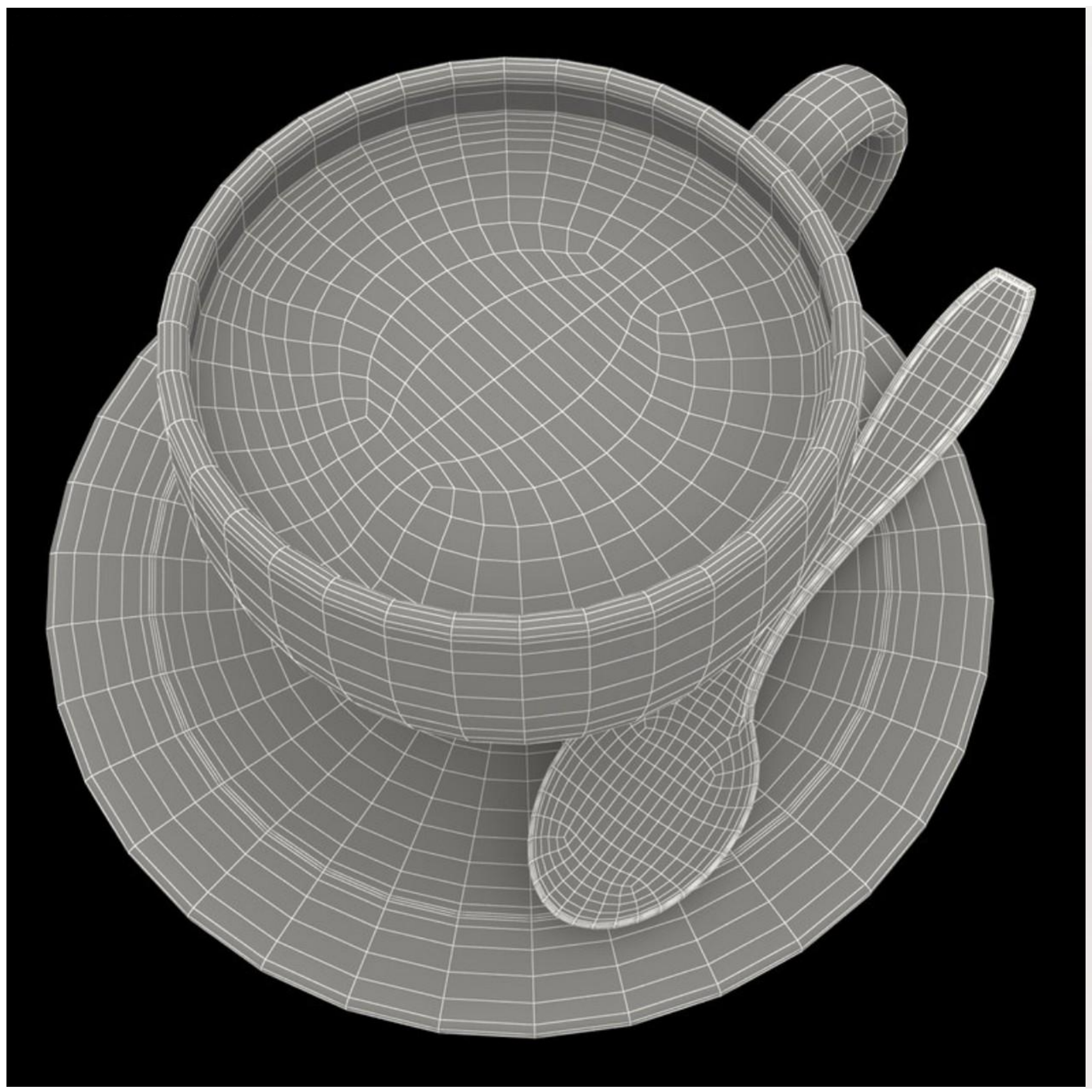
Lecture 16-17:

Introduction to Material Modeling

Computer Graphics and Imaging

UC Berkeley CS184

What is Material in Computer Graphics?



3D coffee mug model

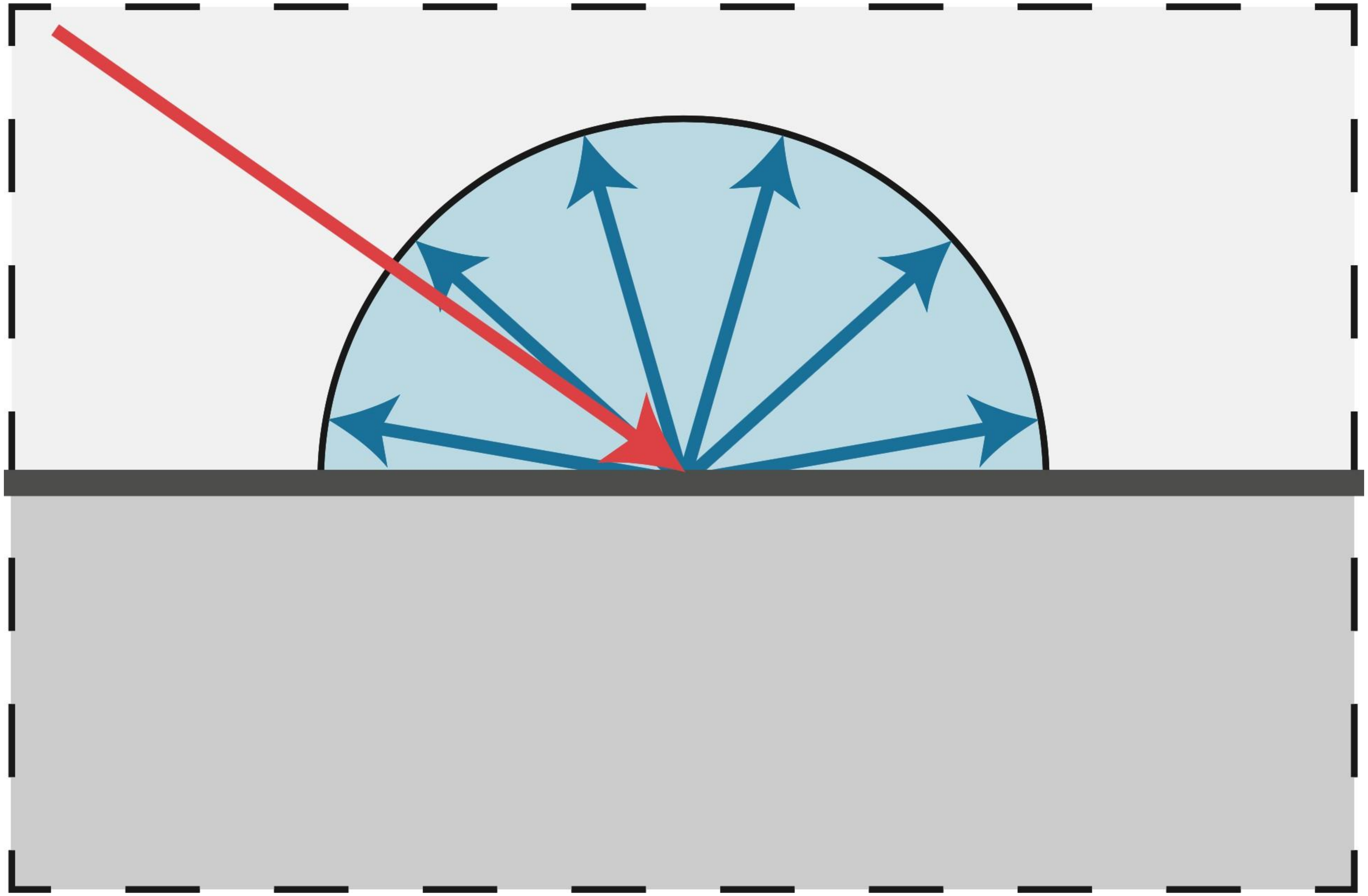
Rendered

Rendered

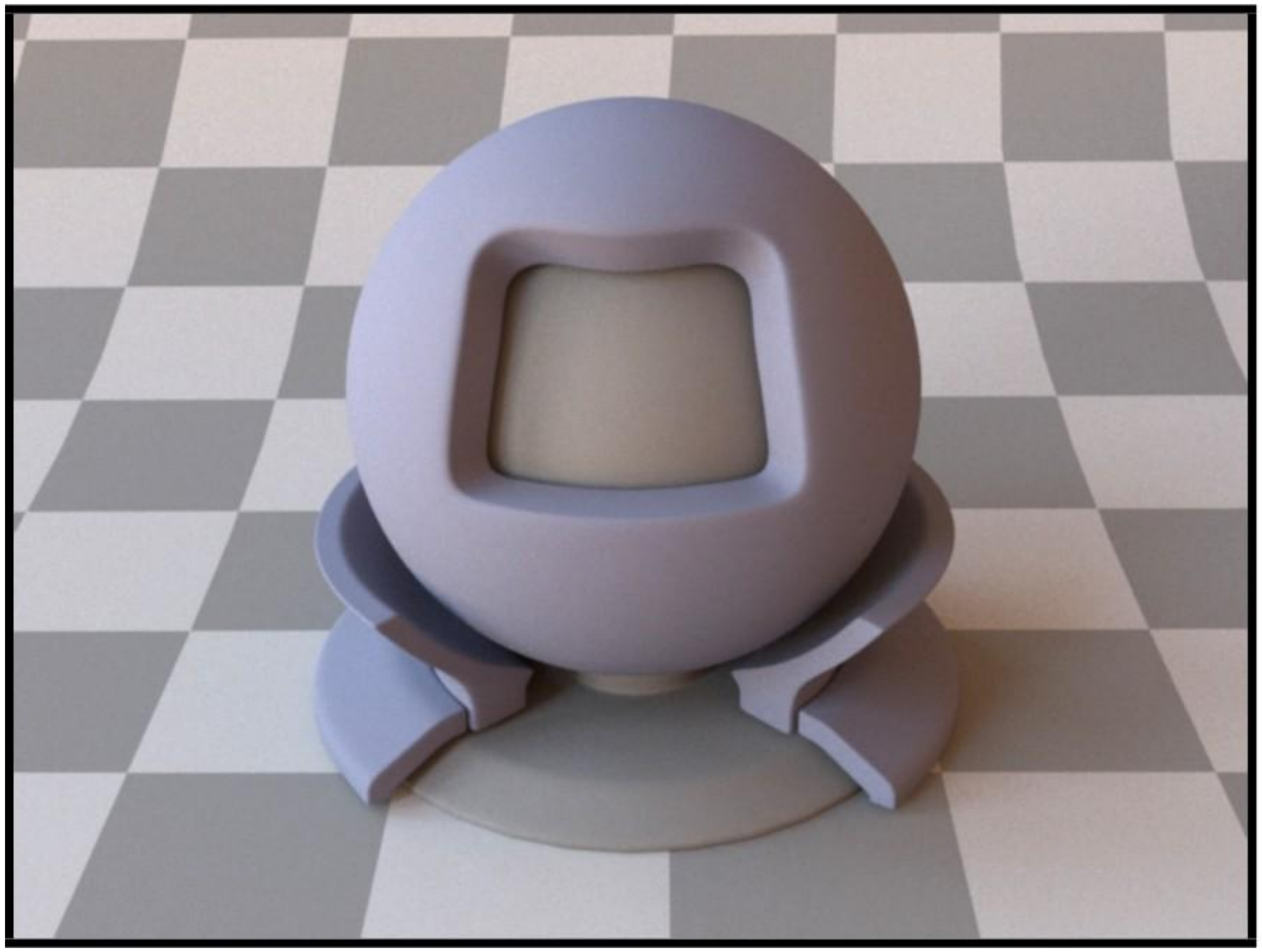
[From TurboSquid, created by artist 3dror]

Material ⇔ BRDF

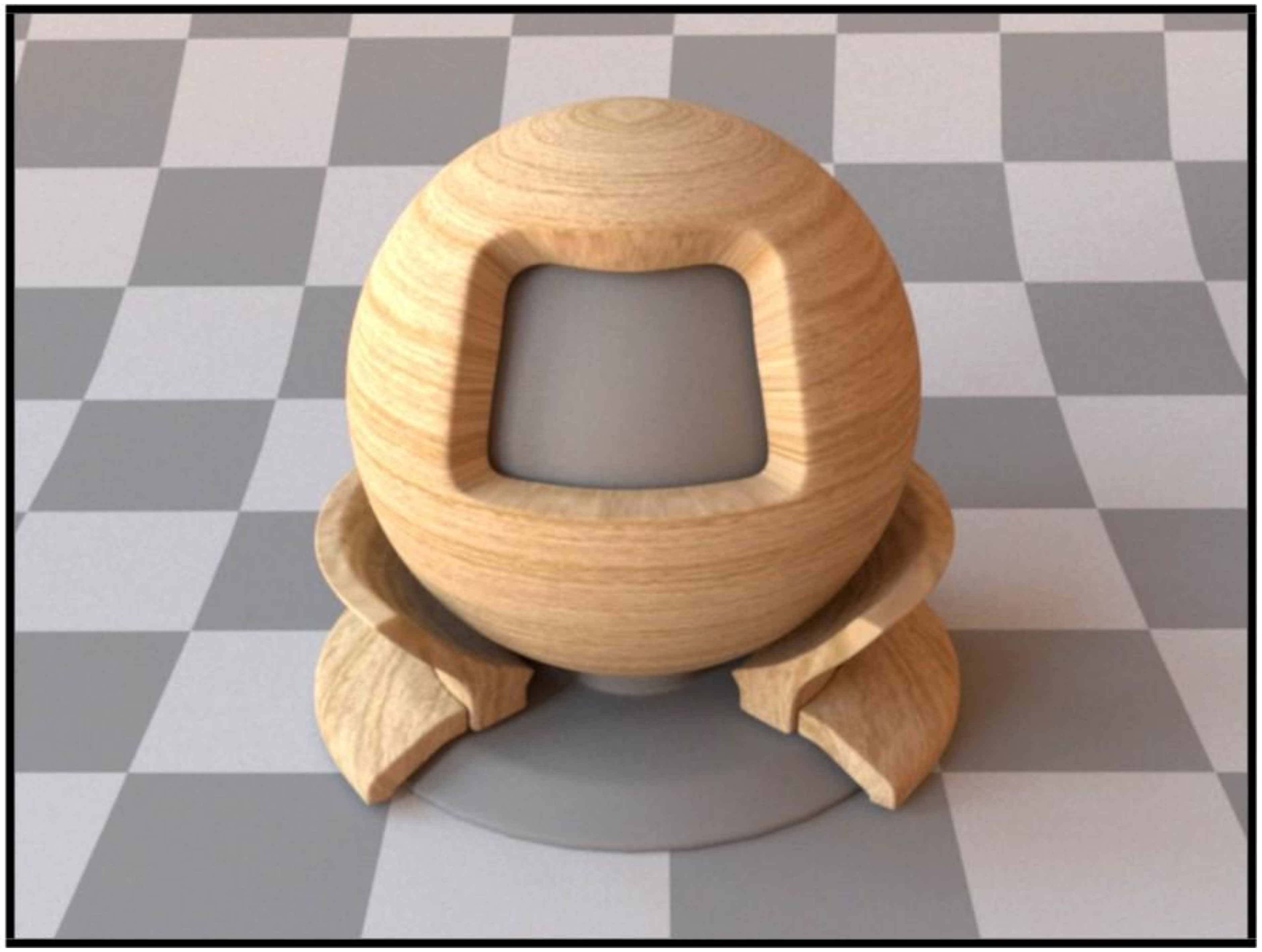
What is this material?



Diffuse / Lambertian Material (BRDF)



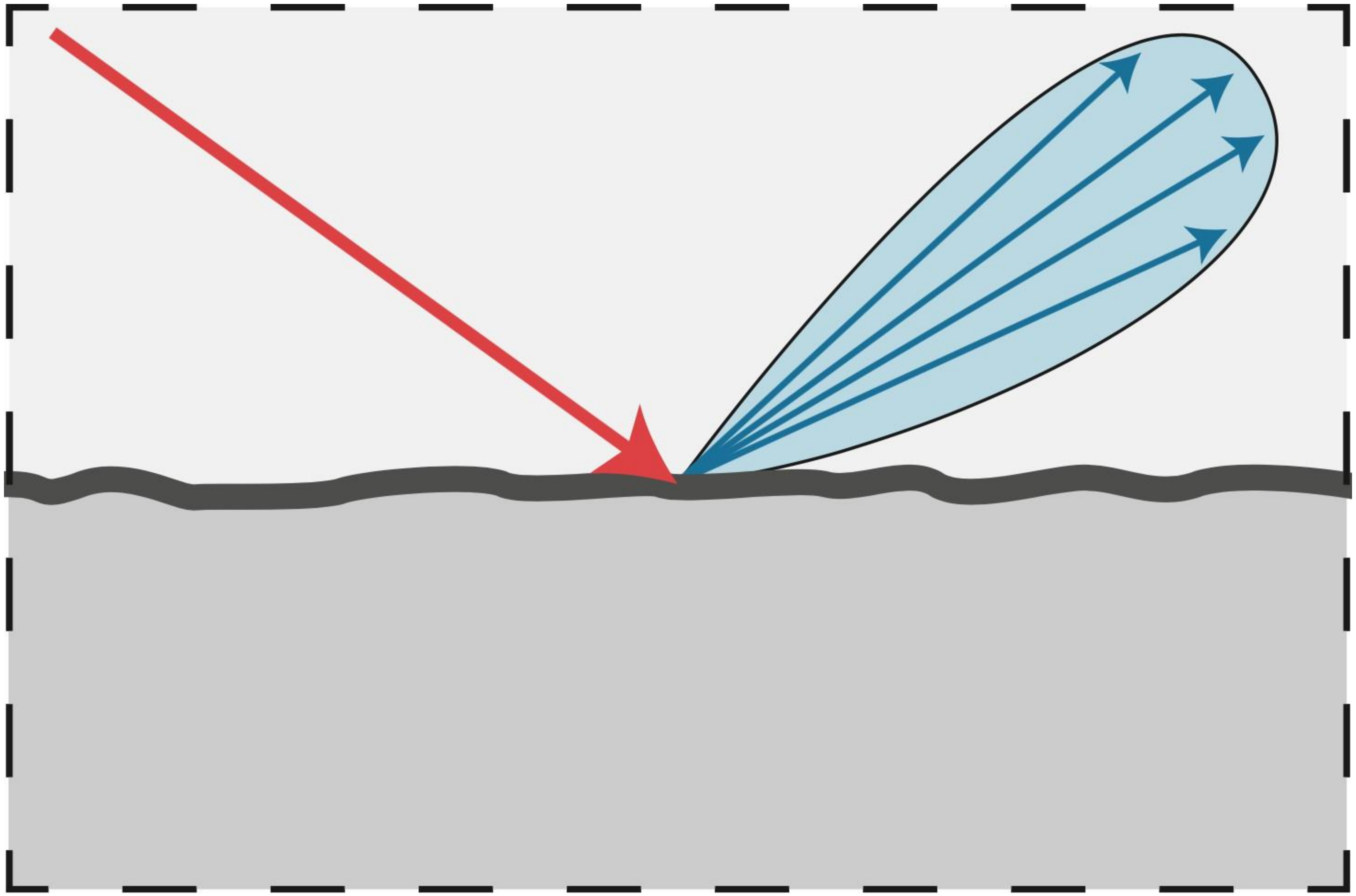
Uniform colored diffuse BRDF



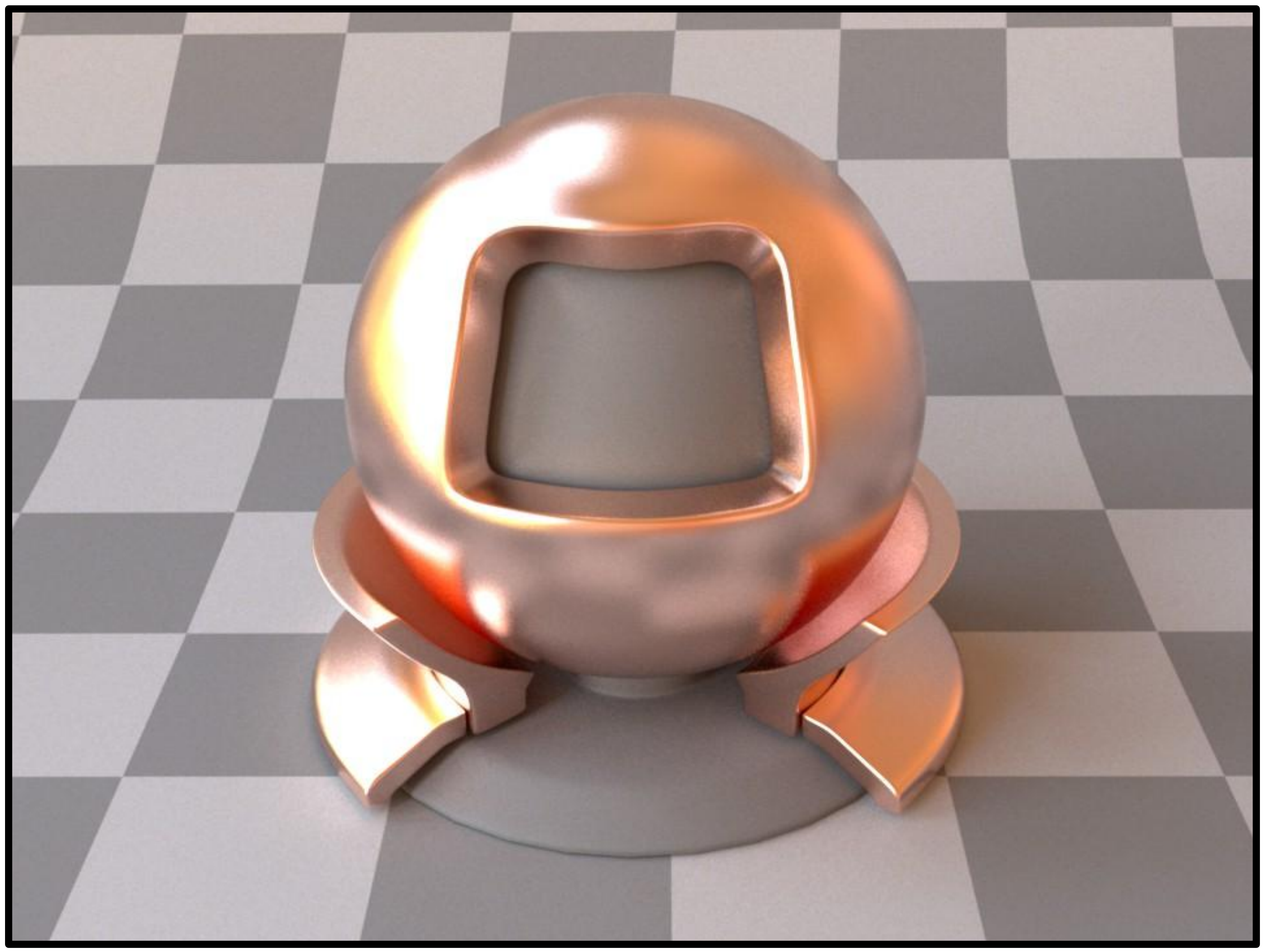
Textured diffuse BRDF

[Mitsuba renderer, Wenzel Jakob, 2010]

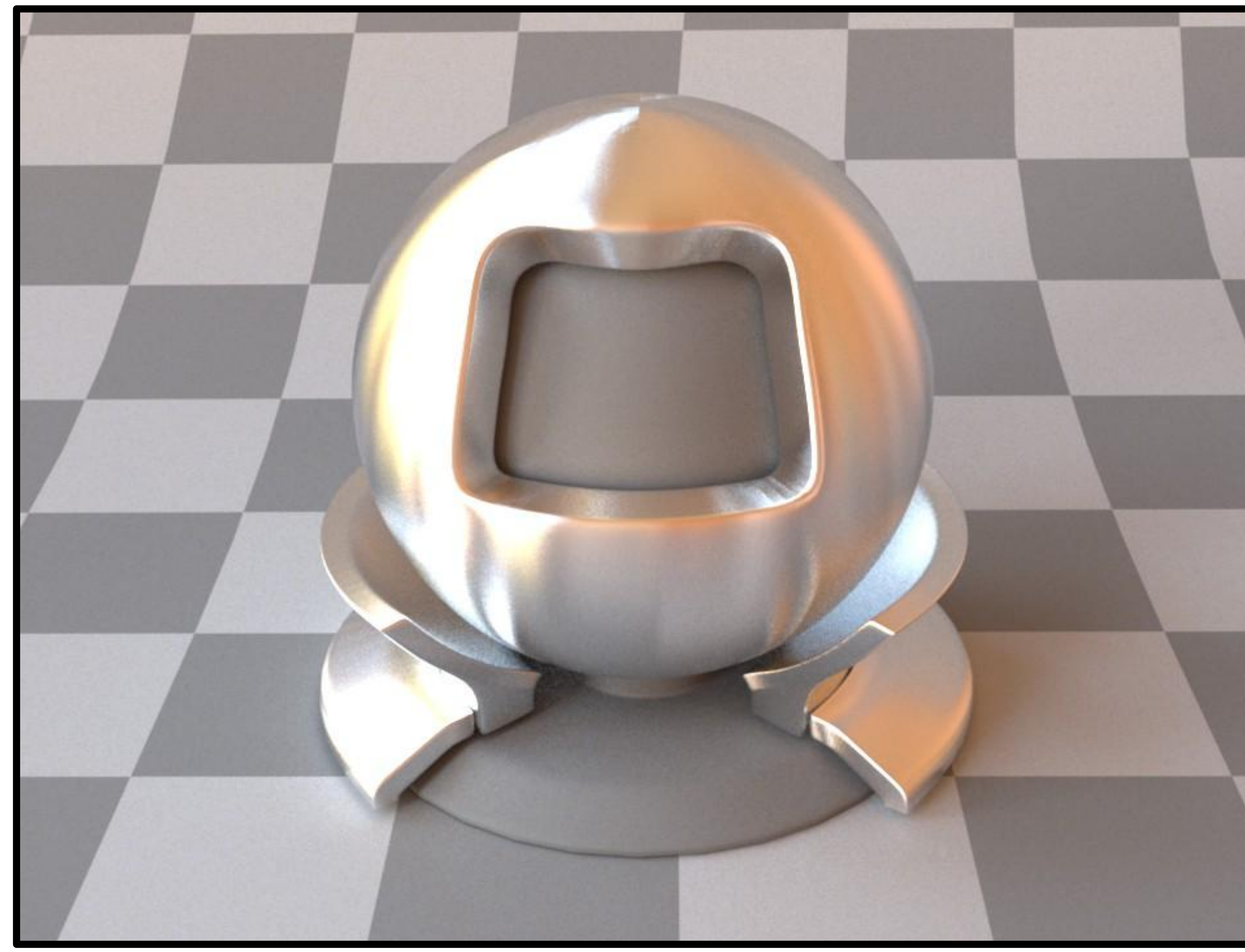
What is this material?



Glossy material (BRDF)



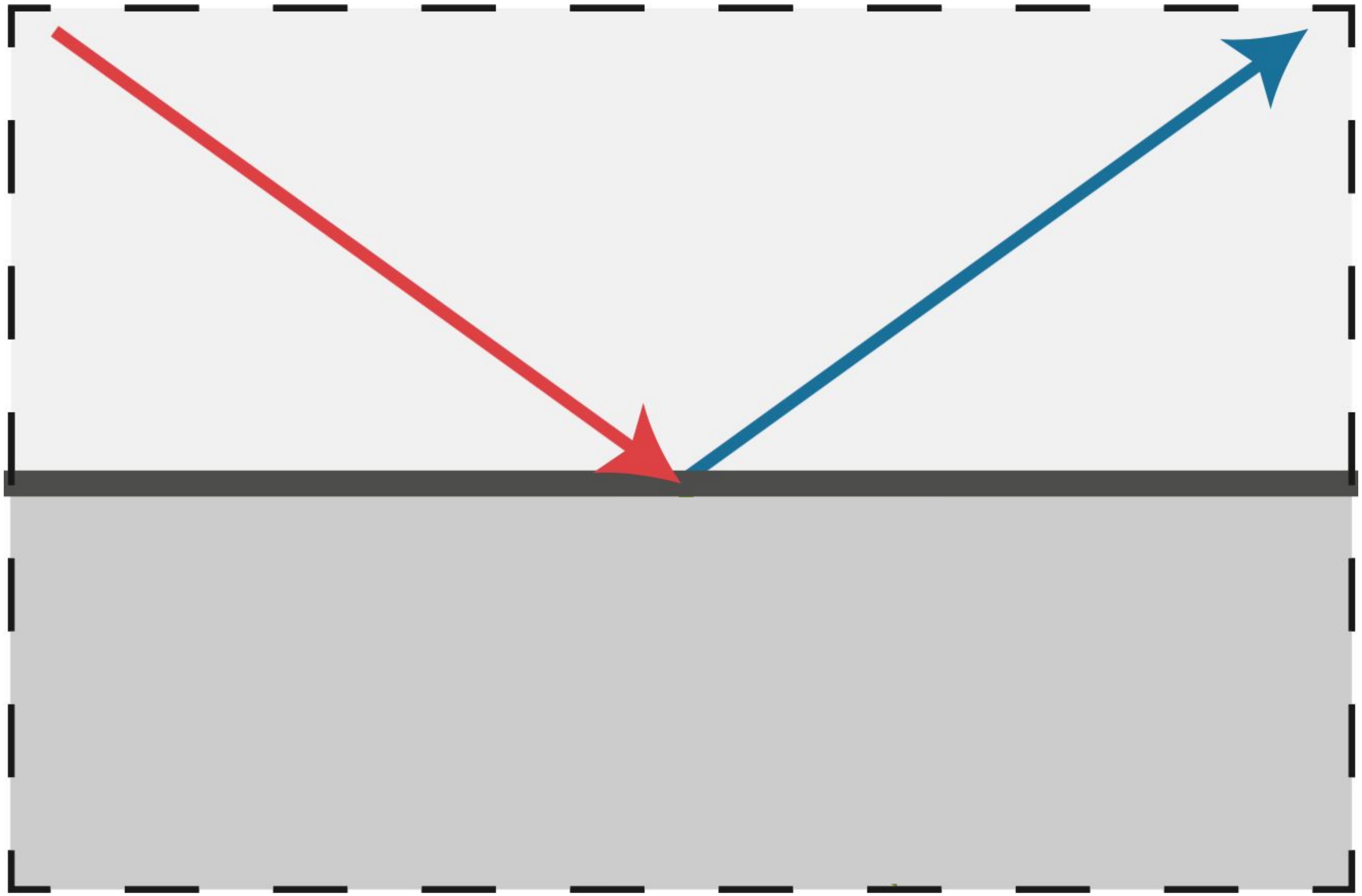
Rough Copper



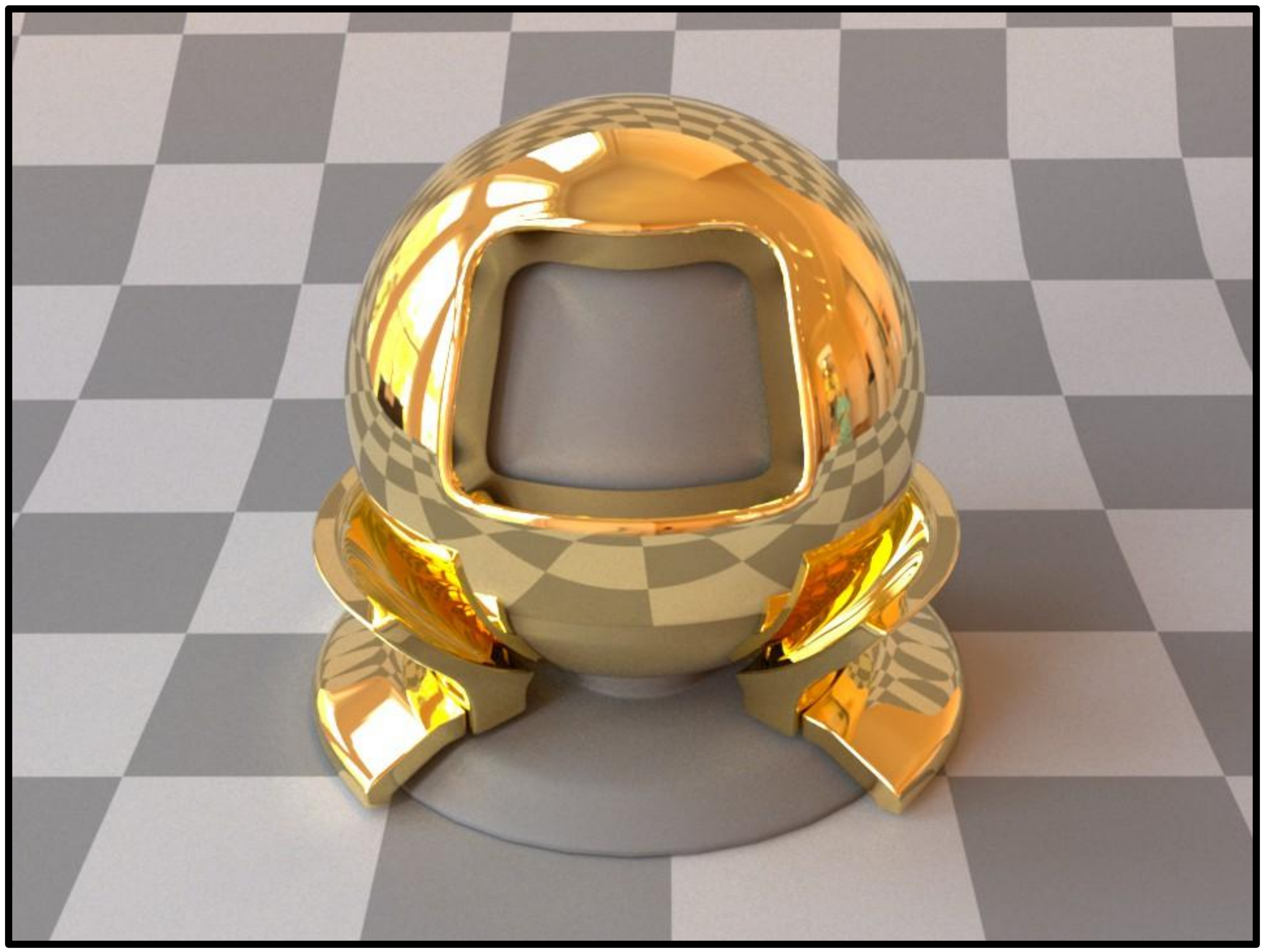
Brushed Aluminum

[Mitsuba renderer, Wenzel Jakob, 2010]

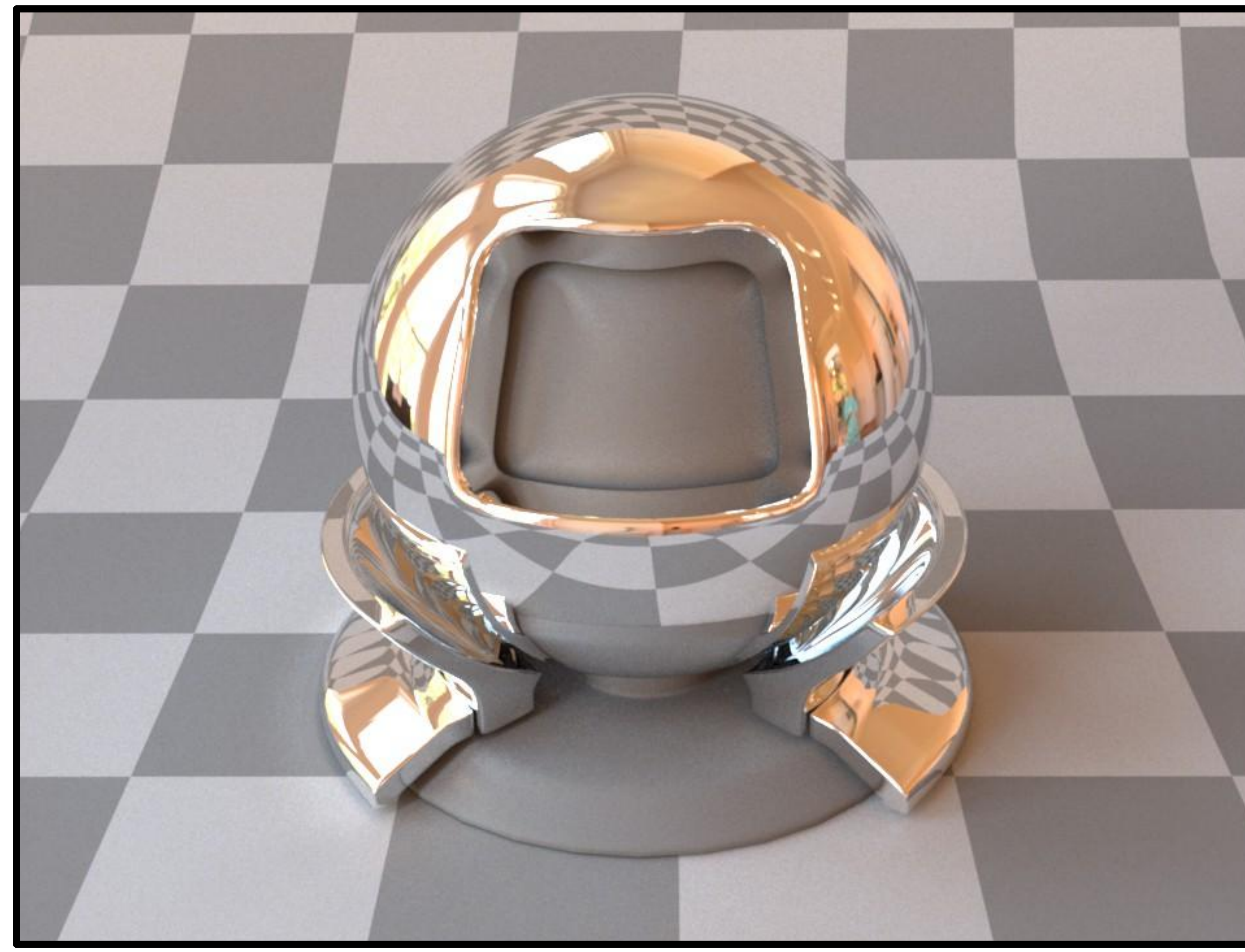
What is this material?



Ideal reflective material (BRDF)



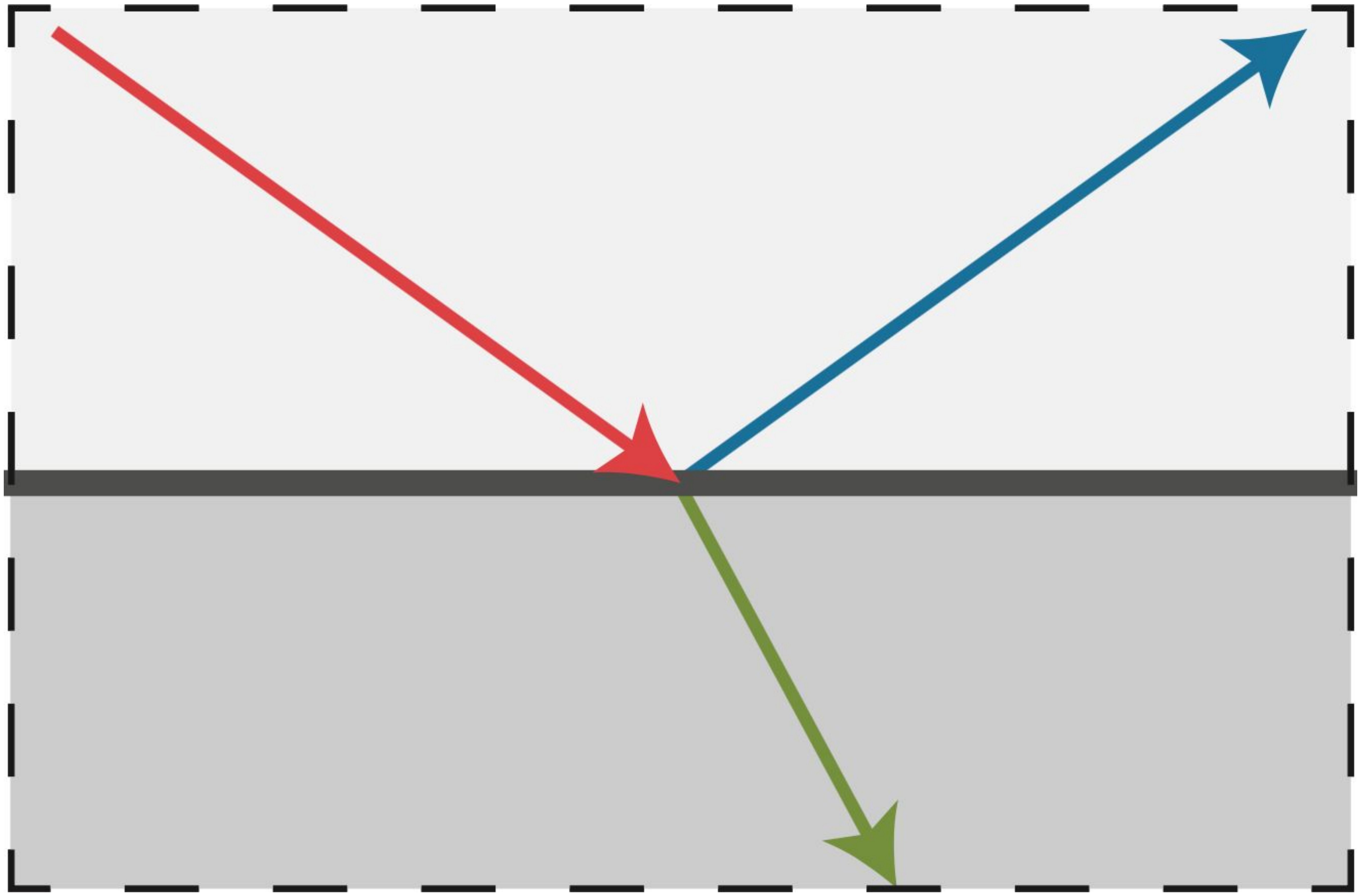
Gold



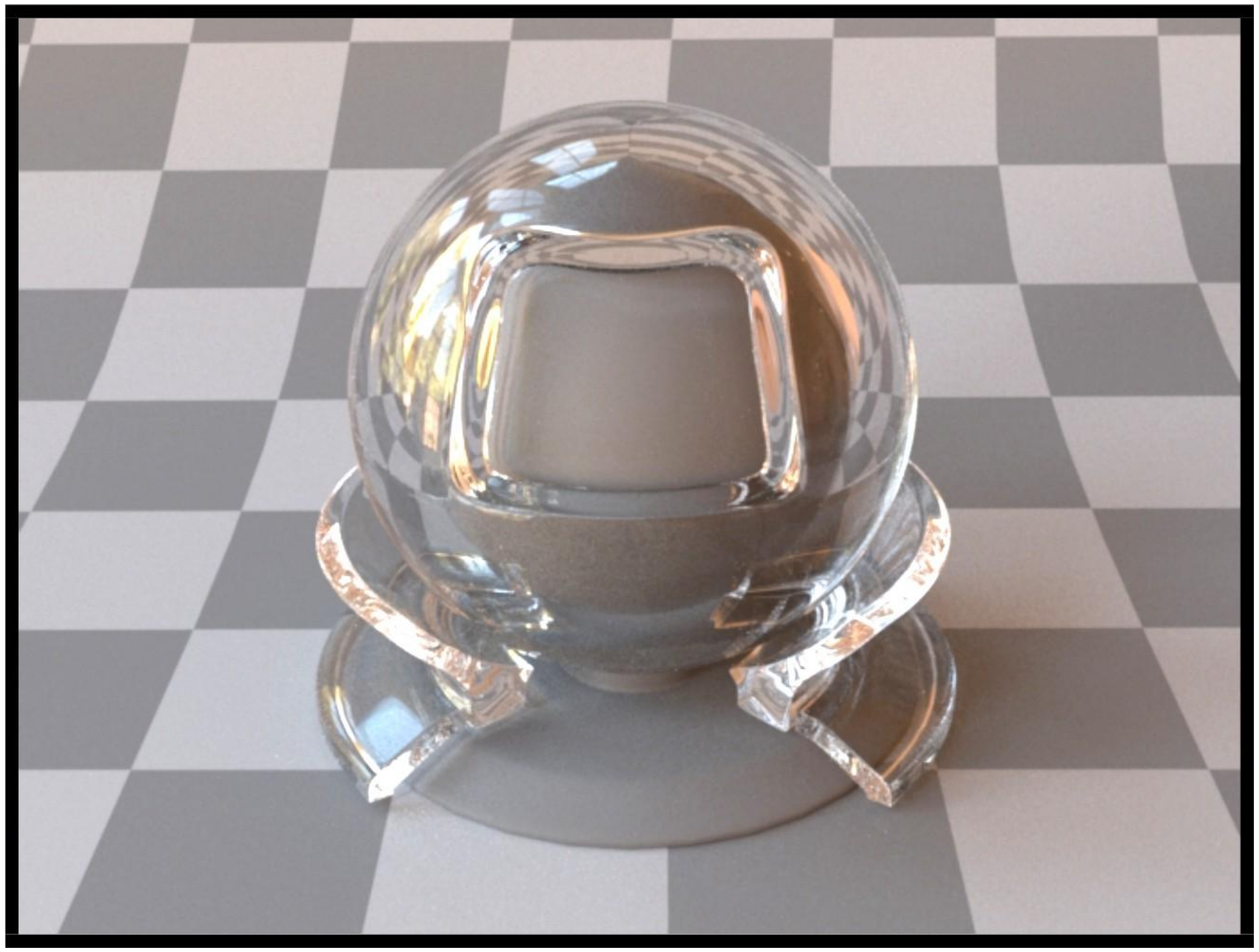
Aluminum

[Mitsuba renderer, Wenzel Jakob, 2010]

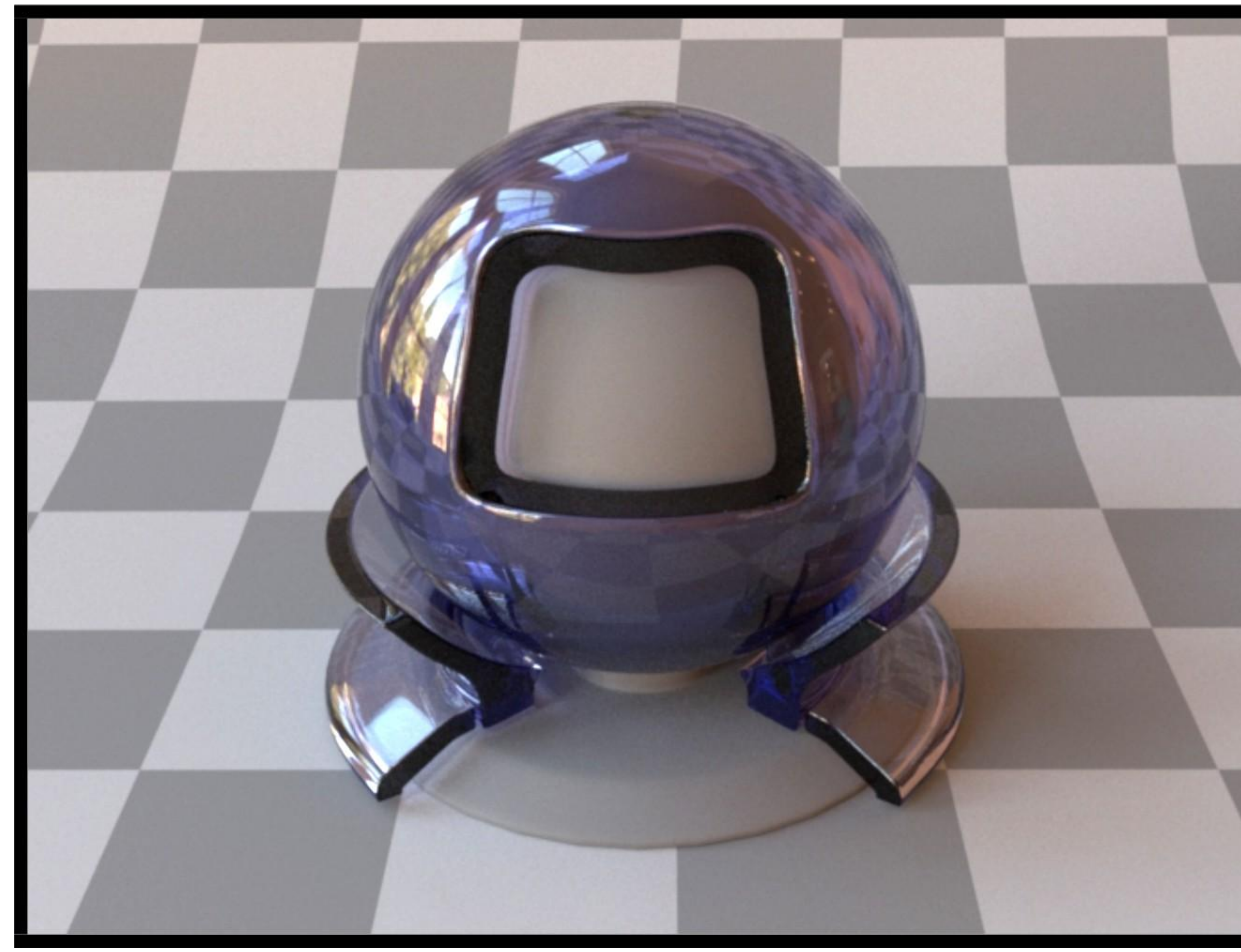
What is this material?



Ideal reflective / refractive material (BSDF*)



Air ⟷ plastic interface

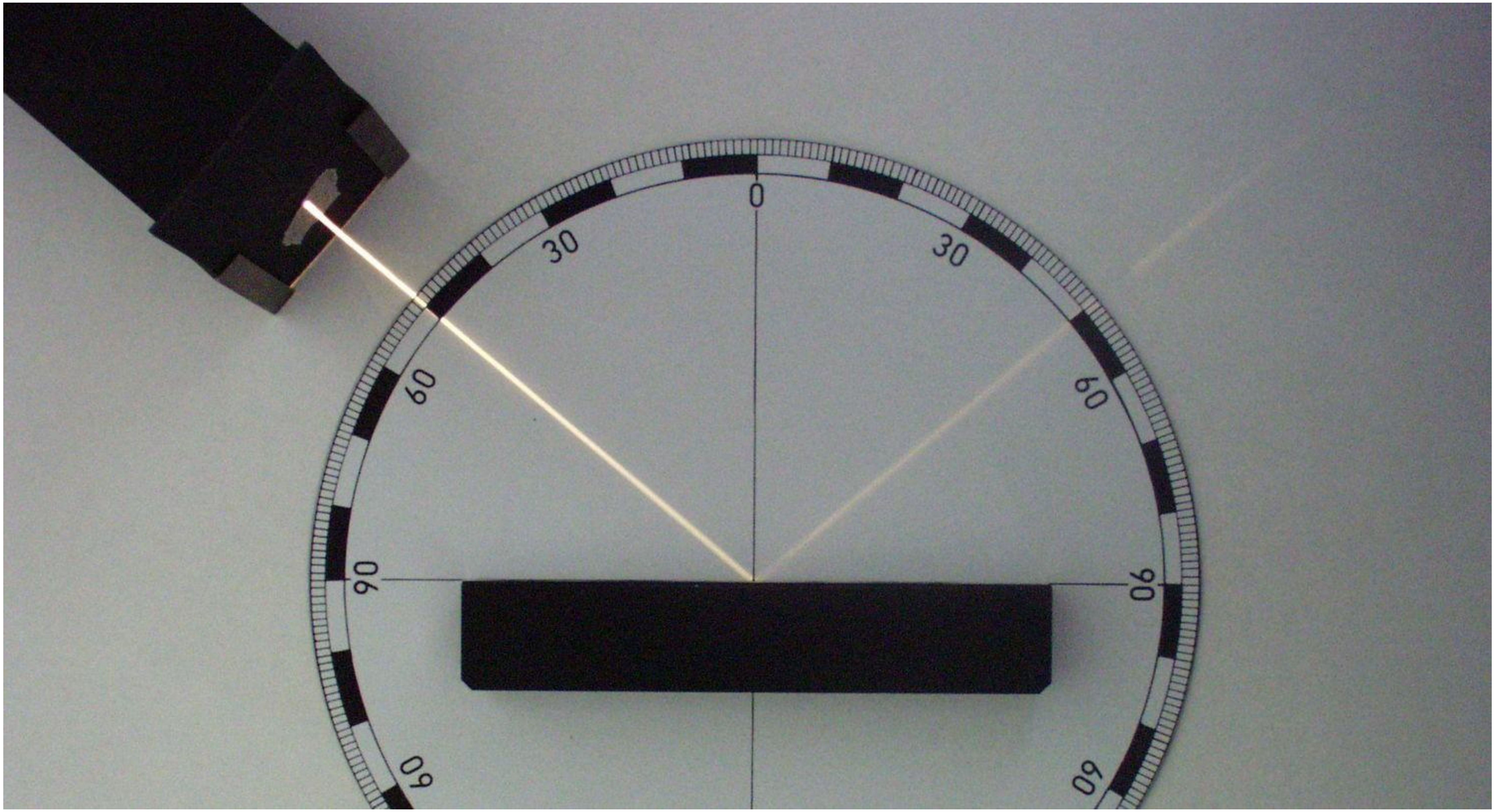


Air ⟷ glass interface
(with absorption)

[Mitsuba renderer, Wenzel Jakob, 2010]

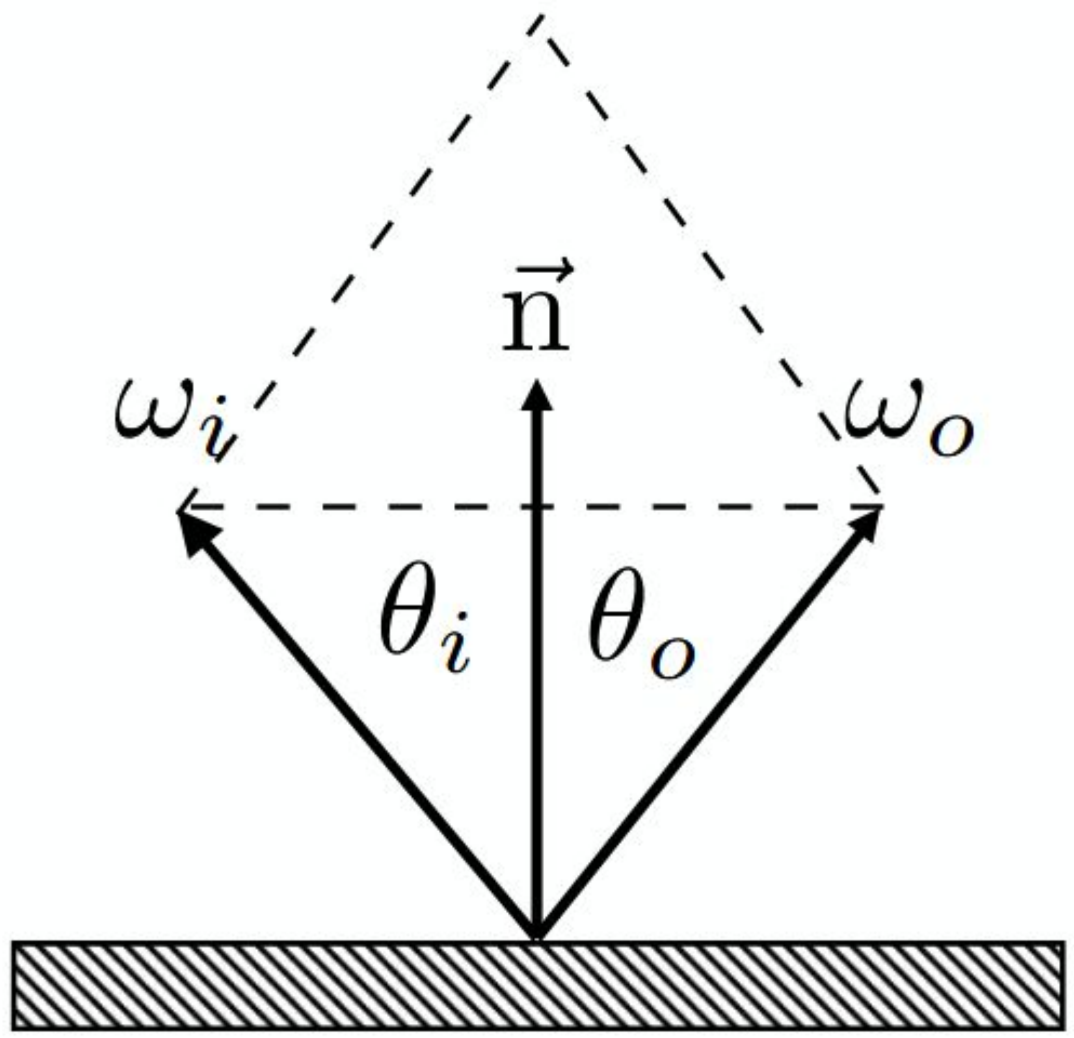
Ideal Reflection and Refraction

Perfect Specular Reflection

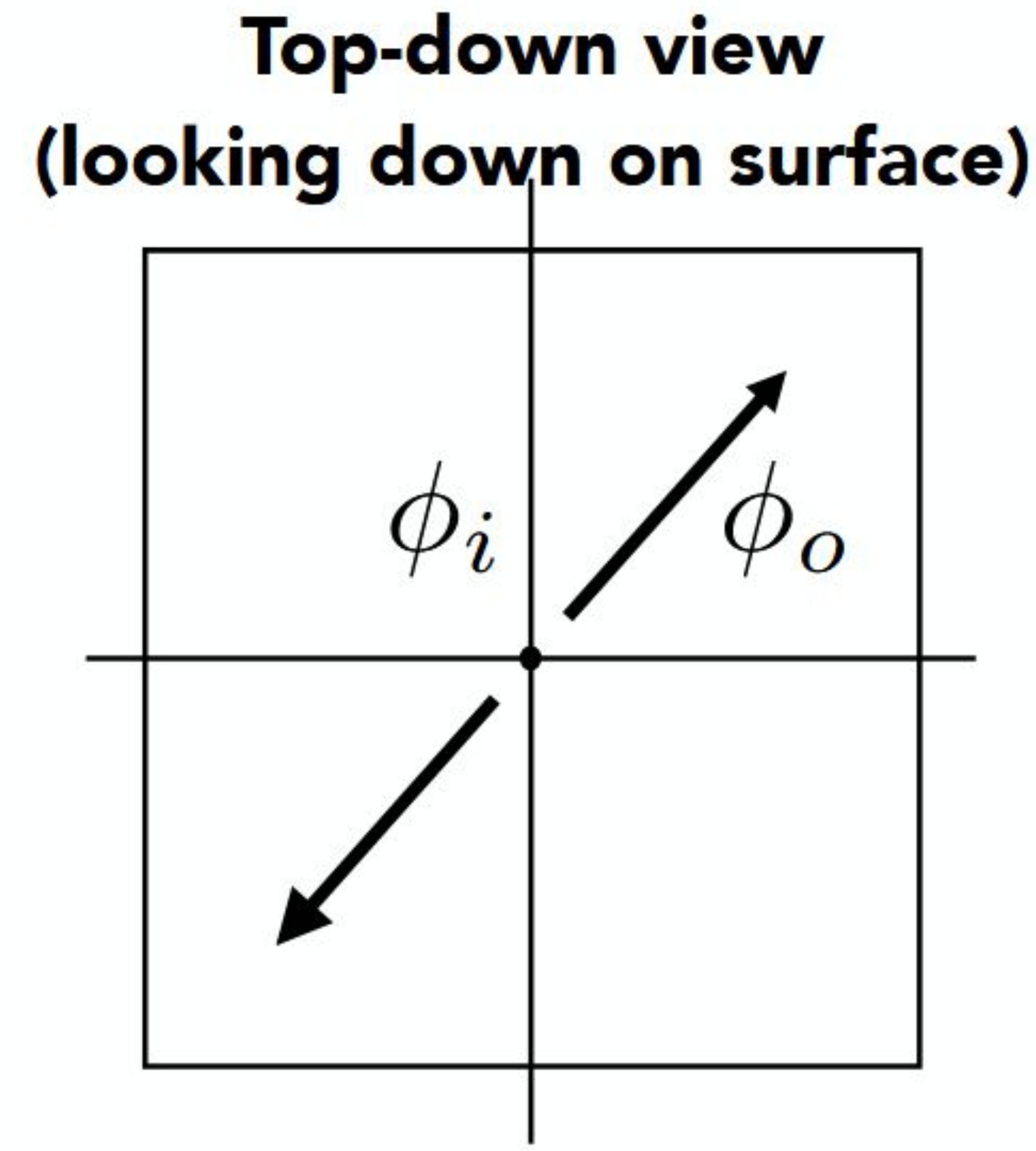


[Zátonyi Sándor]

Perfect Specular Reflection



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

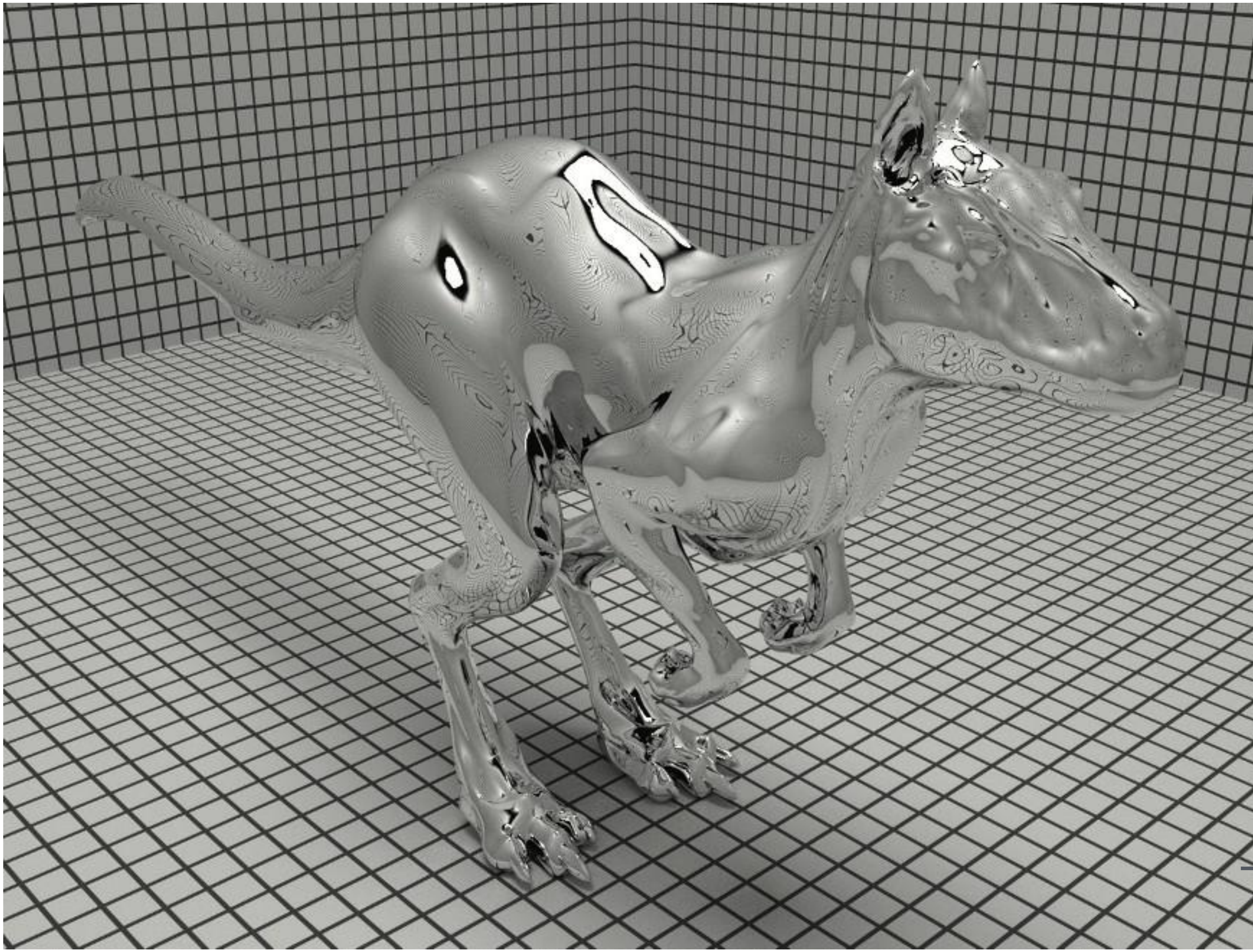


$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Perfect Specular Reflection BRDF



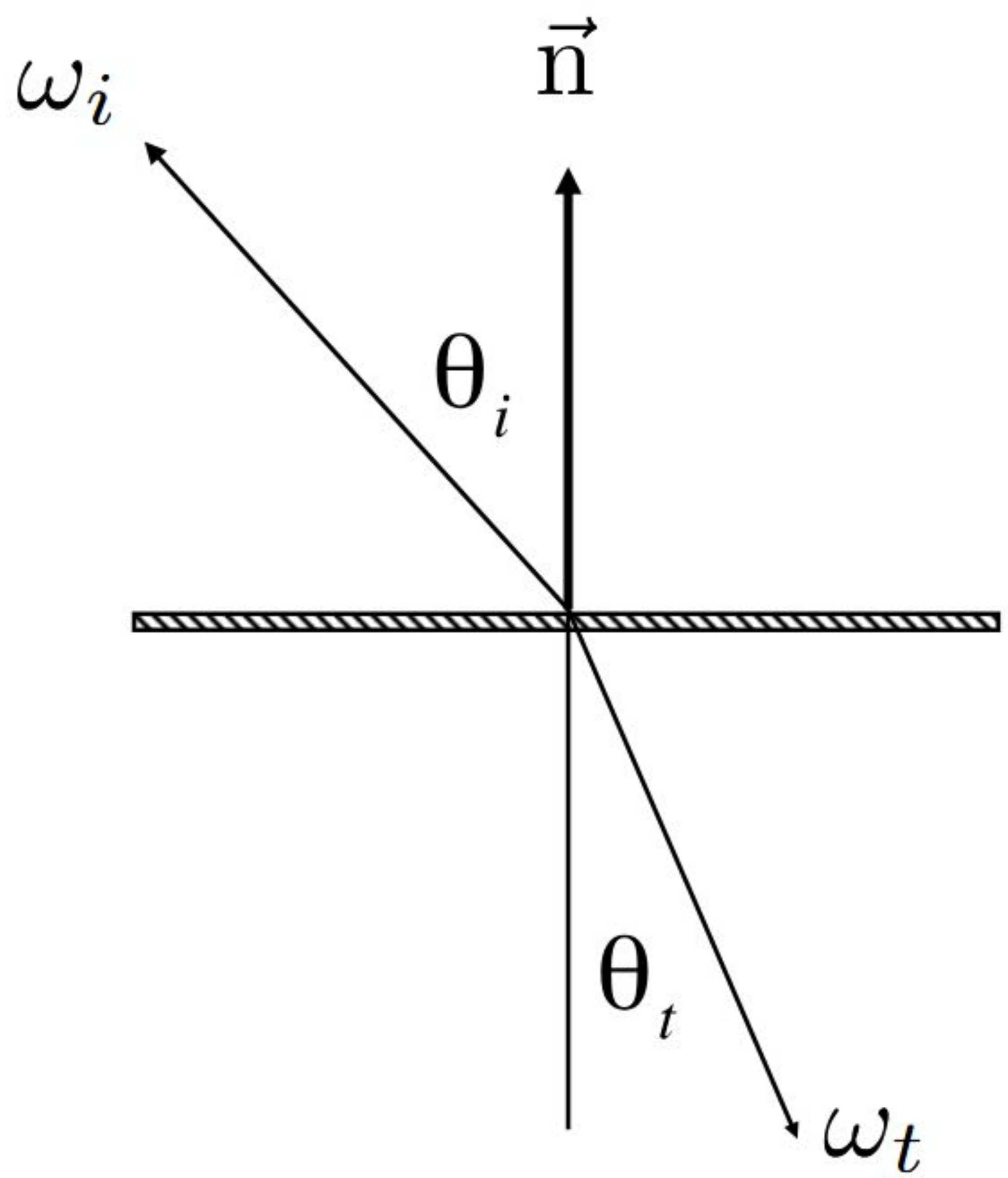
PBRT

Specular Refraction

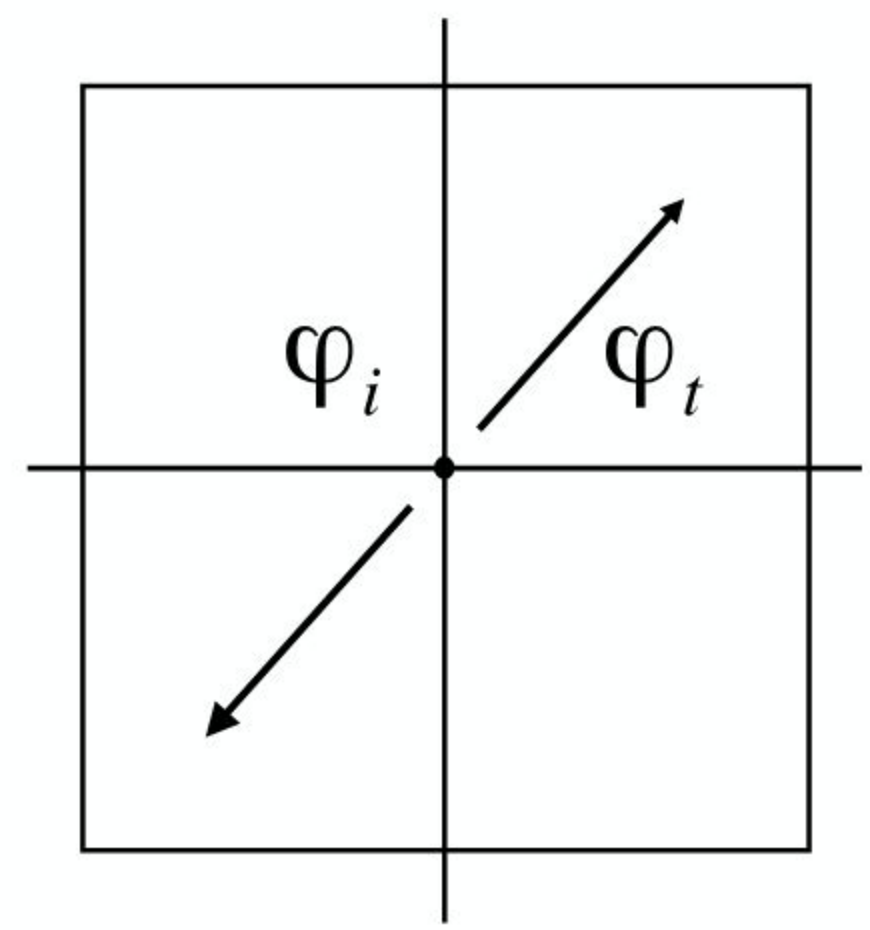
In addition to reflecting off surface, light may be transmitted through surface.

Light refracts when it enters a new medium.

Snell's Law



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

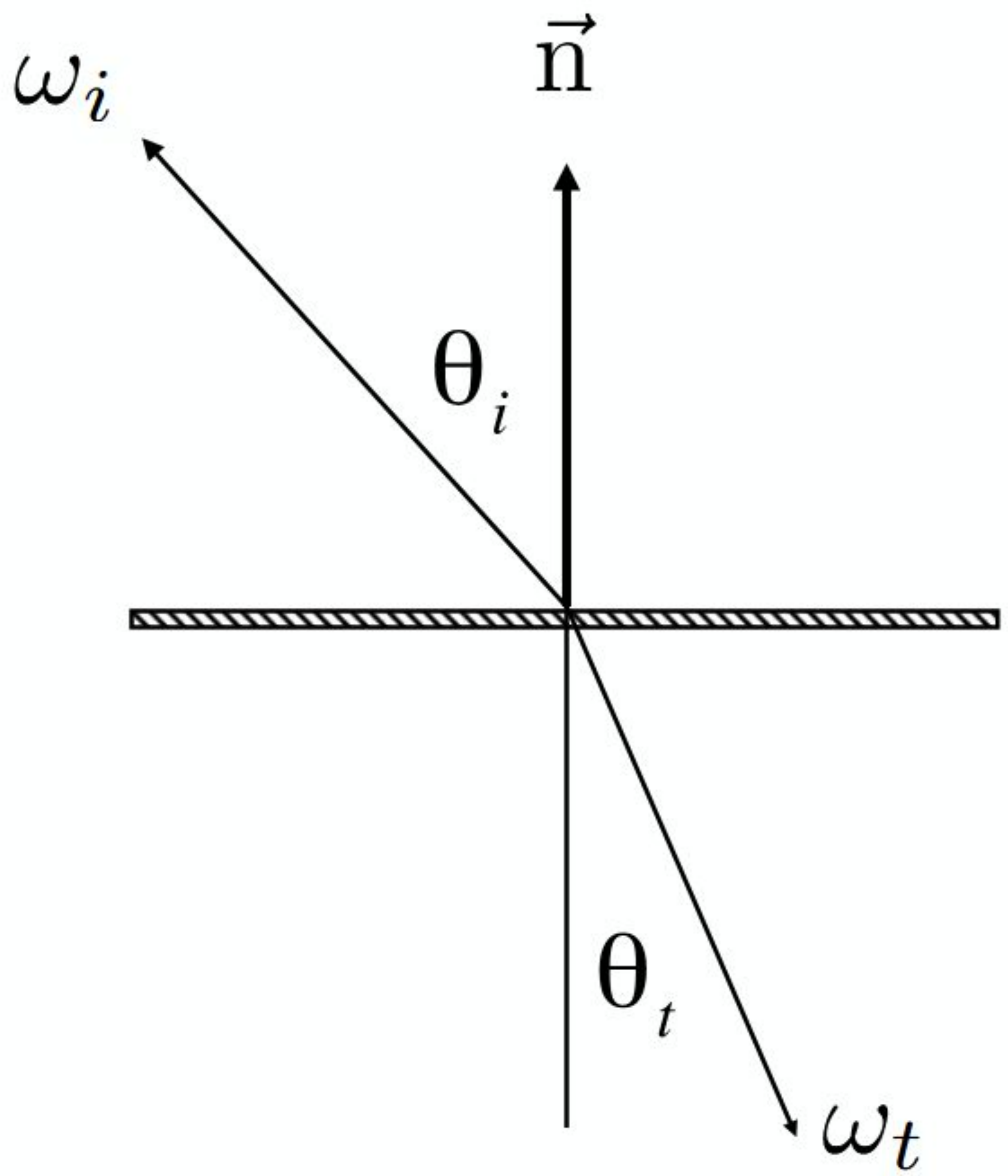


$$\varphi_t = \varphi_i \pm \pi$$

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



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

$$\begin{aligned}\cos\theta_t &= \sqrt{1-\sin^2\theta_t} \\ &= \sqrt{1-\left(\frac{\eta_i}{\eta_t}\right)^2 \sin^2\theta_i} \\ &= \sqrt{1-\left(\frac{\eta_i}{\eta_t}\right)^2 (1-\cos^2\theta_i)}\end{aligned}$$

Total internal reflection:

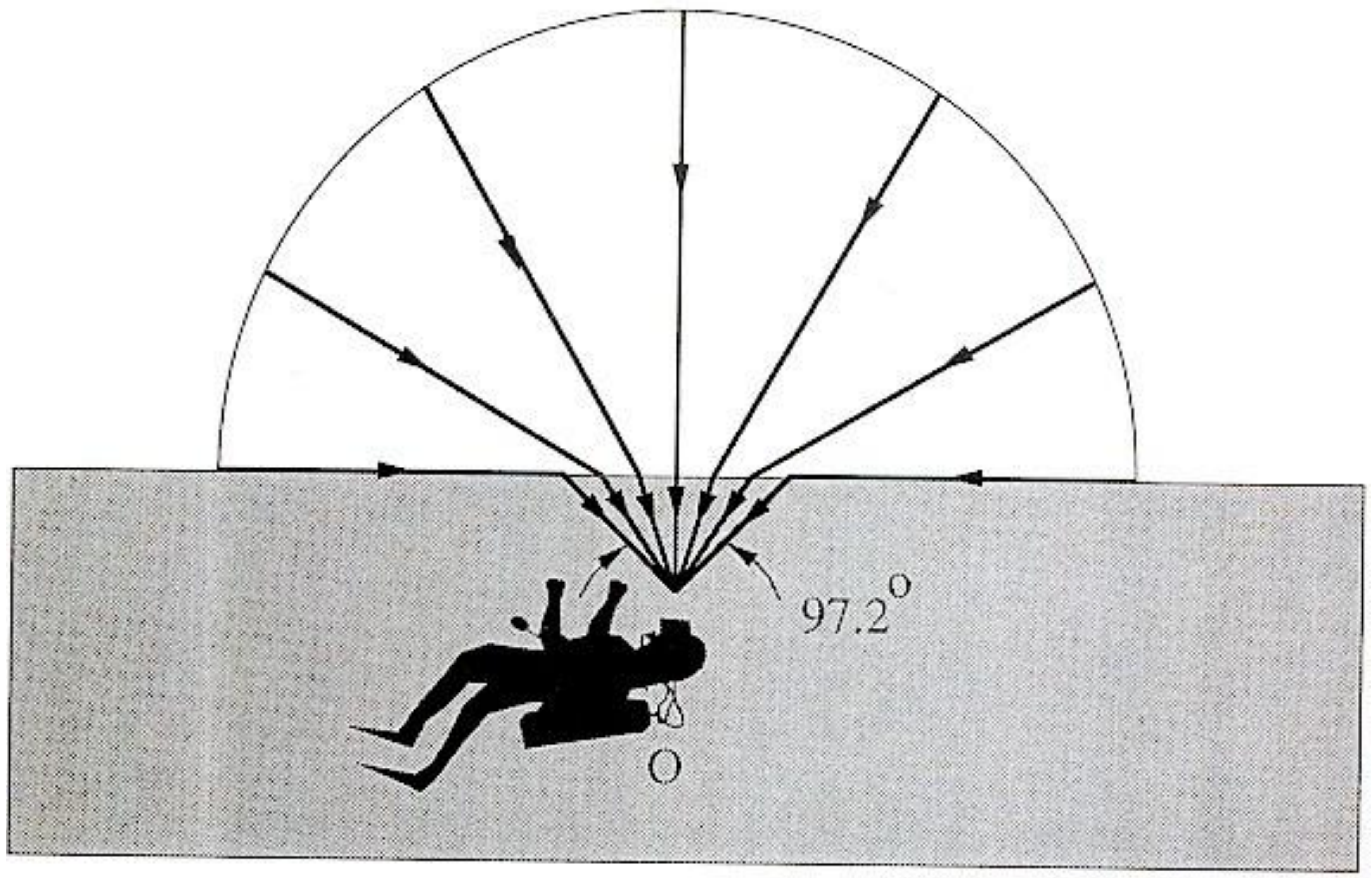
$$1-\left(\frac{\eta_i}{\eta_t}\right)^2 (1-\cos^2\theta_i) < 0$$

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.

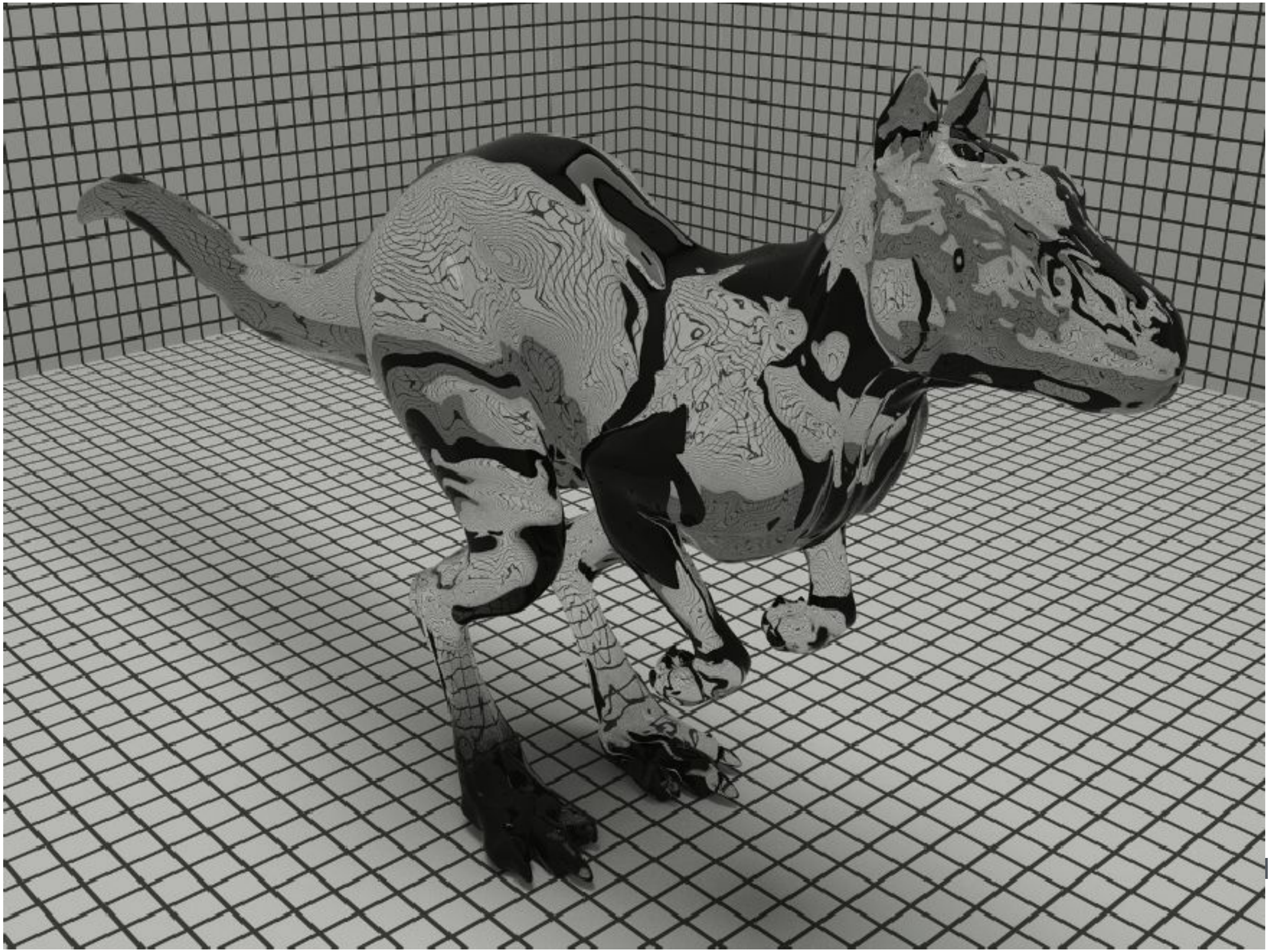
Snell's Window

Total internal reflection



[Livingston and Lynch]

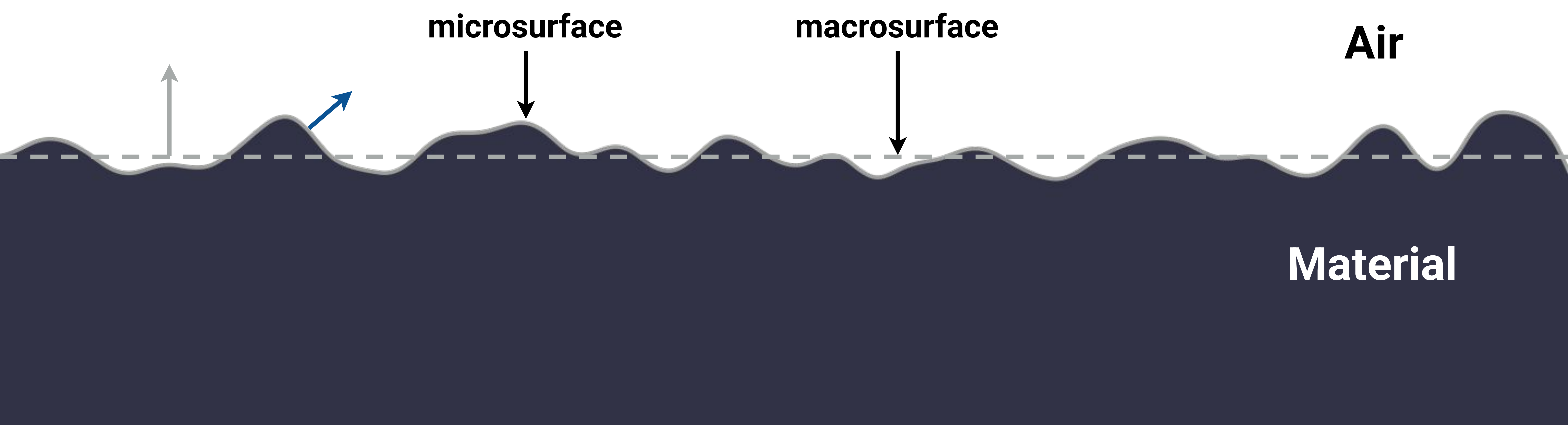
Fresnel Reflection & Transmission



Microfacet Material Model

Microfacet Reflection

Microfacet Theory



Microfacet BRDF

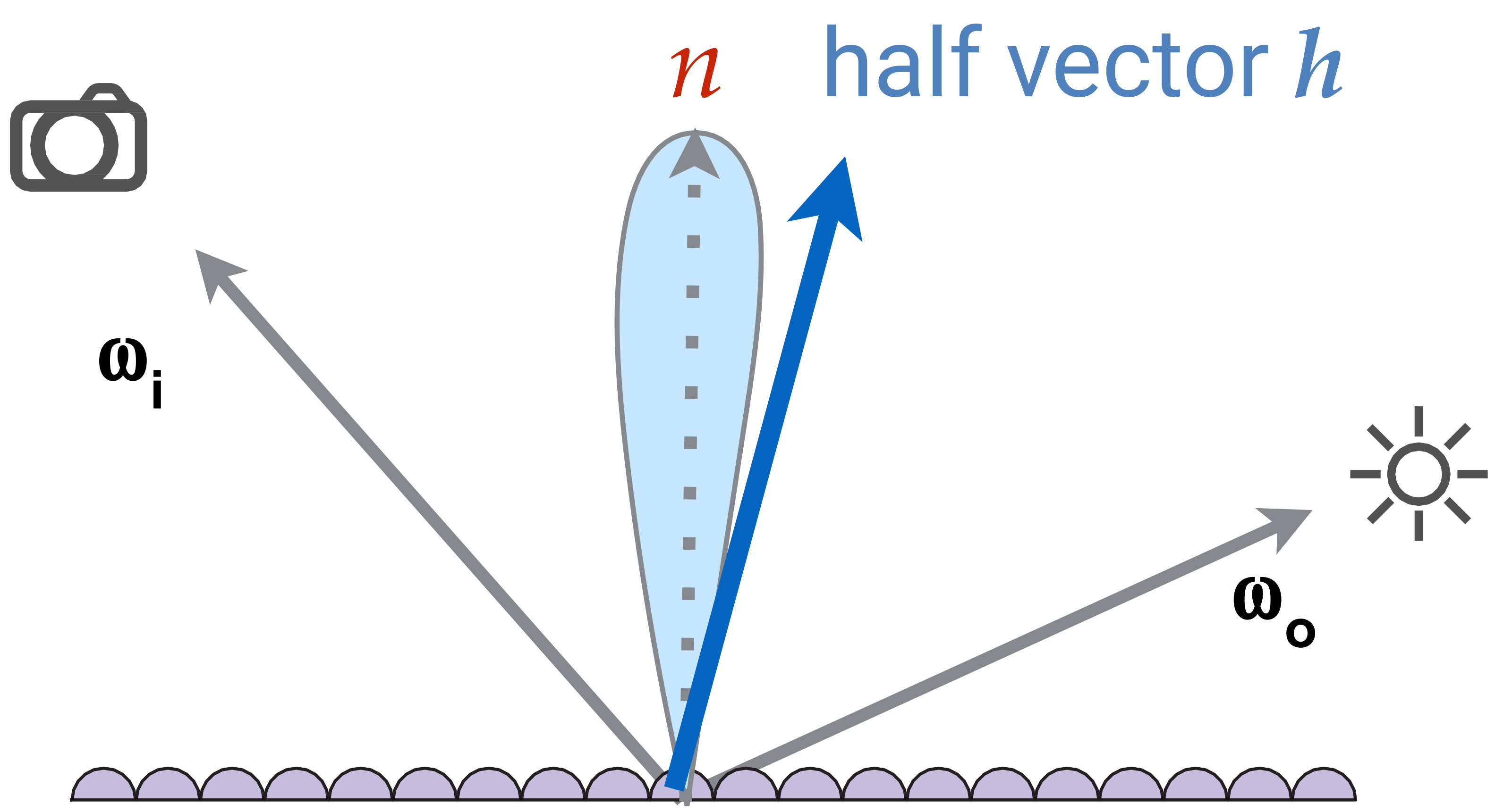
- **Key idea:** The distribution of microfacet normals across a surface describes how smooth or rough a surface is.

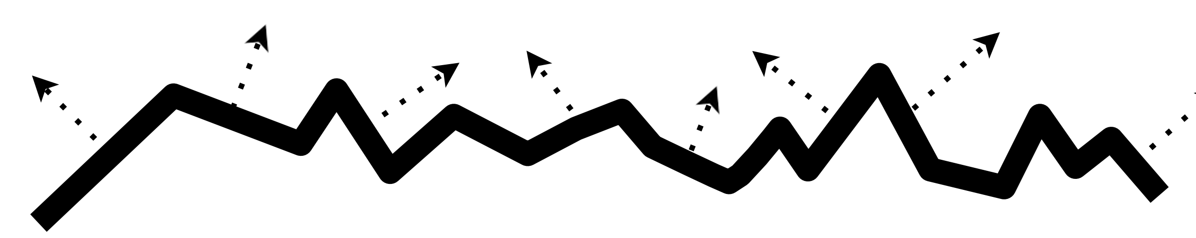
Microfacet BRDF

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

Microfacet BRDF

- **What kind of microfacets reflect ω_i to ω_o?**
  (hint: microfacets are just tiny mirrors)





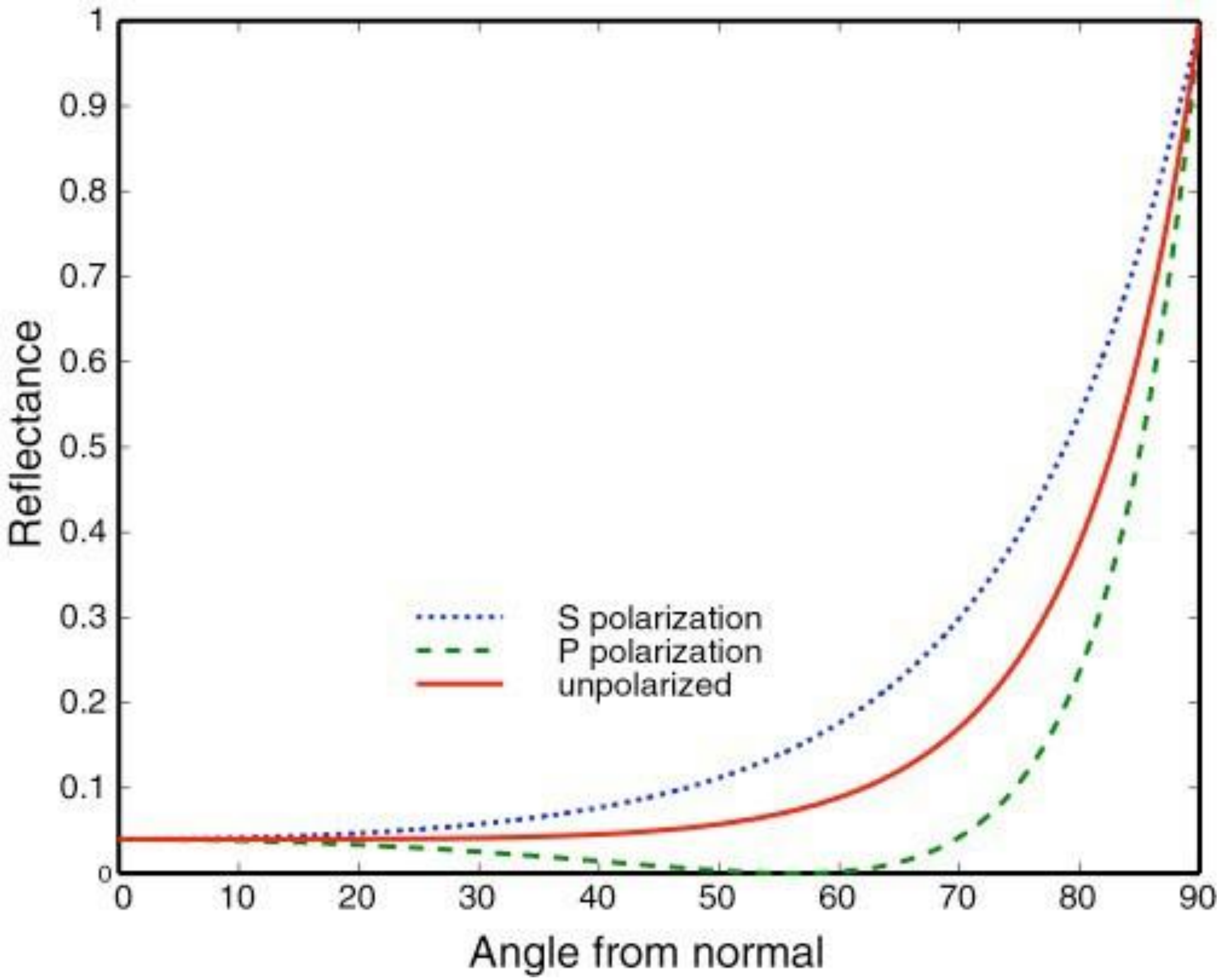
Fresnel Reflection Term

Reflectance depends on incident angle (and polarization of light)

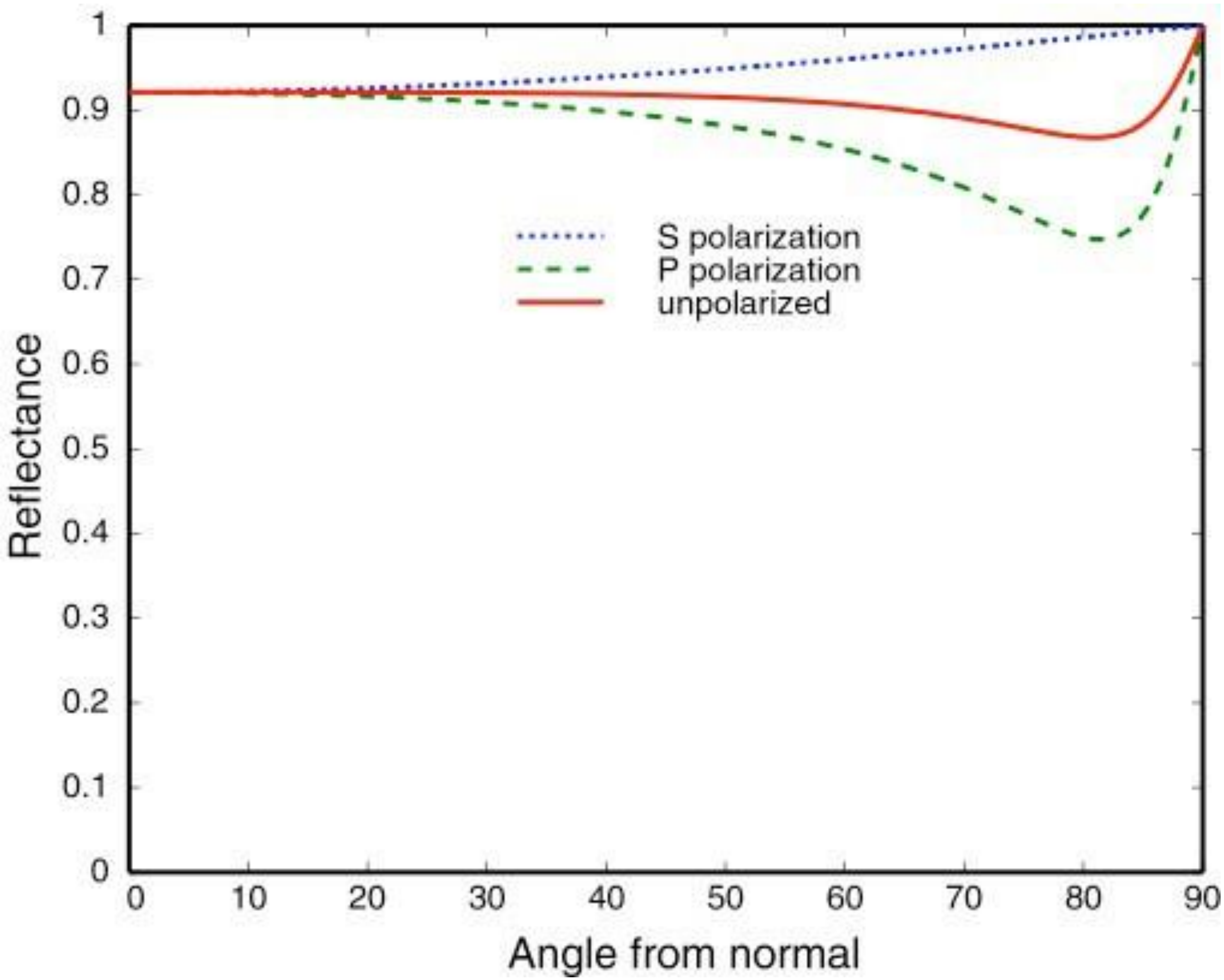
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

Fresnel Term (Dielectric, η =1.5)



Fresnel Term for a Conductor (metal)



Microfacet BRDF: Examples

[Autodesk Fusion 360]

Anisotropic BRDFs

Isotropic vs Anisotropic Reflection

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

Inside an elevator

Isotropic vs Anisotropic Reflection

Isotropic

Anisotropic

Anisotropic BRDF: Brushed Metal

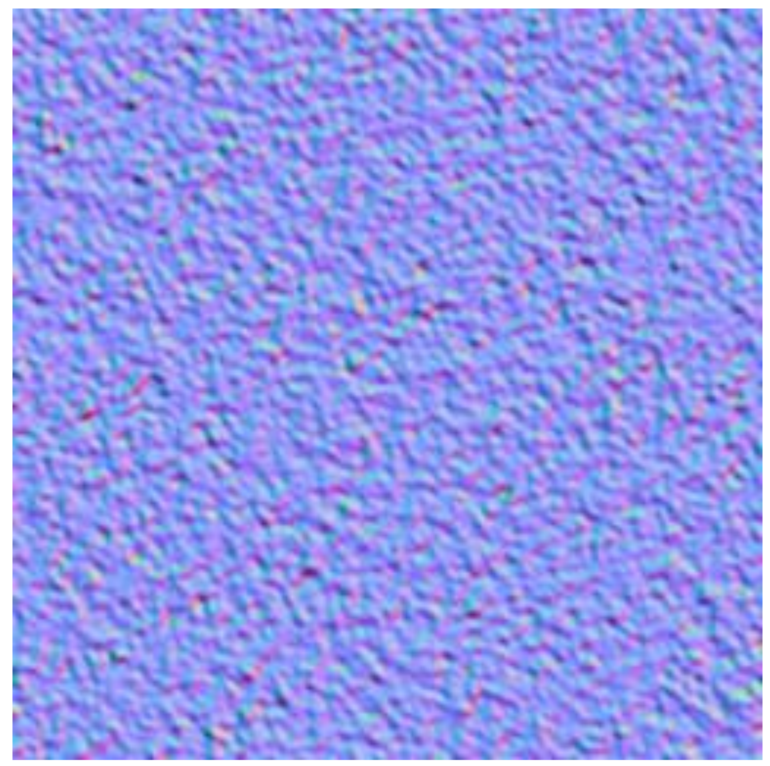
- How is the pan brushed?

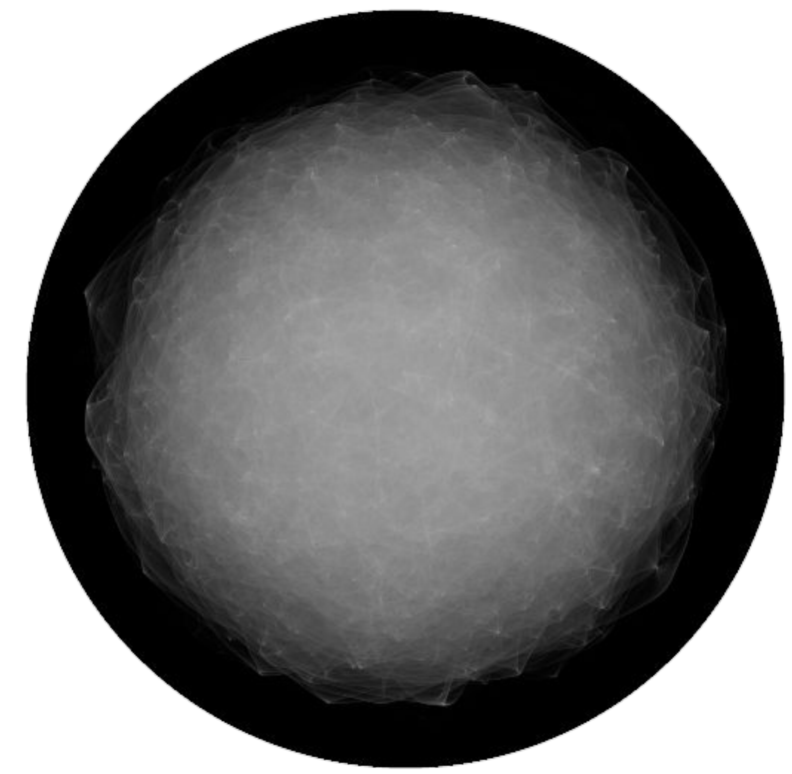
[VRay renderer]

Isotropic / Anisotropic Materials (BRDFs)

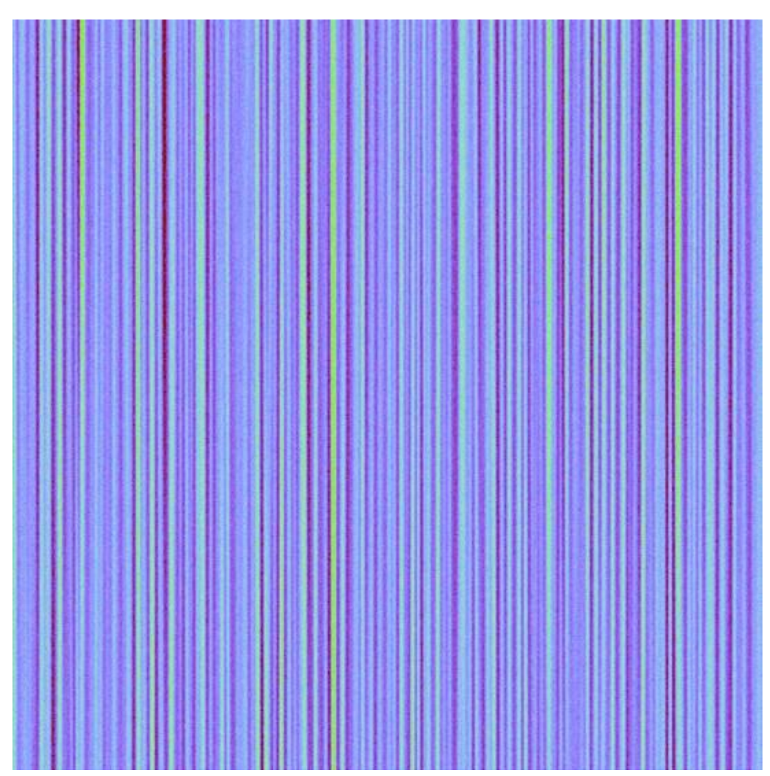
- **Key: directionality of underlying surface**

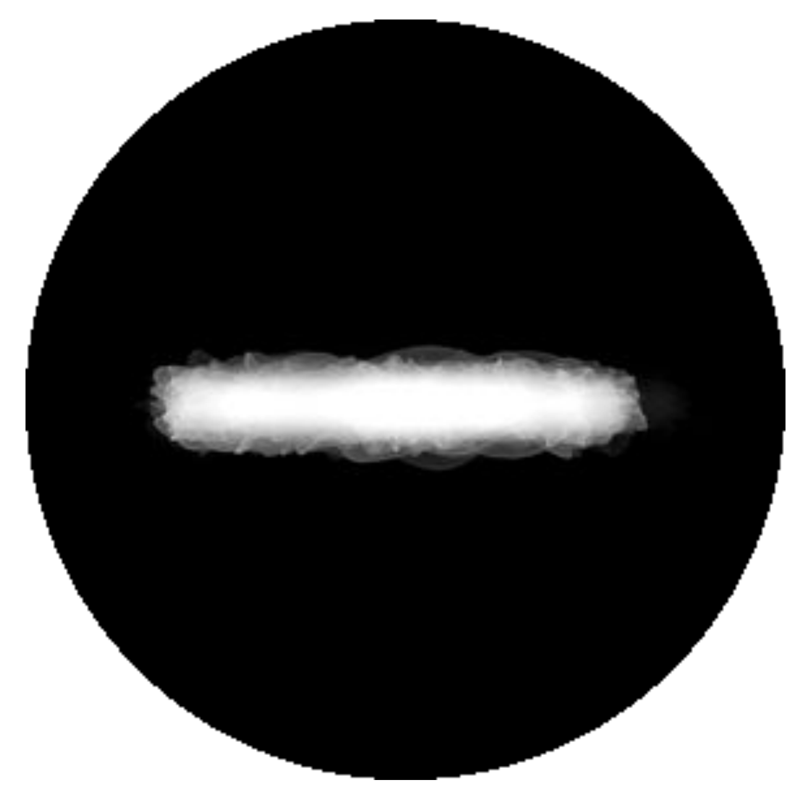
Isotropic





Anisotropic





Surface (normals)

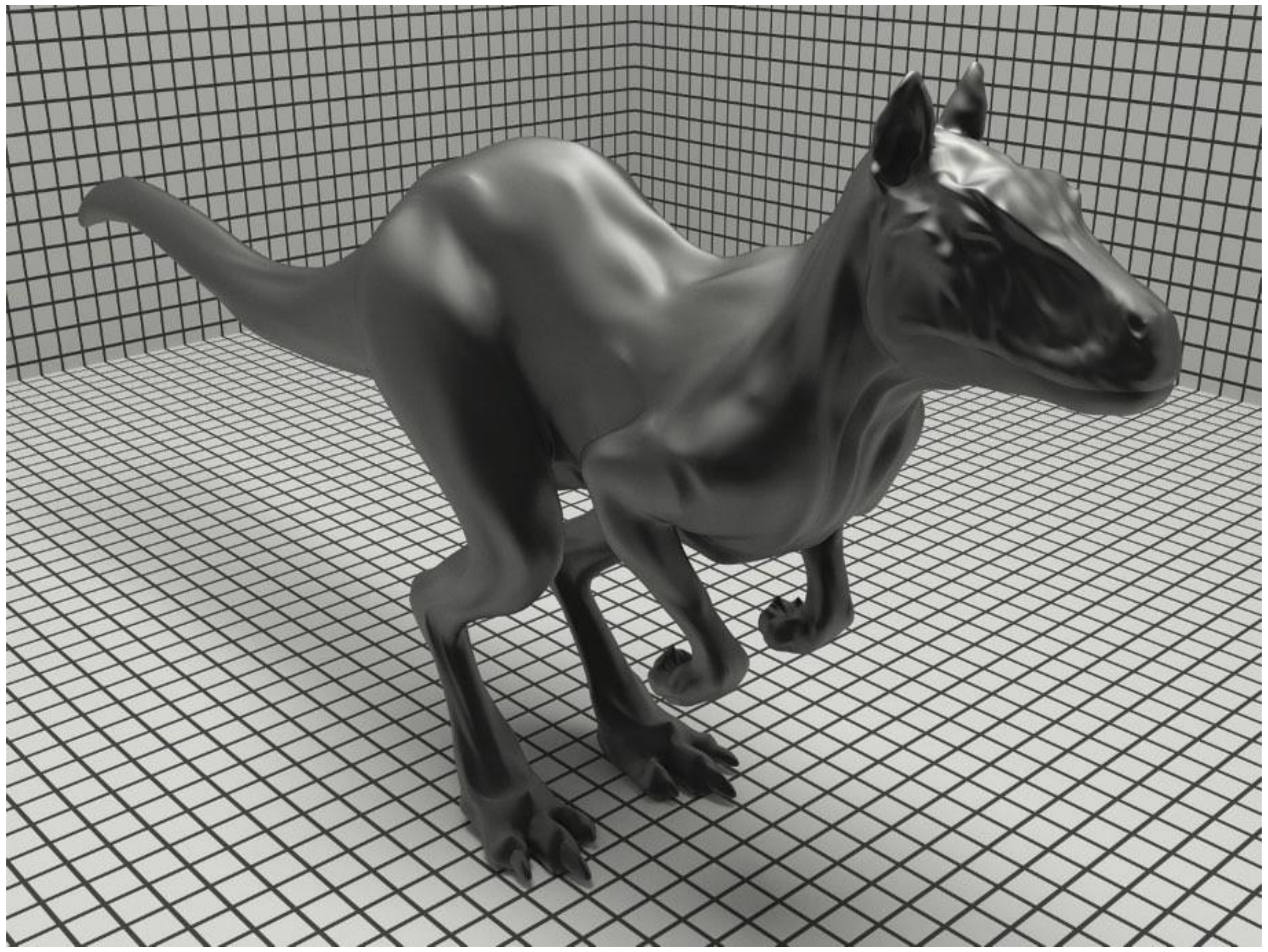
BRDF (fixed ω_i varying ω_o)

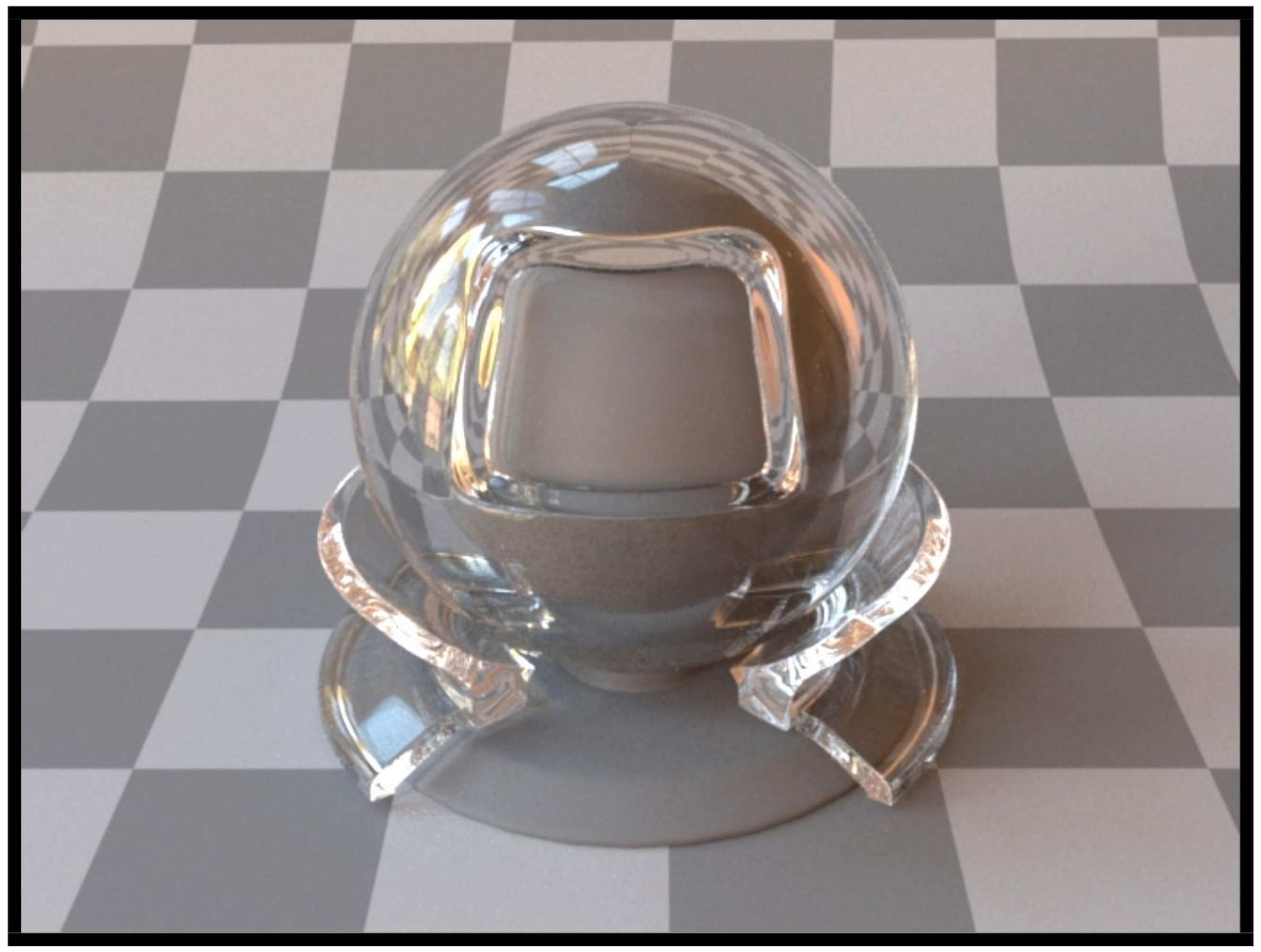
Isotropic BRDFs

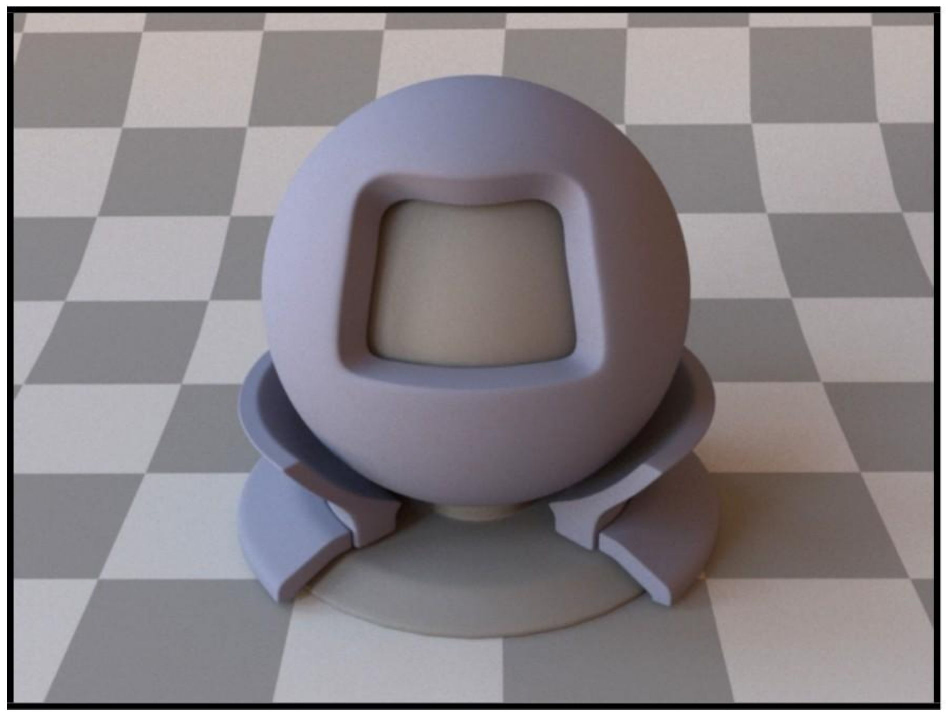
Reflection independent of azimuthal angle ϕ

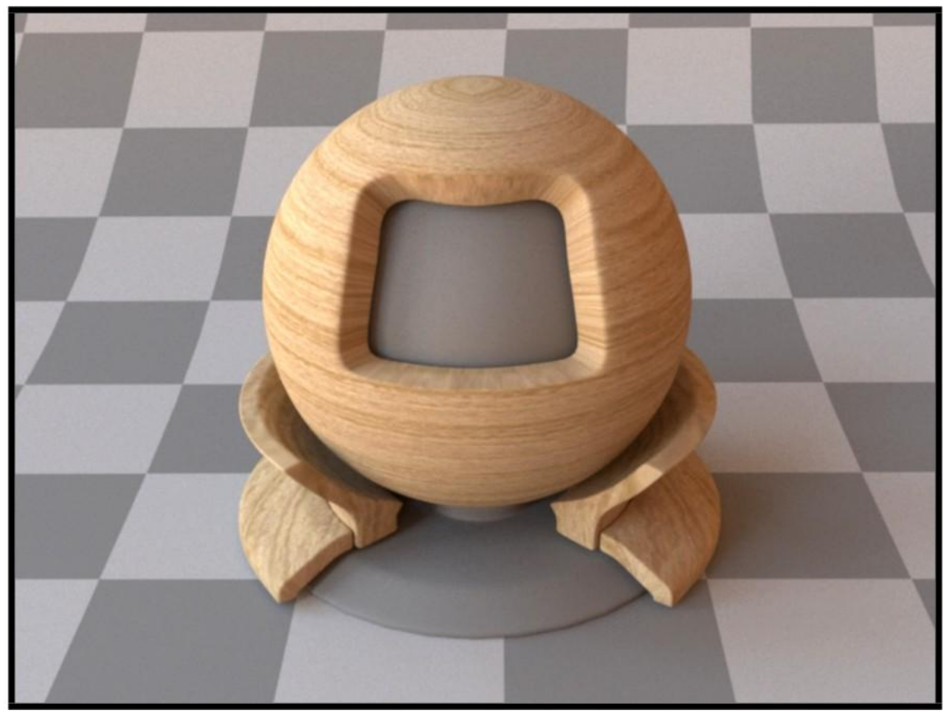
$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = f_r(\theta_i, \theta_r, \phi_r - \phi_i)$$

Results from surface microstructure
that lacks directional structure







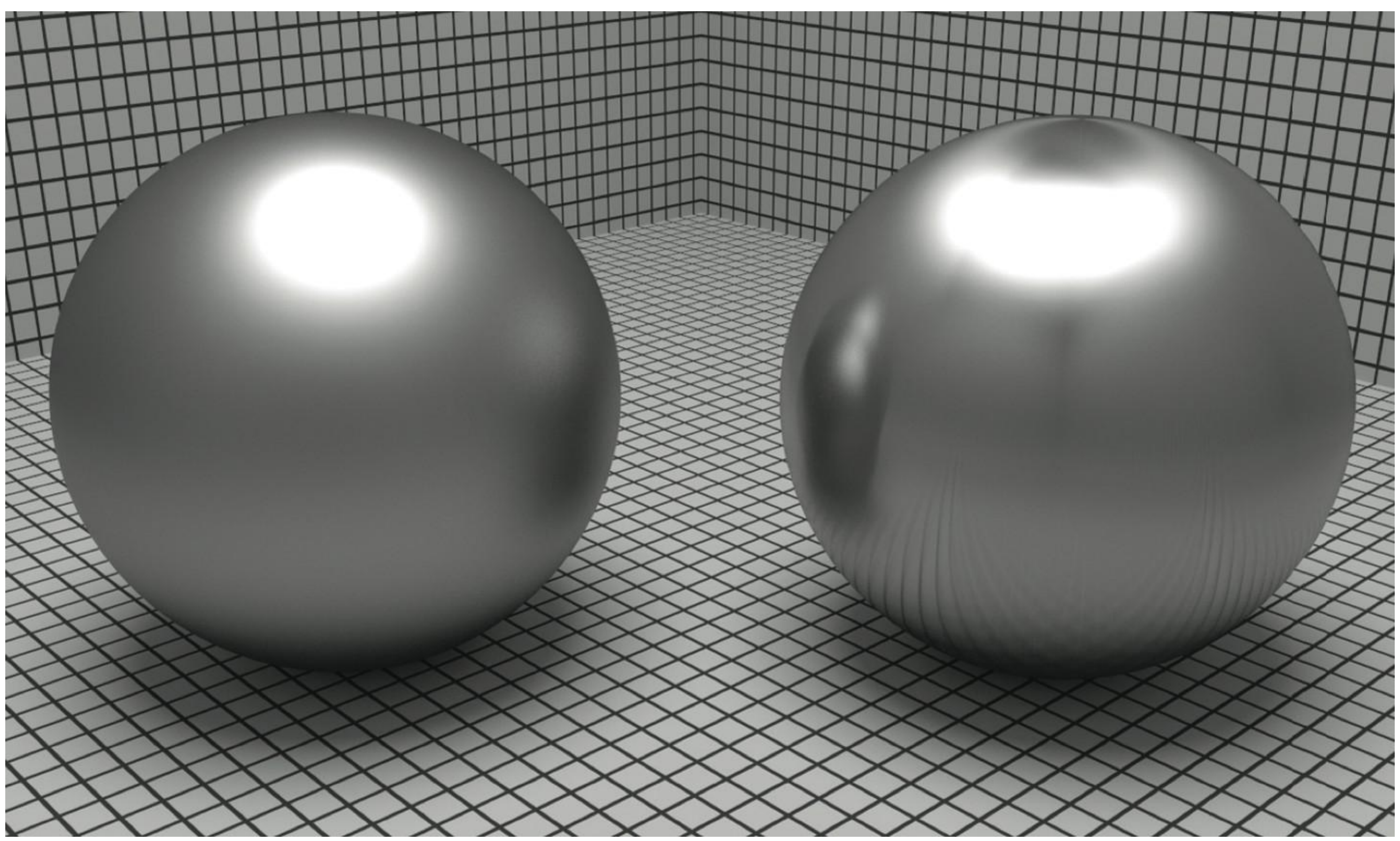


Anisotropic BRDFs

Reflection **dependent** 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

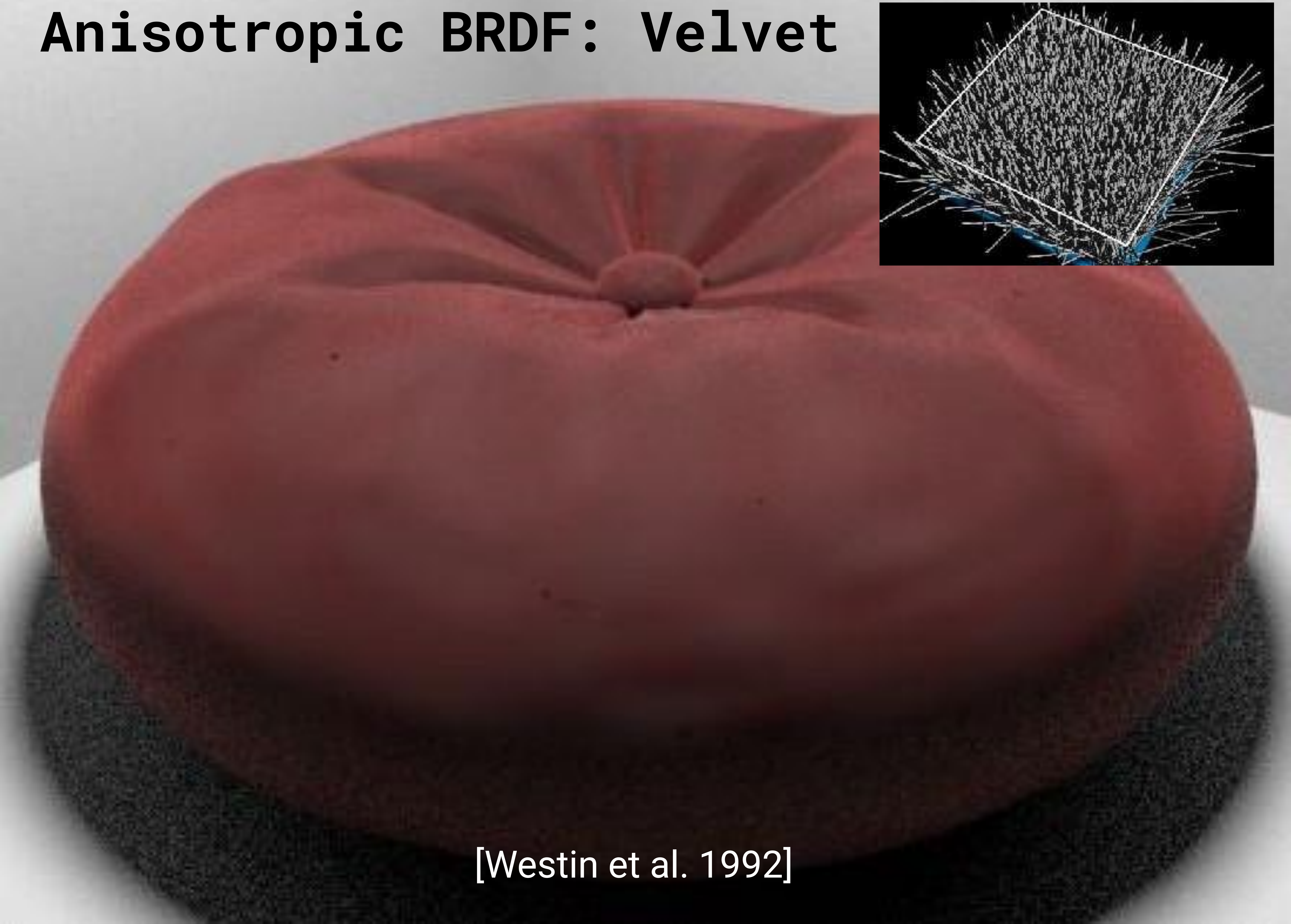


Lima

Anisotropic BRDF: Nylon

[Westin et al. 1992]

Anisotropic BRDF: Velvet



[Westin et al. 1992]

Sampling of Advanced Material Modeling

Detailed + Shiny Material

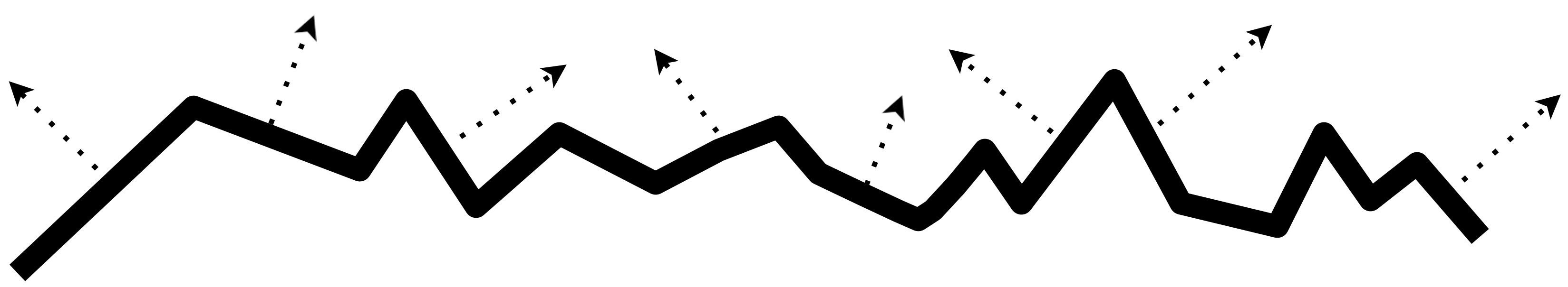
Microfacet Model

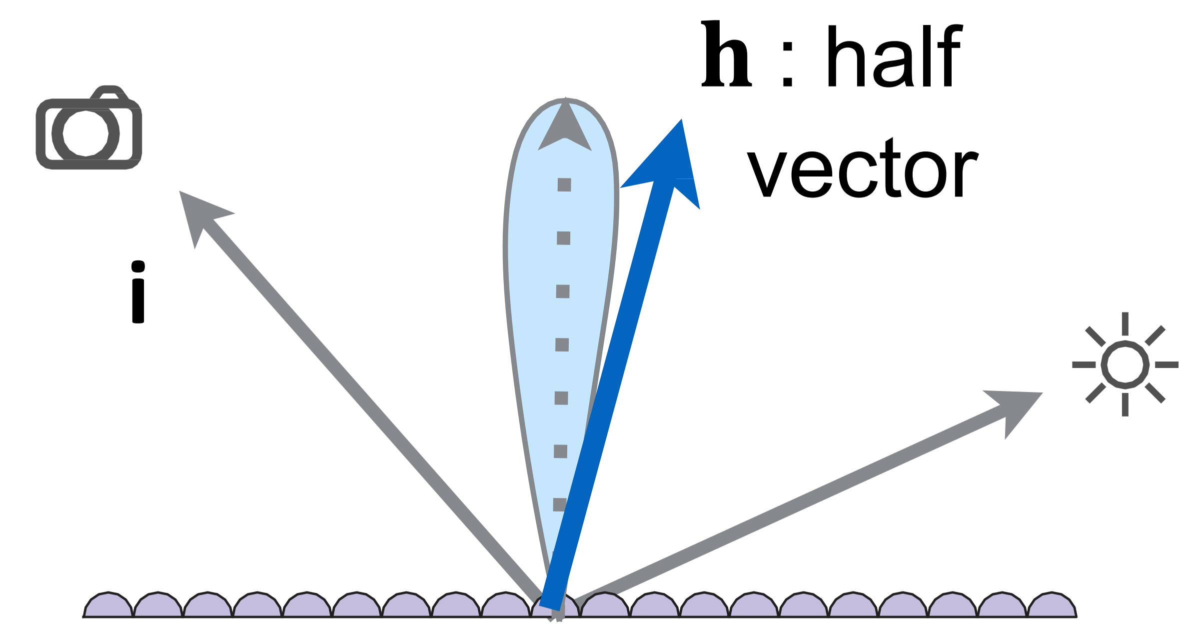
Why details?

Microfacet
model

Microfacet Model

Recap: Microfacet BRDF





Surface = Specular microfacets + statistical normals

Fresnel term

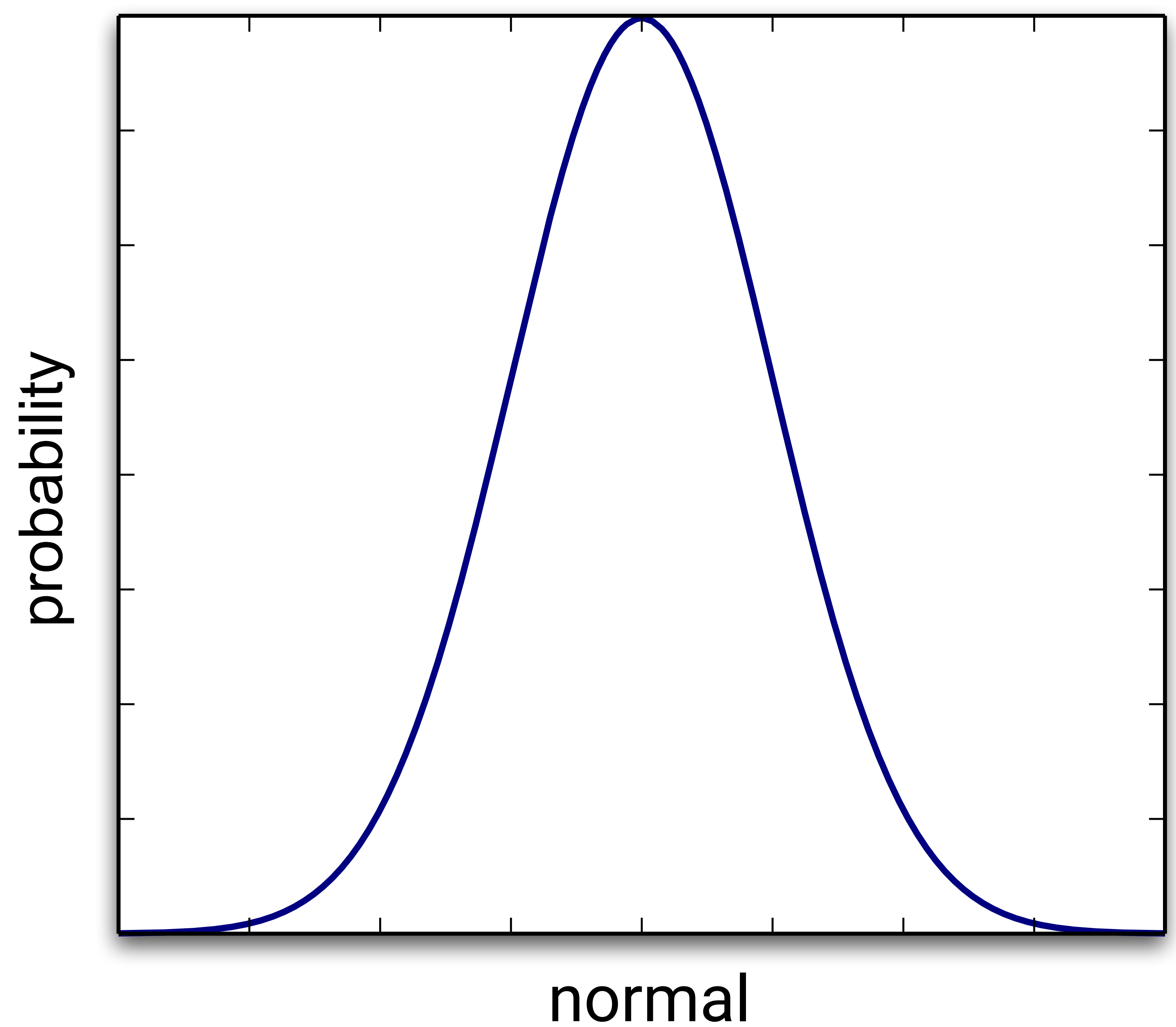
Shadow masking term

Normal Distribution function (NDF)

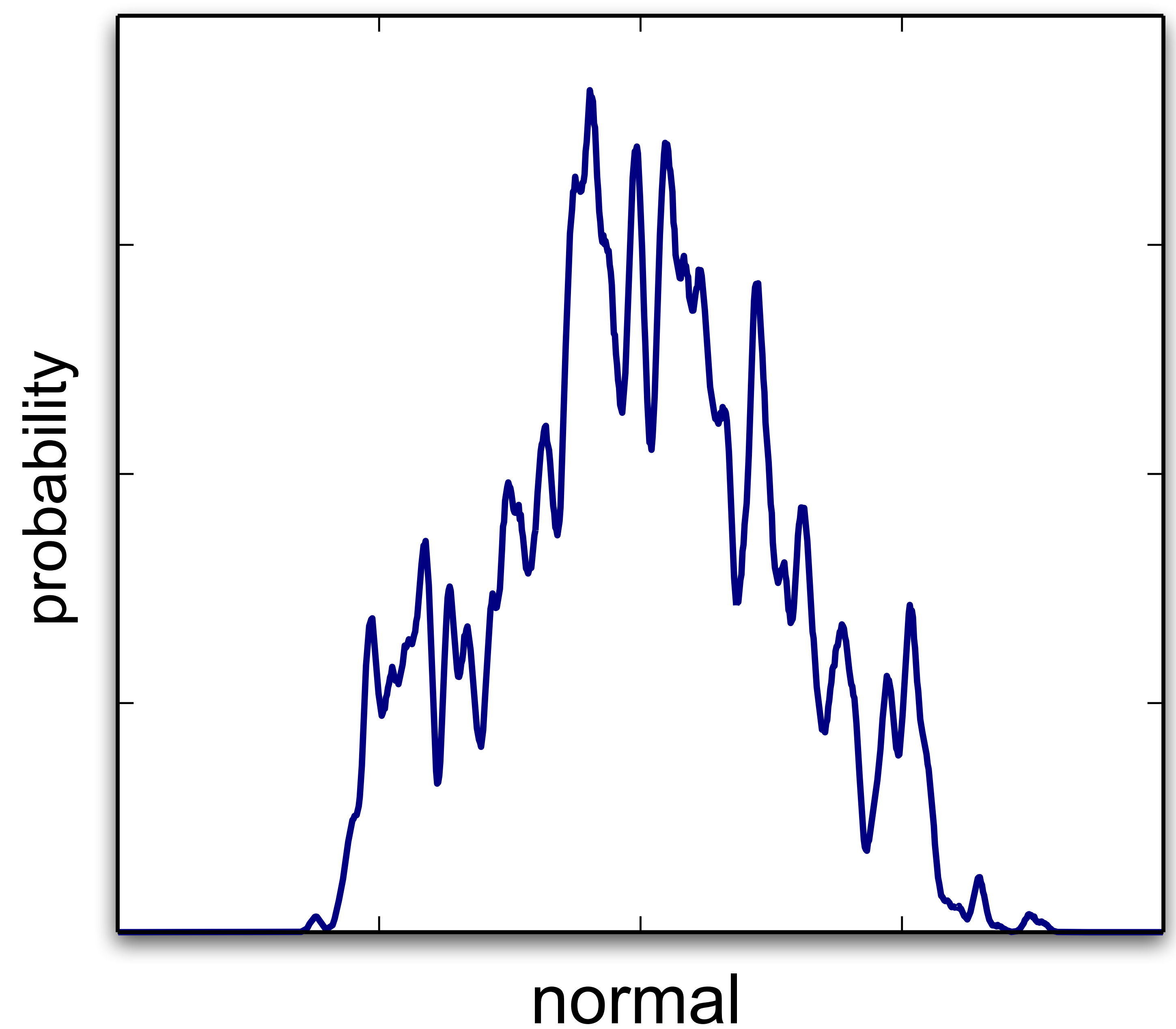
$$f(i,o) = \frac{\mathbf{F}(i,h)\,\mathbf{G}(i,o,h)\,\boxed{\mathbf{D}(h)}}{4(n \cdot i)(n \cdot o)}$$

Statistical NDF vs. Actual NDF

Normal Distribution Function (NDF)



What we calculate
(microfacet — statistical)

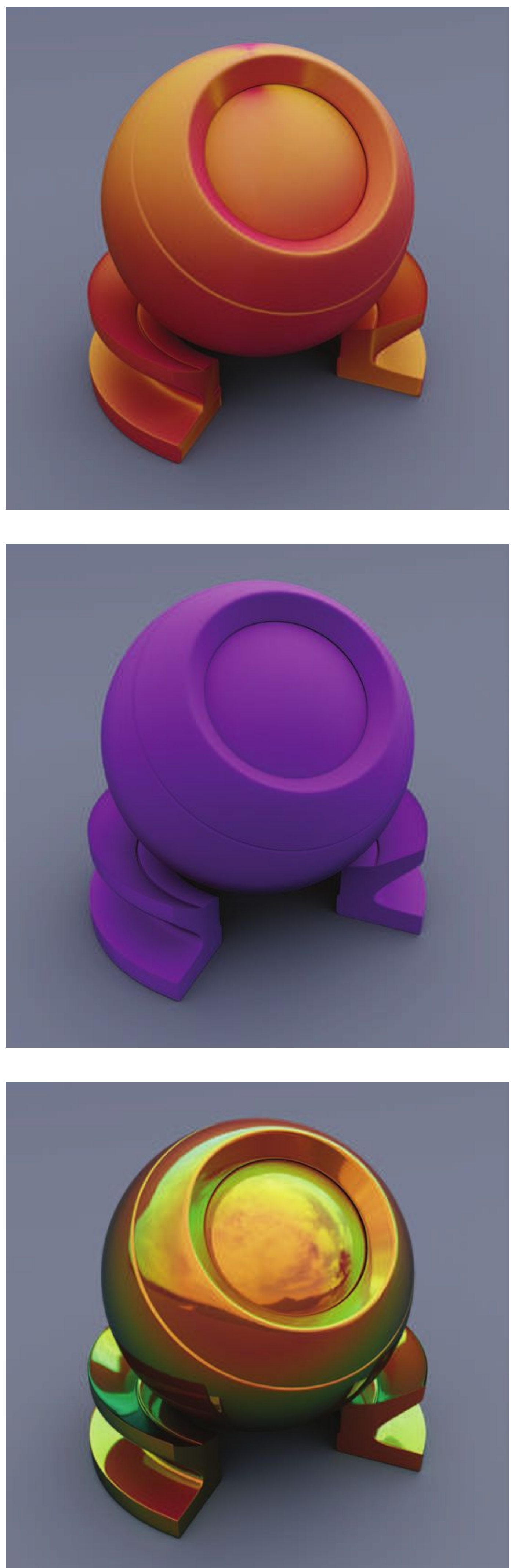


What we want

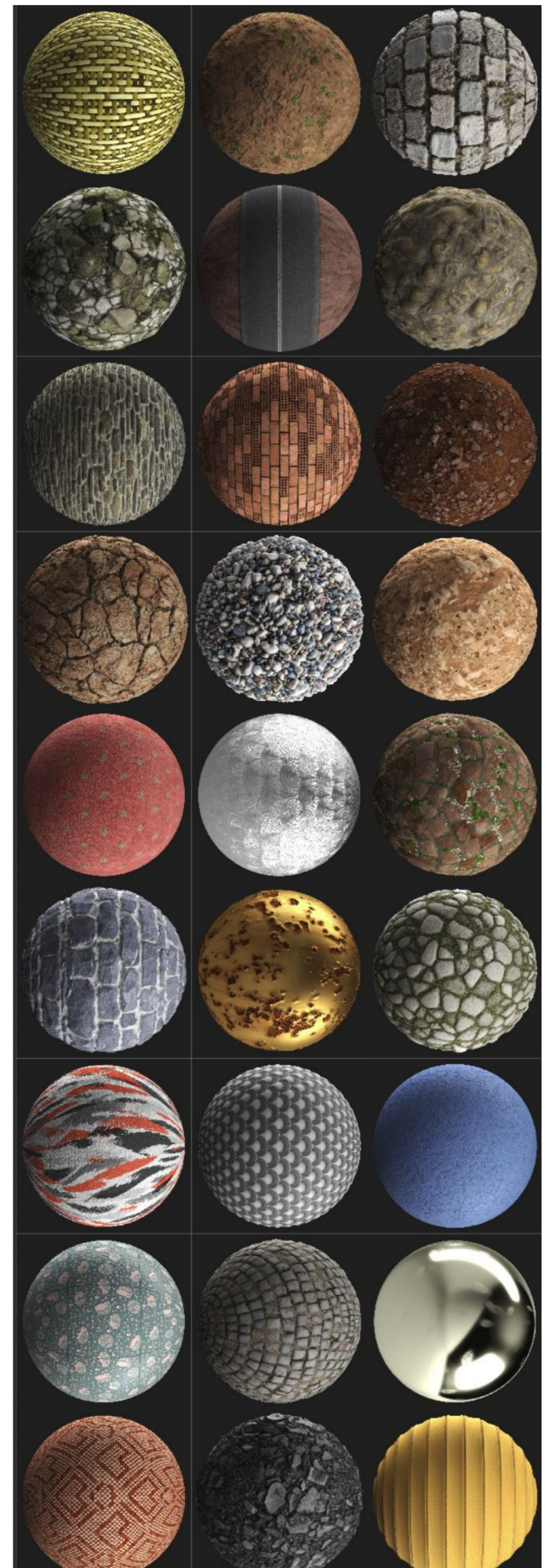
Multi-Scale Surface Modeling

Multi-Scale Surface Modeling

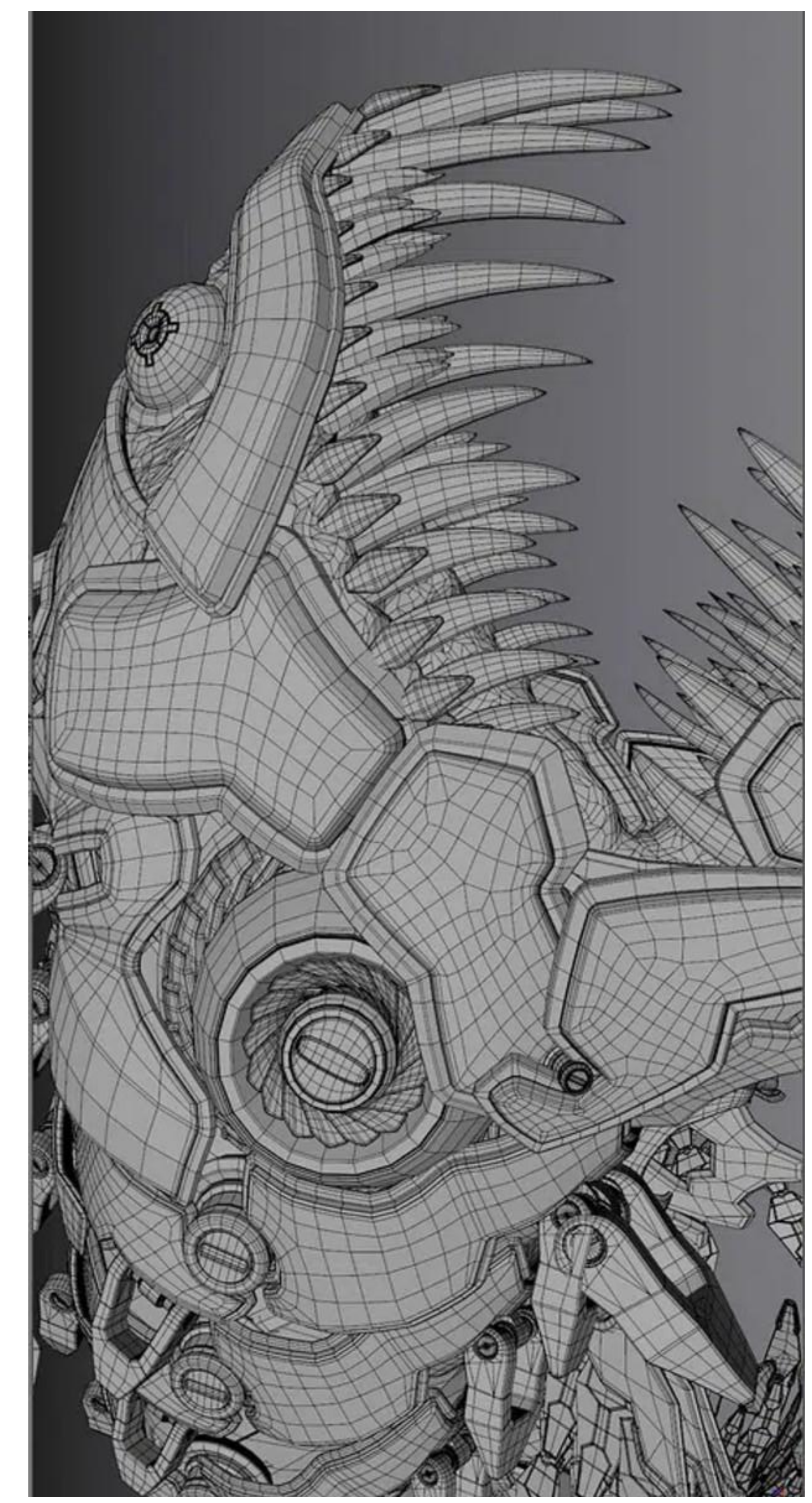
BRDF



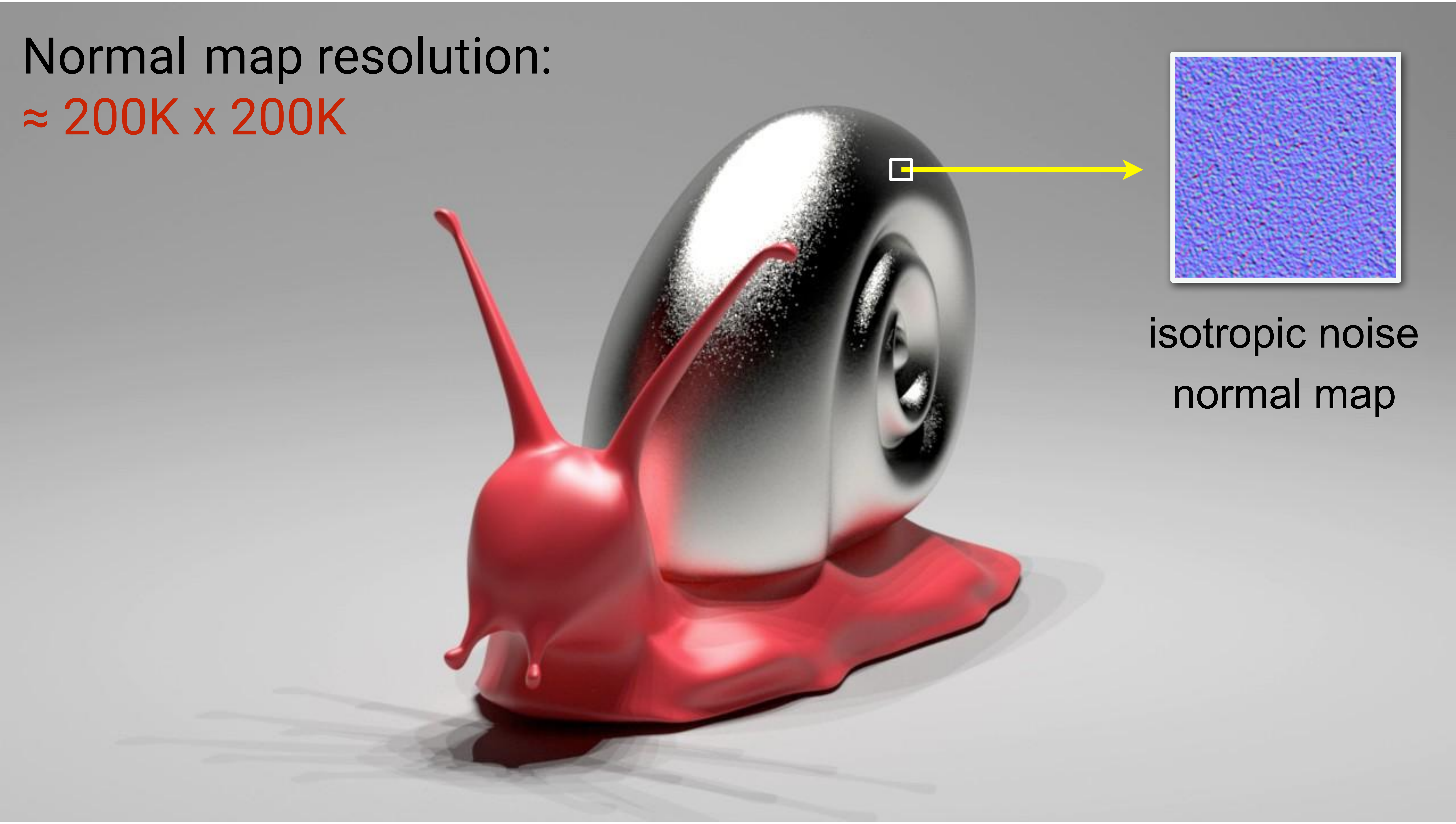
Textures



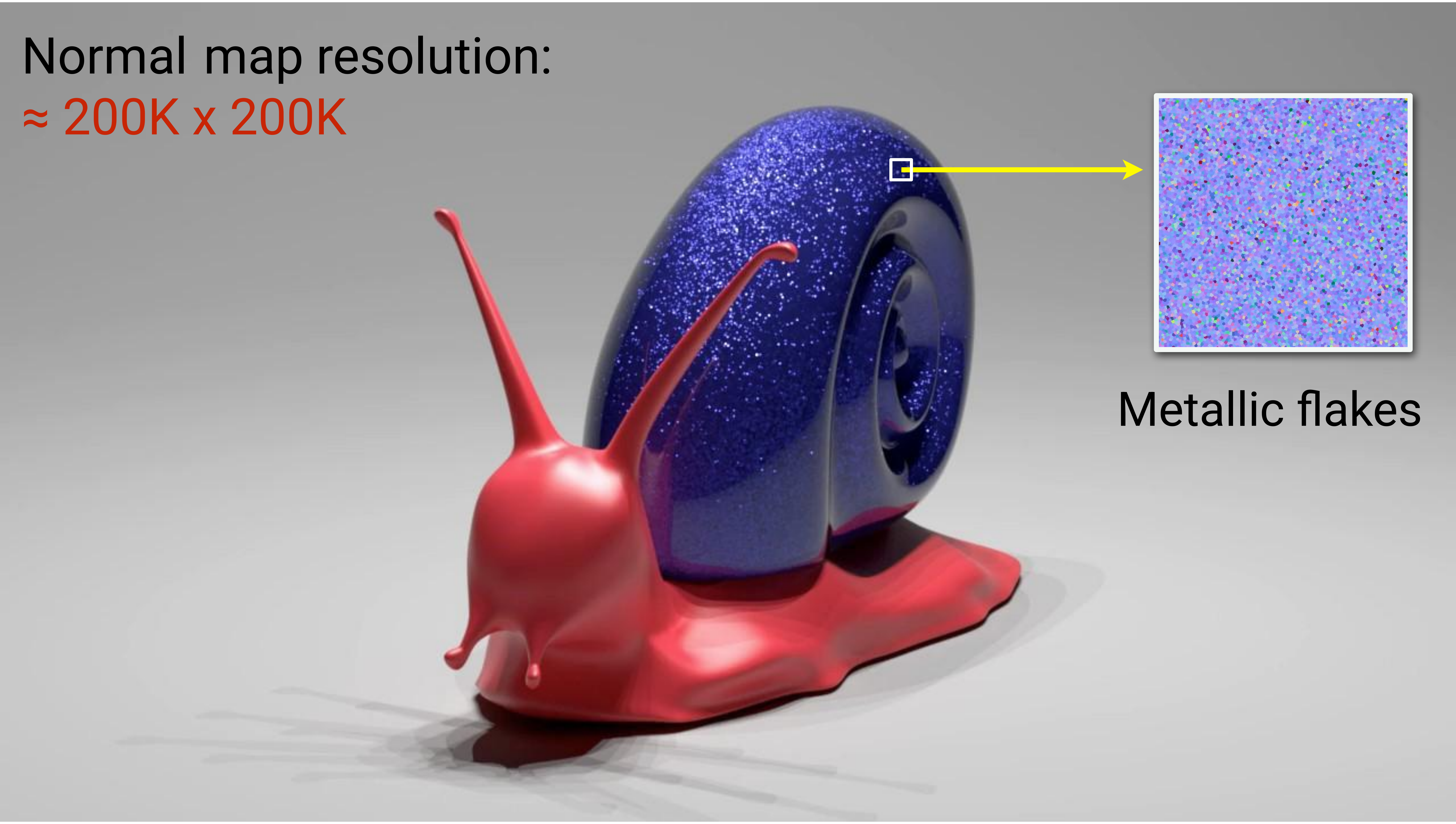
Geometry

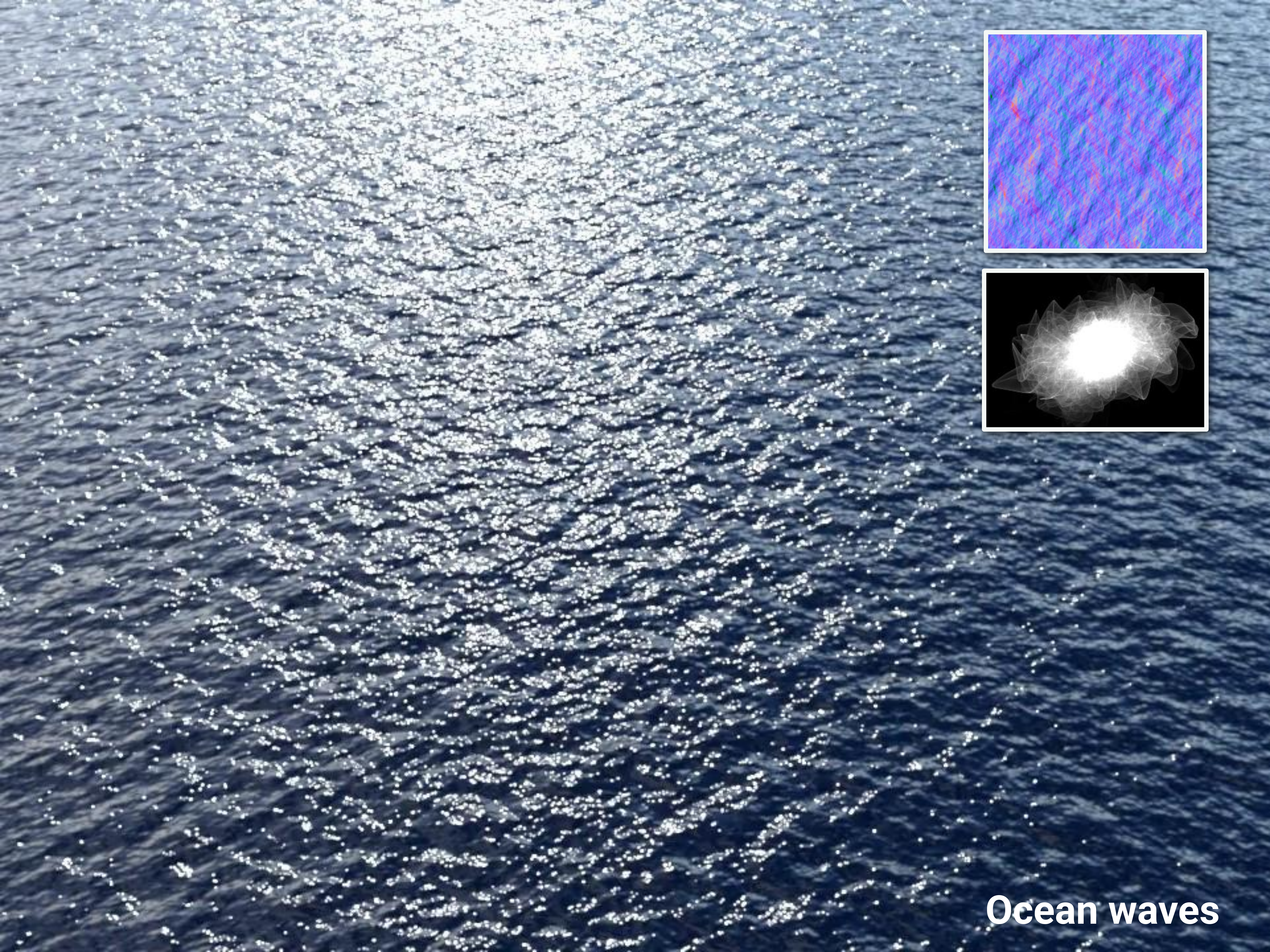


Define Details



Different Details

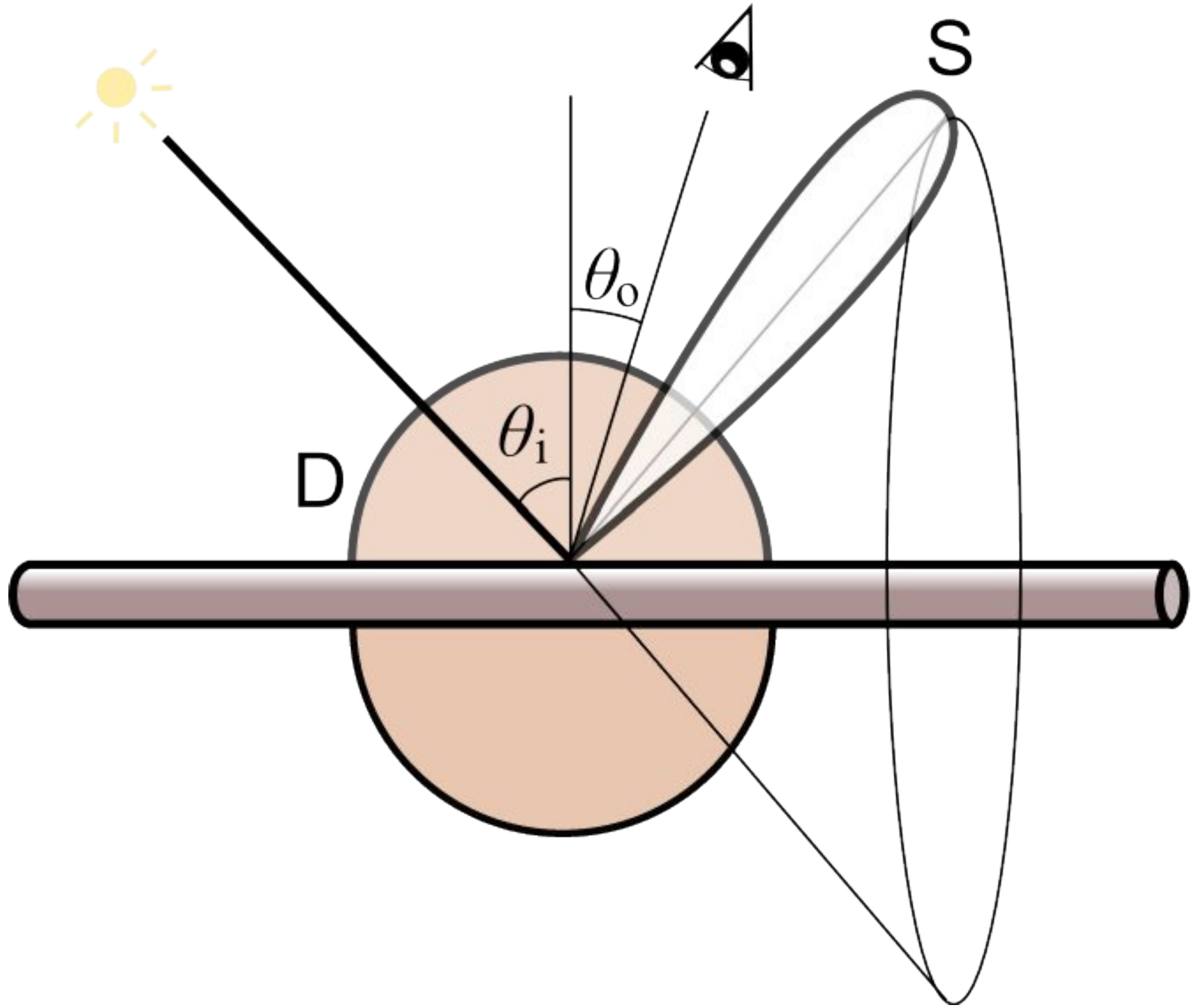



Ocean waves

Hair Appearance Models

Hair Appearance

Kajiya-Kay Model

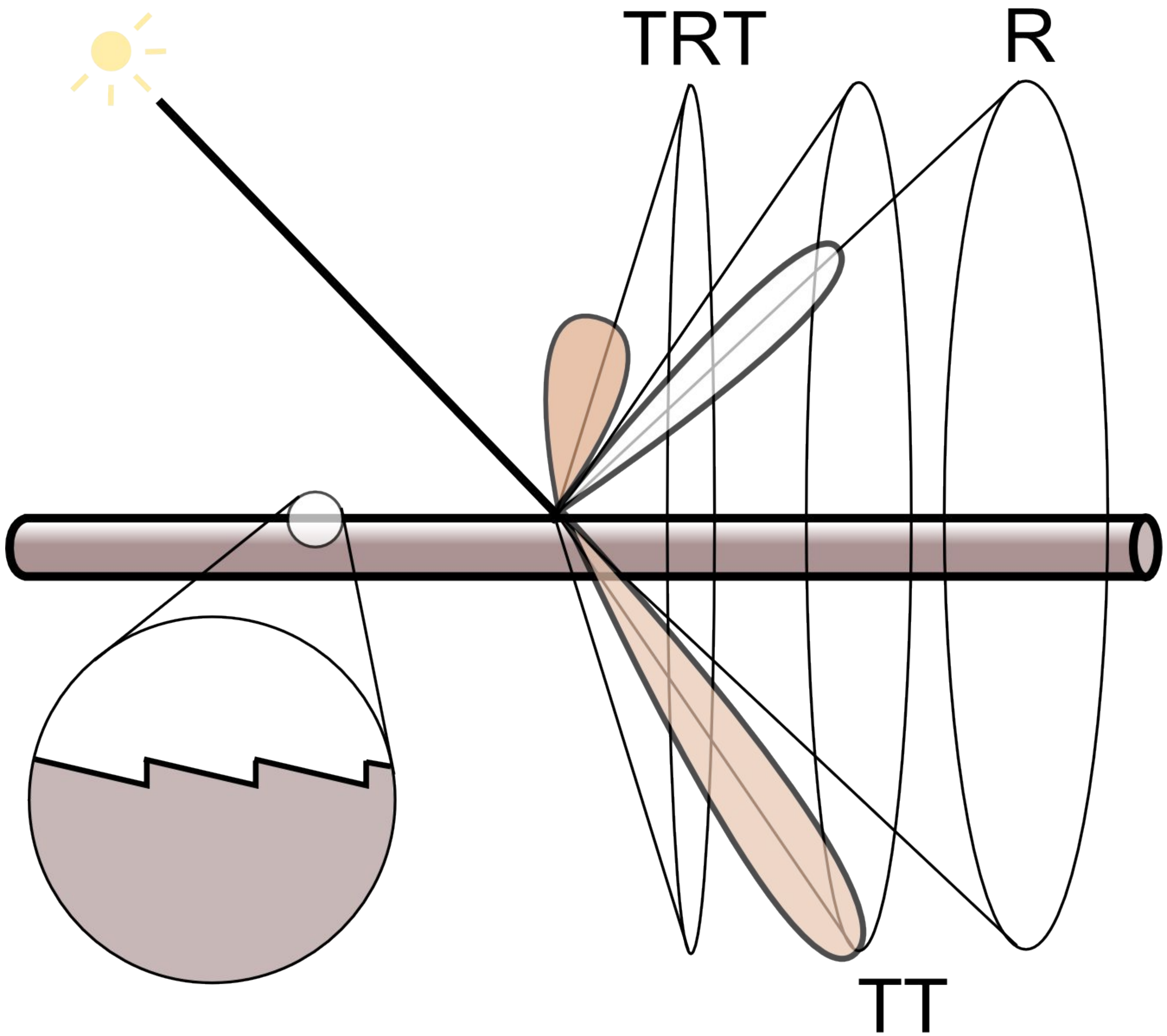


[Image courtesy of Chiwei Tseng]

Kajiya-Kay Model

[Yuksel et al. 2008]

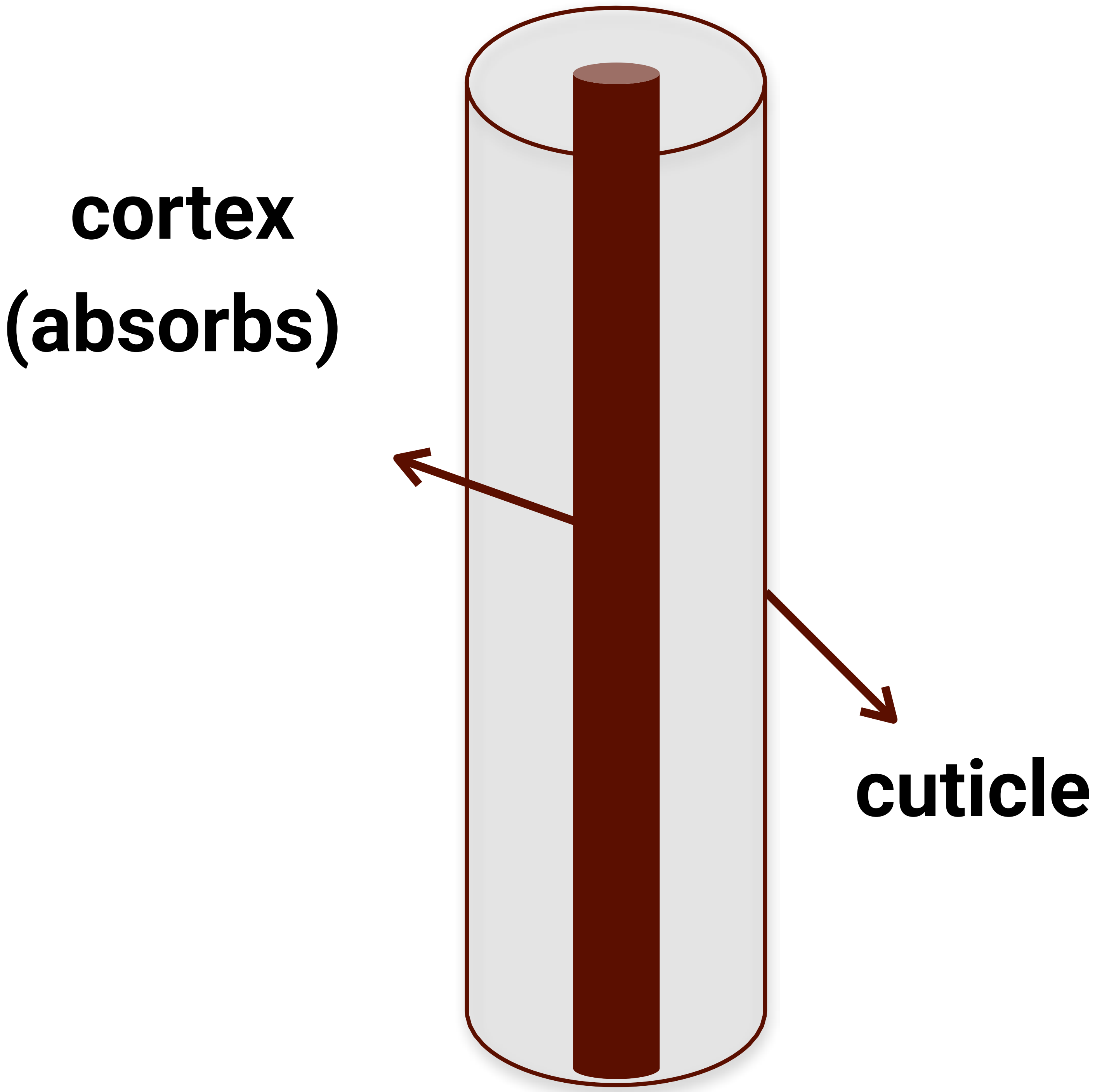
Marschner Model



[Image courtesy of Chiwei Tseng]

Marschner Model

Model a glass-like cylinder



[Marschner et al. 2003]

Marschner model

[Marschner et al. 2003]

[d'Eon et al. 2011]

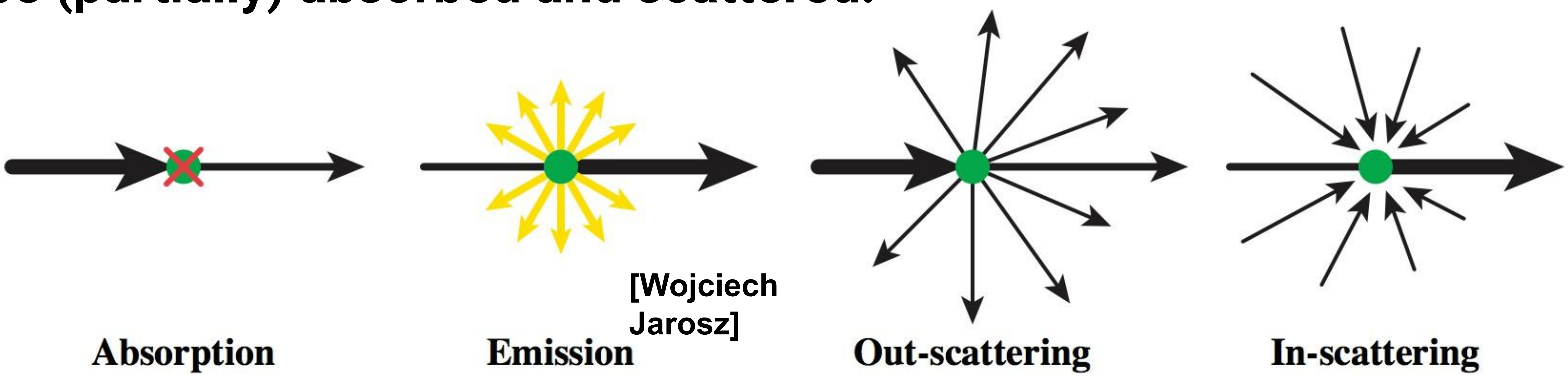
Participating Media

Participating Media: Fog

Participating Media: Cloud

Participating Media

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

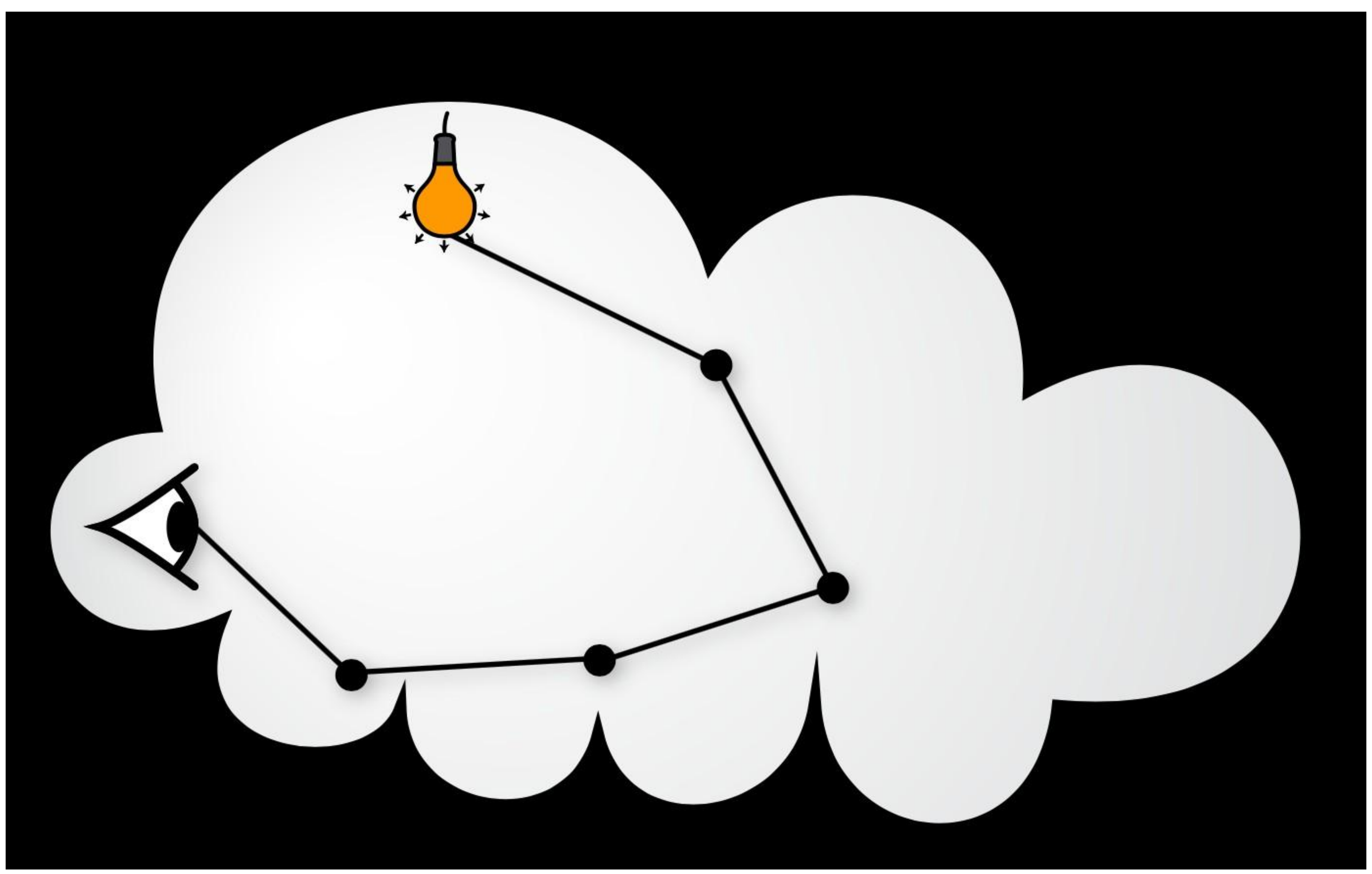


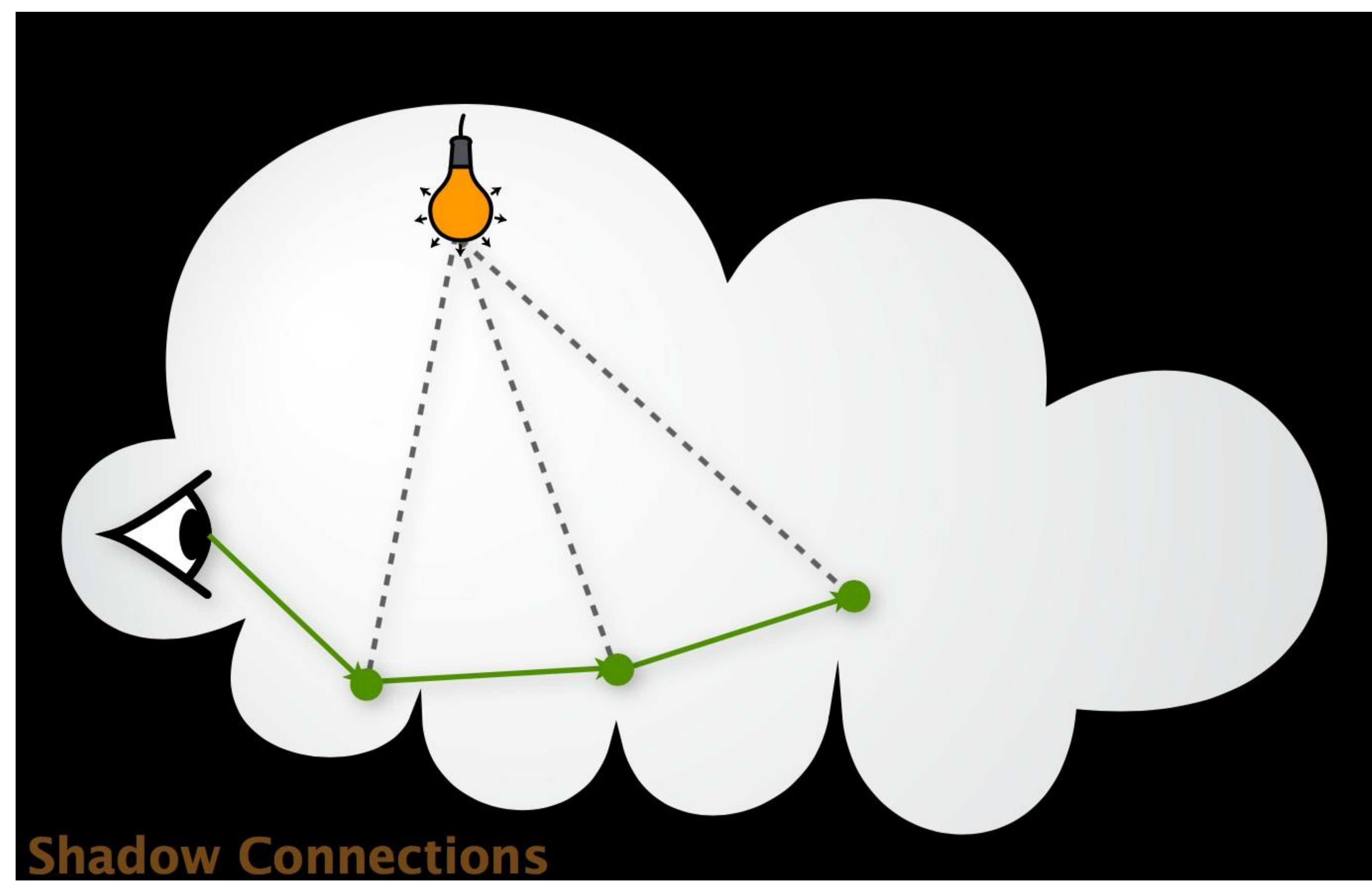
[Wojciech Jarosz]

Participating Media: Rendering

Ray Marching Algorithm:

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





[Derek Nowrouzezahrai]

Participating Media: Cloud

Participating Media: Application

[Big Hero 6, 2014 Disney]

Translucent Material

(specified participating media)

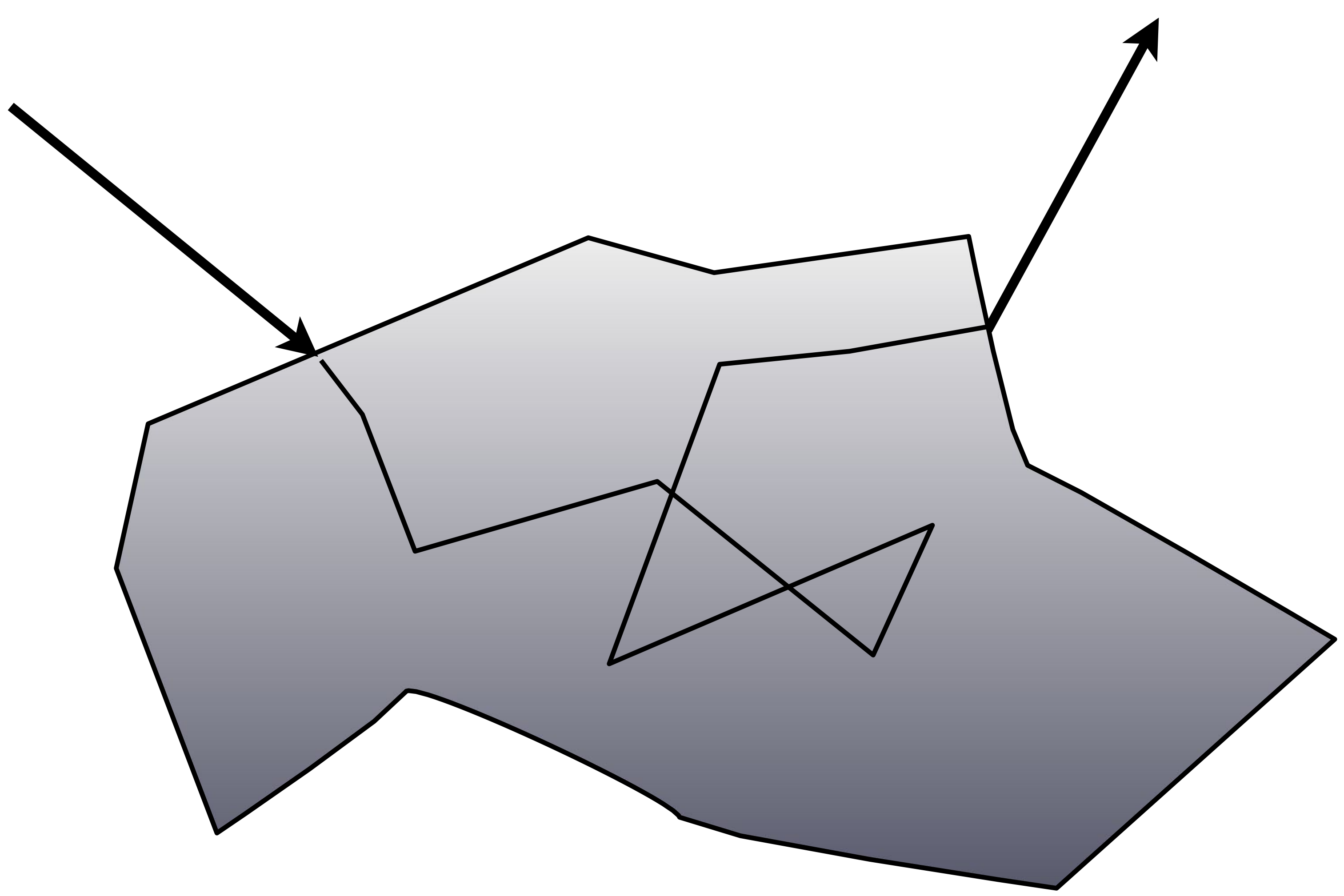
Translucent Material: Jade

Translucent Material: Jellyfish

Subsurface Scattering

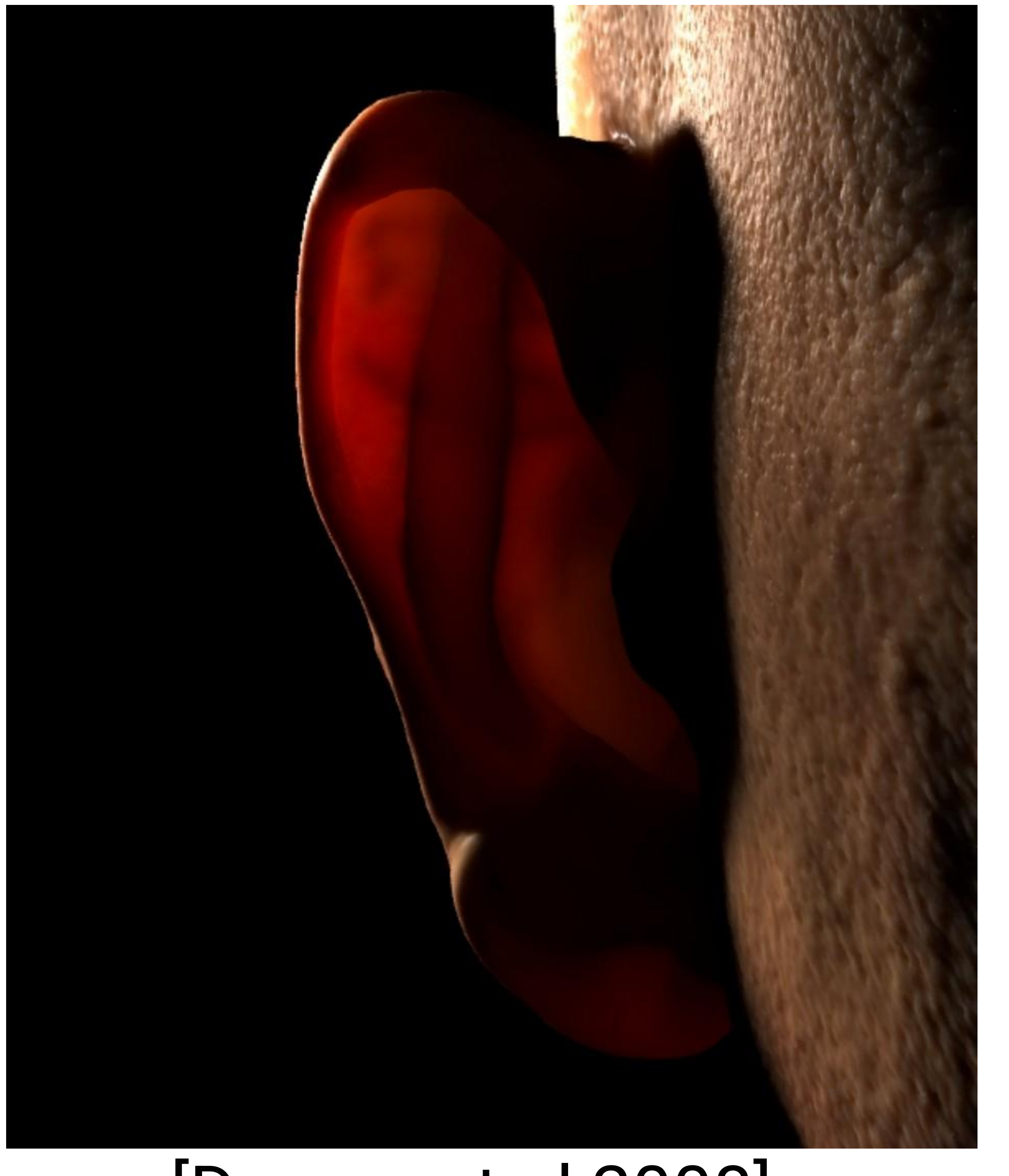
Visual characteristics of many surfaces caused by light exiting at different points than it enters

- Violates a fundamental assumption of the BRDF



- And is 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:**

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

BRDF

[Jensen et al. 2001]

BSSRDF

[Jensen et al. 2001]

BRDF vs BSSRDF

BRDF BSSRDF

[Jensen et al. 2001]

Inverse Rendering

*Recovering **geometry**, **materials**, **lighting**, and **cameras** from images*

What is inverse rendering?

Forward rendering (this class)

Geometry

Material

Light

Cameras

Rendered images

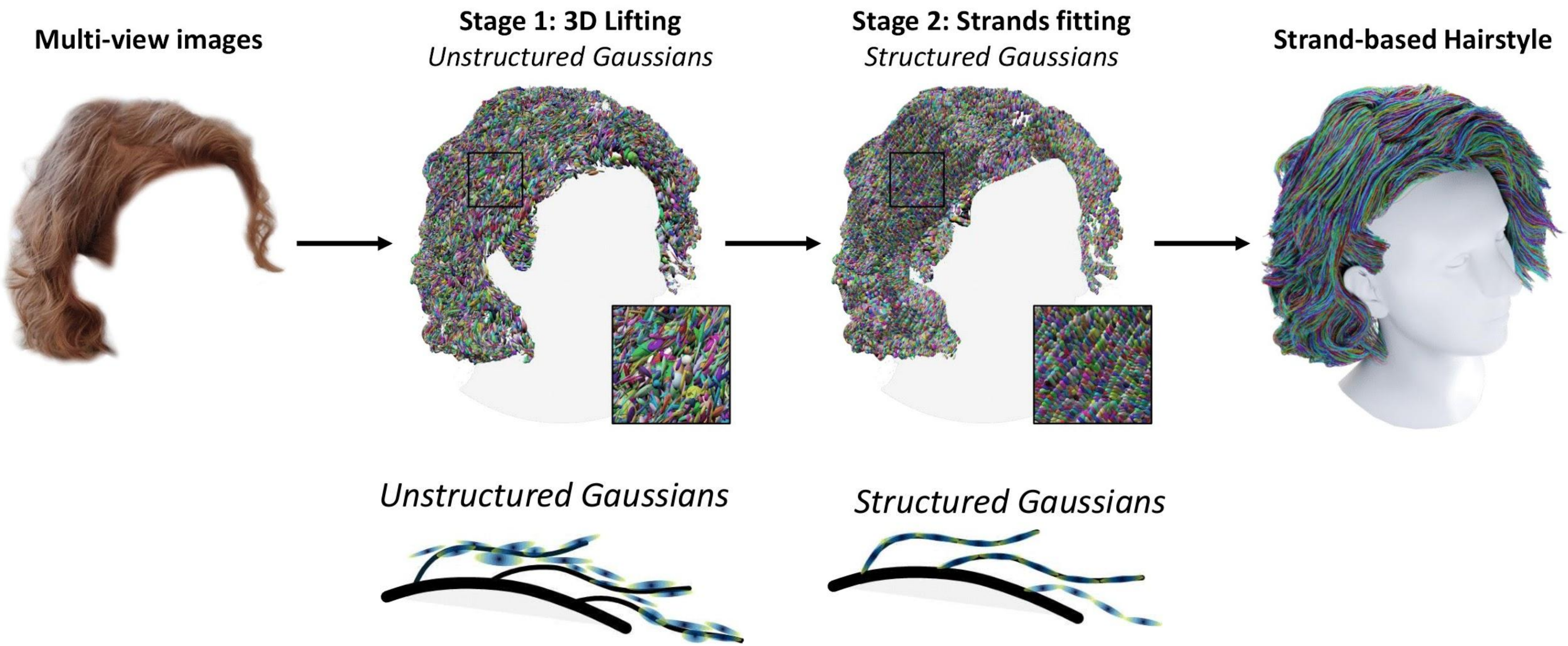
Use physically accurate models
to render pretty images

Inverse Rendering for Hair

Input video Reconstruction Rendering

“Gaussian Haircut ✂️”, ECCV 2024

Inverse Rendering for Hair



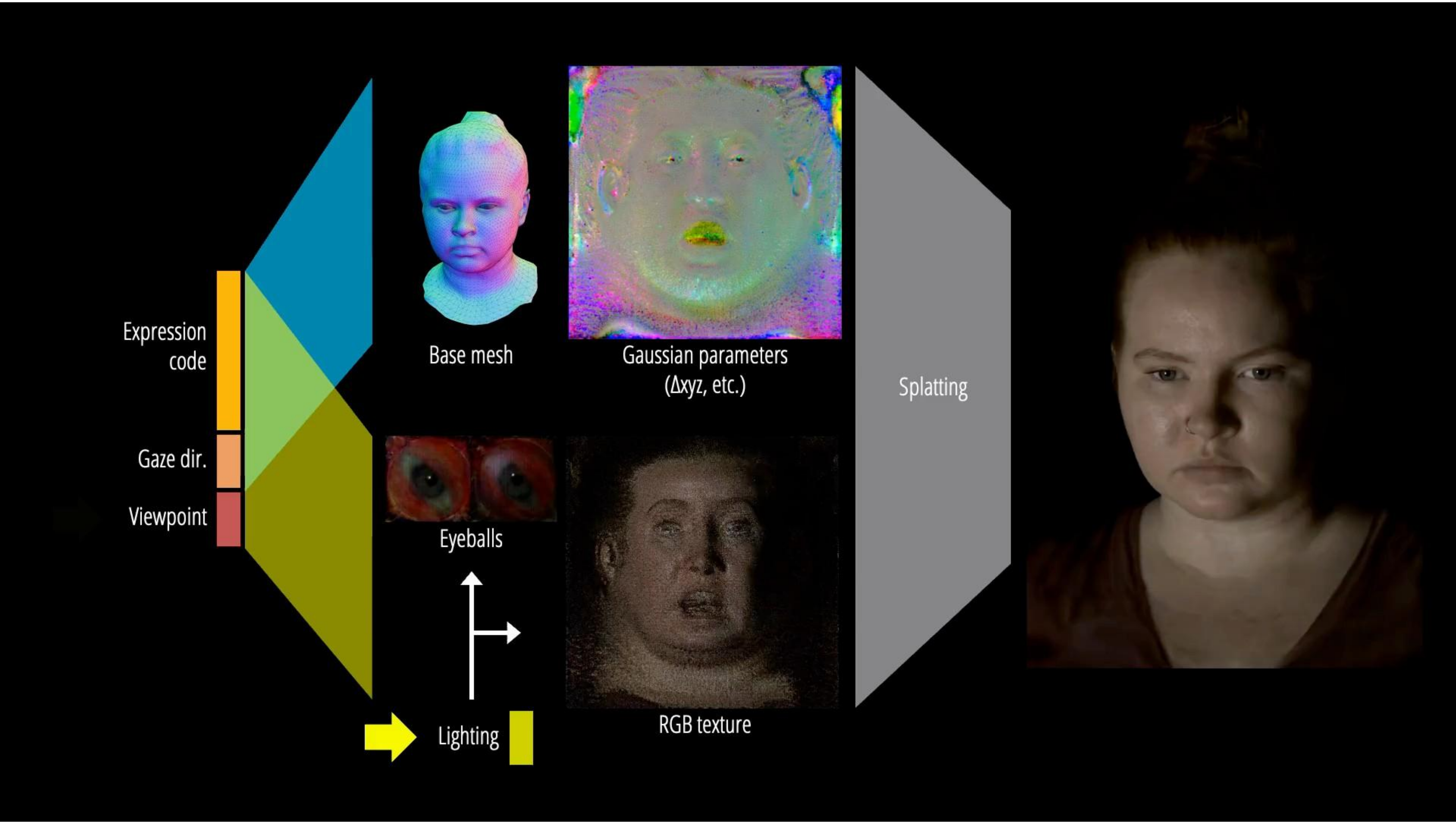
"Gaussian Haircut ✂️", ECCV 2024

Inverse Rendering for Humans

“Relightable Gaussian Codec Avatars”, CVPR 2024

Meta

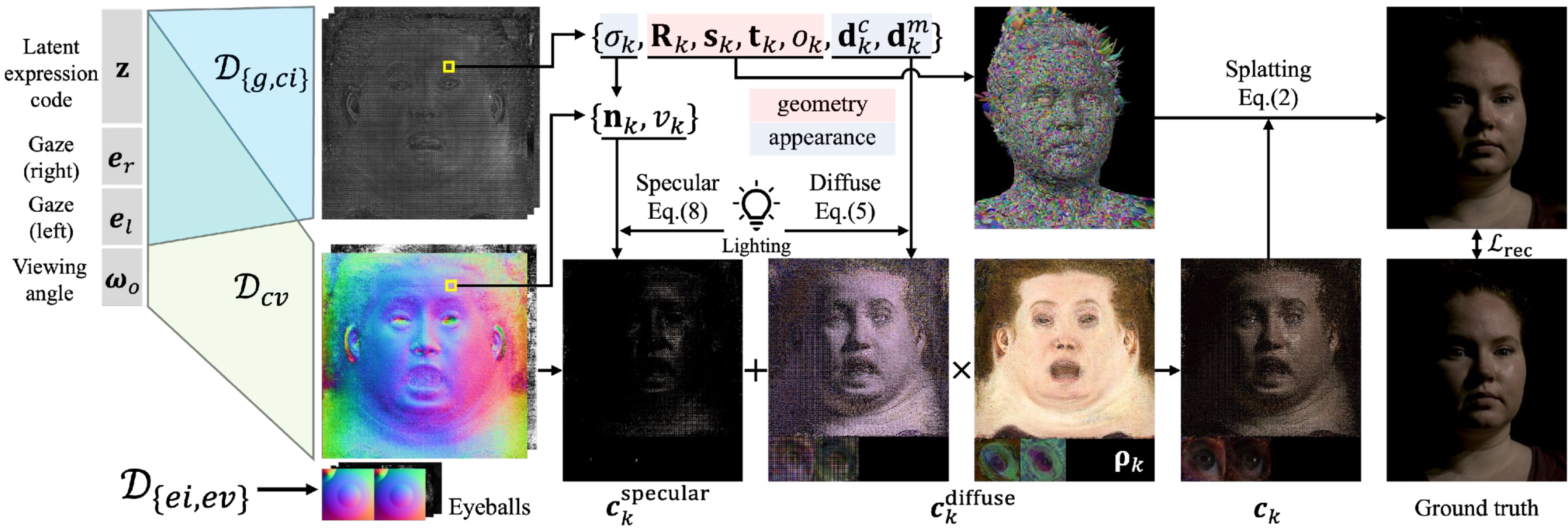
Inverse Rendering for Humans



"Relightable Gaussian Codec Avatars", CVPR 2024

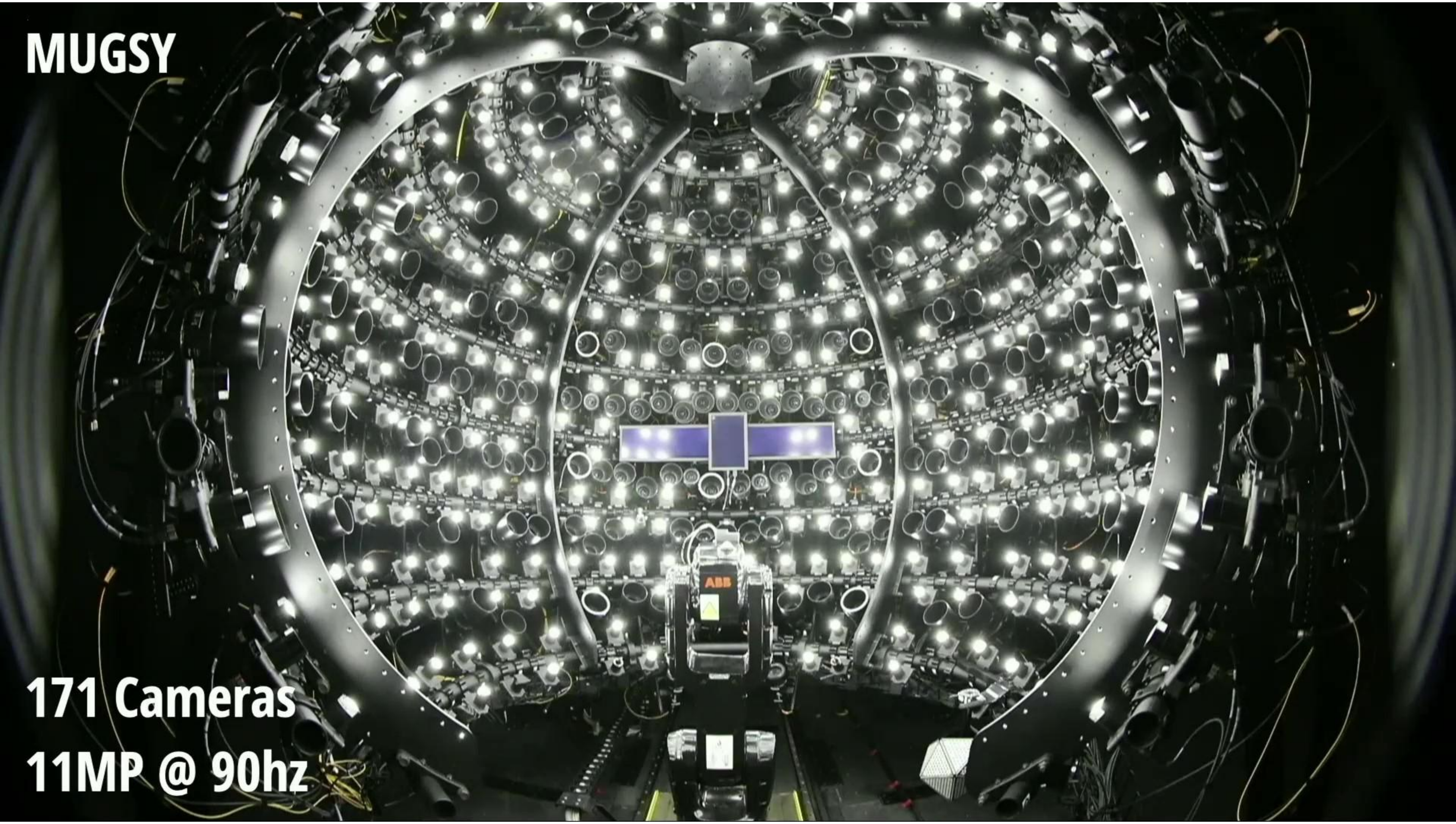
Meta

Inverse Rendering for Humans



“Relightable Gaussian Codec Avatars”, CVPR 2024

Inverse Rendering for Humans



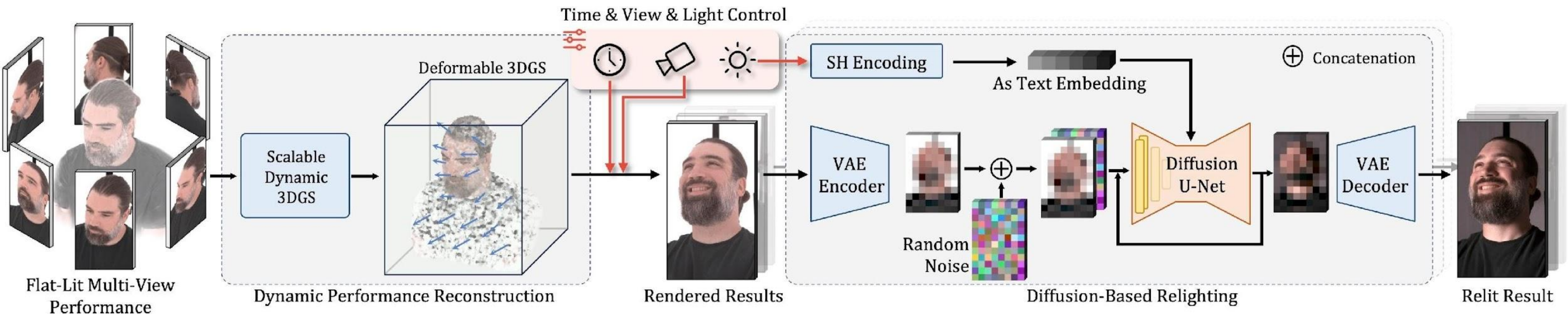
https://www.uploadvr.com/meta-codec-avatars-iphone-scan/

Meta

Inverse Rendering for Humans

"DifFRelight", SIGGRAPH Asia 2024

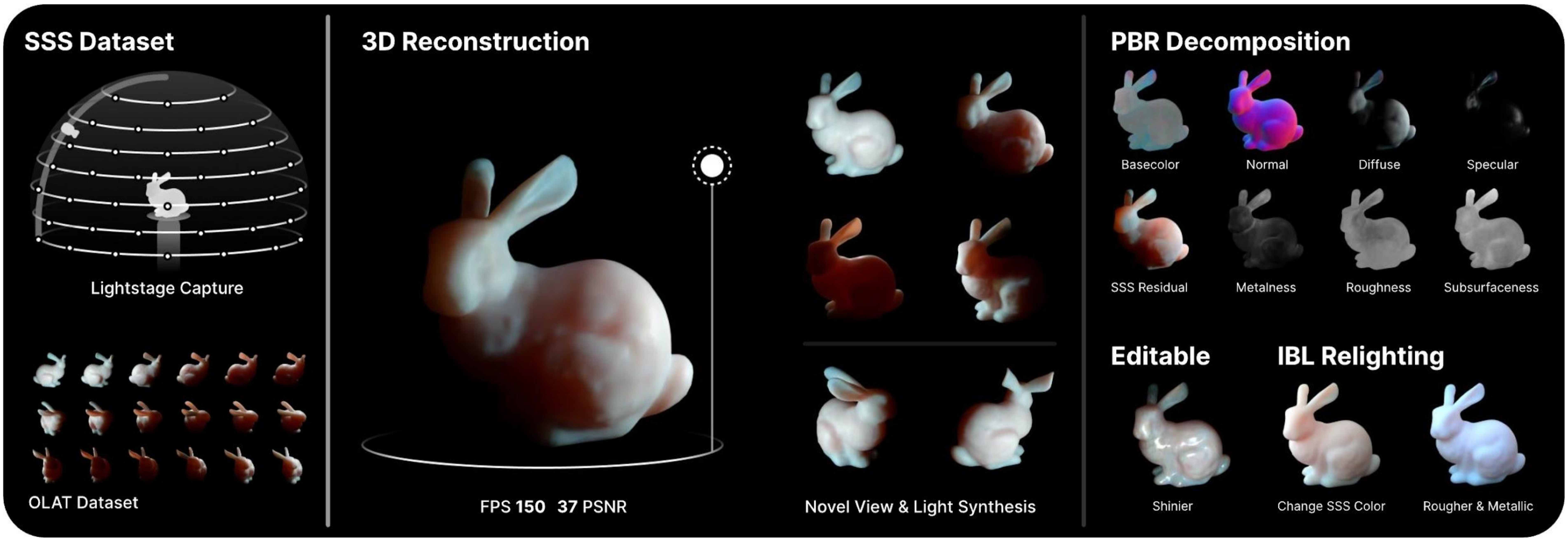
Inverse Rendering for Humans



“DiffRelight”, SIGGRAPH Asia 2024

EYELINE STUDIOS™ POWERED BY NETFLIX

Inverse Rendering for Objects

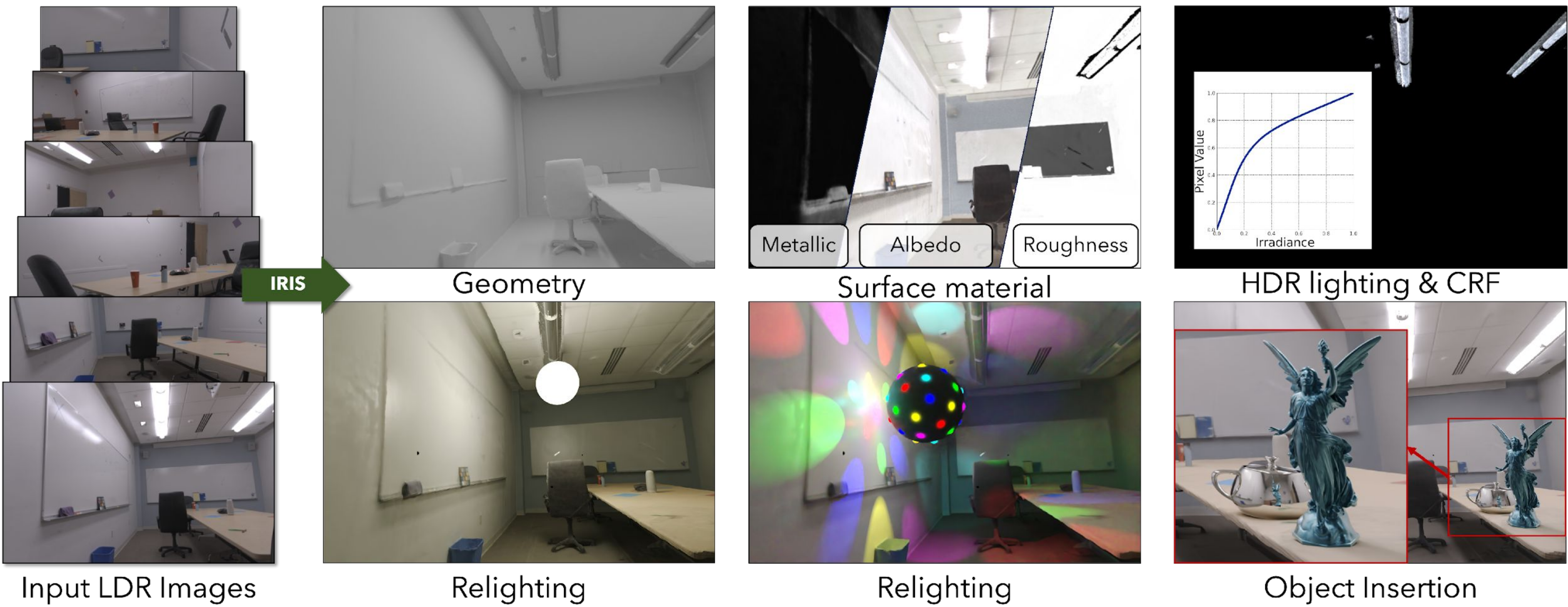


“Subsurface Scattering for Gaussian Splatting”

Inverse Rendering for Objects

“Subsurface Scattering for Gaussian Splatting”

Inverse Rendering for Scenes



“IRIS: Inverse Rendering of Indoor Scenes”

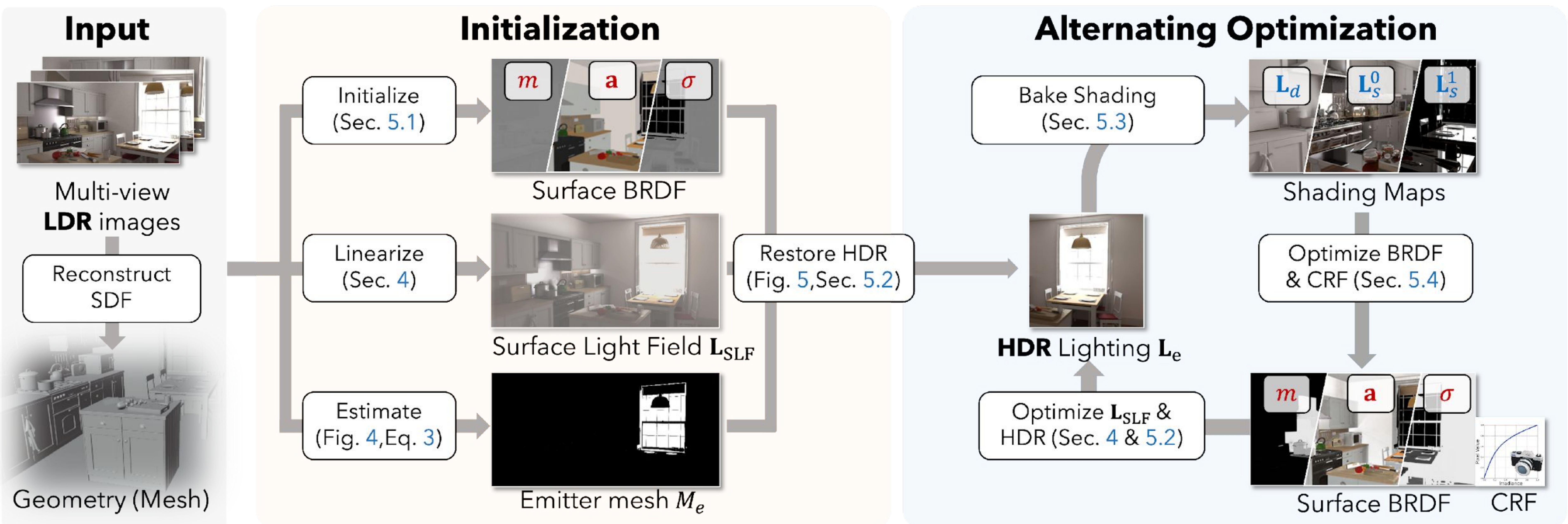
Inverse Rendering for Scenes

“IRIS: Inverse Rendering of Indoor Scenes”

Inverse Rendering for Scenes

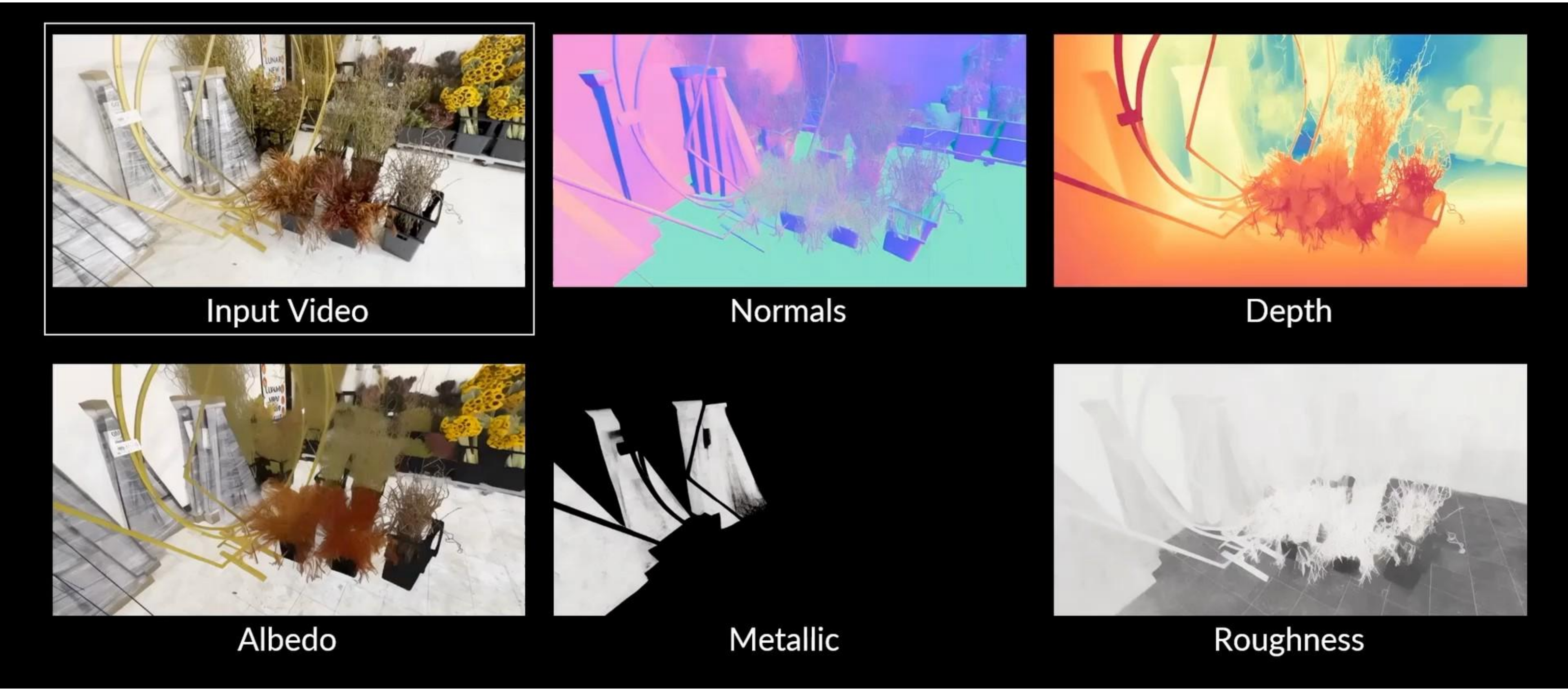
“IRIS: Inverse Rendering of Indoor Scenes”

Inverse Rendering for Scenes



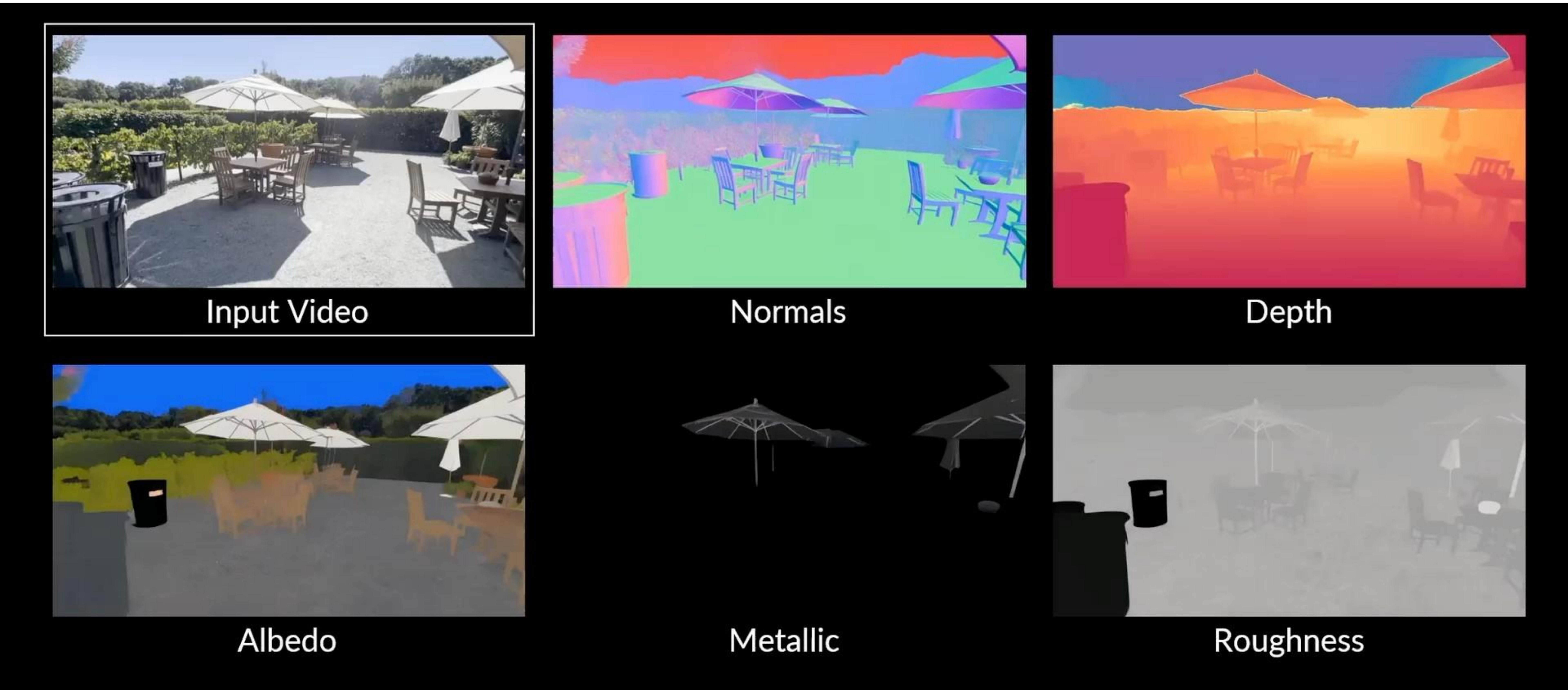
“IRIS: Inverse Rendering of Indoor Scenes”

Inverse Rendering for Scenes



“DiffusionRenderer”, CVPR 2025

Inverse Rendering for Scenes



“DiffusionRenderer”, CVPR 2025

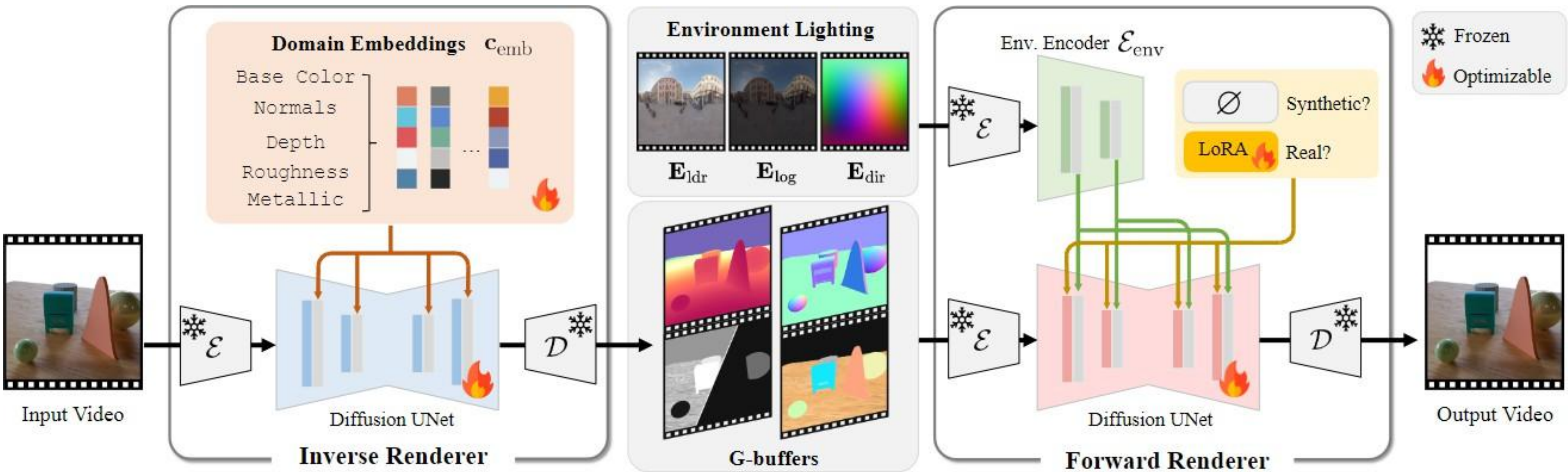
Inverse Rendering for Scenes

Object Insertion

Hover over each image to see the background without the virtual object.

“DiffusionRenderer”, CVPR 2025

Inverse Rendering for Scenes



“DiffusionRenderer”, CVPR 2025

Acknowledgments

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