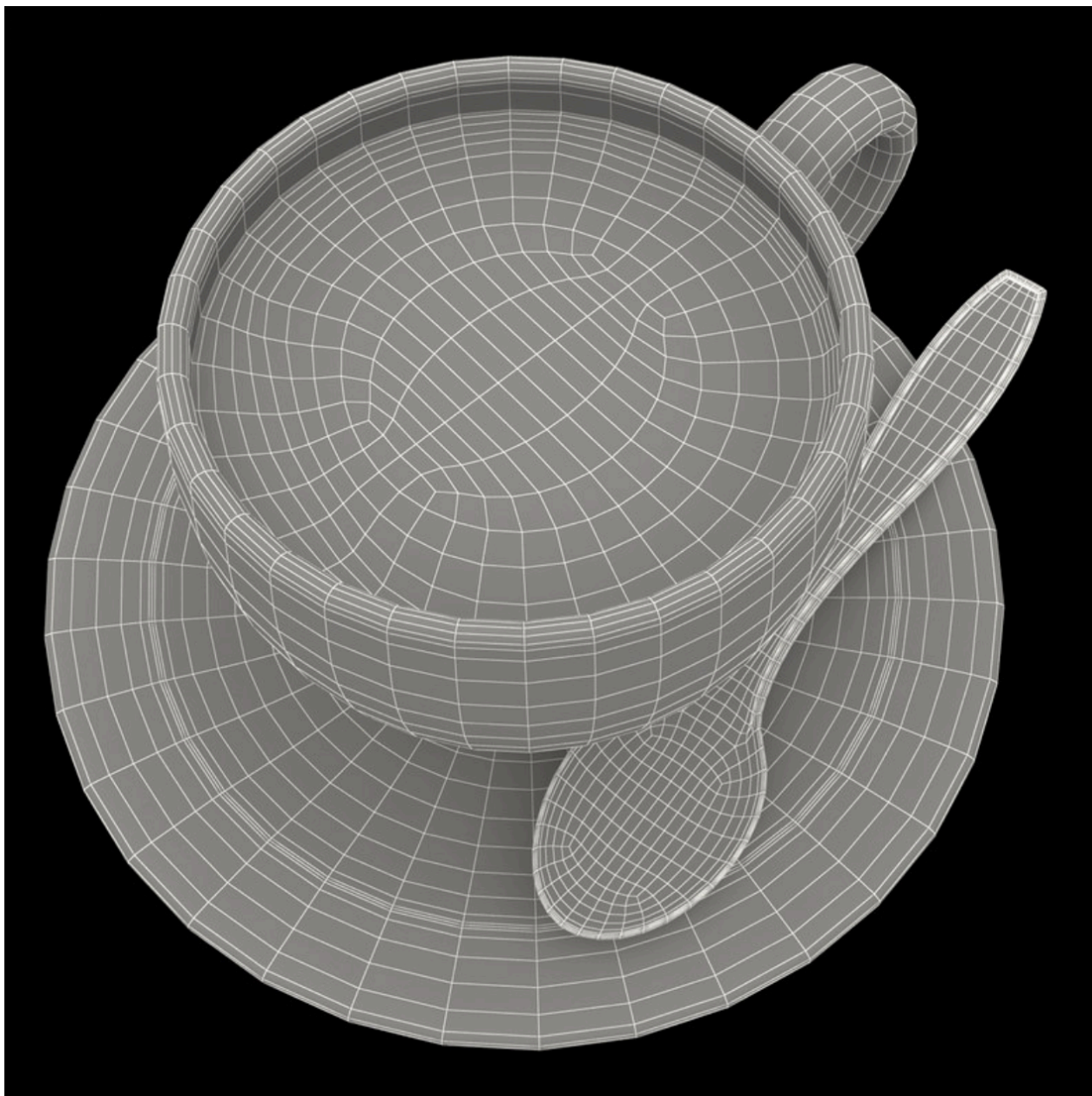


Lecture 14:

Introduction to Material Modeling

**Computer Graphics and Imaging
UC Berkeley CS184/284A**

What is Material in Computer Graphics?



3D coffee mug model



Rendered

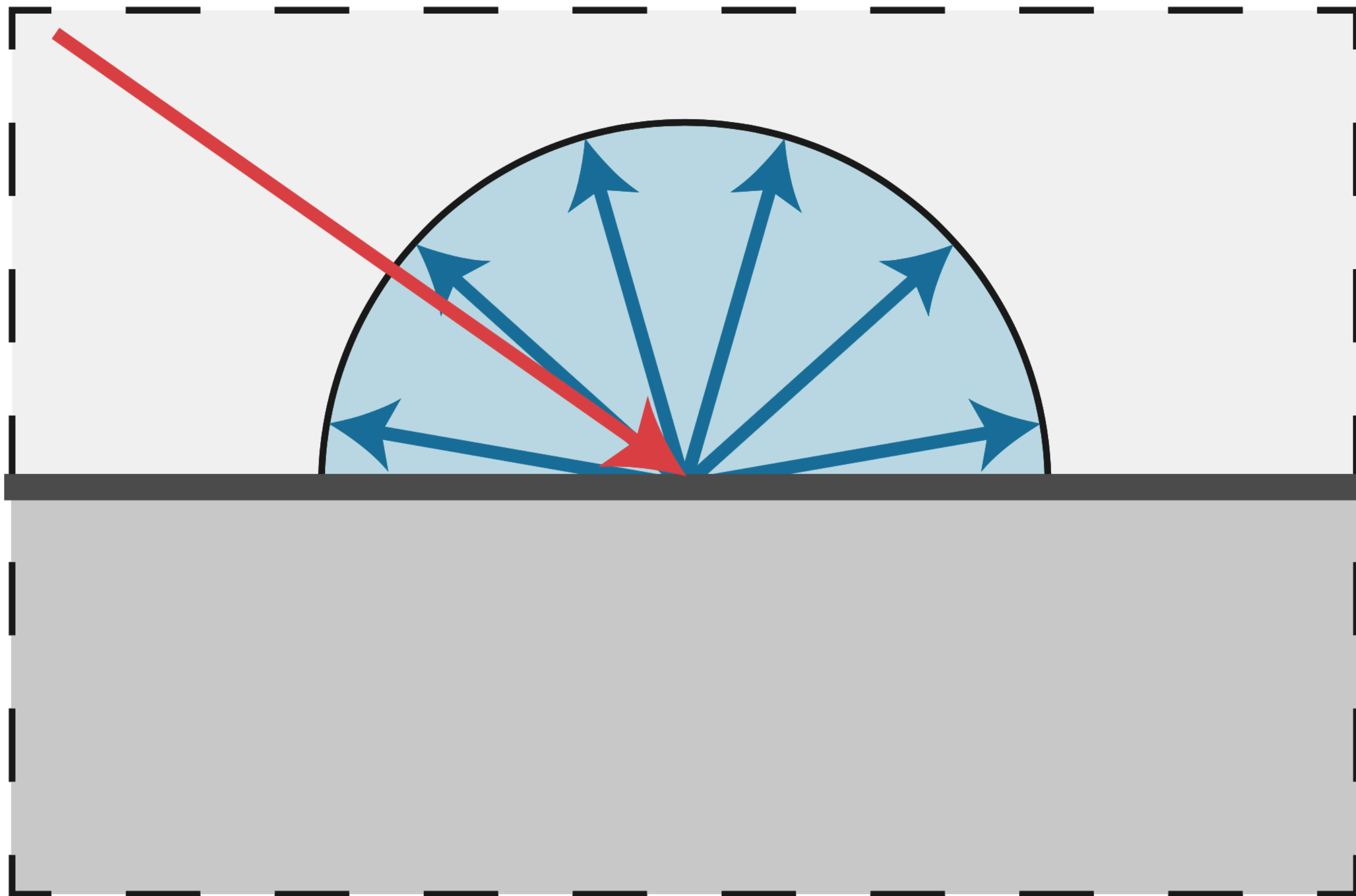


Rendered

[From TurboSquid, created by artist 3dror]

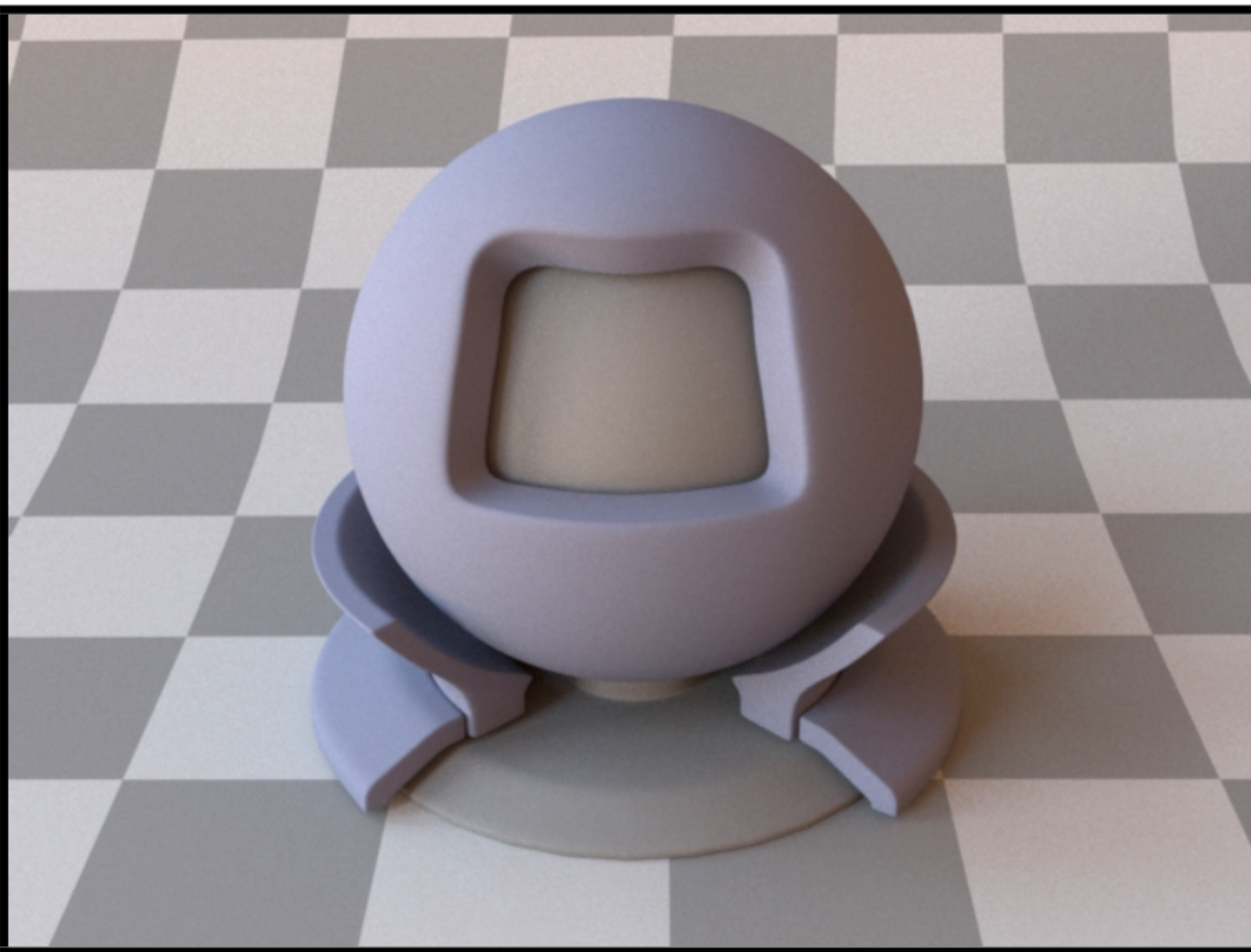
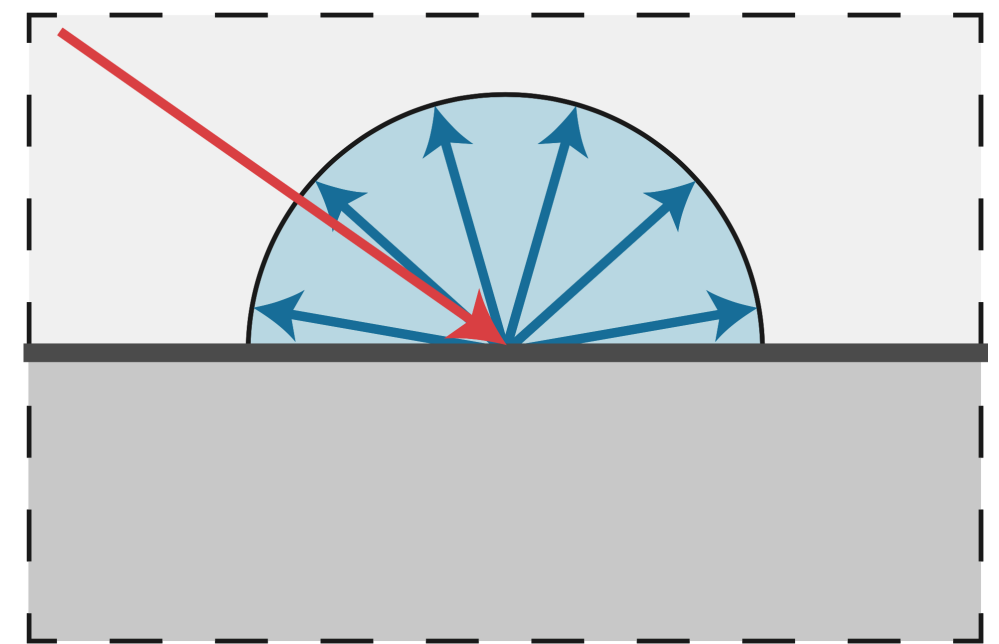
Material == BRDF

What is this material?

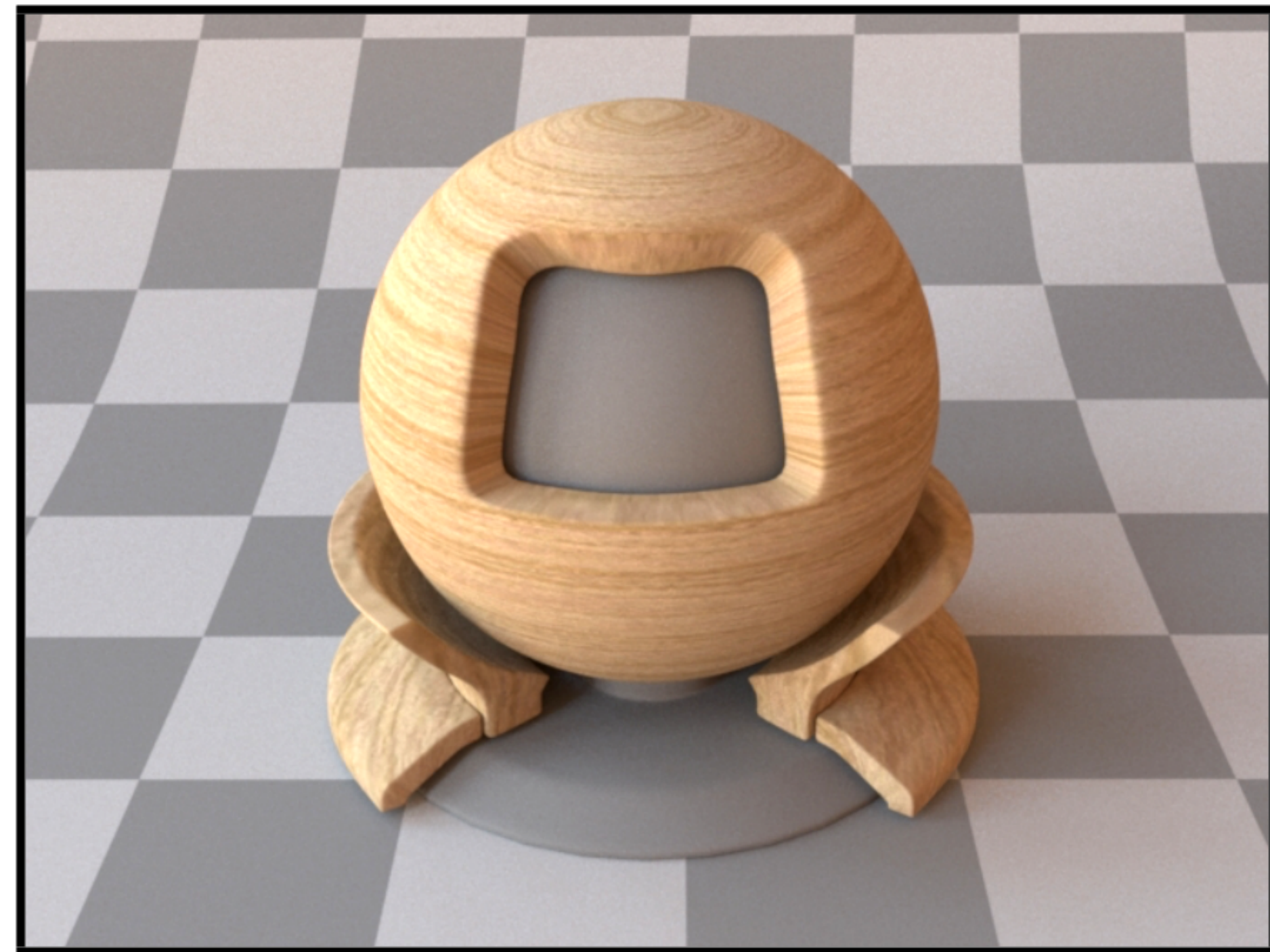


Diffuse / Lambertian Material (BRDF)

Definition: The bidirectional reflectance distribution function (BRDF) represents how much light is reflected into each outgoing direction from each incoming direction



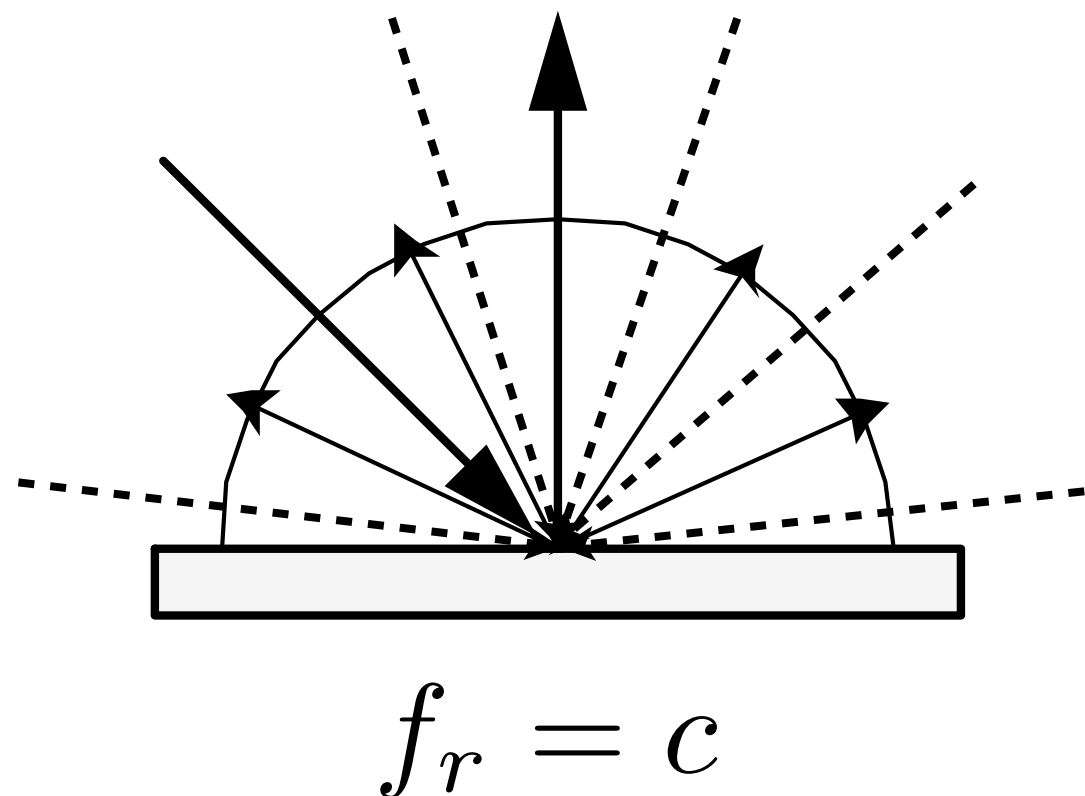
Uniform colored diffuse BRDF



Textured diffuse BRDF

Diffuse / Lambertian Material

Light is equally reflected in each output direction

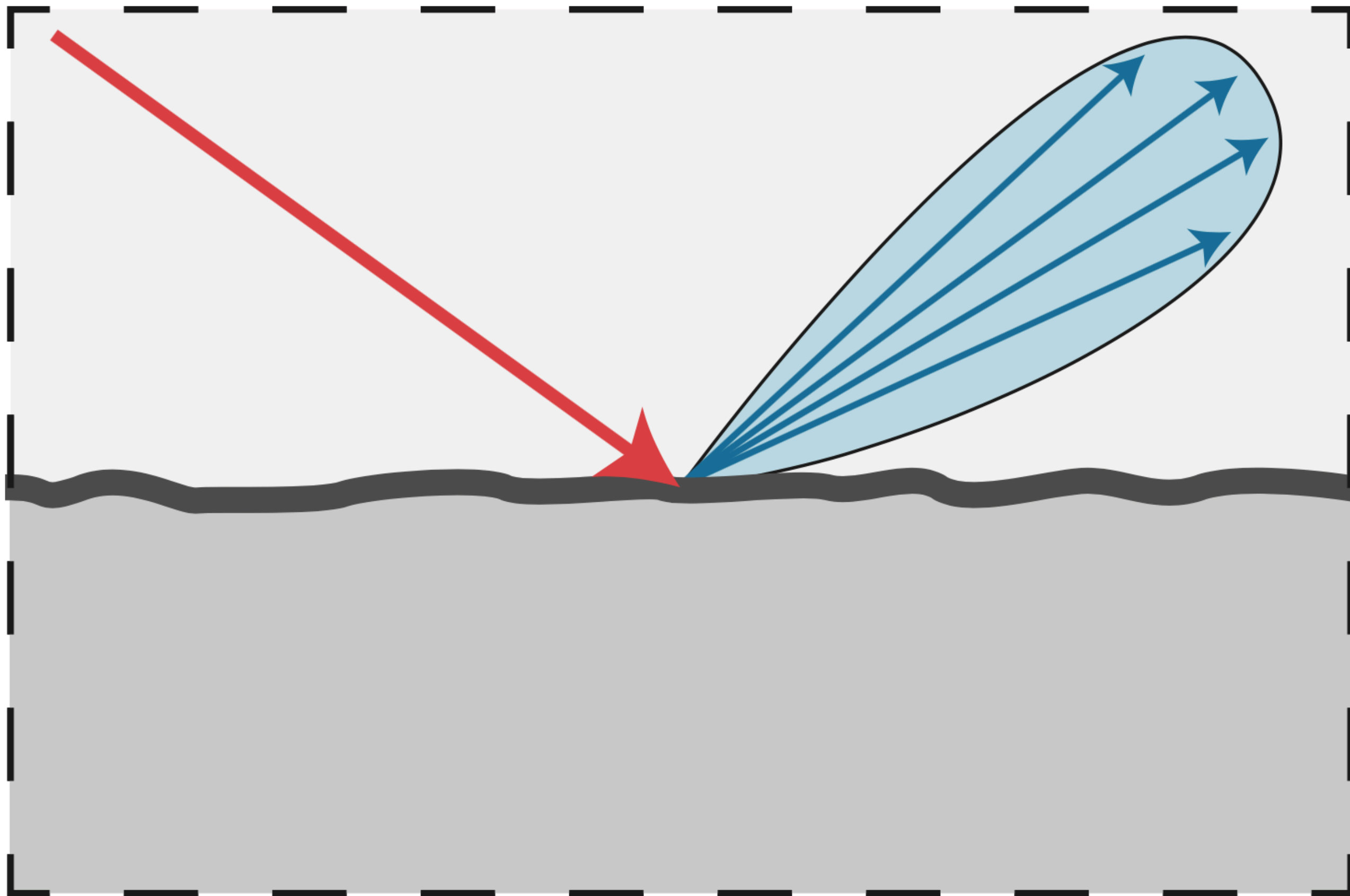


Suppose the incident lighting is **uniform**:

$$\begin{aligned} L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos \theta_i \, d\omega_i \\ &= f_r L_i \int_{H^2} \cos \theta_i \, d\omega_i \\ &= \pi f_r L_i \end{aligned}$$

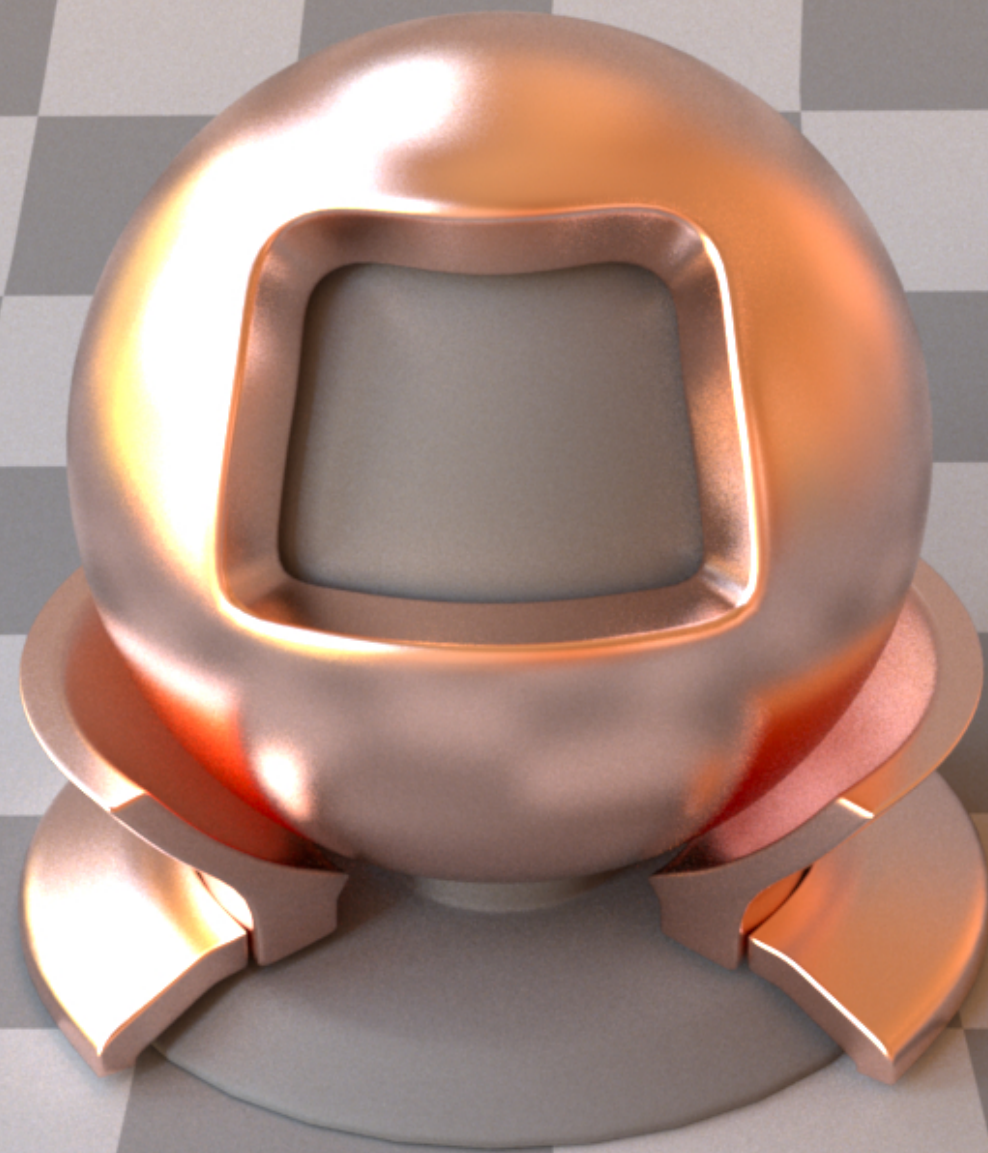
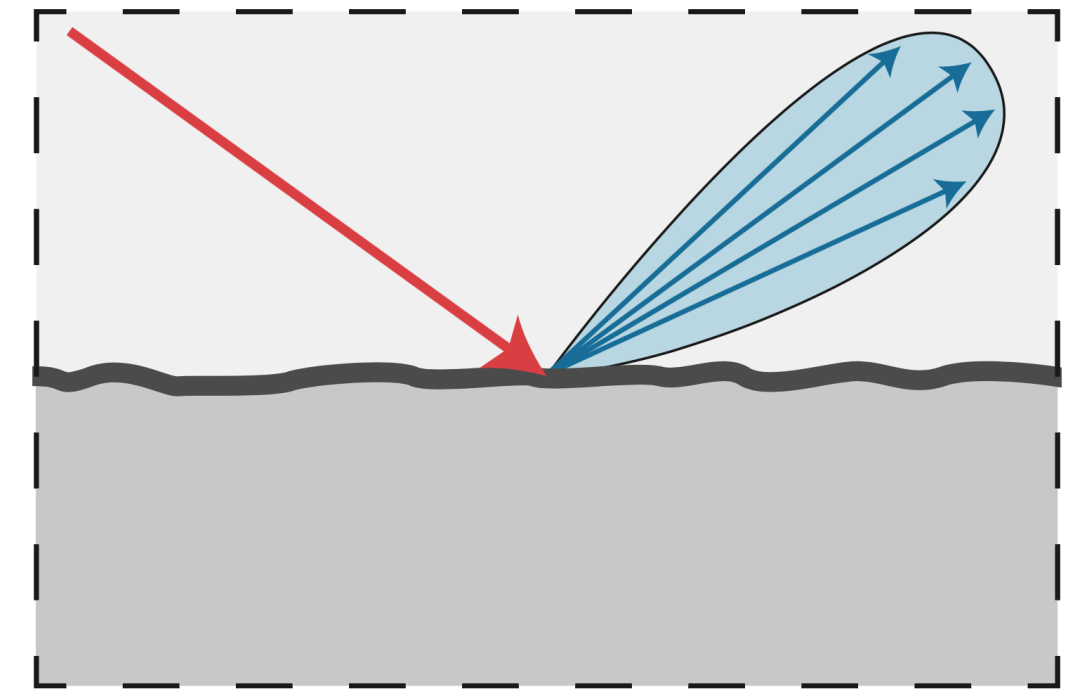
$$f_r = \frac{\rho}{\pi} \quad \text{— albedo (color)}$$

What is this material?

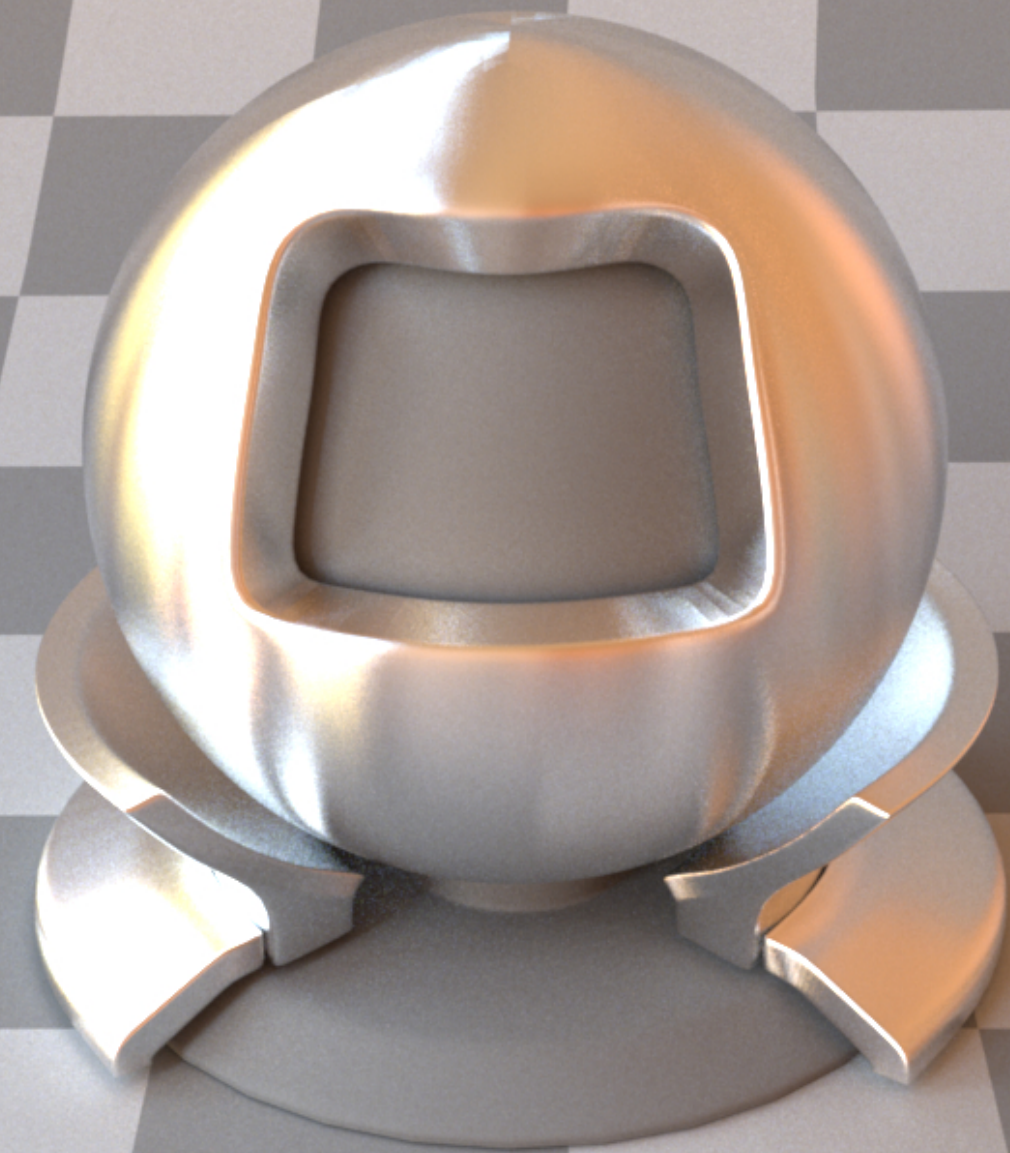


Glossy material (BRDF)

Definition: The bidirectional reflectance distribution function (BRDF) represents how much light is reflected into each outgoing direction from each incoming direction

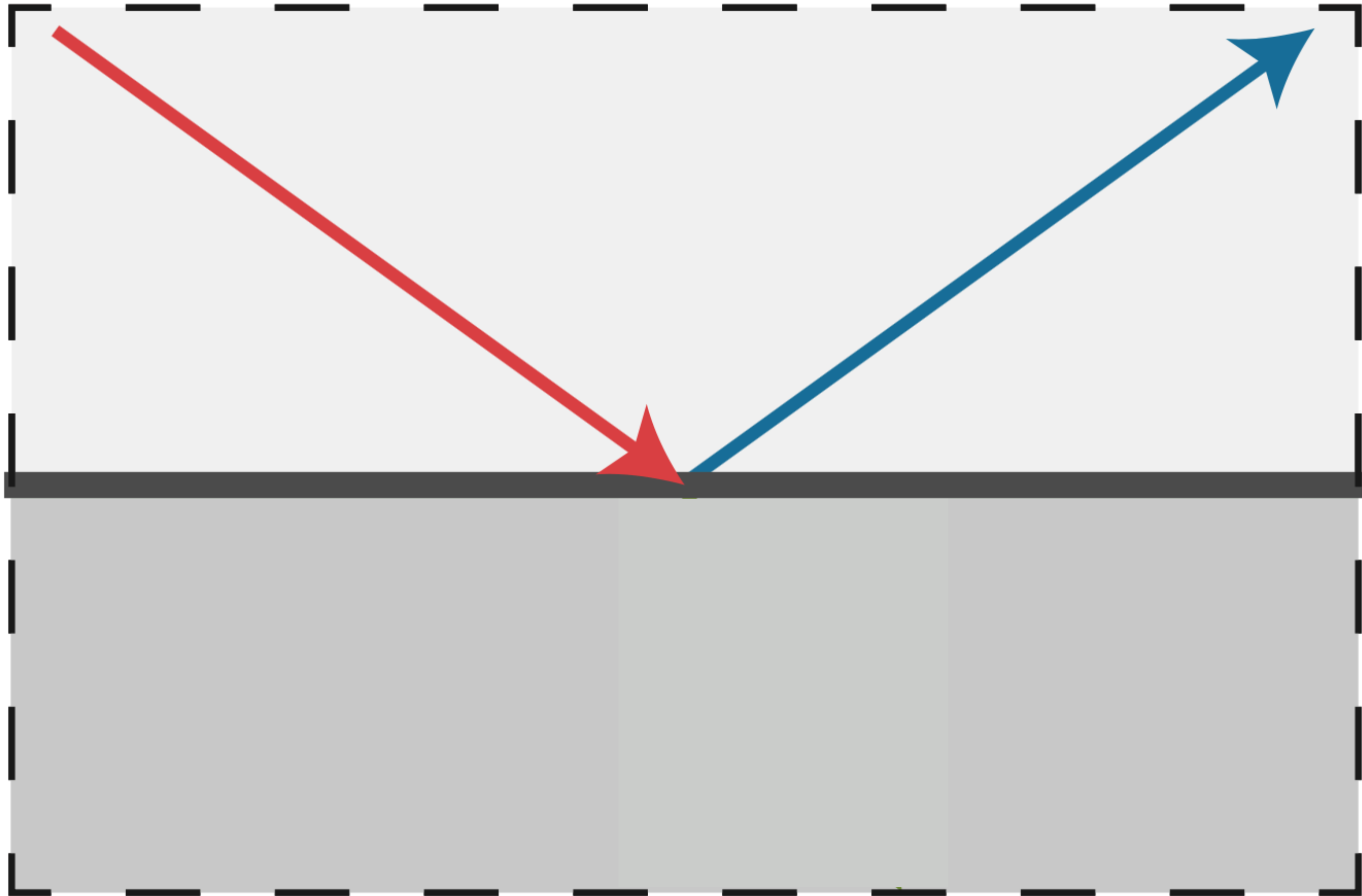


Rough Copper

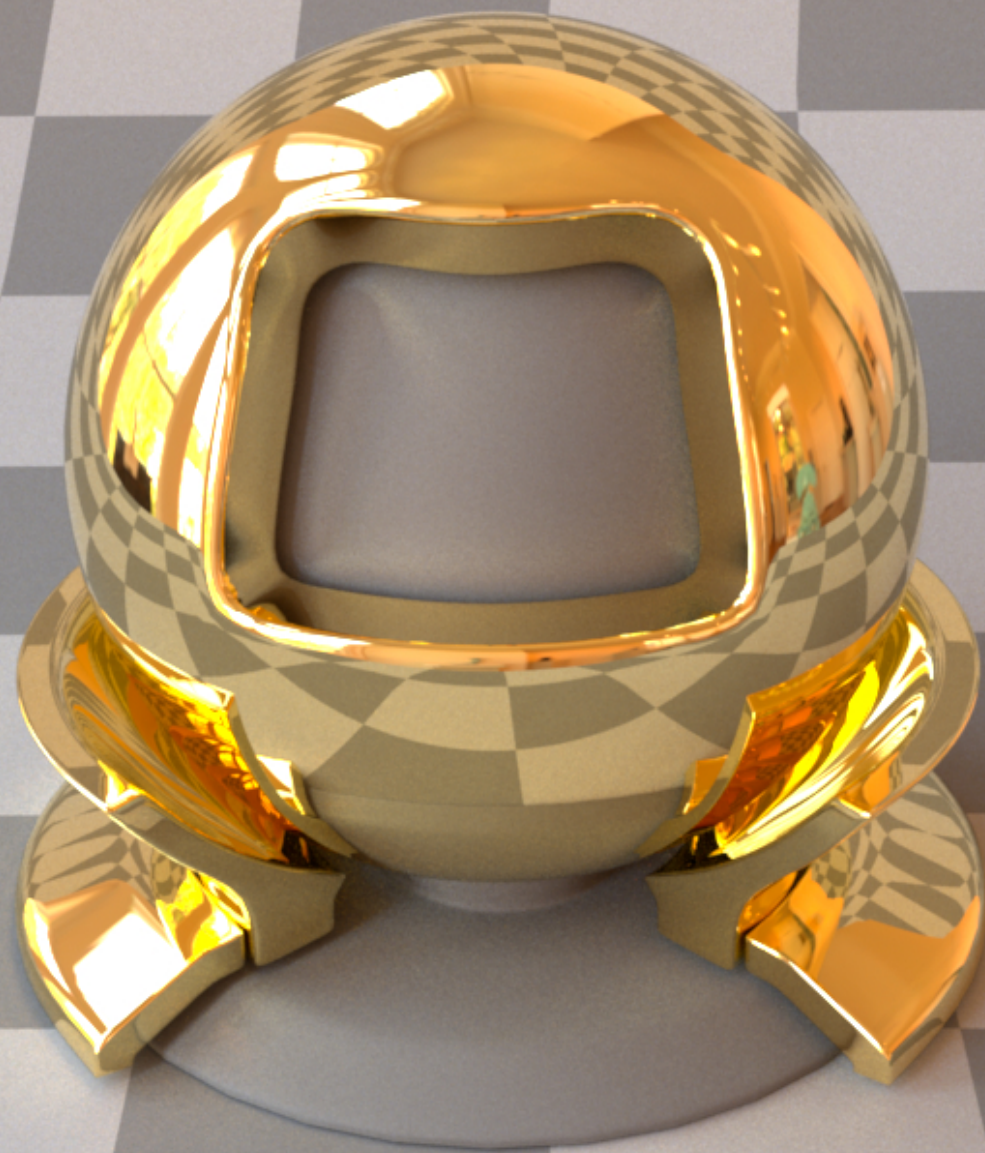
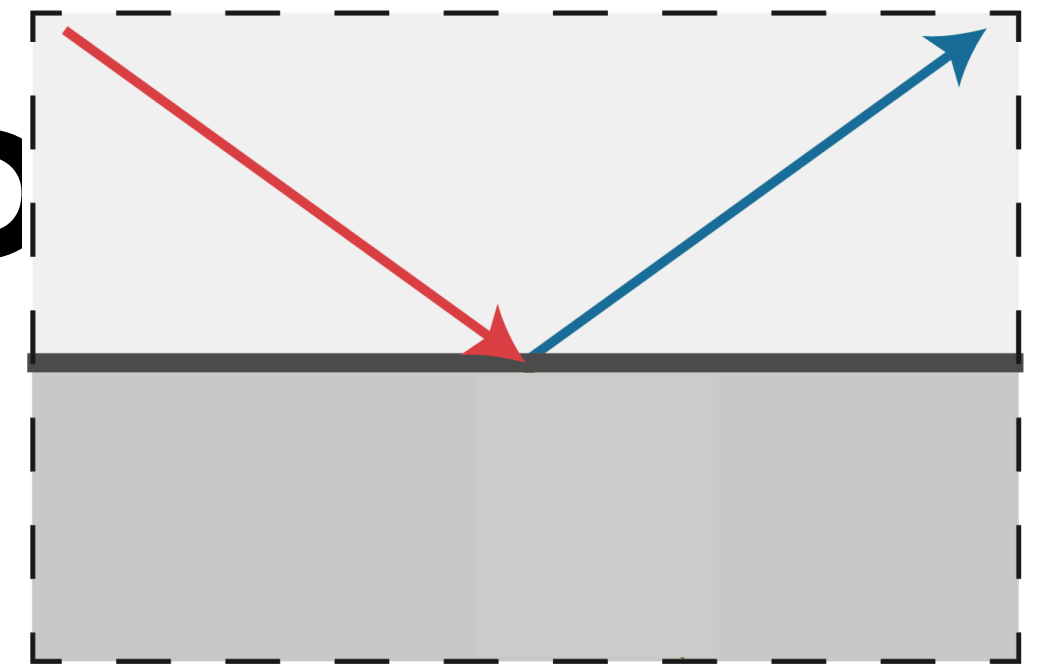


Brushed Aluminum

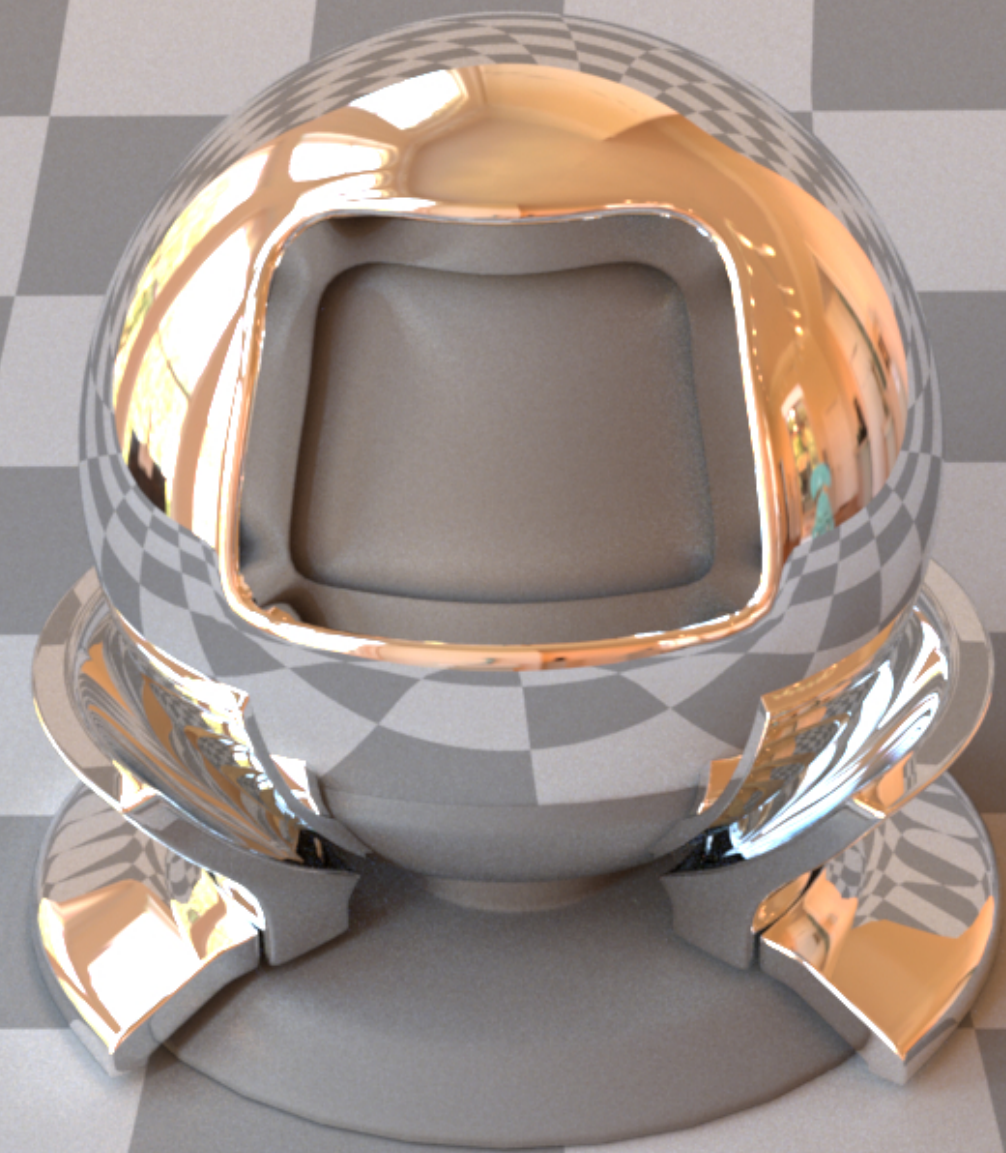
What is this material?



Ideal reflective material (BRD

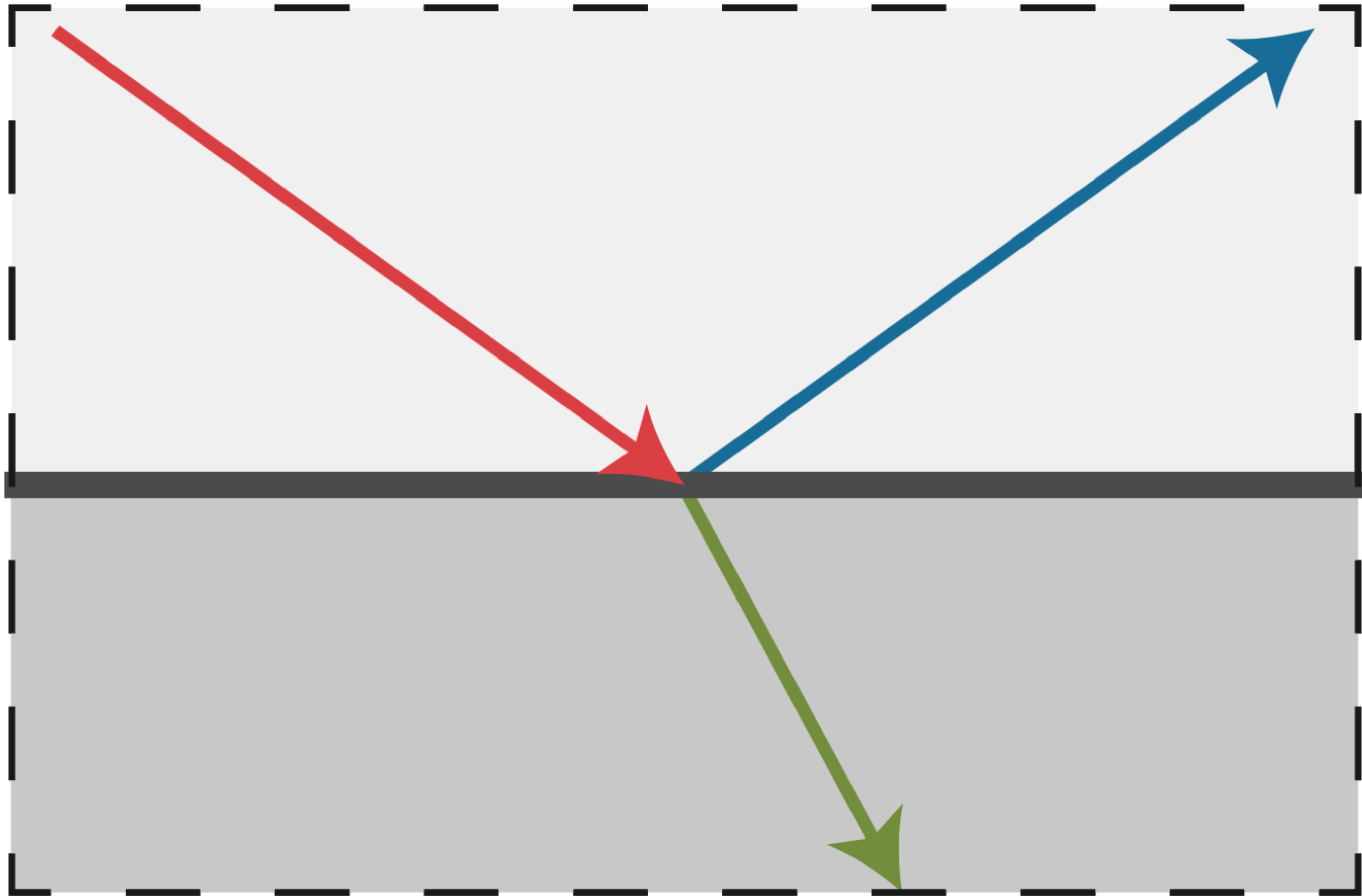


Gold



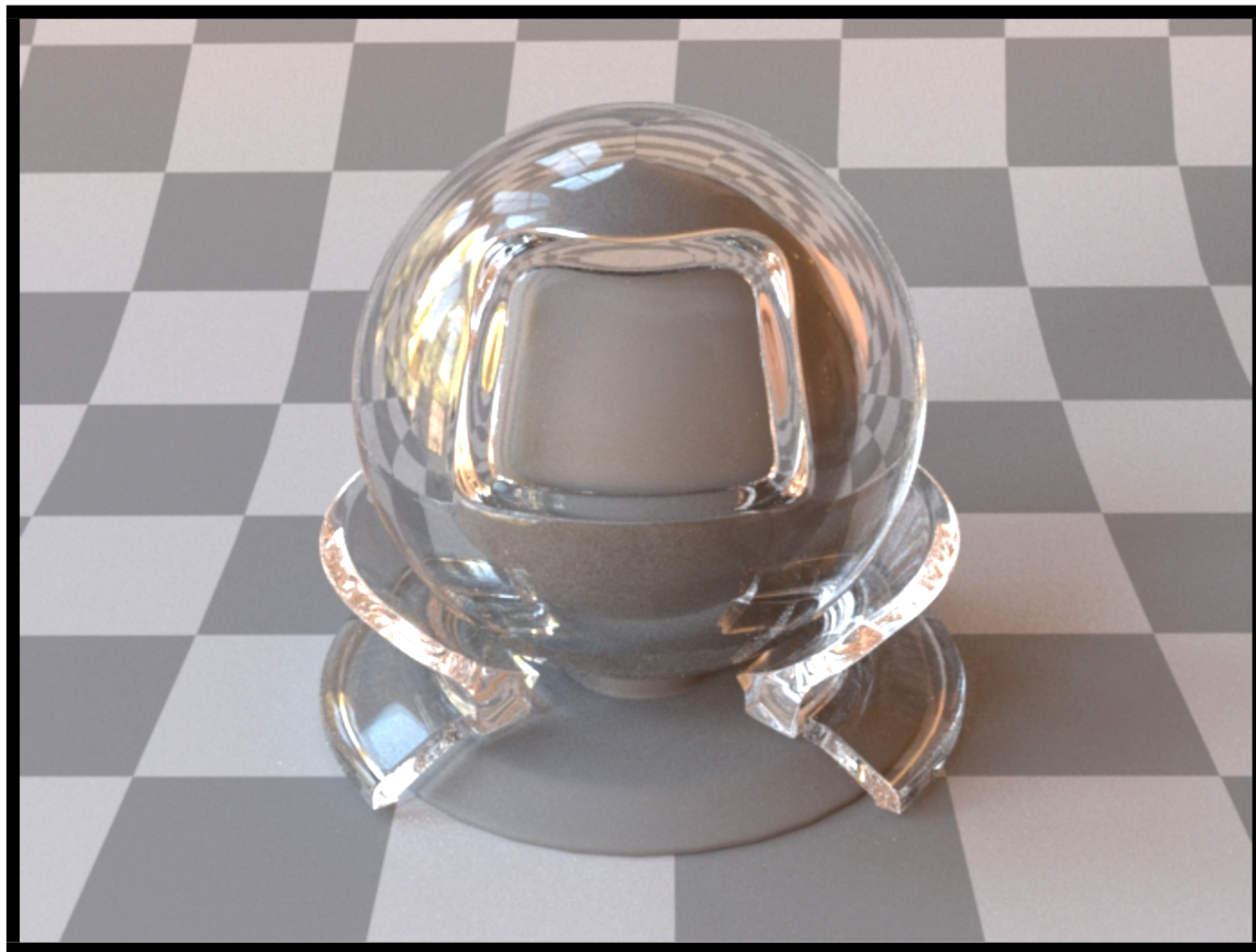
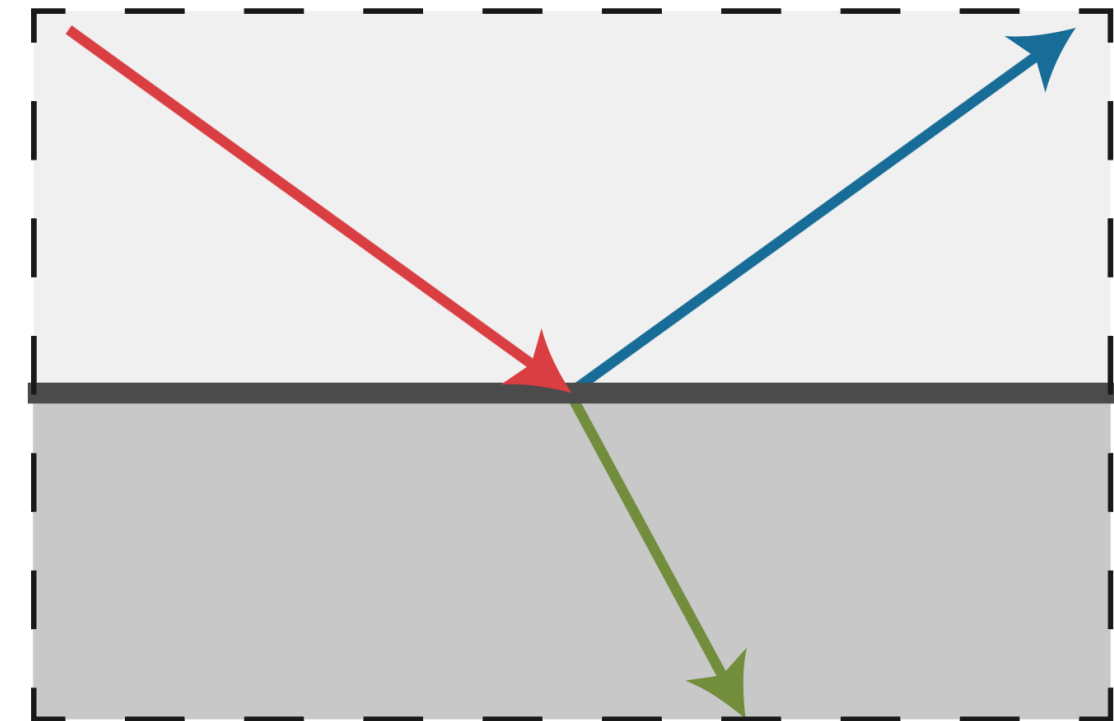
Aluminum

What is this material?

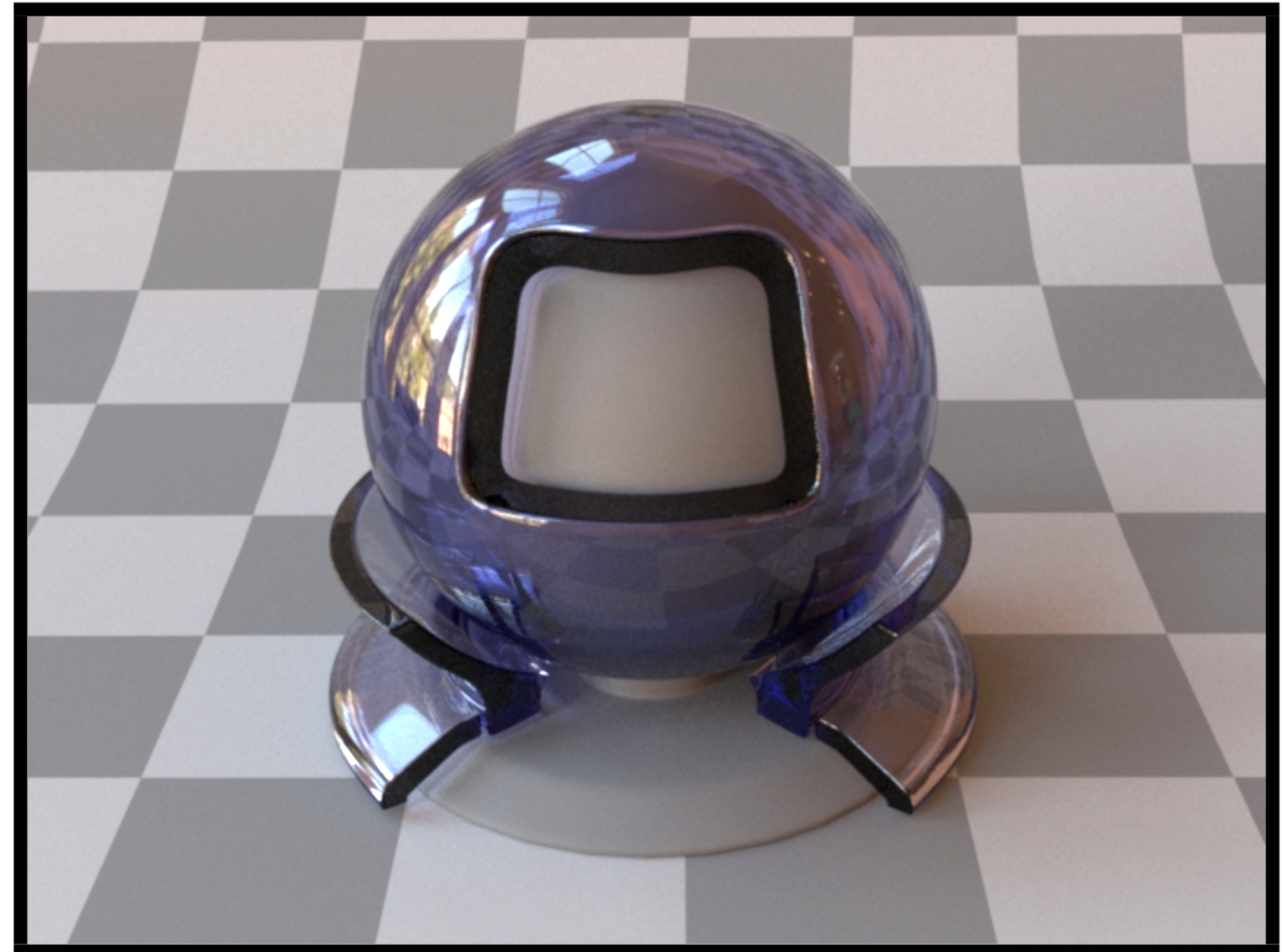


Ideal reflective / refractive material (BSDF*)

Definition: The bidirectional reflectance distribution function (BRDF) represents how much light is reflected into each outgoing direction from each incoming direction



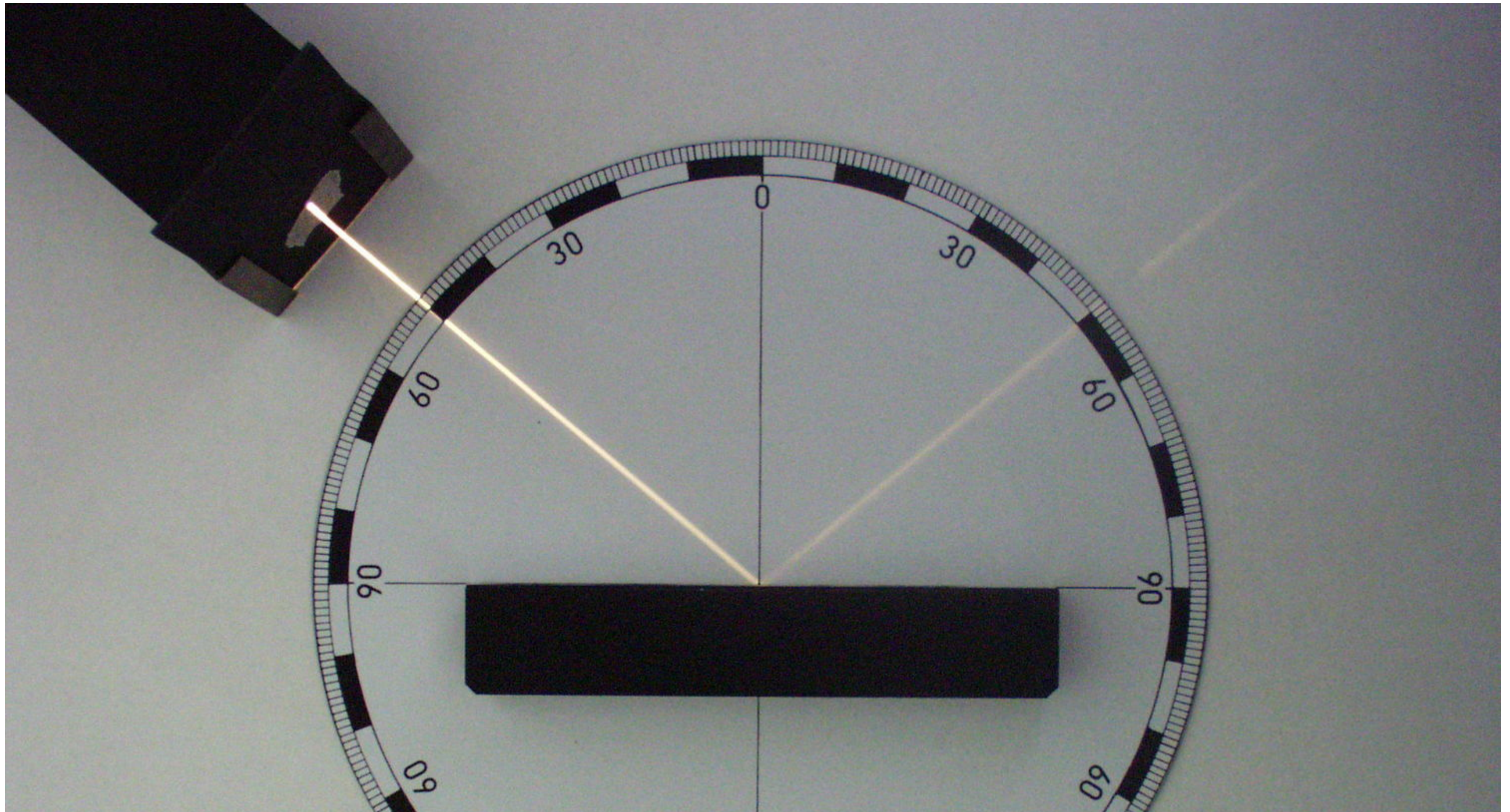
Air $\leftrightarrow$ plastic interface



**Air $\leftrightarrow$ glass interface
(with absorption)**

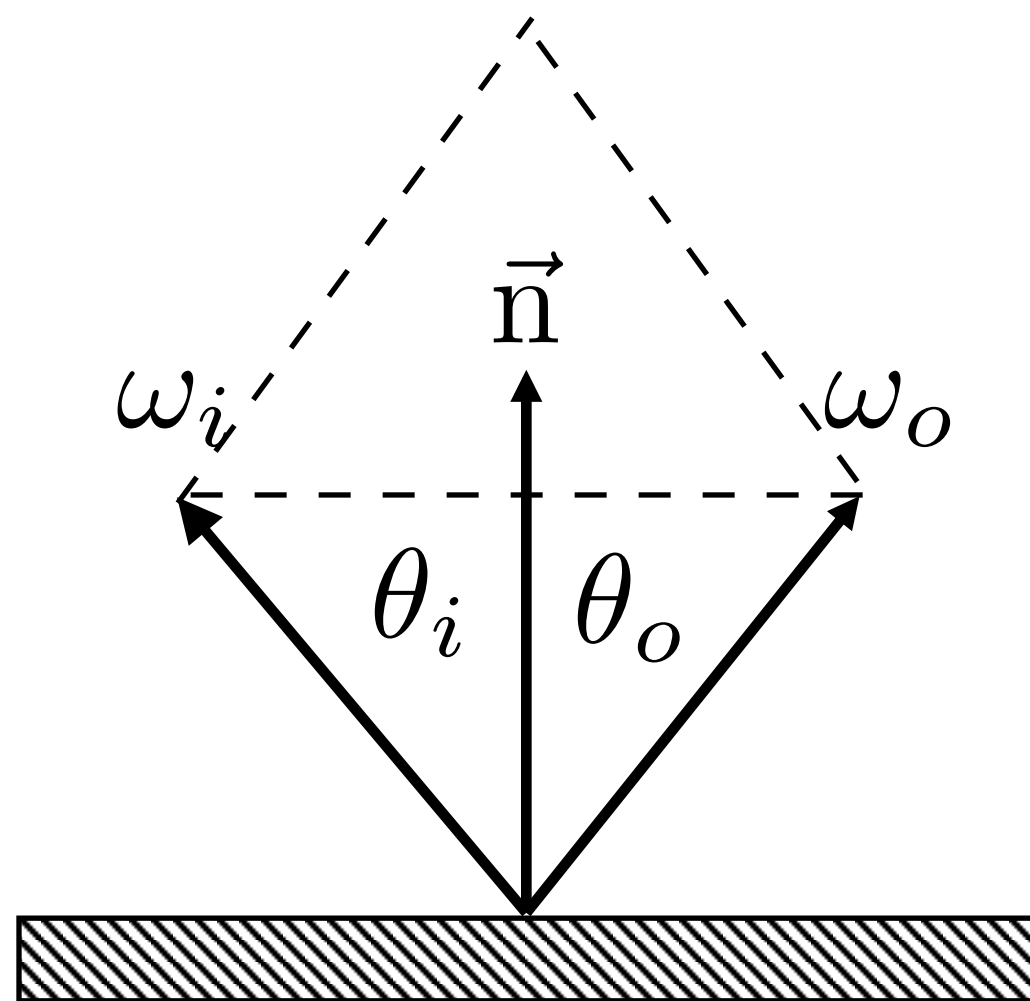
Ideal Reflection and Refraction

Perfect Specular Reflection



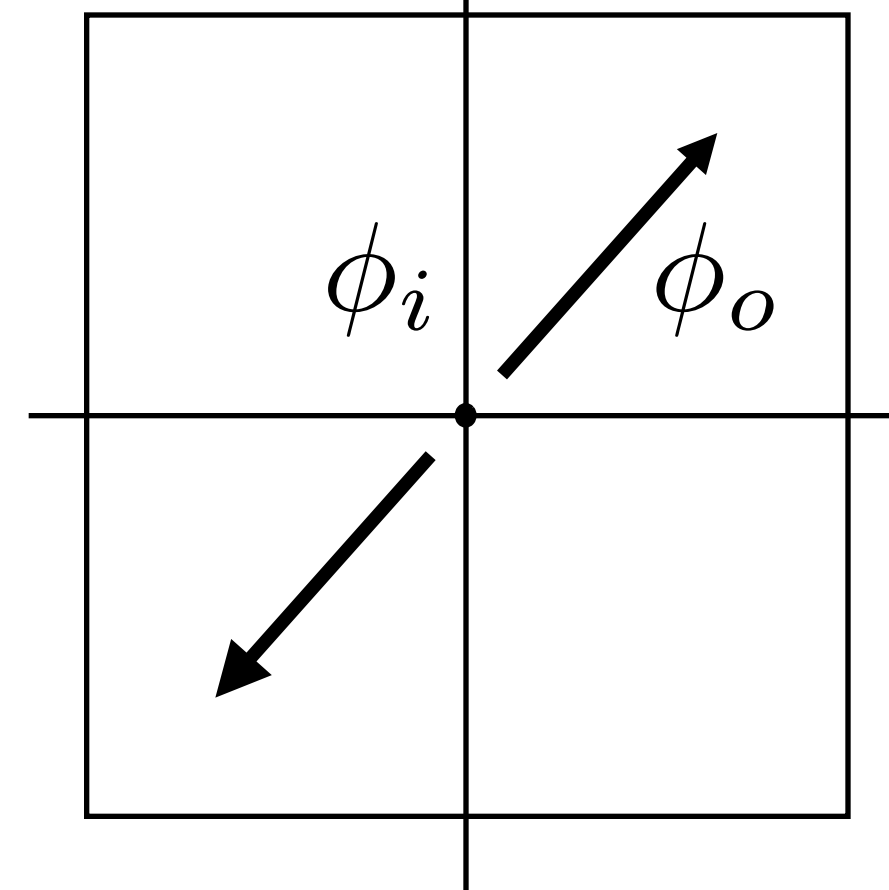
[Zátonyi Sándor]

Perfect Specular Reflection



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

Top-down view
(looking down on surface)



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

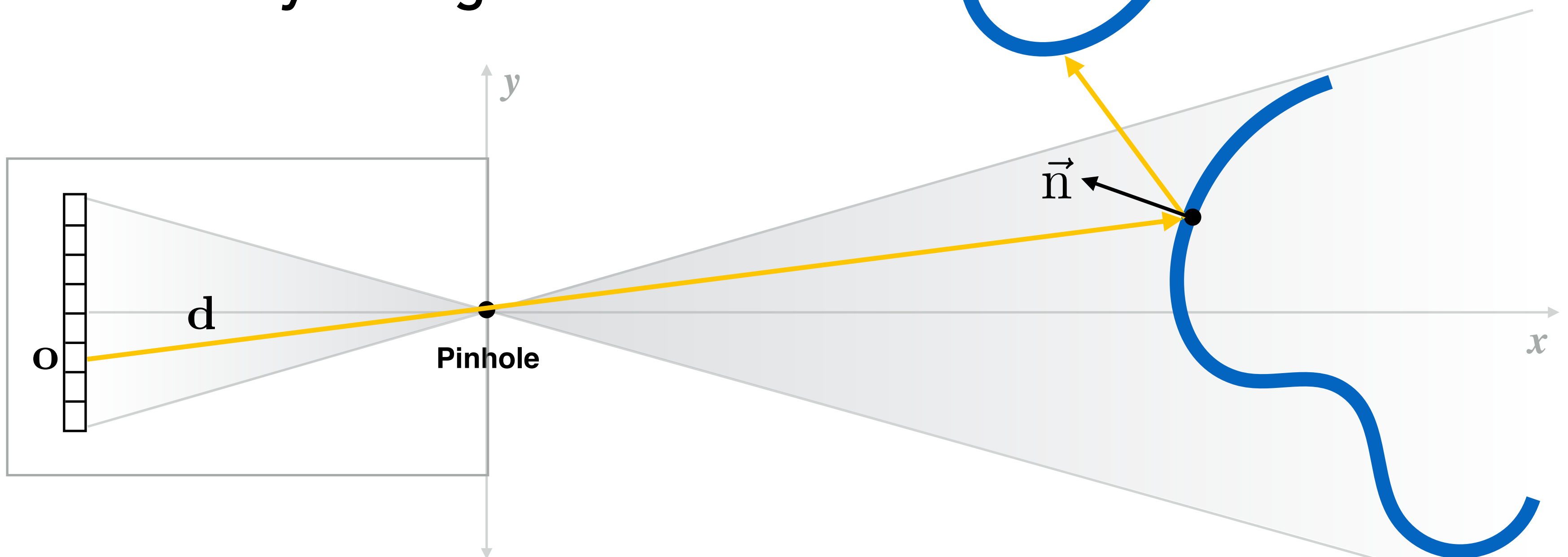
$$\omega_o + \omega_i = 2 \cos \theta \vec{n} = 2(\omega_i \cdot \vec{n})\vec{n}$$

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

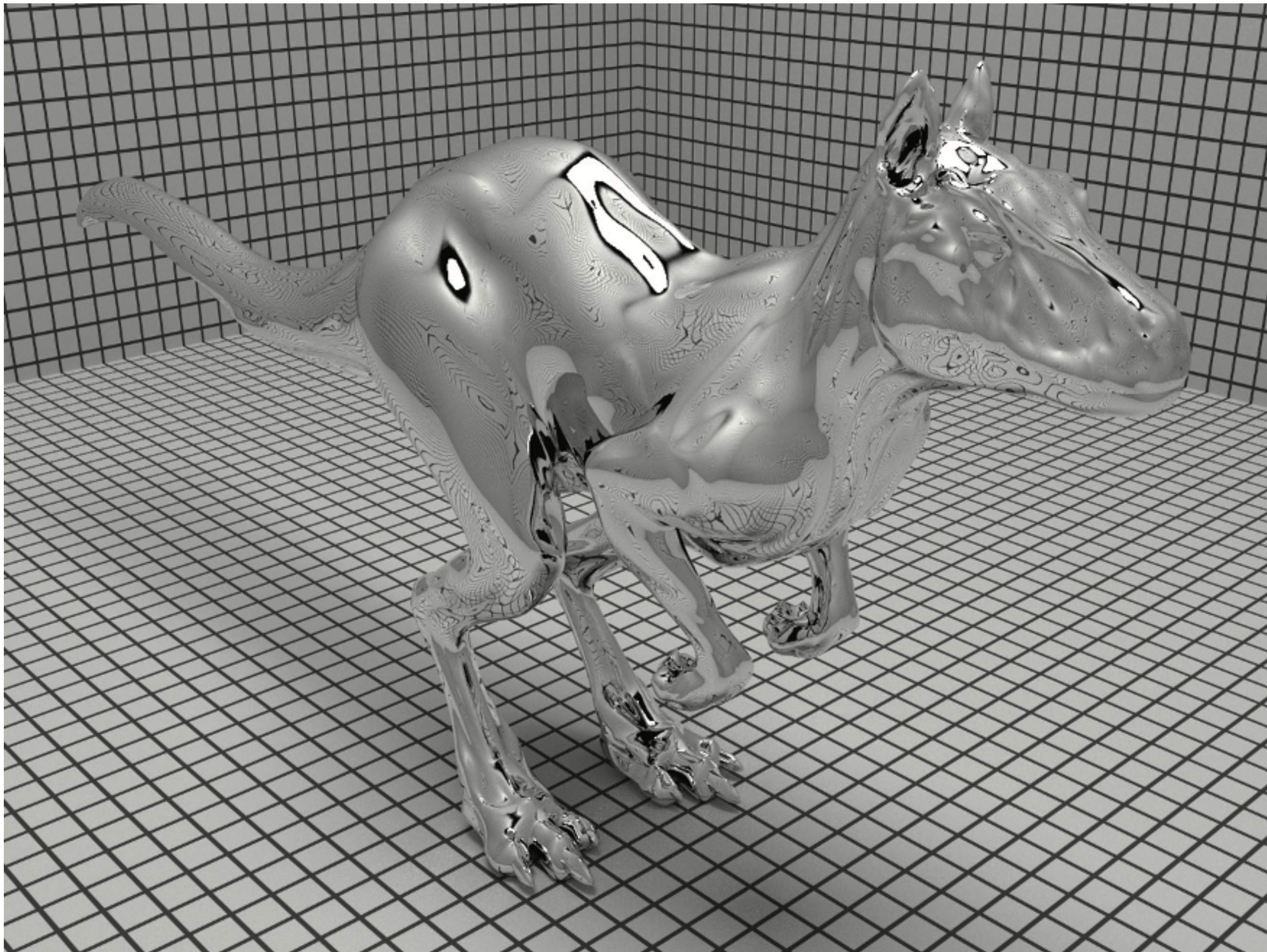
Specular Reflection & the Reflection Equation

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

Whitted's ray tracing method!



Perfect Specular Reflection BRDF

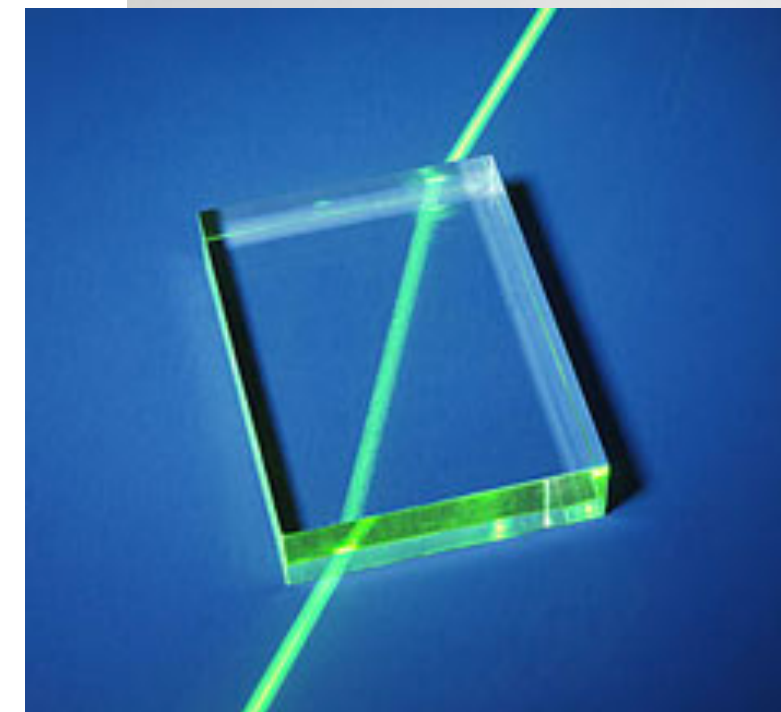


PBRT

Specular Refraction

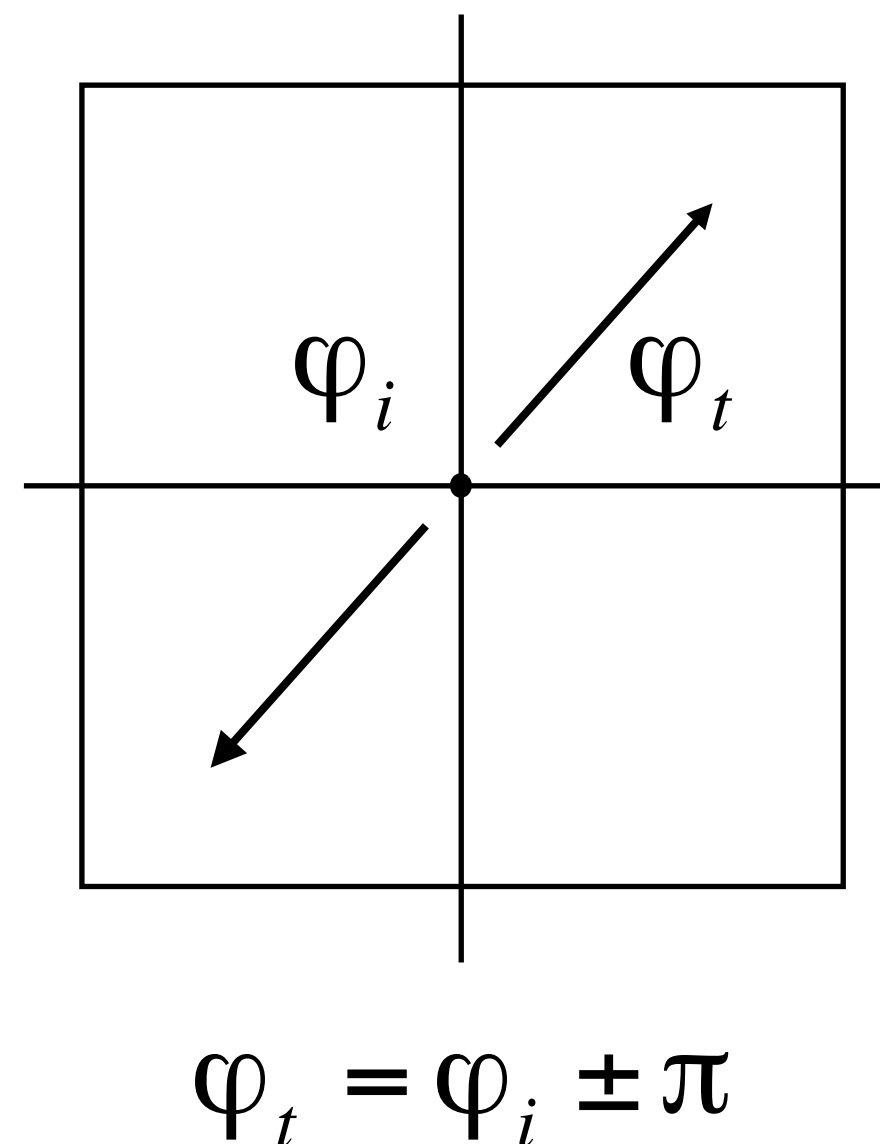
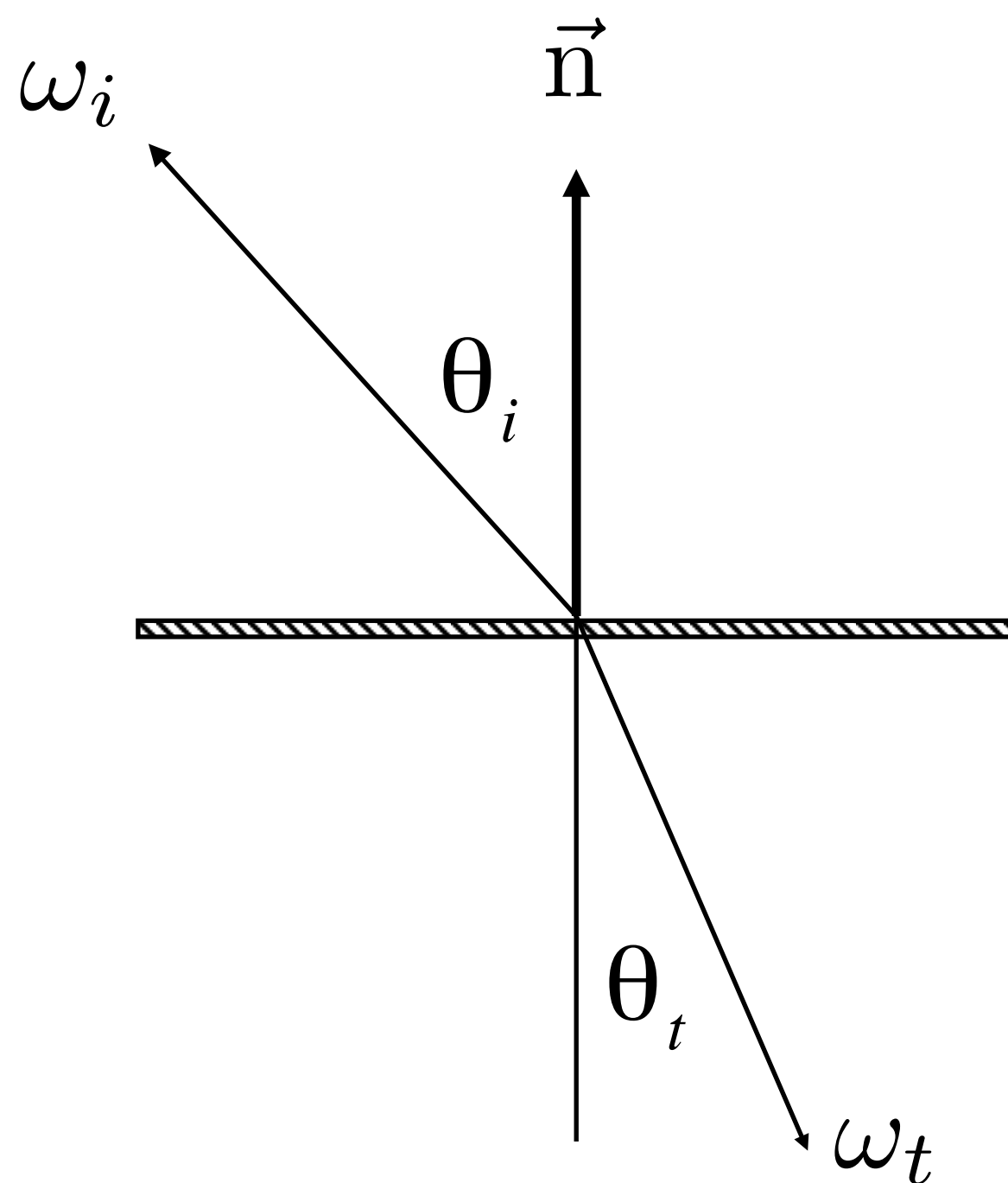
In addition to reflecting off surface, light may be transmitted through surface.

Light refracts when it enters a new medium.



Snell's Law

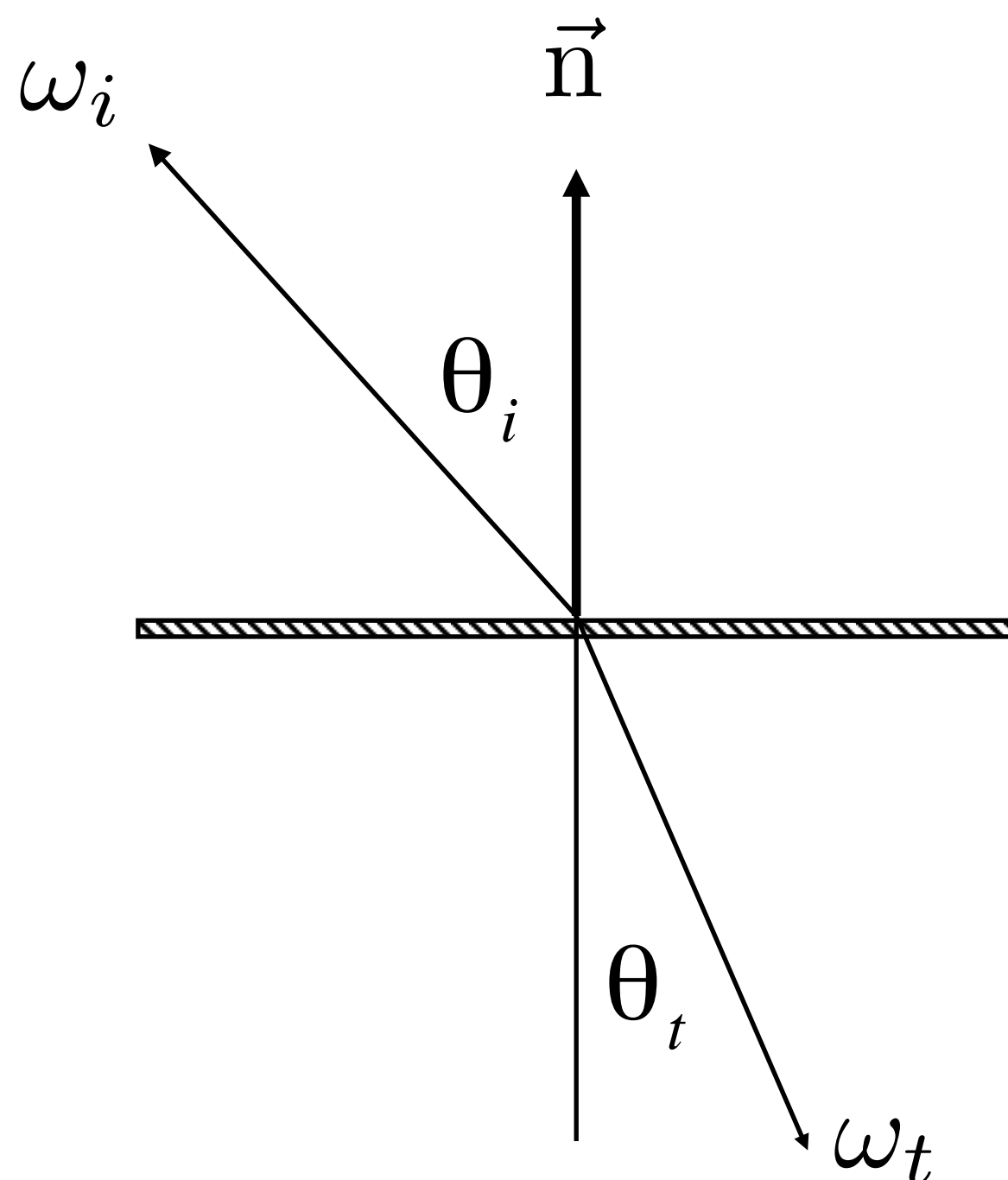
Transmitted angle depends on
index of refraction (IOR) for incident ray
index of refraction (IOR) for exiting ray



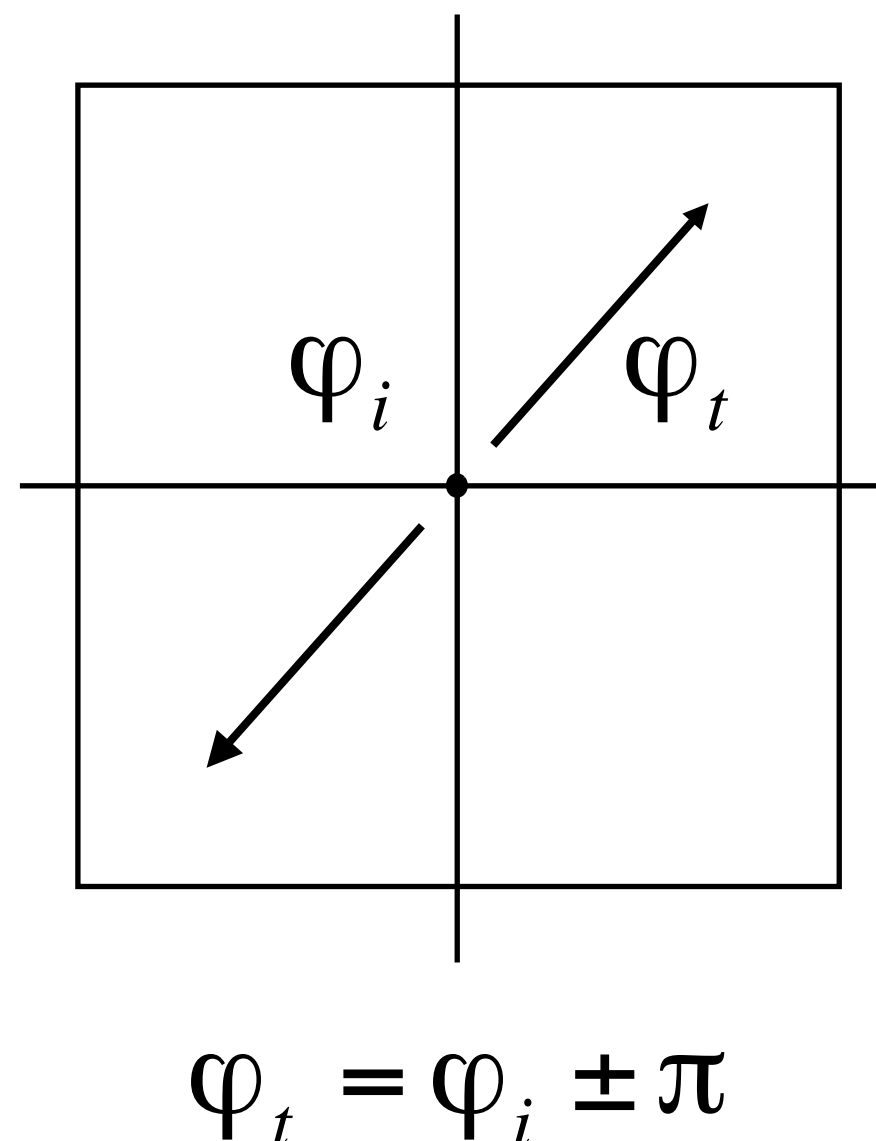
$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

Snell's Law

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



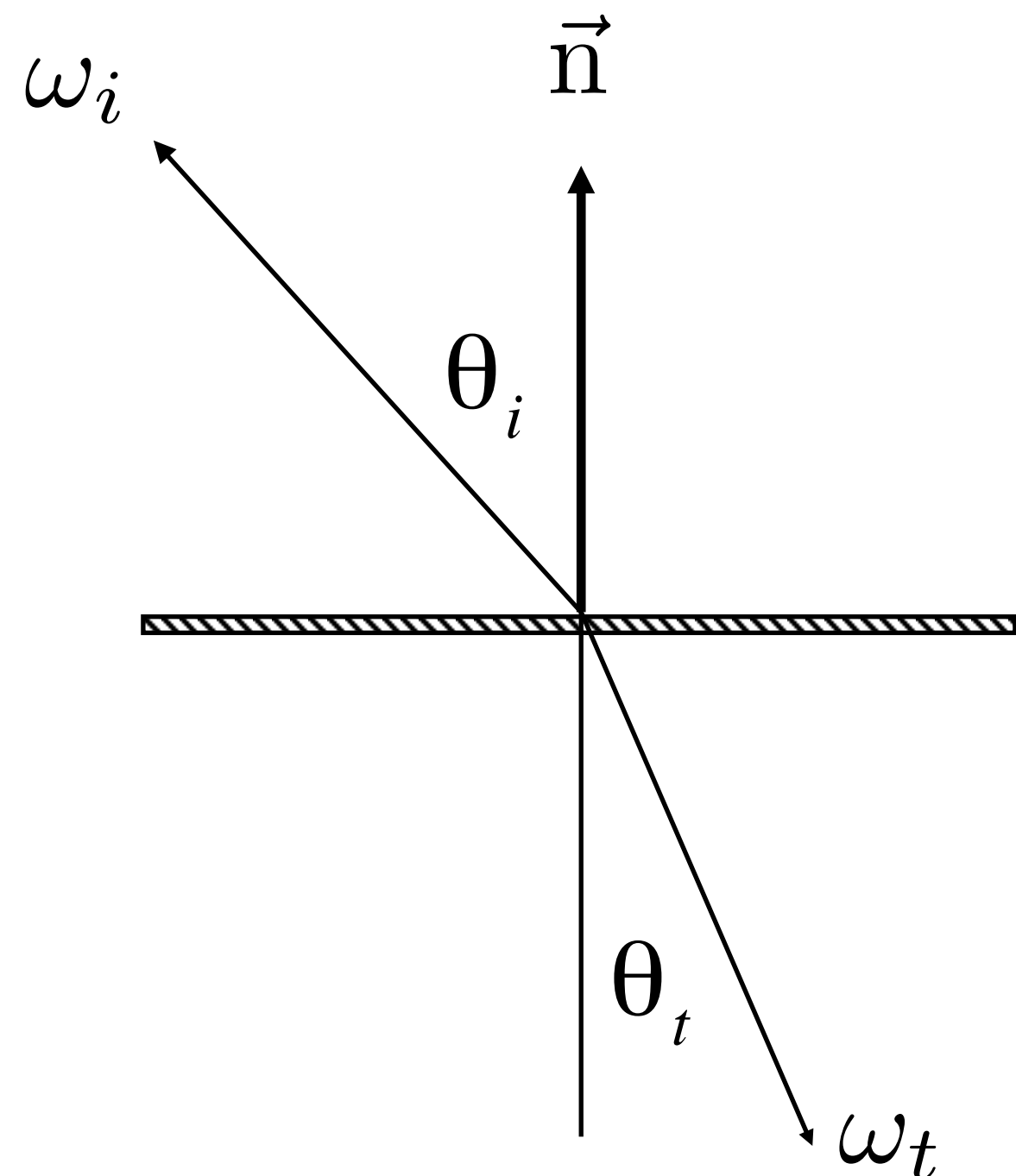
$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$



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



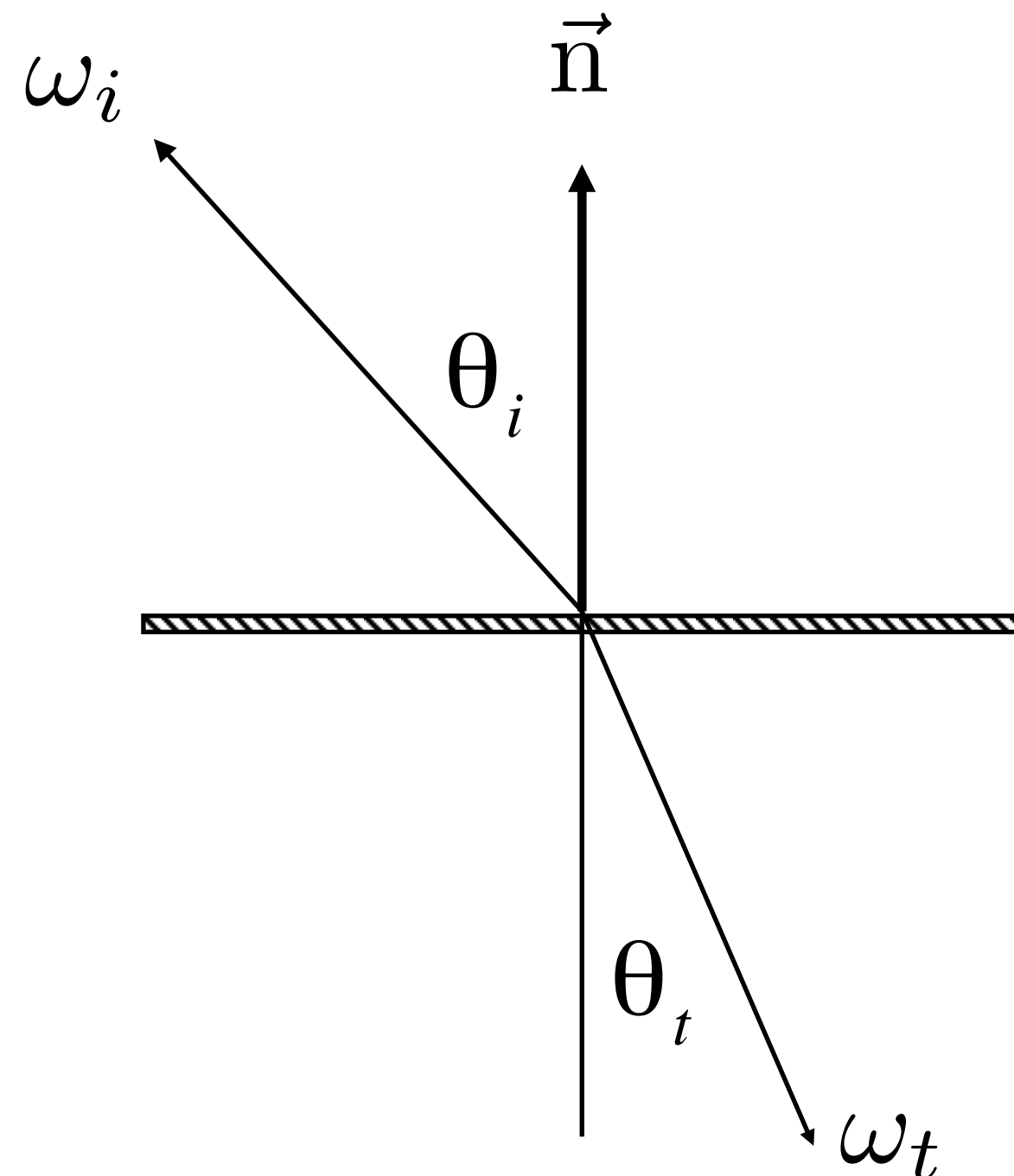
$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

$$\cos \theta_t = \sqrt{1 - \sin^2 \theta_t}$$

$$= \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 \sin^2 \theta_i}$$

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

Law of Refraction



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

$$\cos \theta_t = \sqrt{1 - \sin^2 \theta_t}$$

$$= \sqrt{1 - \left(\frac{\eta_i}{\eta_t}\right)^2 \sin^2 \theta_i}$$

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

Total internal reflection:

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.

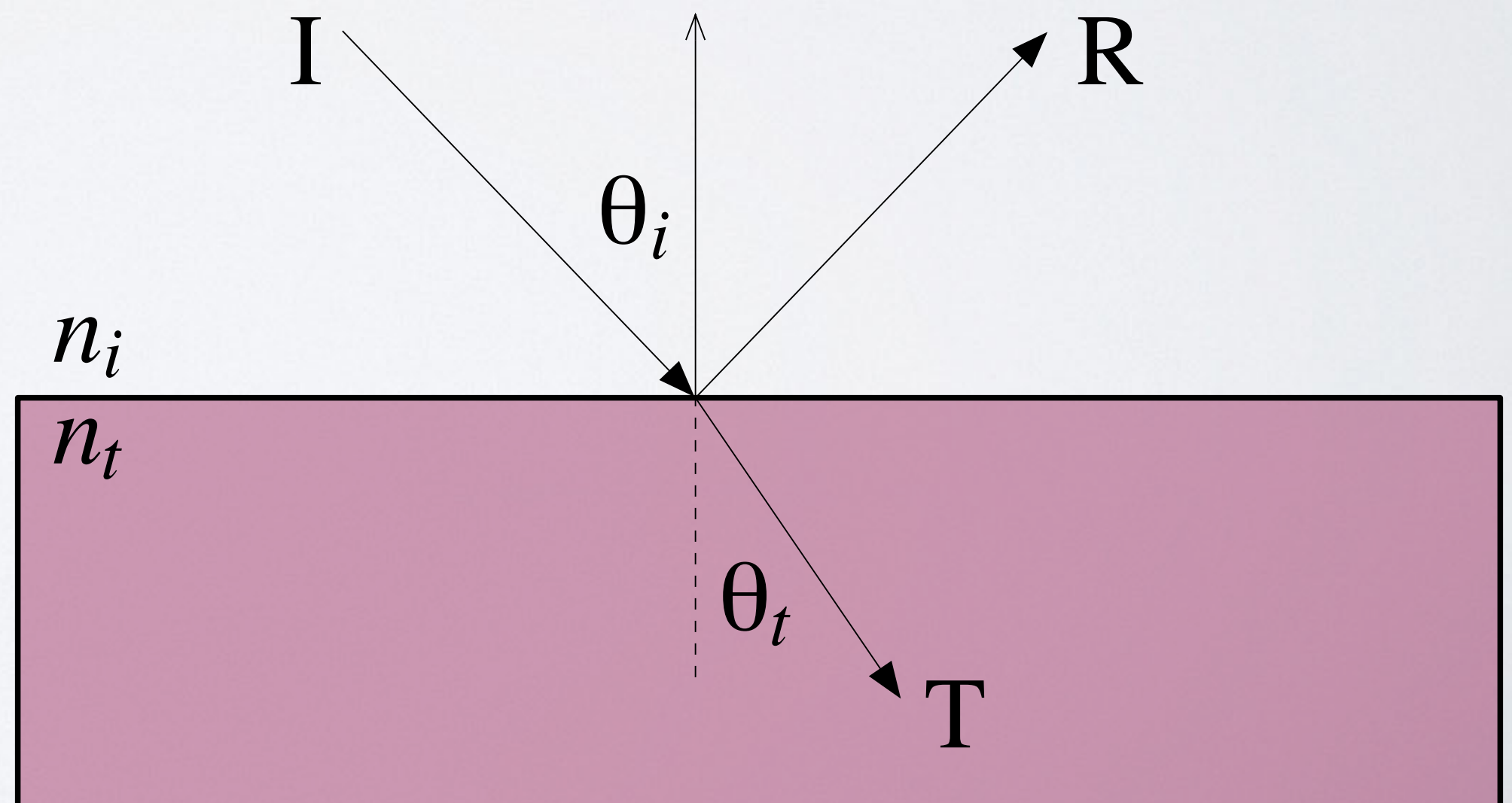
$$1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2 \theta_i) < 0$$

Refracted Rays

- Transparent materials bend light
 - Snell's Law $\frac{n_i}{n_t} = \frac{\sin \theta_t}{\sin \theta_i}$ (see clever formula in text...)

$$\sin \theta_t > 1$$

Total (internal) reflection



Refracted Rays

- Coefficient on transmitted ray depends on θ
- Schlick approximation to Fresnel Equations

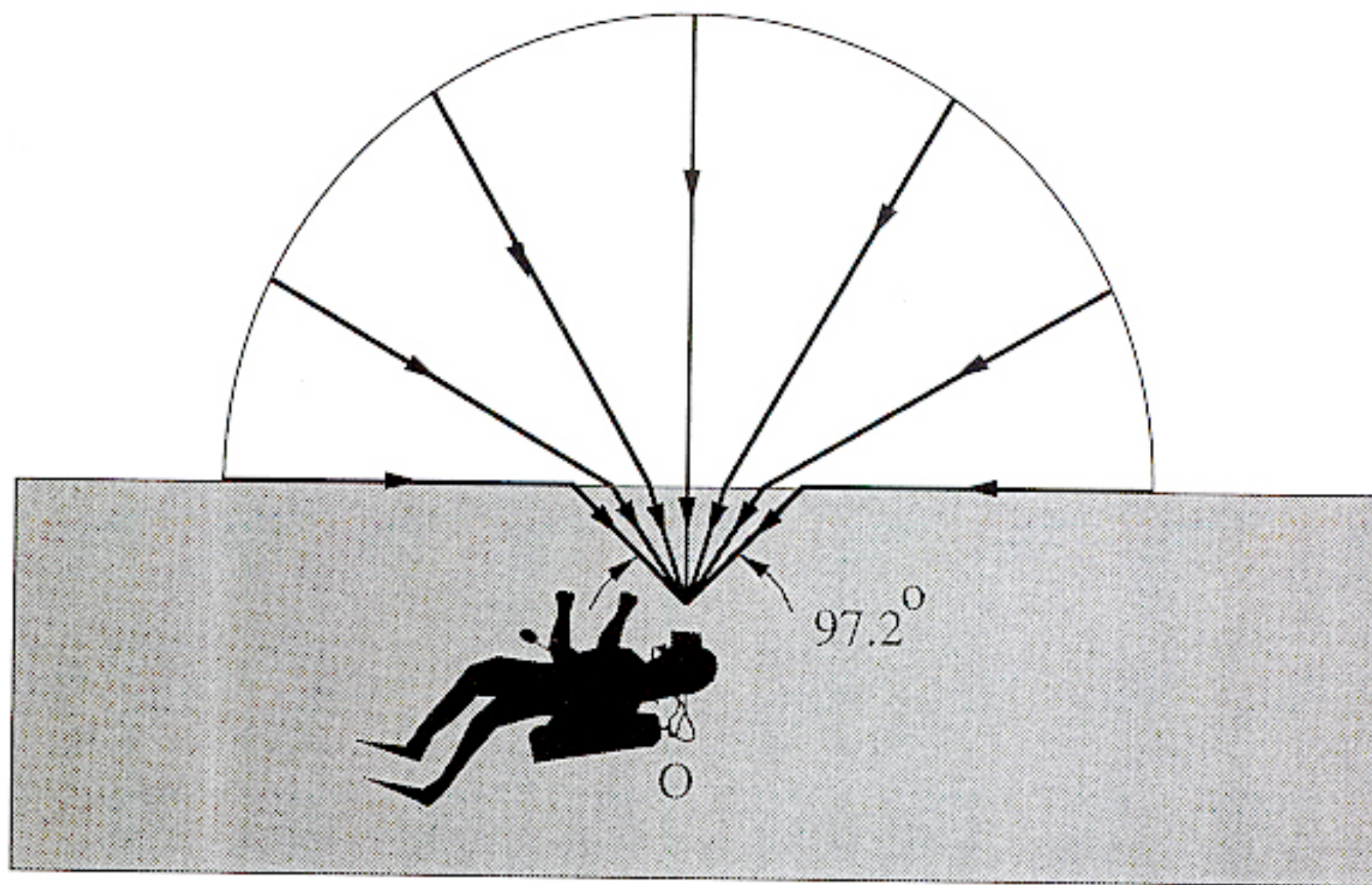
$$k_t(\theta_i) = k_0 + (1 - k_0)(1 - \cos \theta_i)^5$$

$$k_0 = \left(\frac{n_t - 1}{n_t + 1} \right)^2$$

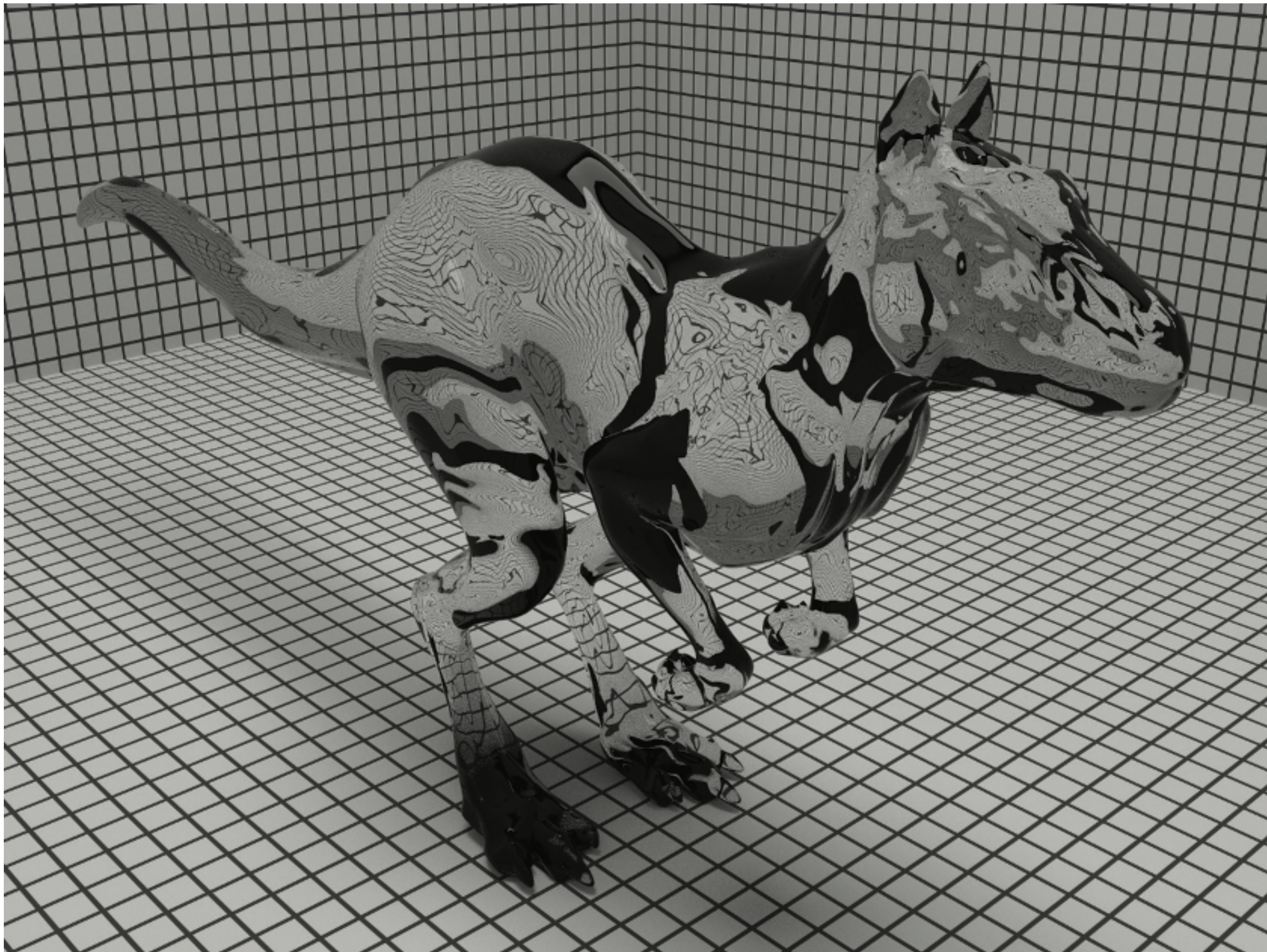
- Attenuation
 - Wavelength (color) dependent
 - Exponential with distance

Snell's Window/Circle

Total internal reflection



Fresnel Reflection & Transmission



PBRT

Microfacet Material Model

Microfacet Reflection



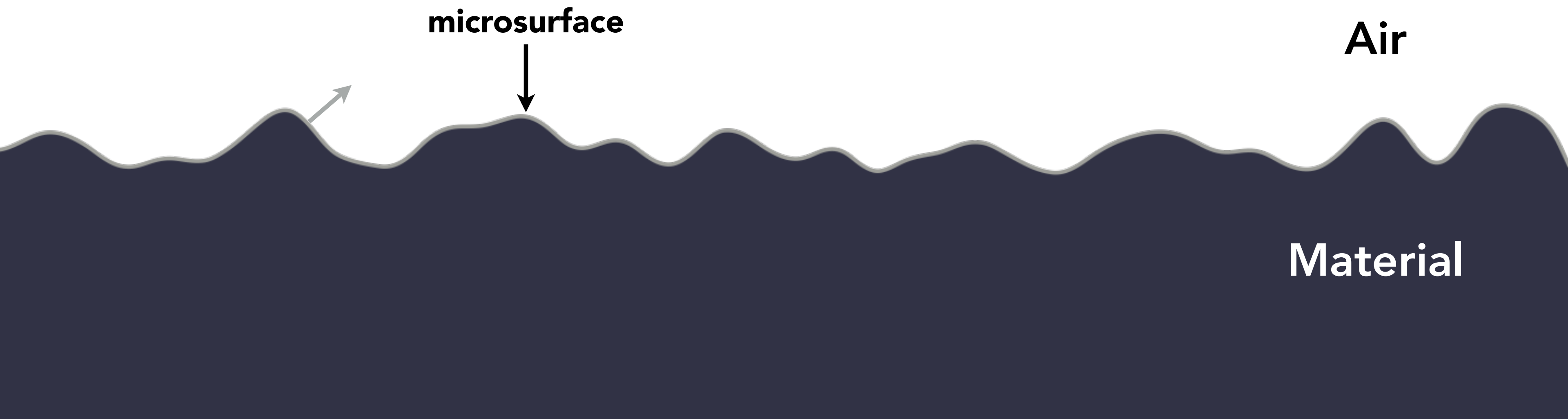
https://twitter.com/Cmdr_Hadfield/status/318986491063828480/photo/1

Microfacet Theory

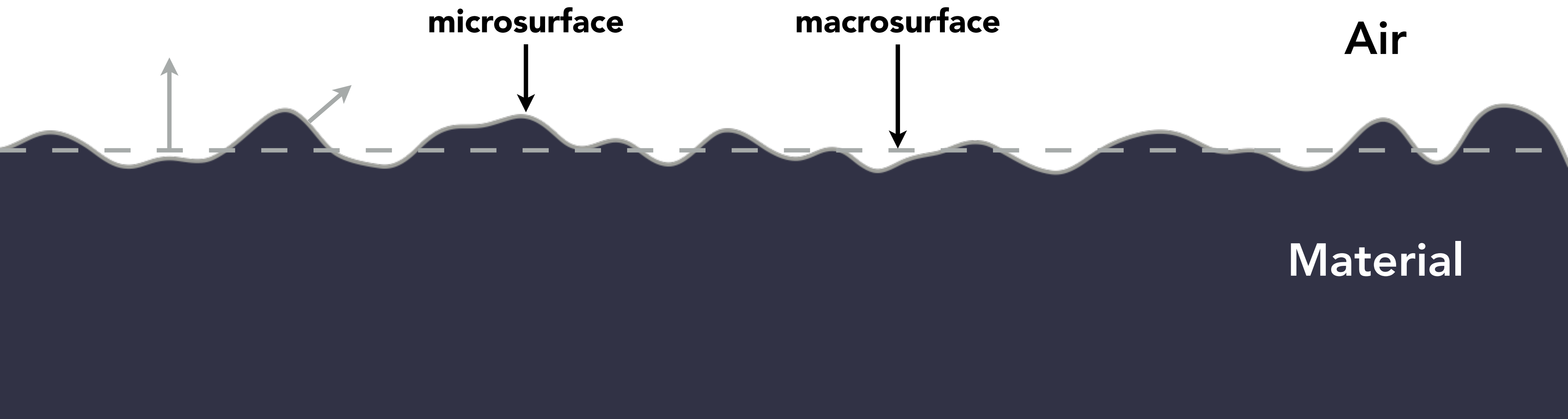
Air

Material

Microfacet Theory



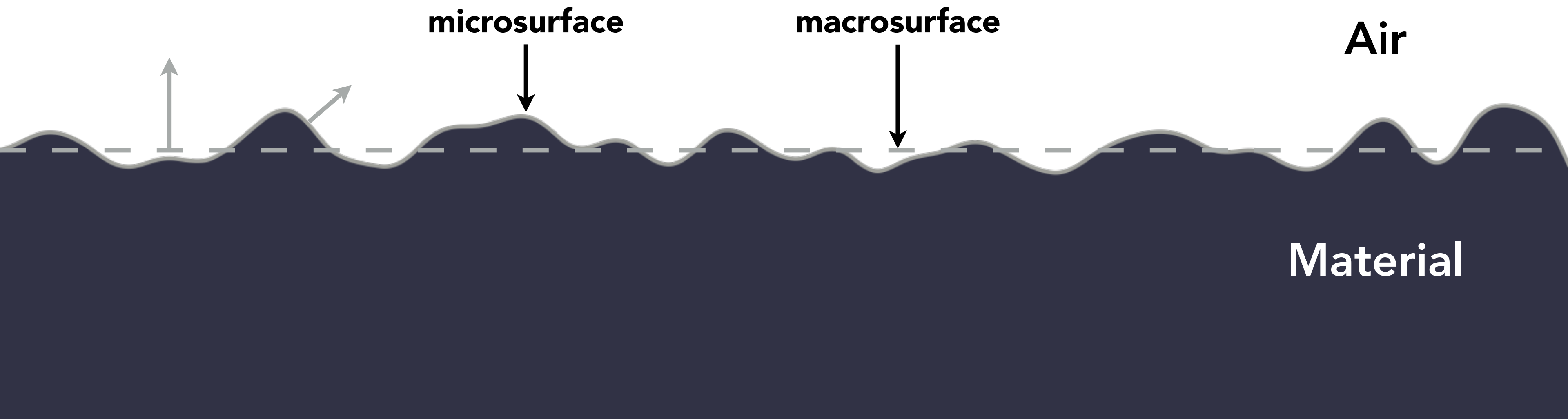
Microfacet Theory



Microfacet Theory

Rough surface

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



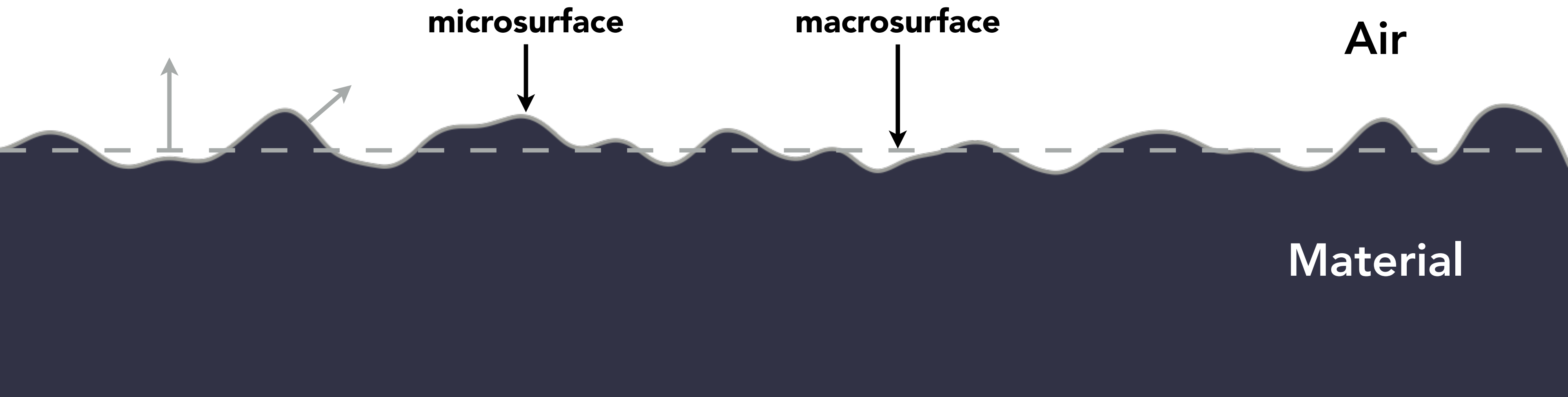
Microfacet Theory

Rough surface

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

Individual elements of surface act like **mirrors**

- Known as "microfacets"
- Each microfacet has its own normal vector

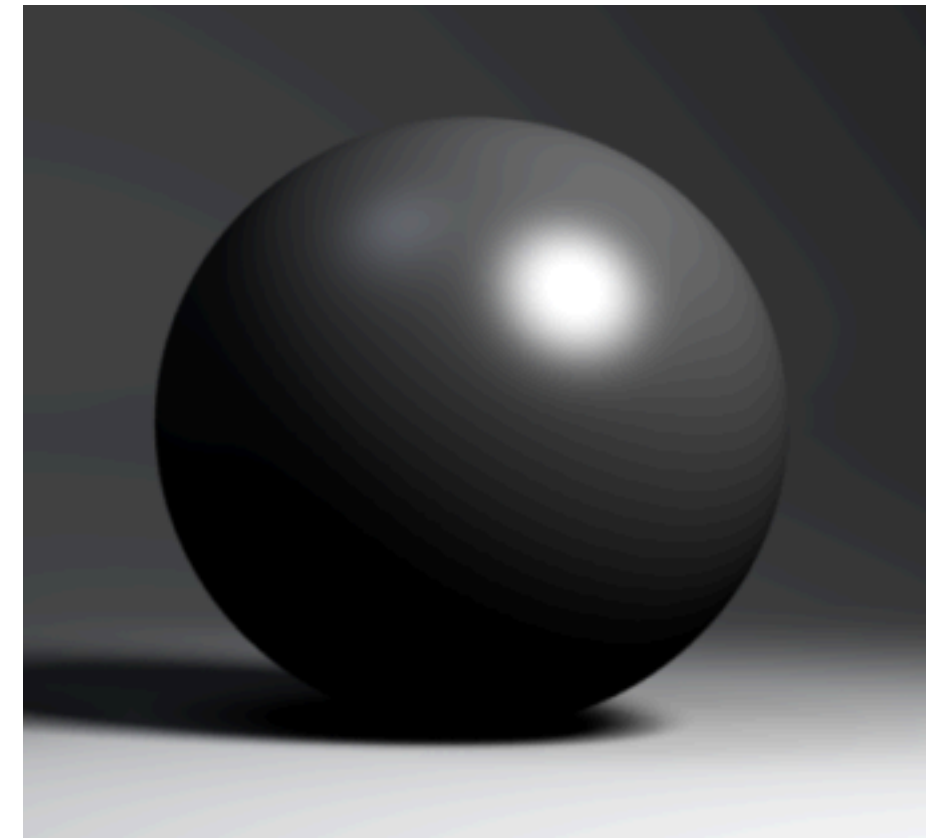
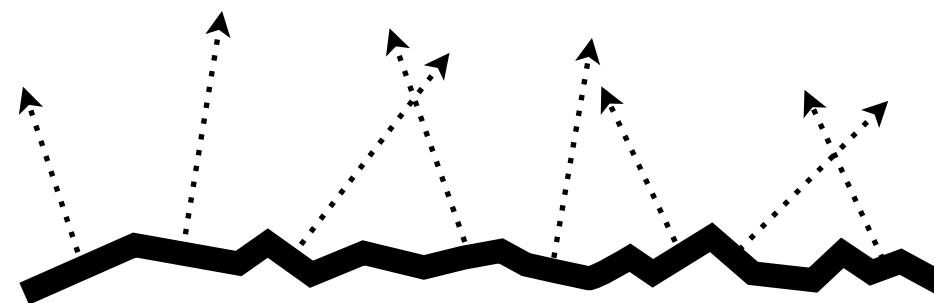
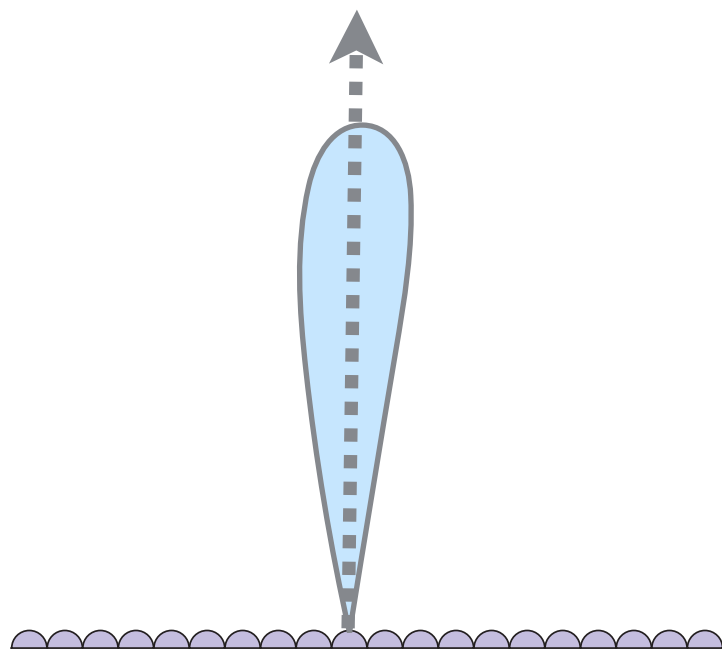


Microfacet BRDF

- Key: the **distribution** of microfacets' normals

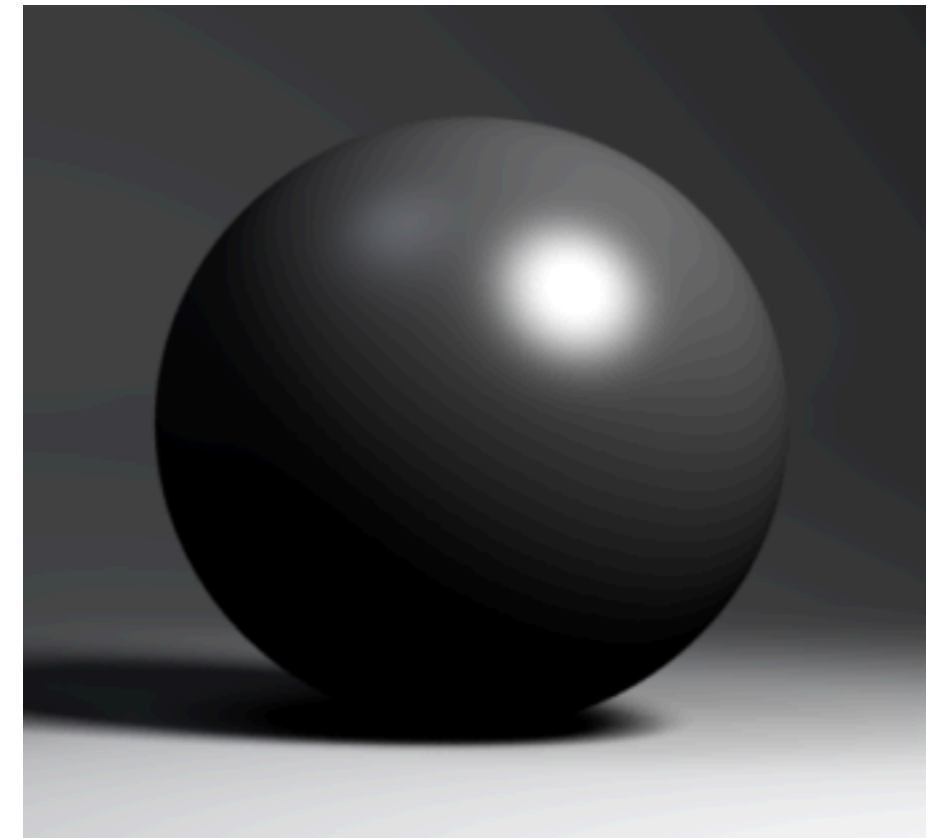
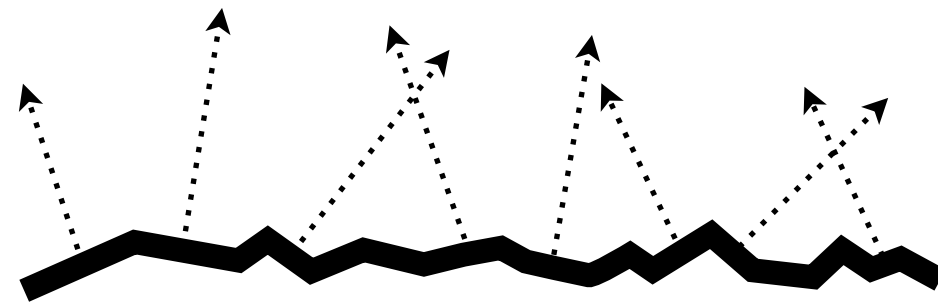
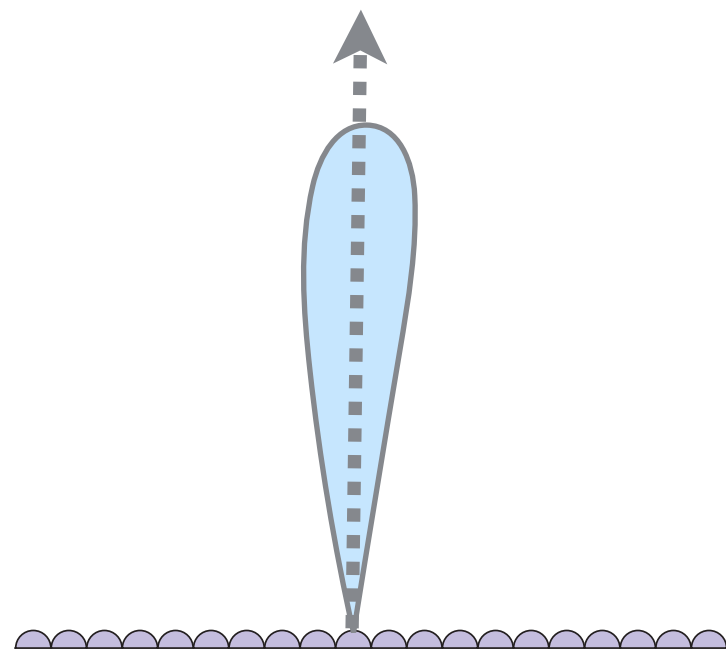
Microfacet BRDF

- Key: the **distribution** of microfacets' normals
 - Concentrated $\iff$ glossy

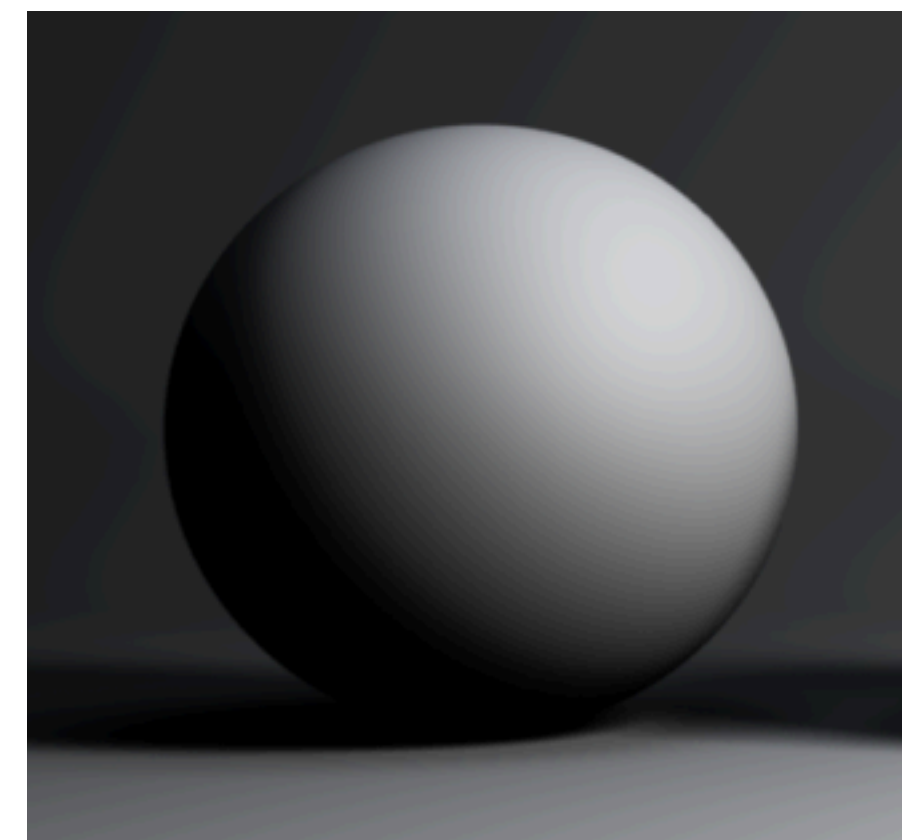
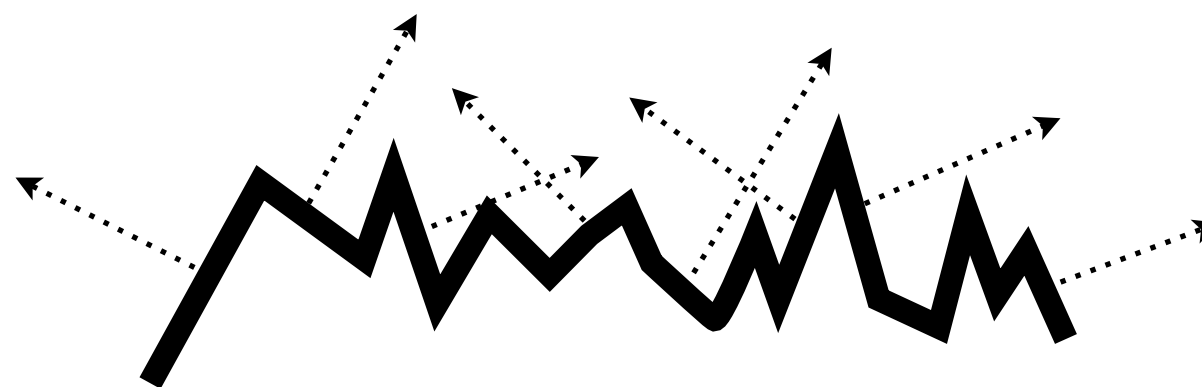
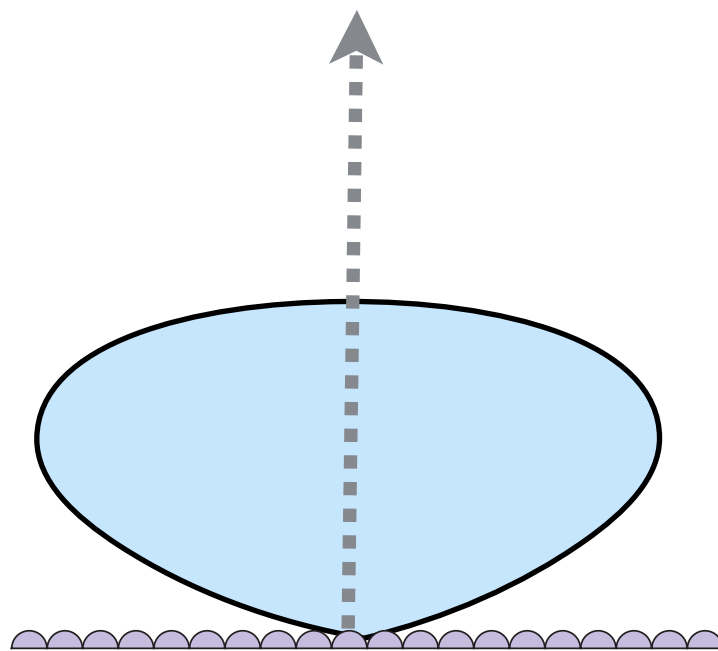


Microfacet BRDF

- Key: the **distribution** of microfacets' normals
 - Concentrated $\Leftrightarrow$ glossy

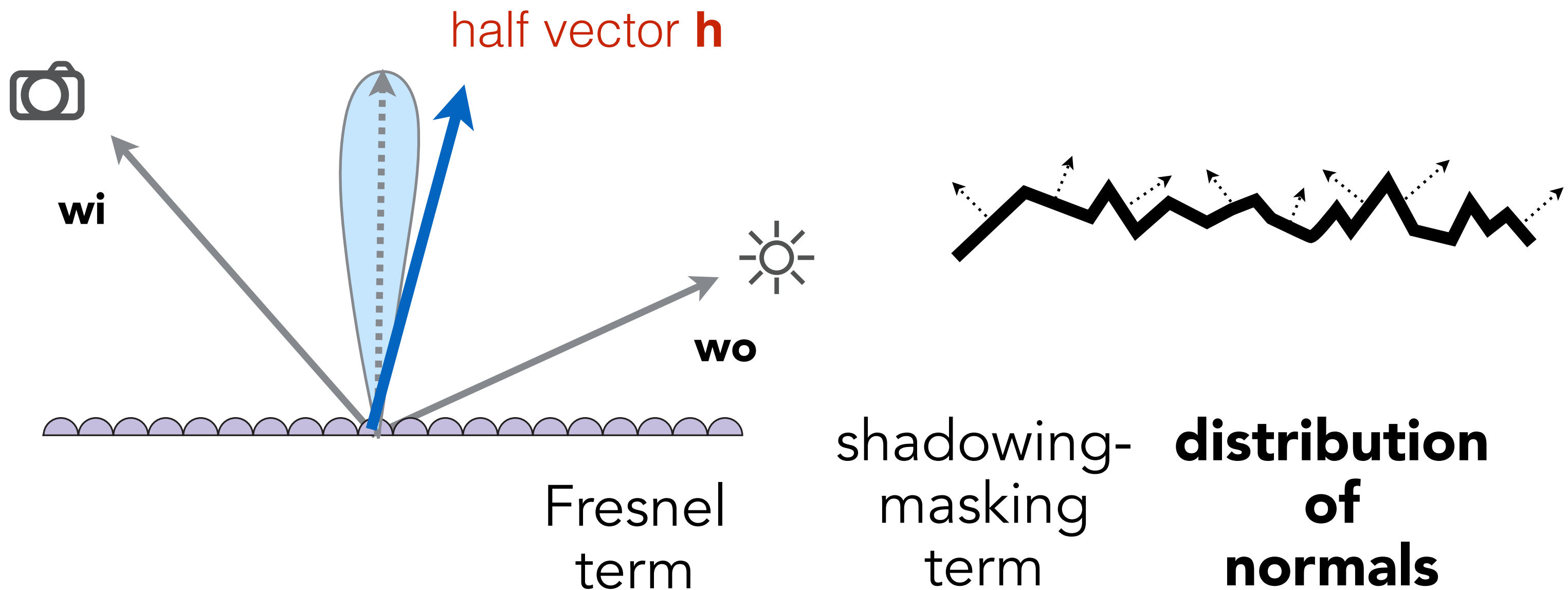


- Spread out $\Leftrightarrow$ diffuse



Microfacet BRDF

- What kind of microfacets reflect w_i to w_o ?
(hint: microfacets are mirrors)



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

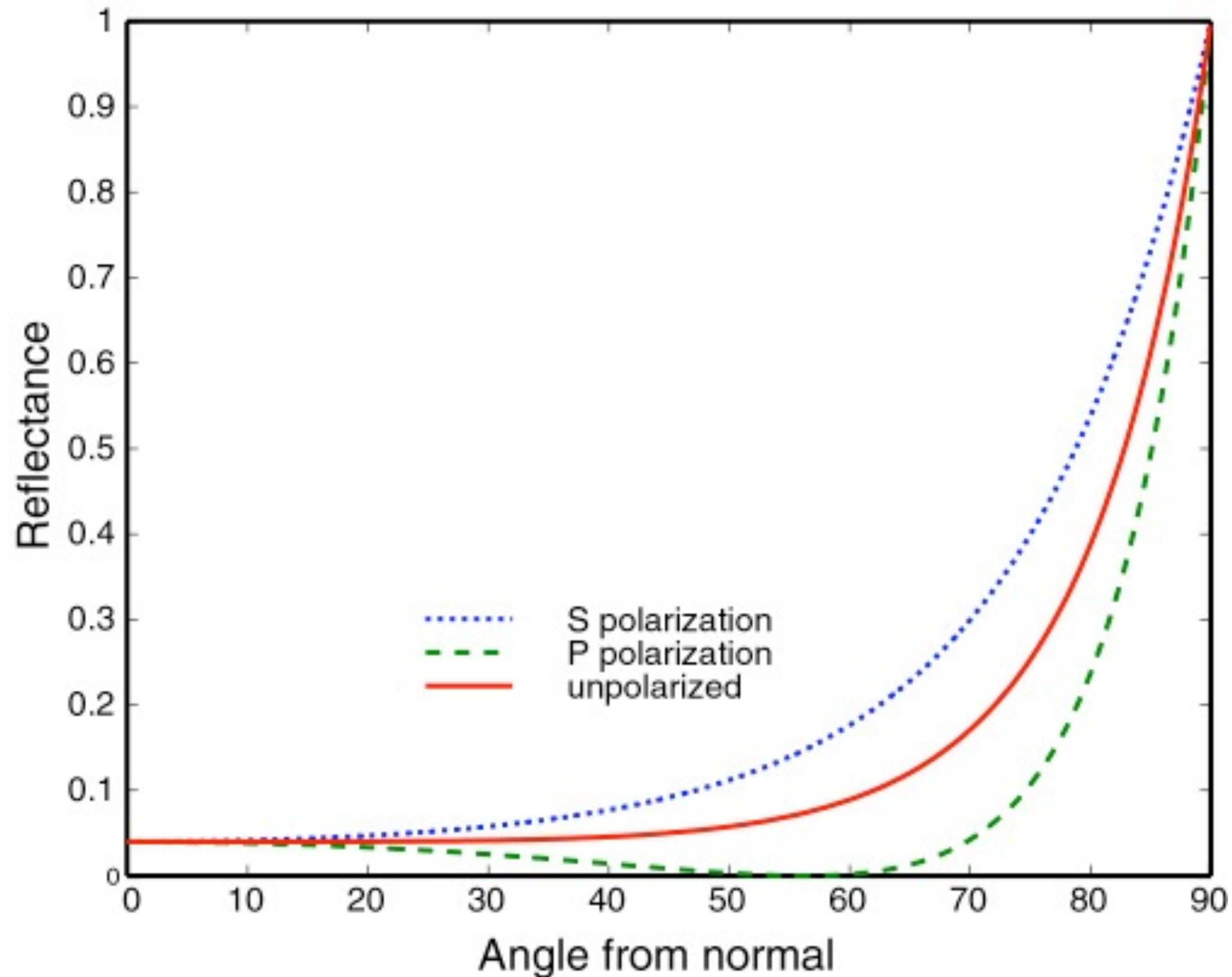
Fresnel Reflection Term

Reflectance depends on incident angle (and polarization of light)

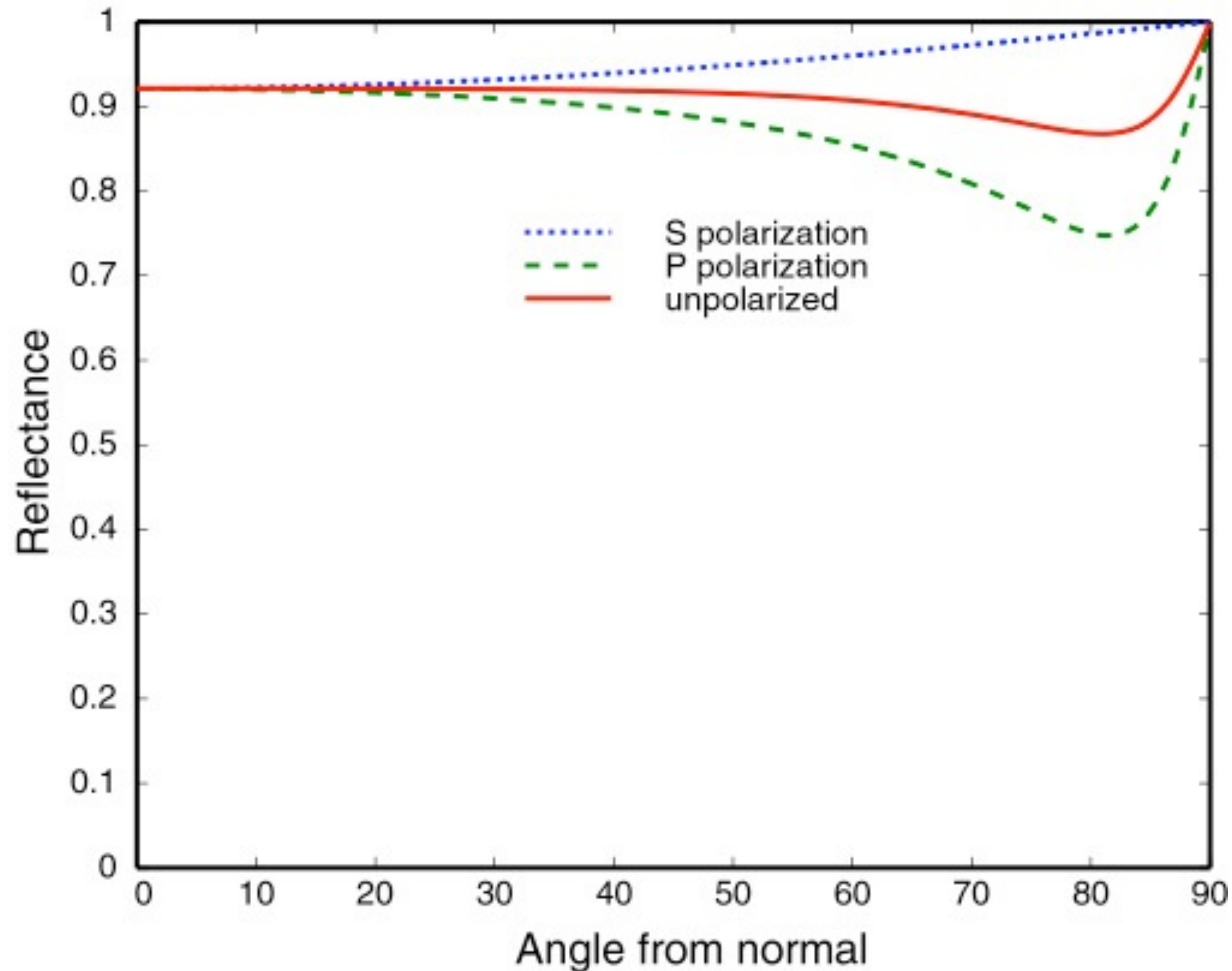


This example: reflectance increases with grazing angle

Fresnel Term (Dielectric, $\eta = 1.5$)



Fresnel Term (Conductor)



Microfacet BRDF: Examples

[Autodesk Fusion 360]

Microfacet BRDF: Examples



[Autodesk Fusion 360]

Microfacet BRDF: Examples



[Autodesk Fusion 360]

Microfacet BRDF: Examples



[Autodesk Fusion 360]

CS184/284A

S26 - O'Brien

Anisotropic BRDFs

Isotropic vs Anisotropic Reflection

- So far, Point light + Metal = Round / Elliptical highlight
- But some reflection highlights look very different

Isotropic vs Anisotropic Reflection

- So far, Point light + Metal = Round / Elliptical highlight



Isotropic vs Anisotropic Reflection



Isotropic



Anisotropic

Anisotropic BRDF: Brushed Metal

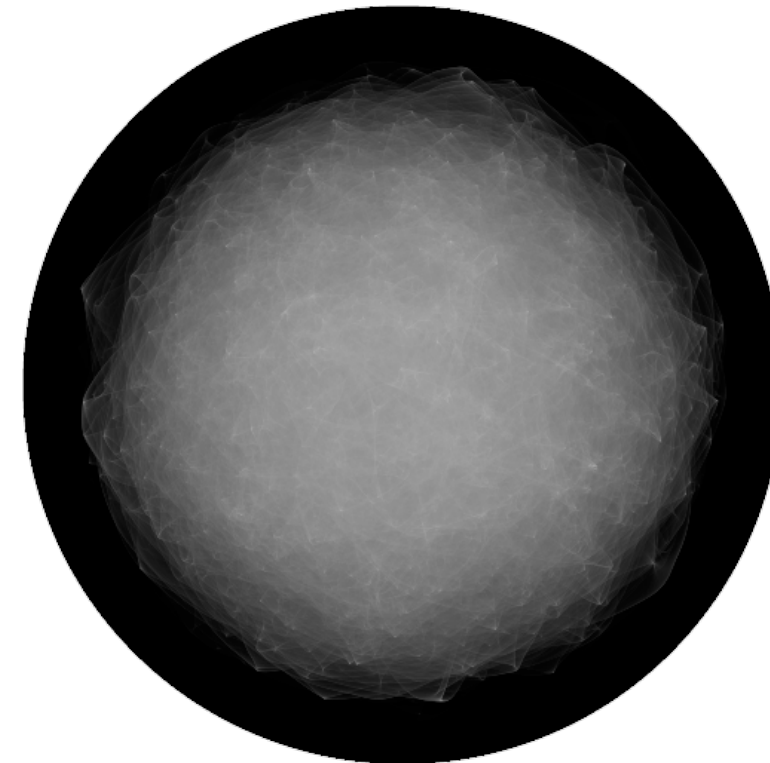
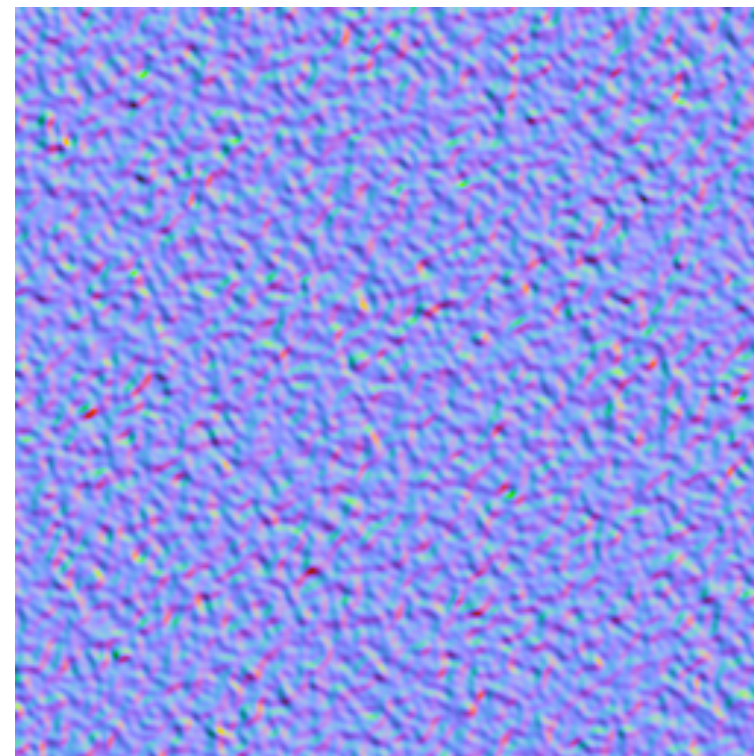
- How is the pan brushed?



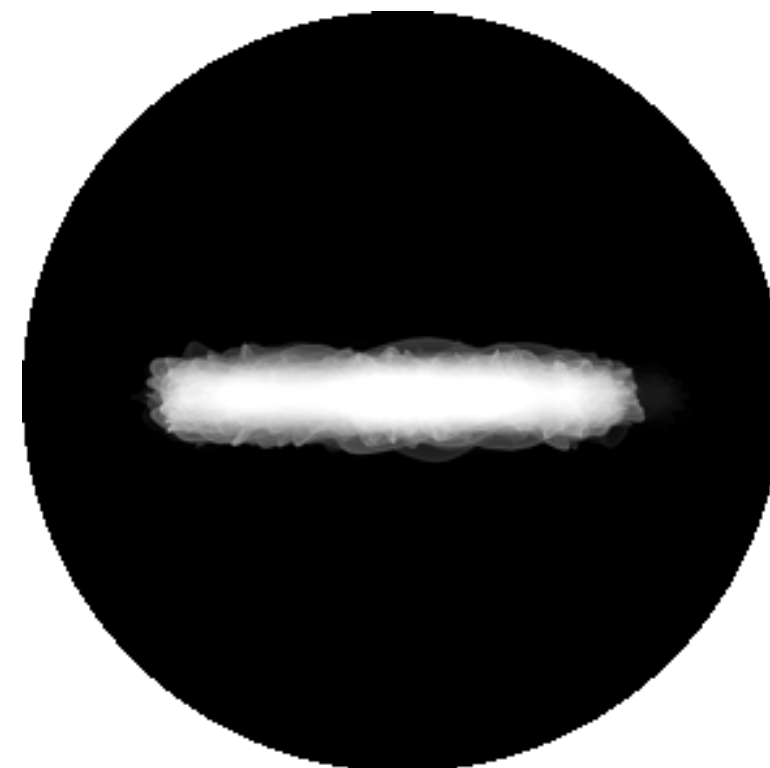
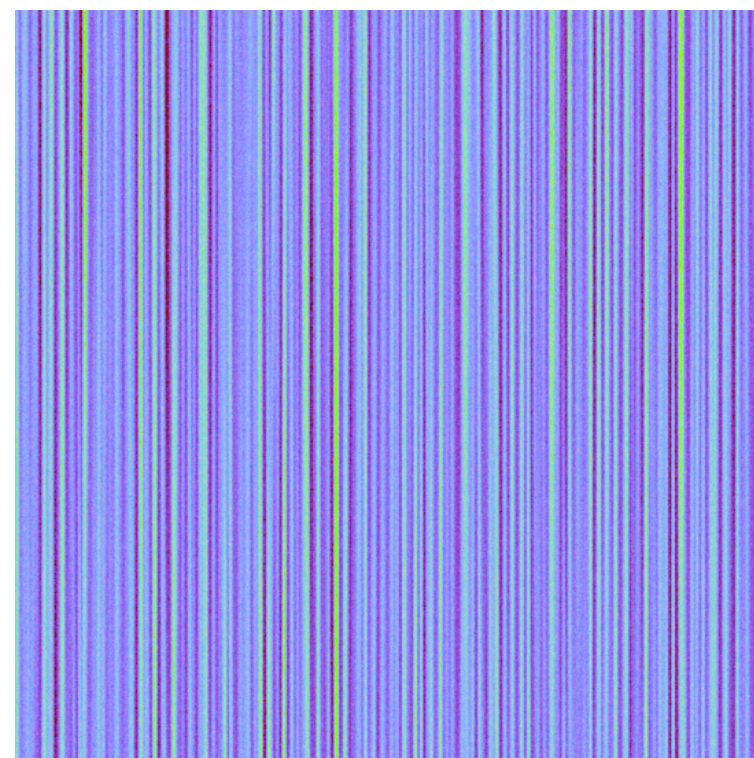
Isotropic / Anisotropic Materials (BRDFs)

- Key: **directionality** of underlying surface

Isotropic



Anisotropic



Surface (normals)

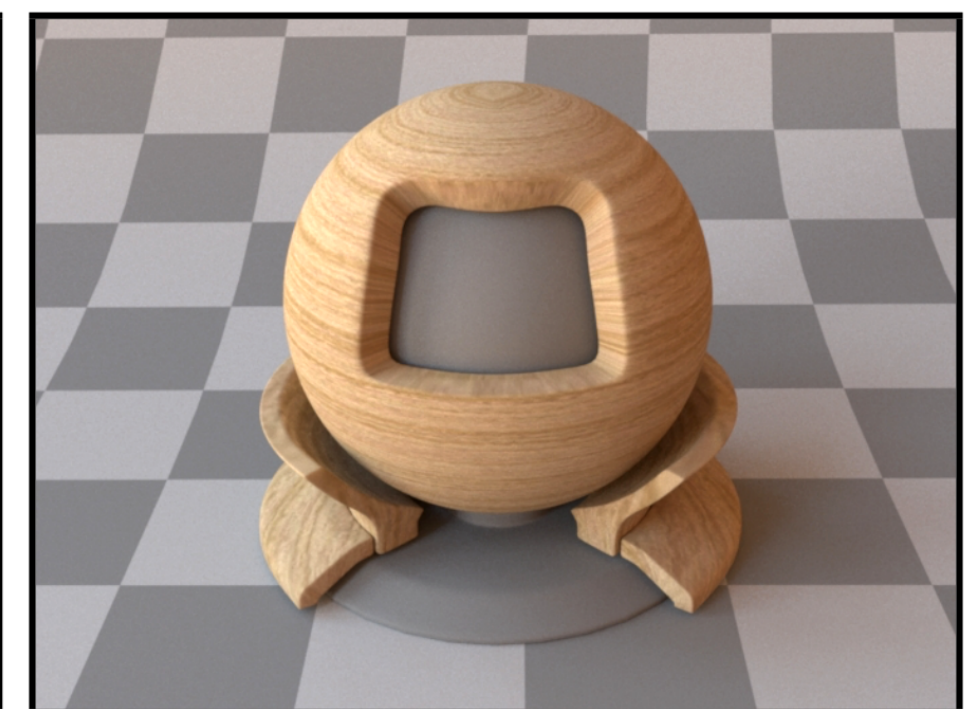
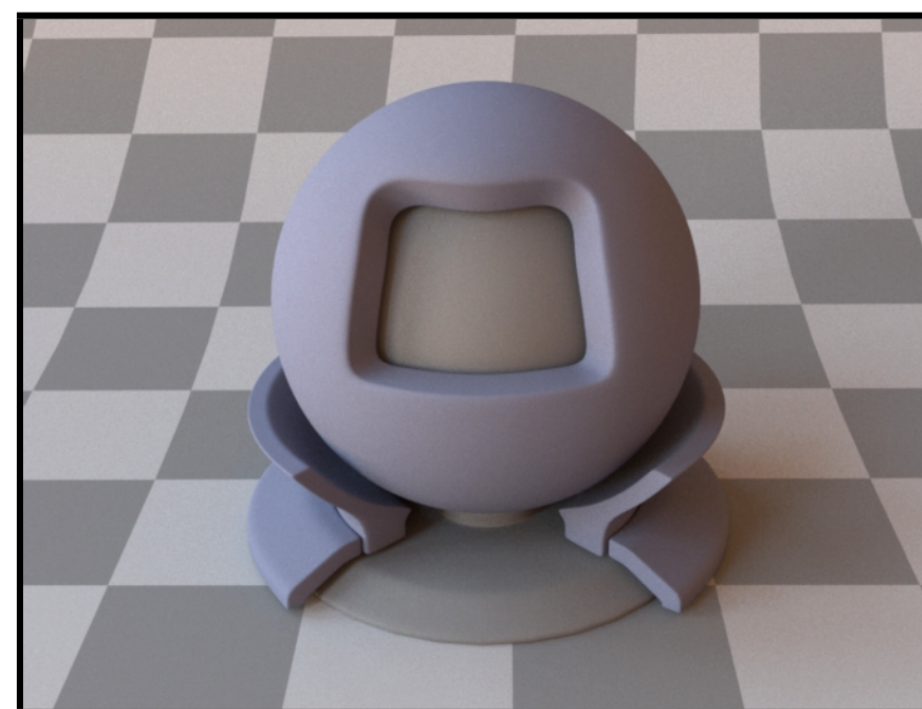
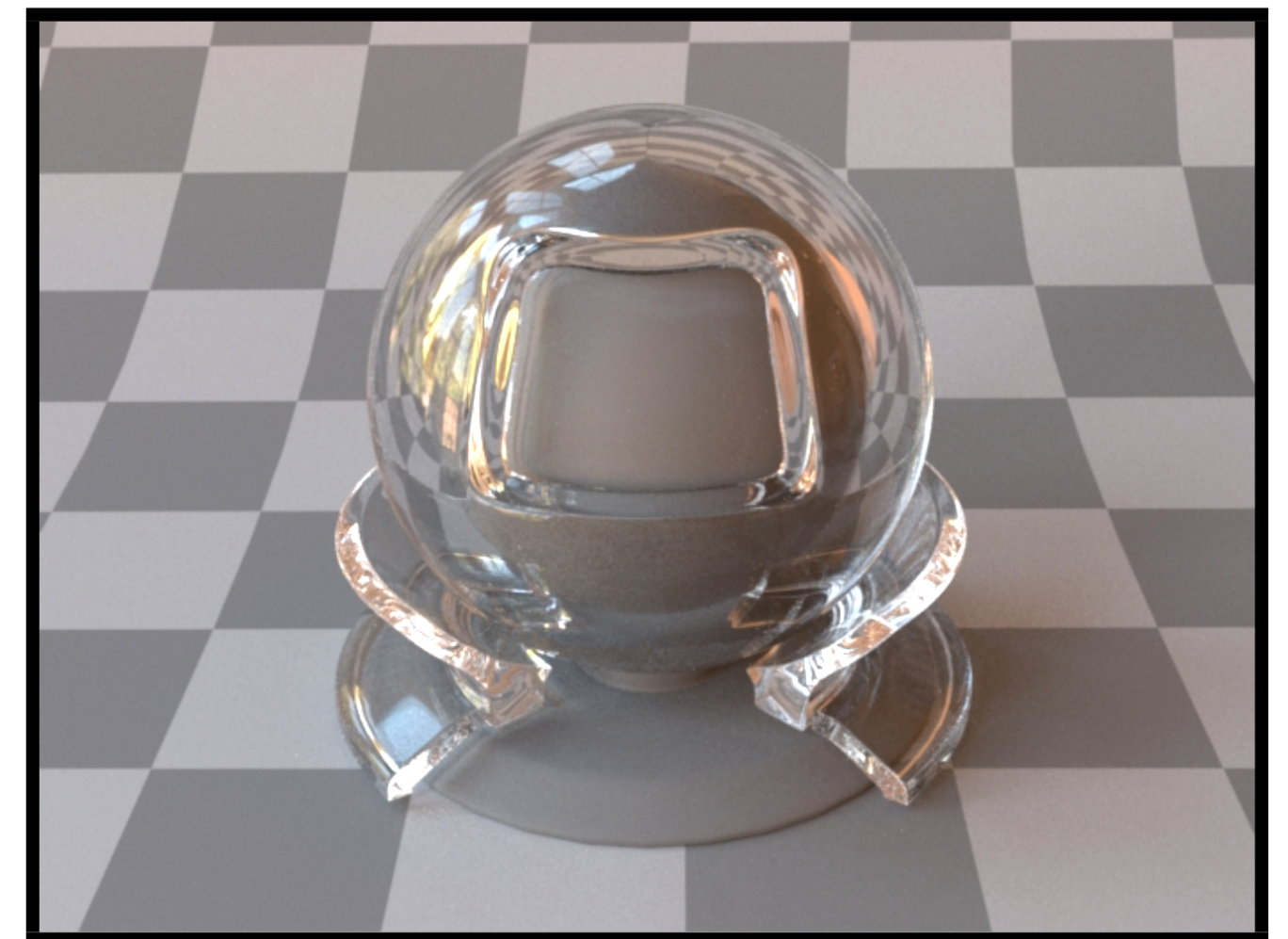
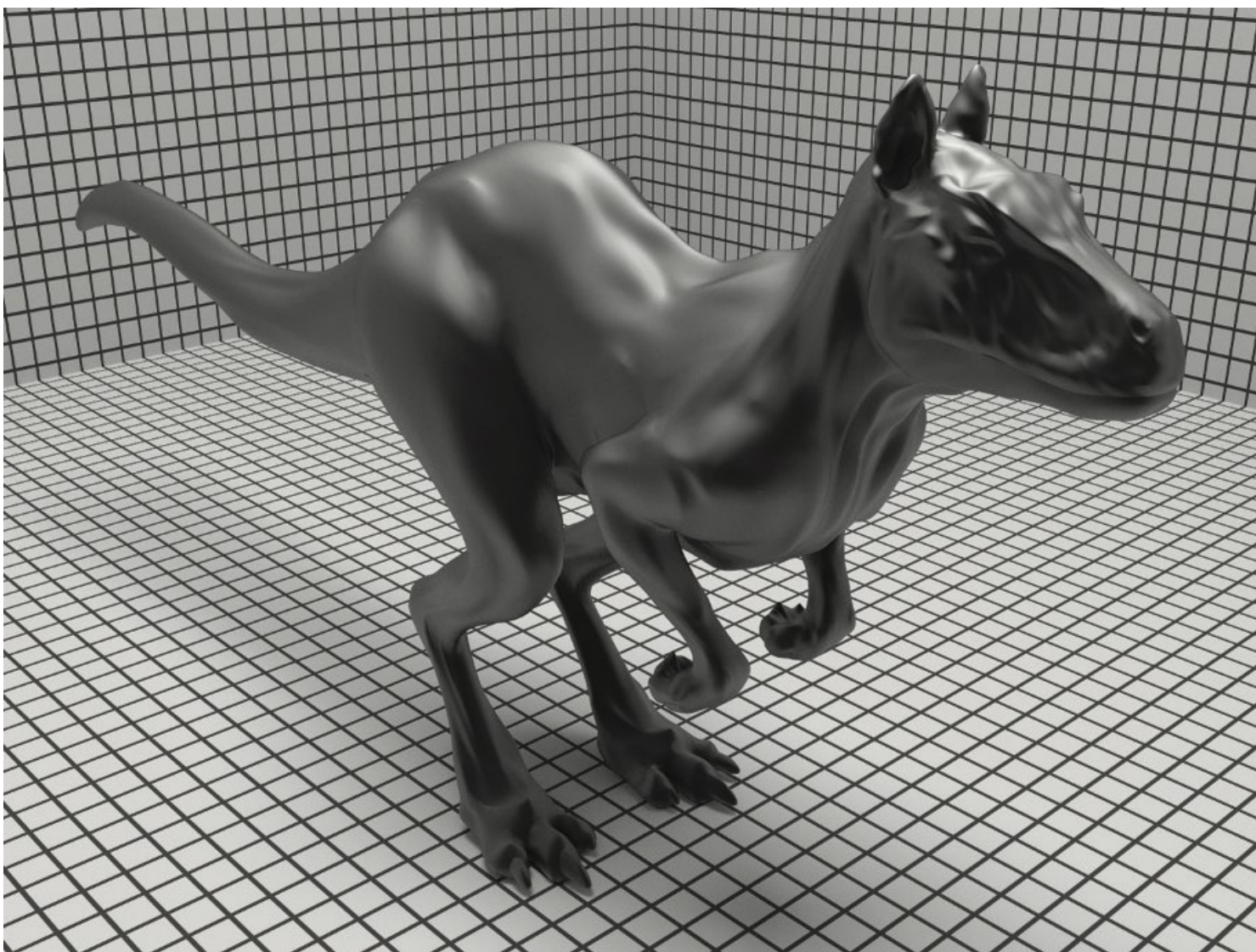
BRDF (fix w_i , vary w_o)

Isotropic BRDFs

Reflection independent of azimuthal angle ϕ

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = f_r(\theta_i, \theta_r, \phi_r - \phi_i)$$

Results from surface microstructure that lacks directional structure

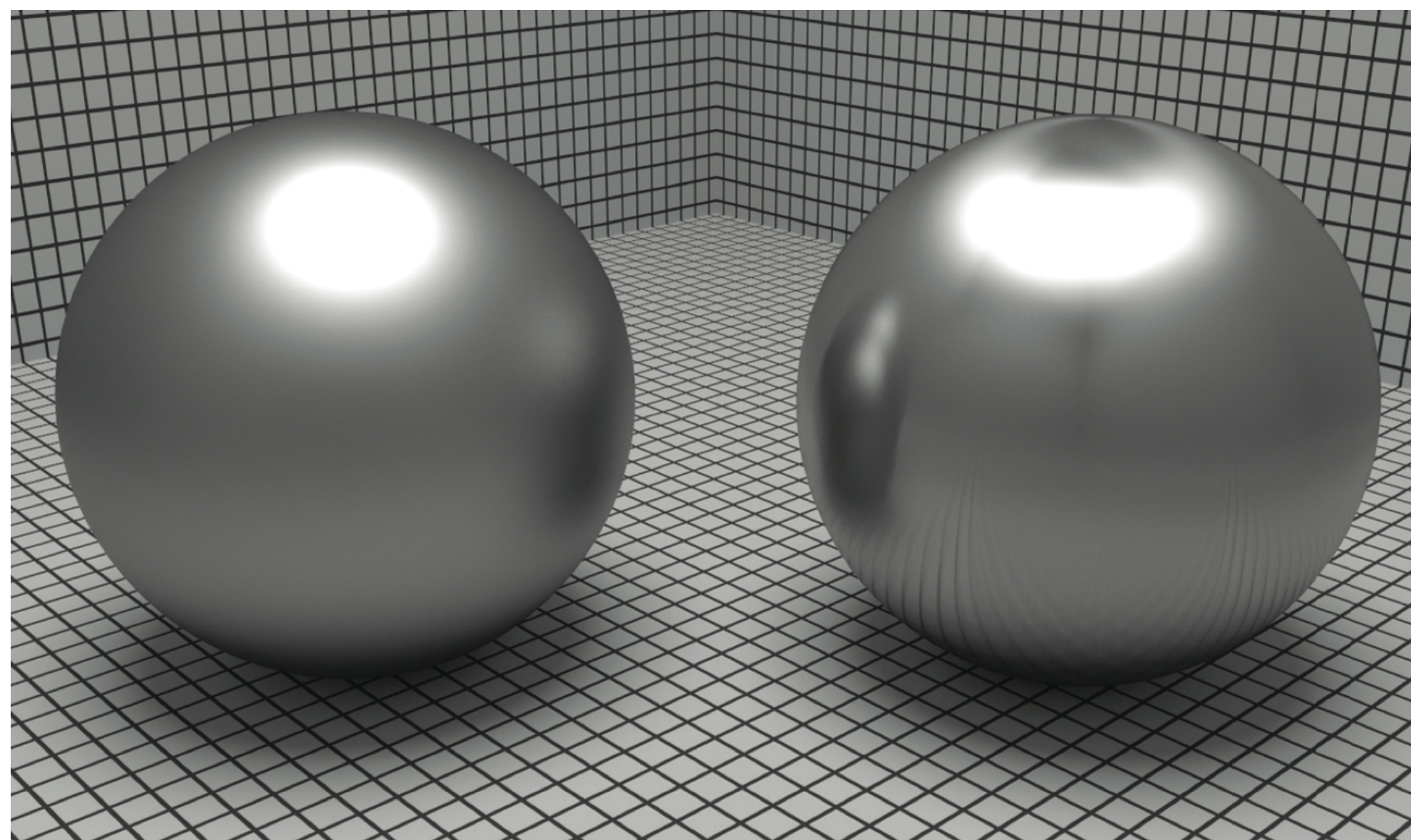


Anisotropic BRDFs

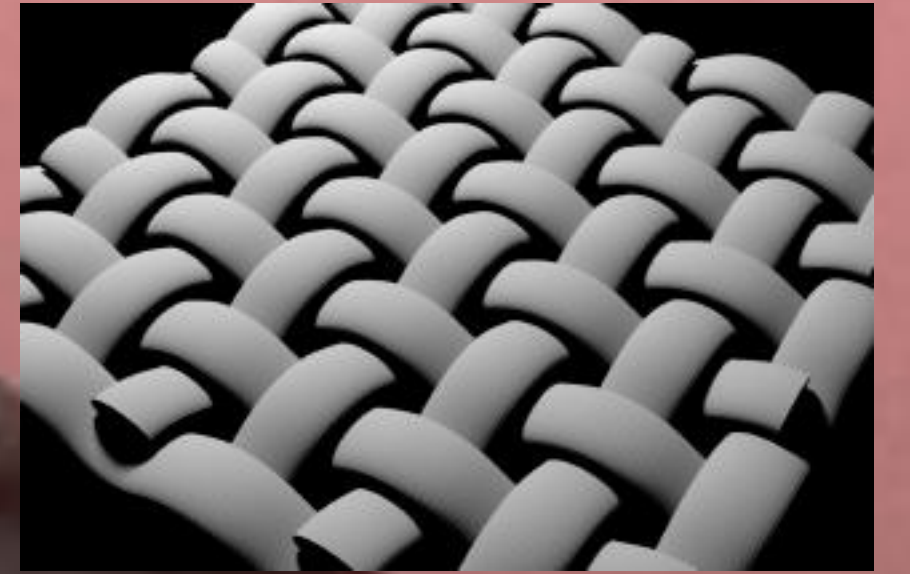
Reflection depends on azimuthal angle ϕ

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) \neq f_r(\theta_i, \theta_r, \phi_r - \phi_i)$$

Results from oriented microstructure of surface, e.g., brushed metal

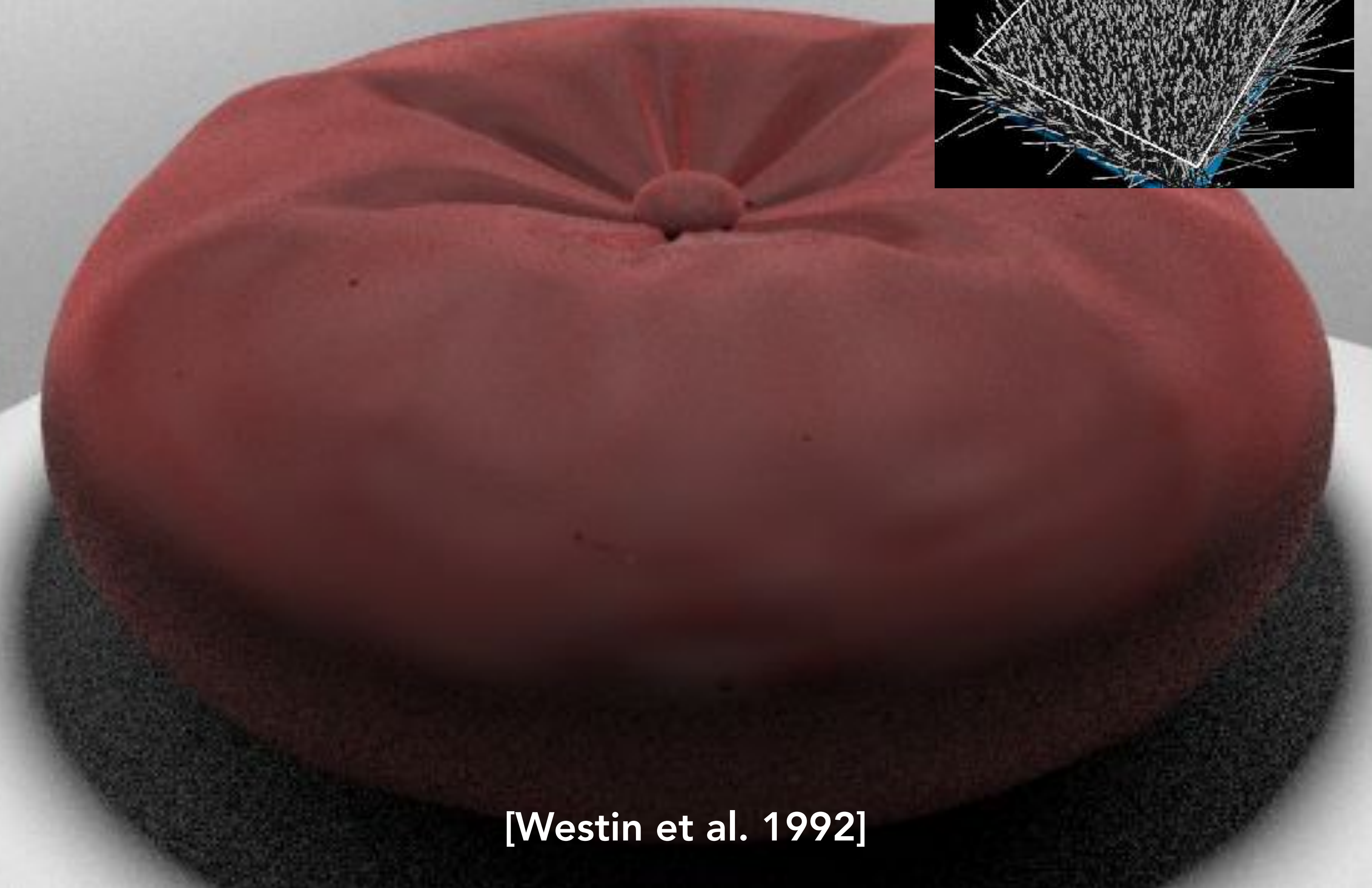
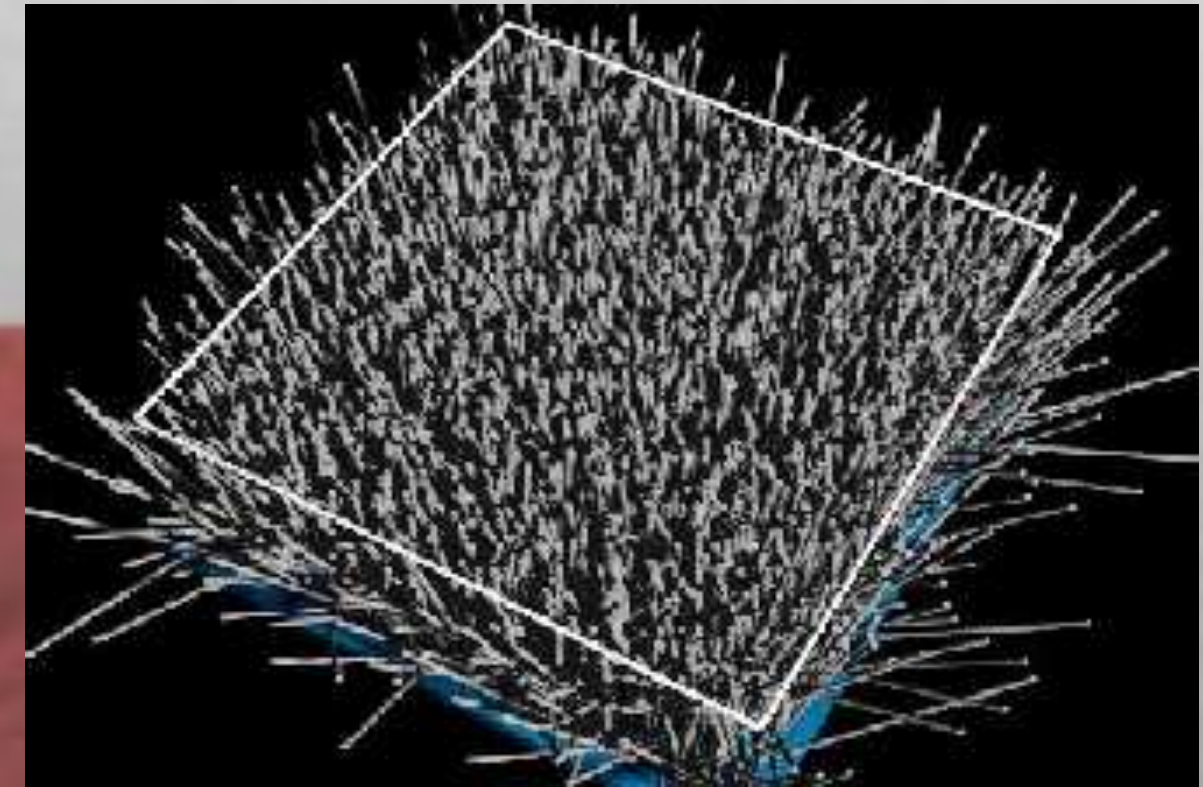


Anisotropic BRDF: Nylon



[Westin et al. 1992]

Anisotropic BRDF: Velvet



[Westin et al. 1992]

Anisotropic BRDF: Velvet



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

Anisotropic BRDF: Velvet



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

**Sampling of Advanced
Material Modeling Topics
(Slides courtesy Prof Lingqi Yan)**

Detailed / Glinty Material

Why details?

**Microfacet
model**



Why details?

**Microfacet
model**



Why details?

**[Yan et al.
2014, 2016]**



Why details?

**[Yan et al.
2014, 2016]**



Why details?

**[Yan et al.
2014, 2016]**

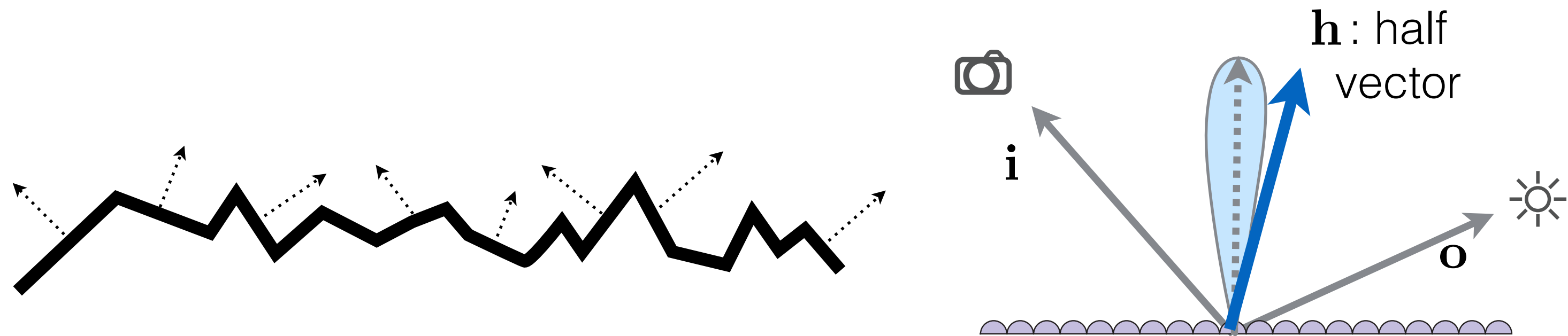


Why details?

**[Yan et al.
2014, 2016]**



Recap: Microfacet BRDF



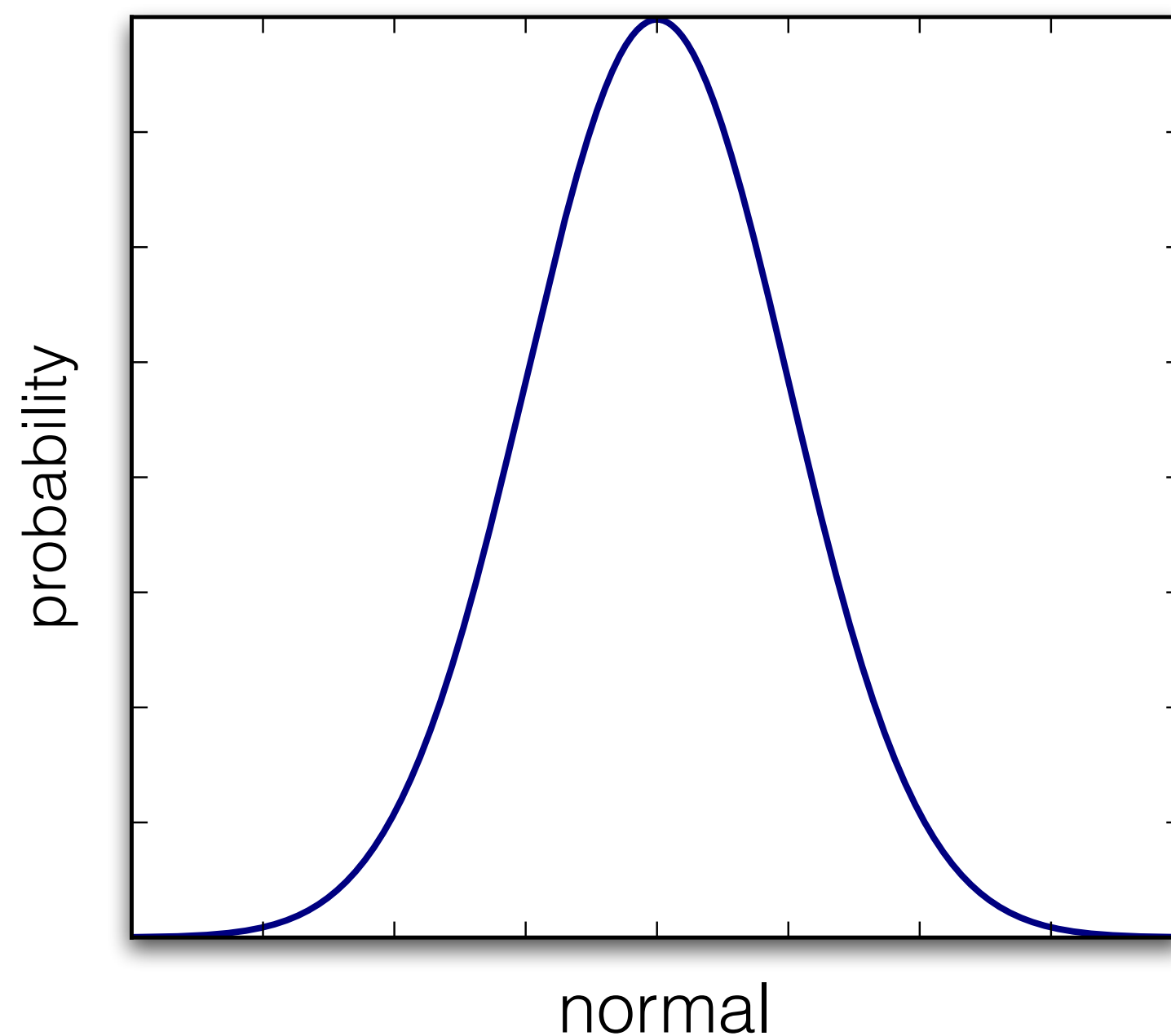
Surface = **Specular** microfacets + **statistical** normals

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

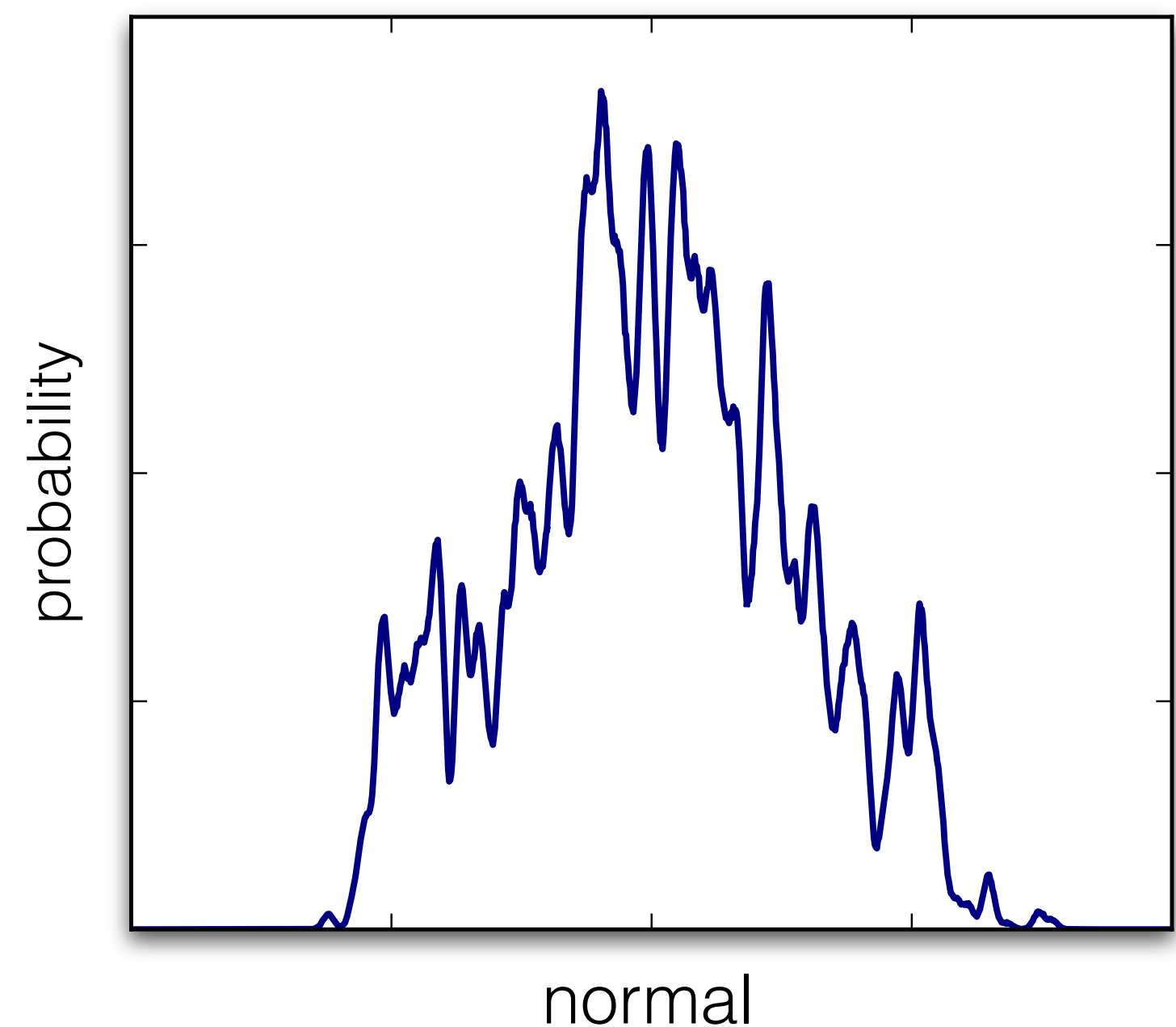
NDF: Normal Distribution Function

Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

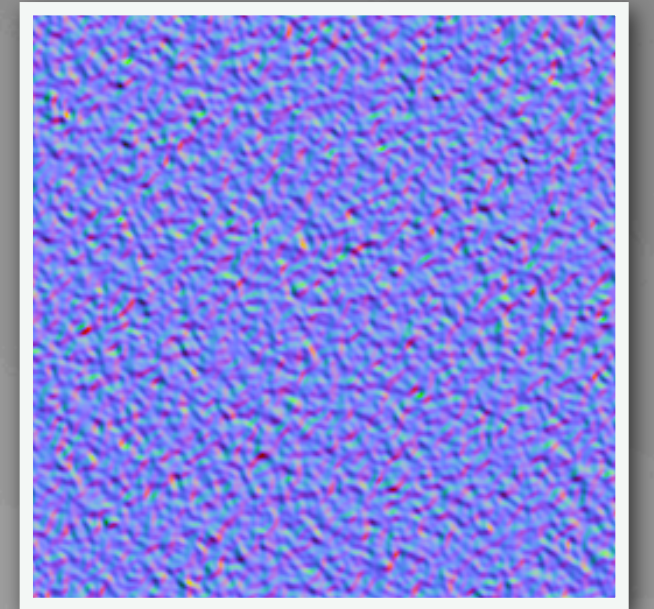
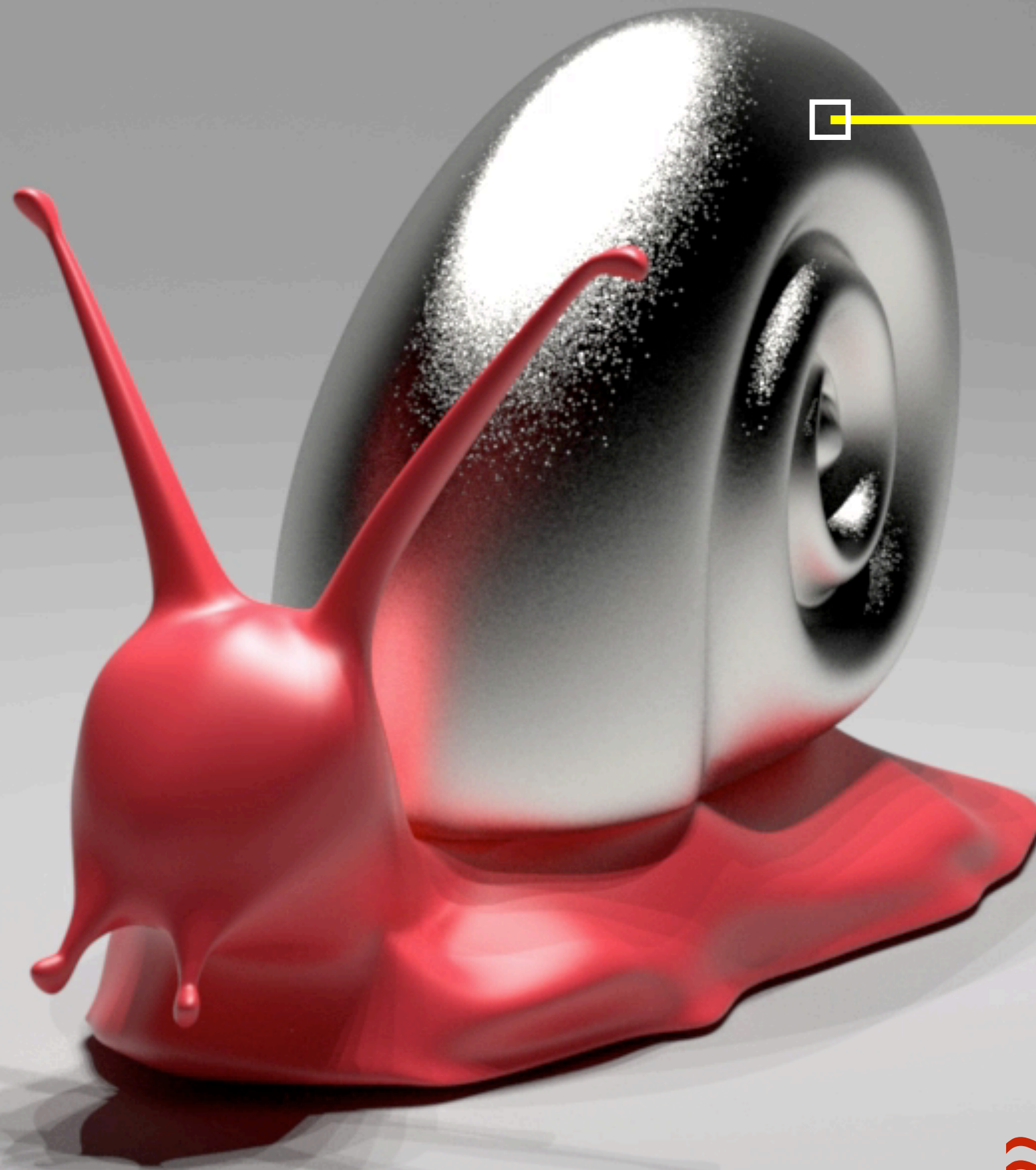


What we have
(microfacet — statistical)



What we want

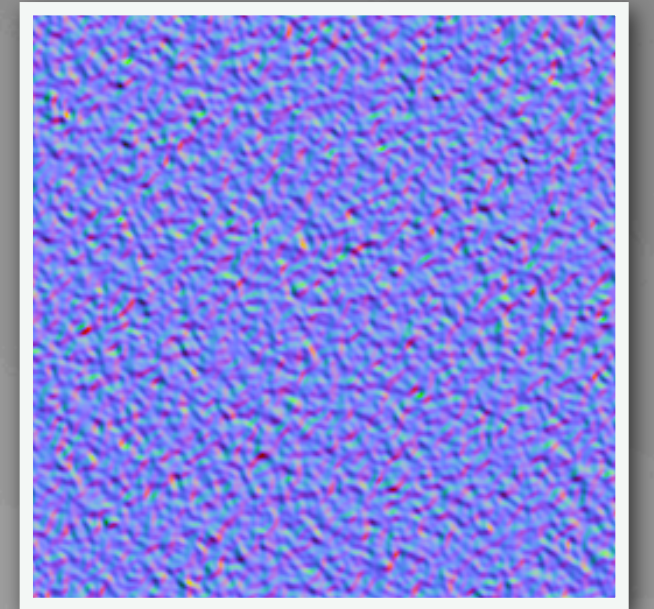
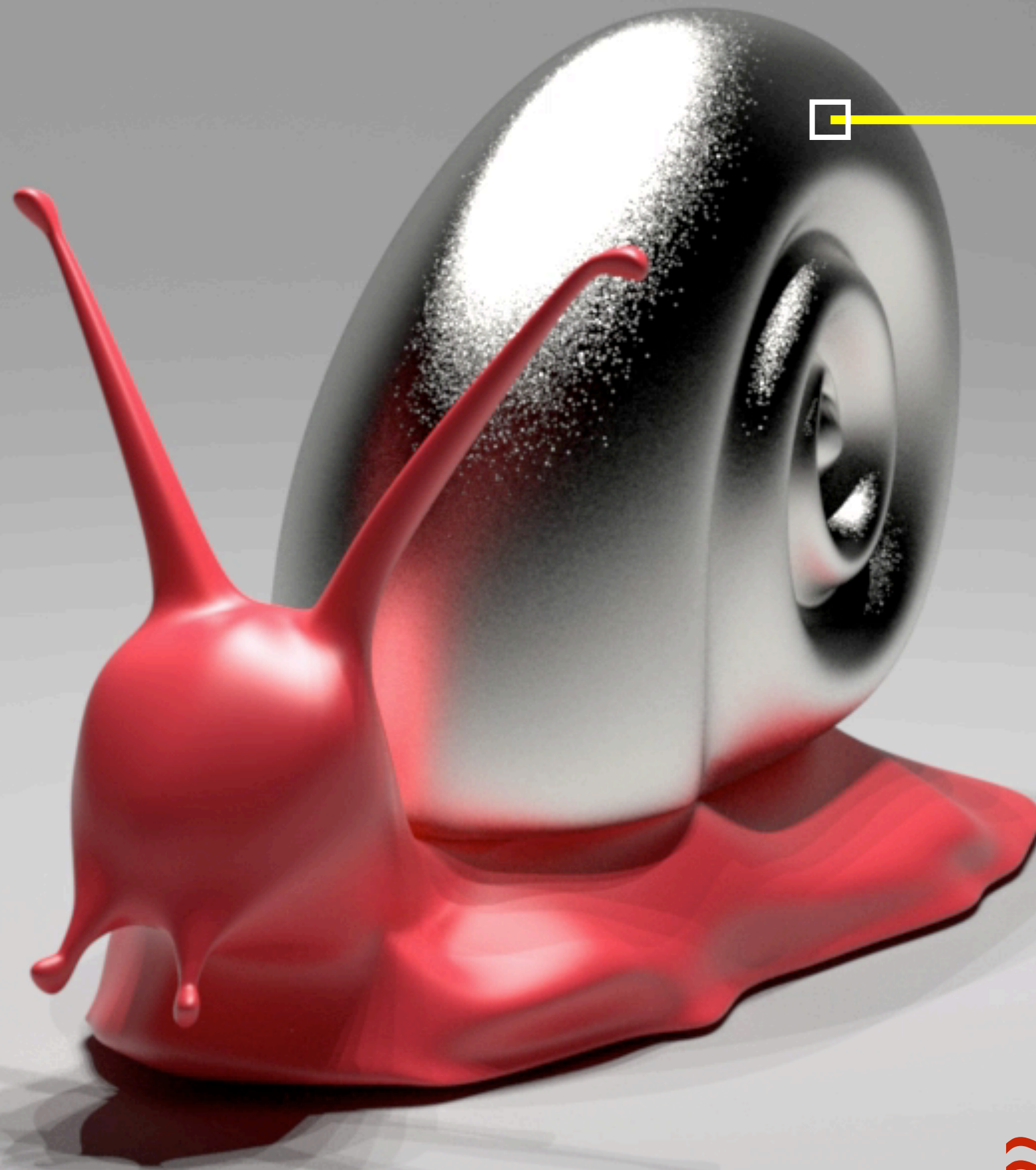
Define Details



isotropic noise
normal map

Normal map
resolution:
 $\approx 200K \times 200K$

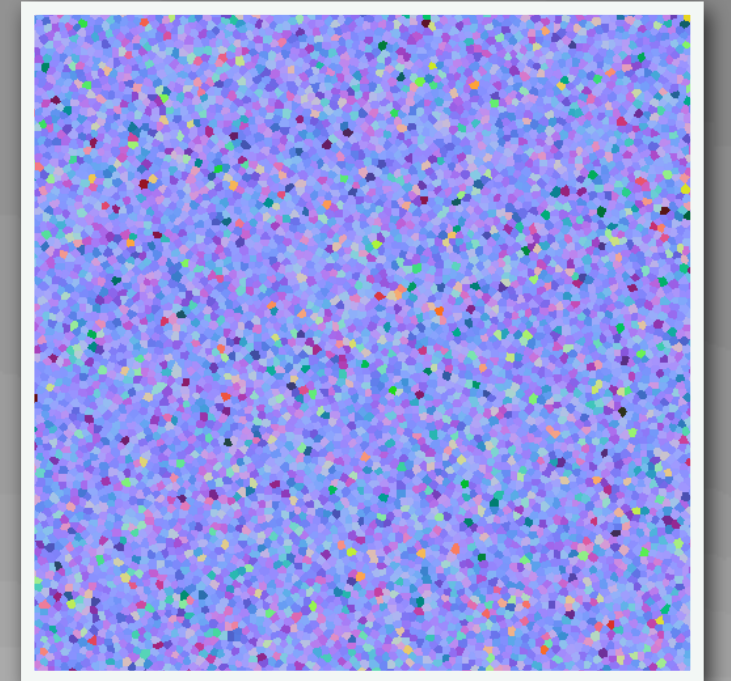
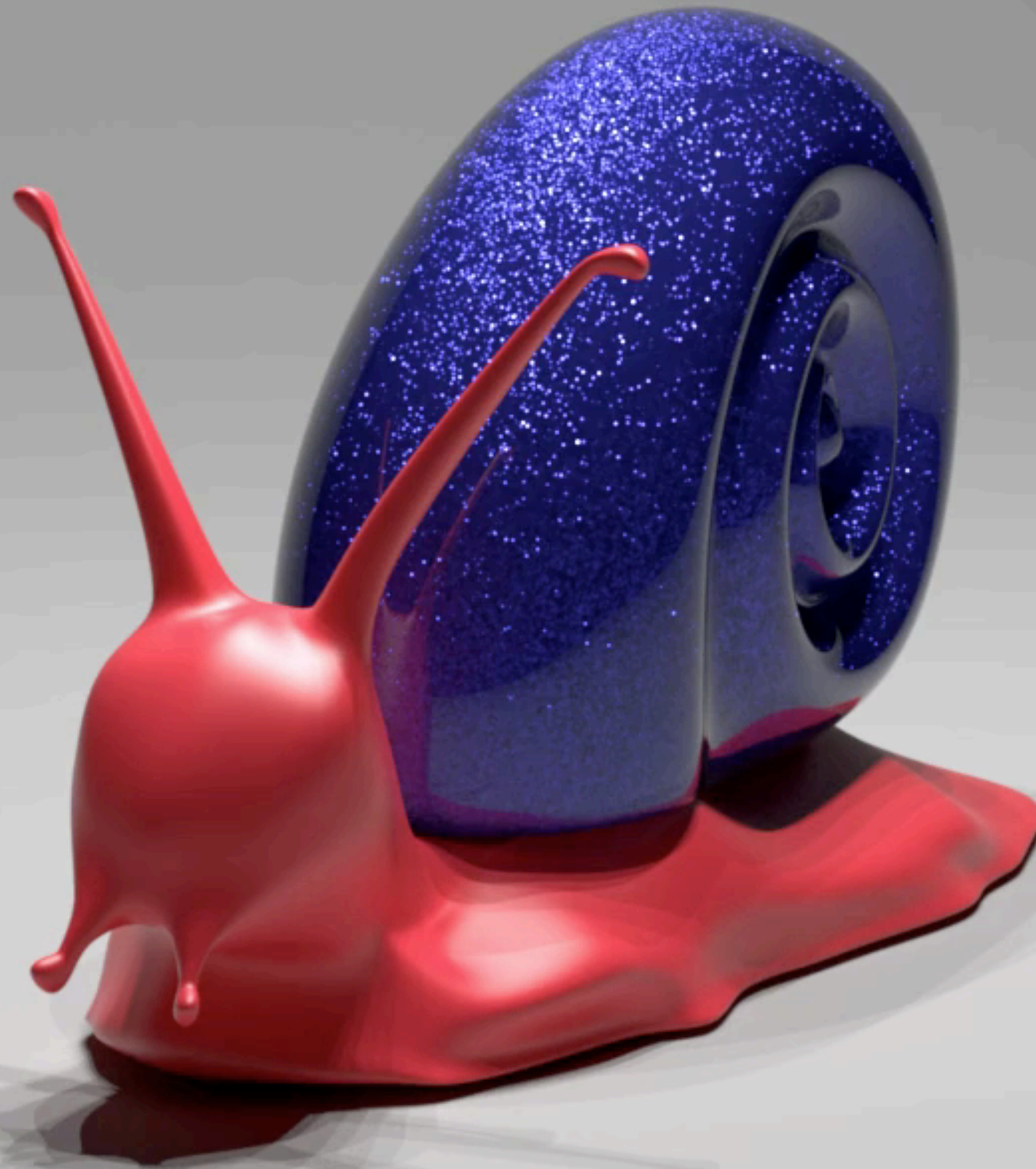
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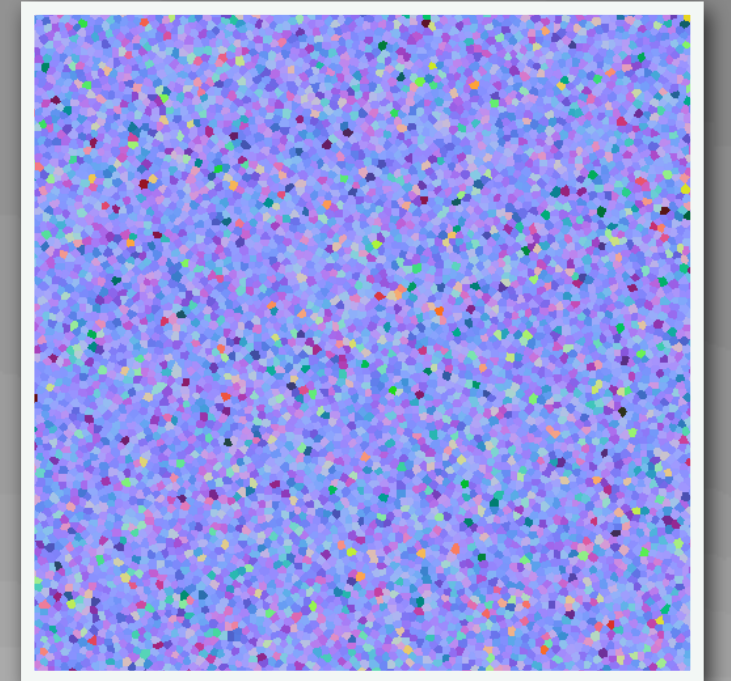
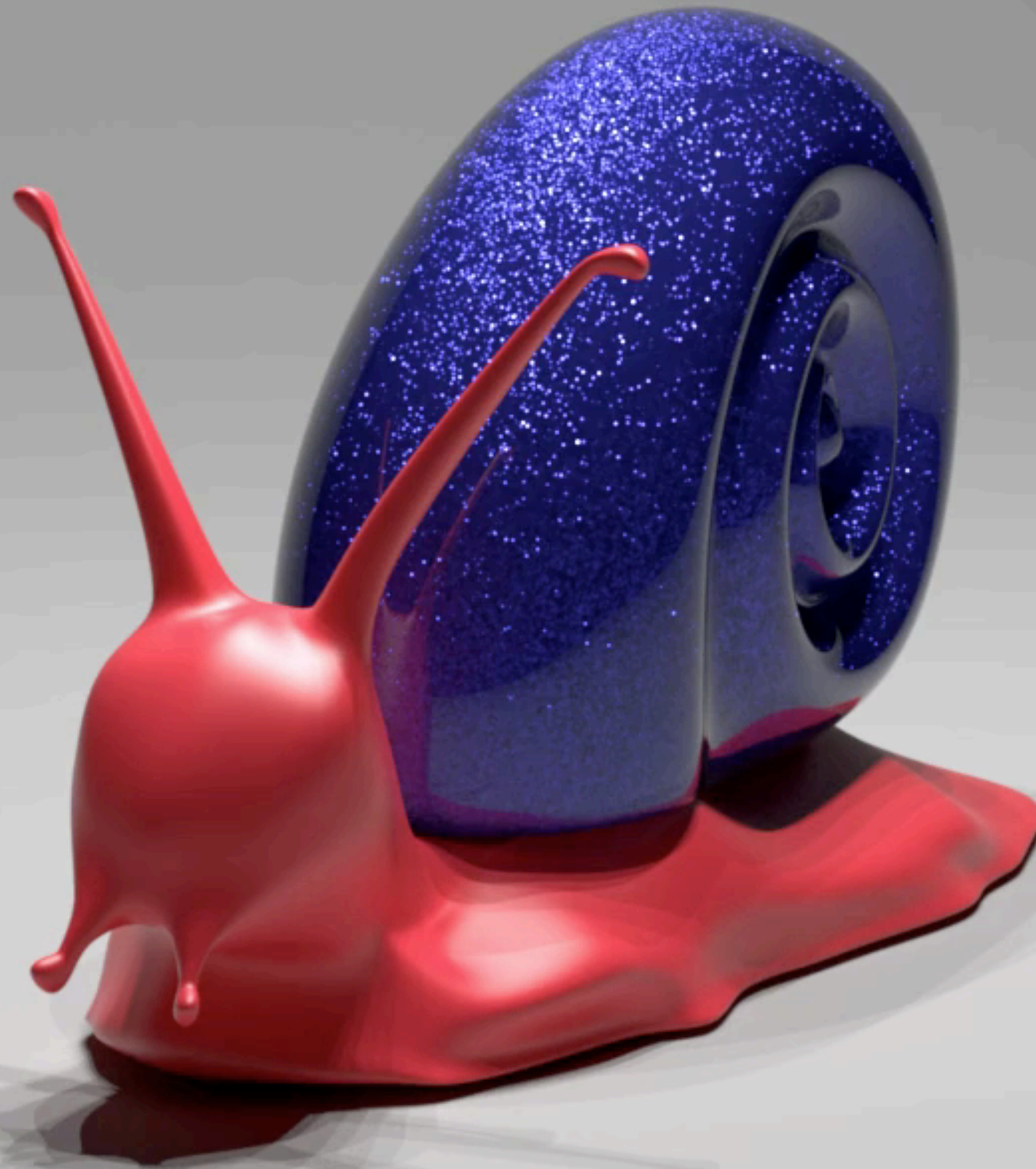
Normal map
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 $\approx 200K \times 200K$

Different Details

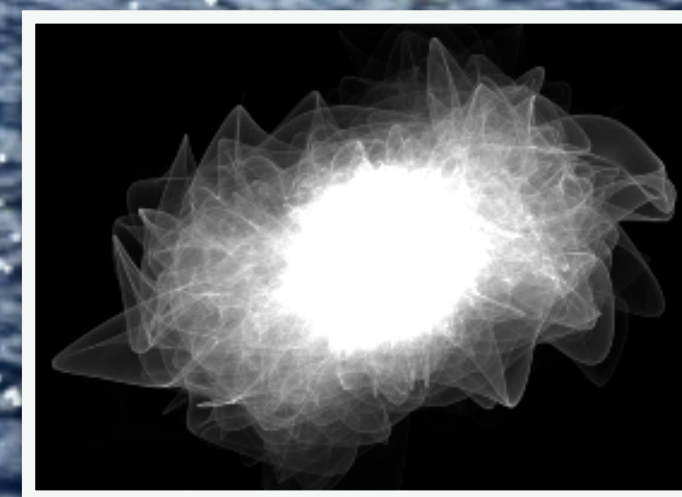
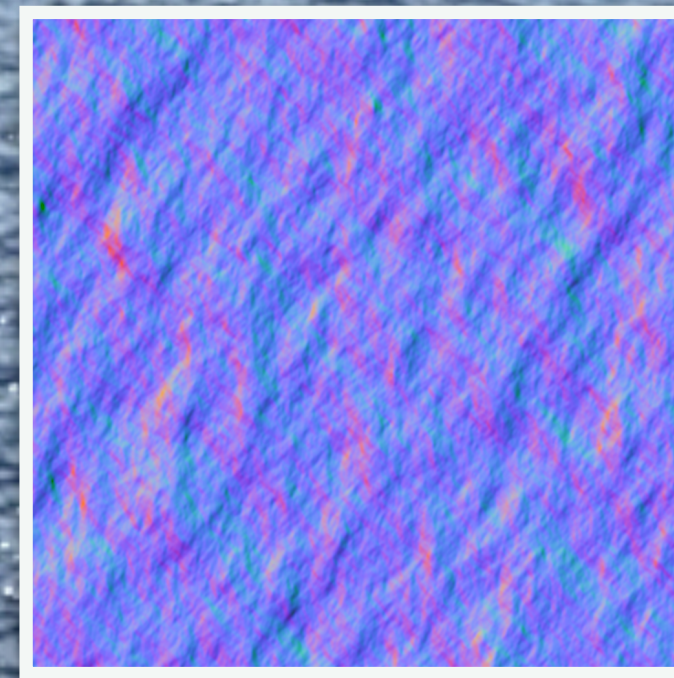
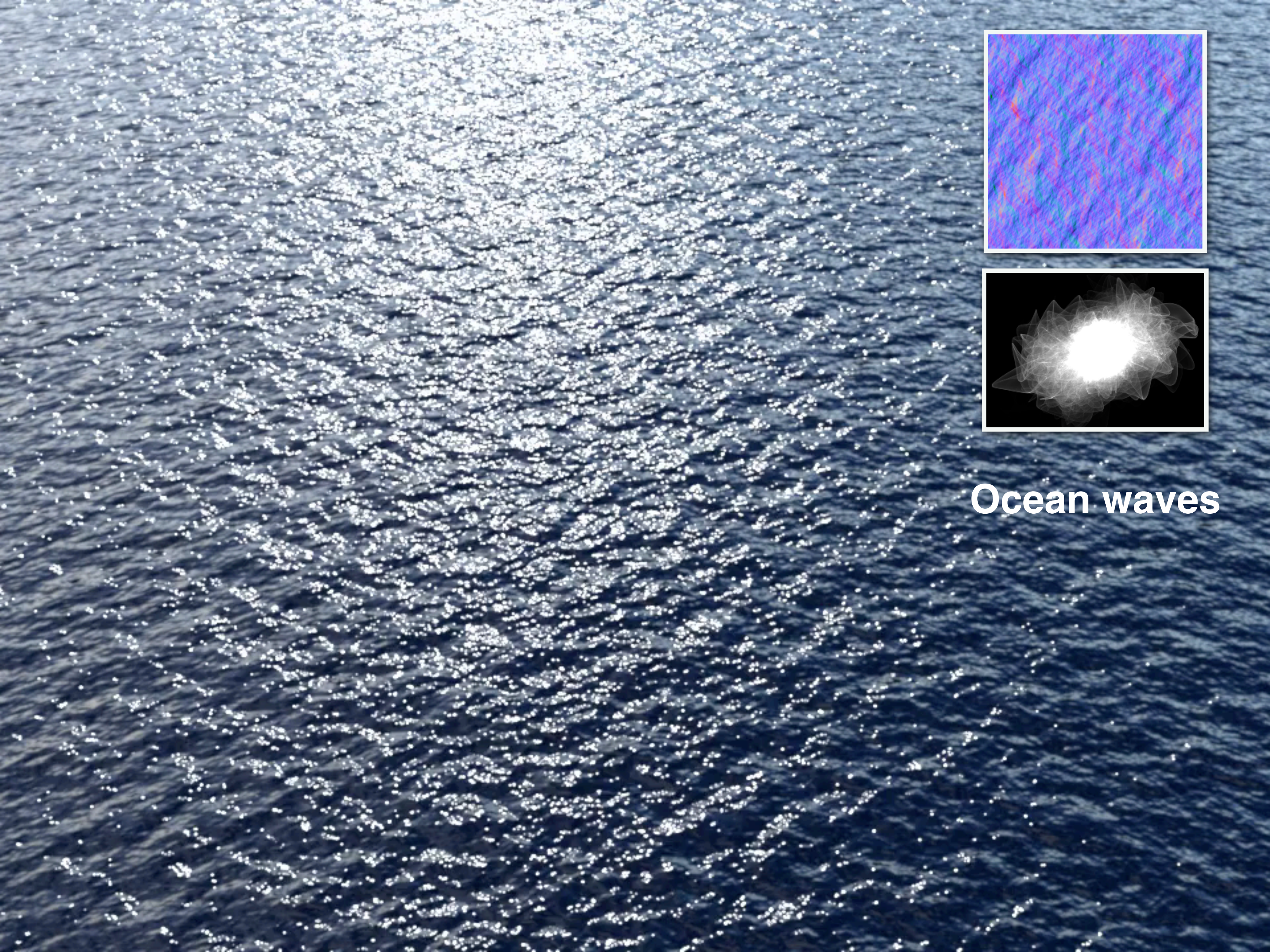


Metallic flakes

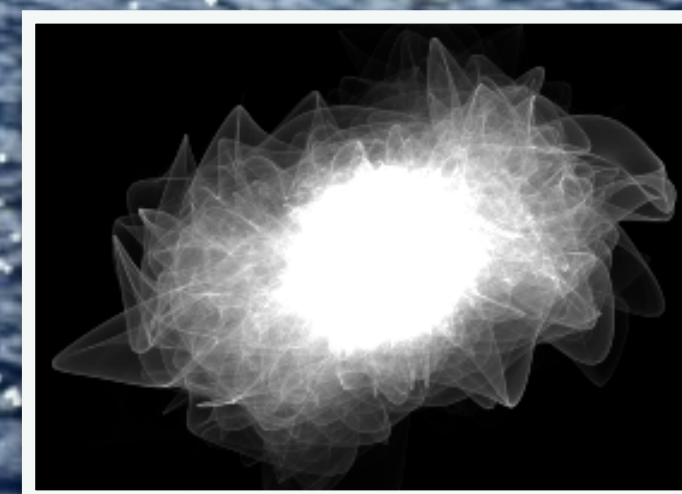
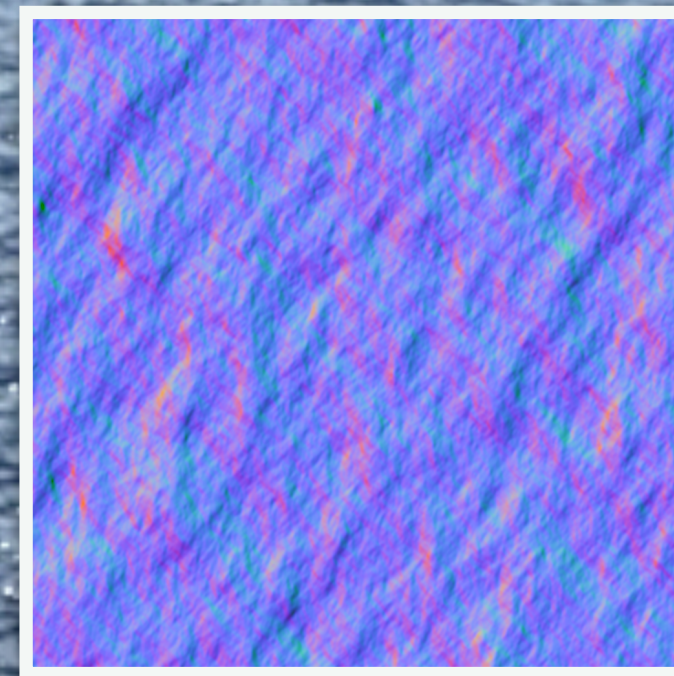
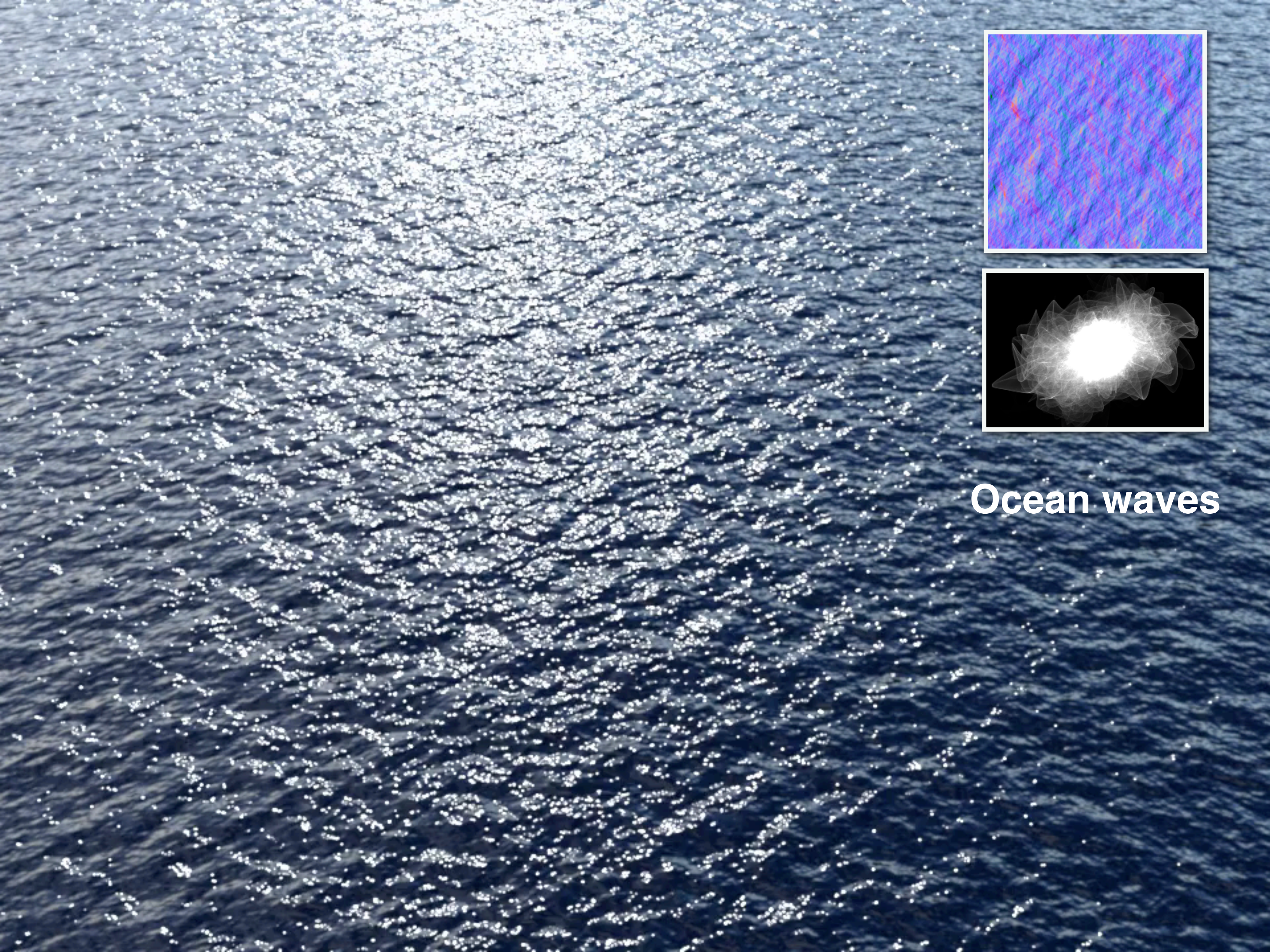
Different Details



Metallic flakes



Ocean waves



Ocean waves

Hair / Fur Appearance Models

Hair Appearance

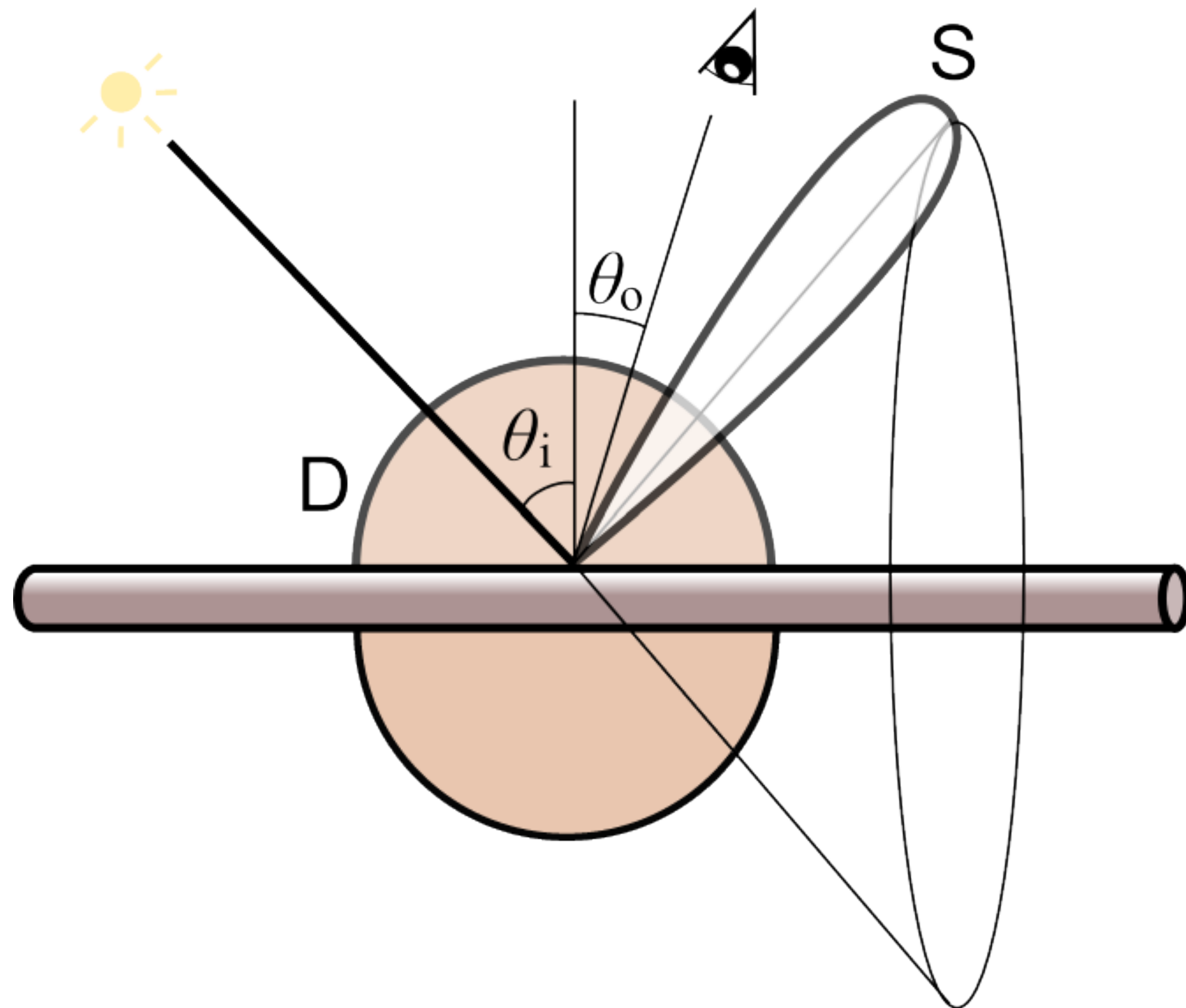


CS184/284A



S26 - O'Brien

Kajiya-Kay Model



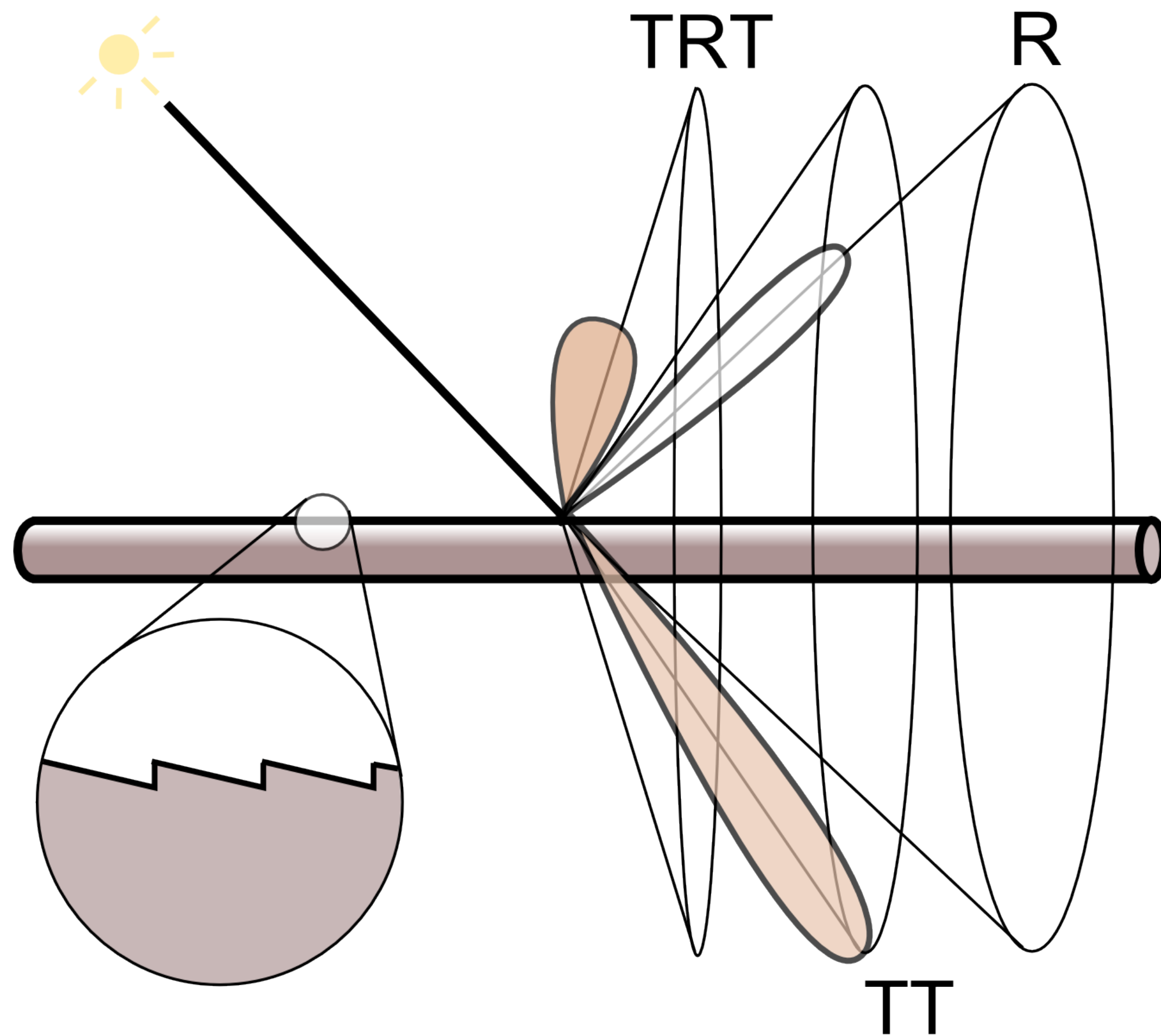
[Image courtesy of Chiwei Tseng]

Kajiya-Kay Model



[Yuksel et al. 2008]

Marschner Model

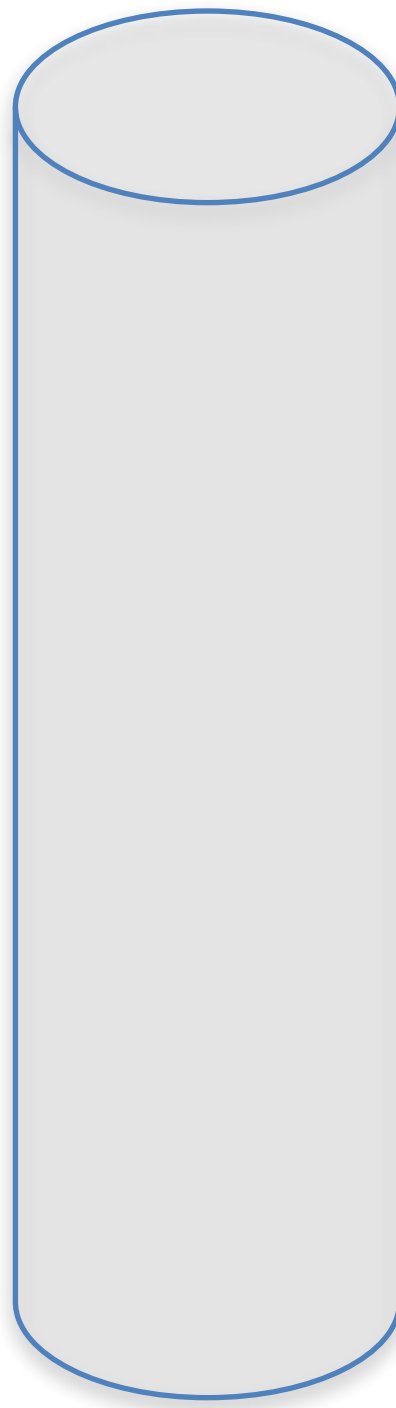


[Image courtesy of Chiwei Tseng]

Marschner Model

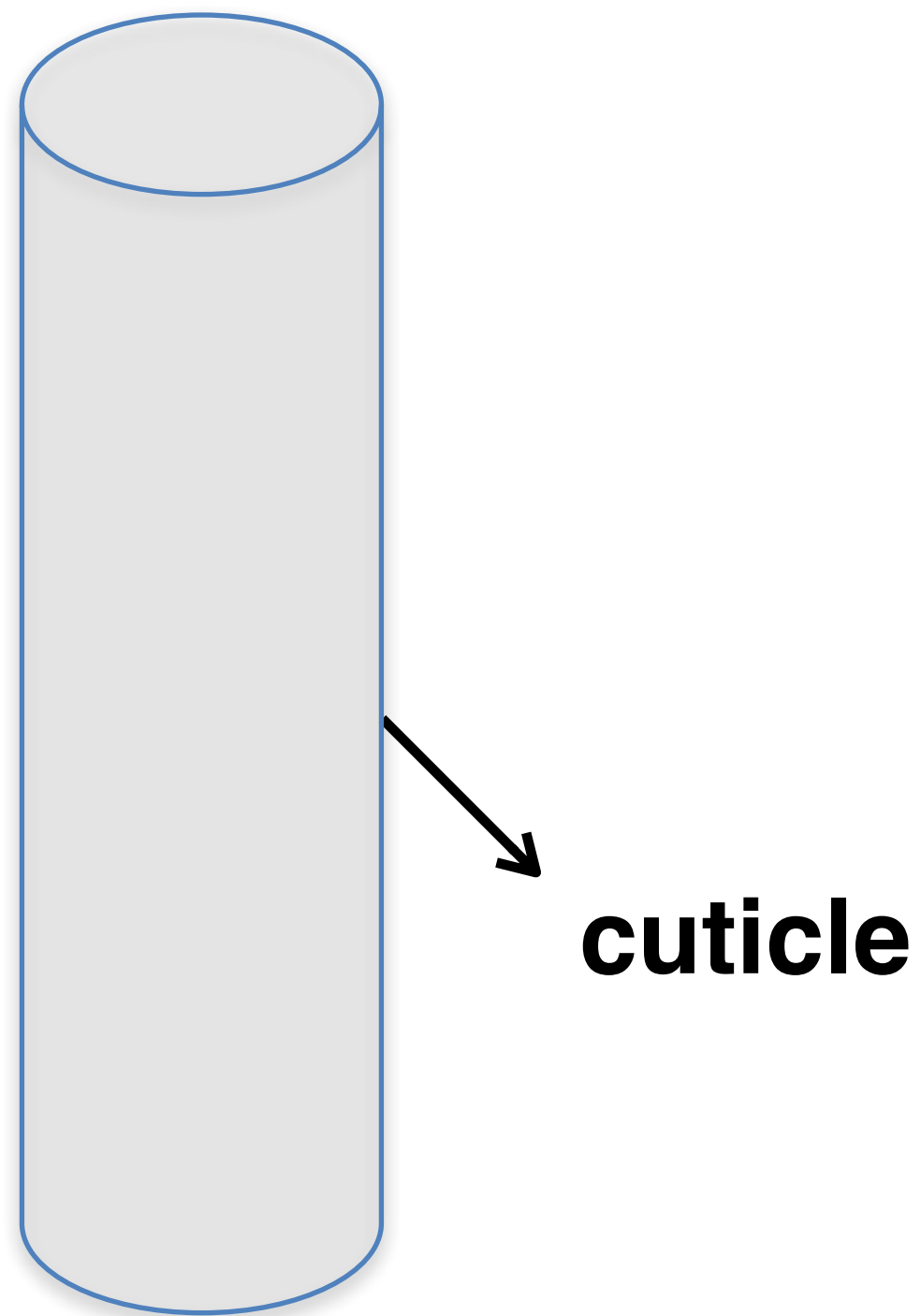
Marschner Model

- Glass-like cylinder



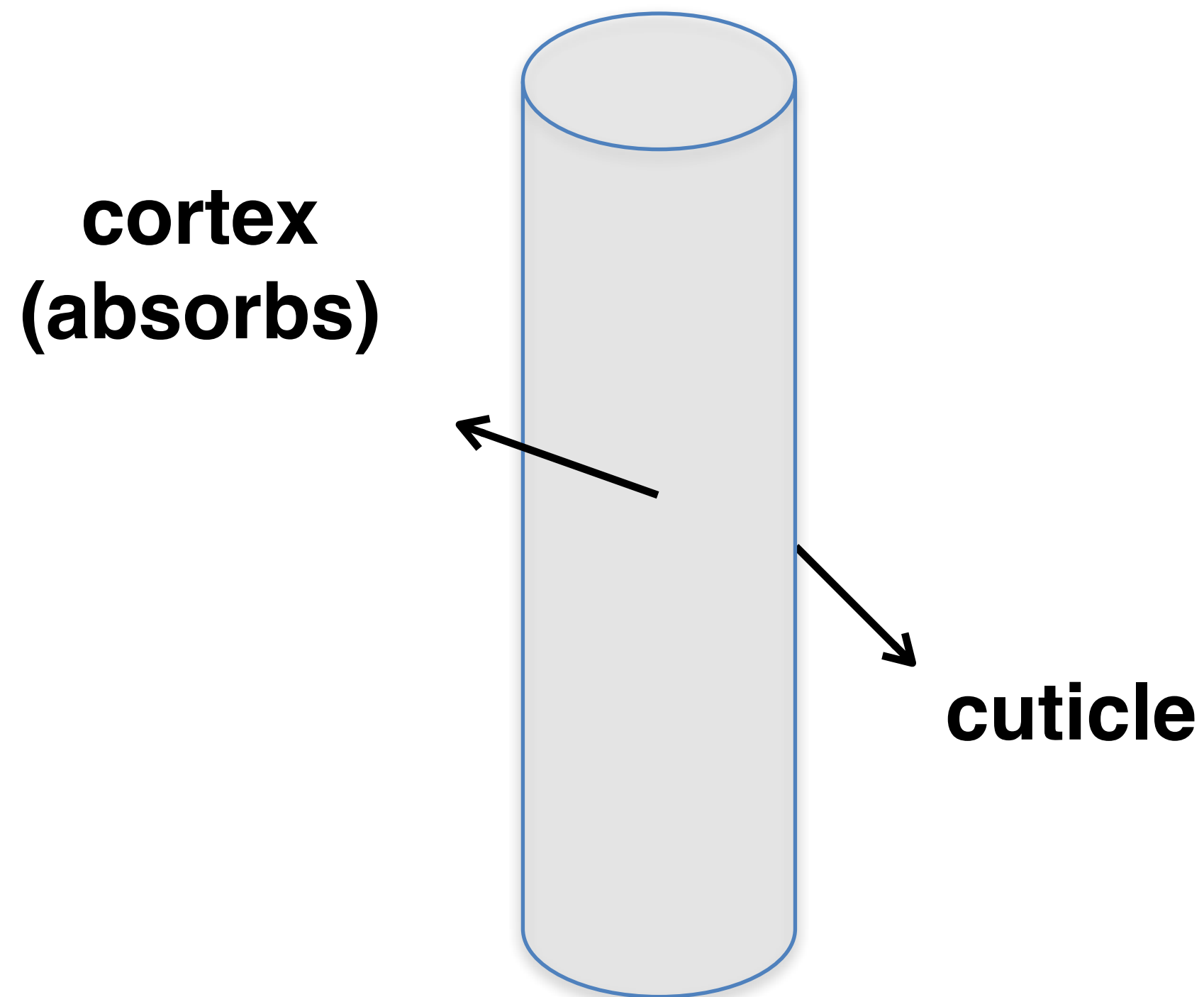
Marschner Model

- **Glass-like cylinder**



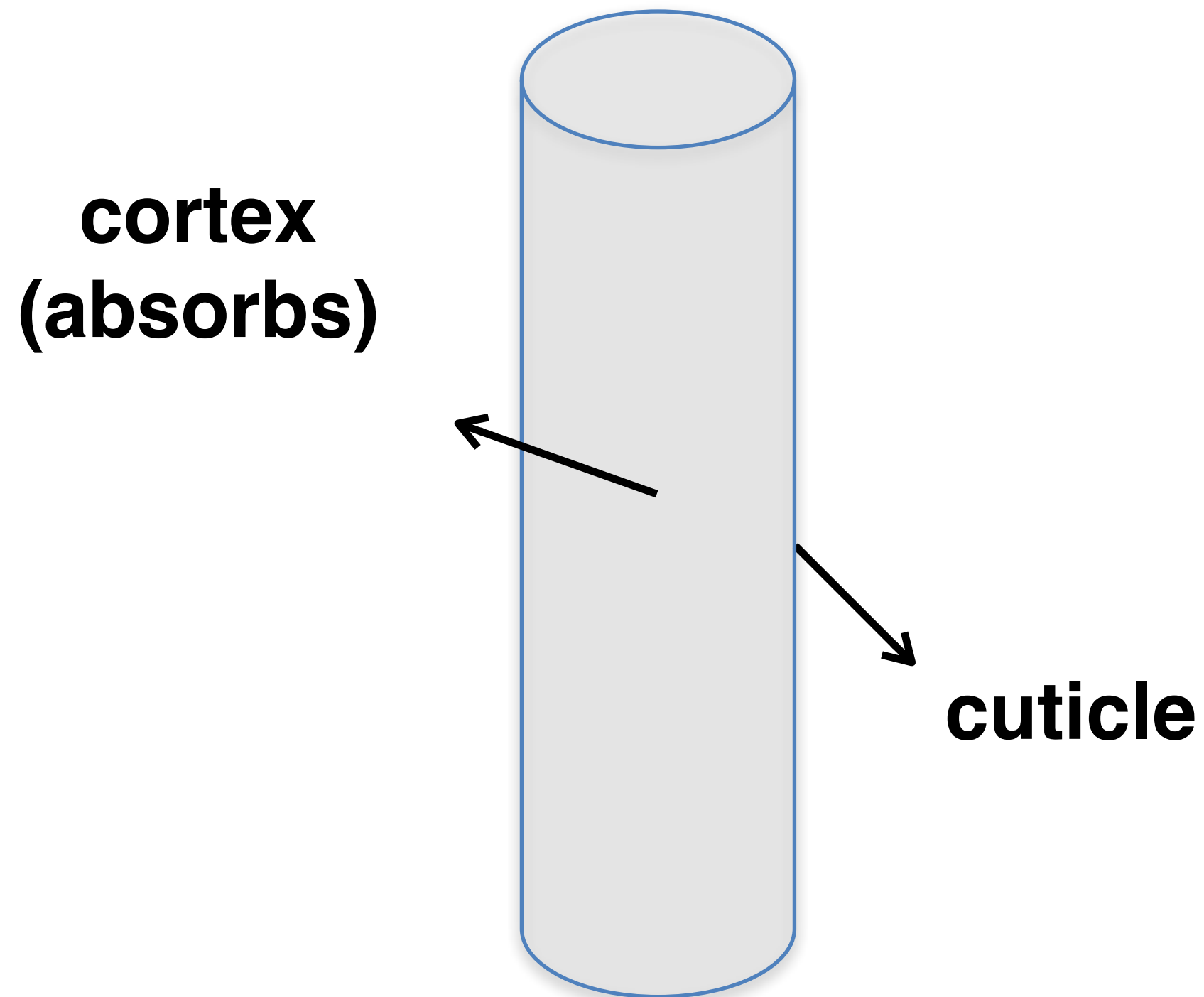
Marschner Model

- Glass-like cylinder

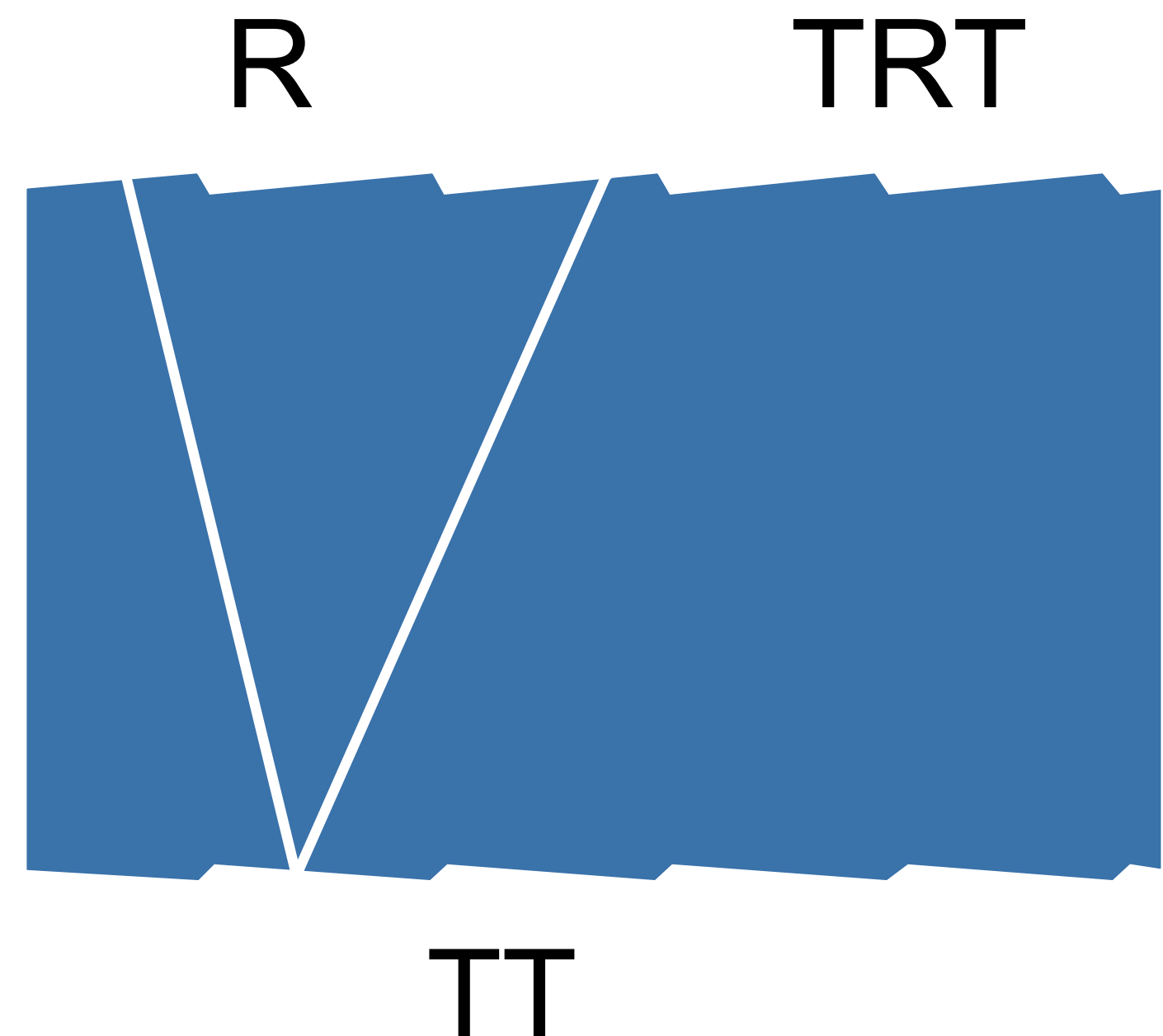


Marschner Model

- Glass-like cylinder

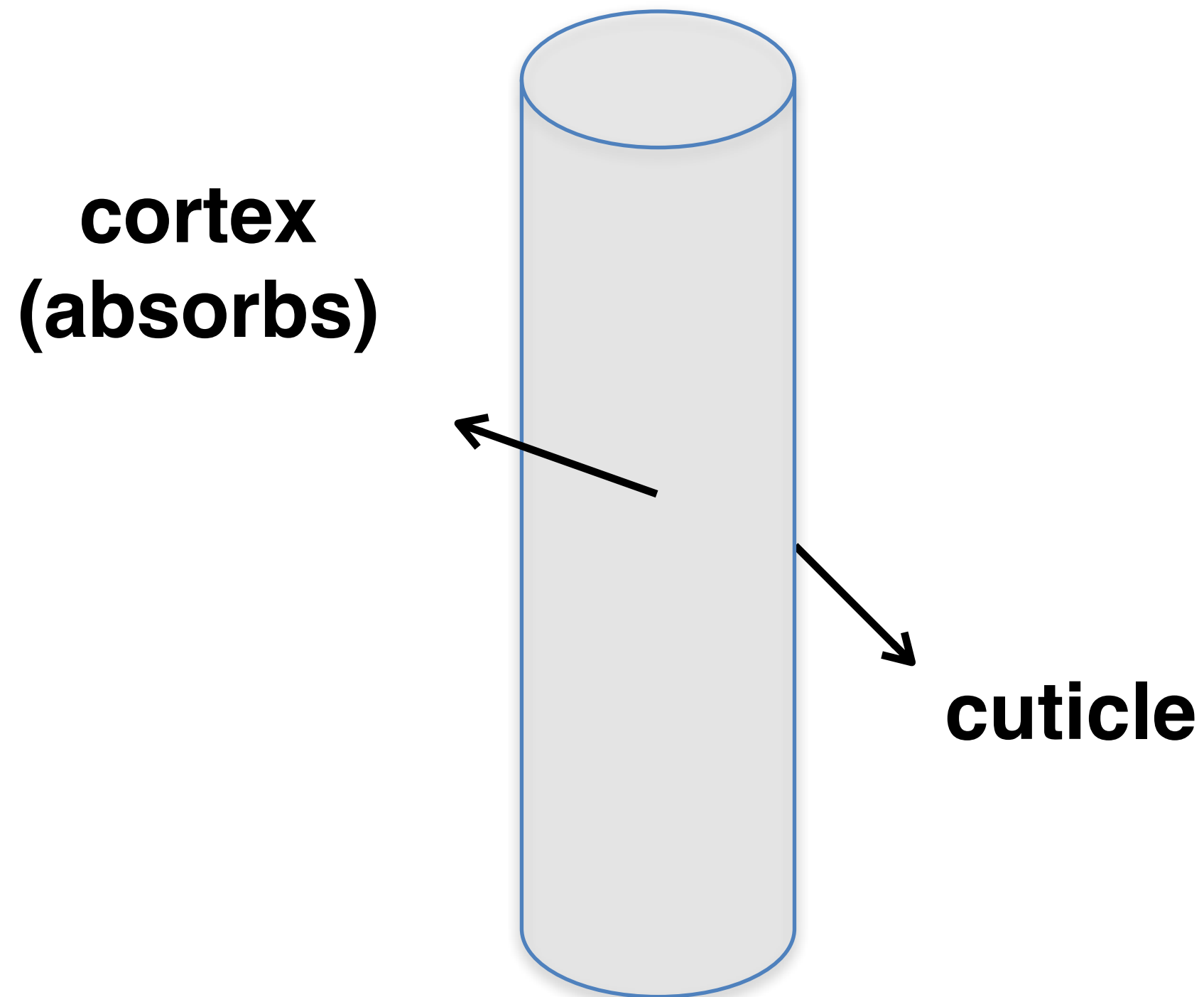


- 3 types of light interactions:
R, TT, TRT
(R: reflection, T: transmission)

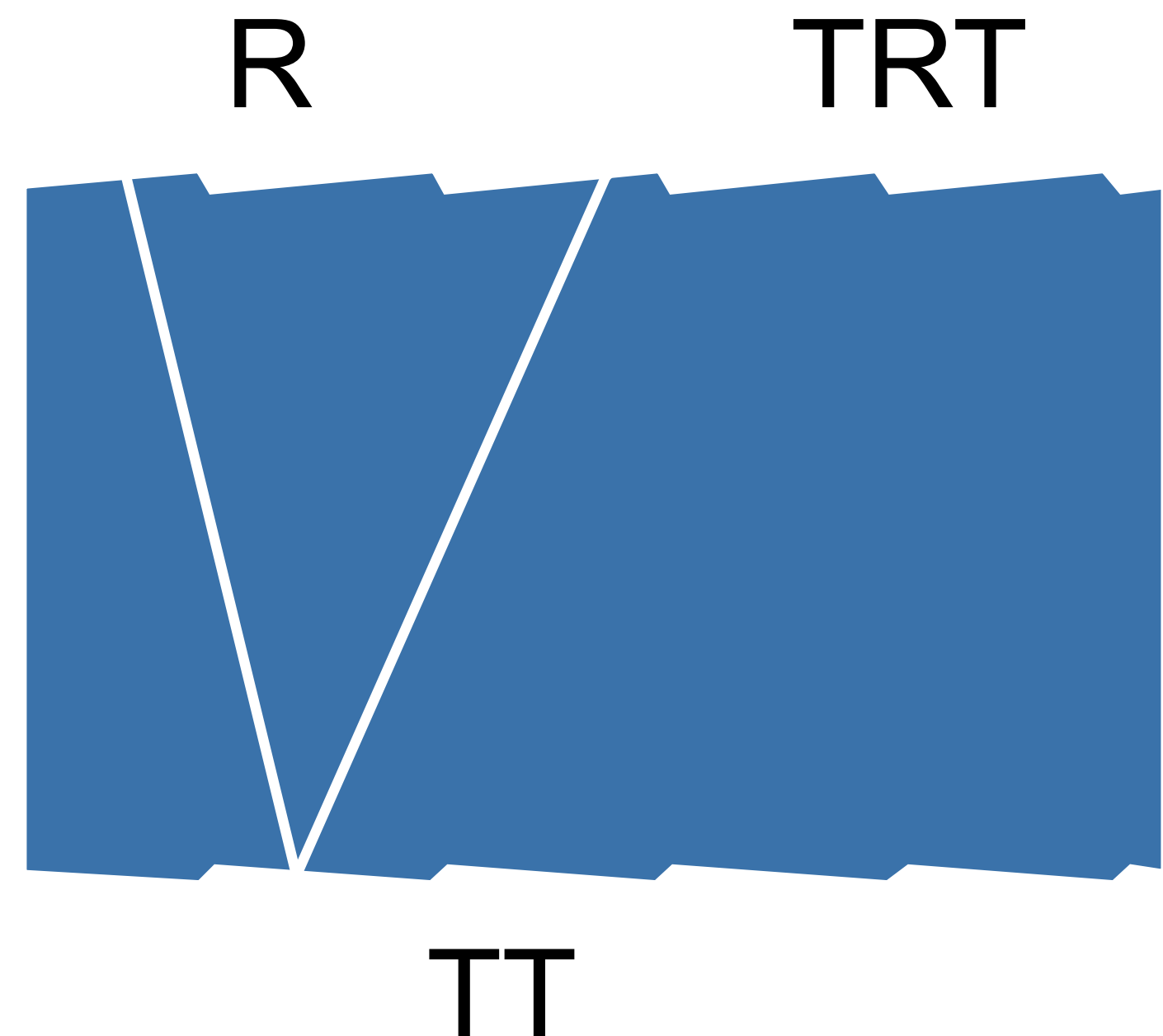


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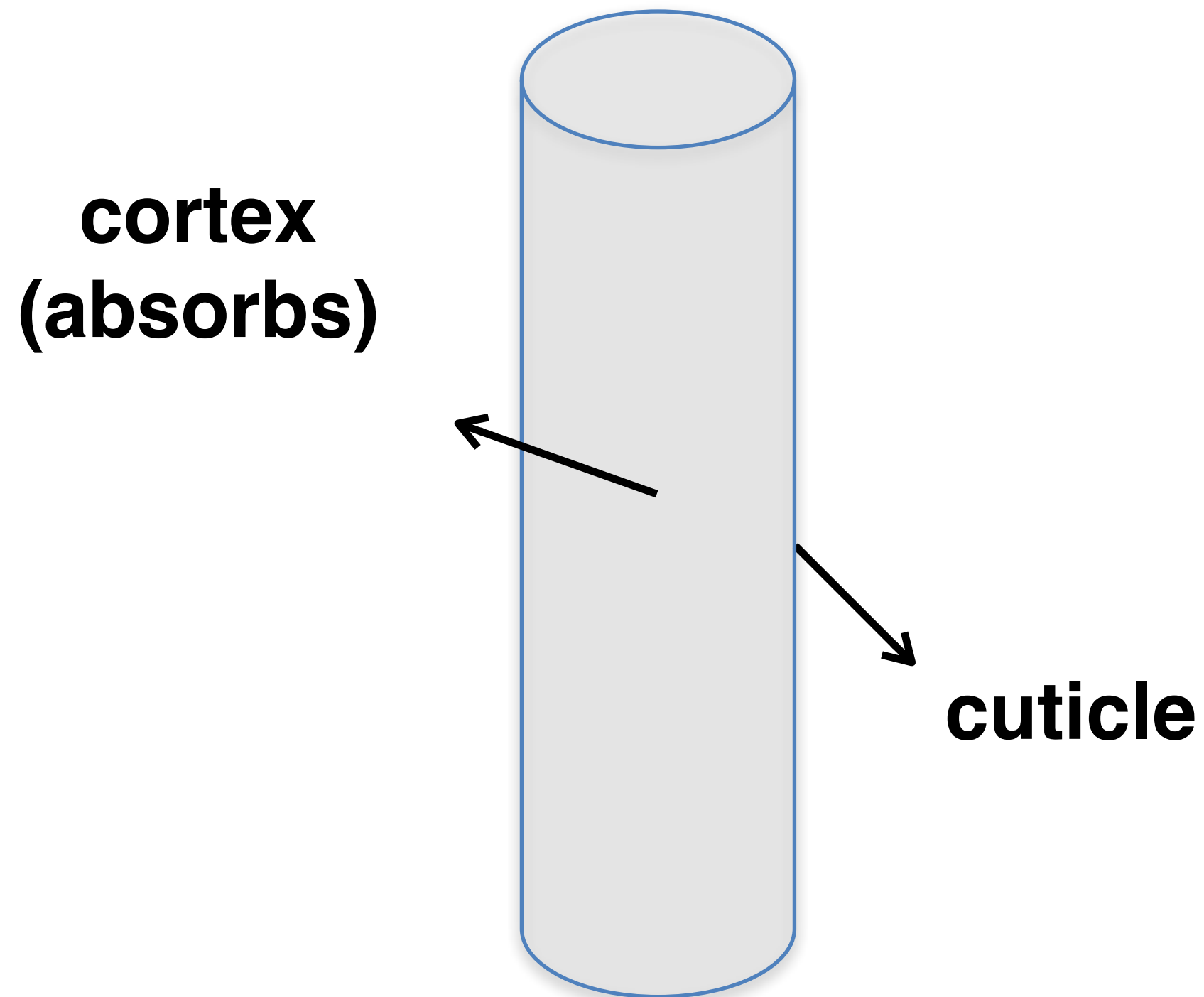


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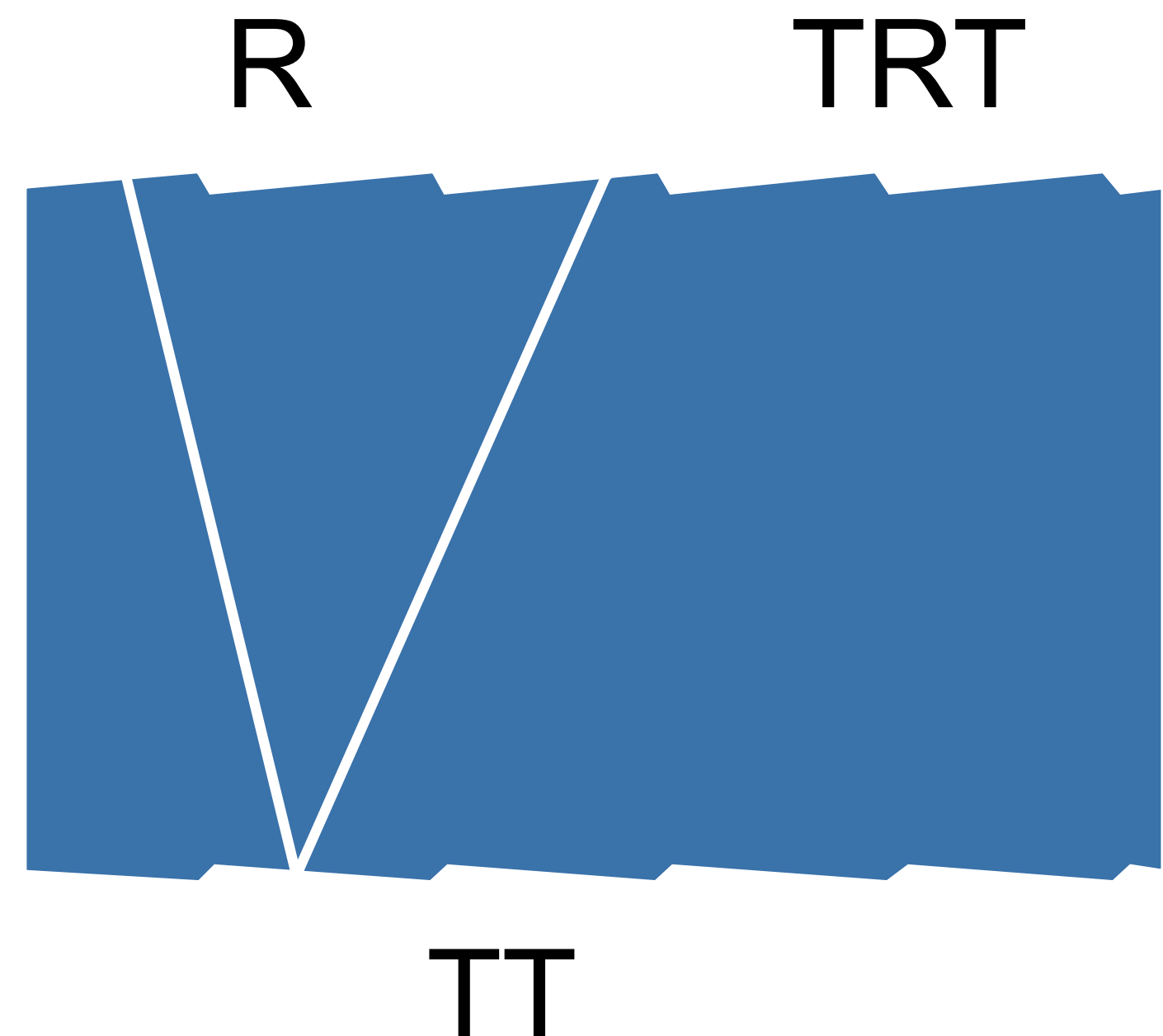


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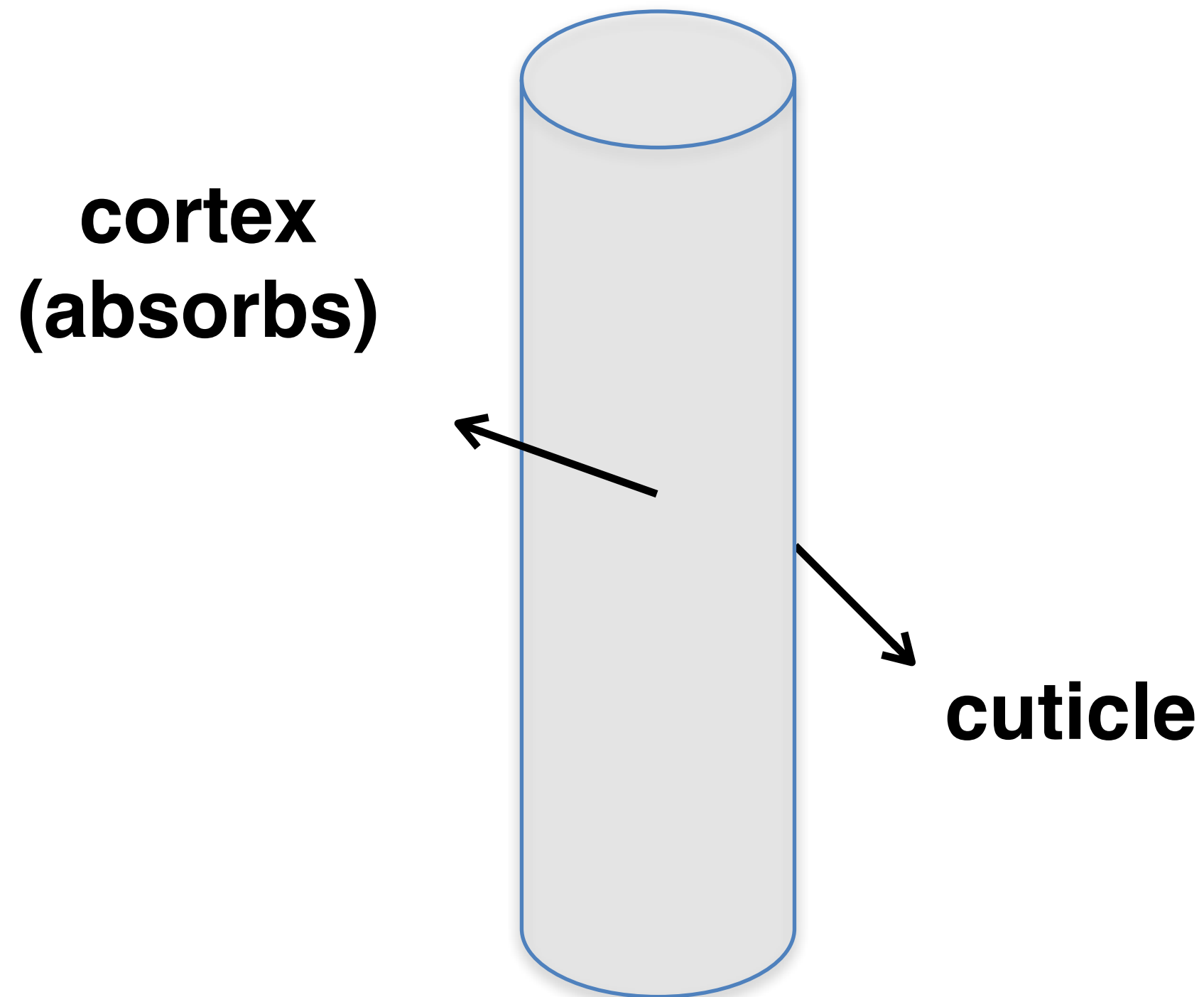


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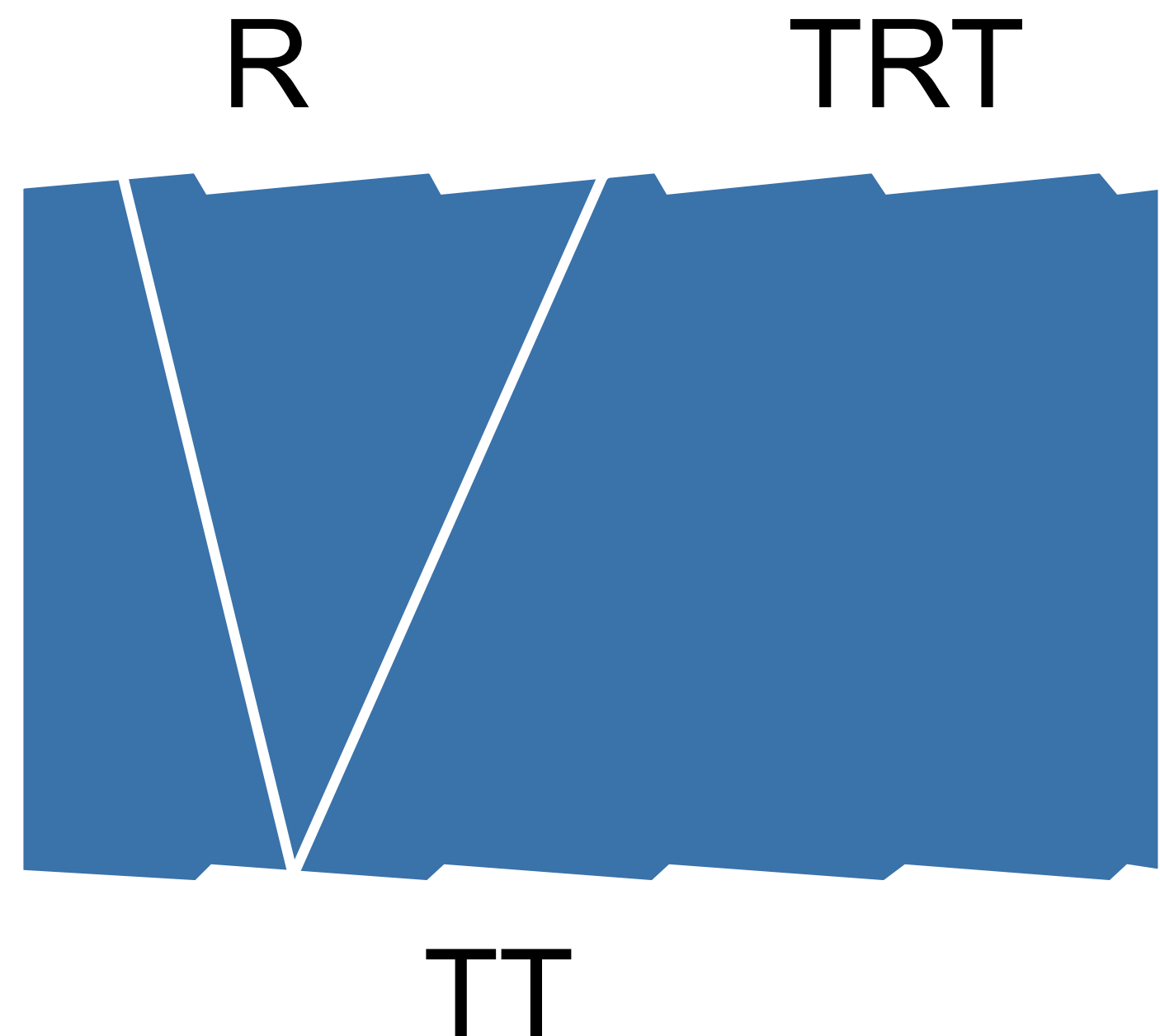


Marschner Model

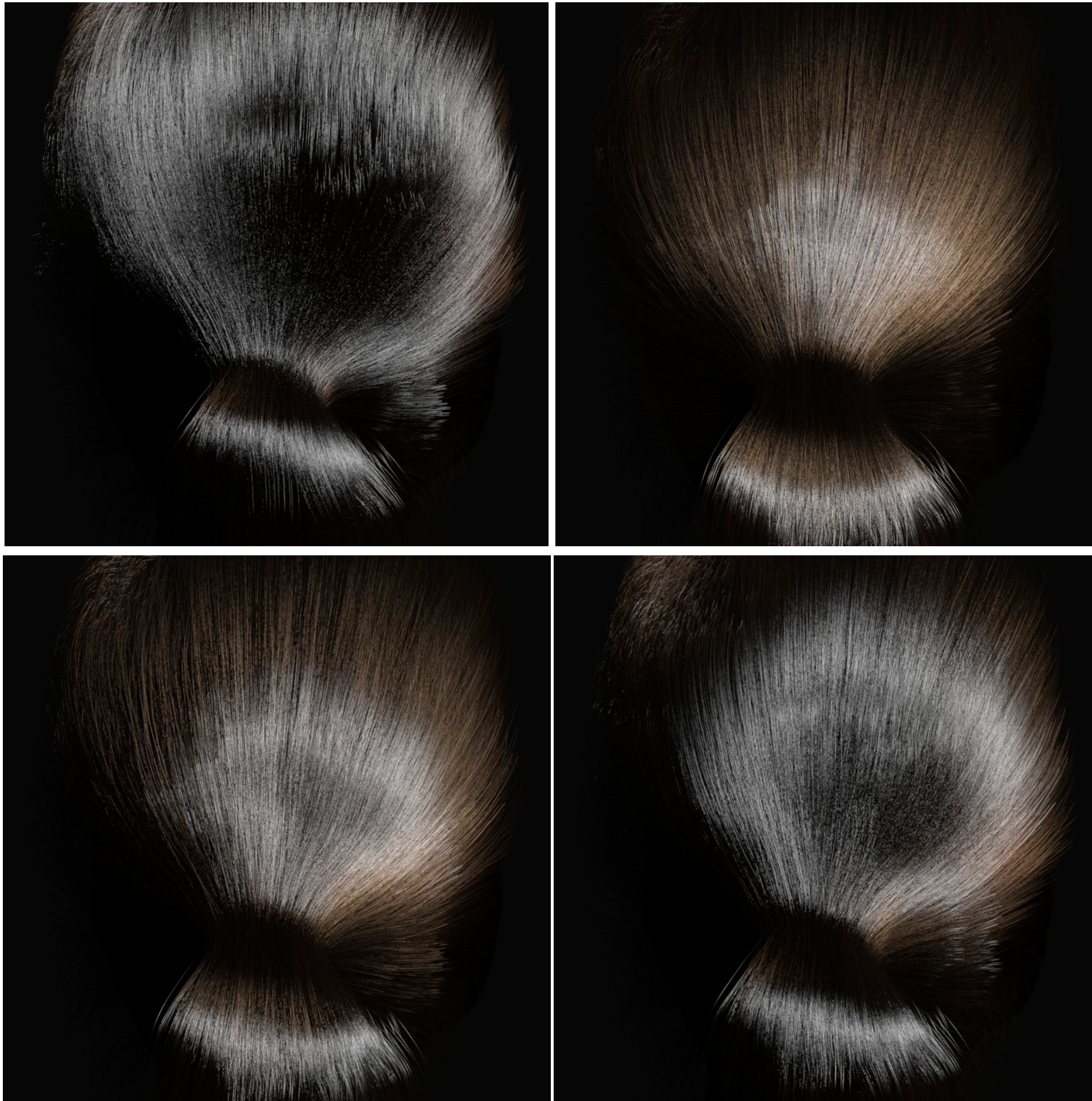
- Glass-like cylinder



- 3 types of light interactions:
R, TT, TRT
(R: reflection, T: transmission)



Marschner model



[Marschner et al. 2003]



[d'Eon et al. 2011]

Participating Media

Participating Media: Fog



[Novák et al. 2012]

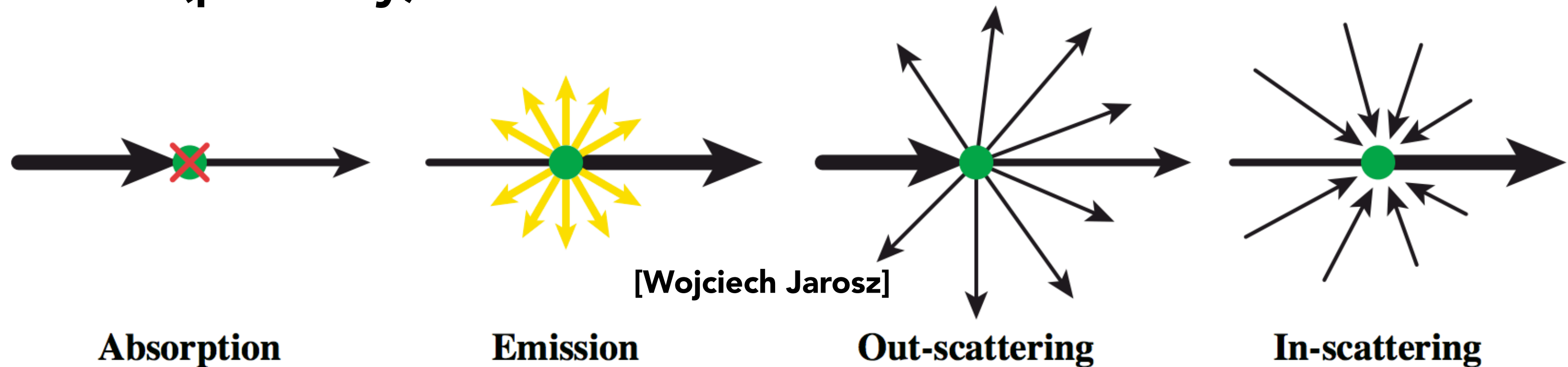
Participating Media: Cloud



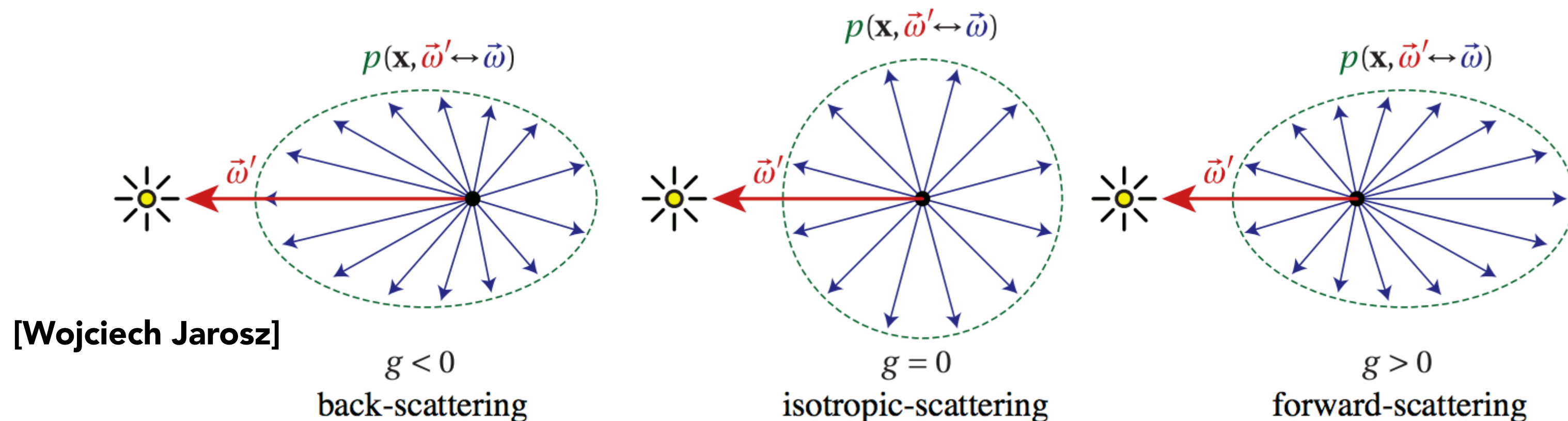
[by thephotographer0]

Participating Media

- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered.

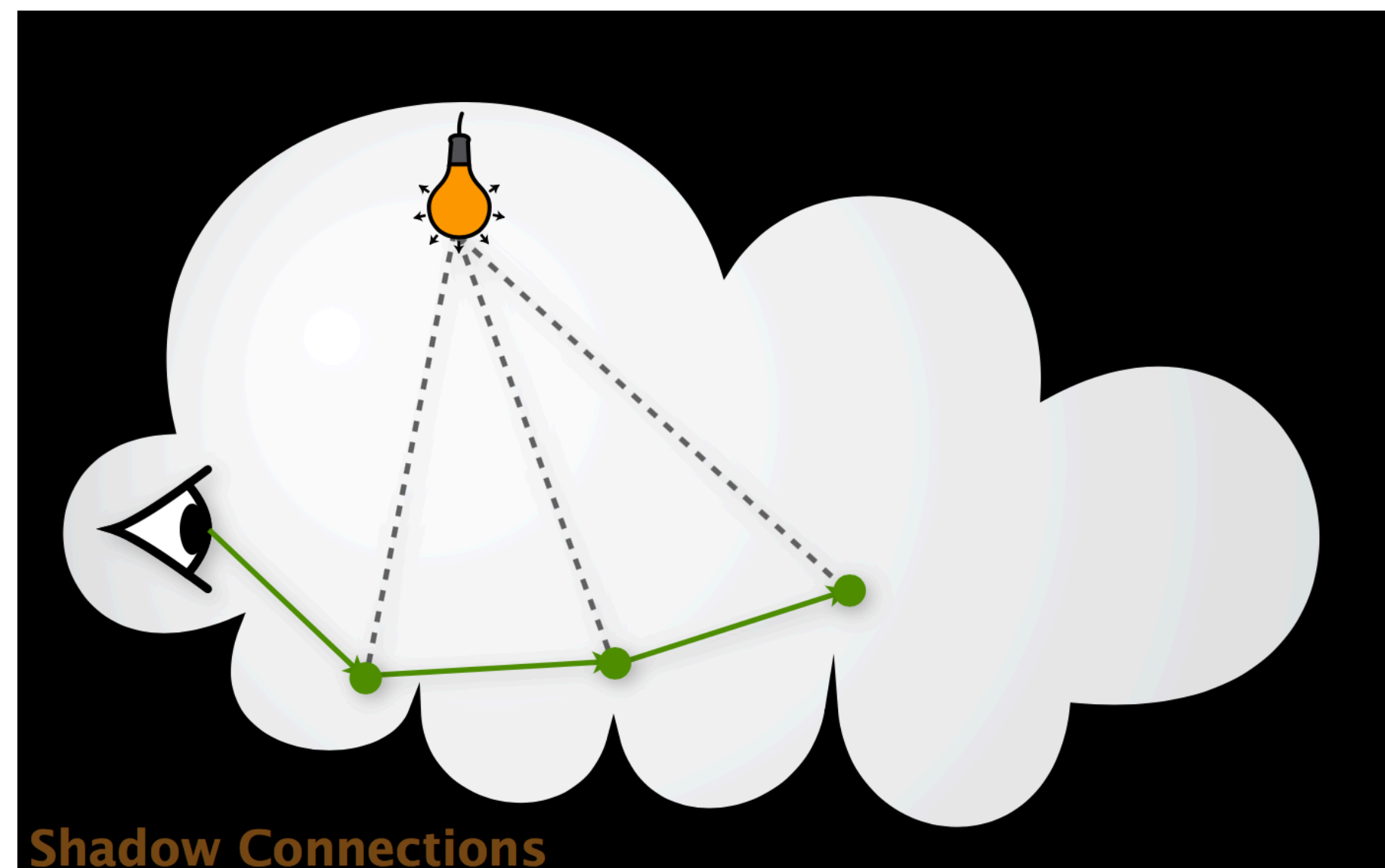
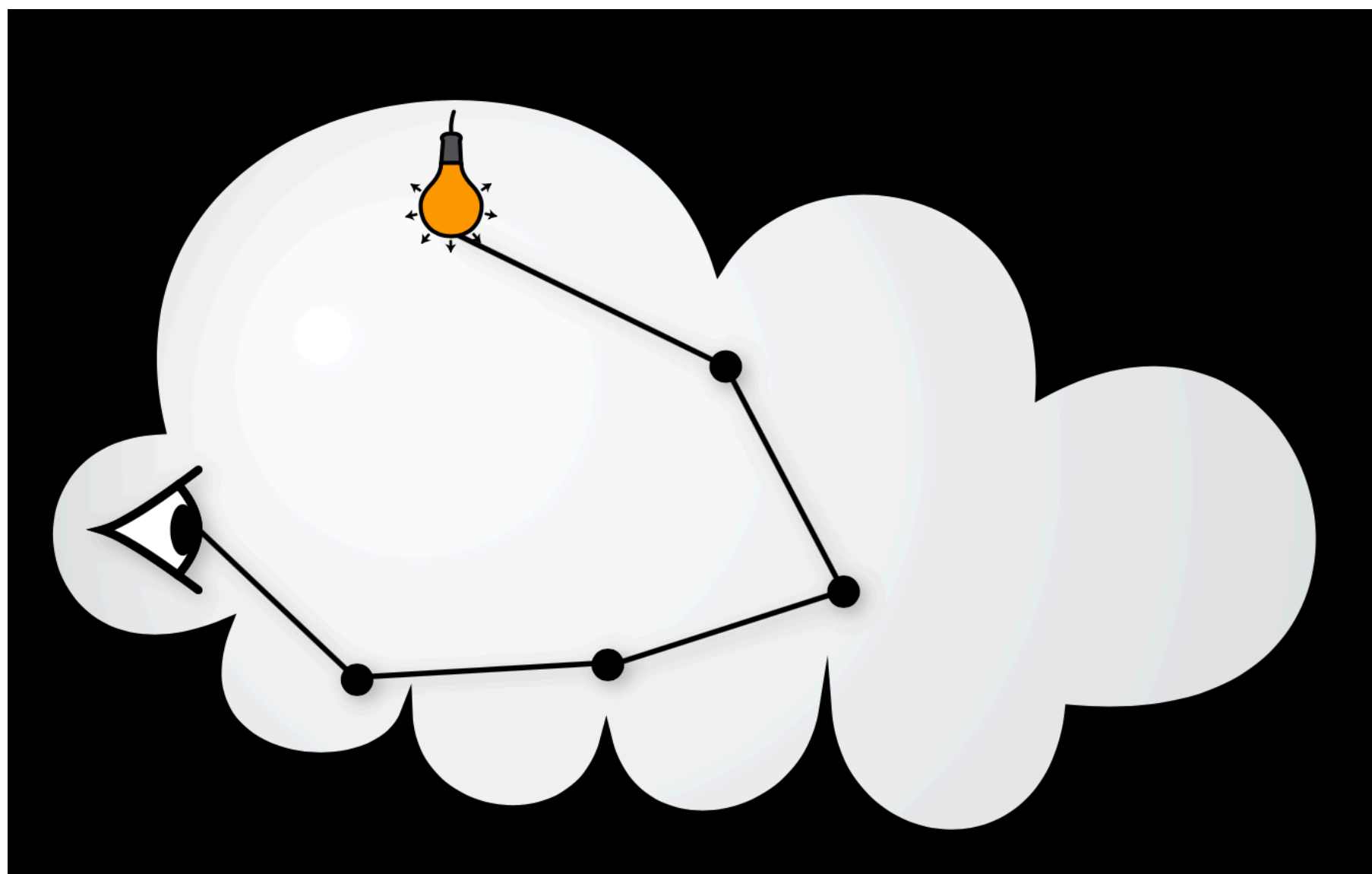


- Use Phase Function to describe the angular distribution of light scattering at any point $\mathbf{x}$ within participating media.



Participating Media: Rendering

- Randomly choose a direction to bounce
- Randomly choose a distance to go straight
- At each 'shading point', connect to the light



[Derek Nowrouzezahrai]

Participating Media: Application



[Big Hero 6, 2014 Disney]

Participating Media: Application



[Assassin's Creed Syndicate. 2015 Ubisoft]

Participating Media: Application



[Assassin's Creed Syndicate. 2015 Ubisoft]

Translucent Material
(specific participating media)

Translucent Material: Jade



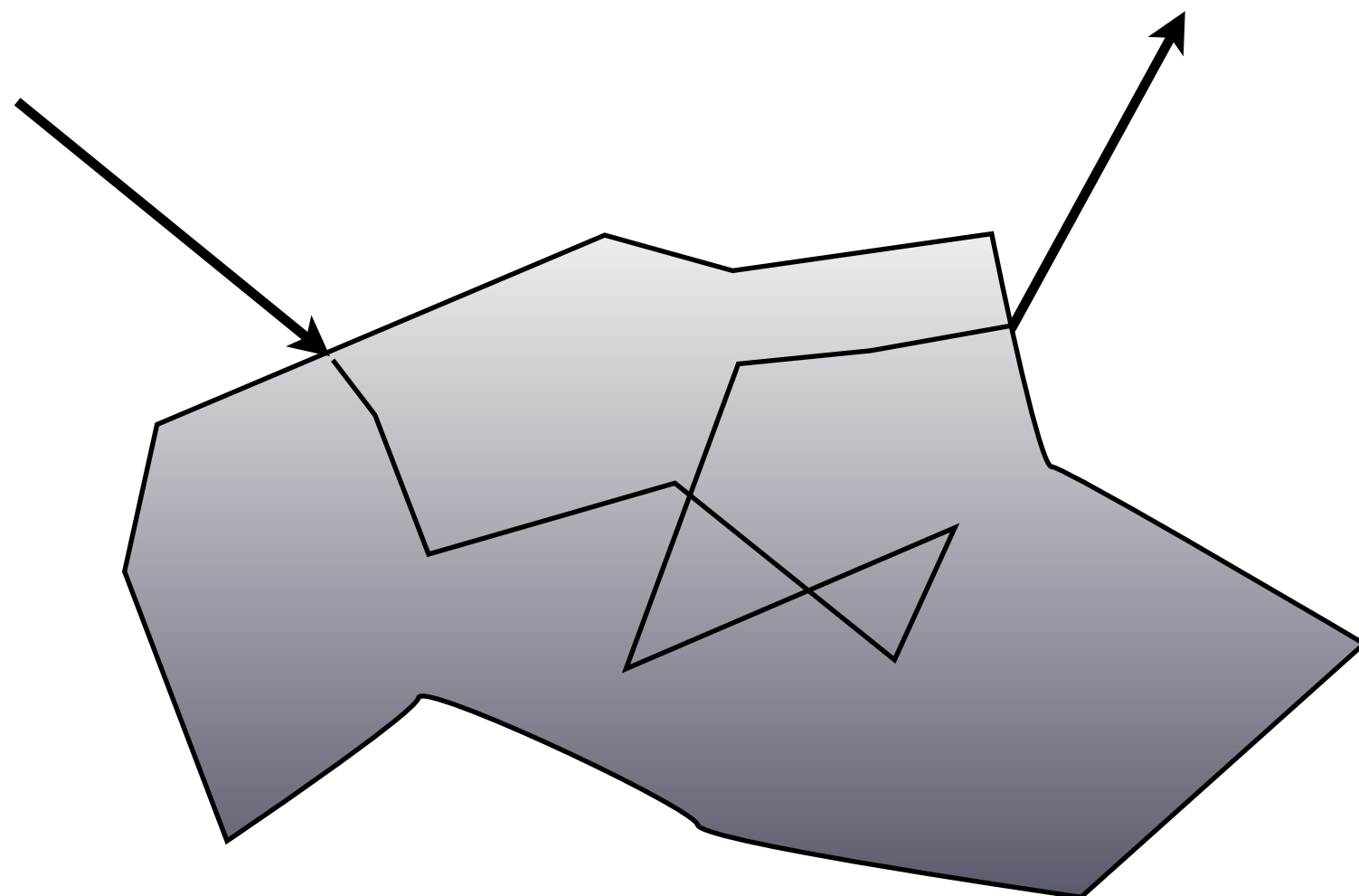
Translucent Material: Jellyfish



Subsurface Scattering

Visual characteristics of many surfaces caused by light exiting at different points than it enters

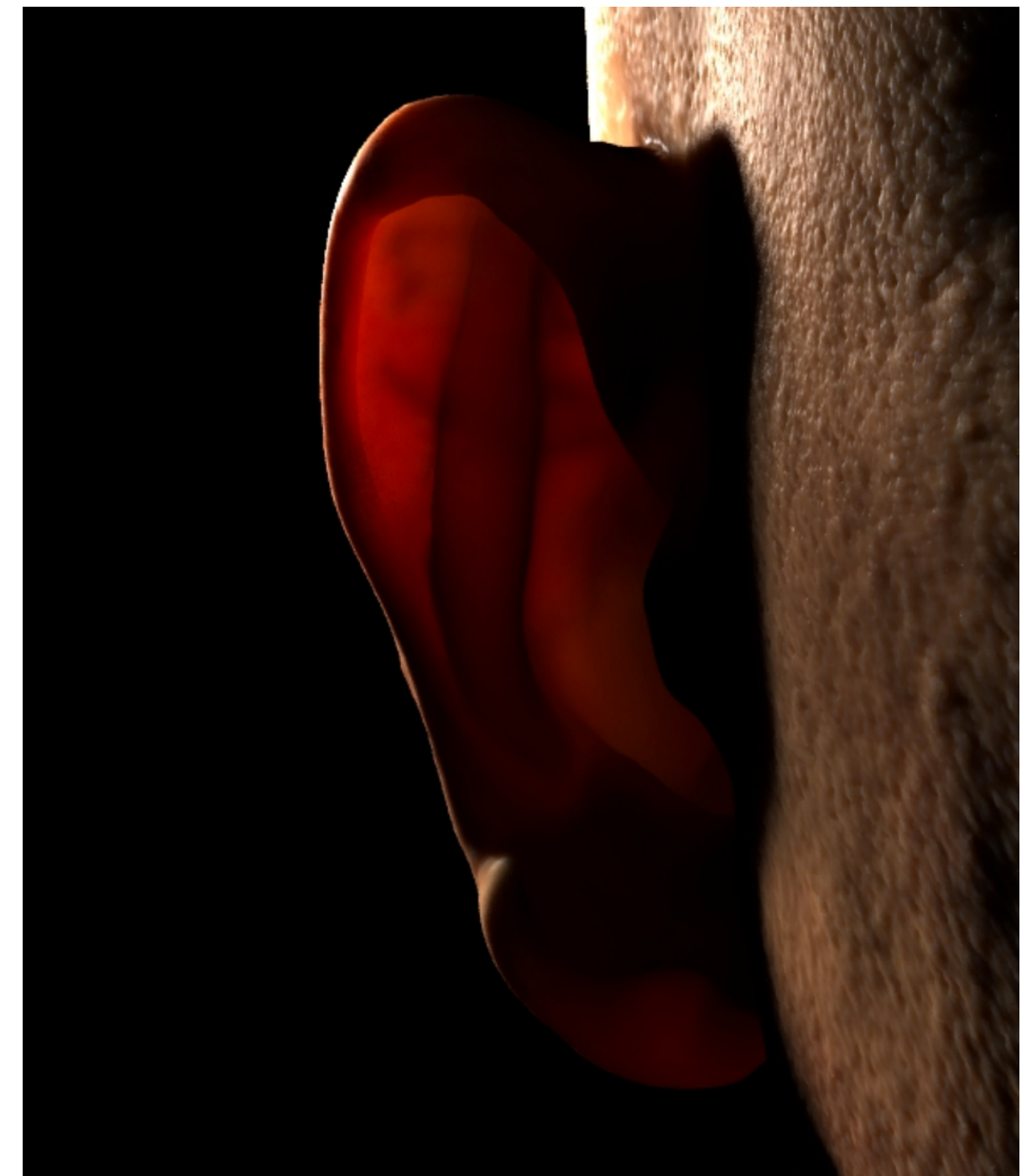
- Violates a fundamental assumption of the BRDF



- Different from transparent



[Jensen et al 2001]



[Donner et al 2008]

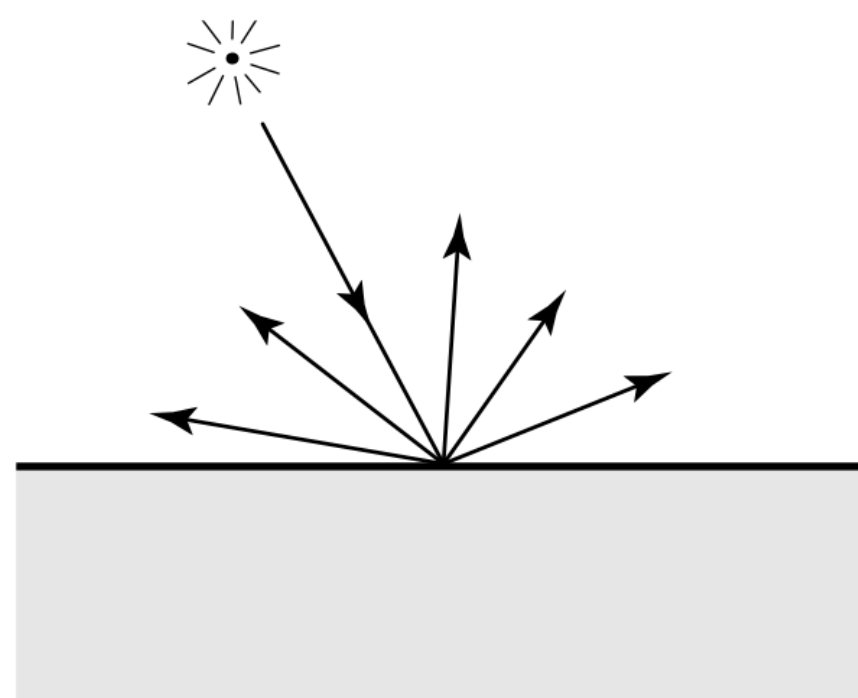
Scattering Functions

- BSSRDF: generalization of BRDF; exitant radiance at one point due to incident differential irradiance at another point:

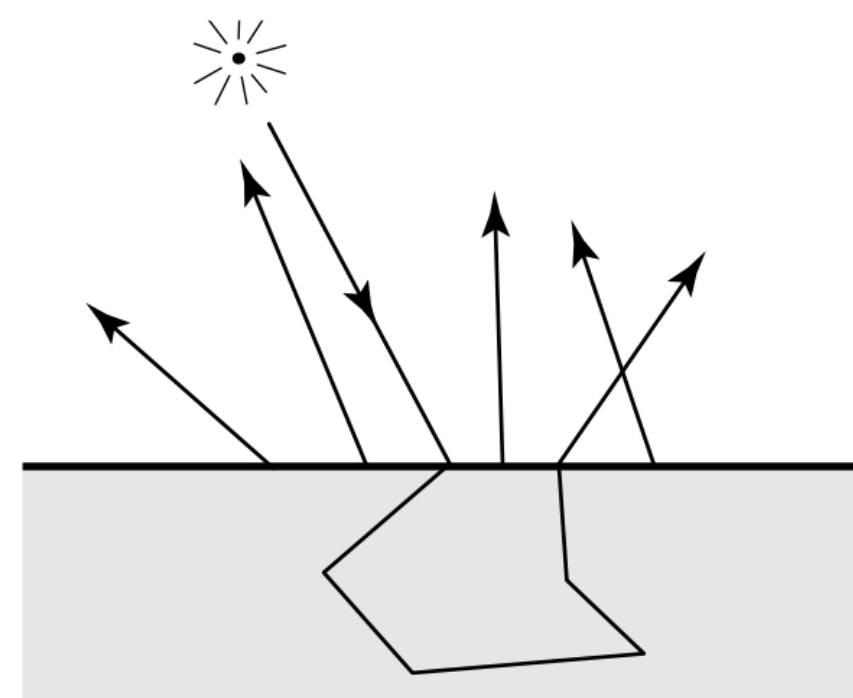
$$S(x_i, \omega_i, x_o, \omega_o)$$

- Generalization of rendering equation: integrating over all points on the surface and all directions (!)

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



BRDF



BSSRDF

BRDF



[Jensen et al. 2001]

BSSRDF



[Jensen et al. 2001]

BRDF vs BSSRDF



BRDF

[Jensen et al. 2001]

BRDF vs BSSRDF



BRDF



BSSRDF

[Jensen et al. 2001]

Acknowledgments

The CS 184 slide set was developed by:

- Ren Ng
- James O'Brien

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- Kayvon Fatahalian
- David Forsyth
- Pat Hanrahan
- Angjoo Kanazawa
- Steve Marschner
- Ben Mildenhall
- Mark Pauly
- Weilun Sun
- Lingqi Yan

Extra

Procedural Appearance

Procedural Appearance

- Can we define details without textures?
 - Yes! Compute a noise function on the fly.



Procedural Appearance

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Procedural Appearance

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 - 3D noise -> internal structure if cut or broken



23 FPS

Solid noise

Procedural Appearance

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23 FPS

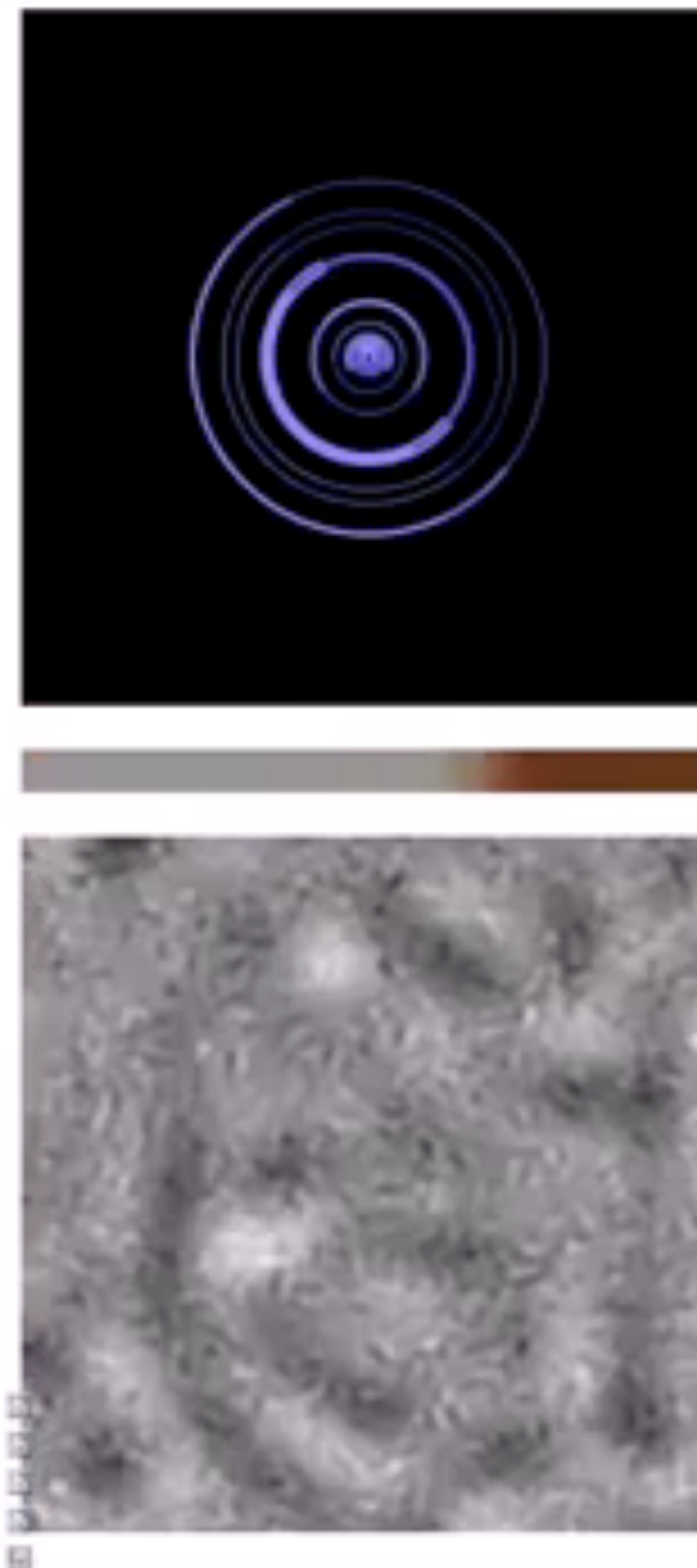
Solid noise

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 - Thresholding
(noise $\rightarrow$ binary noise)

Example:

```
if noise(x, y, z) > threshold:  
    reflectance = 1  
else:  
    reflectance = 0
```

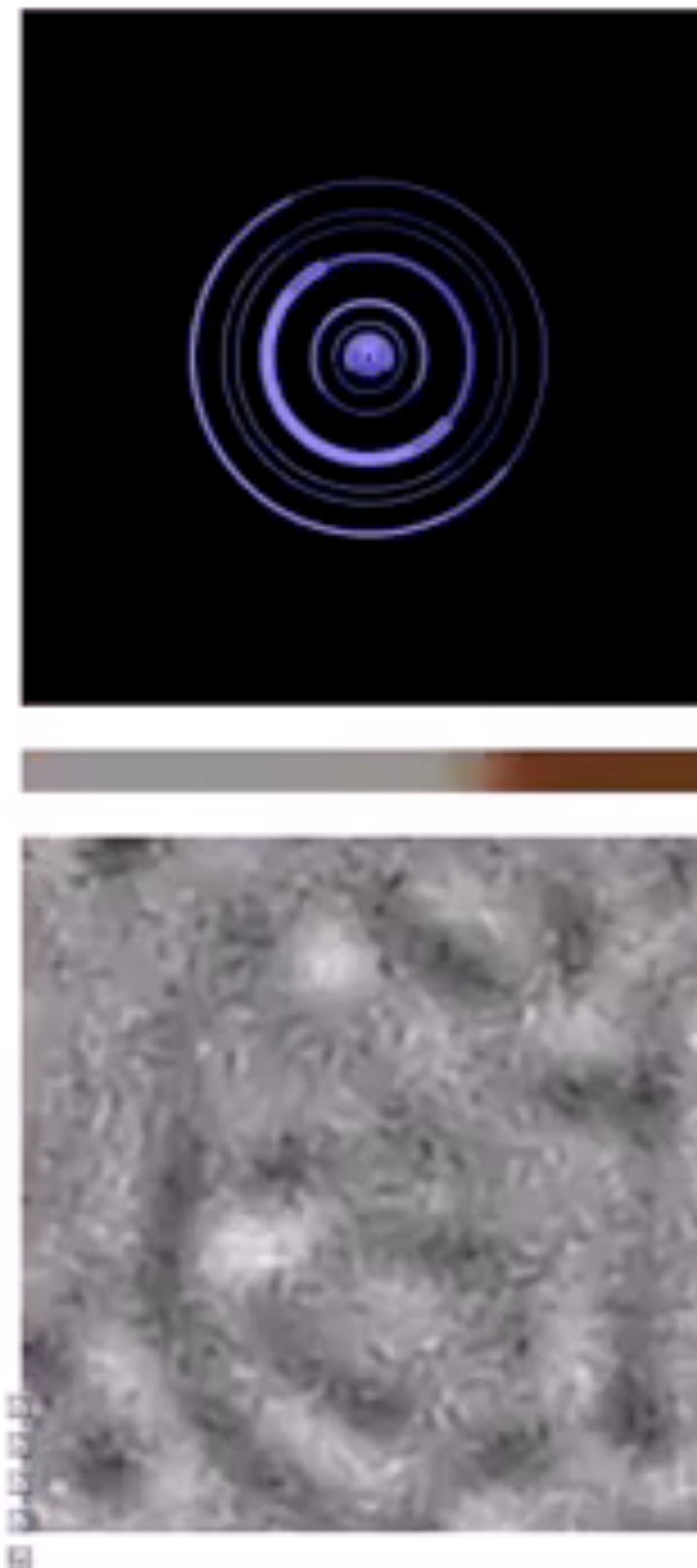


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video of alternative pattern

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