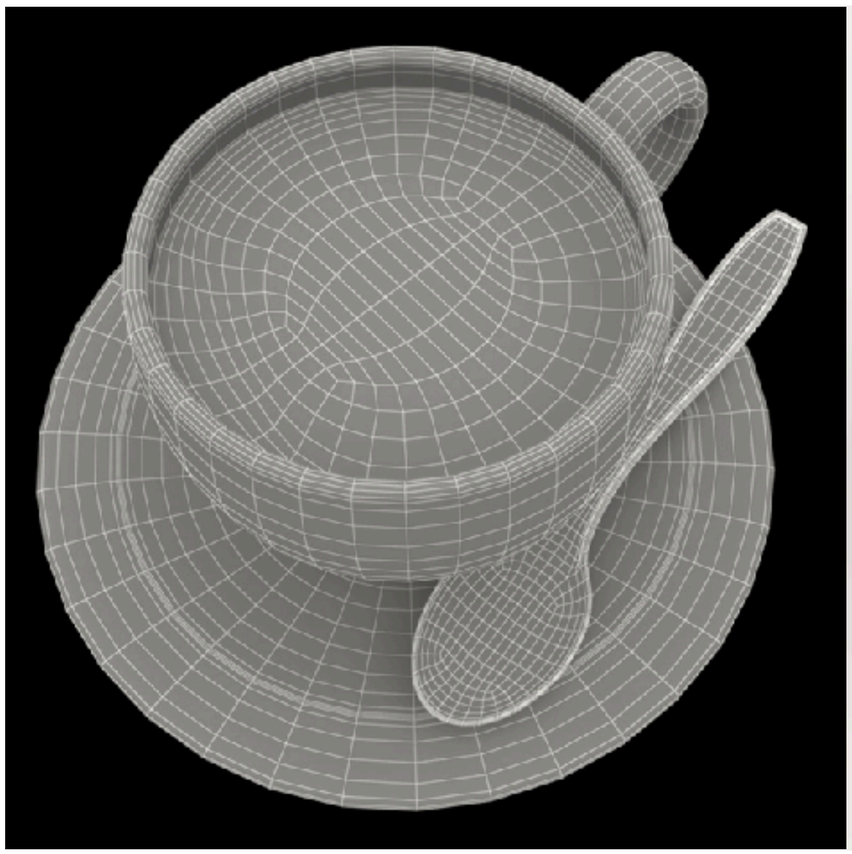
Lecture 14:

# Introduction to Material Modeling

Computer Graphics and Imaging
UC Berkeley CS184/284A

# What is Material in Computer Graphics?



3D coffee mug model

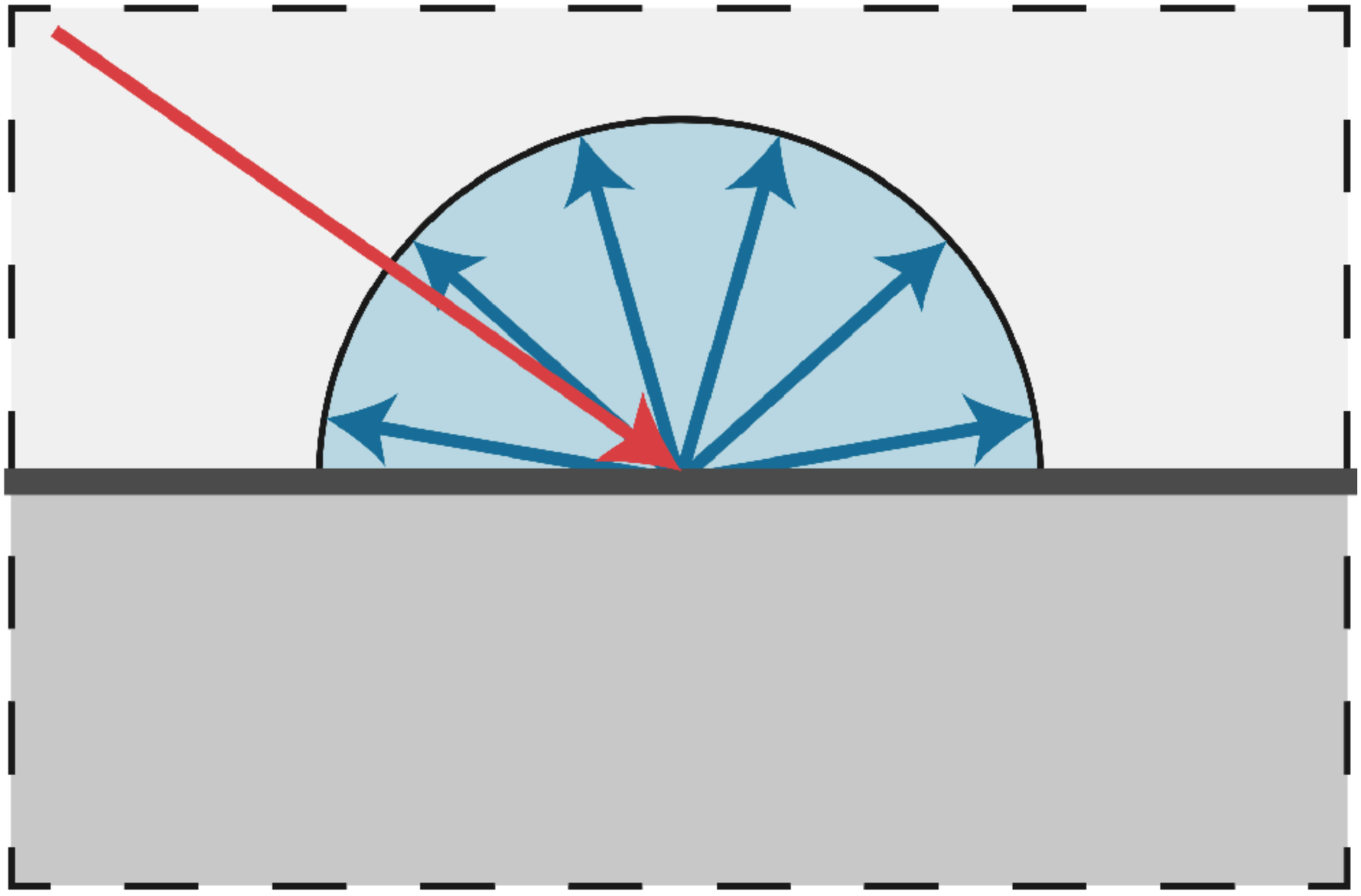
Rendered

Rendered

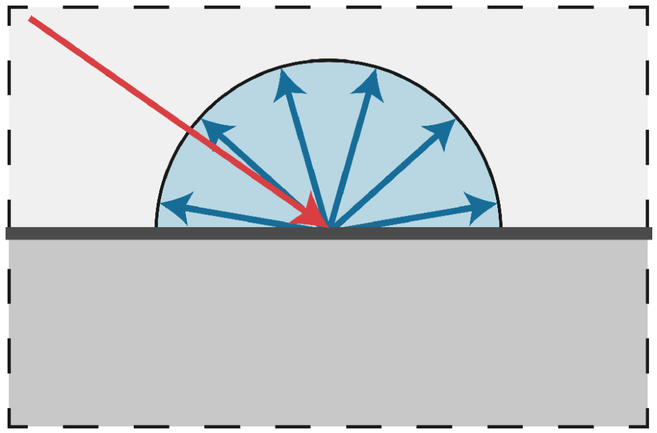
[From TurboSquid, created by artist 3dror]

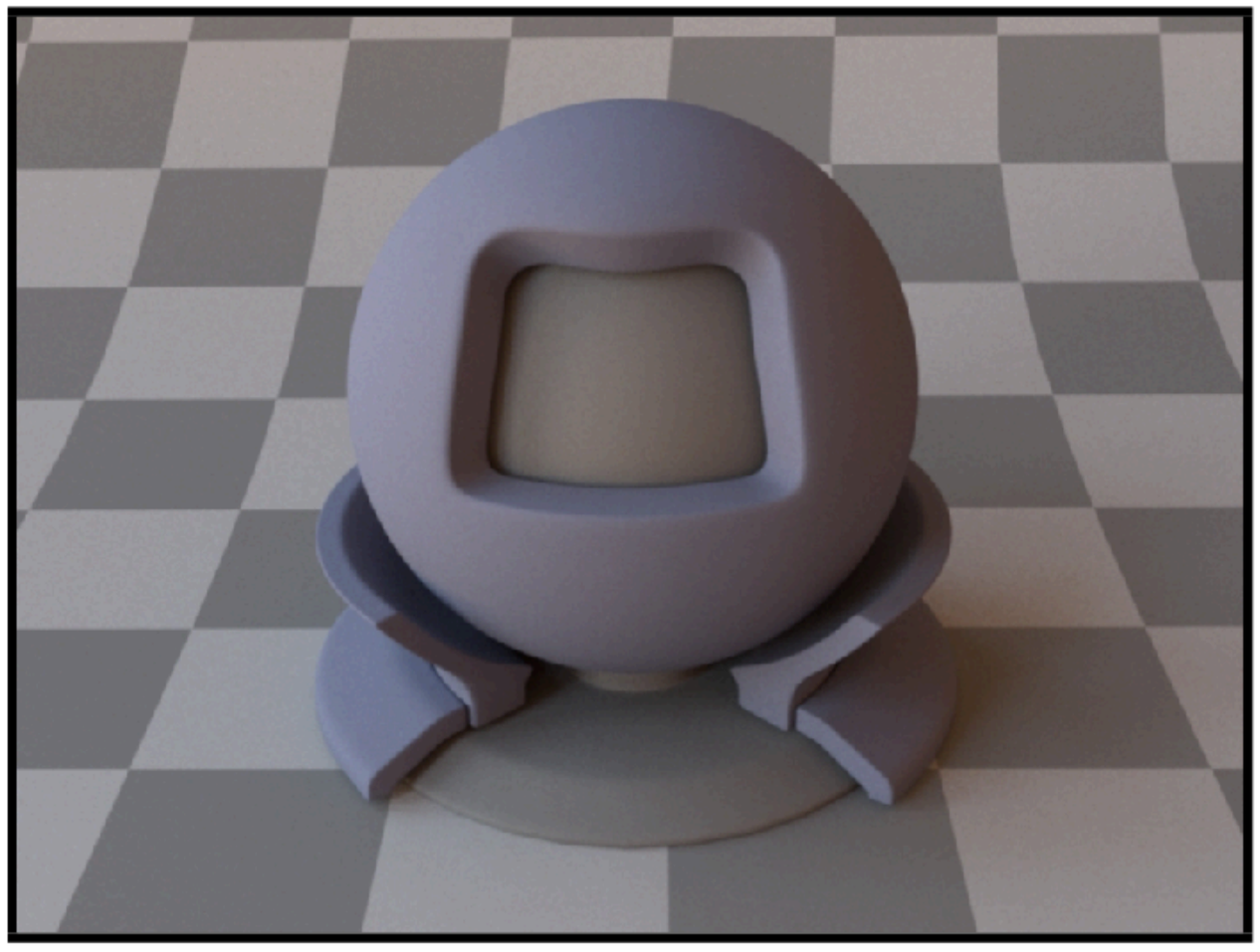
# Material == BRDF

# What is this material?

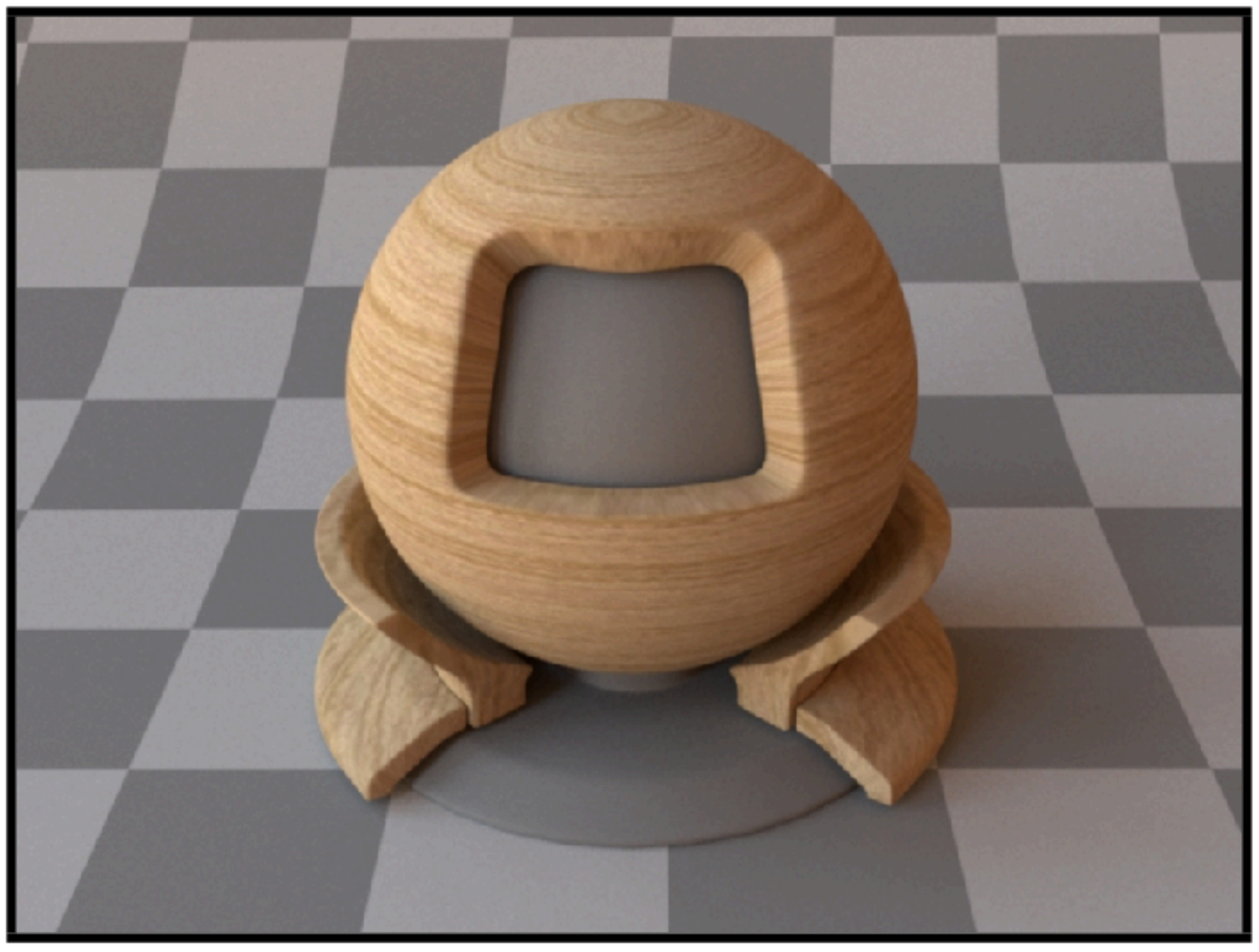


# Diffuse / Lambertian Material (BRDF)





Uniform colored diffuse BRDF

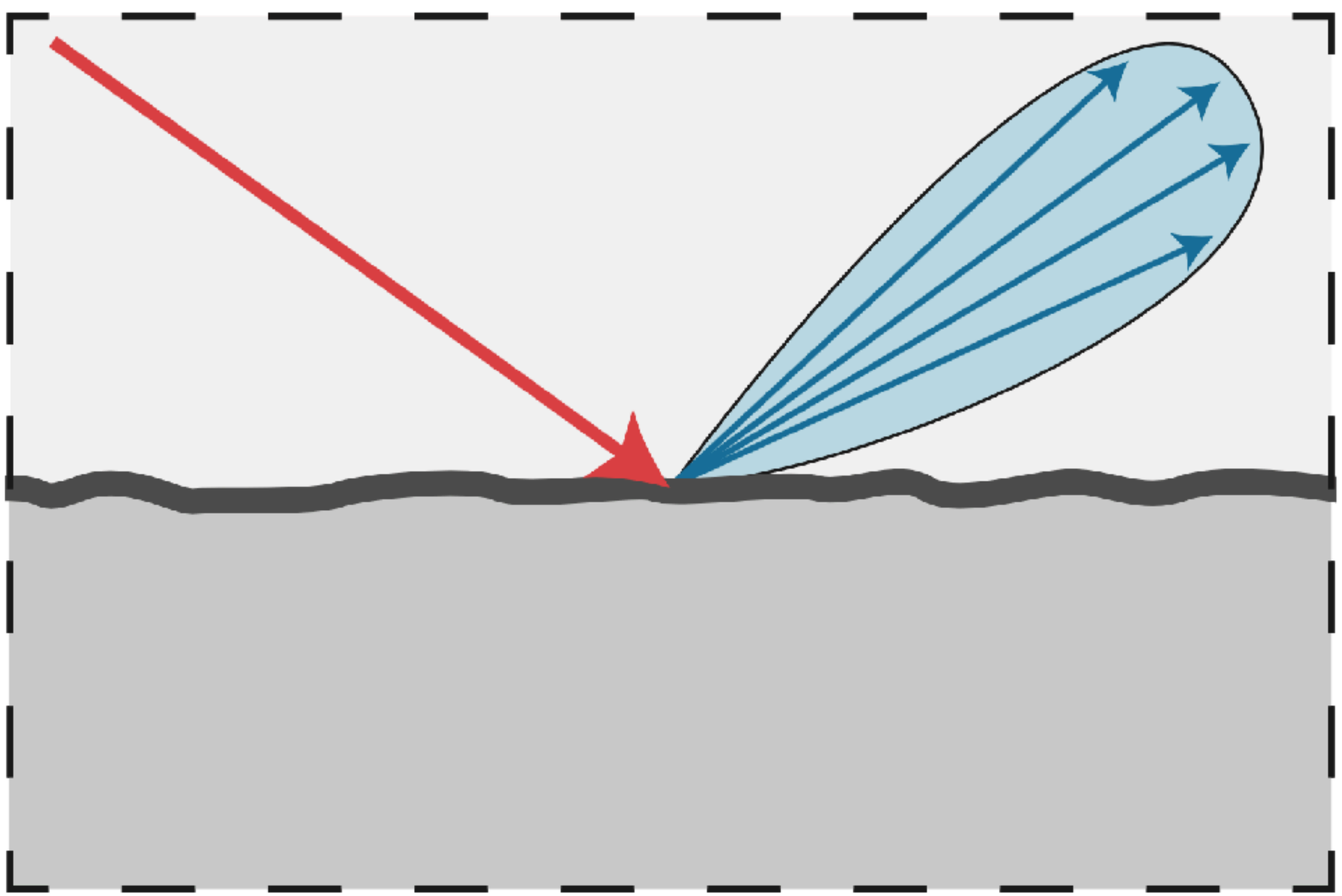


Textured diffuse BRDF

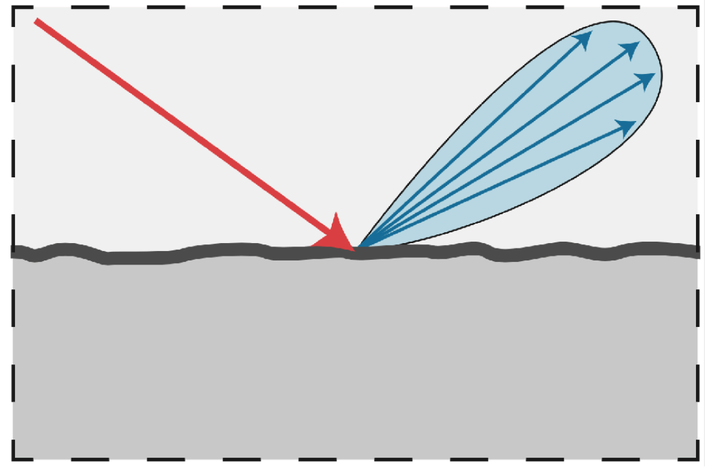


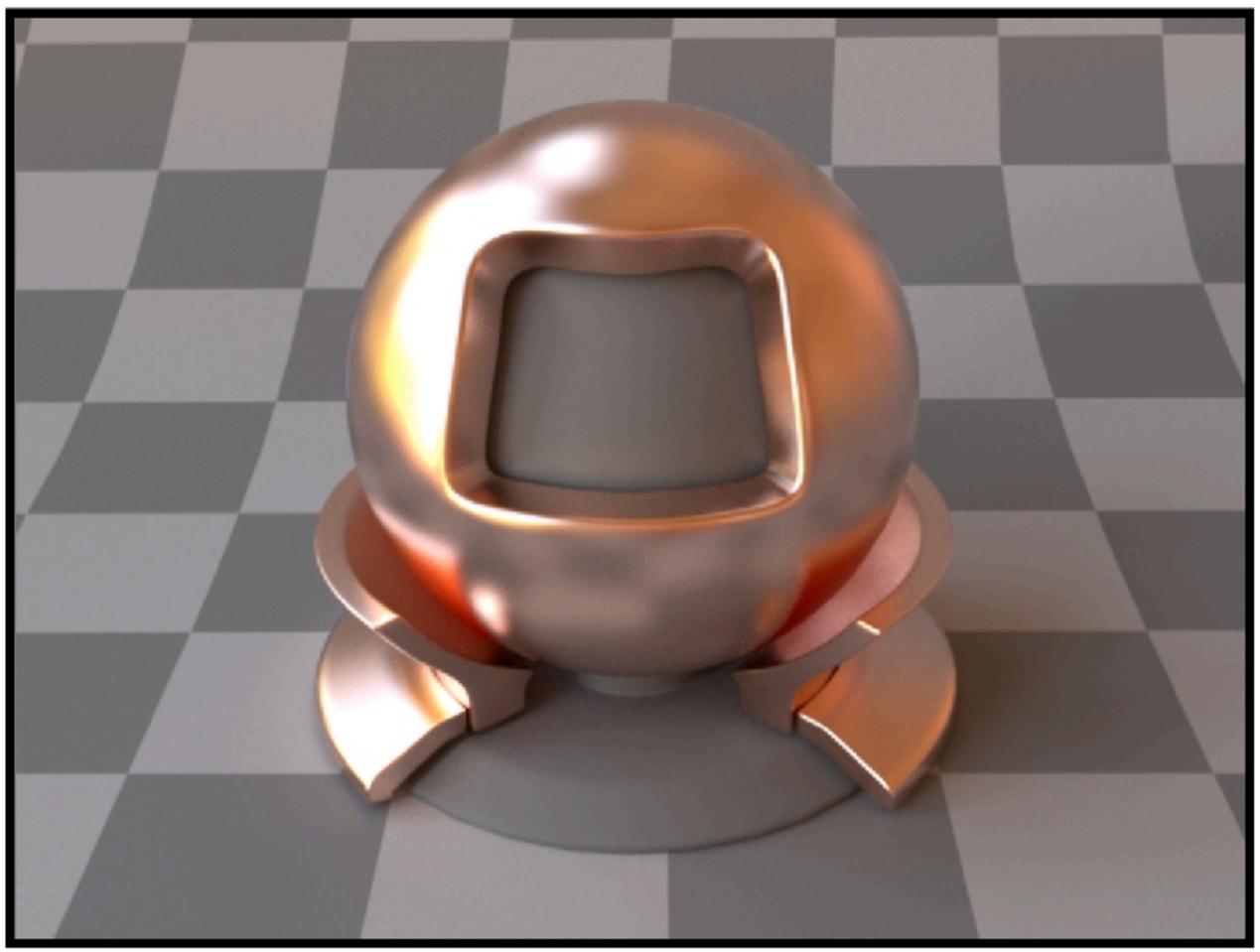
[Mitsuba renderer, Wenzel Jakob, 2010]

# What is this material?

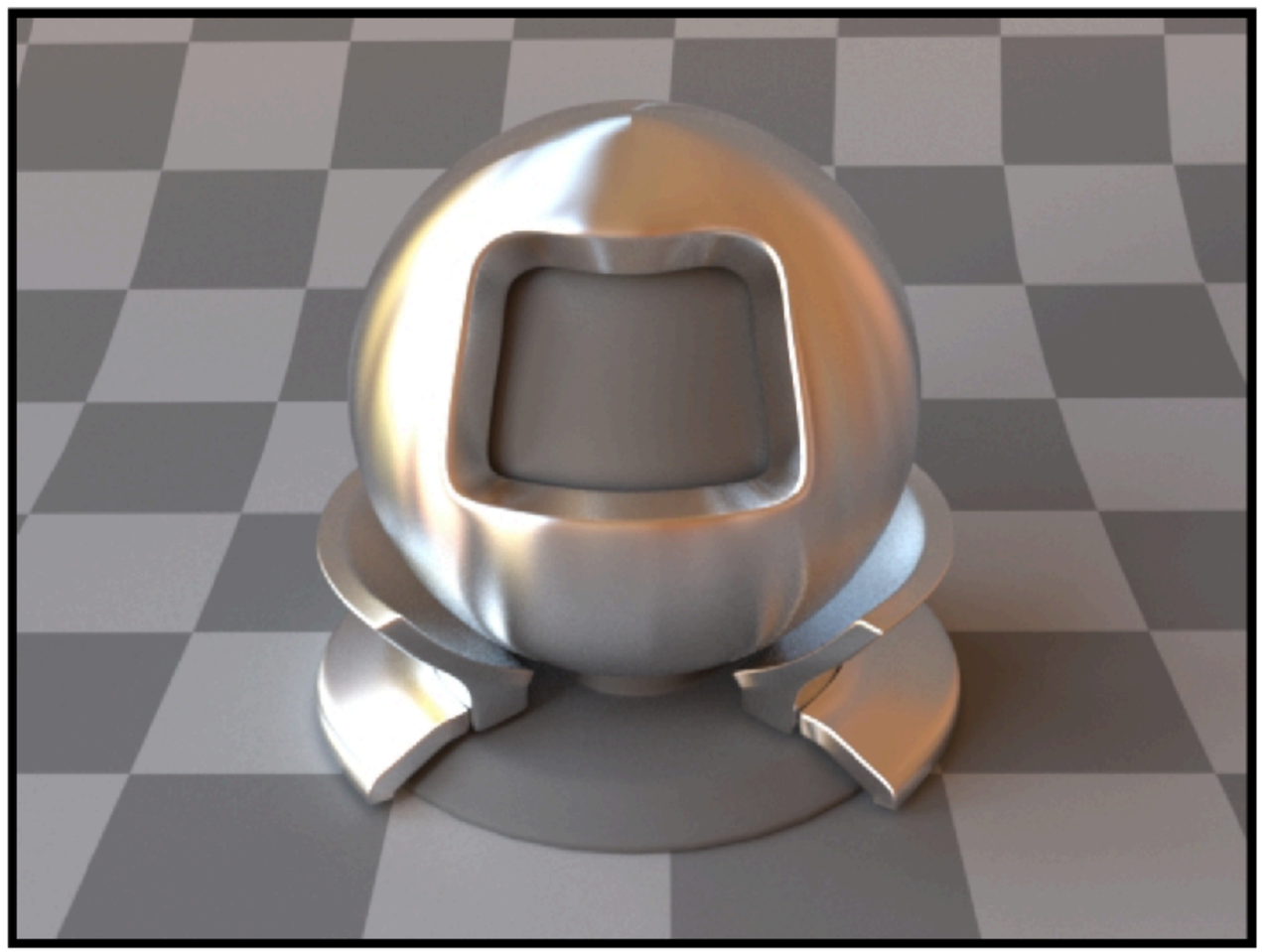


# Glossy material (BRDF)



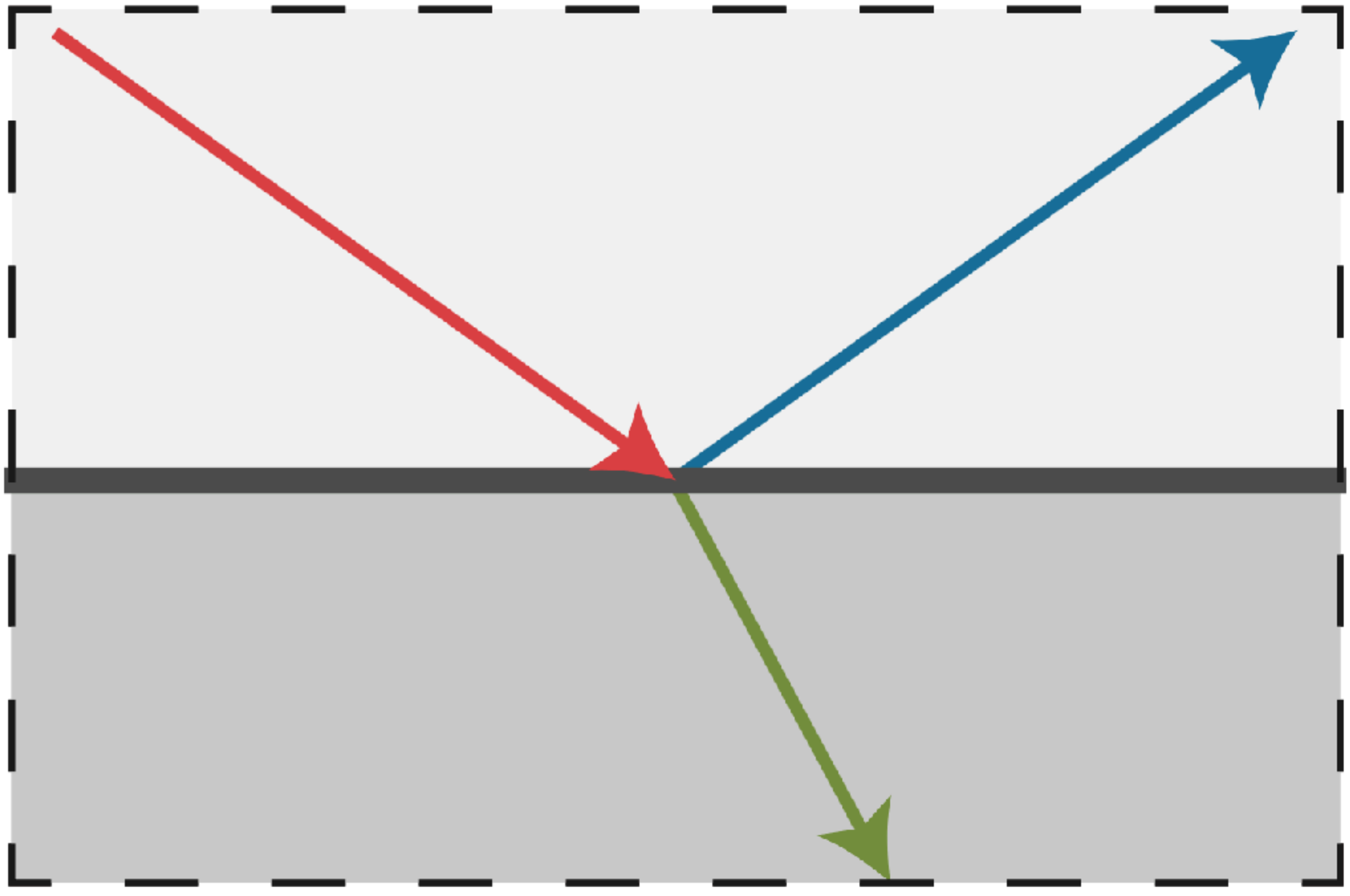


Copper

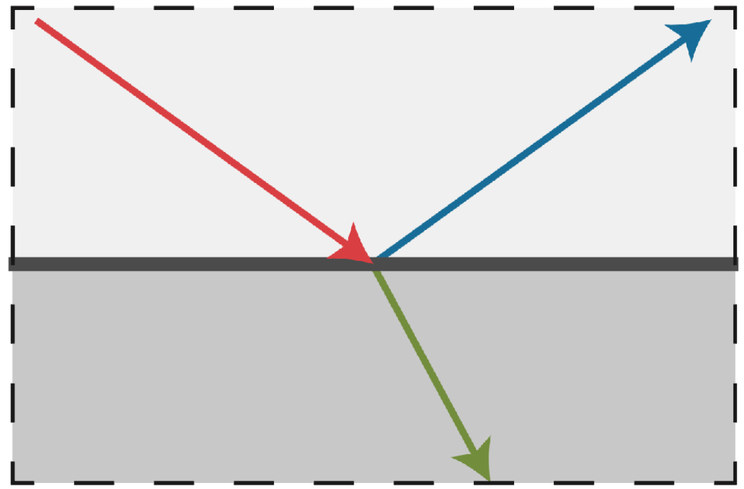


Aluminum

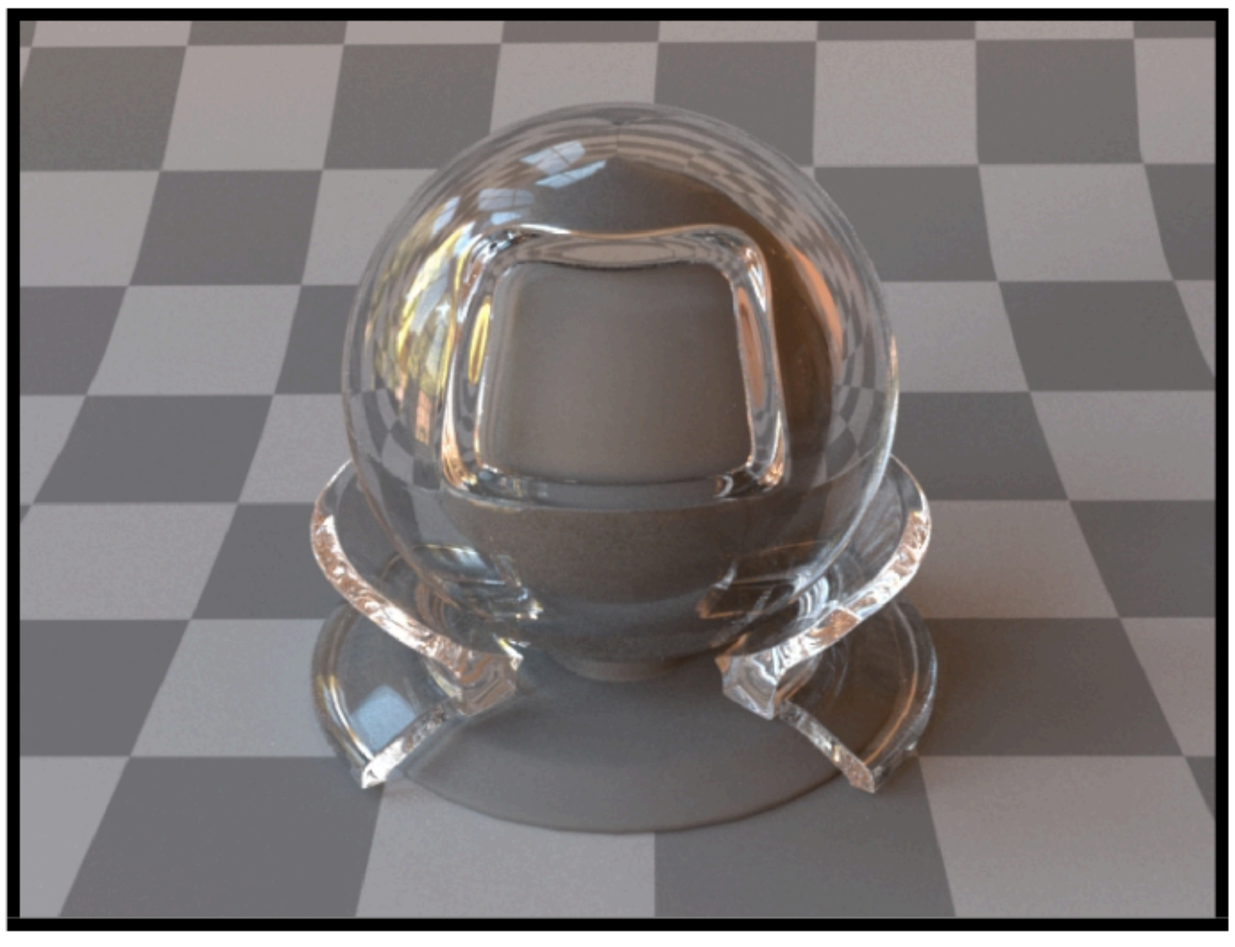
# What is this material?



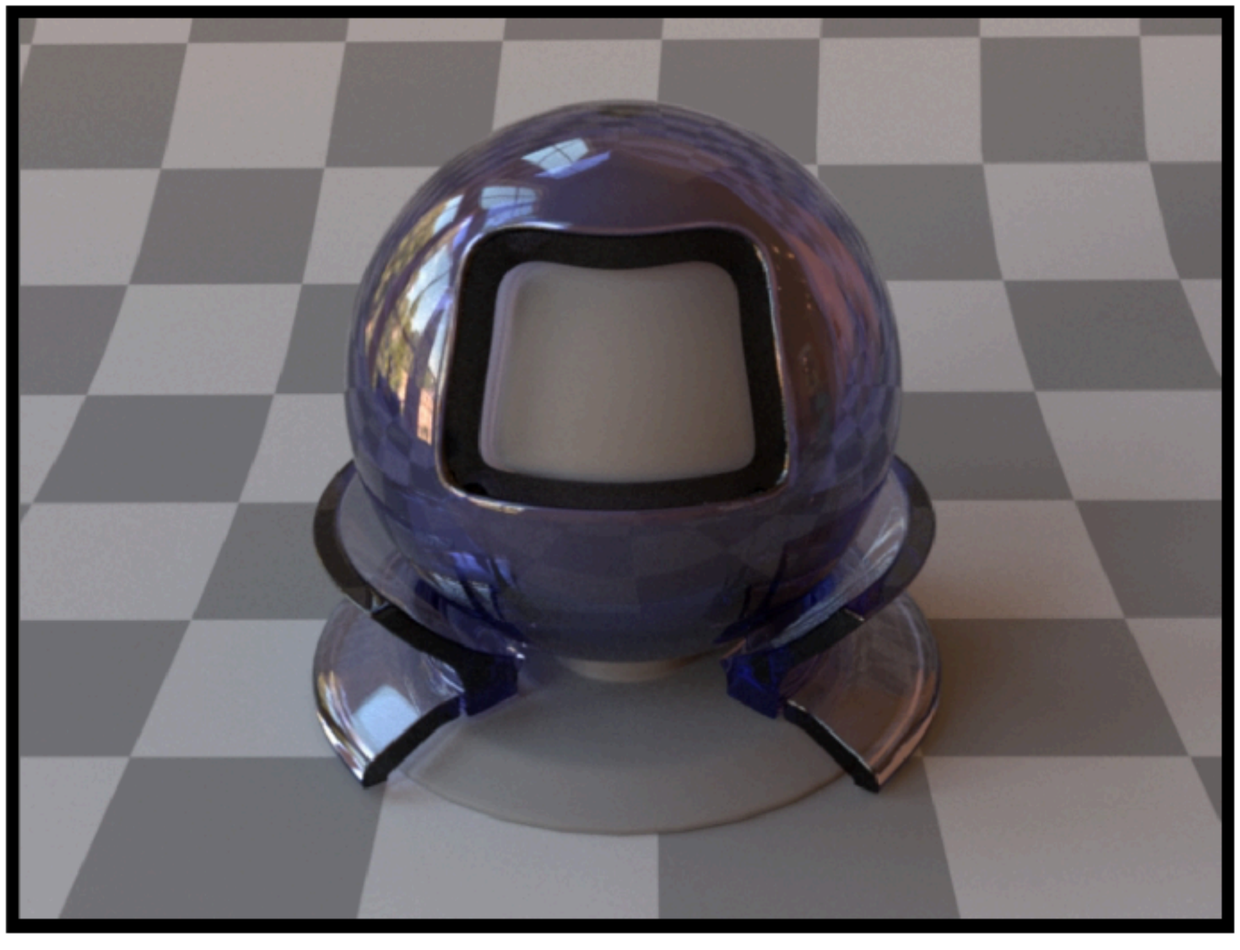
# Ideal reflective / refractive material (BSDF*)



[Mitsuba renderer, Wenzel Jakob, 2010]

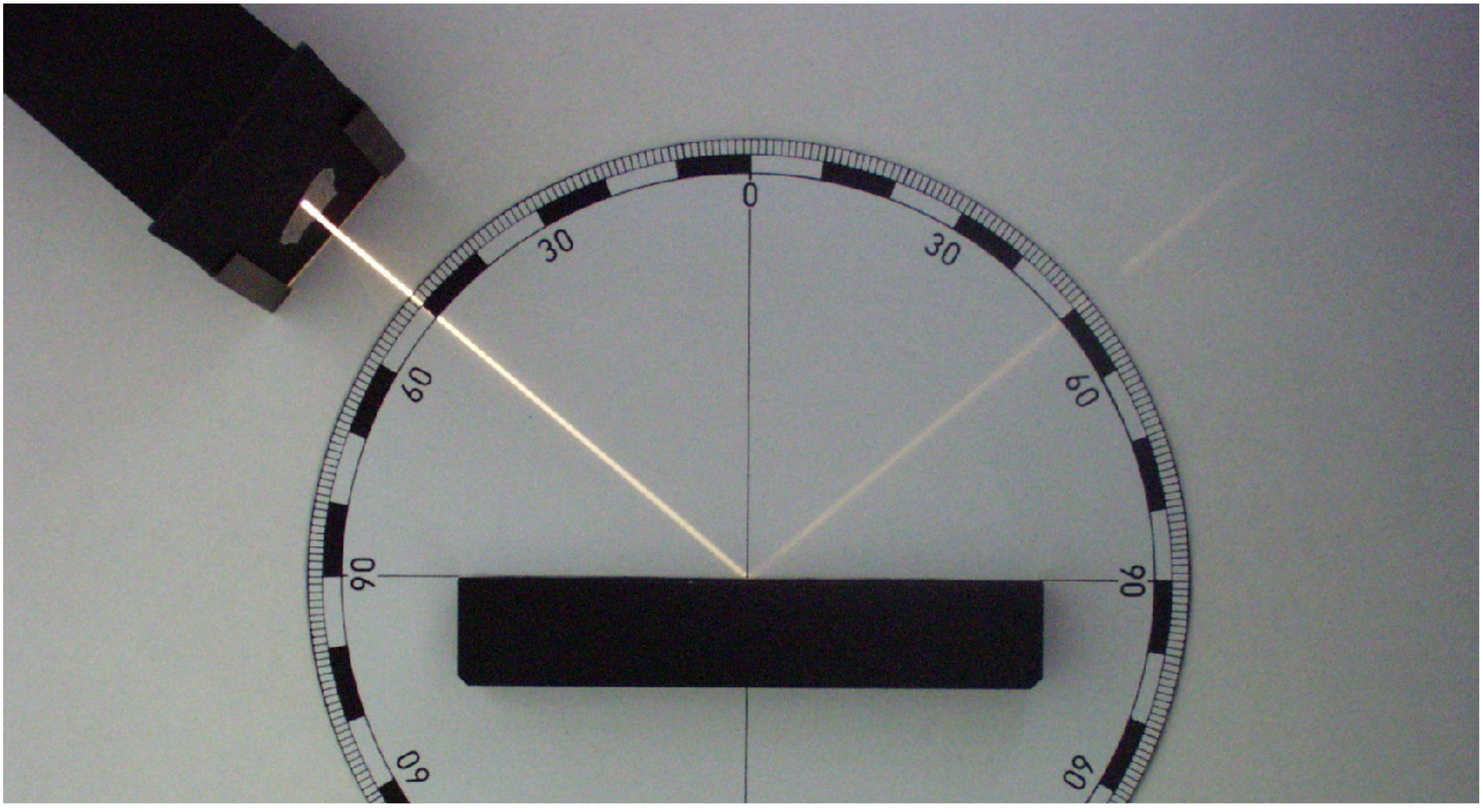


Air <-> plastic interface



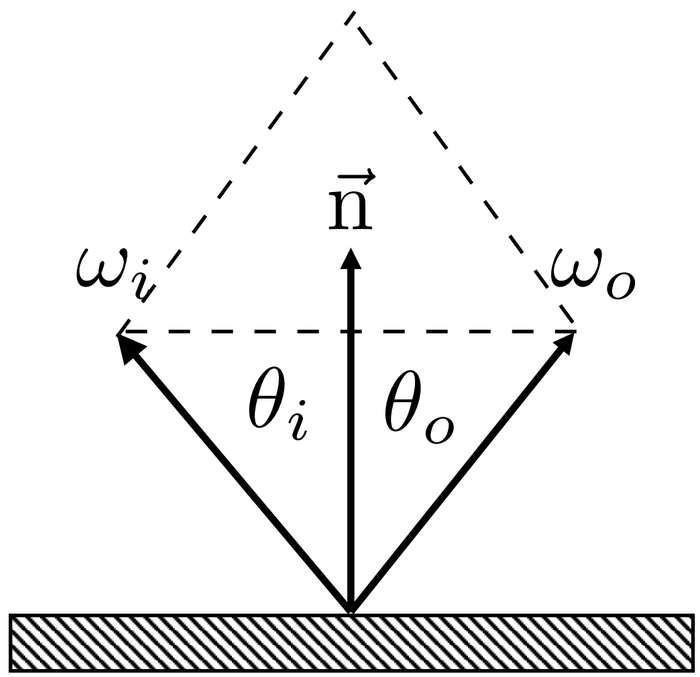
Air <-> glass interface
(with absorption)

# Perfect Specular Reflection



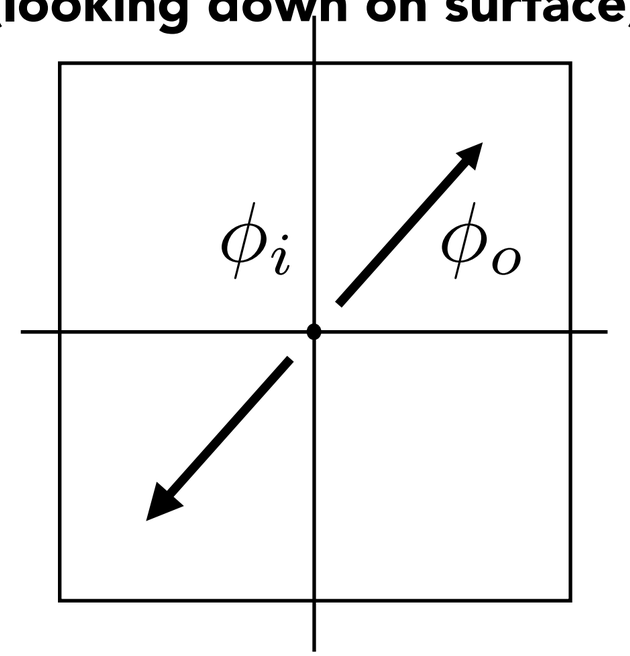

[Zátonyi Sándor]

# Perfect Specular Reflection




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

**Top-down view**
**(looking down on surface)**

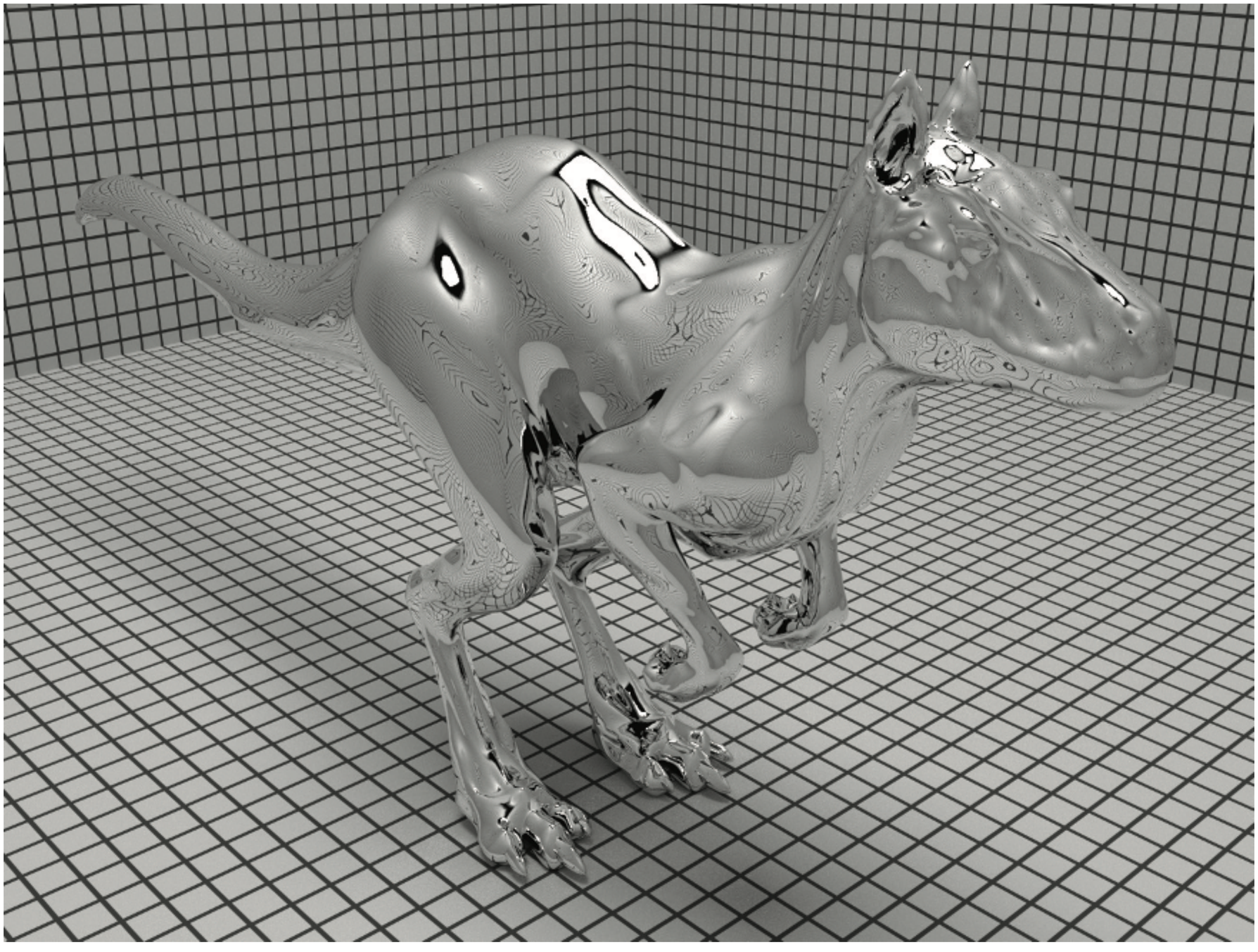



$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

# Perfect Specular Reflection BRDF

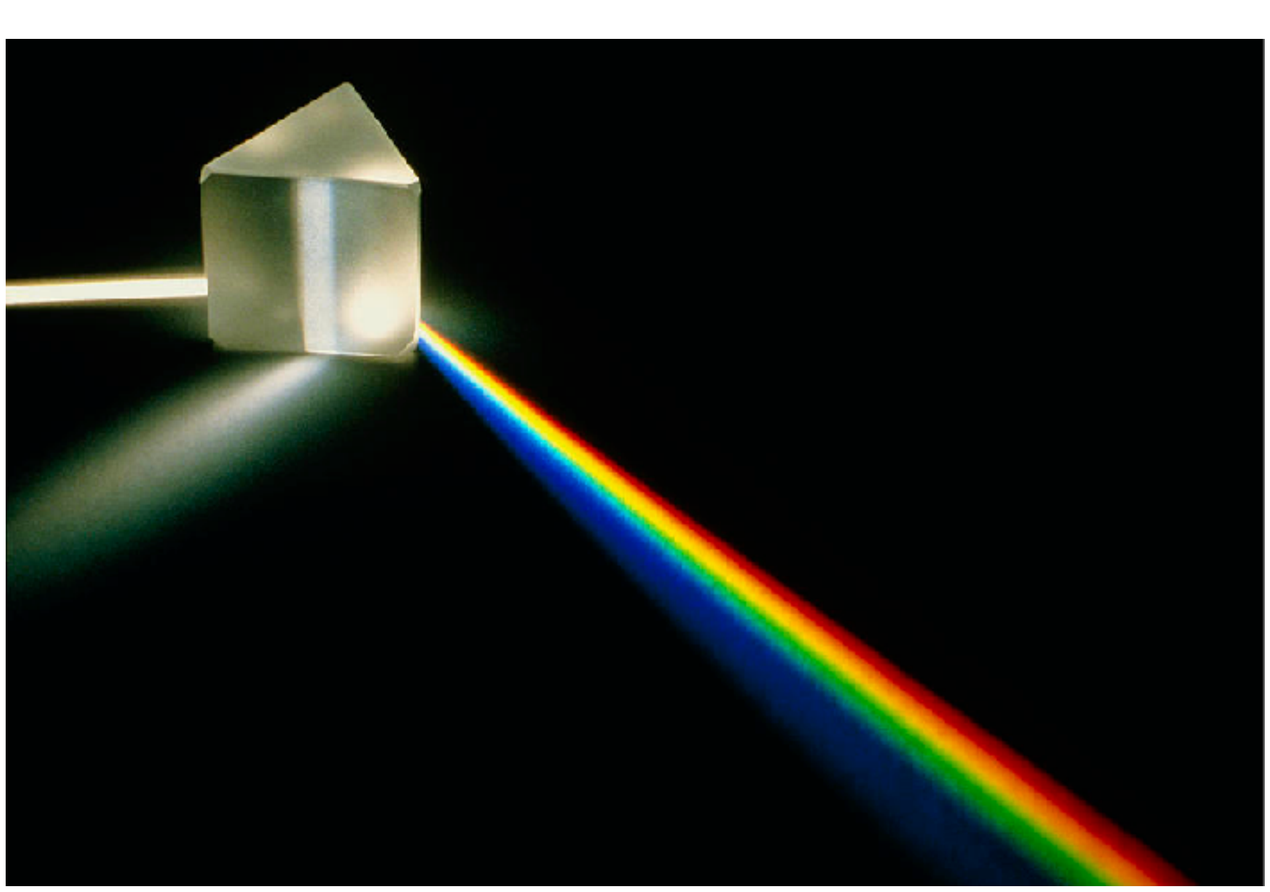


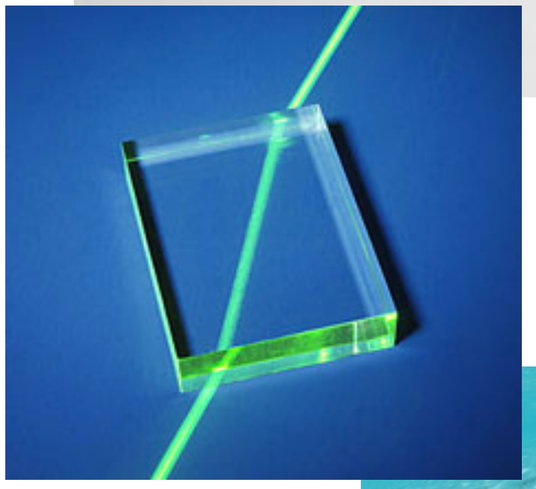
PBRT

# Specular Refraction

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

Light refracts when it enters a new medium.

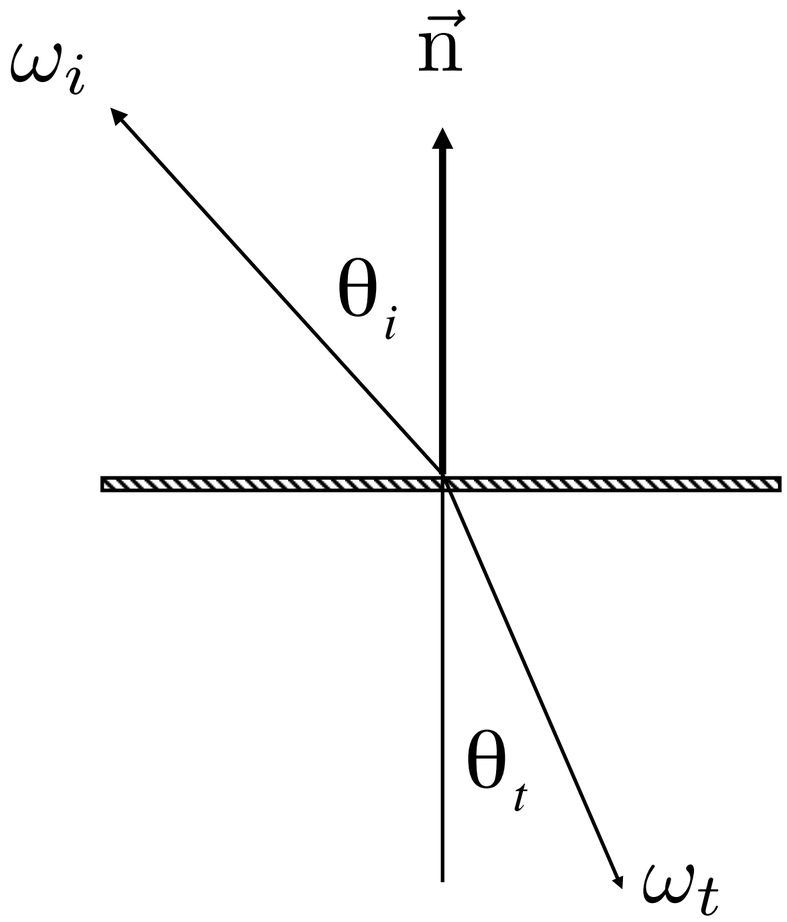




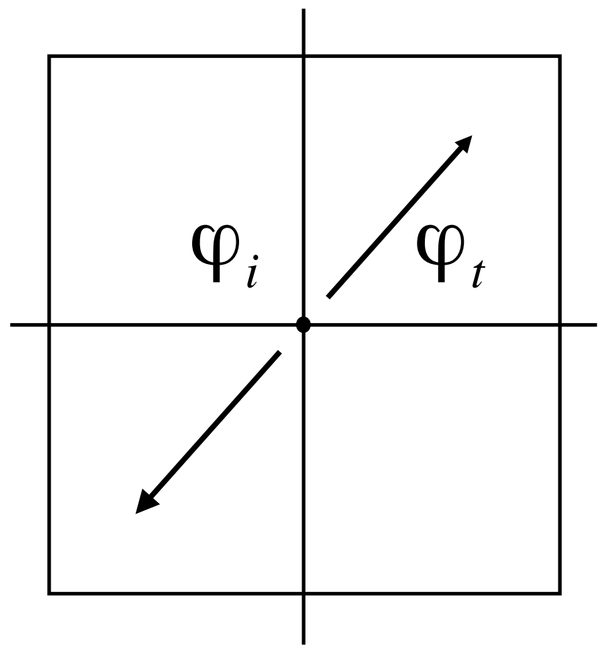
# Snell's Law

**Transmitted angle depends on**

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




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

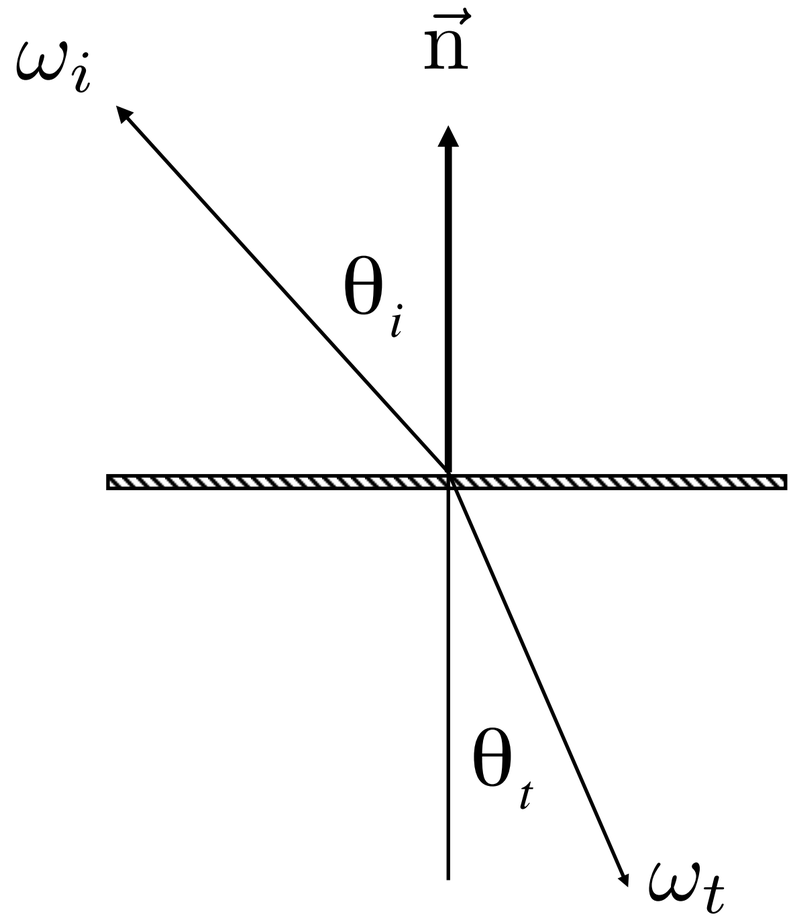



$$\varphi_t = \varphi_i \pm \pi$$

| Medium | $\eta$* |
|---|---|
| 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




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

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

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

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

## Total internal reflection:

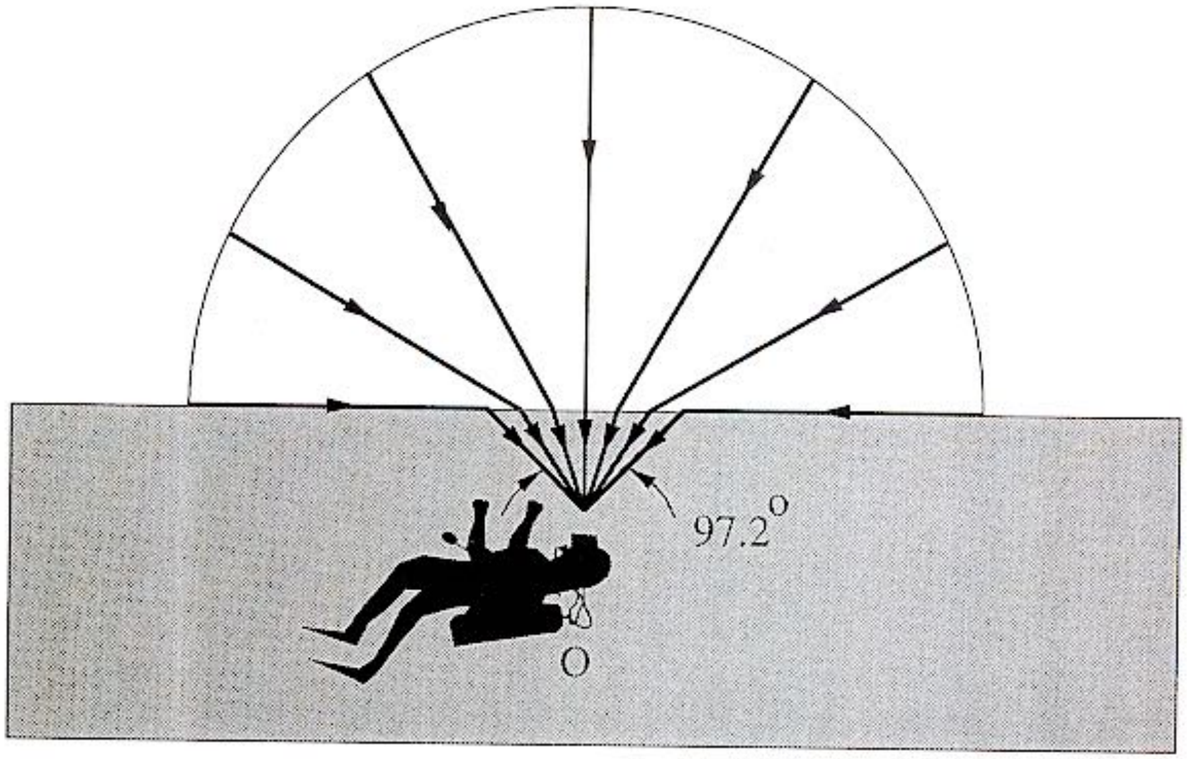
$$1 - \left(\frac{\eta_i}{\eta_t}\right)^2 (1 - \cos^2\theta_i) < 0$$

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




# Microfacet Material Model

# Microfacet Reflection

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

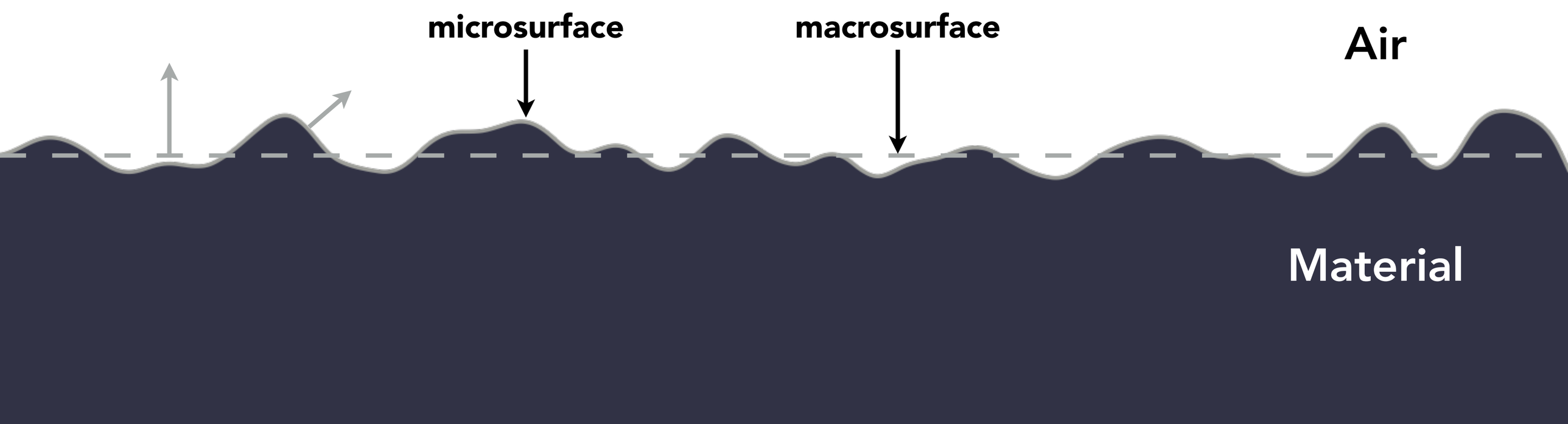
# Microfacet Theory

Rough surface

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

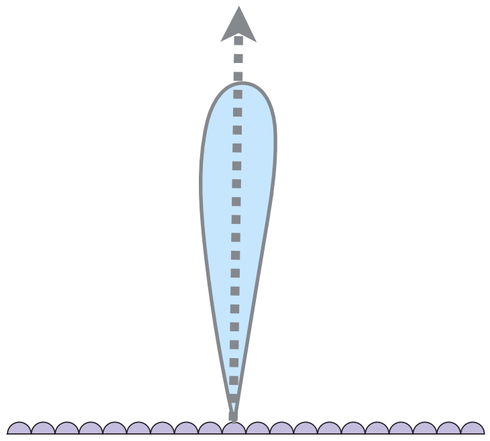
Individual elements of surface act like mirrors

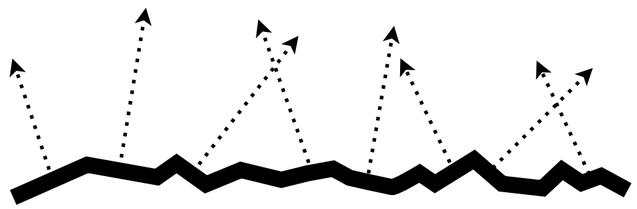
- Known as “microfacets”
- Each microfacet has its own normal vector

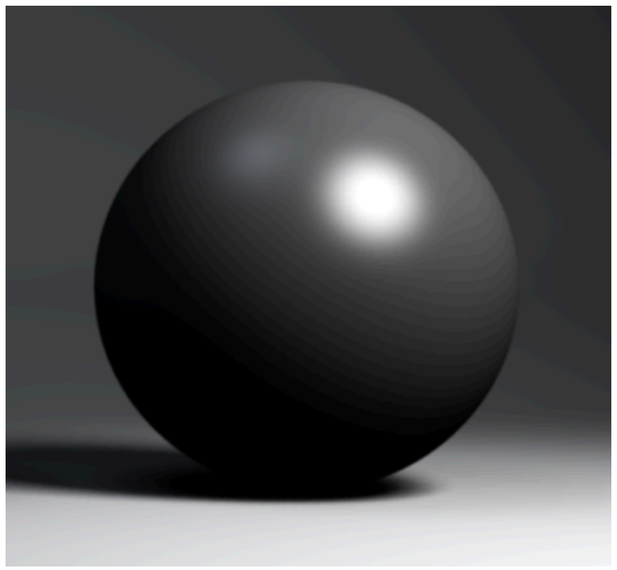


# Microfacet BRDF

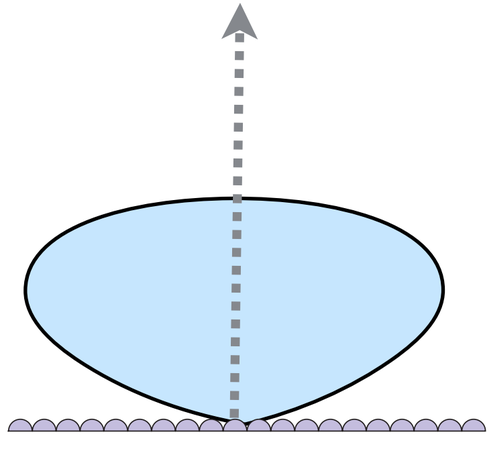
- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

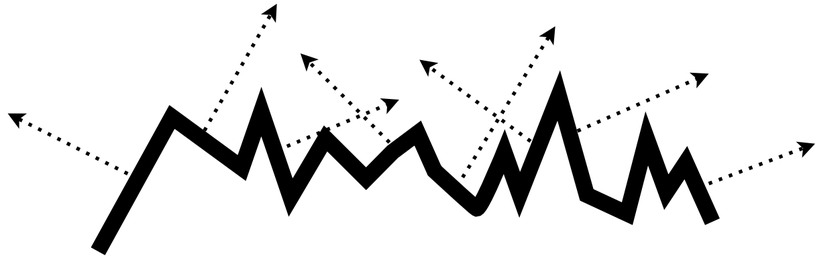


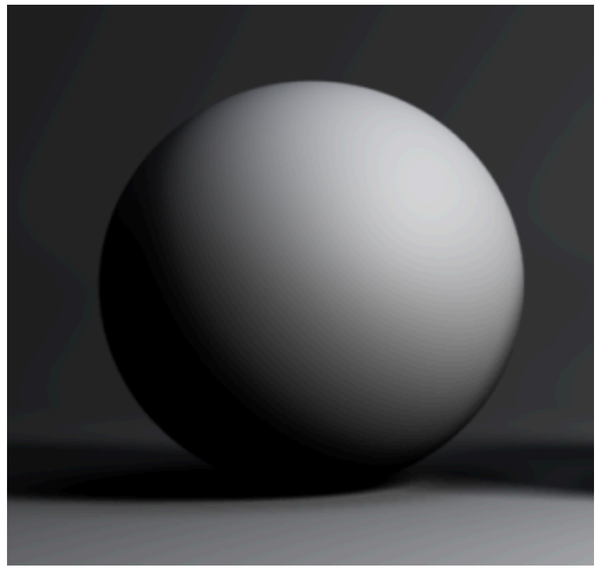




  - Spread out <==> diffuse

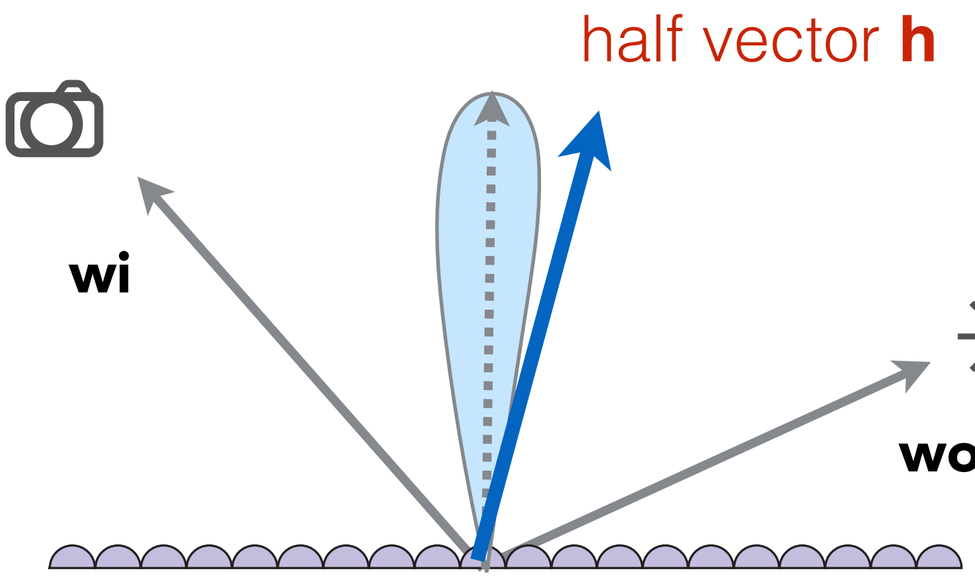






# Microfacet BRDF

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




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

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

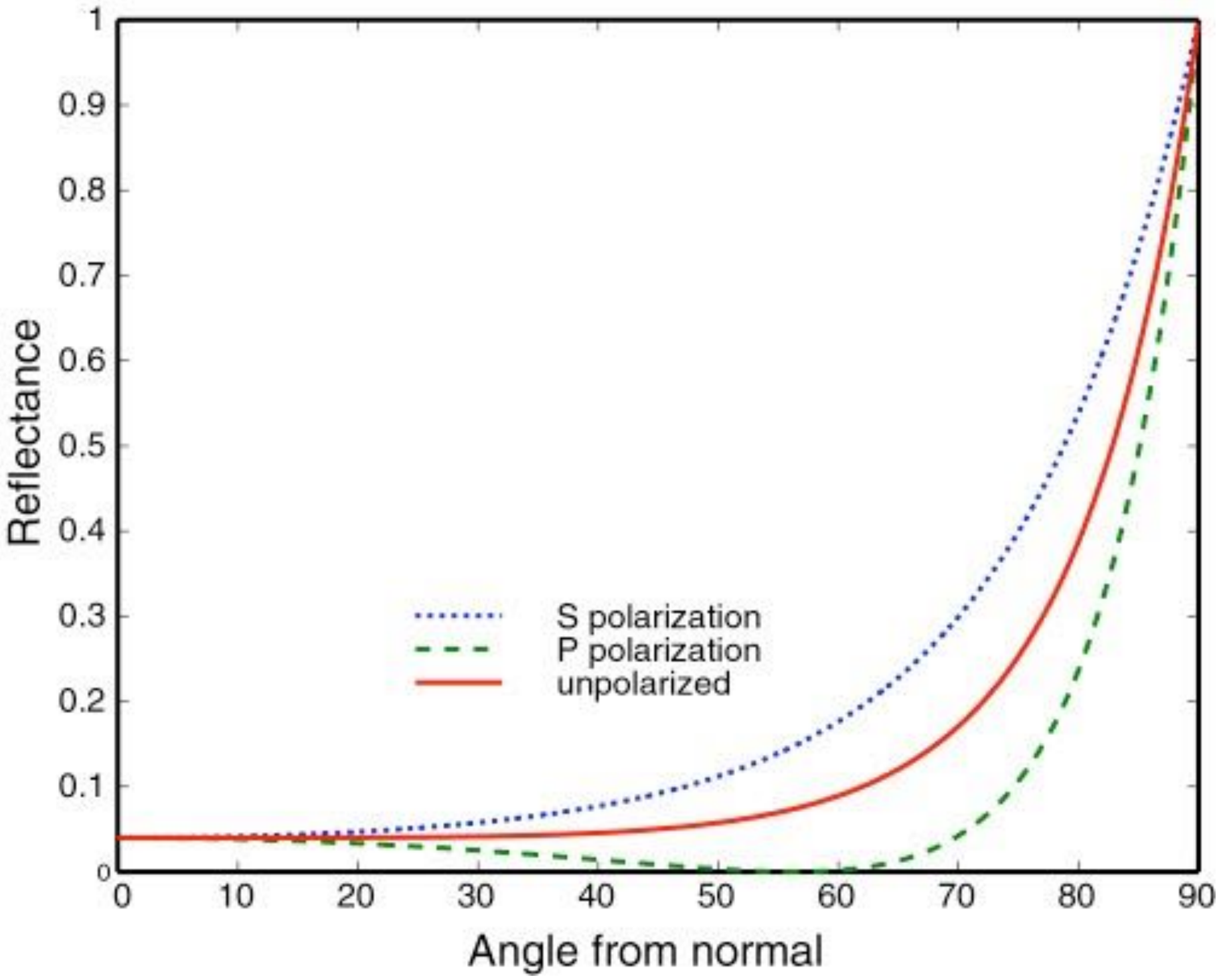
# Fresnel Reflection Term

Reflectance depends on incident angle (and polarization of light)

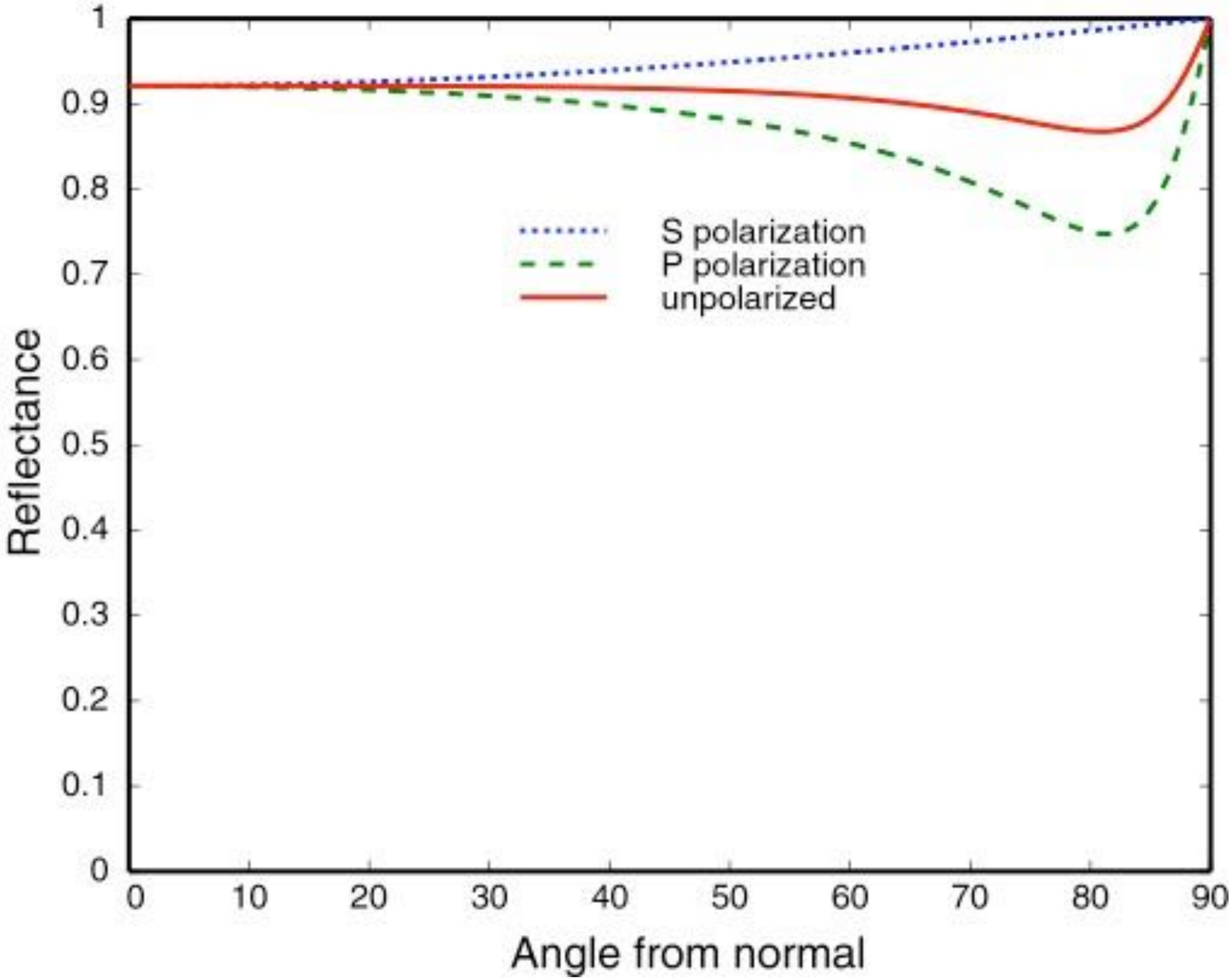

This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

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



# Fresnel Term (Conductor)



# Microfacet BRDF: Examples

[Autodesk Fusion 360]

# Anisotropic BRDFs

# Isotropic vs Anisotropic Reflection

- So far, Point light + Metal = Round / Elliptical highlight
- What can we see inside many metal elevators?

# Isotropic vs Anisotropic Reflection

Isotropic

Anisotropic

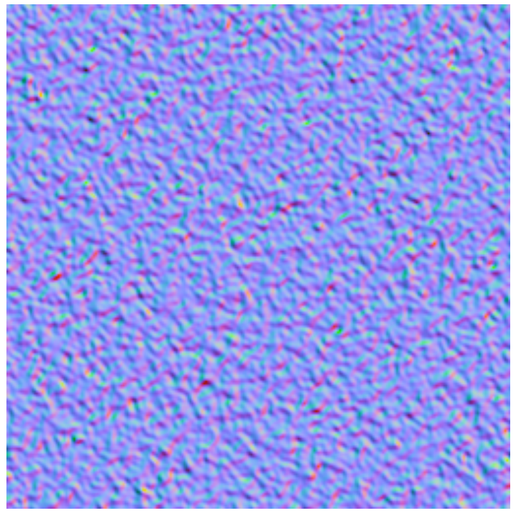
# Anisotropic BRDF: Brushed Metal

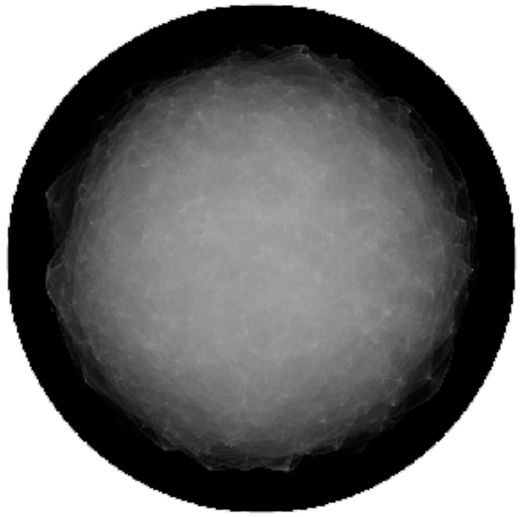
- How is the pan brushed?

# Isotropic / Anisotropic Materials (BRDFs)

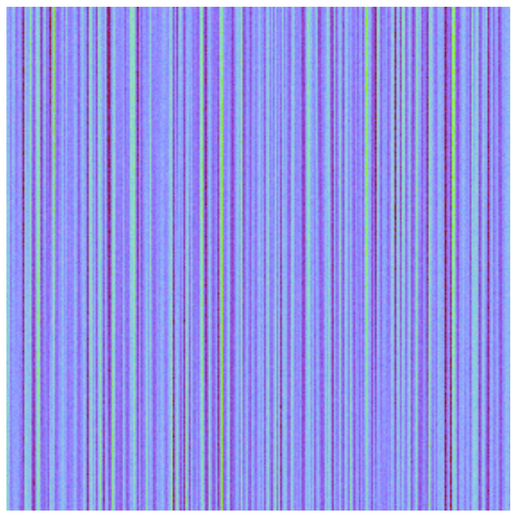
- Key: directionality of underlying surface

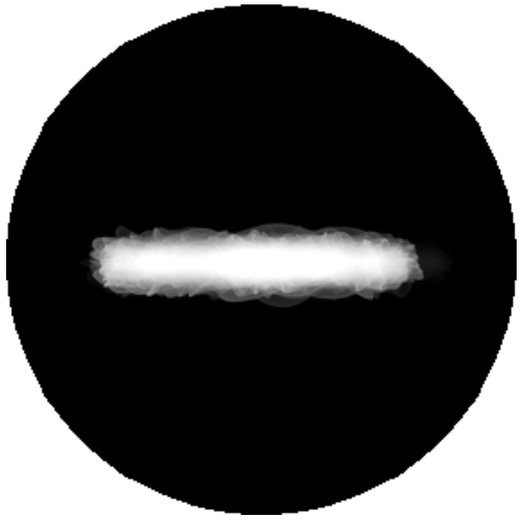
**Isotropic**





**Anisotropic**





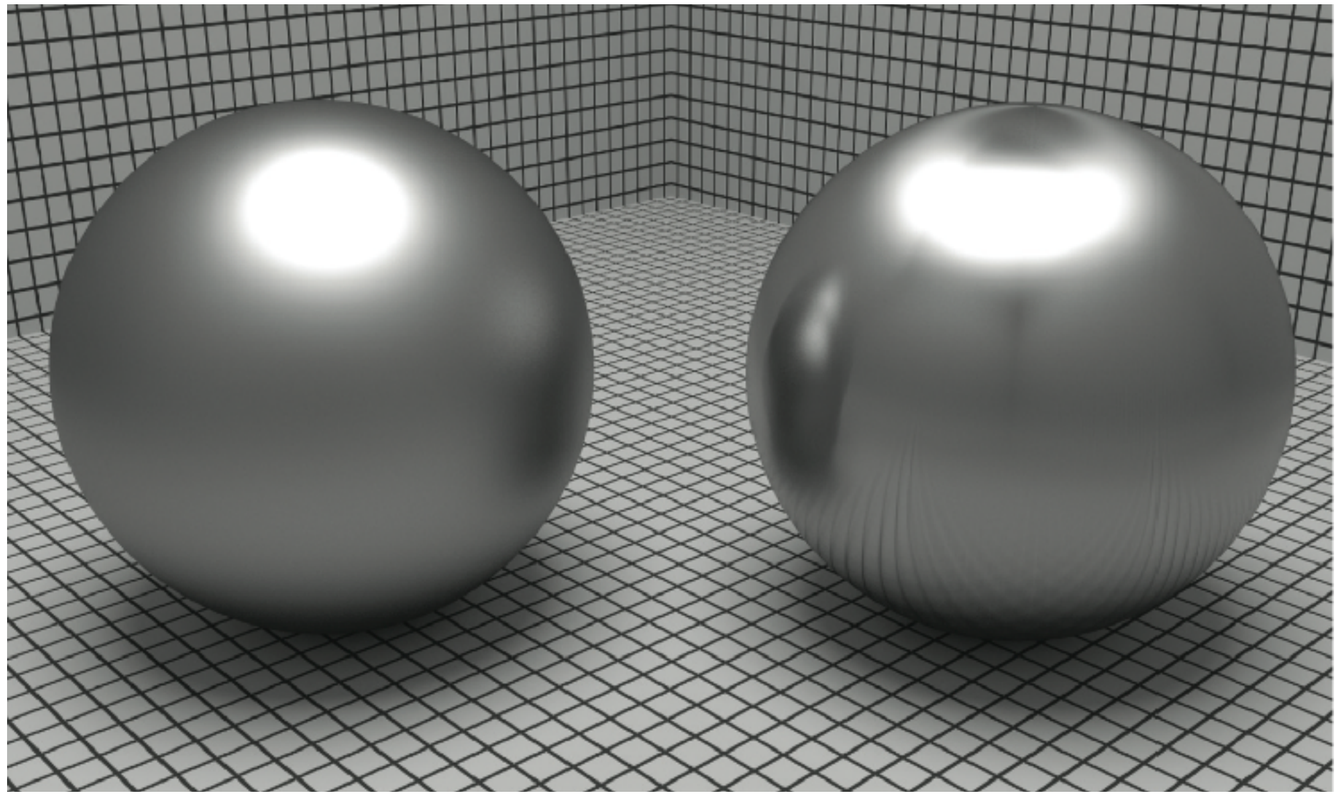
**Surface (normals)** **BRDF (fix wi, vary wo)**

# Anisotropic BRDFs

**Reflection depends on azimuthal angle $\phi$**

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

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



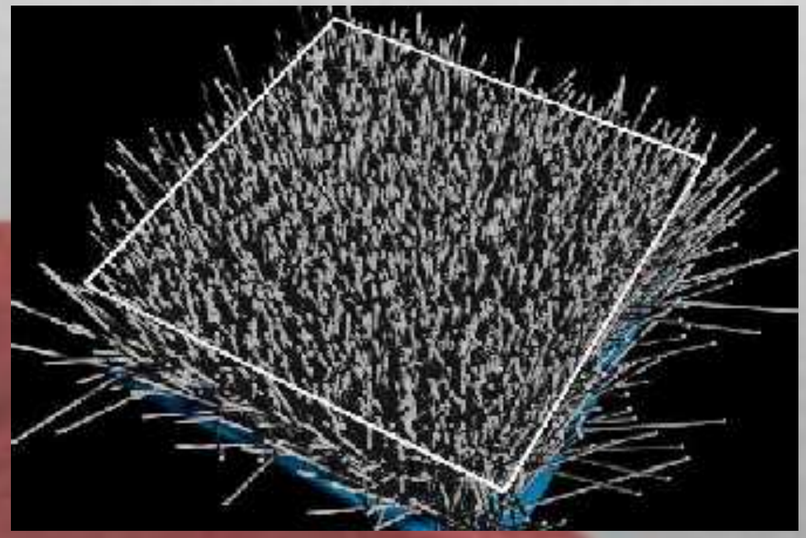


Kanazawa & Ng

# Anisotropic BRDF: Nylon

[Westin et al. 1992]

# Anisotropic BRDF: Velvet



[Westin et al. 1992]

# Anisotropic BRDF: Velvet

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

# Sampling of Advanced Material Modeling Topics

# Detailed / Glinty Material

# Why details?

Microfacet model

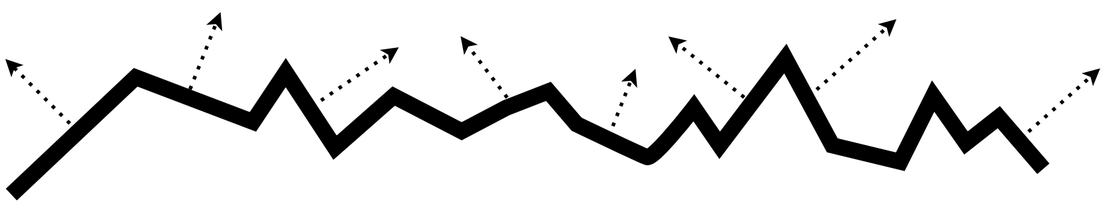
# Why details?

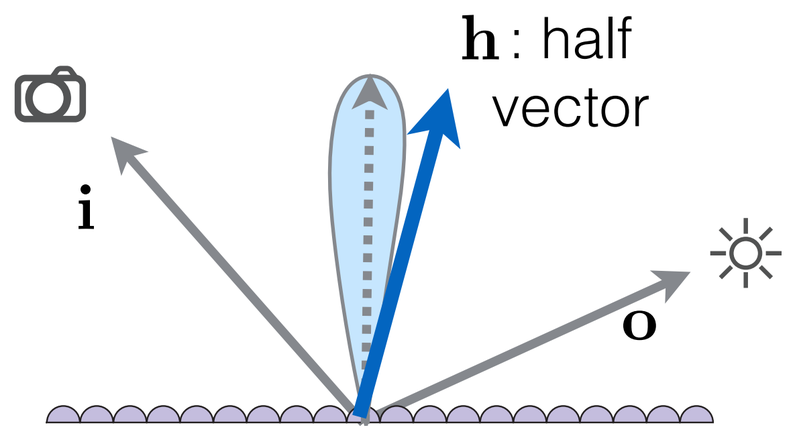
[Yan et al. 2014, 2016]

# Why details?

[Yan et al. 2014, 2016]

# Recap: Microfacet BRDF



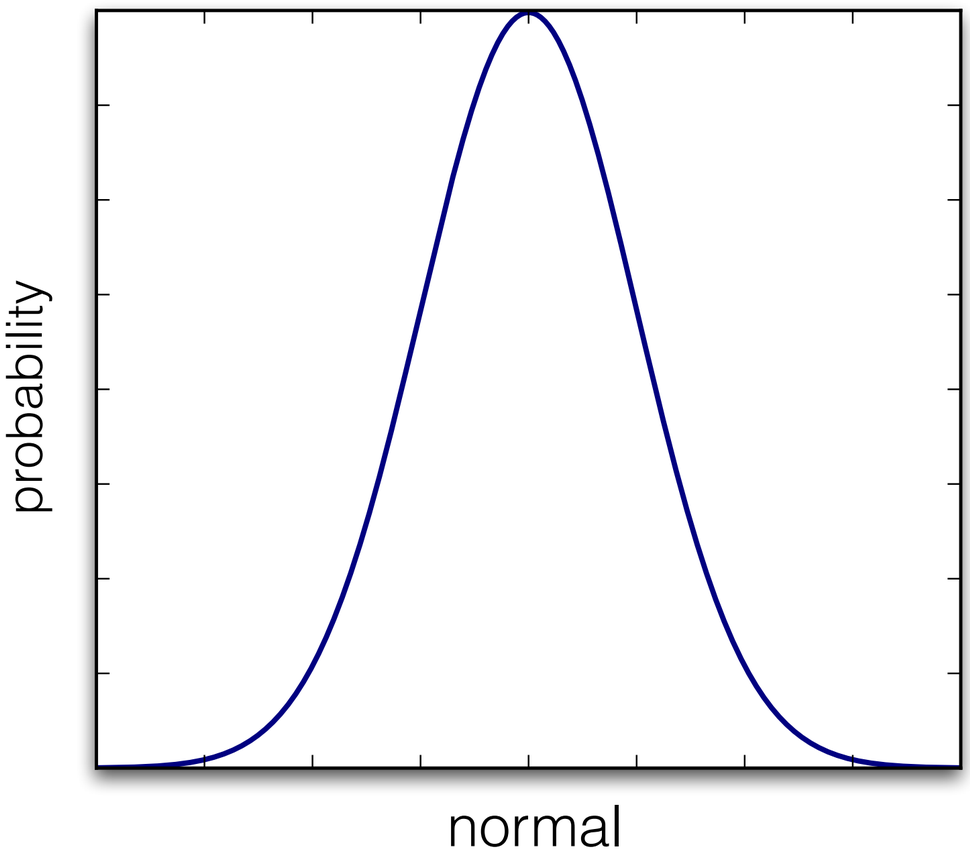



Surface = Specular microfacets + statistical normals

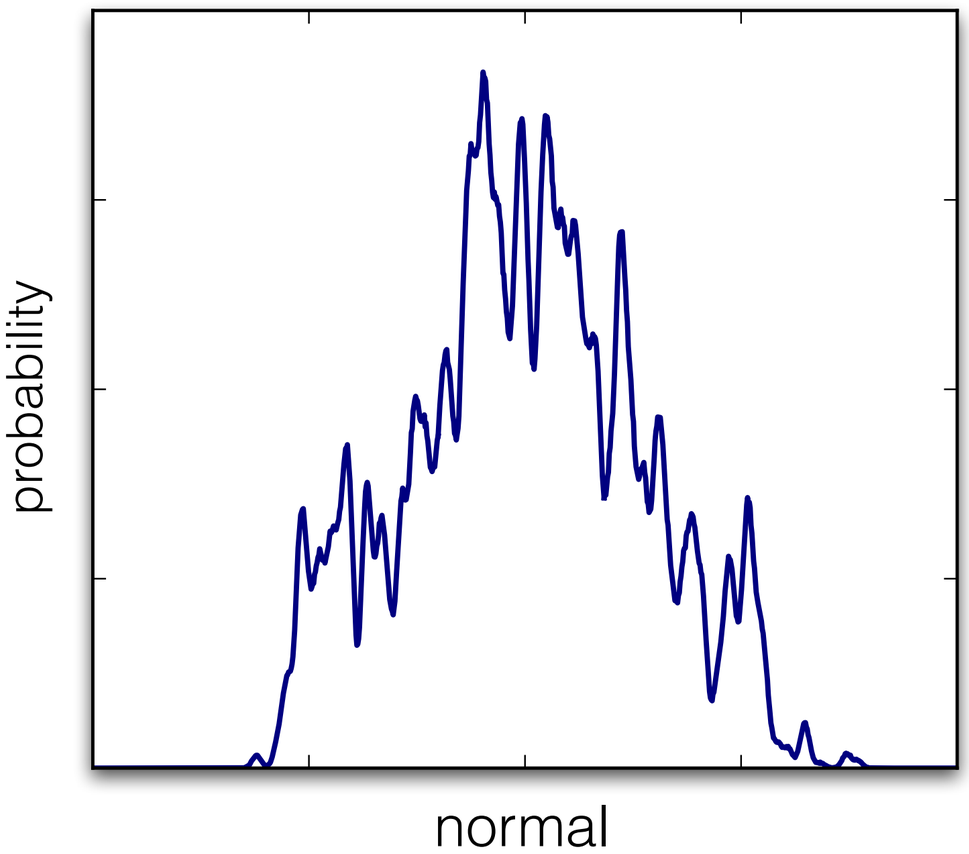
$$f(\mathbf{i},\mathbf{o}) = \frac{\mathbf{F}(\mathbf{i},\mathbf{h})\mathbf{G}(\mathbf{i},\mathbf{o},\mathbf{h})\mathbf{D}(\mathbf{h})}{4(\mathbf{n},\mathbf{i})(\mathbf{n},\mathbf{o})}$$

NDF: Normal Distribution Function

# Statistical NDF vs. Actual NDF

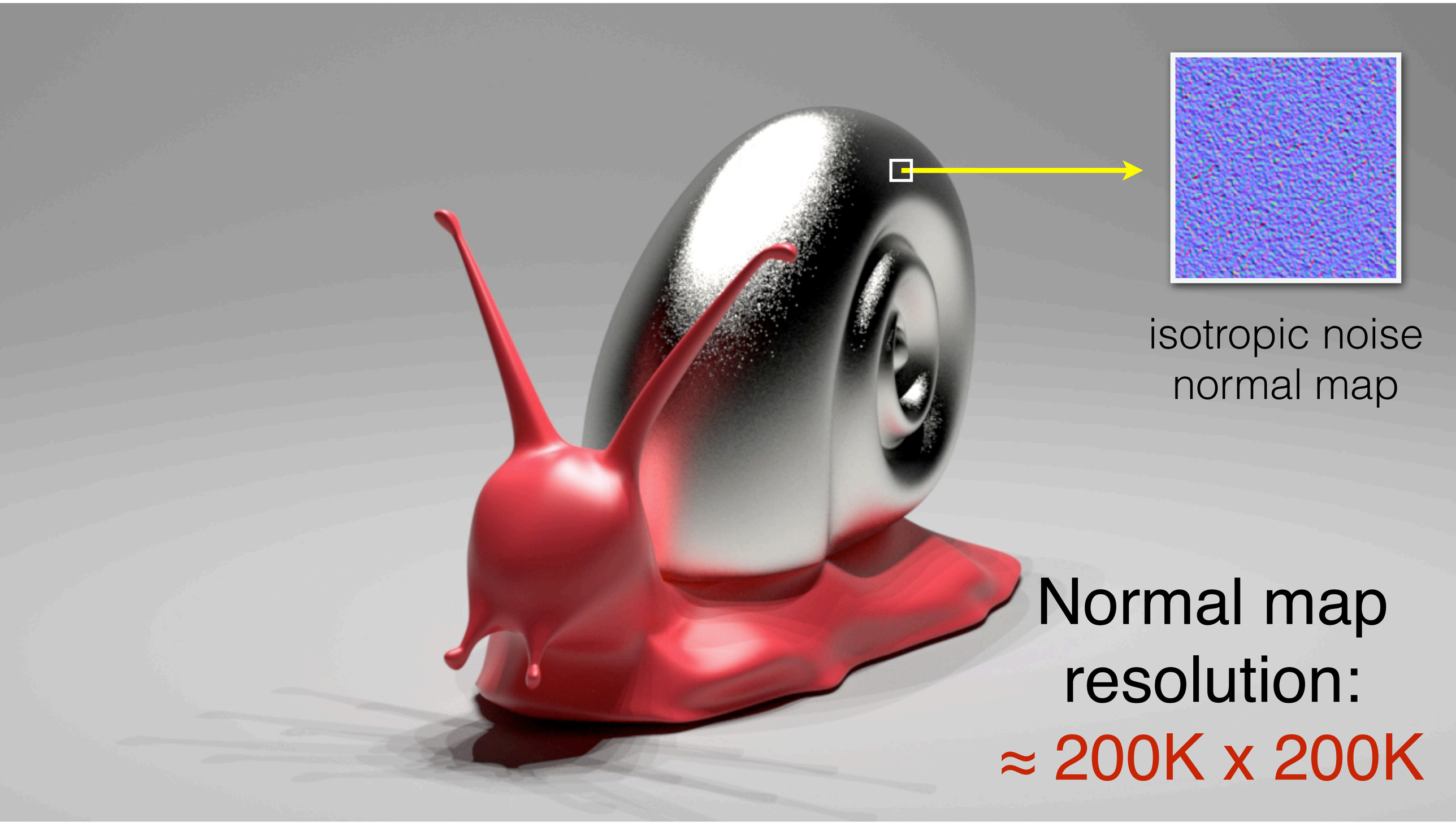



What we have
(microfacet — statistical)

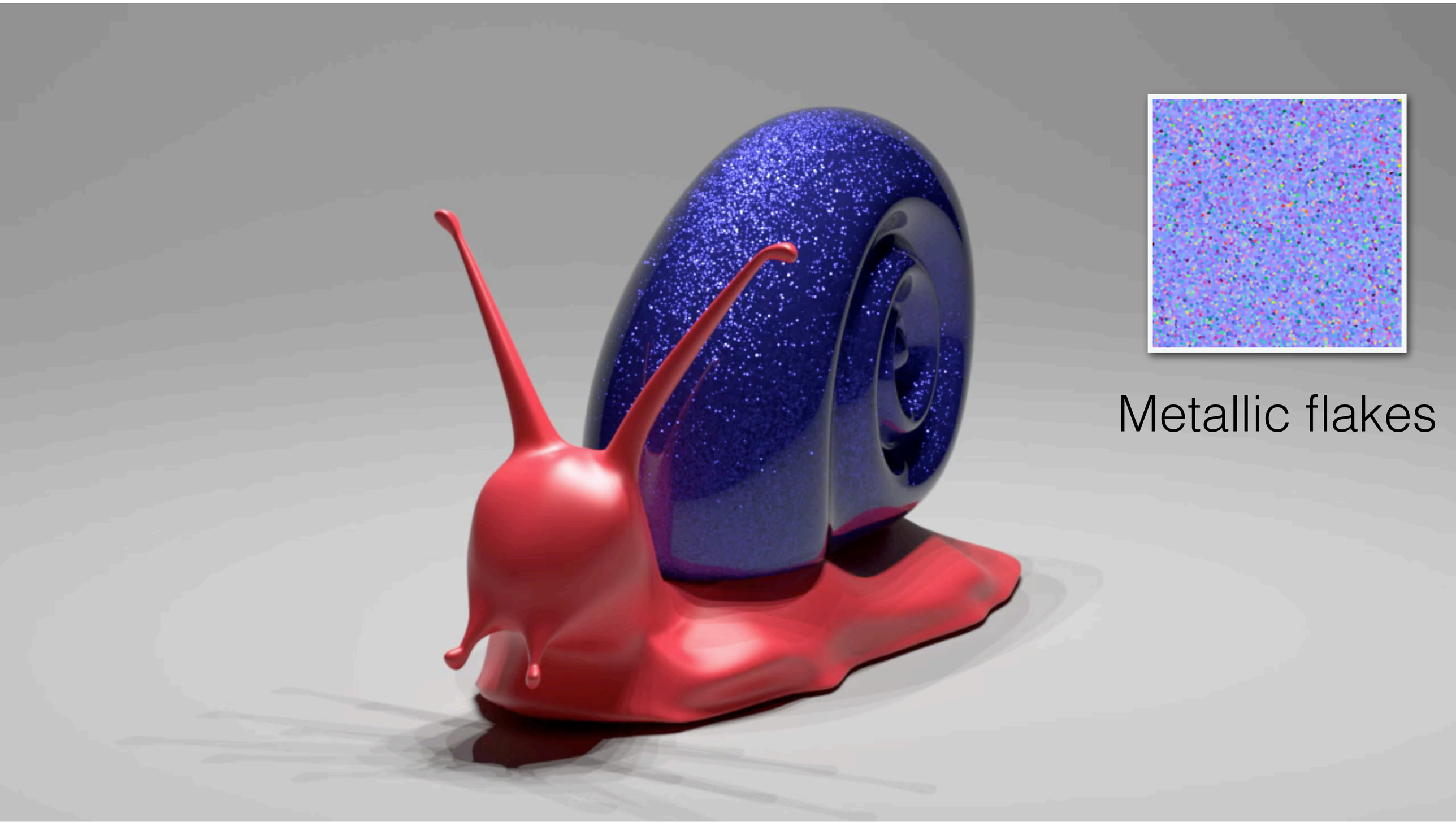



What we want

# Define details

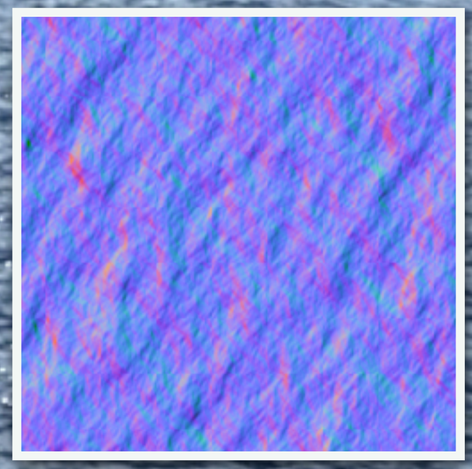


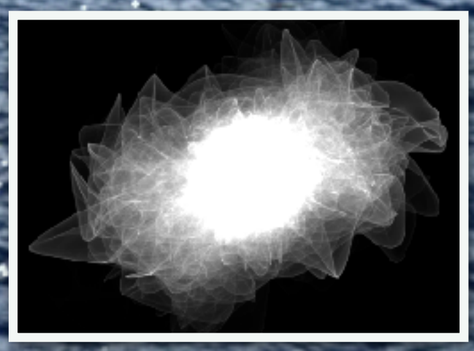
# Different details





Metallic flakes



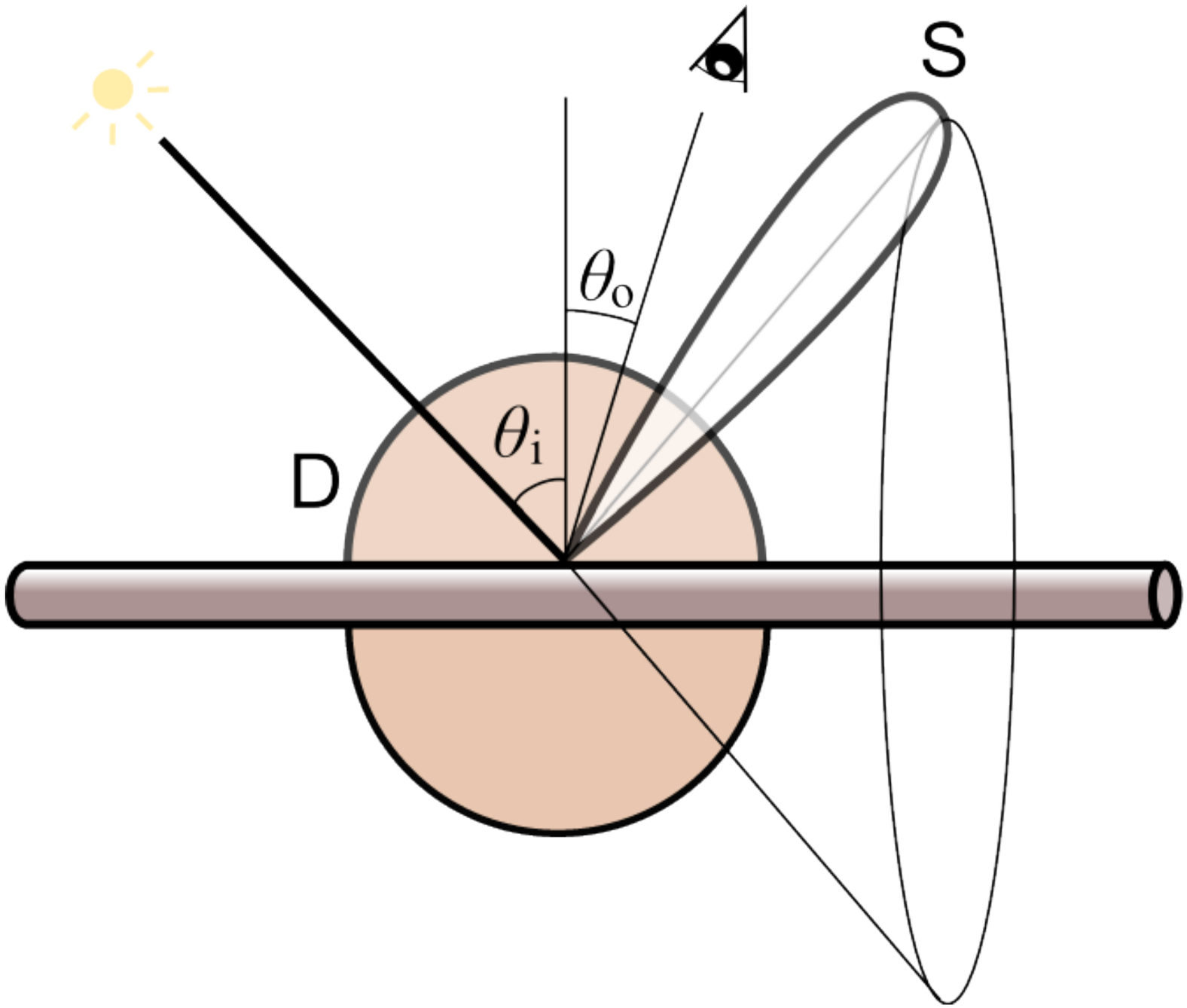


# Ocean waves

# Hair / Fur Appearance Models

# Hair Appearance

# Kajiya-Kay Model

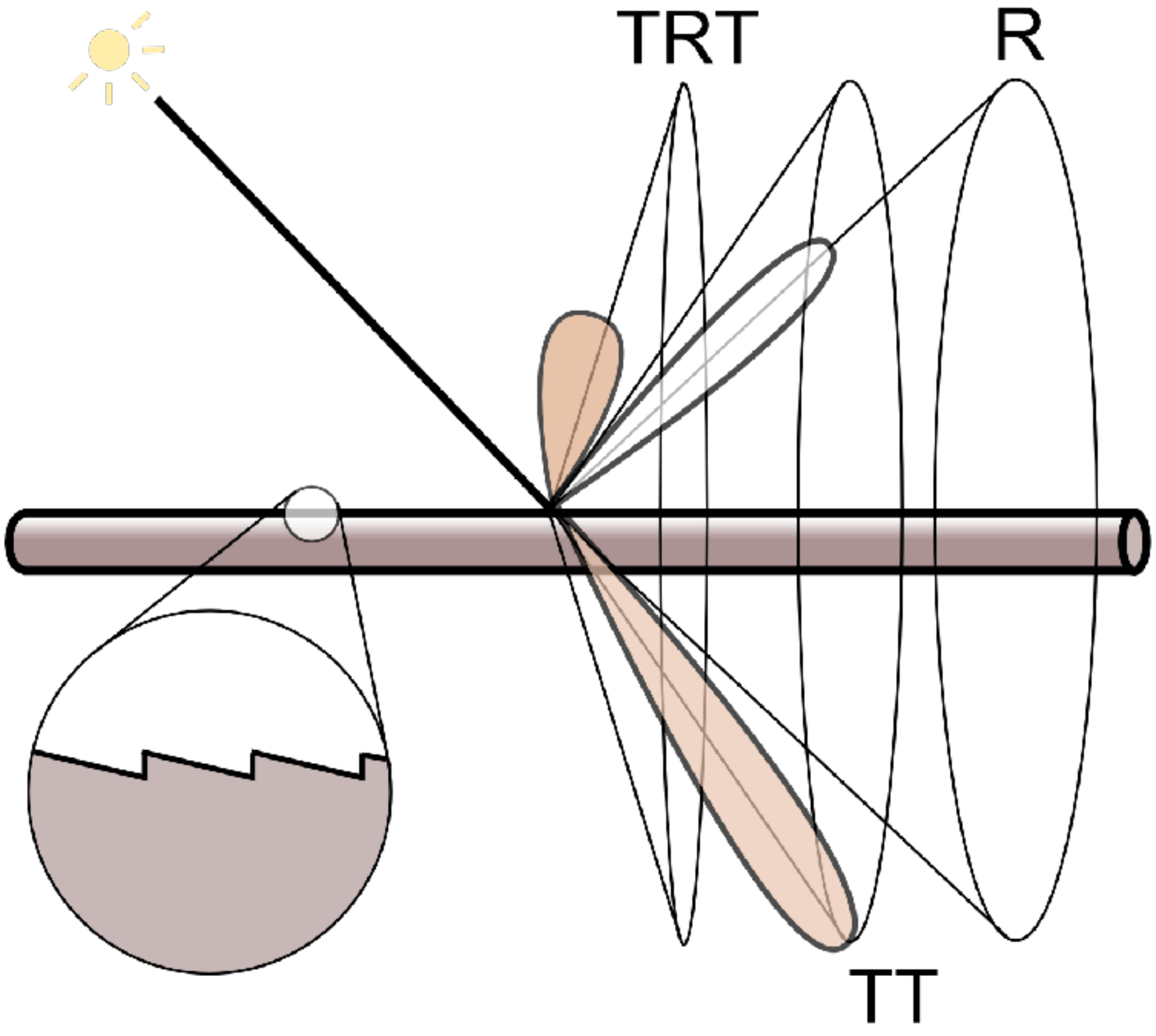



[Image courtesy of Chiwei Tseng]

# Kajiya-Kay Model

[Yuksel et al. 2008]

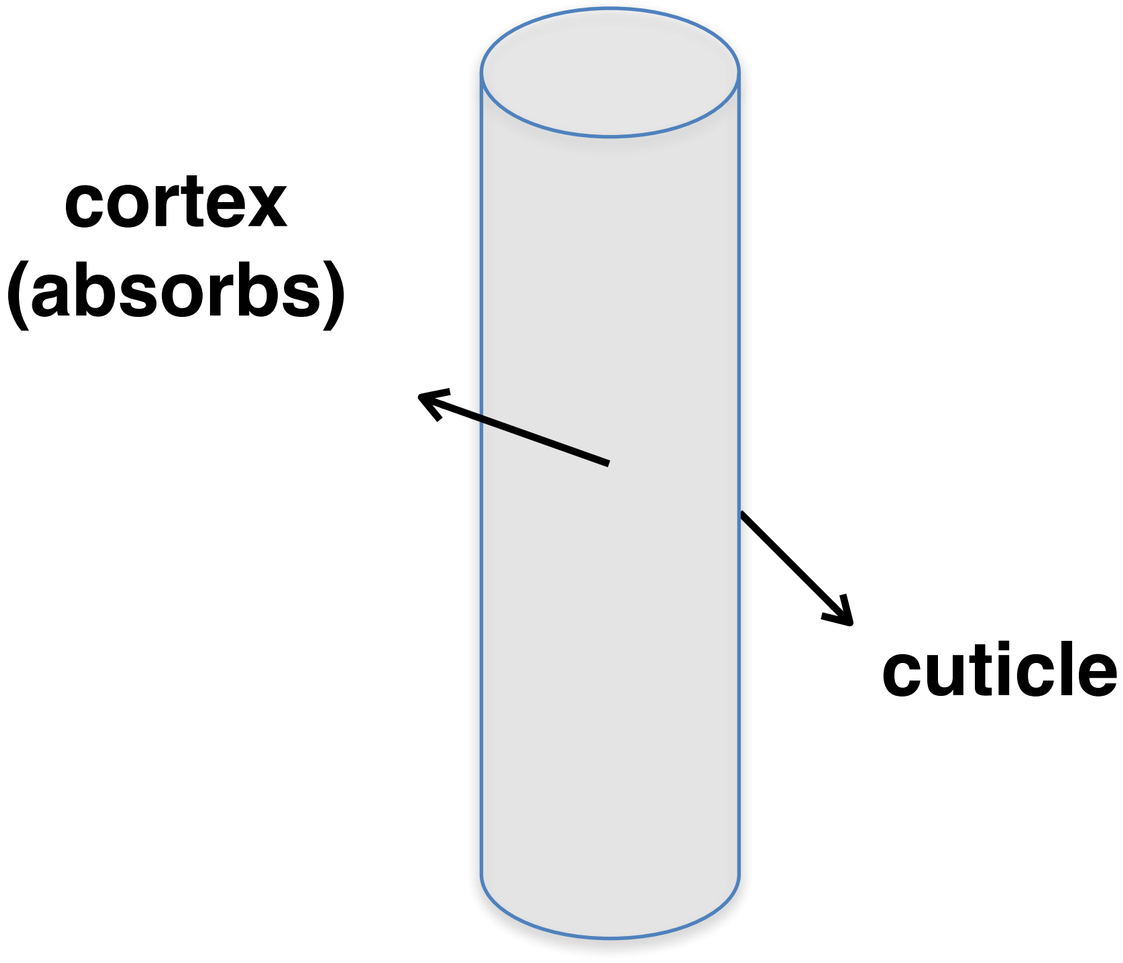
# Marschner Model



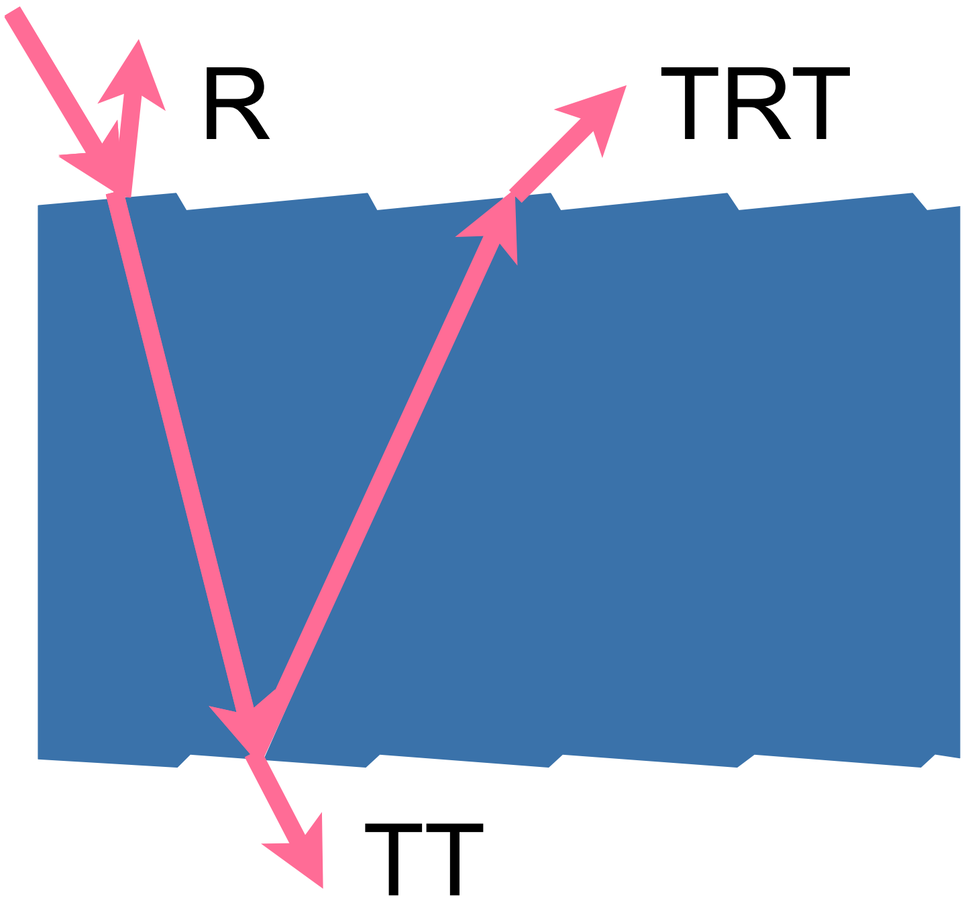

[Image courtesy of Chiwei Tseng]

# 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]

# Hair Appearance Model: Application


[Final Fantasy XV. 2016 Square Enix]

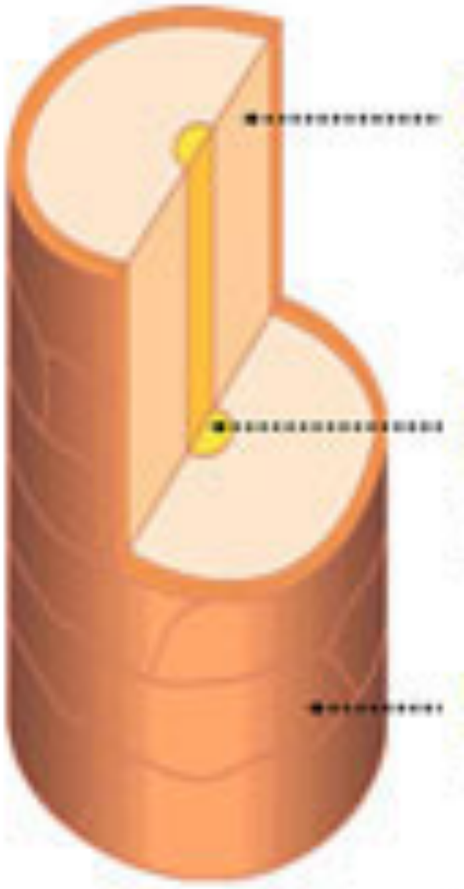
# Fur Appearance — As Human Hair

- Cannot represent diffusive and saturated appearance


**Rendered as human hair**
**[Marschner et al. 2003]**

**Rendered as animal fur**
**[Yan et al. 2015]**

# Human Hair vs Animal Fur



Cortex

- Contains pigments
- Absorbs light

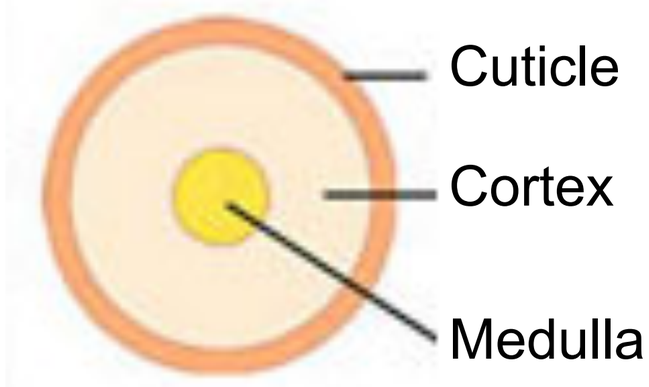
Medulla

- Complex structure
- Scatters light

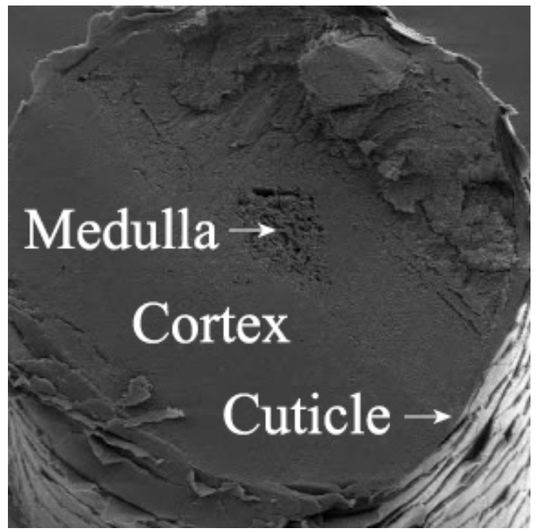
Cuticle

- Covered with scales

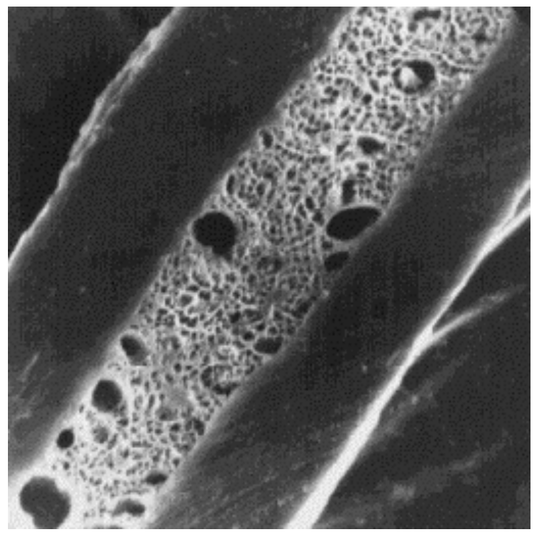
**Common for hair/fur fibers**




Human




Cougar



**Difference between hair/fur fibers**

**600,000 fur fibers**

1024 samples / pixel

36.9 min / frame

# Hamster

# Double Cylinder Model: Application



[War for the Planet of the Apes. 2017 movie]
(2018 Oscar Nominee for Best Visual Effects)

# Participating Media

# Participating Media: Fog

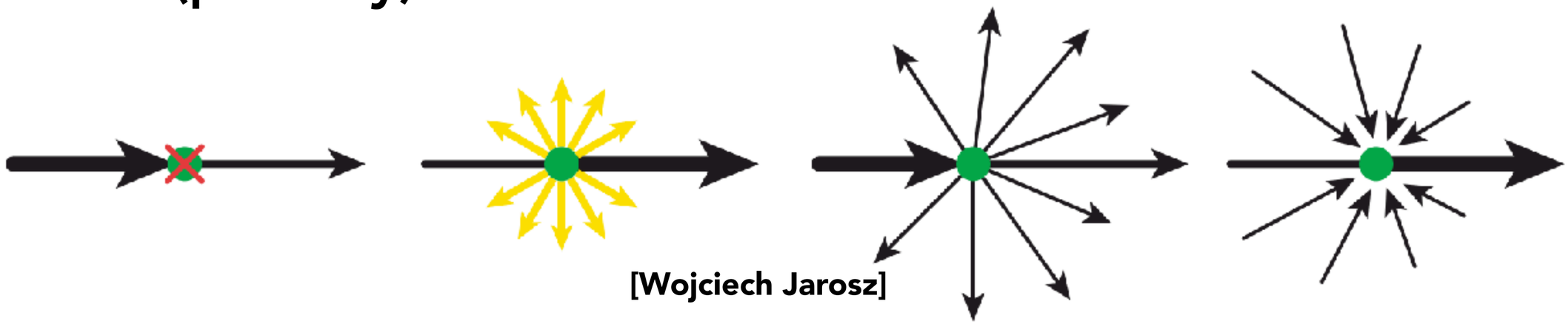
[Novák et al. 2012]

# Participating Media: Cloud

[by thephotographer0]

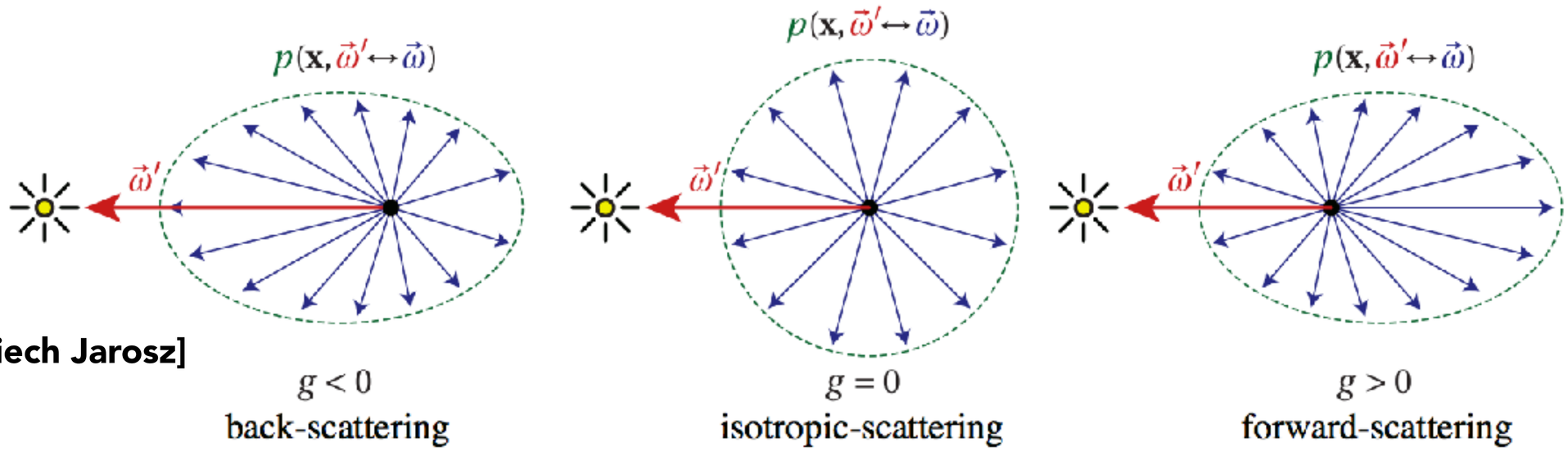
# Participating Media

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




[Wojciech Jarosz]

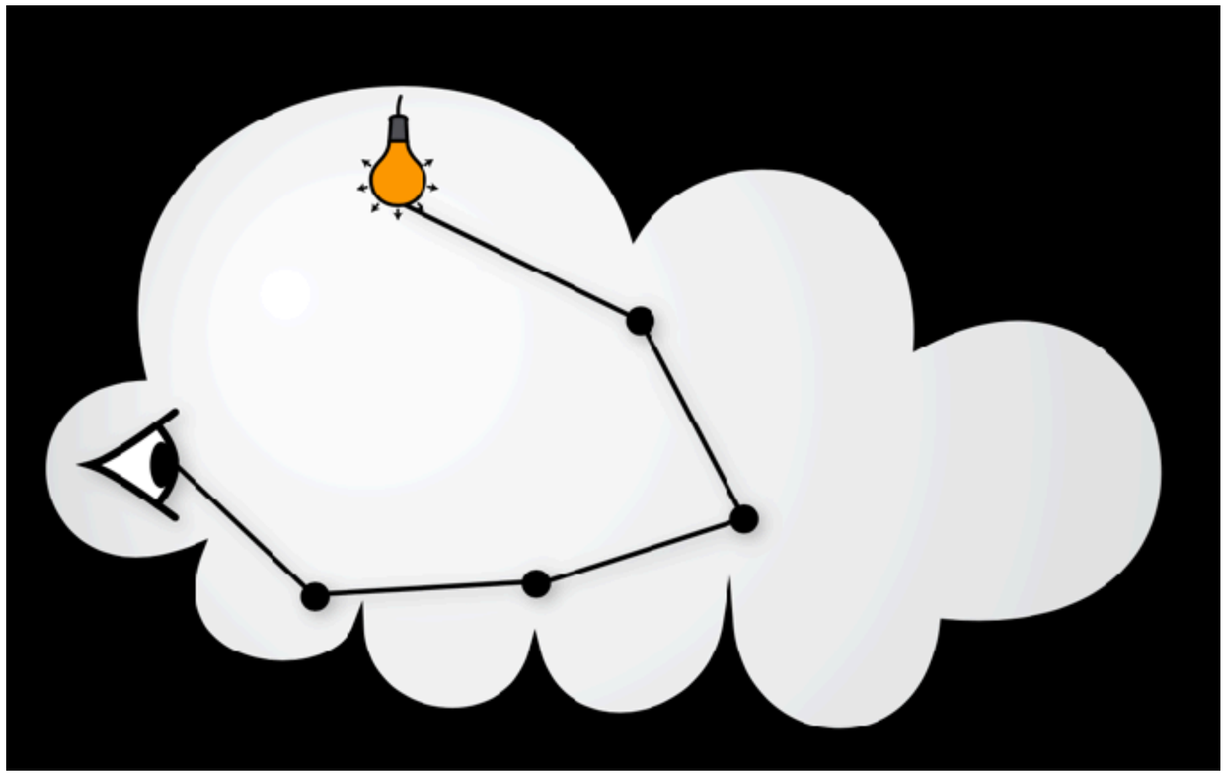
- Use Phase Function to describe the angular distribution of light scattering at any point x within participating media.

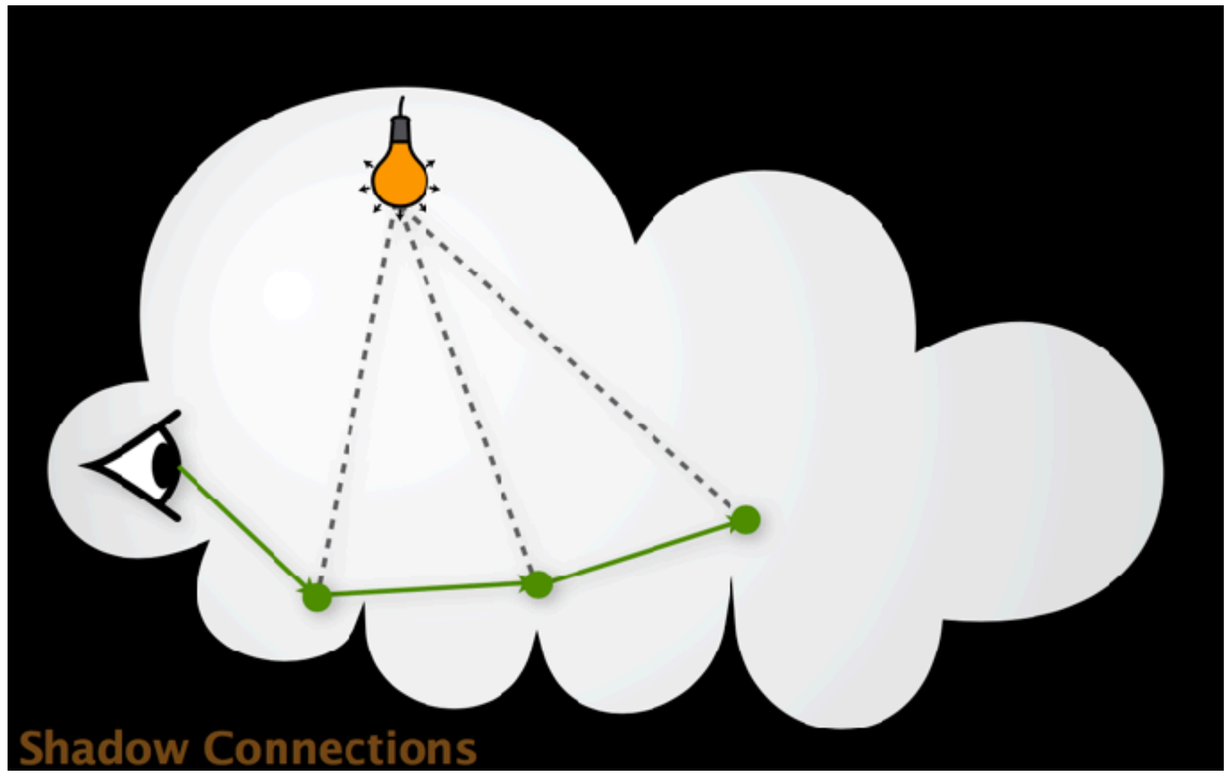



[Wojciech Jarosz]

# 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]

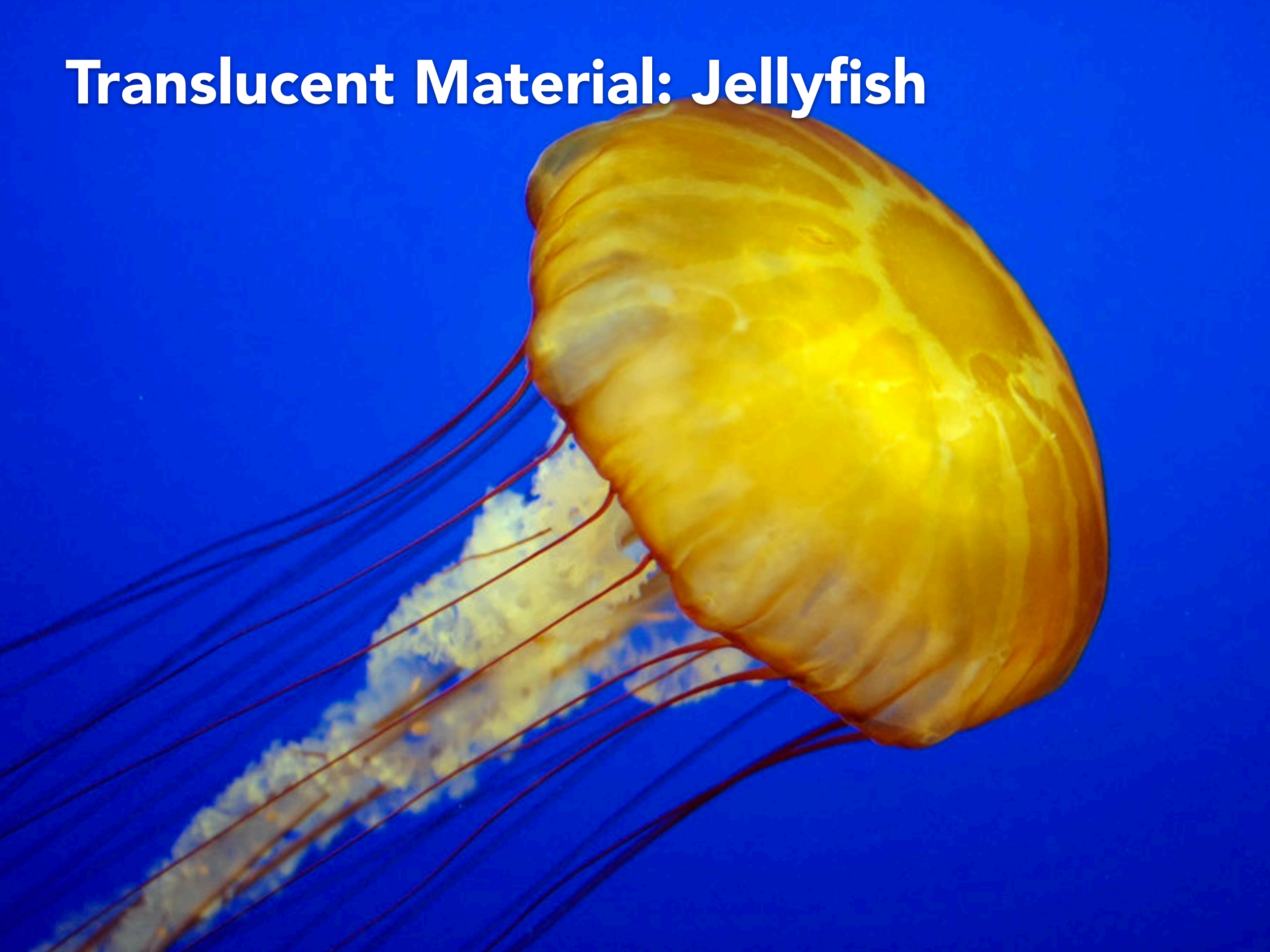
# Participating Media: Demo


[Stomakhin et al. 2014]

# Translucent Material (specific participating media)

# Translucent Material: Jade

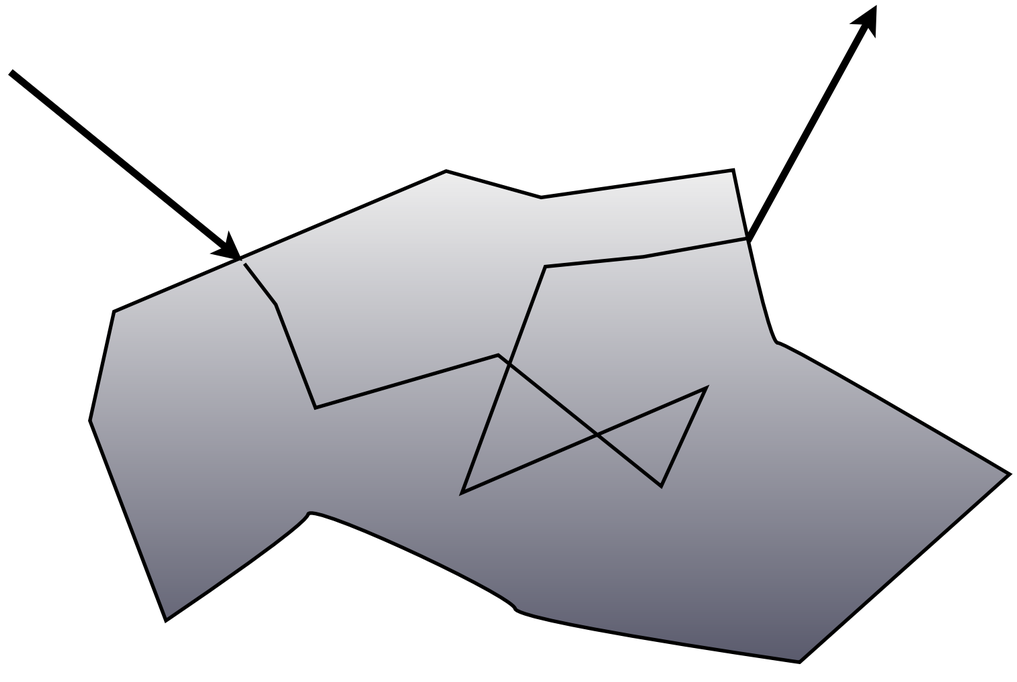
# Translucent Material: Jellyfish



# 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]

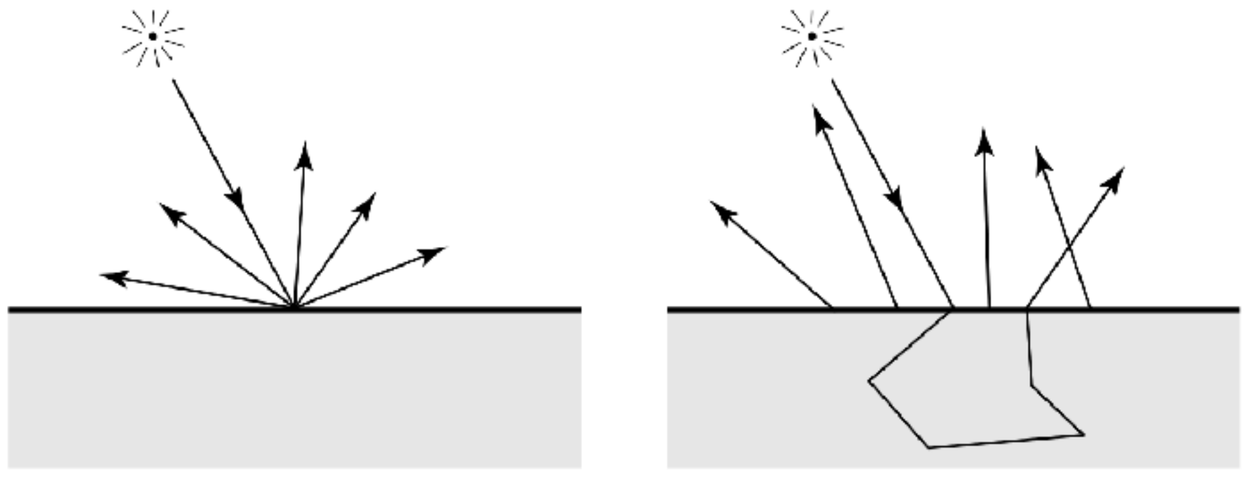
# Scattering Functions

- 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 (!)

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



BRDF BSSRDF

[Jensen et al. 2001]

# BRDF

[Jensen et al. 2001]

# BSSRDF

[Jensen et al. 2001]

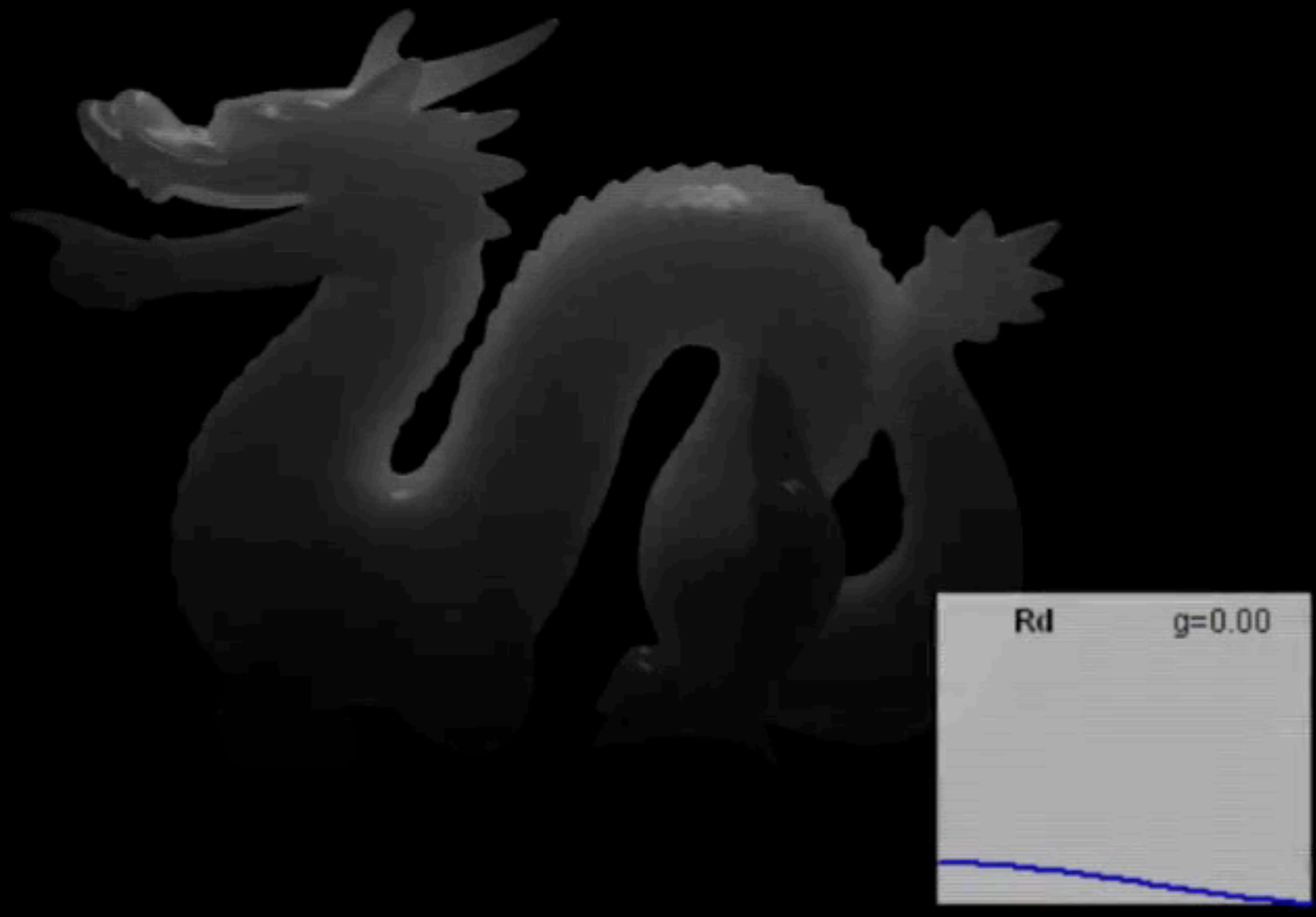
# BRDF vs BSSRDF

BRDF

BSSRDF

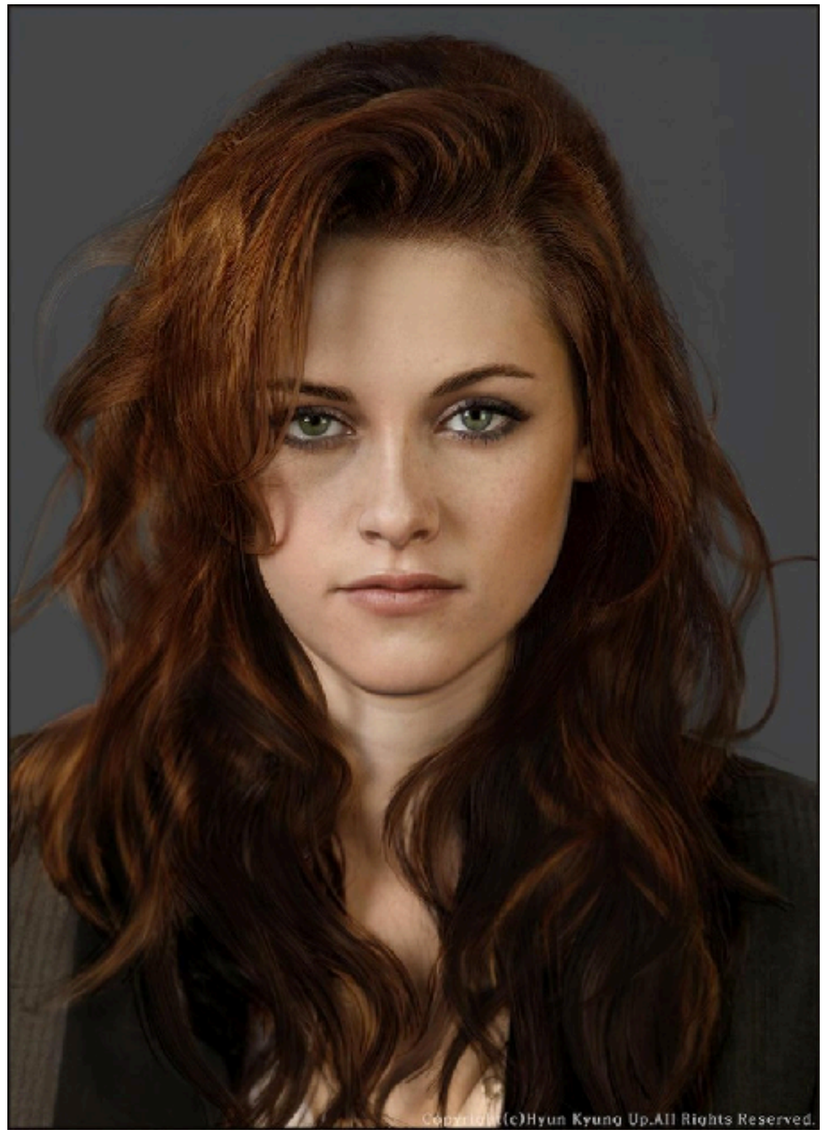
[Jensen et al. 2001]

# BSSRDF: Demo



# BSSRDF: Application

[Artist: Teruyuki and Yuka]




[Artist: Hyun Kyung]

[Artist: Dan Roarty]

https://cgelves.com/10-most-realistic-human-3d-models-that-will-wow-you/

# Acknowledgments

Thanks to Lingqi Yan, Matt Pharr, Pat Hanrahan and Kayvon Fatahalian for slide resources.