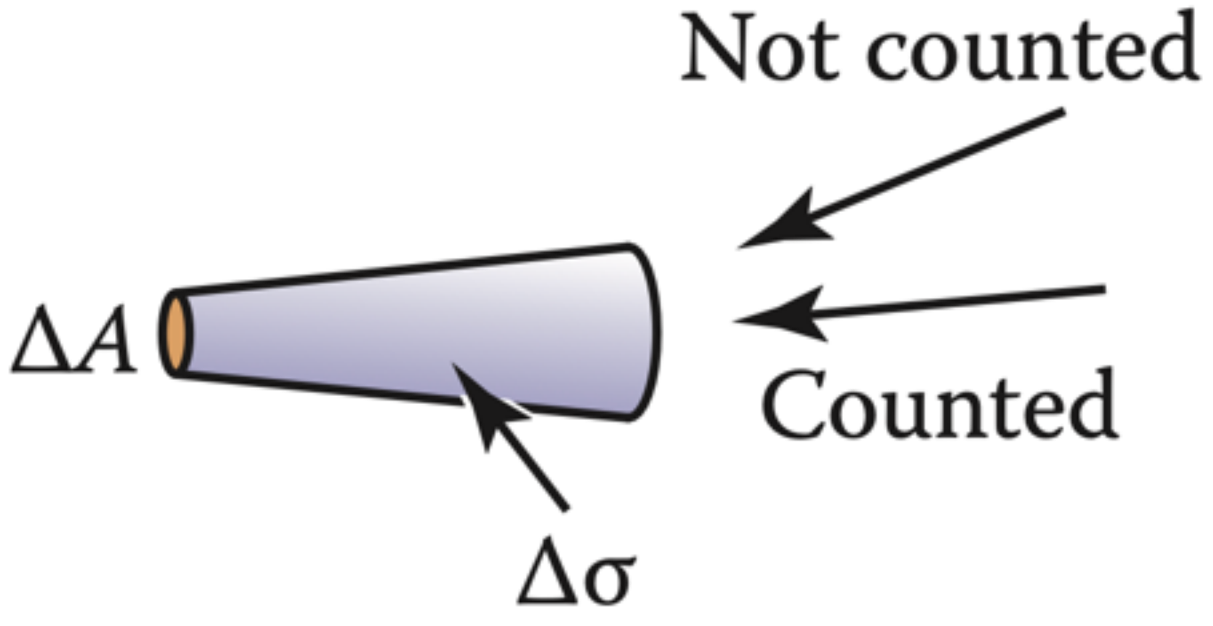
COL781: Computer Graphics

22. Material Appearance

Zeltner and Jakob 2018

Recap: Radiance

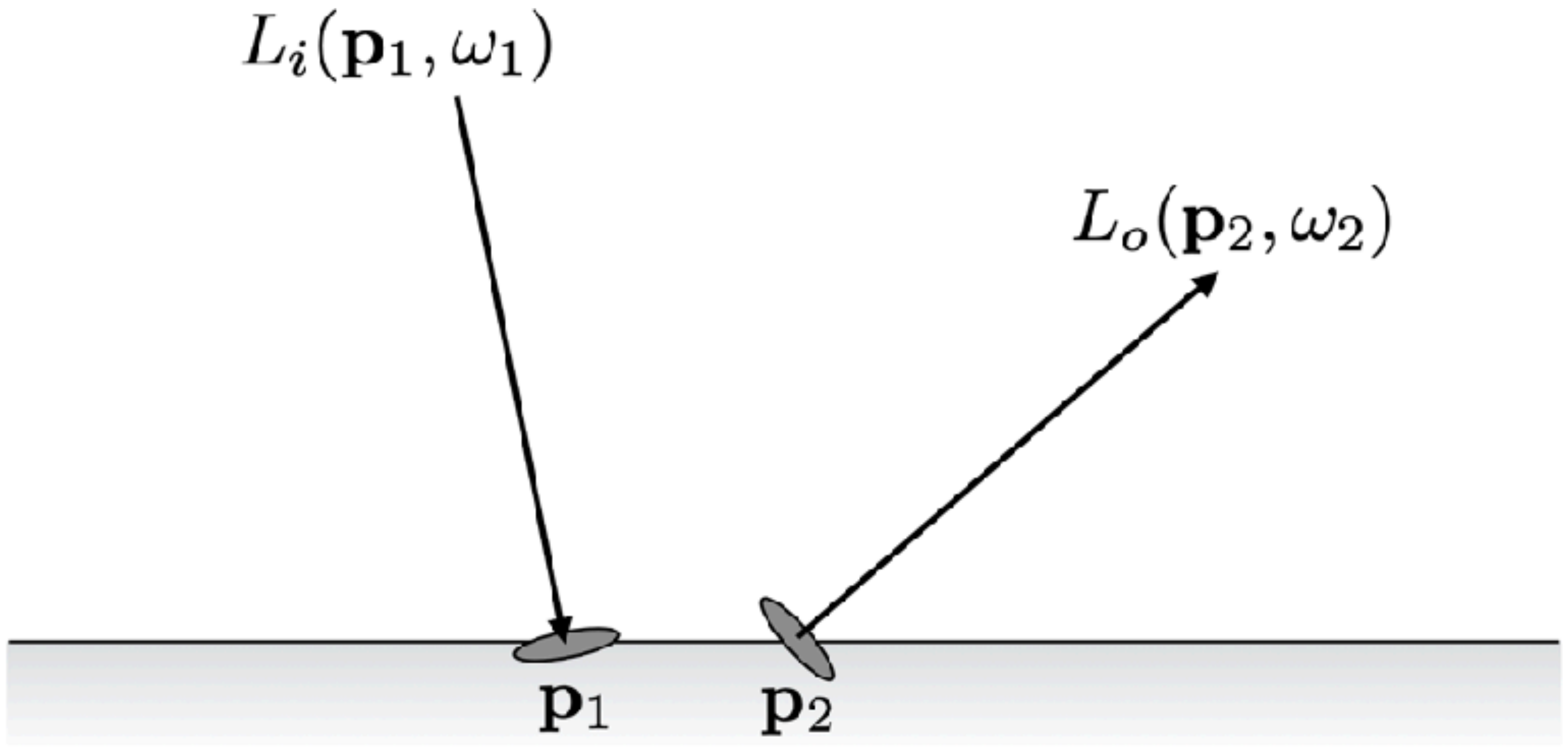
Radiance $L(\mathbf{p}, \boldsymbol{\omega})$ = flux per unit area per unit solid angle



- **incident radiance** L_i: angular distribution of incoming light
- **exitant radiance** L_o: angular distribution of outgoing light (emitted / reflected / transmitted)

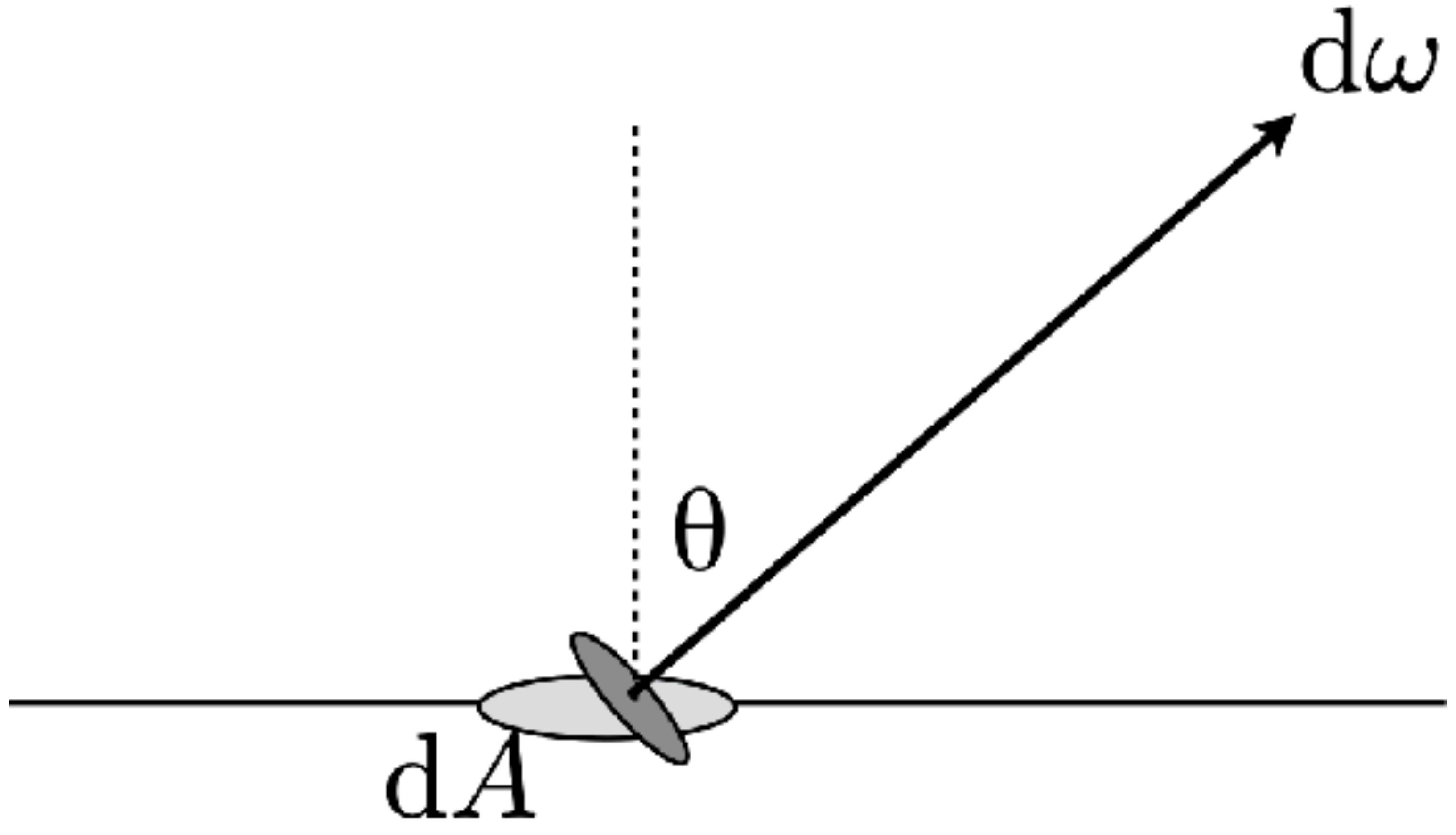
Constant along any ray (in a vacuum)

Radiance is what we want to compute when rendering!



At surface, incident/exitant radiance has a cos(θ) factor:

$$L(\mathbf{p}, \boldsymbol{\omega}) = \frac{\mathrm{d}E}{\mathrm{d}\boldsymbol{\omega} \cos\theta} = \frac{\mathrm{d}\Phi}{\mathrm{d}\boldsymbol{\omega}\, \mathrm{d}A \cos\theta}$$



Why? Irradiance *E* is per unit surface area,
radiance *L* is per unit area normal to the ray

- Why? Because radiance is a property of the ray, not of the surface!

Radiance also spans many orders of magnitude:

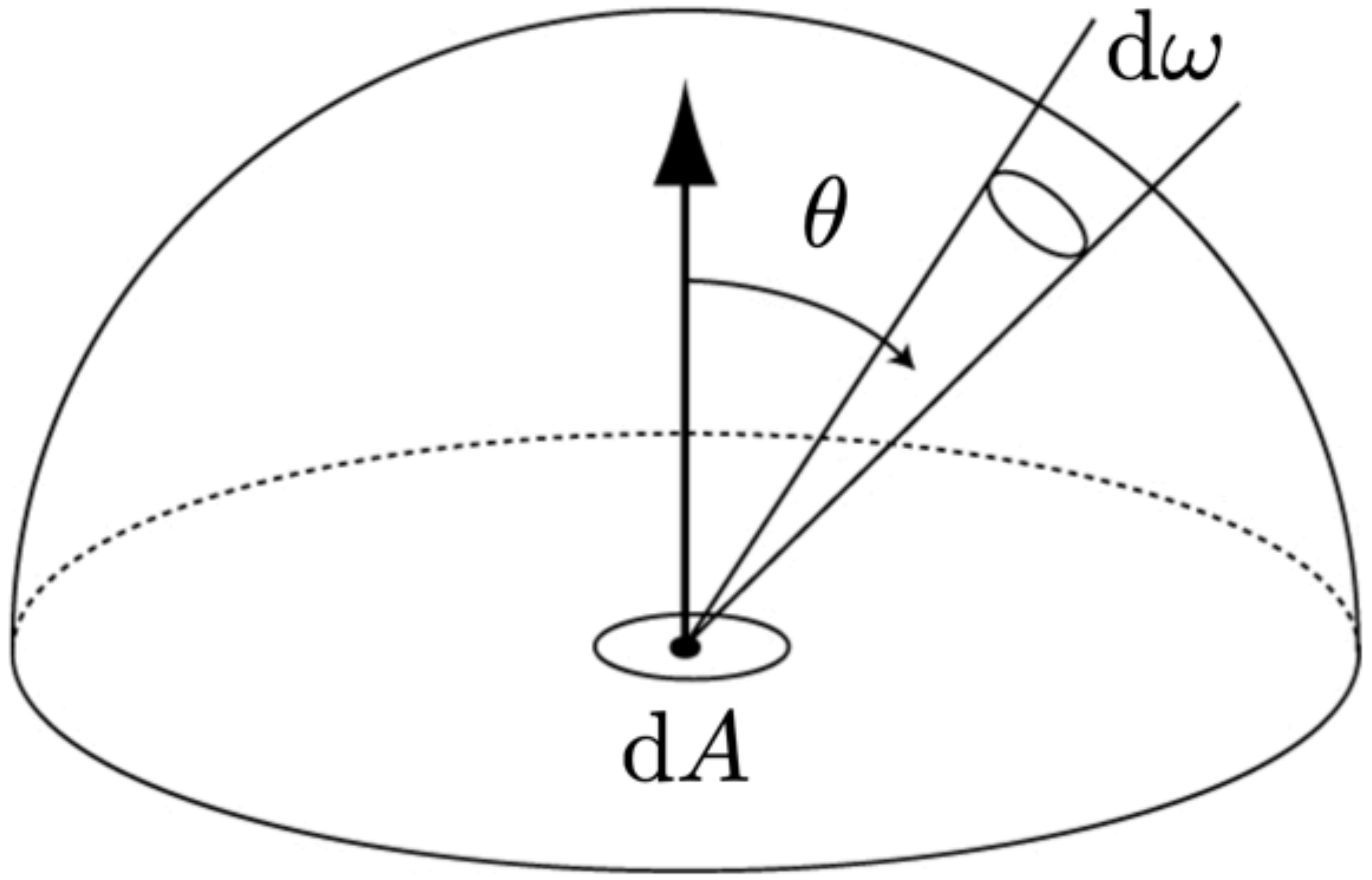
- Surface of the sun: 2,000,000,000 nits (lumen/sr/m^2)
- Sunlight clouds: 30,000
- Clear sky: 3,000
- Cellphone display: 500
- Overcast sky: 300
- Scene at sunrise: 30
- Scene lit by moon: 0.001
- Threshold of vision: 0.000001

Actually this is **luminance**…

Radiance is the fundamental radiometric quantity because we can get everything else by integrating it.

Irradiance on a surface:

$$E(\mathbf{p}) = \int_{H^2} L_i(\mathbf{p}, \boldsymbol{\omega}) \cos(\theta)\, d\boldsymbol{\omega}$$

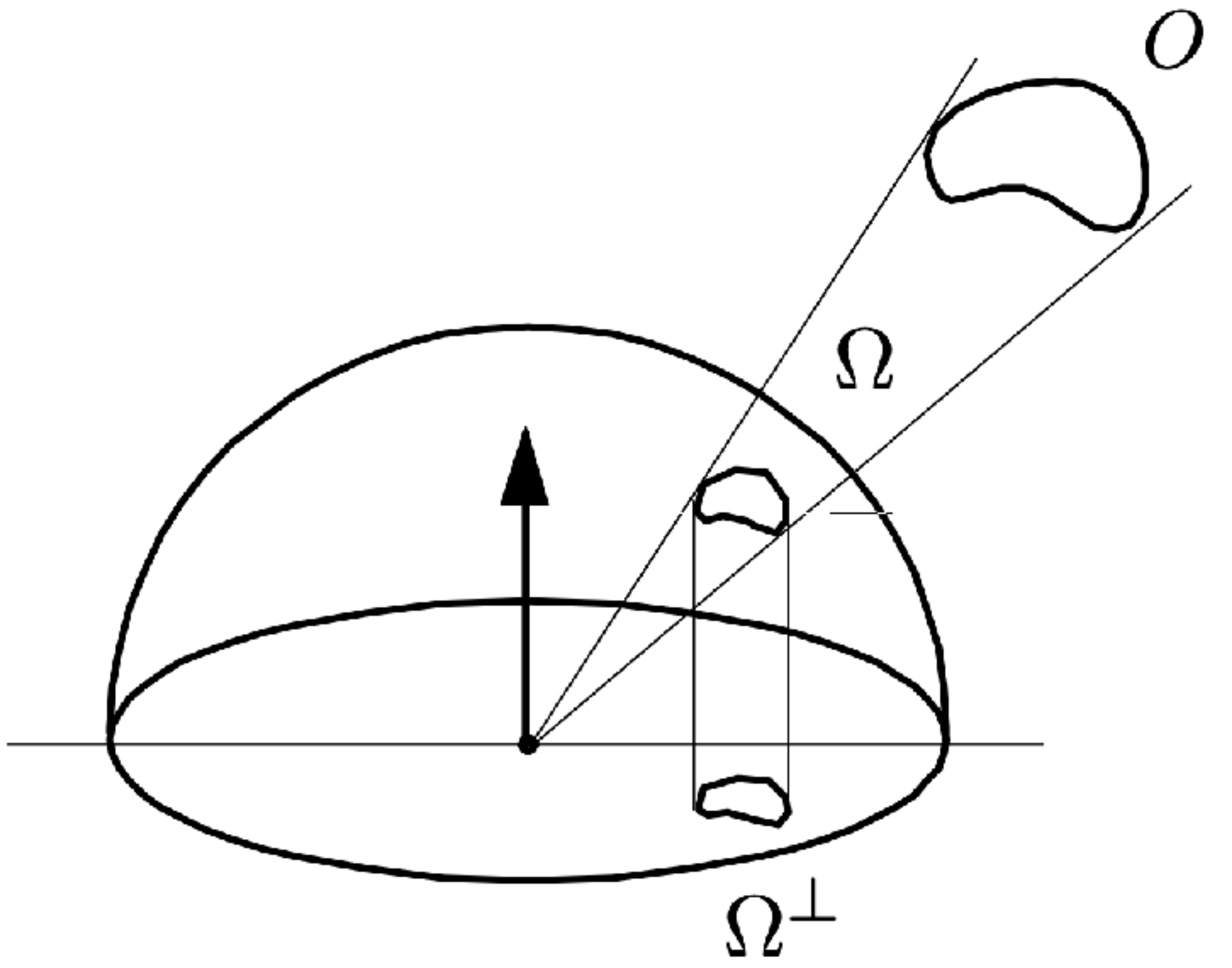


Irradiance due to a uniform area light source emitting radiance L:

$$E(\mathbf{p}) = \int_{H^2} L_i(\mathbf{p}, \boldsymbol{\omega}) \cos(\theta)\, d\boldsymbol{\omega}$$

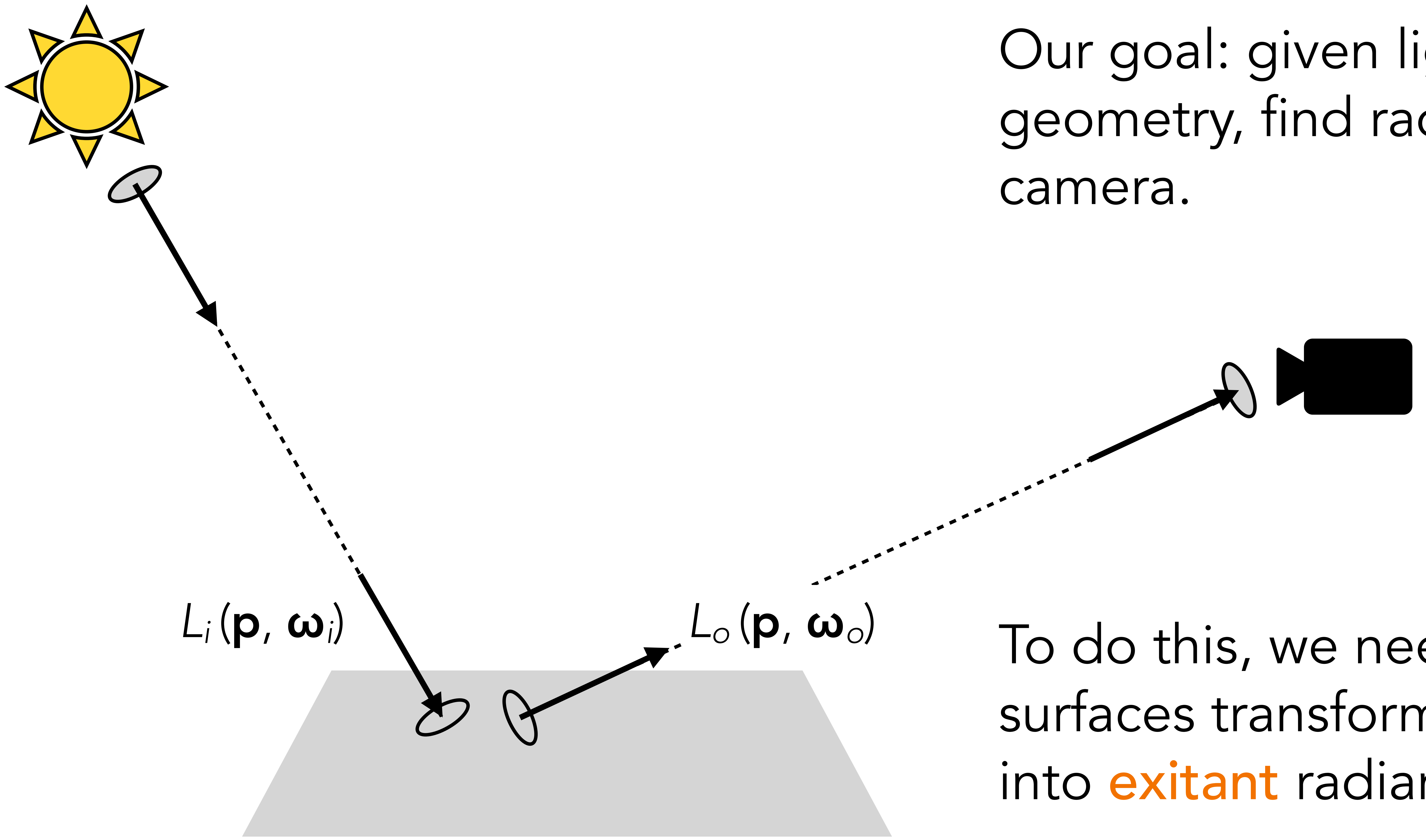
$$= L \int_{\Omega} \cos(\theta)\, d\boldsymbol{\omega}$$

$$= L\Omega^{\perp}$$



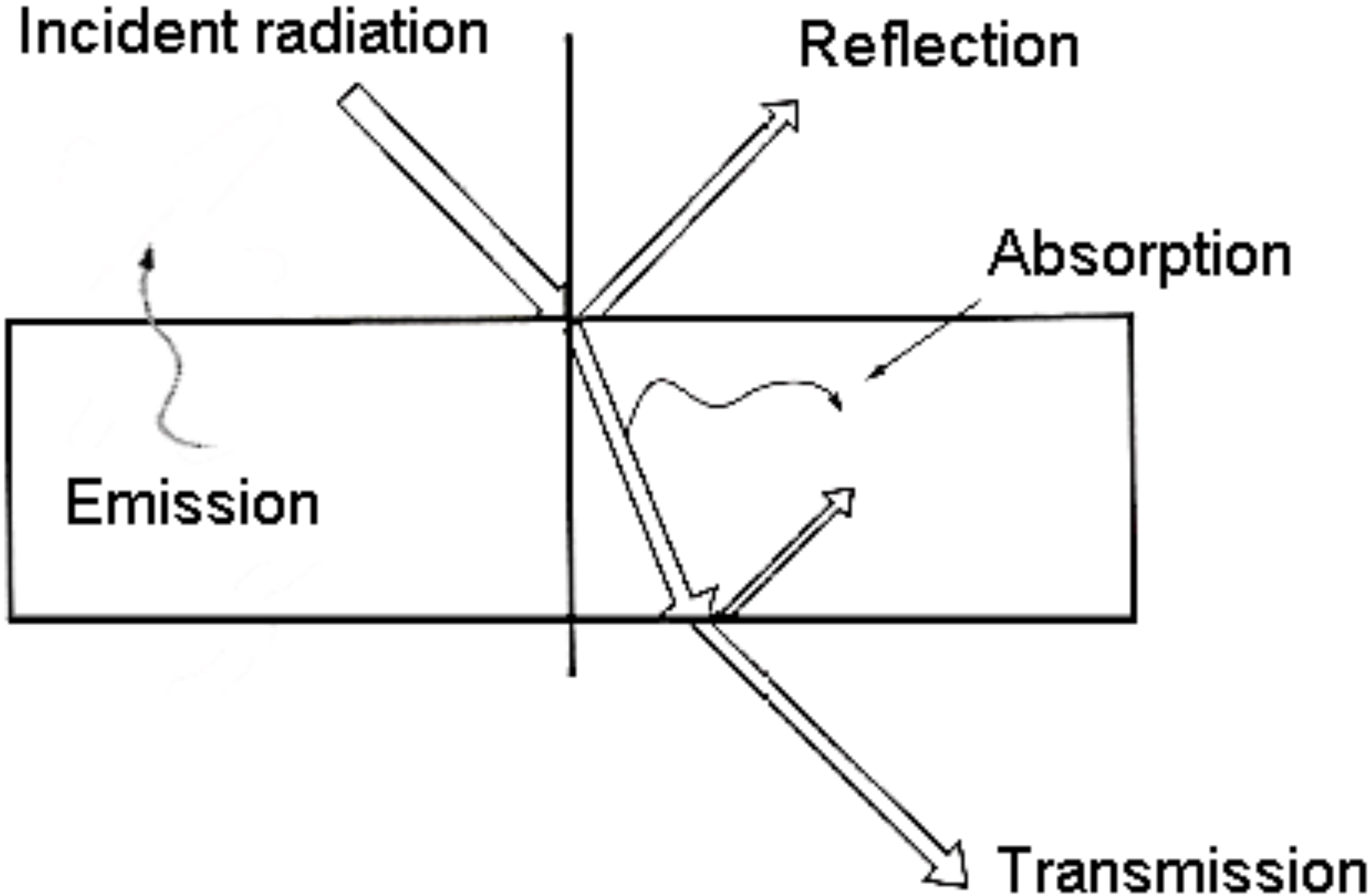
For example, irradiance from an overcast sky with radiance L is just $L\pi$.
(Can you see why?)

Rendering



Our goal: given light sources and scene geometry, find radiance incident on camera.

To do this, we need to know how surfaces transform incident radiance into exitant radiance

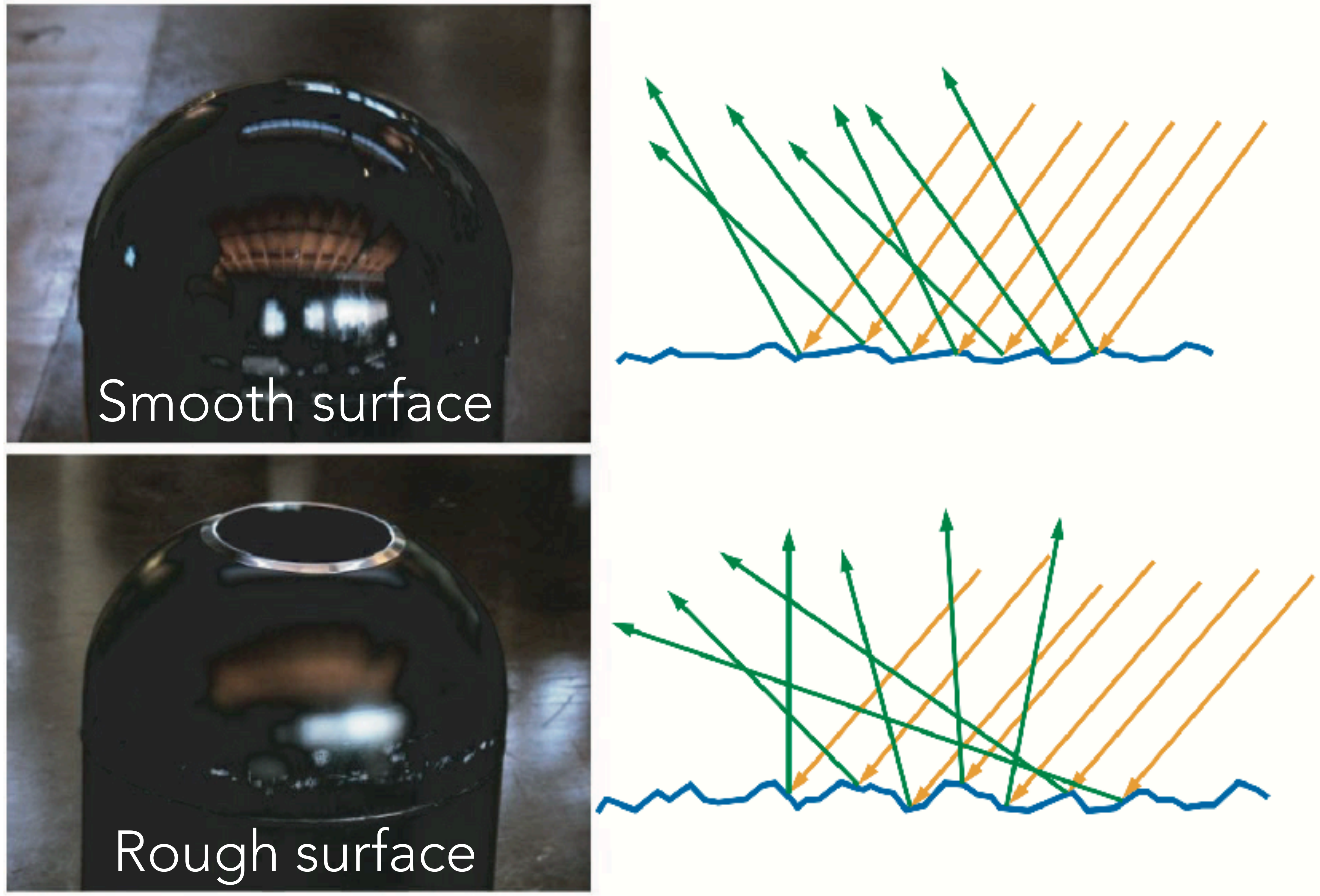

Incident radiation
Reflection
Absorption
Emission
Transmission

Puzzle:

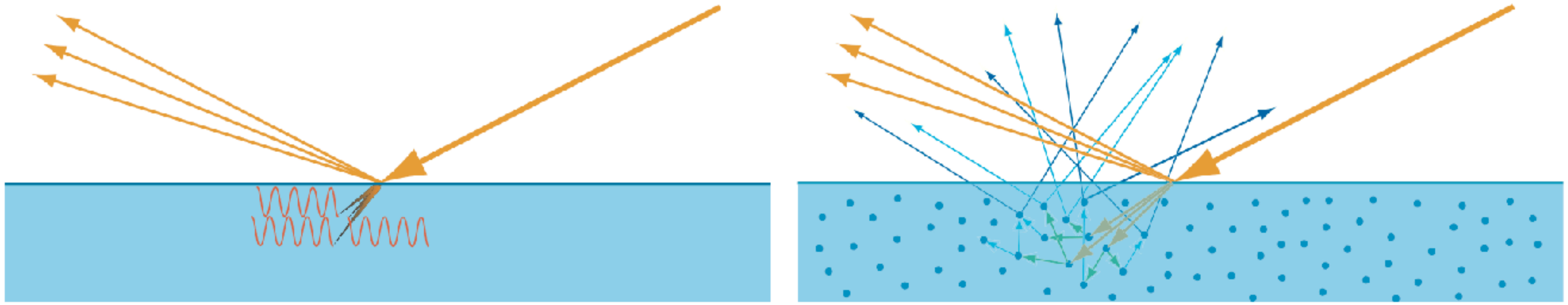
An object looks white if it reflects (almost) all incident light regardless of frequency.

A mirror reflects (almost) all incident light (regardless of frequency).

So what's the difference between a white object and a mirror?



Real-Time Rendering

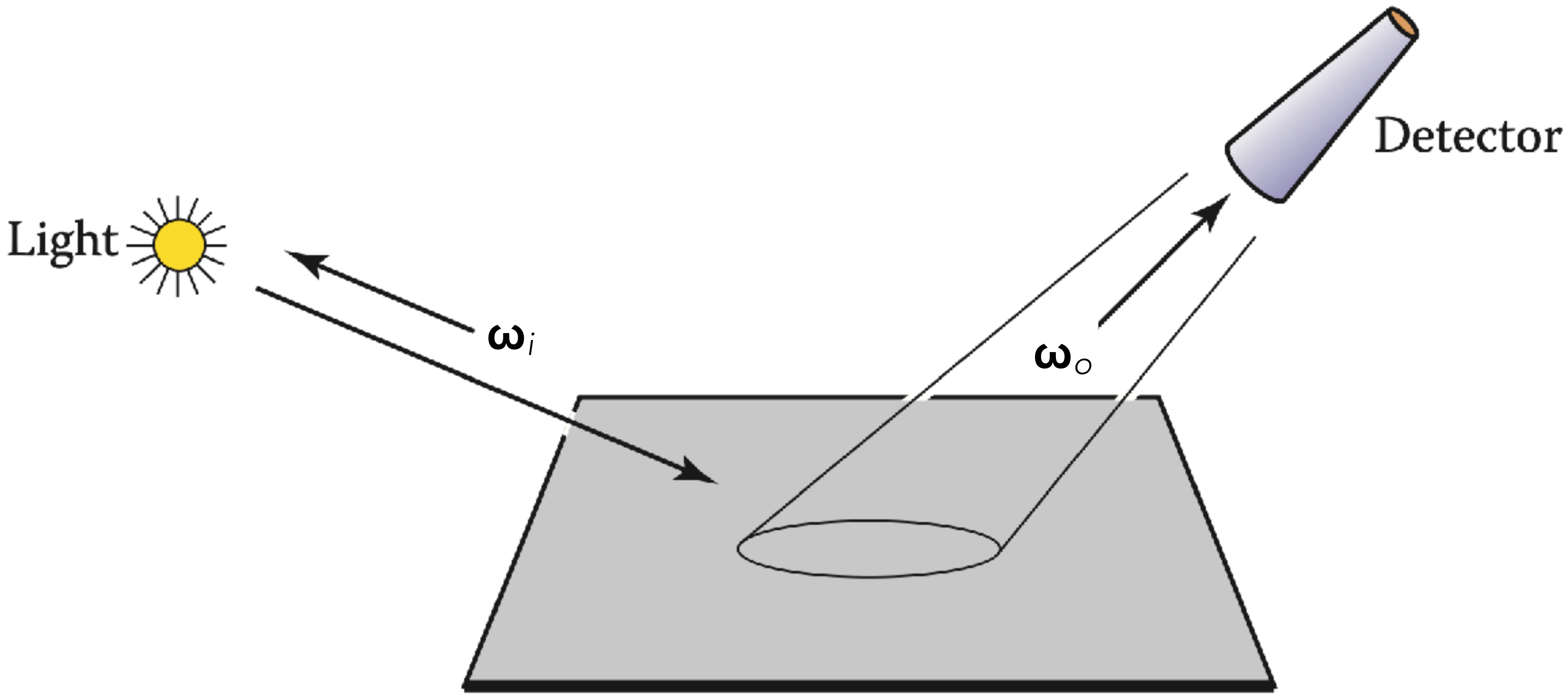


Metals

Non-metals

Real-Time Rendering

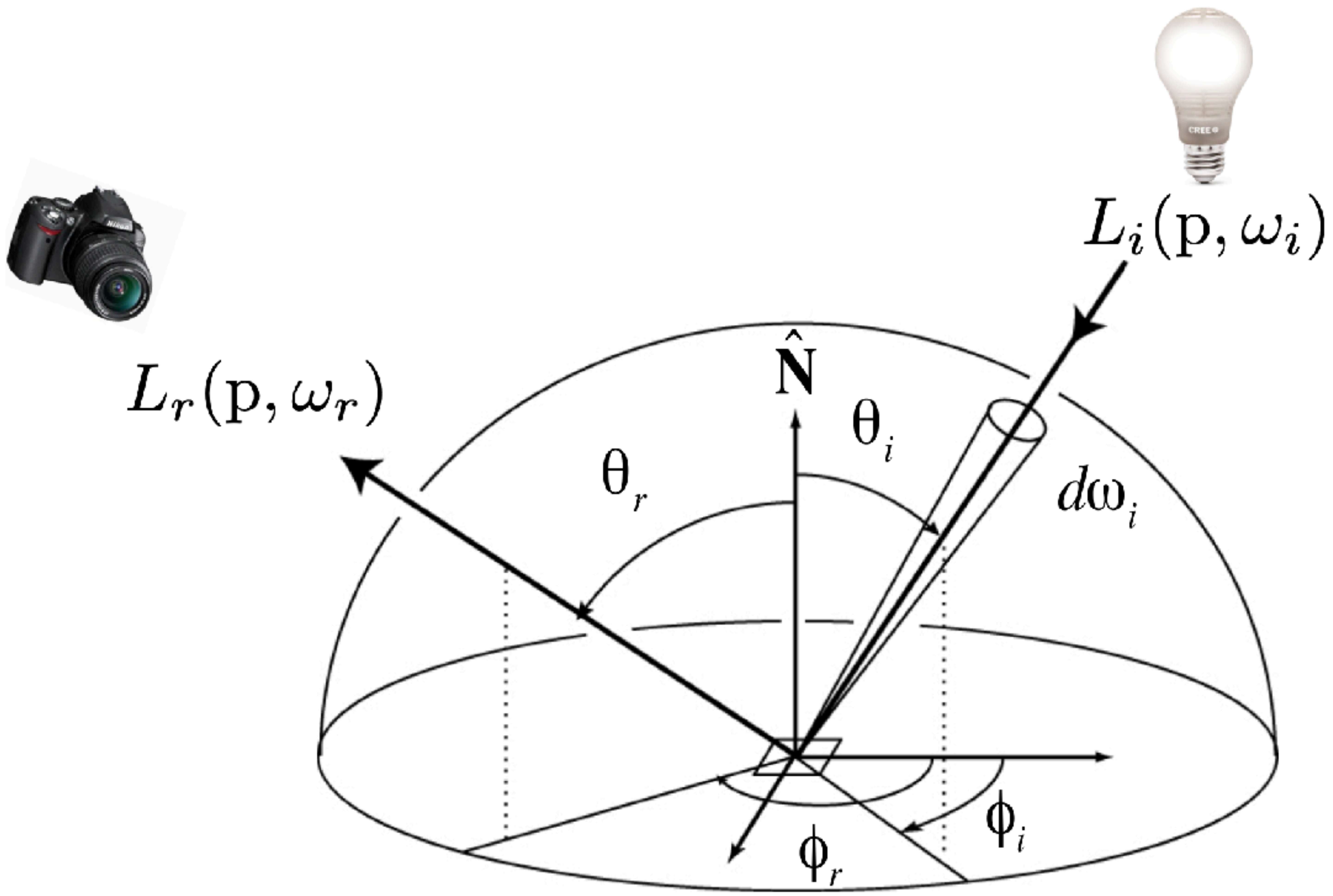
The BRDF



Fundamentals of Computer Graphics

Bidirectional Reflectance Distribution Function

$$f_r(\boldsymbol{\omega}_i \rightarrow \boldsymbol{\omega}_o) = L_o(\mathbf{x}, \boldsymbol{\omega}_o)/E(\mathbf{x})$$



$$L_r(\mathbf{x}, \boldsymbol{\omega}_r) = \int_{H^2} f_r(\boldsymbol{\omega}_i \to \boldsymbol{\omega}_r)\, L_i(\mathbf{x}, \boldsymbol{\omega}_i) \cos(\theta_i)\, d\boldsymbol{\omega}_i$$

Diffuse

Plastic

Red semi-gloss paint

Ford “Mystic Lacquer” paint

Mirror

Gold

Lambertian (diffuse) material

Simplest possible model: BRDF is a constant!

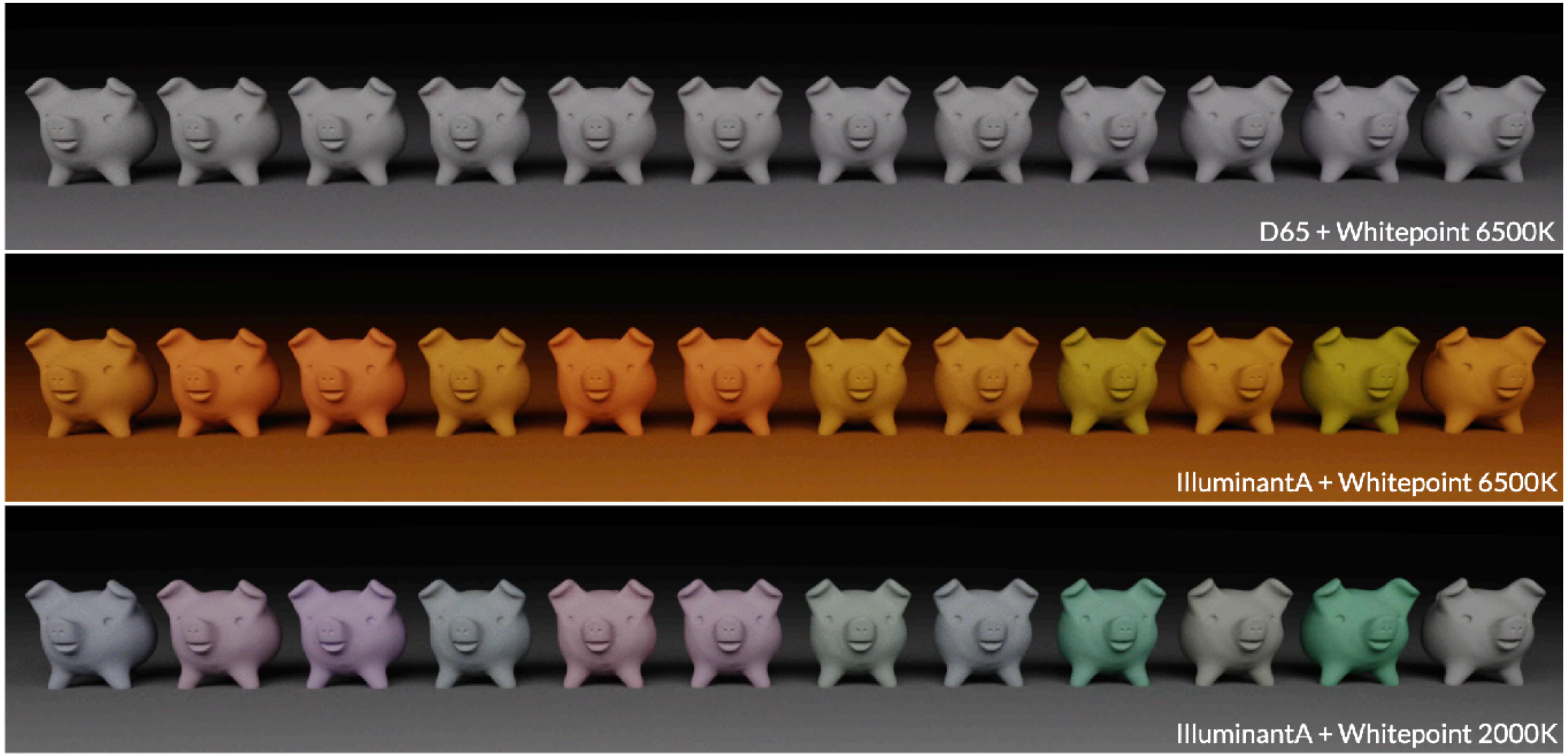
$$L_o(\boldsymbol{\omega}_o) = \int_{H^2} f_r \, L_i(\boldsymbol{\omega}_i) \cos(\theta_i) \, d\boldsymbol{\omega}_i$$

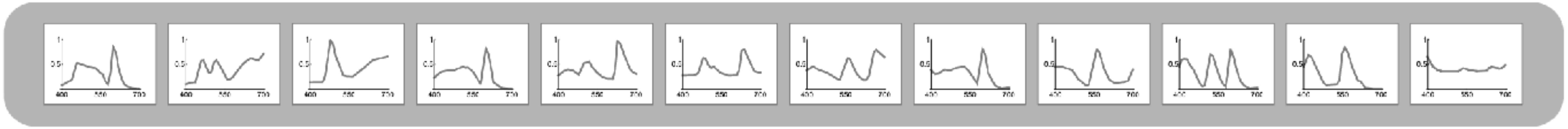
$$= f_r \, E_i$$

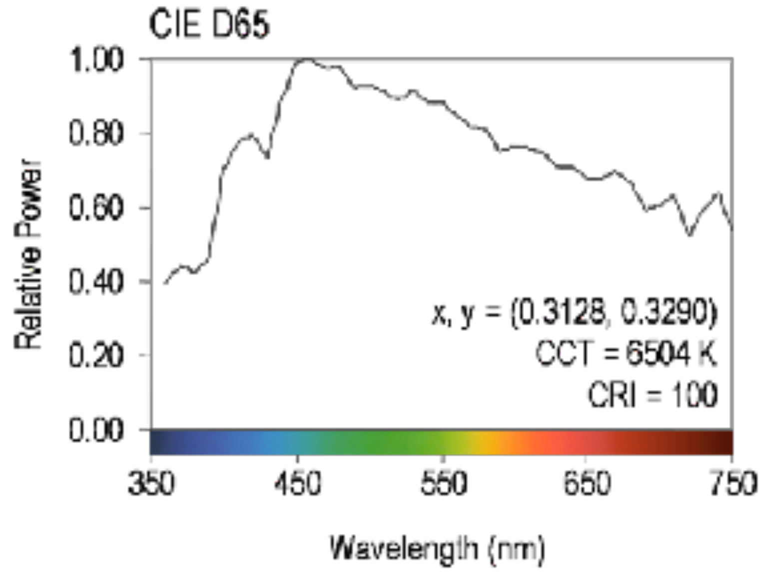
To conserve energy, $f_r = \rho/\pi$ where **albedo** ρ is ≤ 1

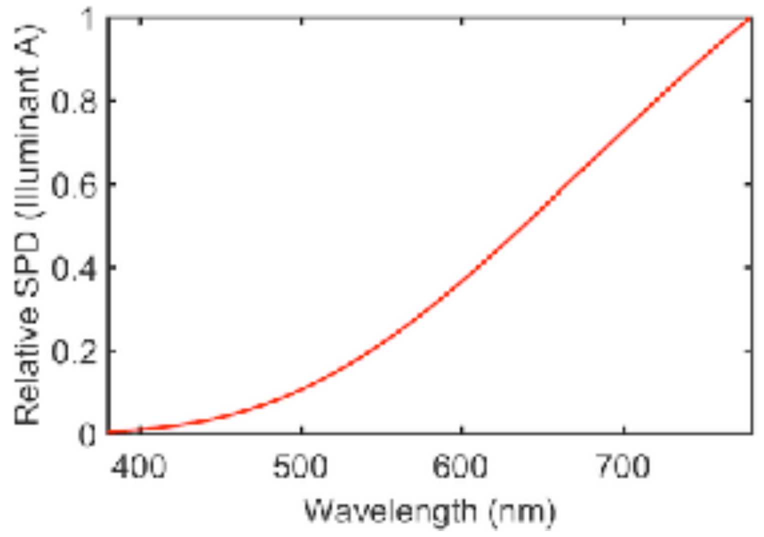
Why? For constant radiance L, total flux density = $L\,\pi$

In principle, we should specify the spectral albedo…



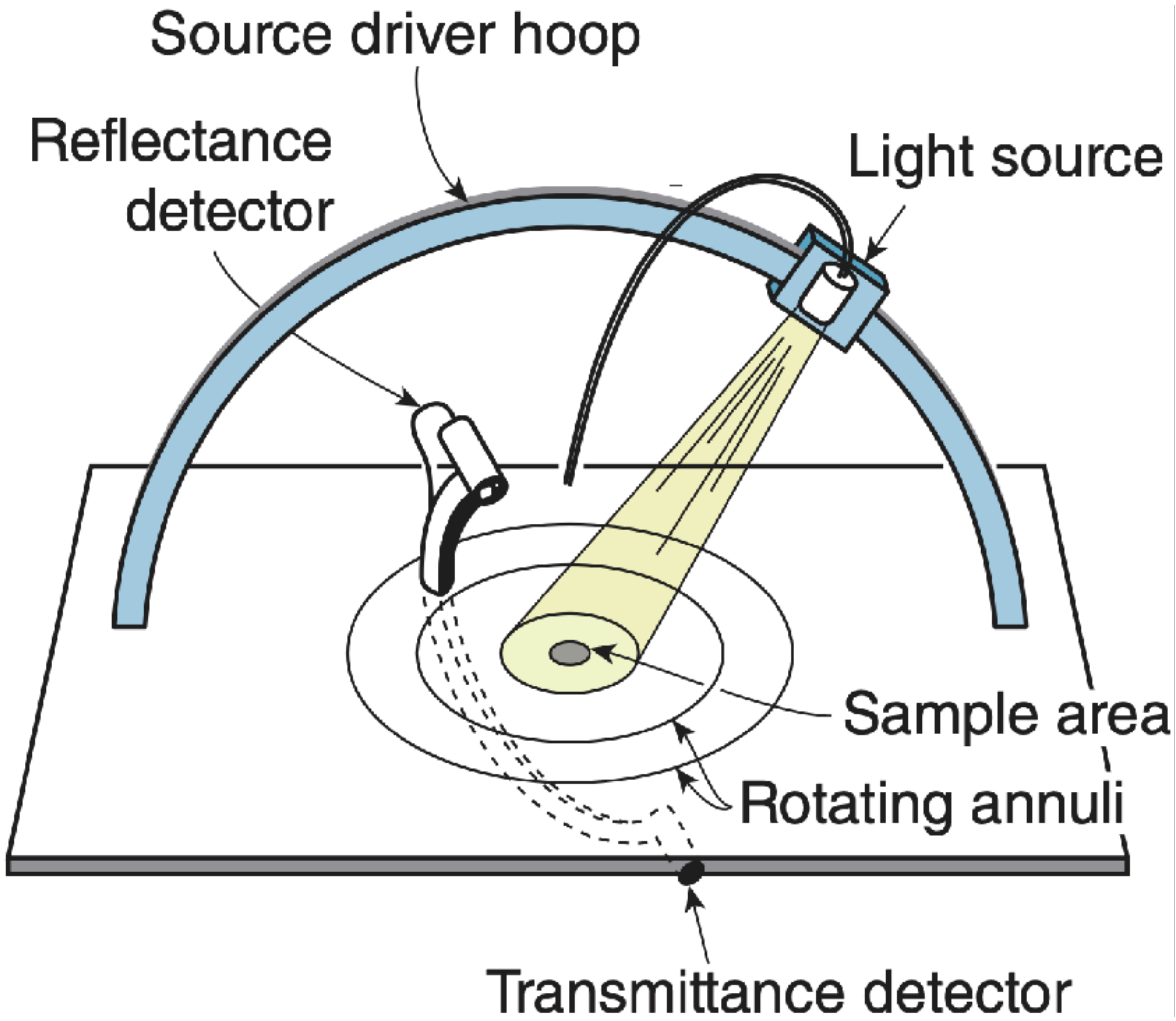






Andrea Weidlich

BRDF acquisition: Gonioreflectometer

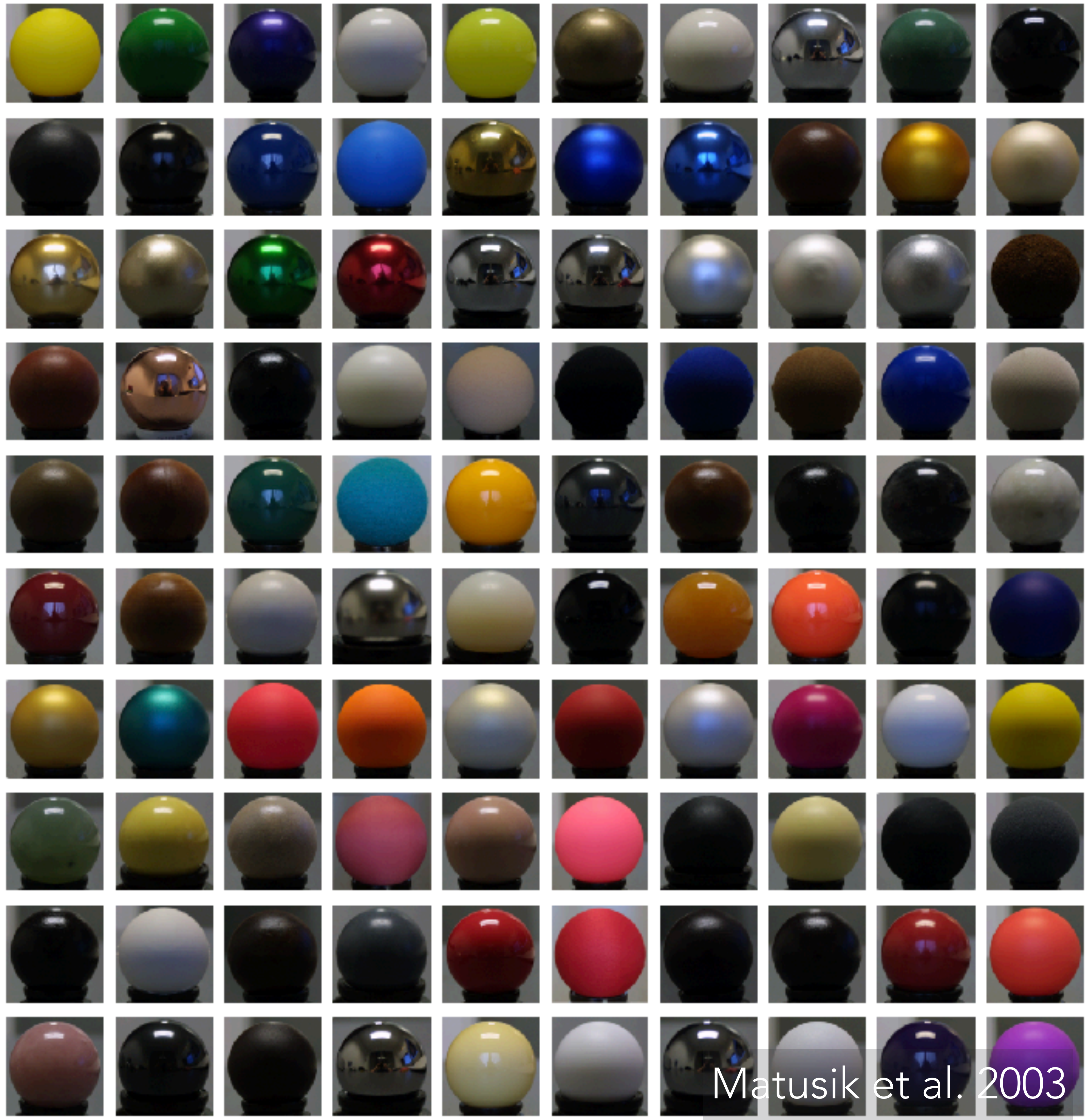


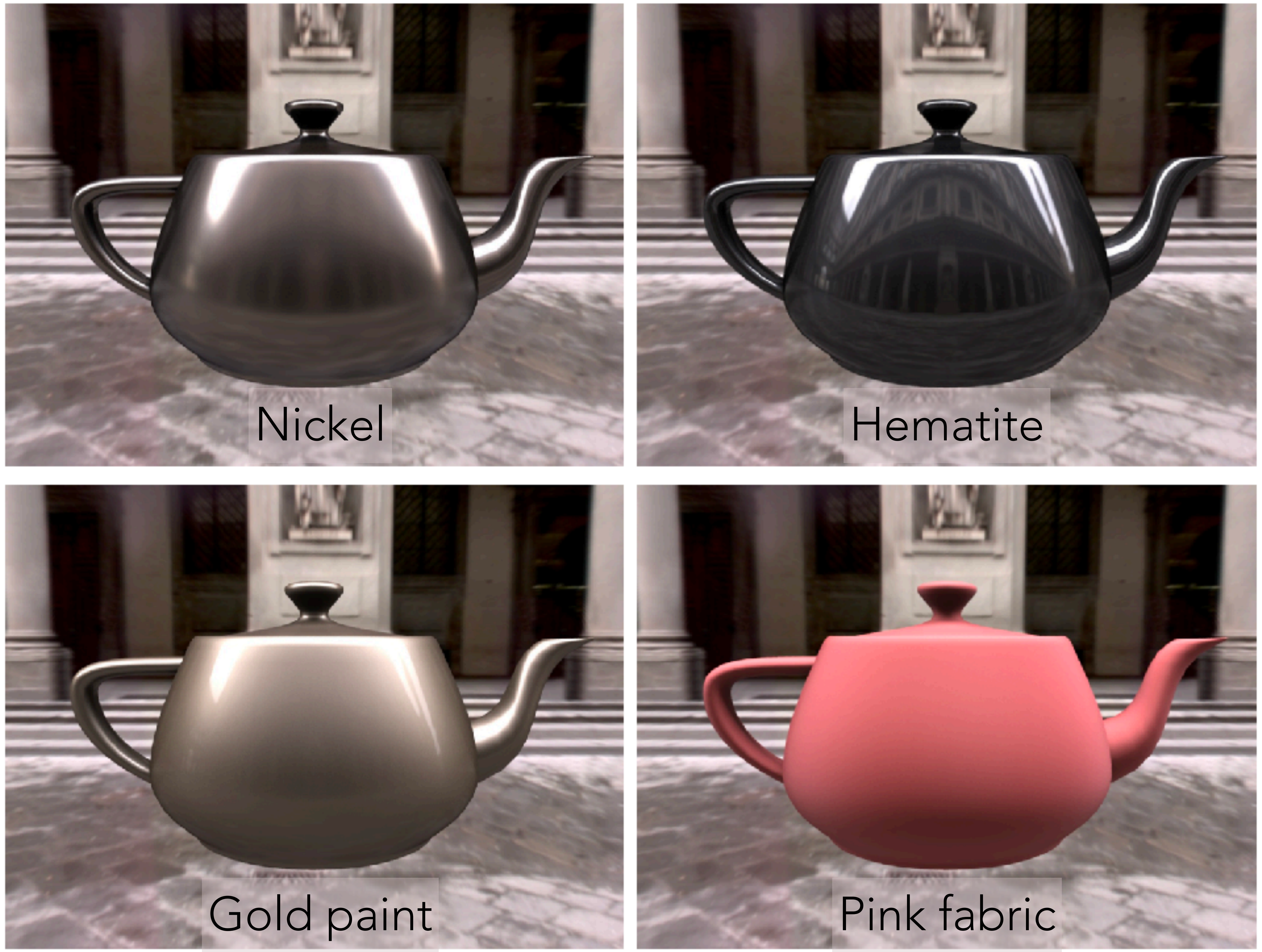
Computer Graphics: Principles and Practice

Matusik et al.'s acquisition setup for isotropic BRDFs


Matusik et al. 2003

MERL BRDF database

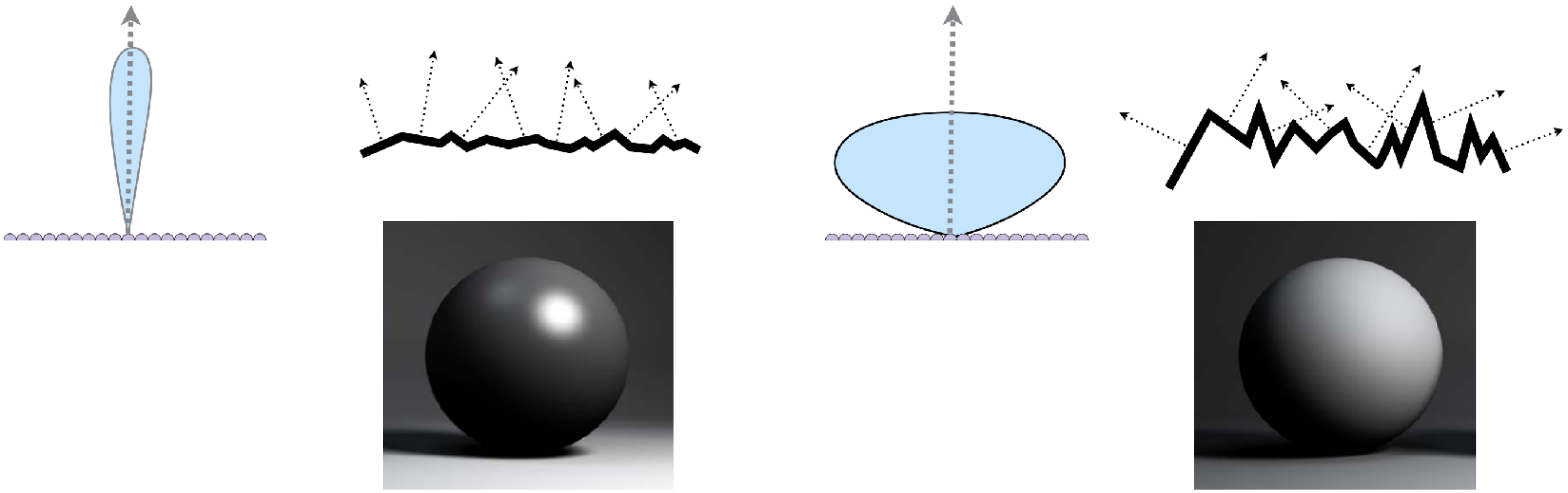


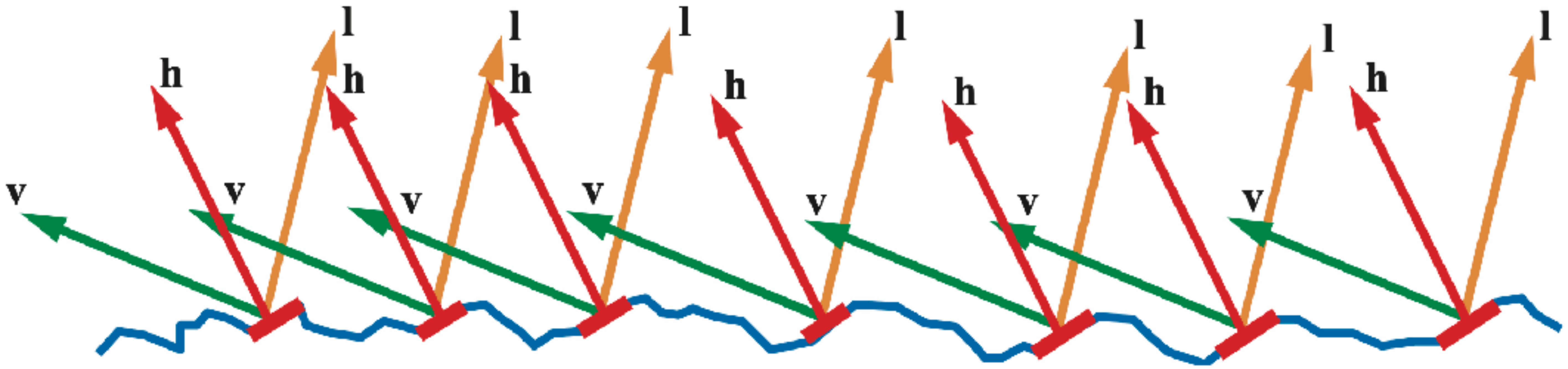


Microfacet models

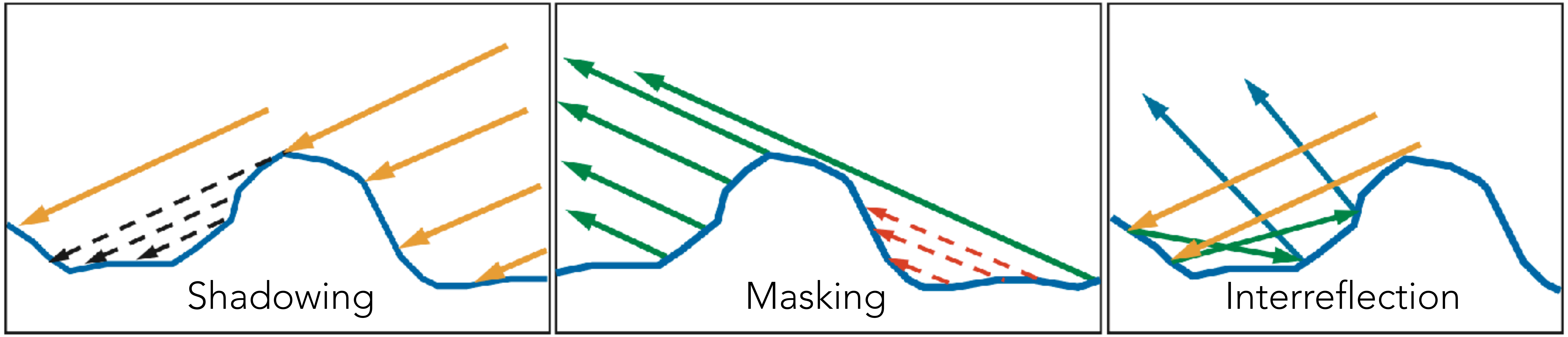
Assume rough surface is actually perfectly specular but bumpy at microscale

Made of small flat patches ("microfacets") with **normal distribution function** $D(\mathbf{h})$





$f_r(\boldsymbol{\ell} \to \mathbf{v}) = D(\mathbf{h})$? Not quite…

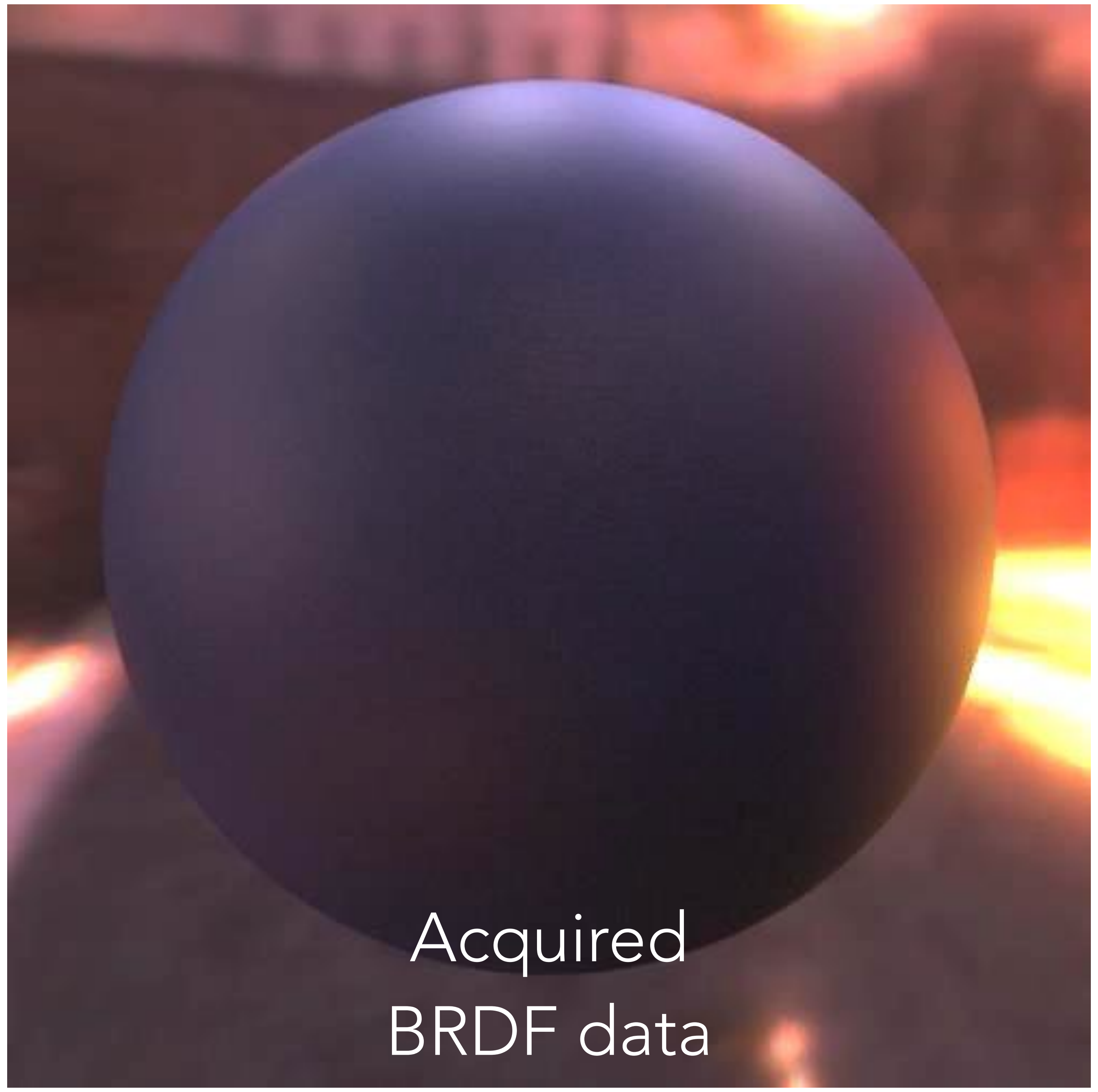


$$f_r(\boldsymbol{\ell} \to \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{v})G(\mathbf{l}, \mathbf{v}, \mathbf{h})D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

$$f_r(\boldsymbol{\ell} \to \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{v})G(\mathbf{l}, \mathbf{v}, \mathbf{h})D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

- $F(\boldsymbol{\ell}, \mathbf{v}) \leq 1$: **Fresnel term**
- $G(\boldsymbol{\ell}, \mathbf{v}, \mathbf{h}) \leq 1$: **Geometry term**
  - Probability that microfacet with normal **h** is visible from both $\boldsymbol{\ell}$ and **v**
  - Accounts for shadowing and masking (interreflections ignored)
- $D(\mathbf{h})$: Normal distribution function

All these terms have
various analytical models…

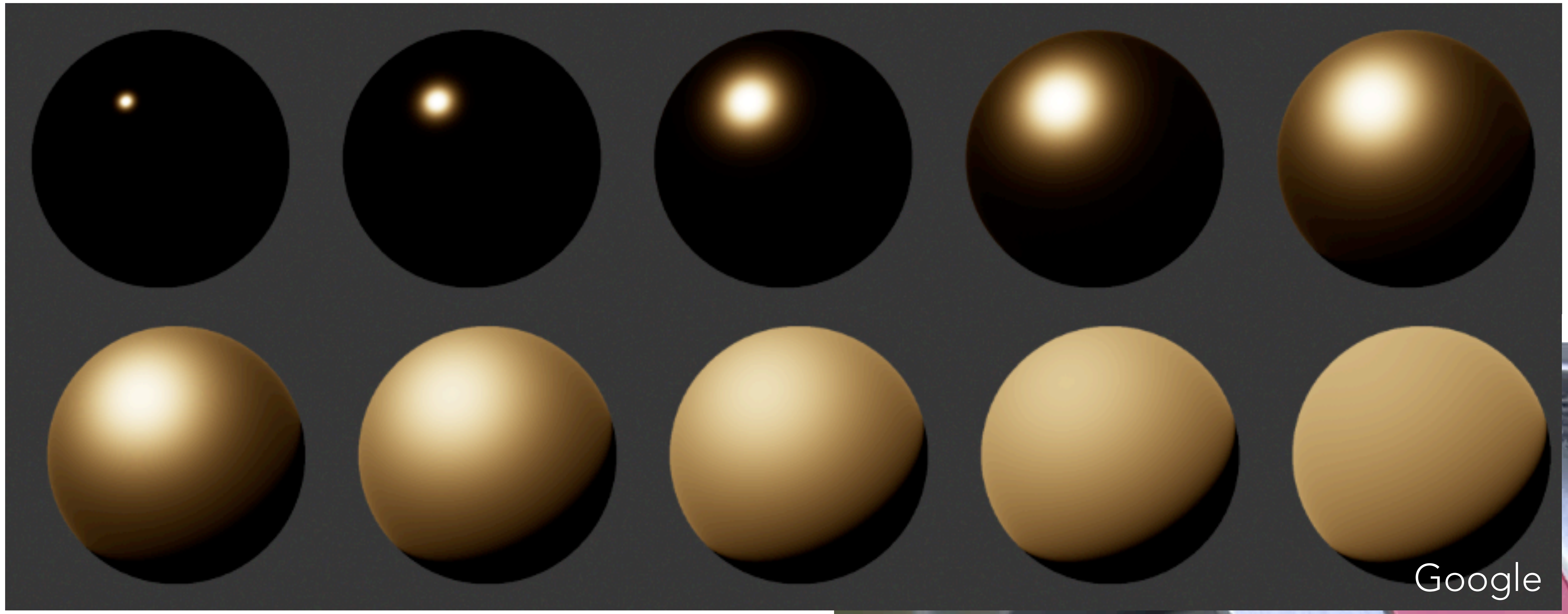


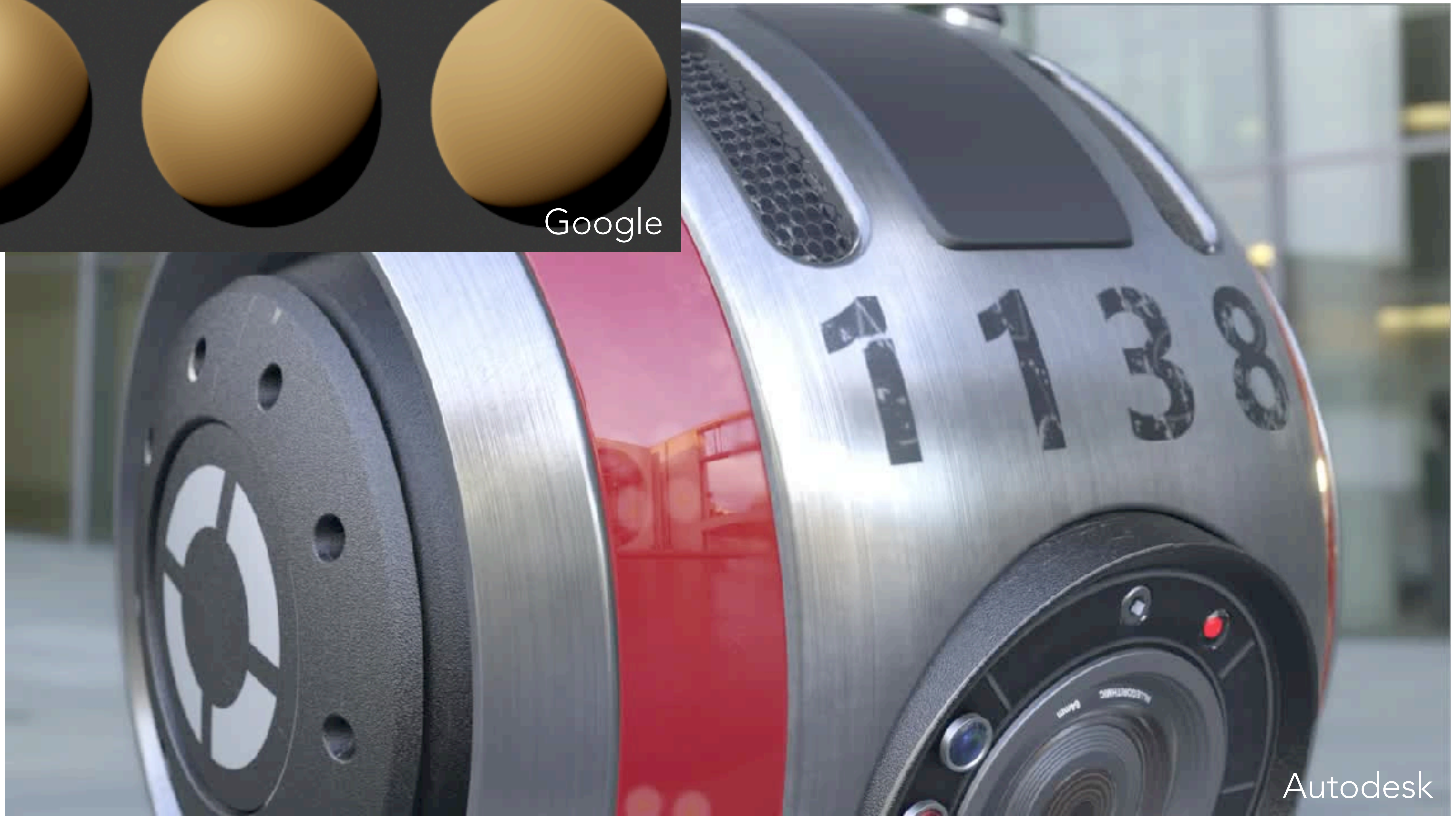
Acquired
BRDF data

Blinn-Phong
model

Cook-Torrance
microfacet model

Wojciech Matusik


Google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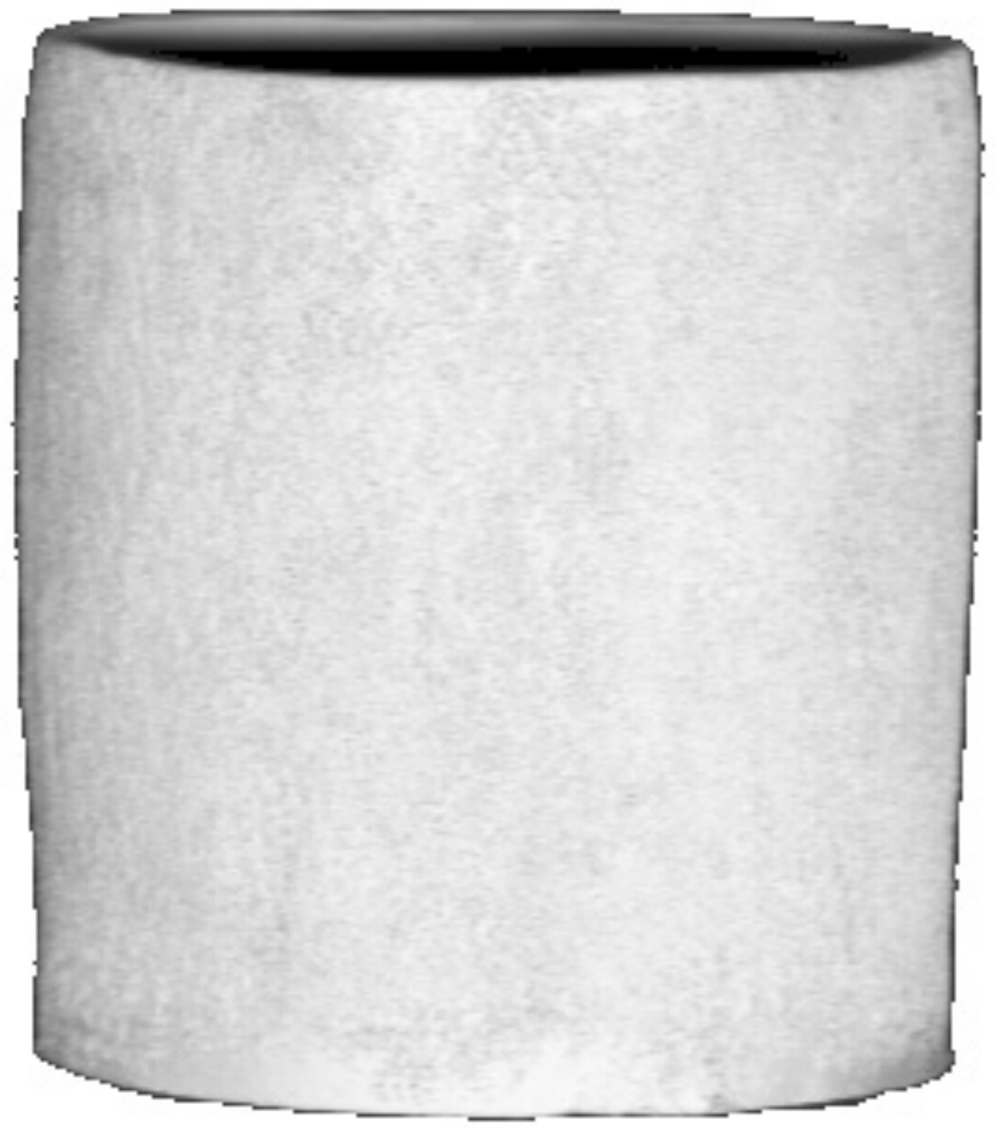
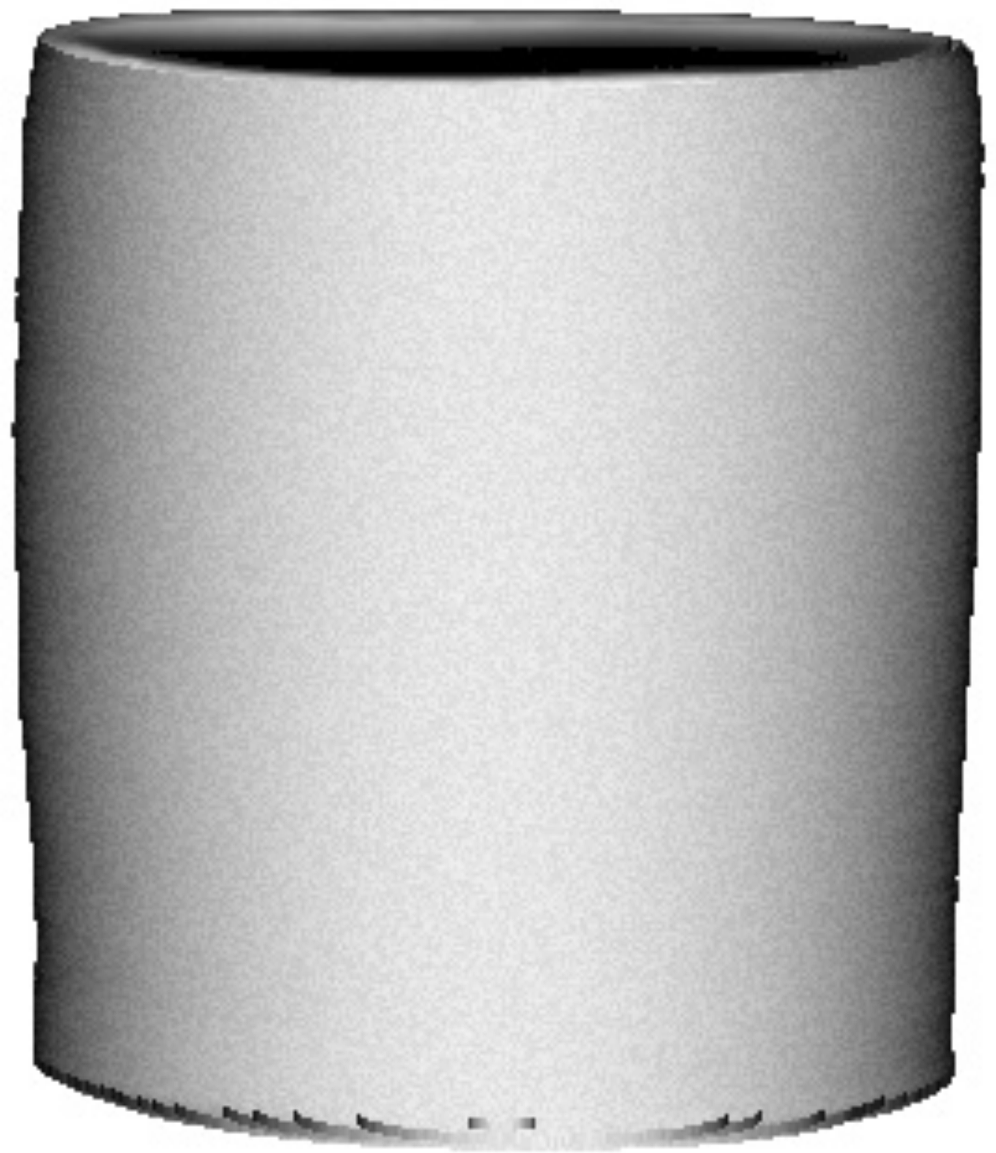
Autodesk

What if the microfacets are diffuse instead of specular?

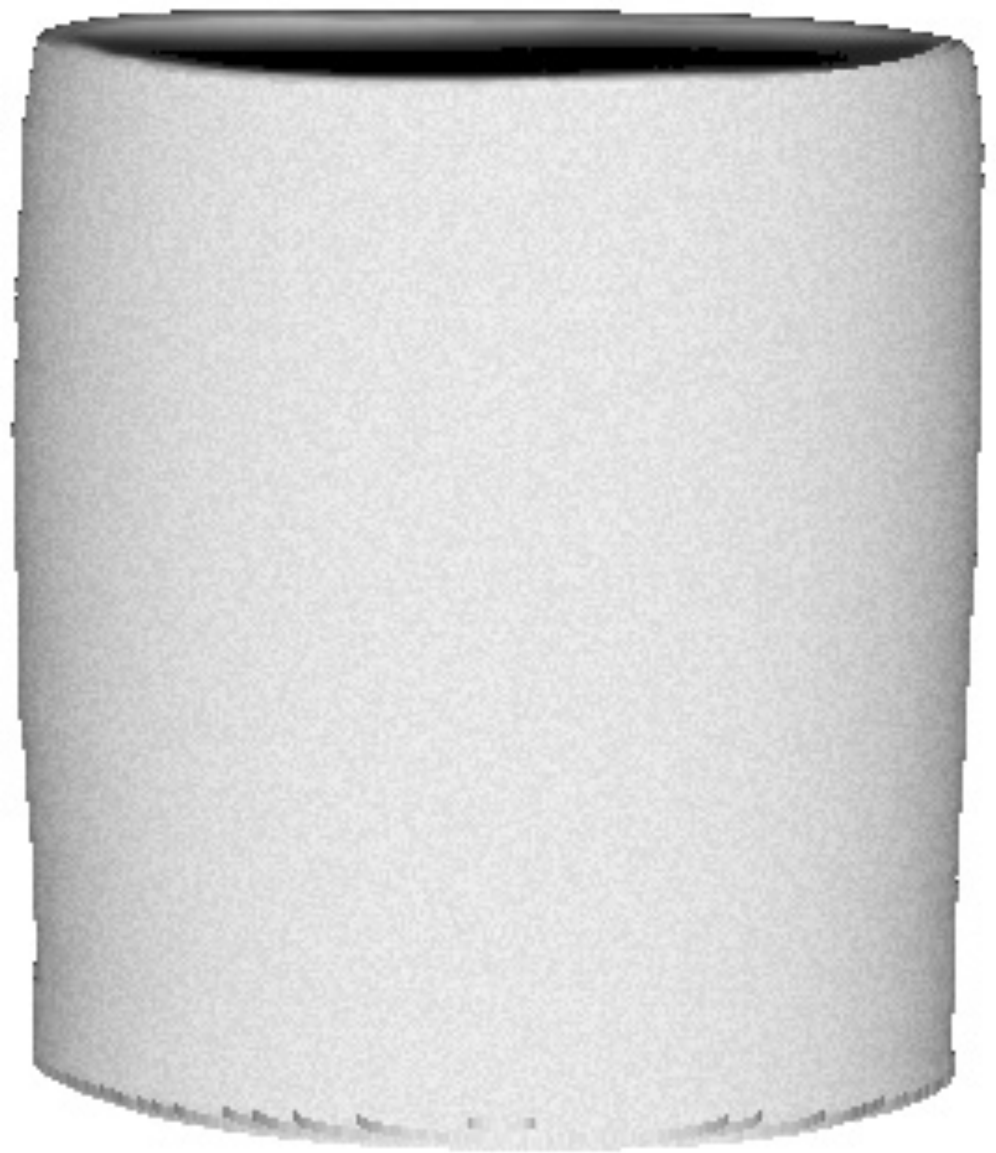
Oren-Nayar model for rough diffuse surfaces



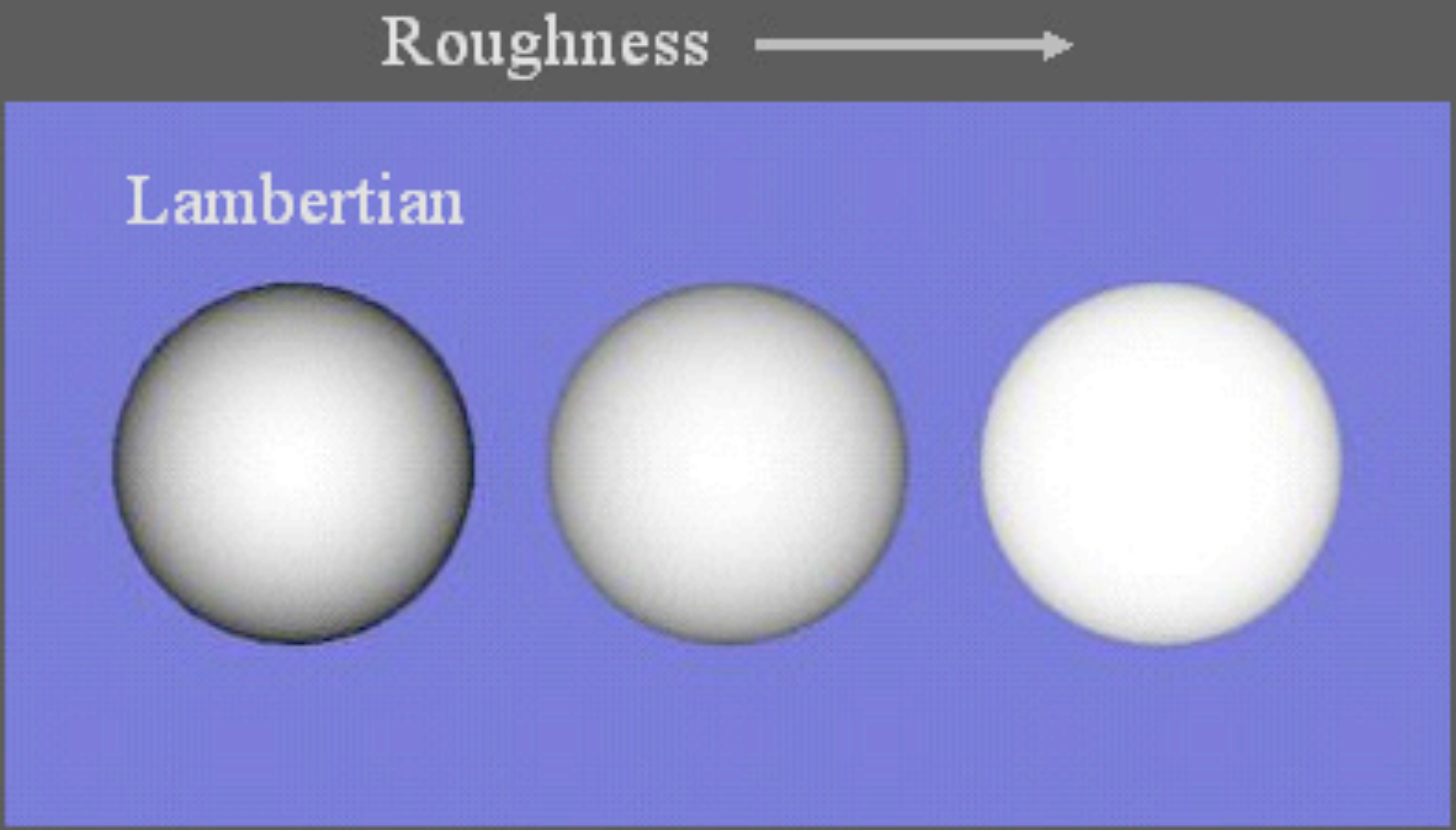
Photograph



Lambertian



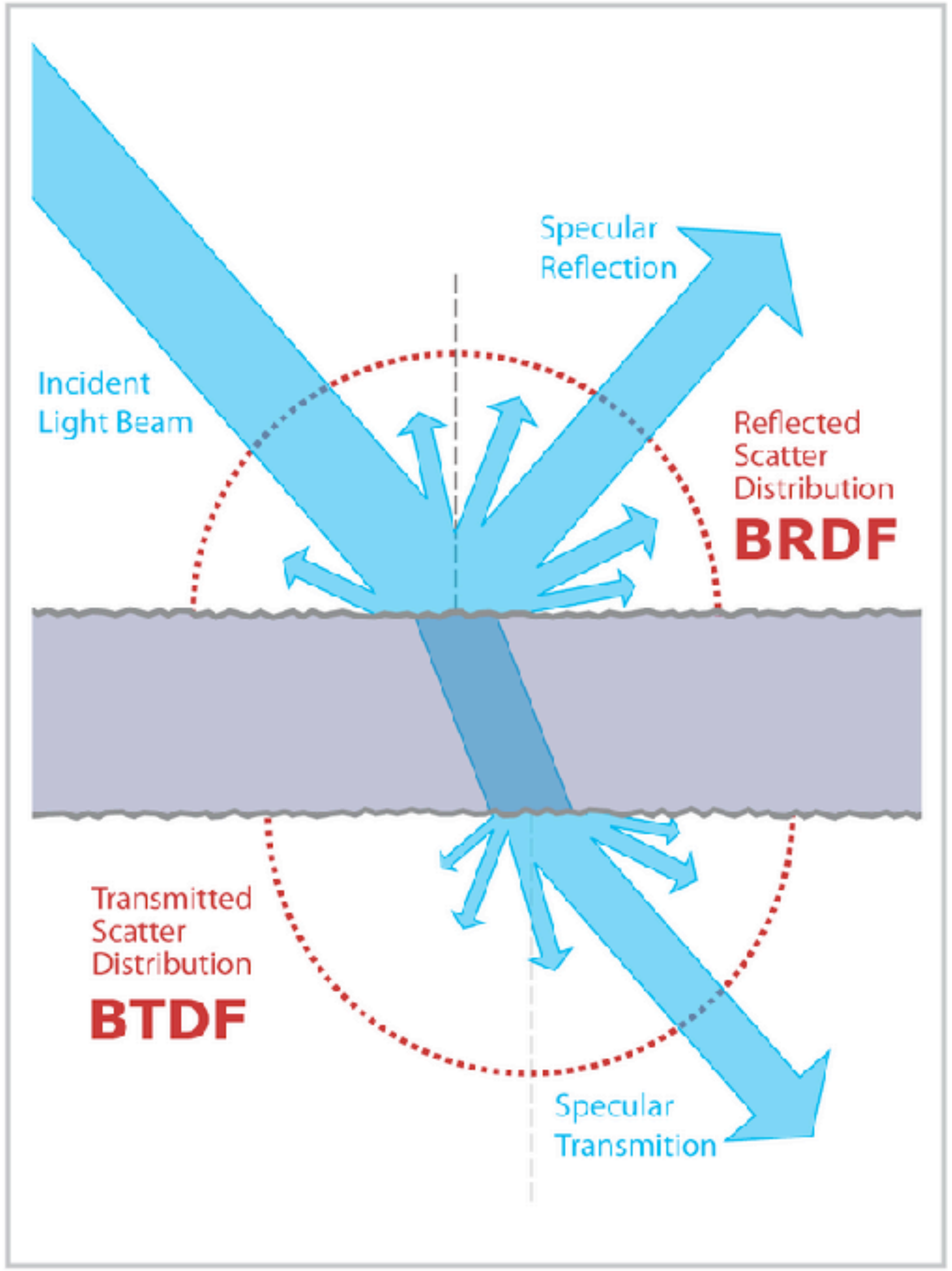
Oren-Nayar



Rendered Spheres

Image of Full Moon

Oren and Nayar


Specular
Reflection
Incident
Light Beam
Reflected
Scatter
Distribution
BRDF
Transmitted
Scatter
Distribution
BTDF
Specular
Transmition

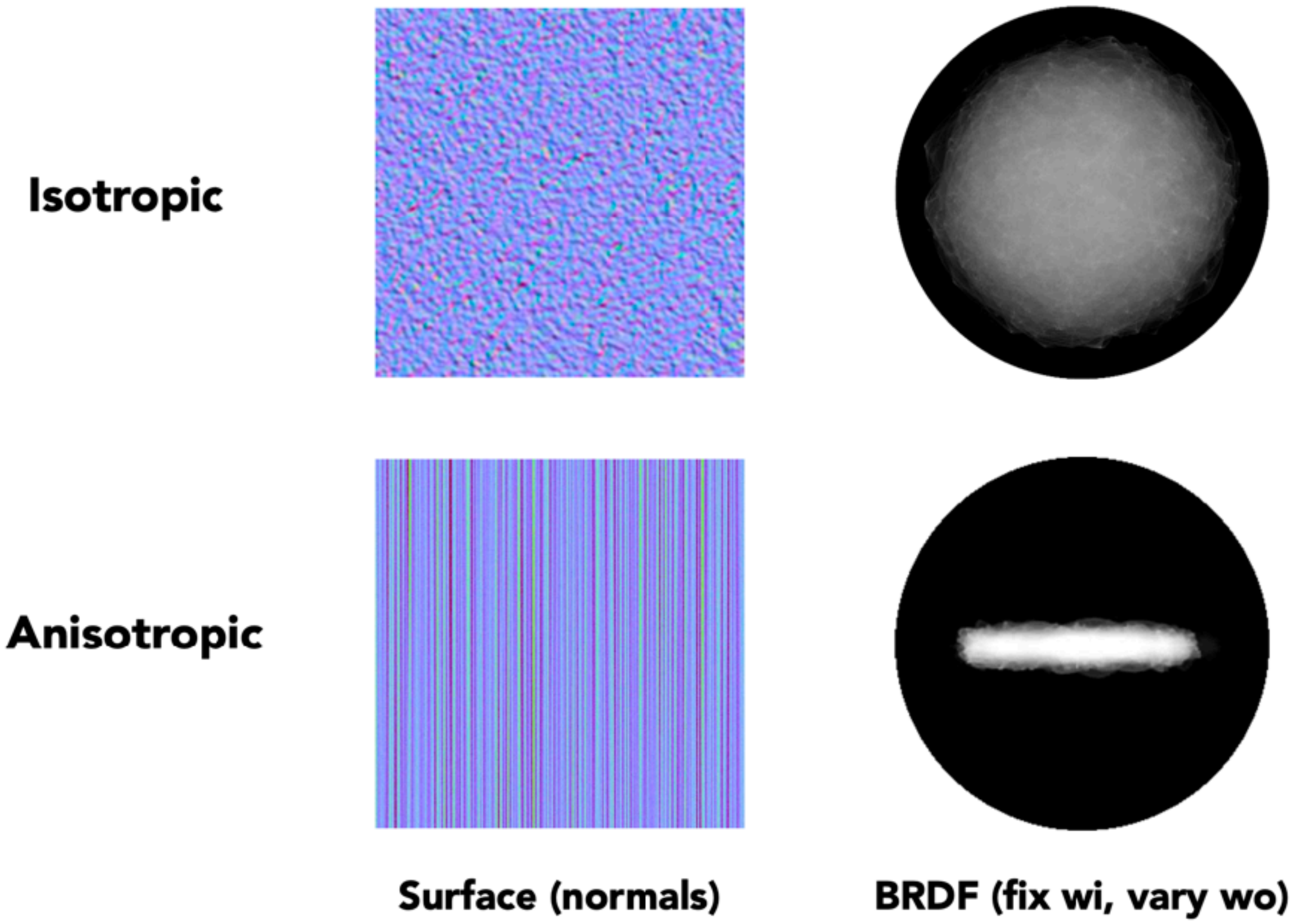

Walter et al. 2007

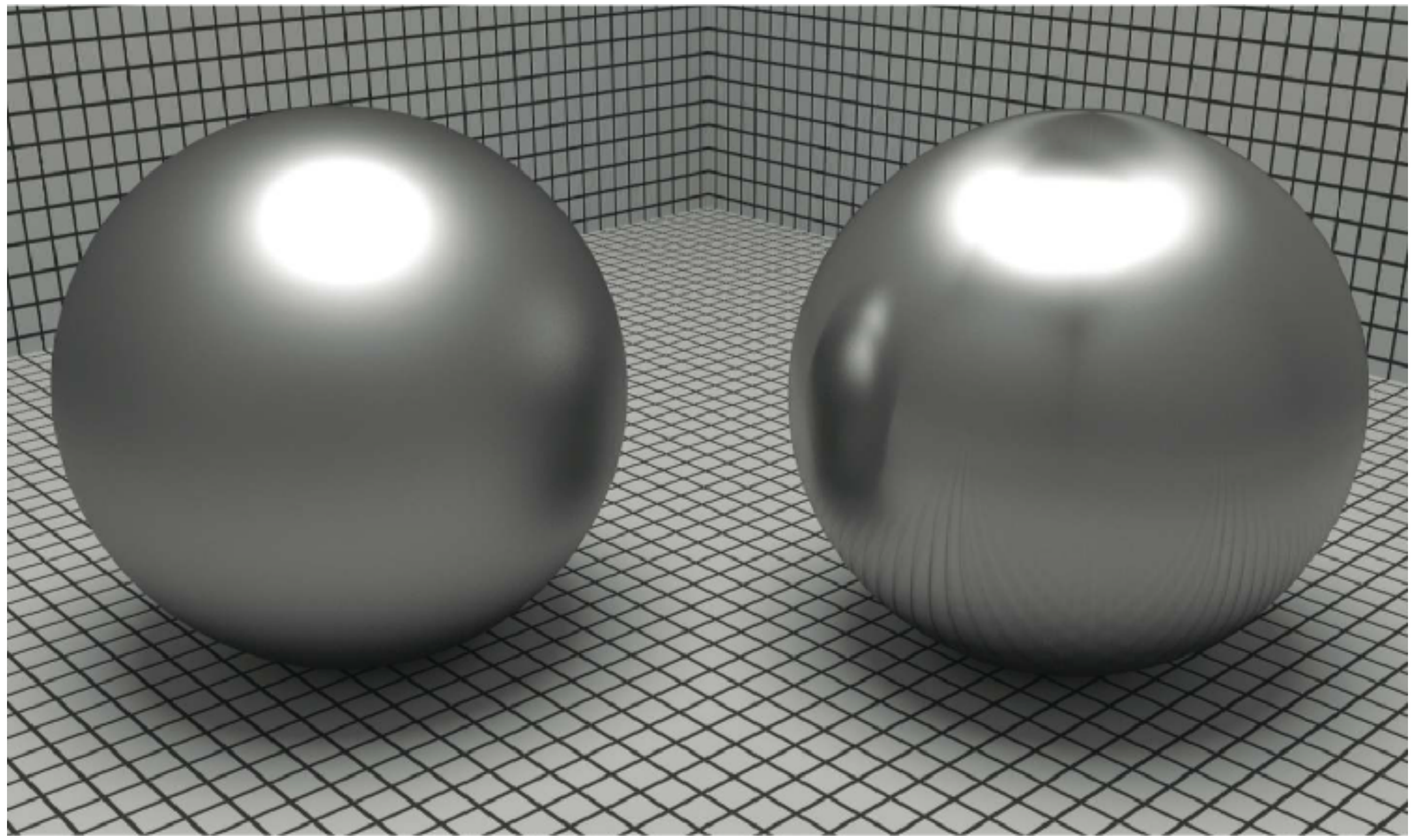

Walter et al. 2007

Quick survey of more complicated materials

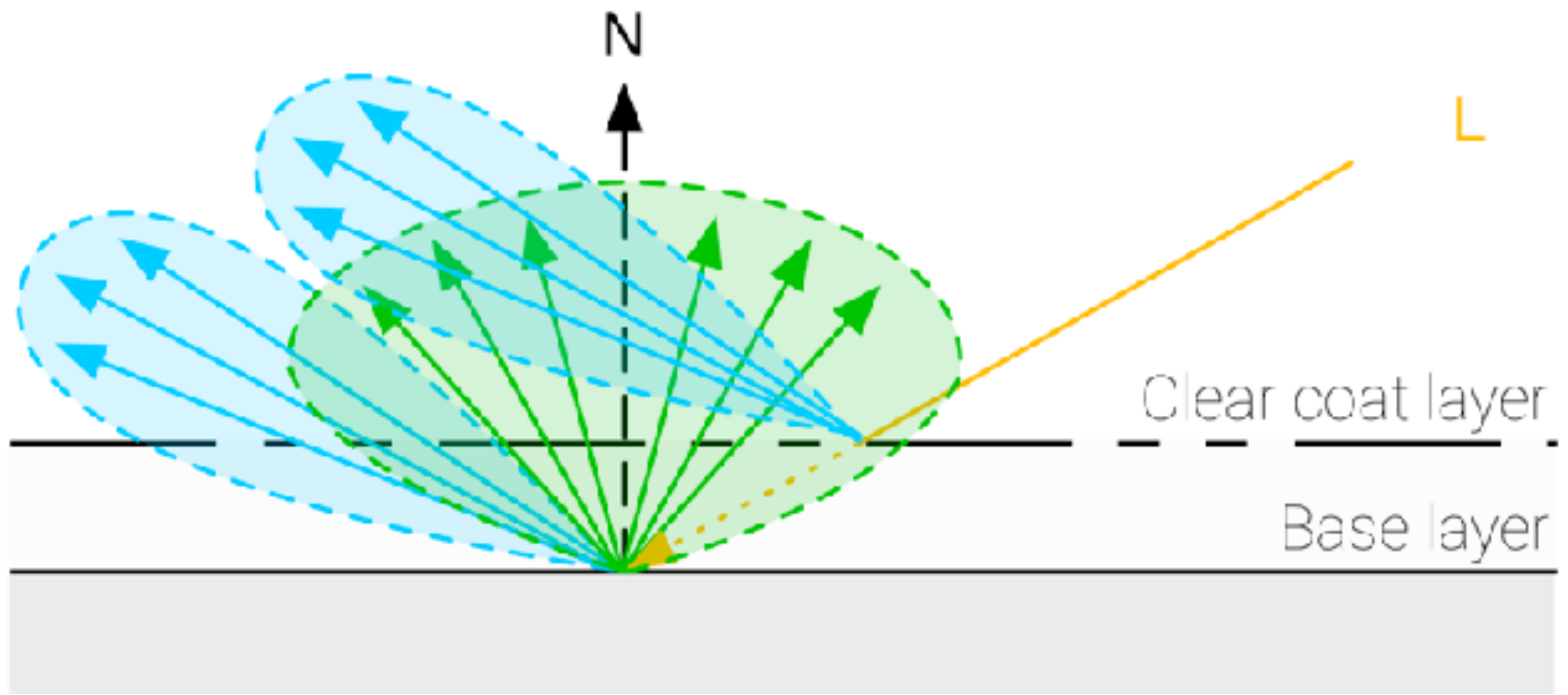
Anisotropic roughness

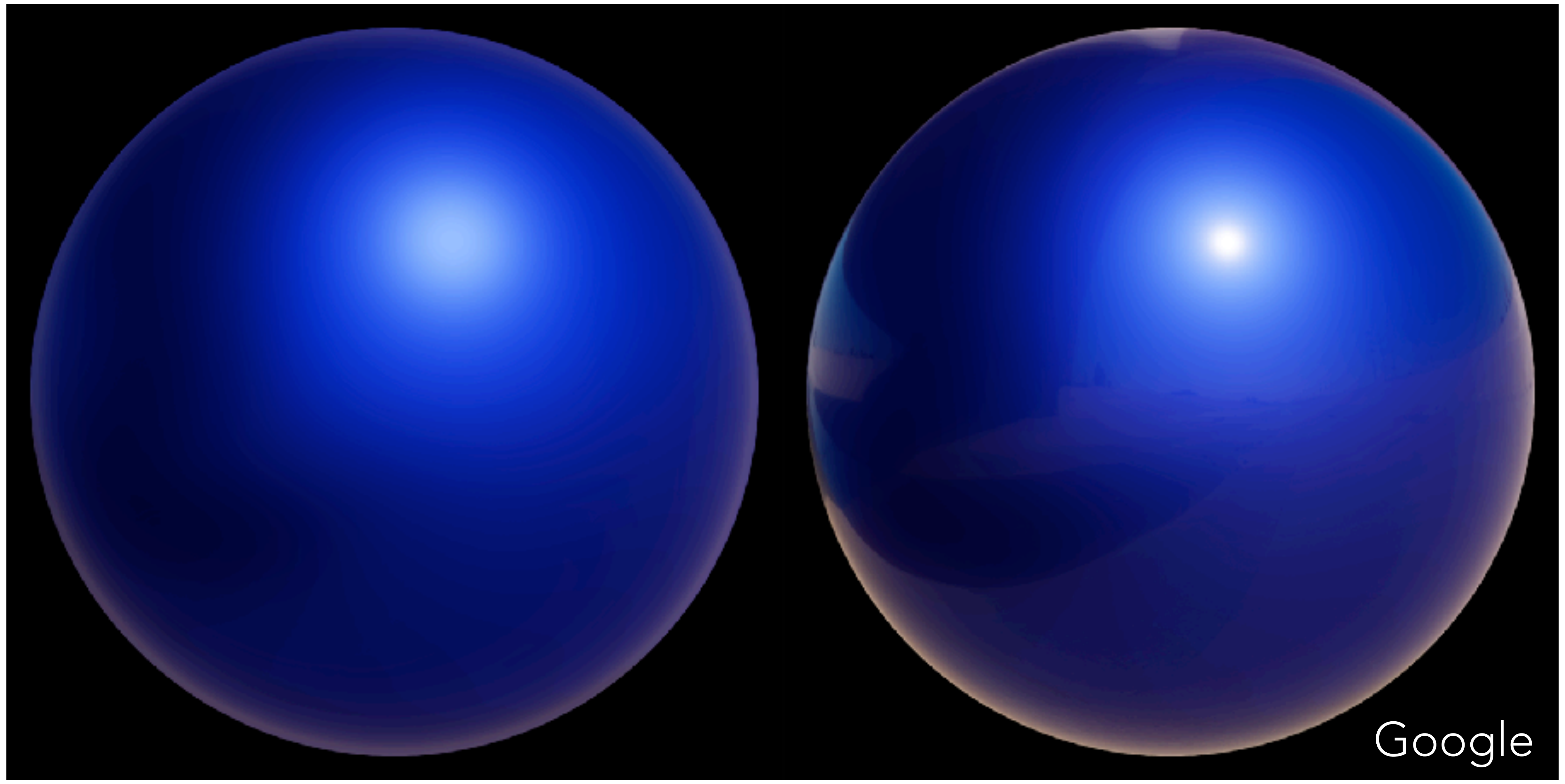
NDF is anisotropic due to oriented microstructure

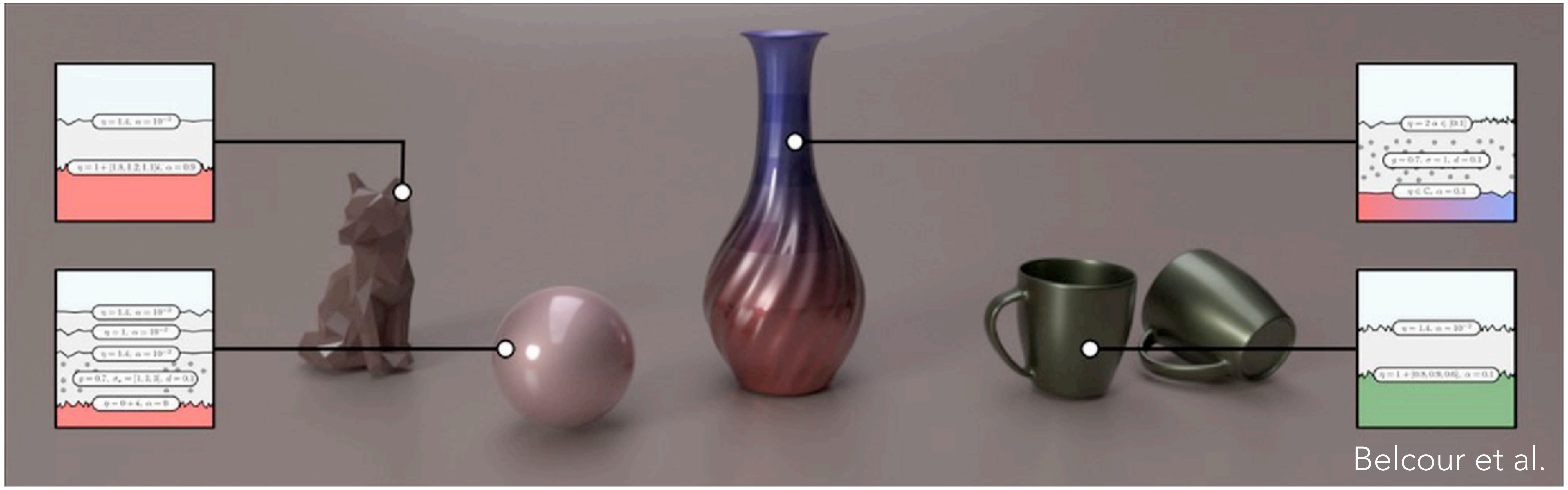




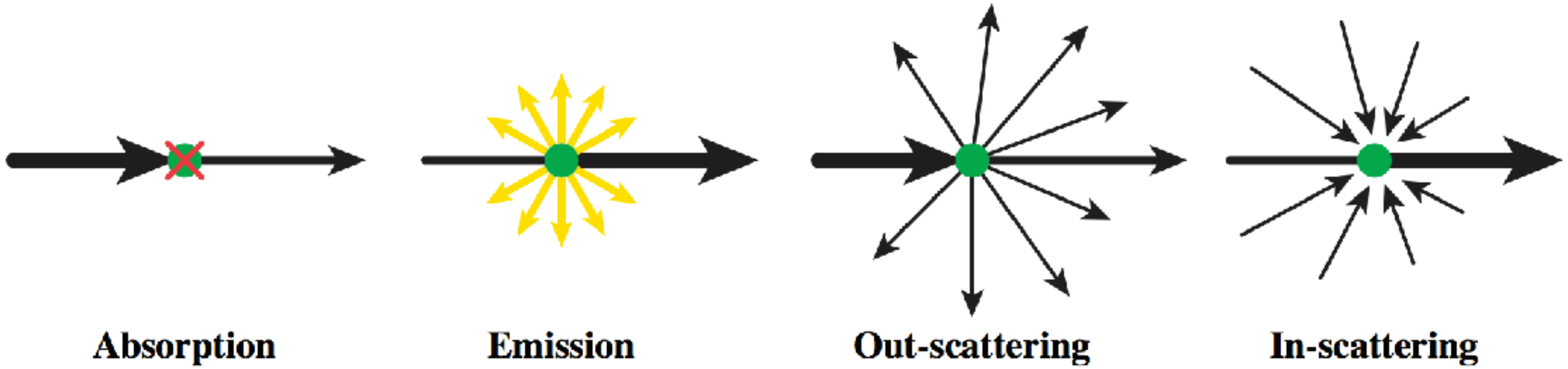
Layered materials





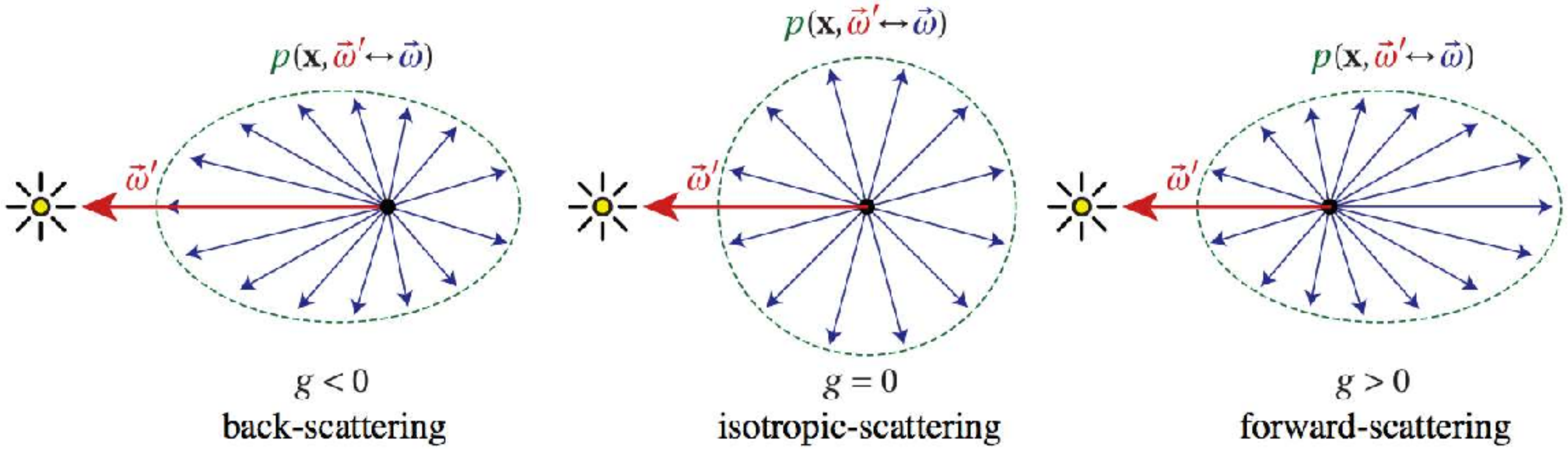


Participating media



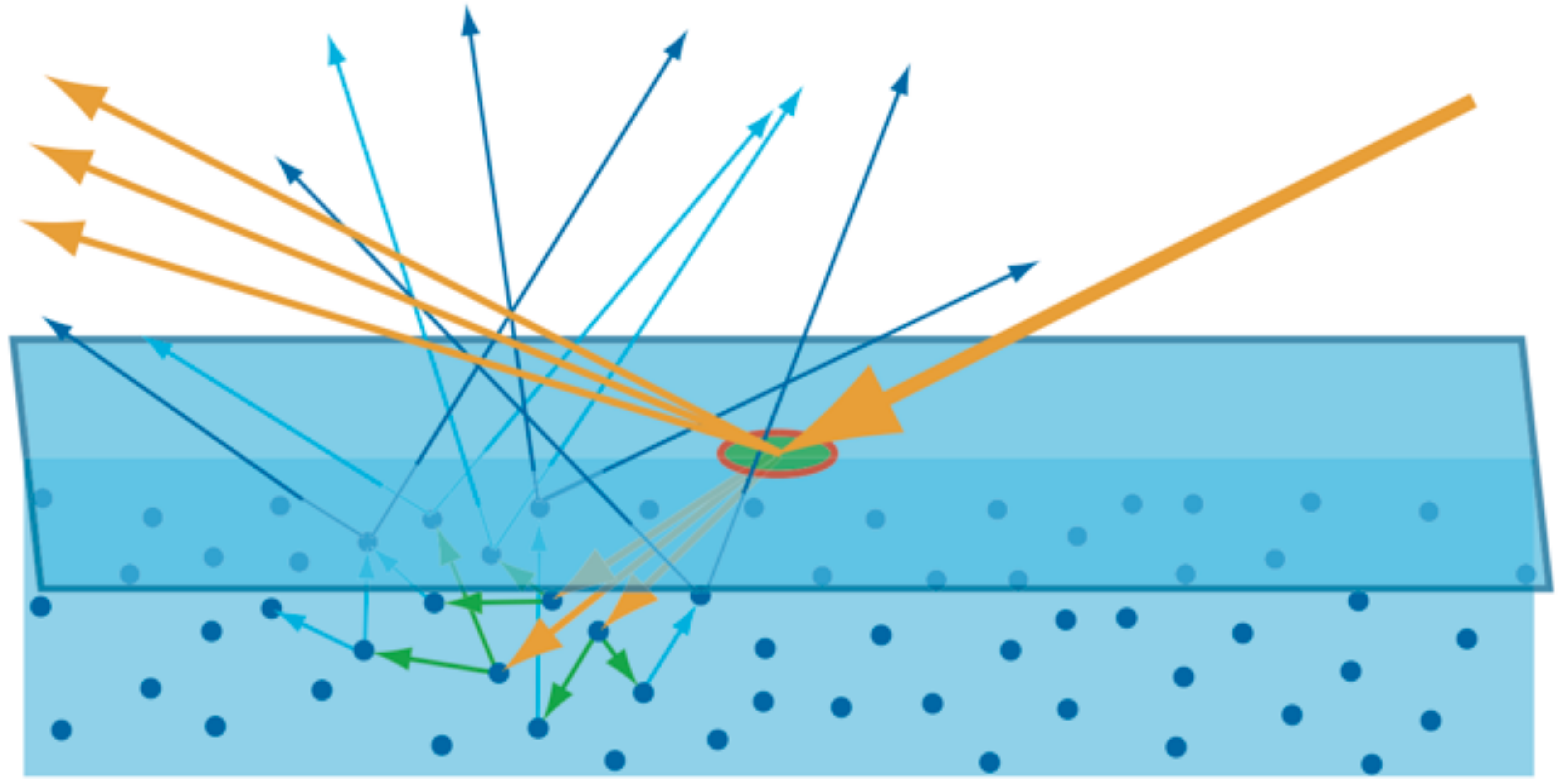
Wojciech Jarosz

Phase function describes distribution of scattered ray directions



Wojciech Jarosz

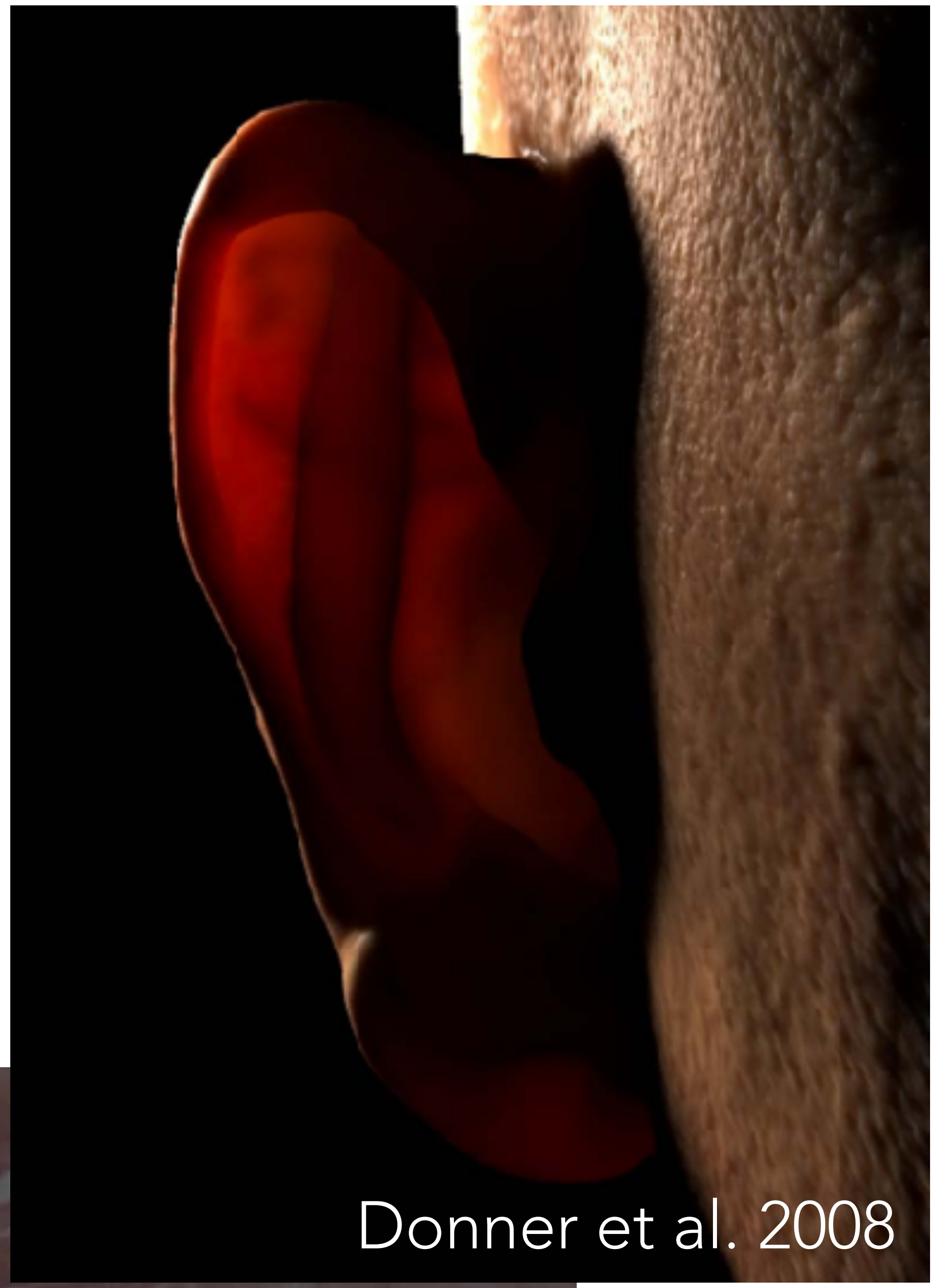
Translucent materials



Real-Time Rendering

Subsurface scattering:
Light bounces around for a non-negligible distance in the material before emerging

Cannot be described by BRDF!

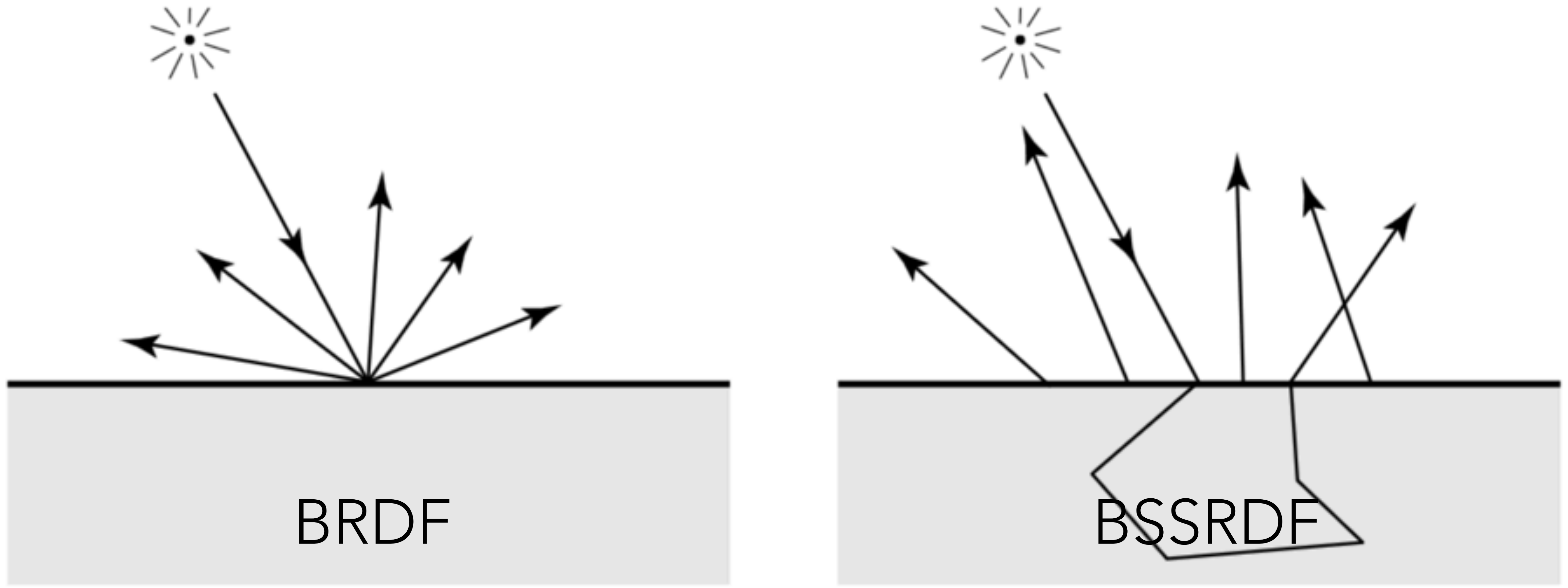


Donner et al. 2008

Jensen et al. 2001

BRDF: R($\boldsymbol{\omega}_i$, $\boldsymbol{\omega}_o$)

BSSRDF (bidirectional surface scattering RDF): $S(\mathbf{x}_i, \boldsymbol{\omega}_i, \mathbf{x}_o, \boldsymbol{\omega}_o)$



Now exitant radiance is

$$L_o(\mathbf{x}_o, \boldsymbol{\omega}_o) = \int_A \int_{H^2} S(\mathbf{x}_i, \boldsymbol{\omega}_i, \mathbf{x}_o, \boldsymbol{\omega}_o)\, L_i(\mathbf{x}_i, \boldsymbol{\omega}_i) \cos(\theta_i)\, d\boldsymbol{\omega}_i\, dA$$

Jensen et al. 2001