RENDERING TUTORIAL III - MATERIALS AND SHADING

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Outline — Materials and Shading

- What is material in Graphics?
- How to render materials (shading)?
- Common materials
- Material acquisition / measurement
- Advanced materials

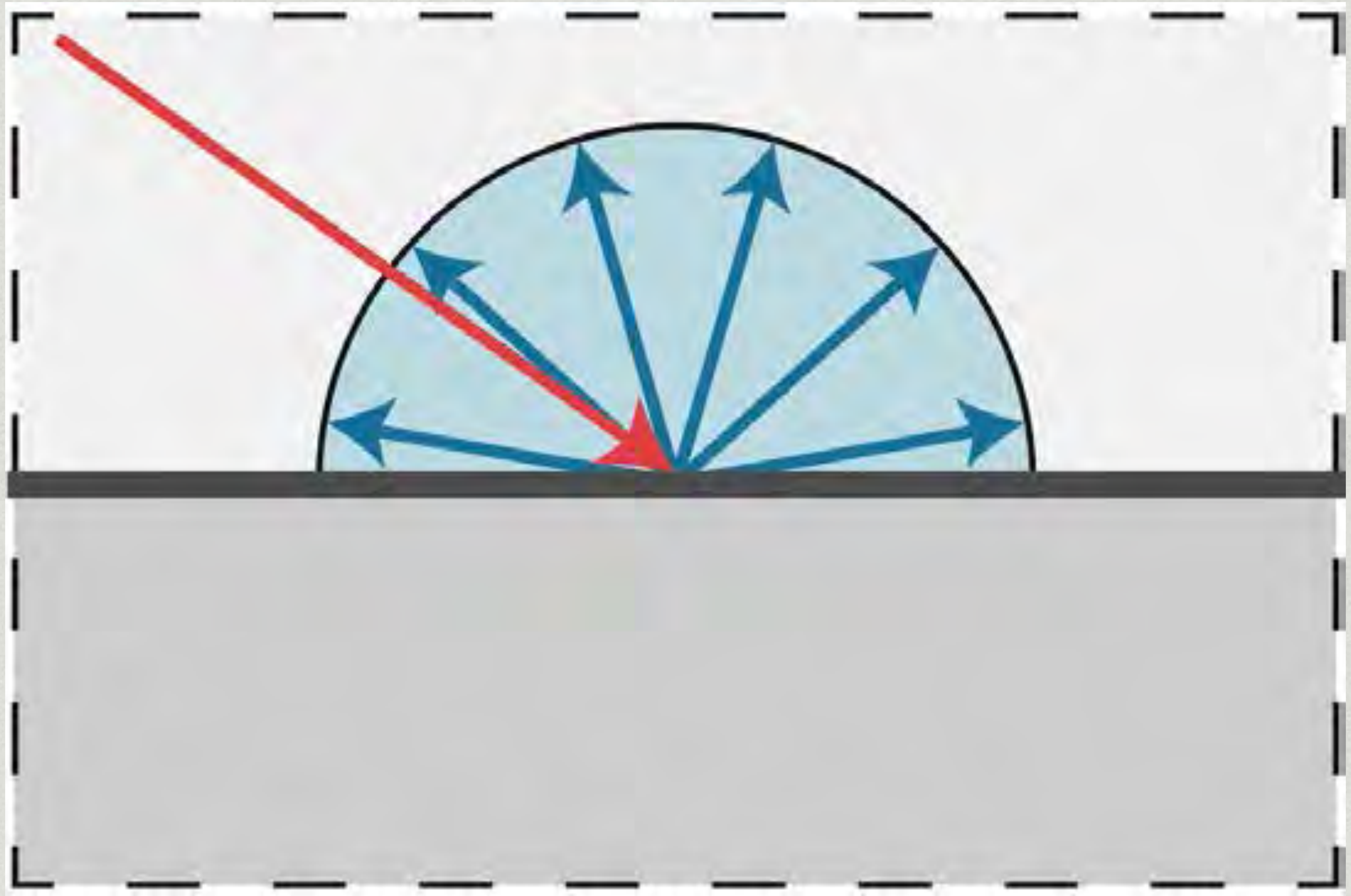
What is material?

- Material is the **reason of appearance**

3D coffee mug model　　Rendered　　Rendered

What is material?

* Material is **how the light interacts objects**



What is material?

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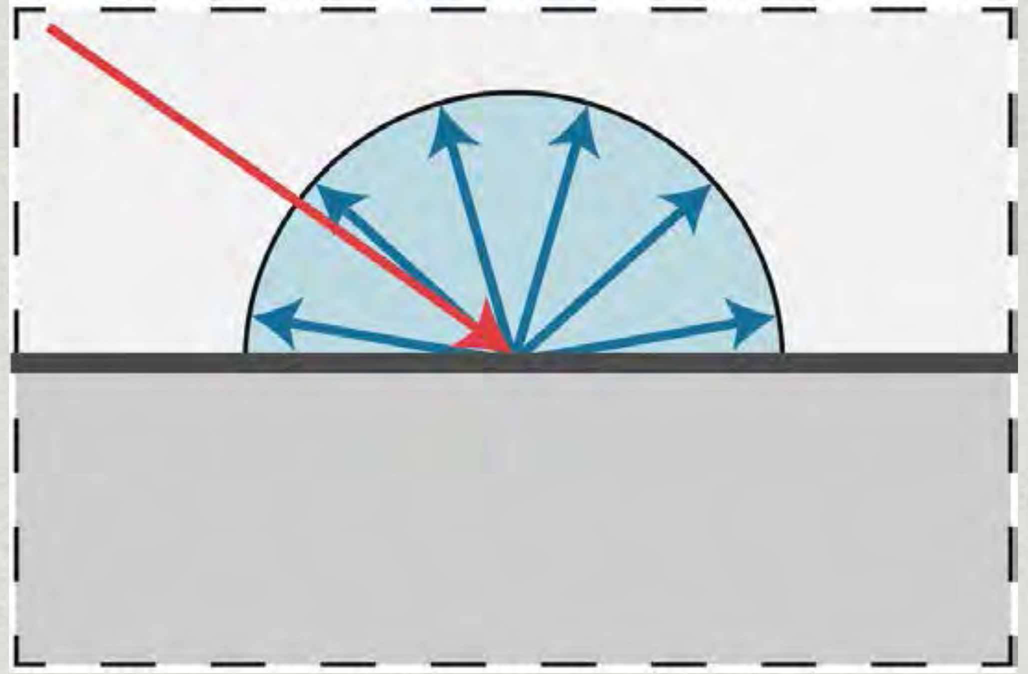
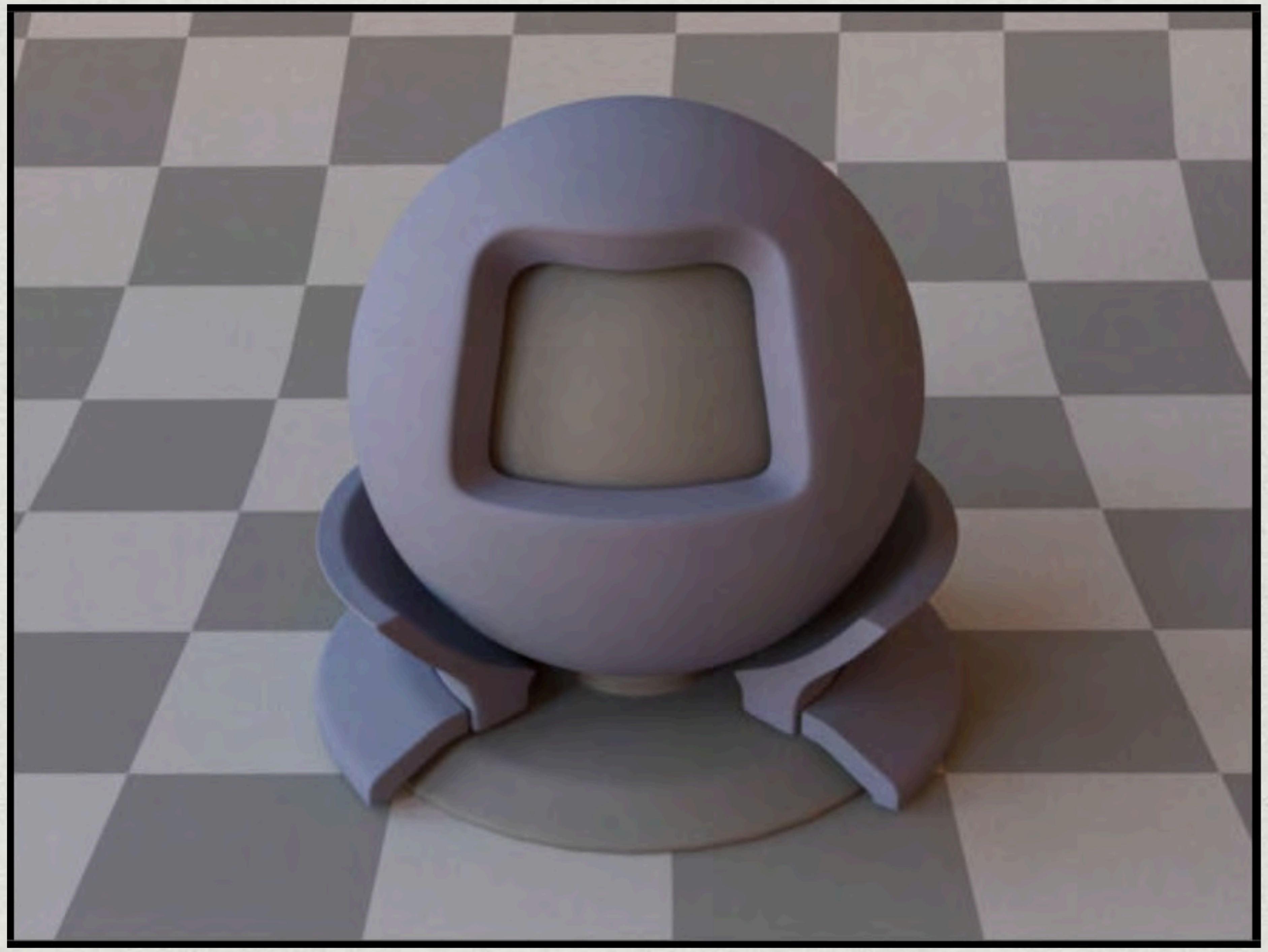
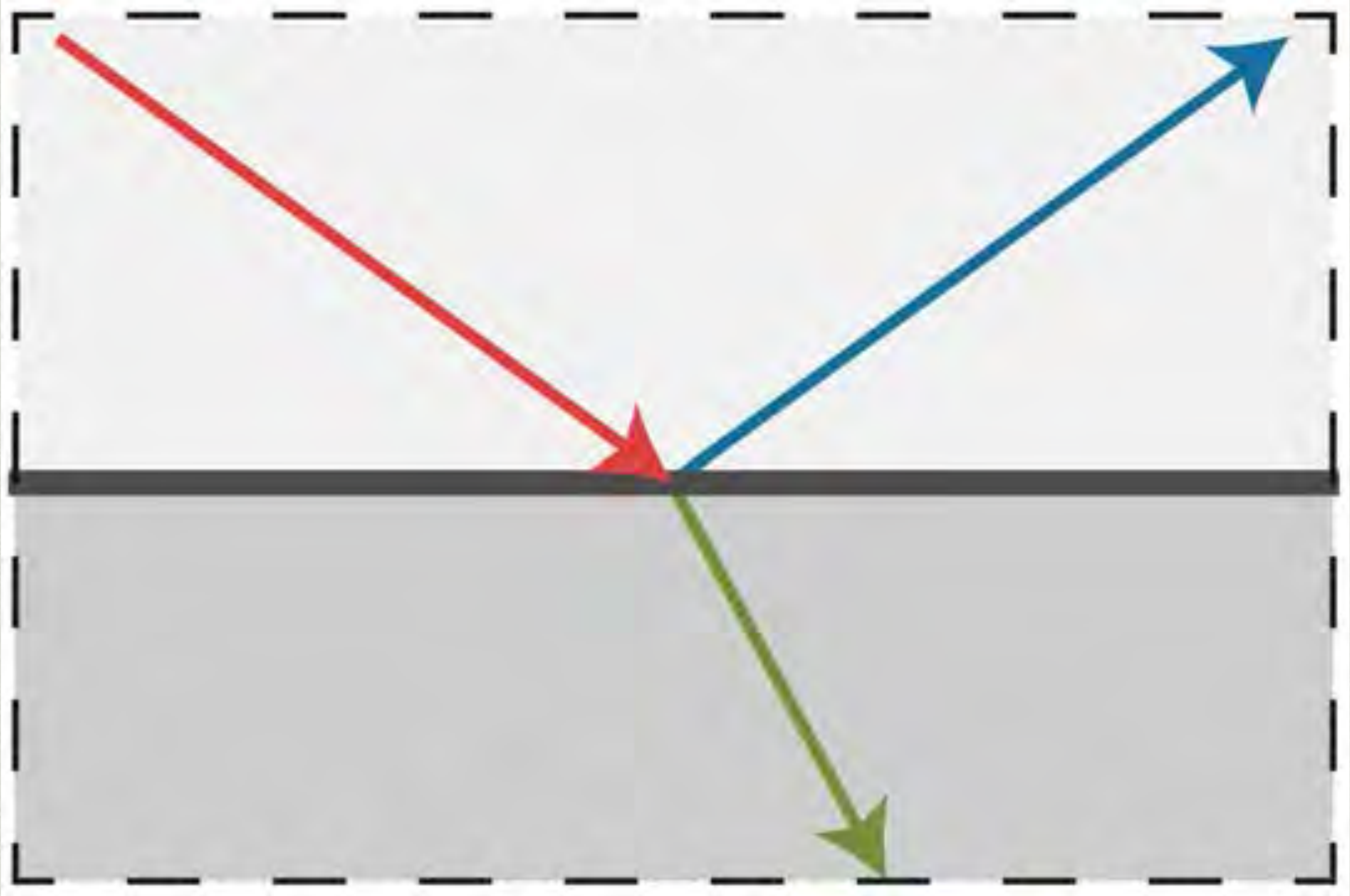




Diffuse

What is this material?

* Material is **how the light interacts objects**



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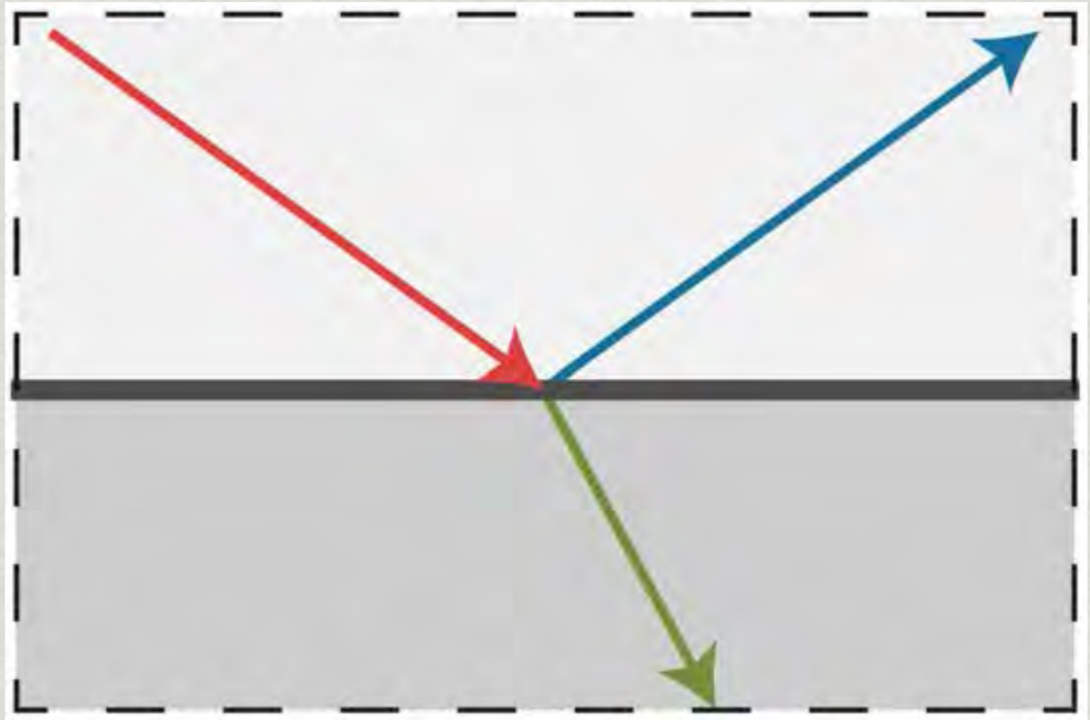
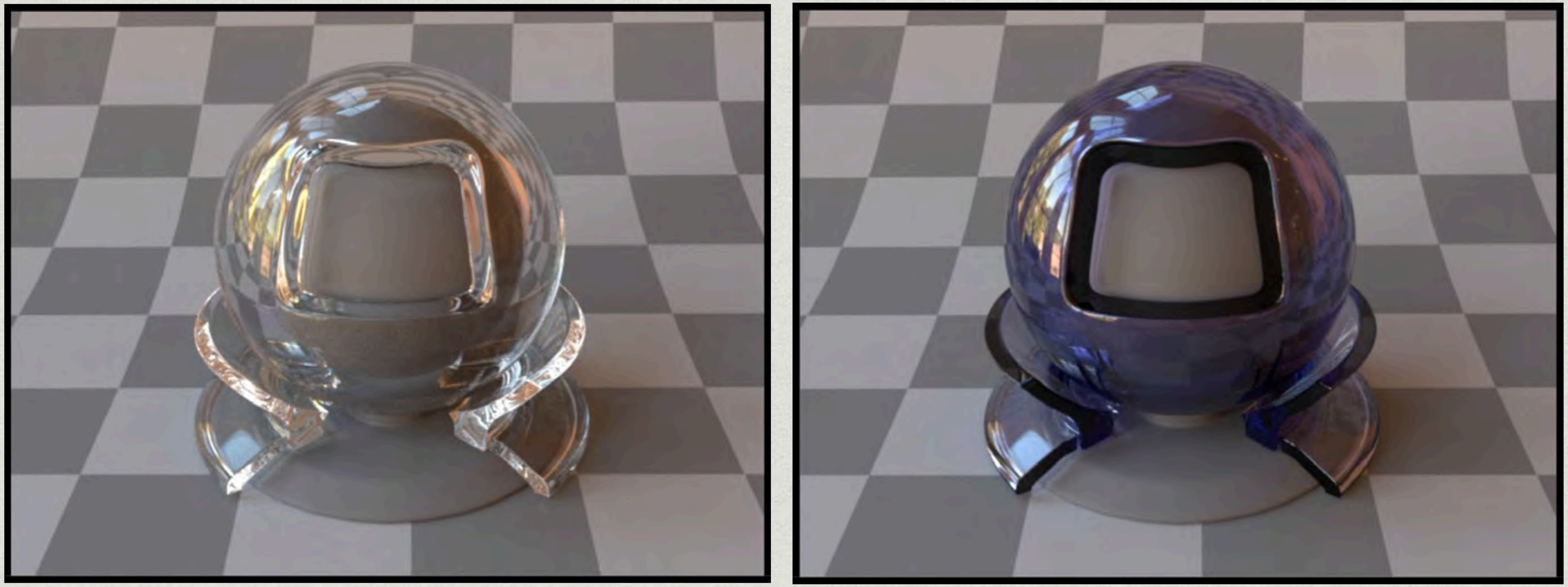
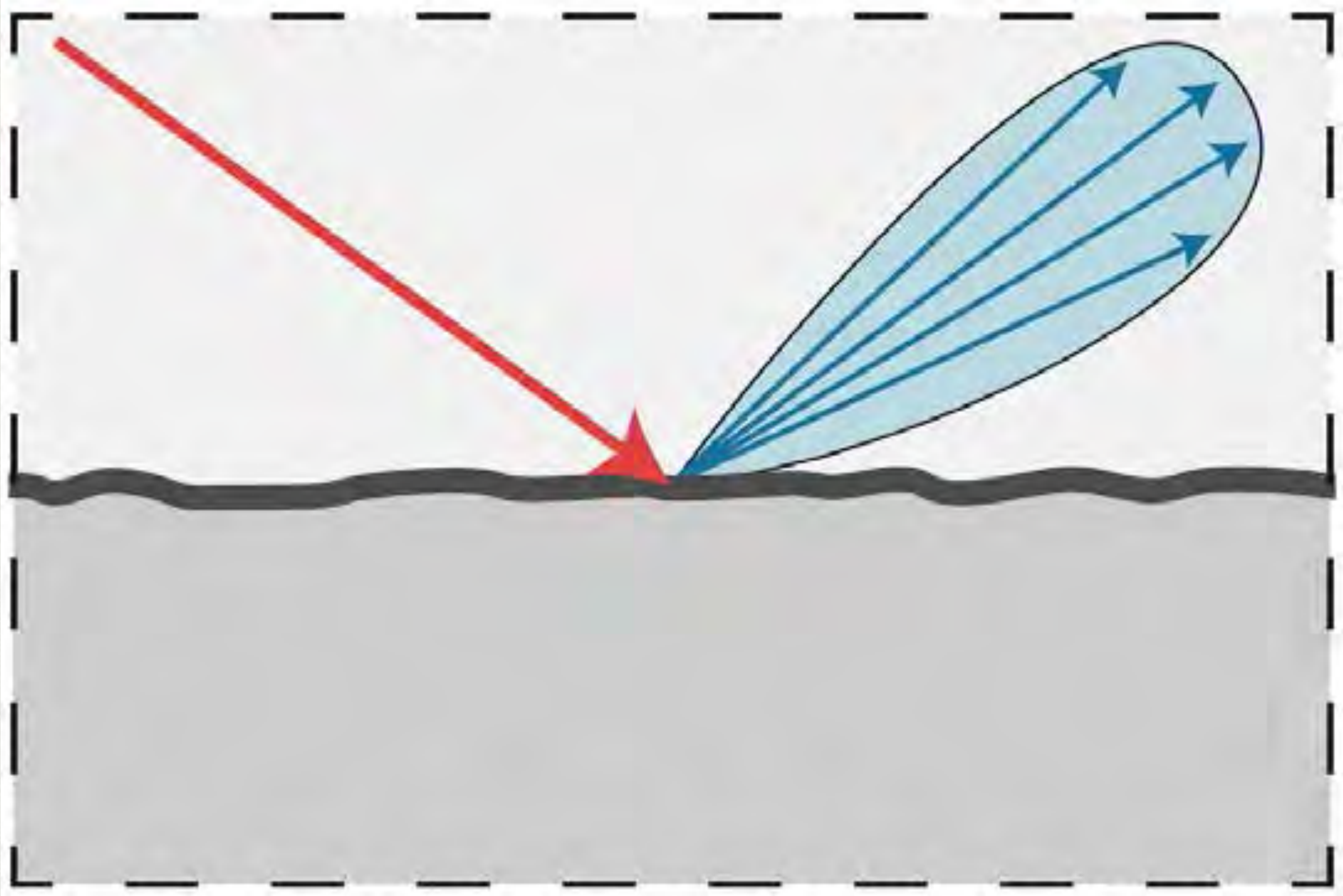




Glass

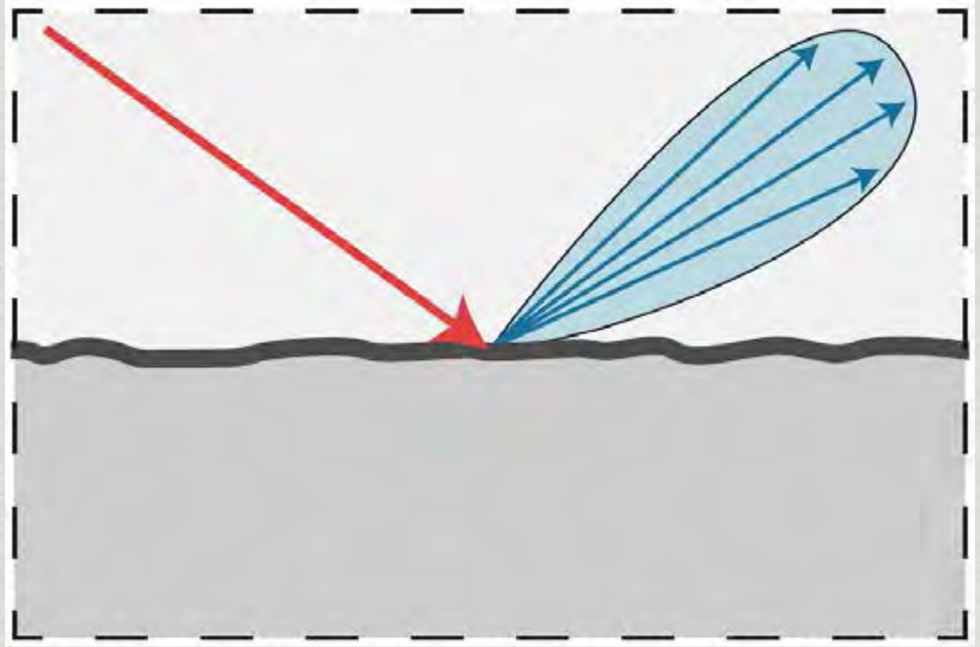
What is this material?

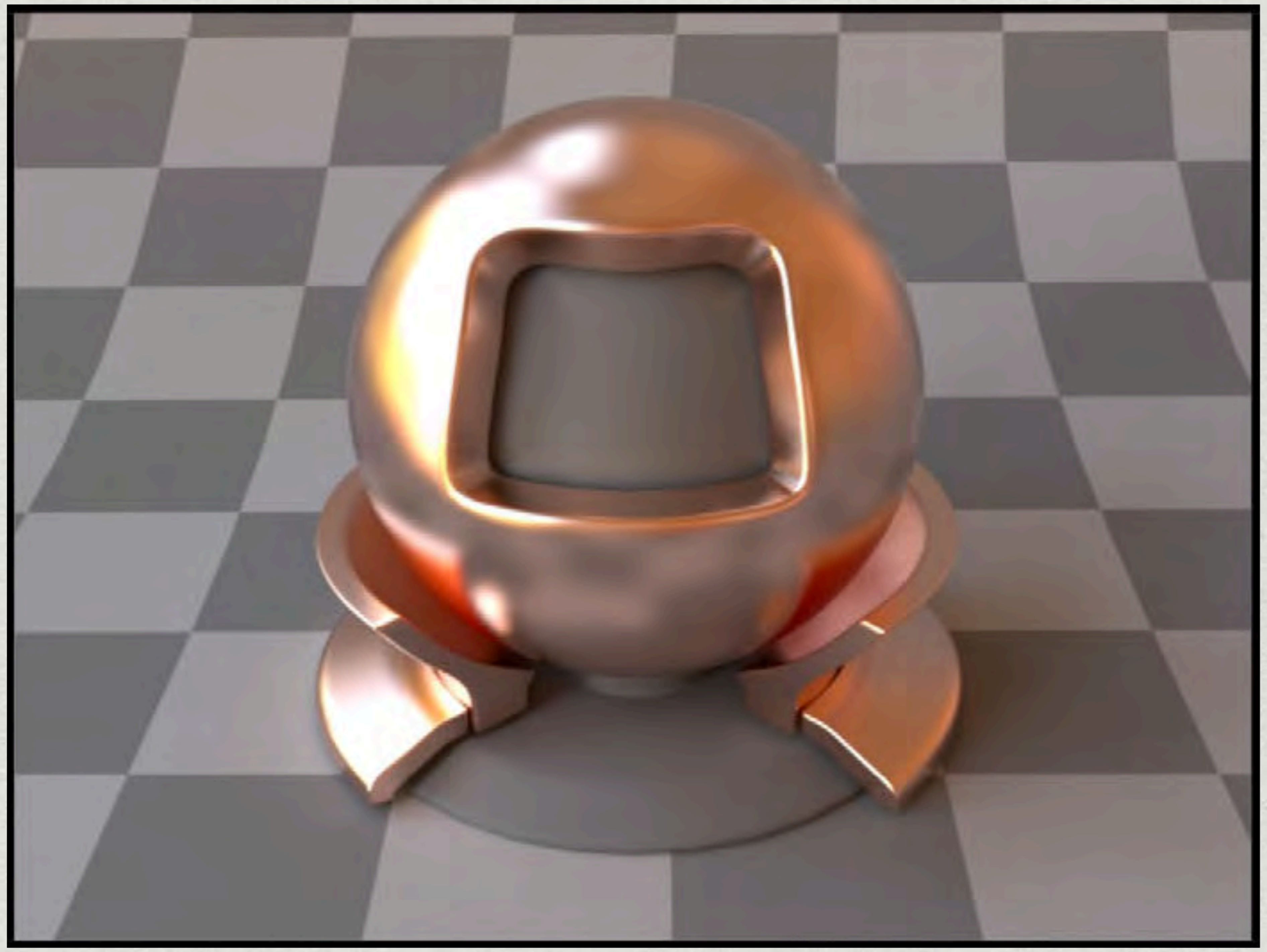
* Material is **how the light interacts objects**



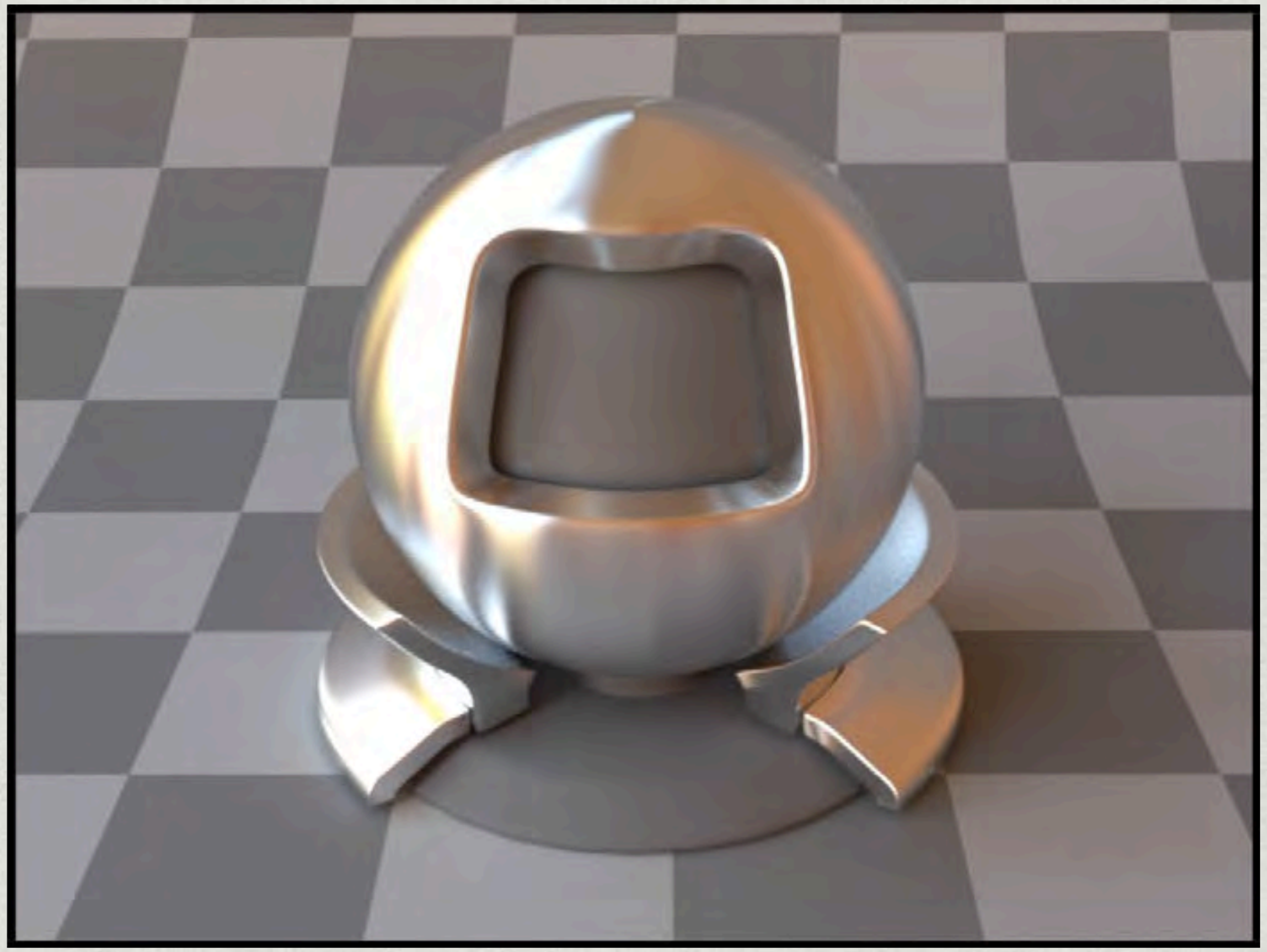
What is material?

- Material is **how the light interacts objects**





Copper



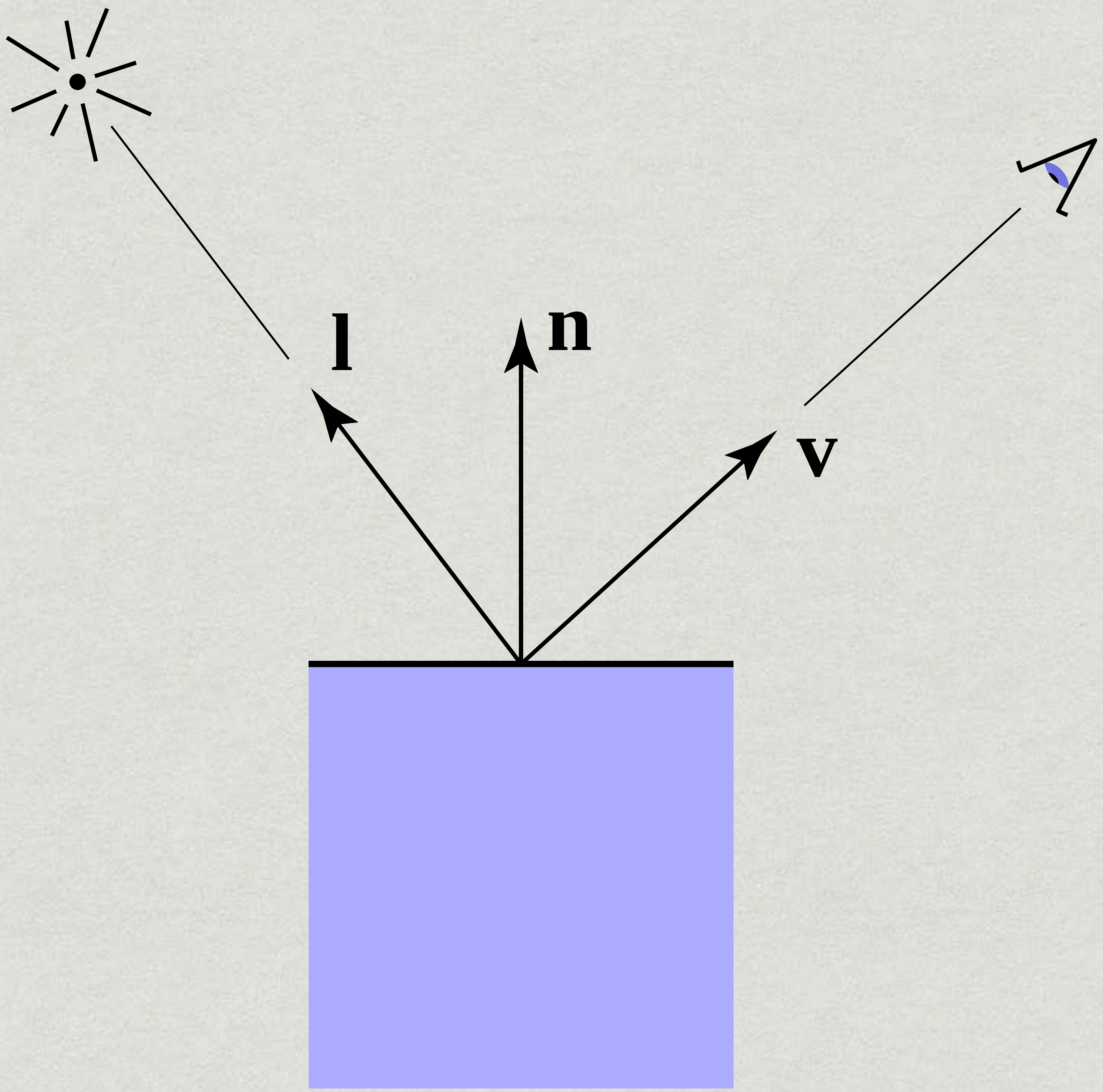
Aluminum

Glossy

Let’s make a material

Let’s make a material — Configuration

- Viewing direction: v
- Light direction: l
- Surface normal: n
- Surface Parameters: (color, shininess)

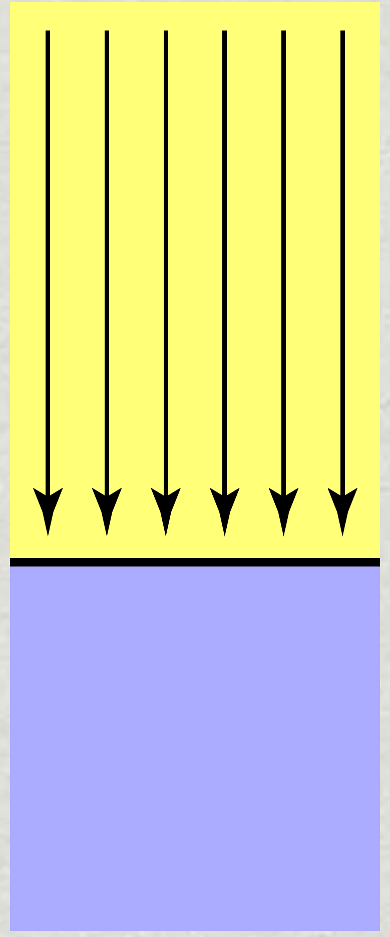


Let’s make a material — Diffuse Term

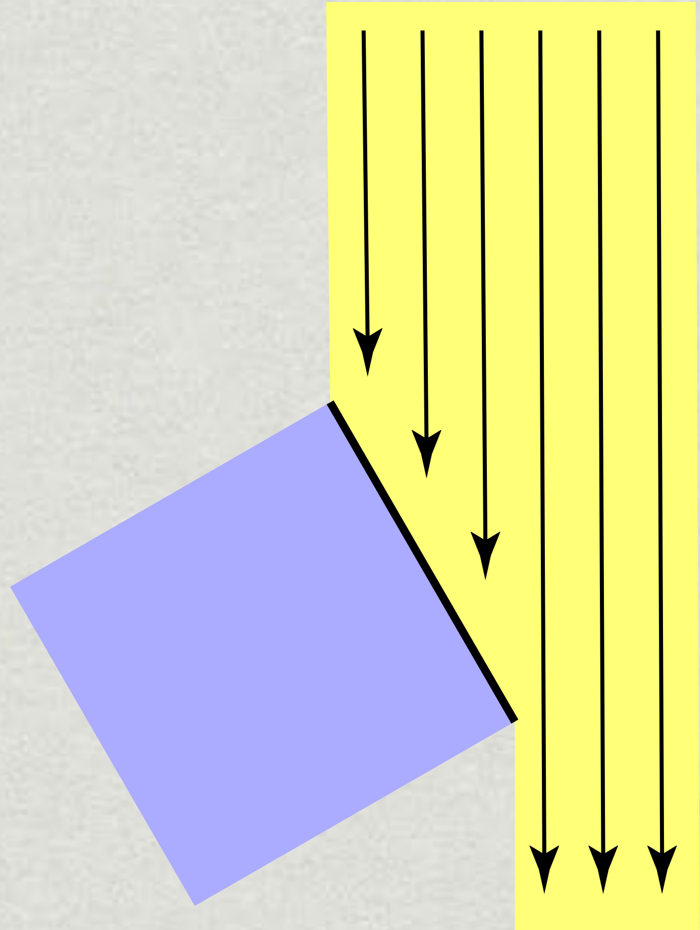
Light is scattered uniformly in all directions

- **Surface color is the same for all viewing directions**

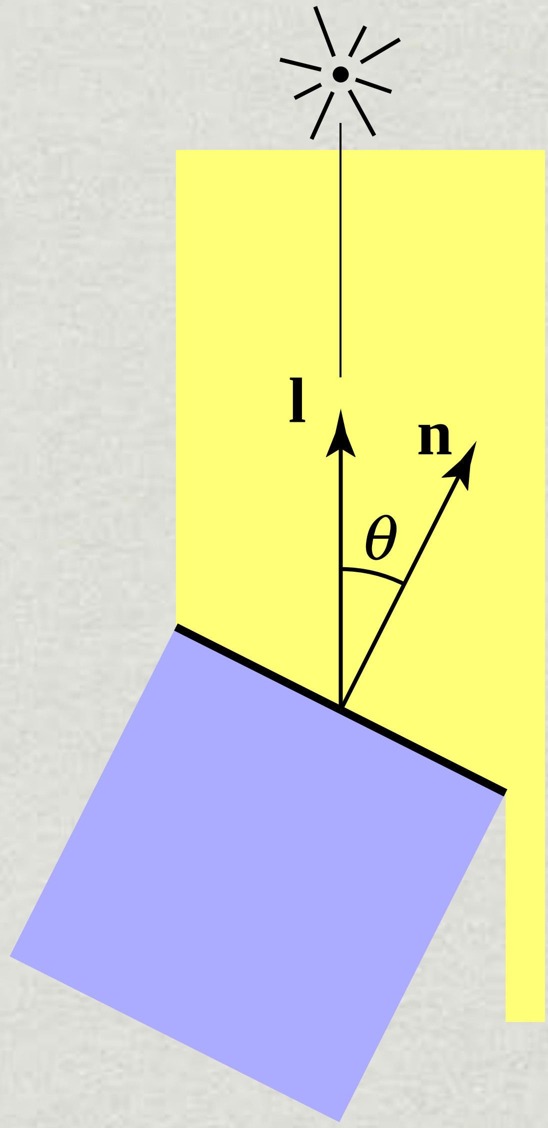
Lambert’s cosine law



Top face of cube receives a certain amount of light

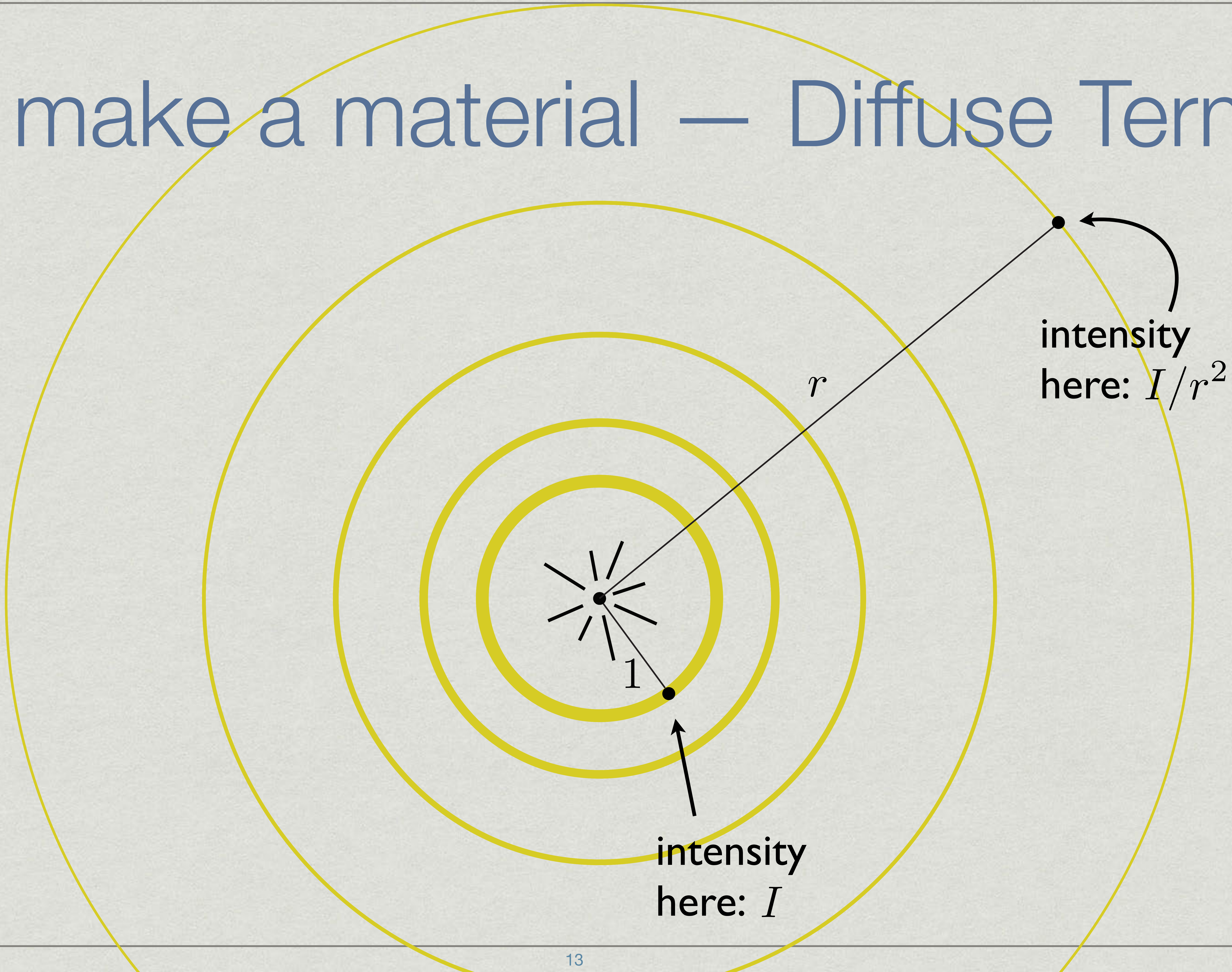


Top face of 60° rotated cube intercepts half the light



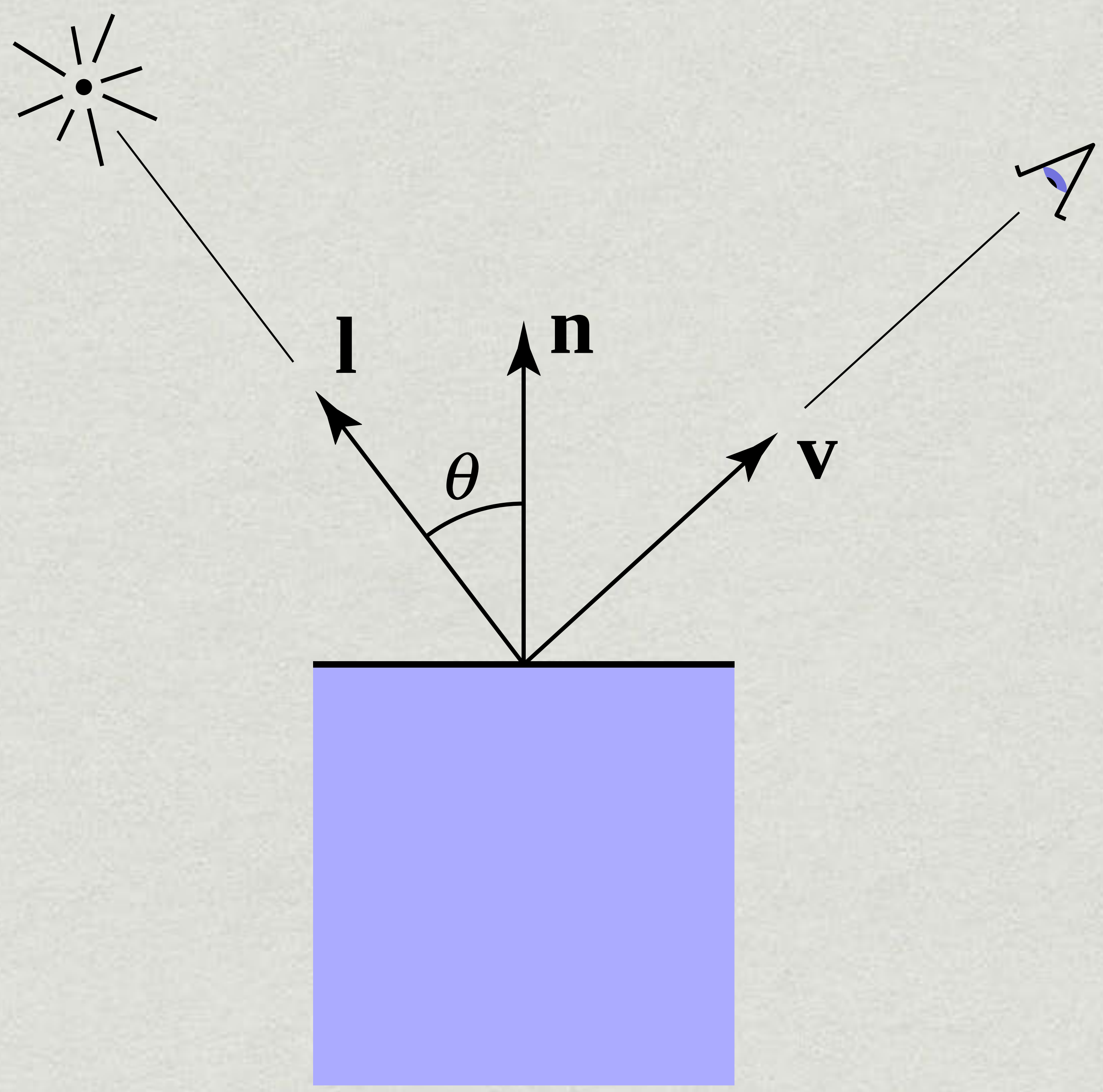
In general, light per unit area is proportional to $\cos\theta = \mathbf{l} \cdot \mathbf{n}$

Let’s make a material — Diffuse Term



Let’s make a material — Diffuse Term

independent of view direction



illumination from source

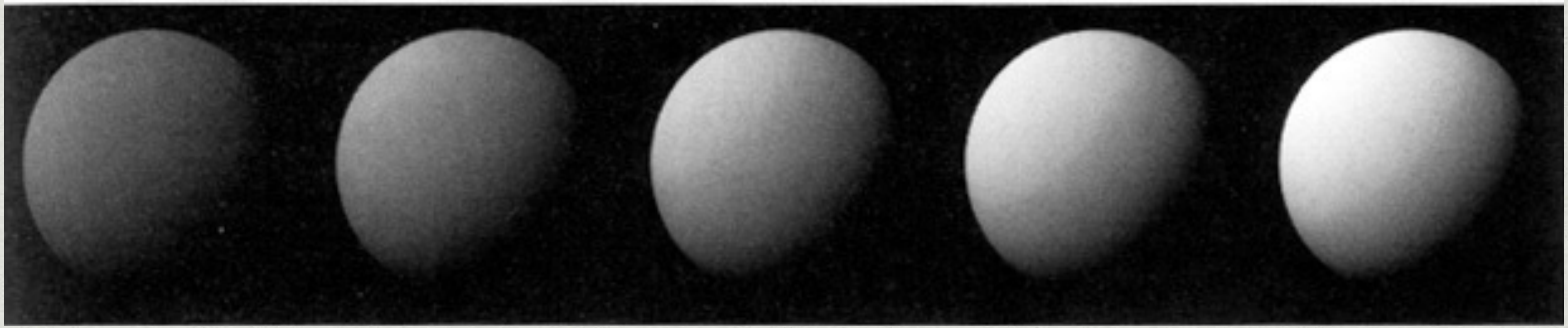
$$L_d = k_d \, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l})$$

diffuse coefficient

diffusely reflected light

Let's make a material — Diffuse Term

Produces matte appearance

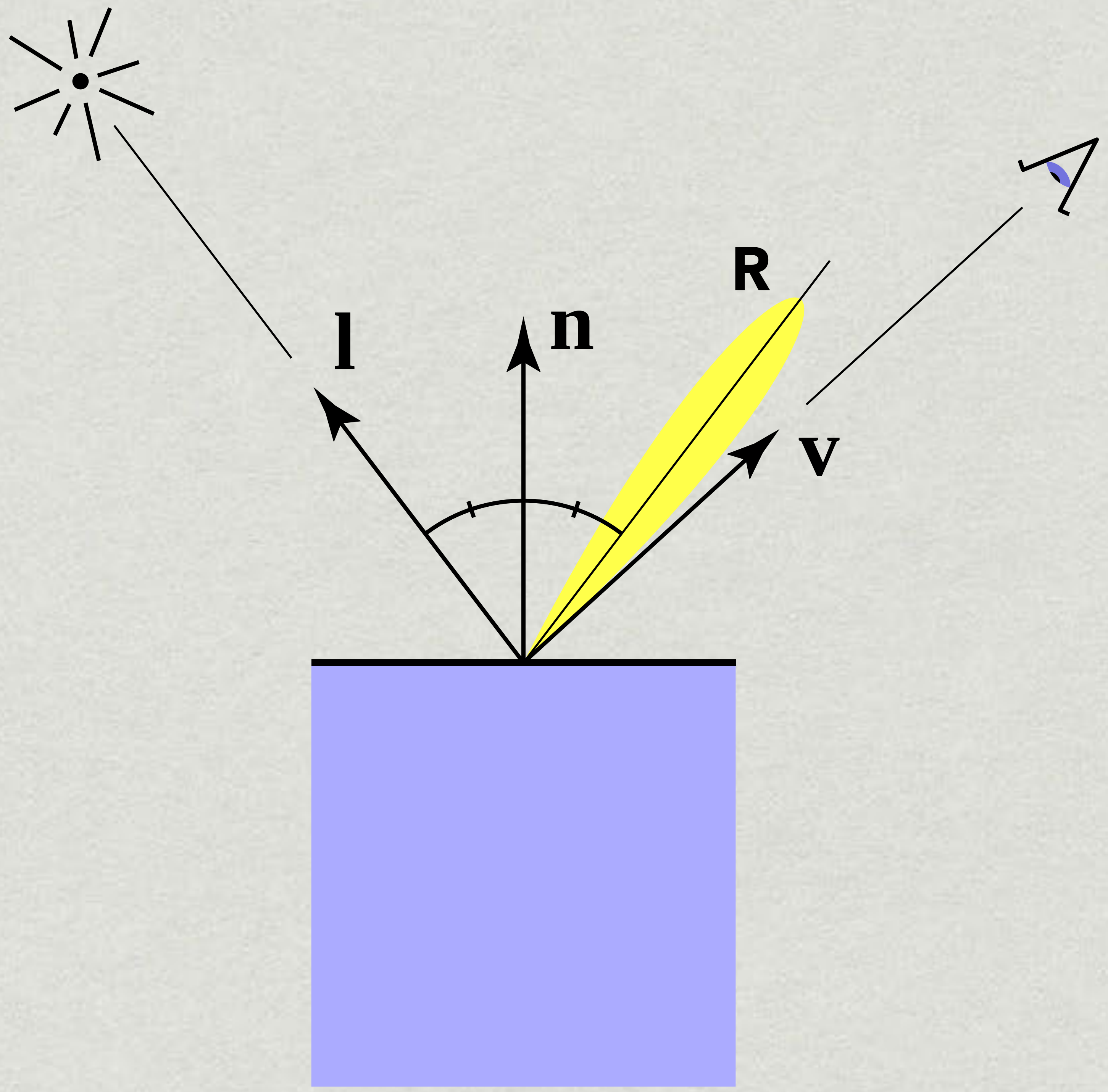


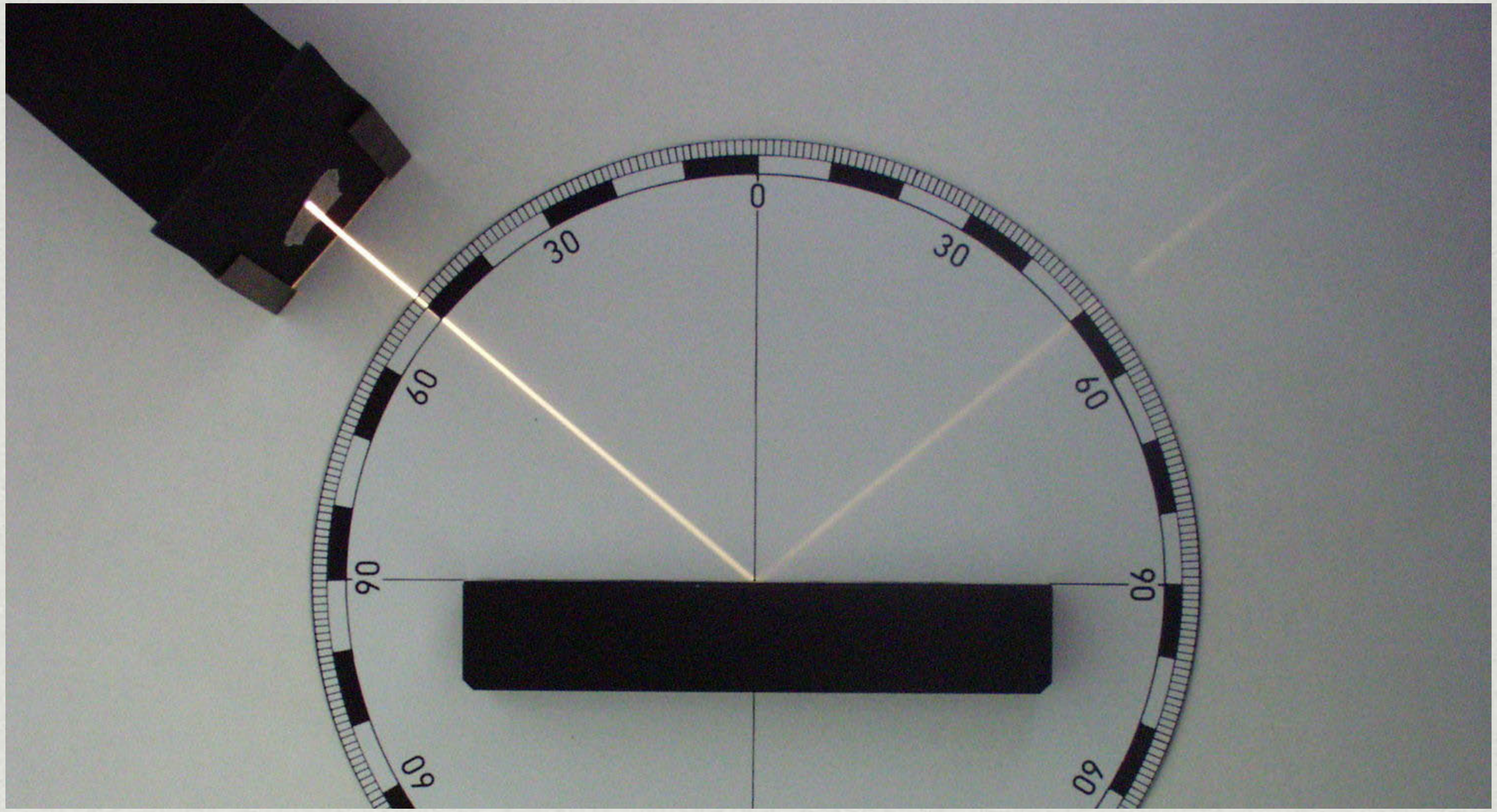
$k_d \longrightarrow$

Let's make a material — Highlight Term

Intensity depends on view direction

- Bright near mirror reflection direction

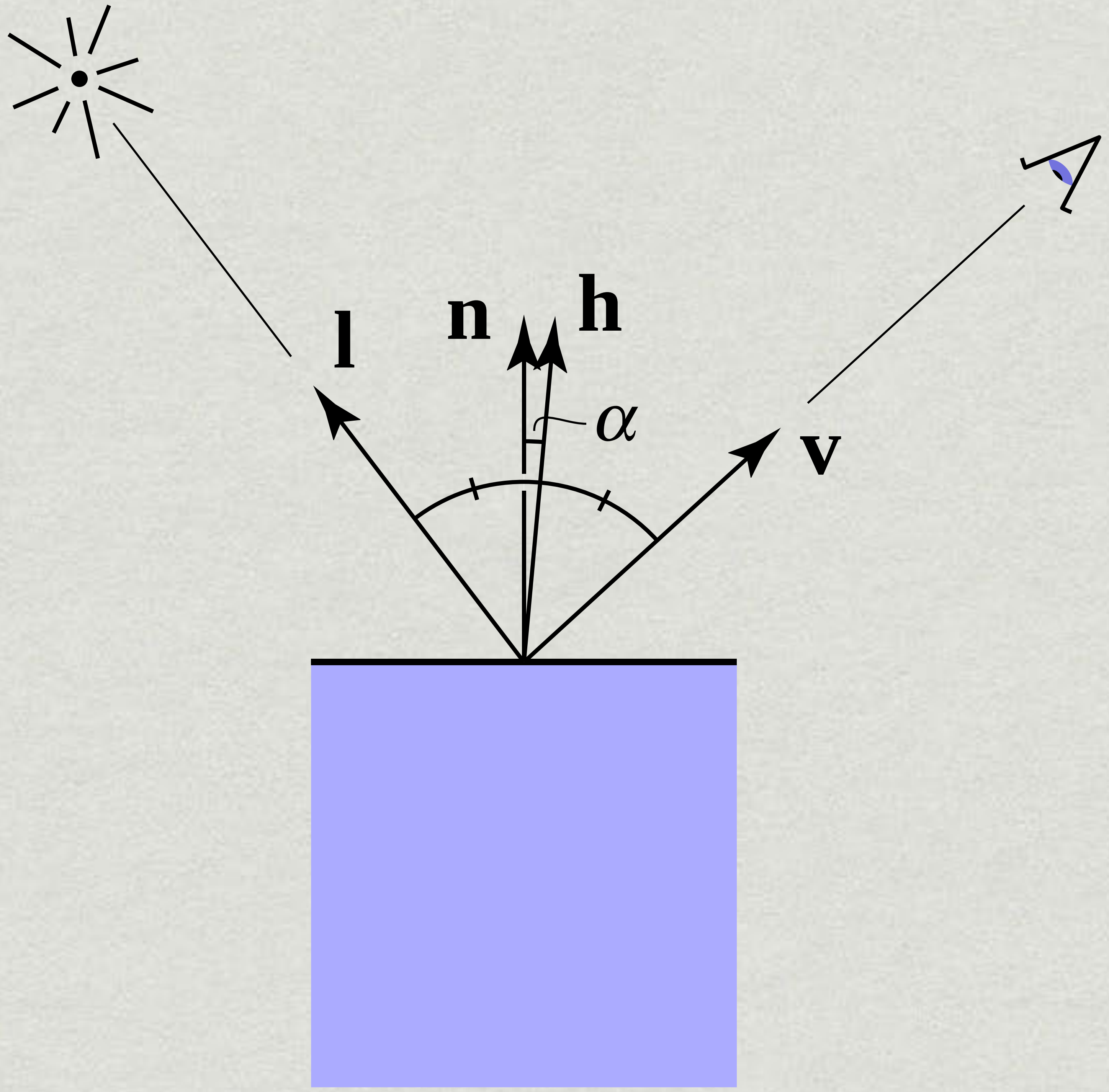




Let's make a material — Highlight Term

Close to mirror ⇔ half vector near normal

- Measure "near" by dot product of unit vectors



$$\mathbf{h} = \mathrm{bisector}(\mathbf{v}, \mathbf{l})$$
$$= \frac{\mathbf{v} + \mathbf{l}}{\|\mathbf{v} + \mathbf{l}\|}$$

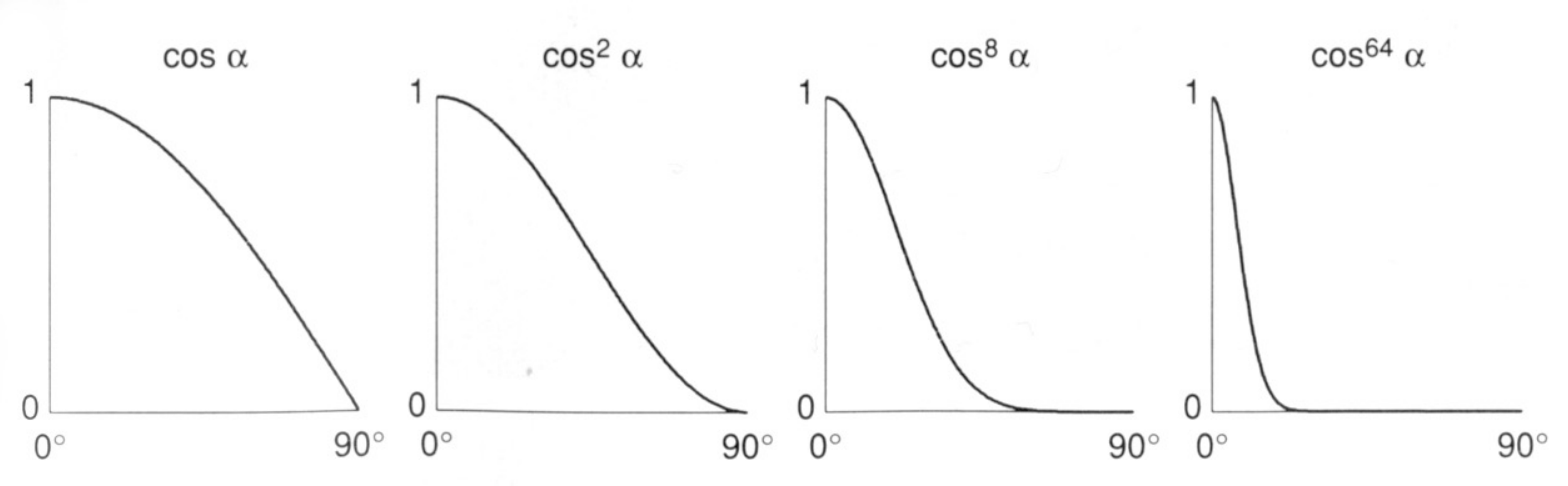
$$L_s = k_s \, (I/r^2) \max(0, \cos\alpha)^p$$
$$= k_s \, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p$$

specularly reflected light

specular coefficient

Let's make a material — Highlight Term

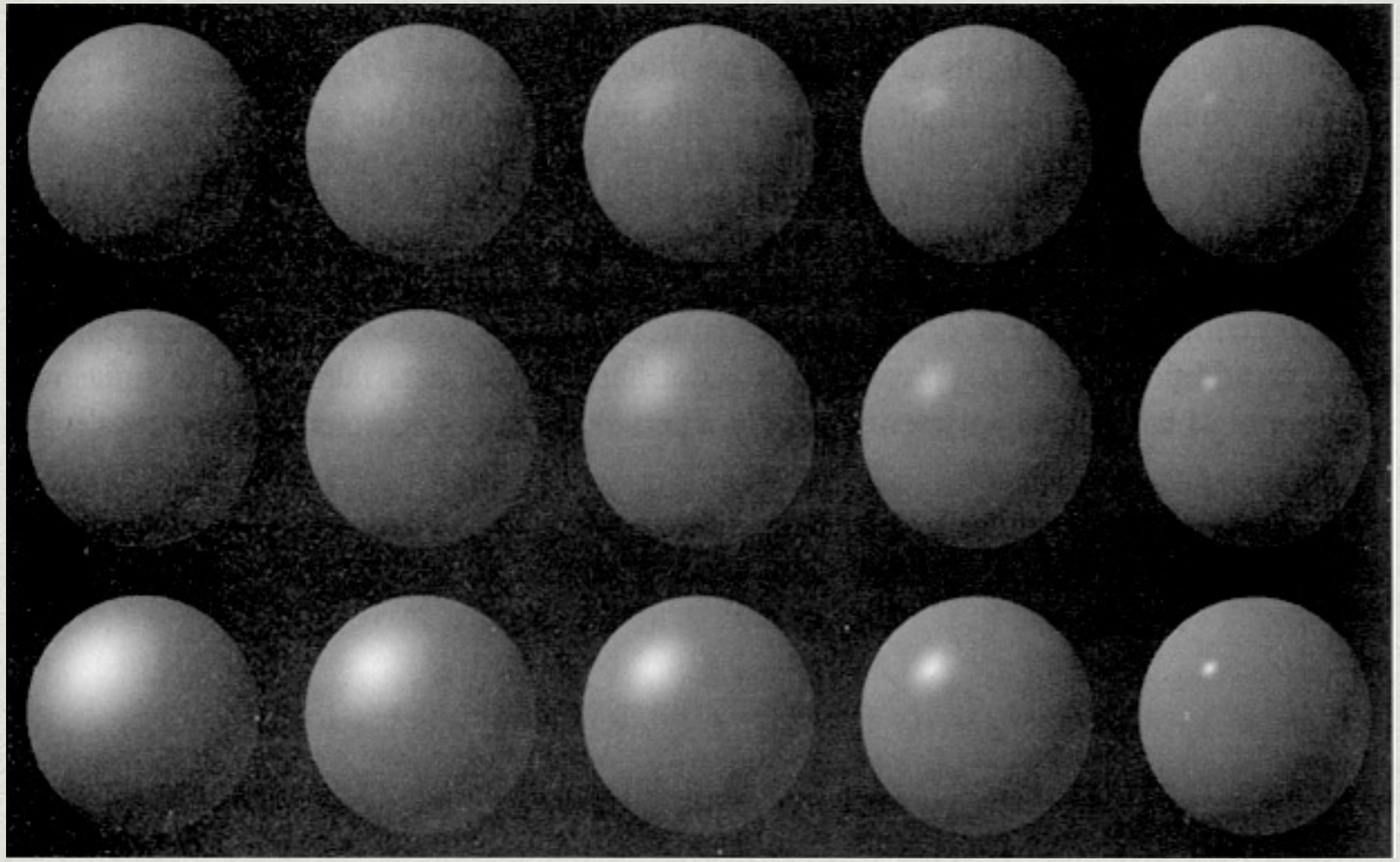
Increasing p narrows the reflection lobe



Let’s make a material — Highlight Term

$$L_s = k_s\,(I/r^2)\,\max(0, \mathbf{n}\cdot\mathbf{h})^p$$

k_s

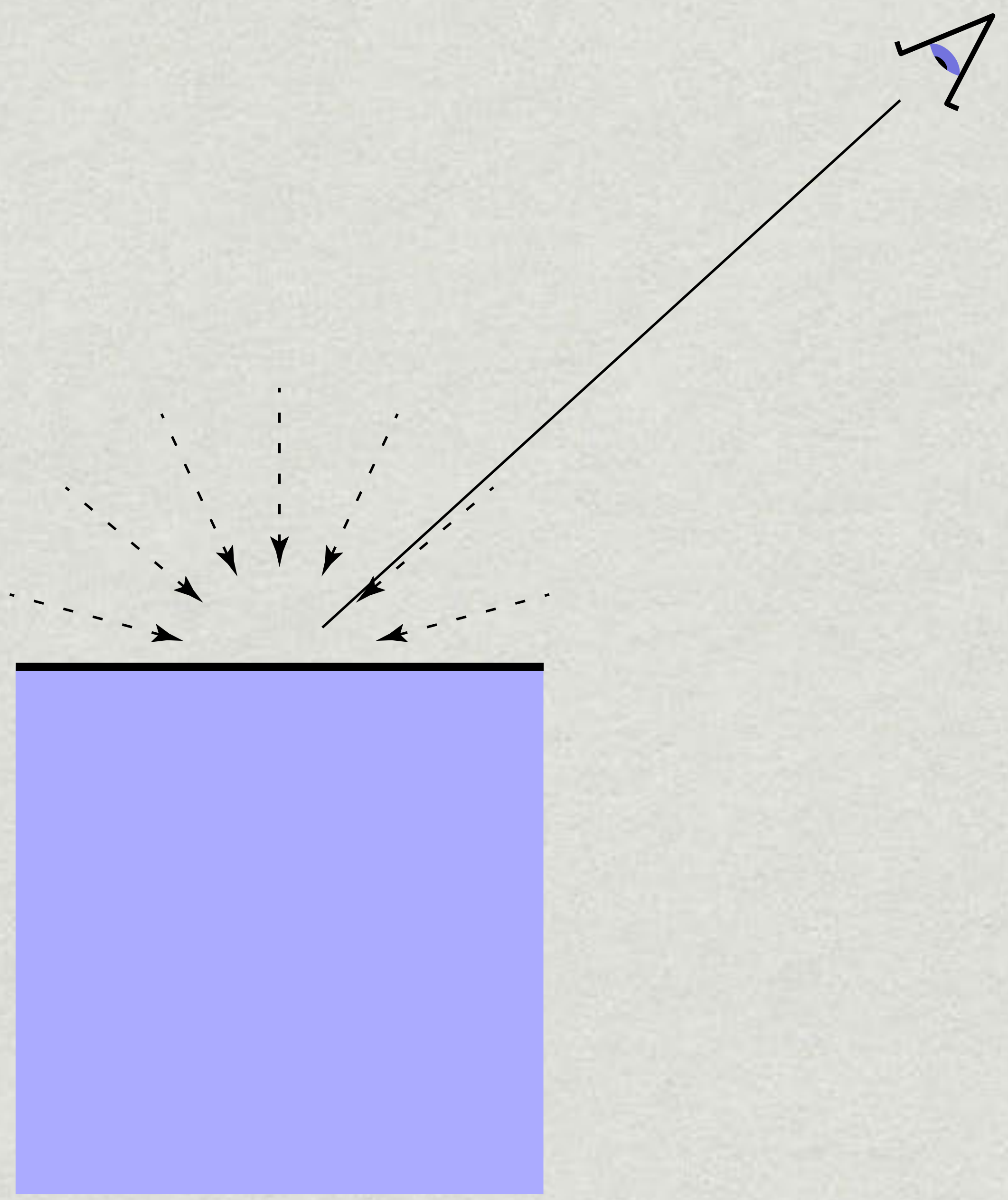


p

Let’s make a material — Ambient Term

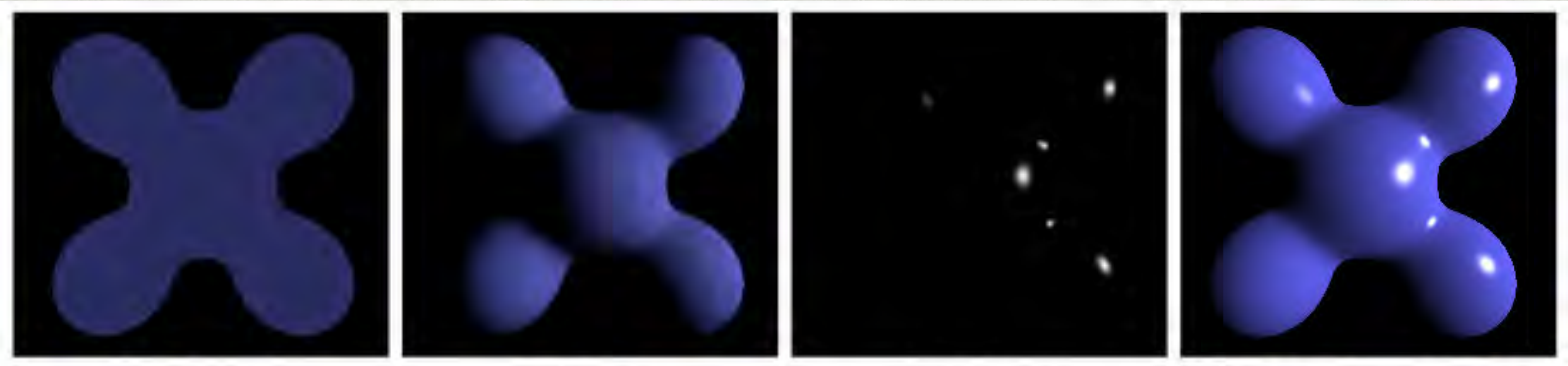
Does not depend on anything

- Add constant color to account for disregarded illumination and fill in black shadows



$$\underbrace{L_a}_{\text{reflected ambient light}} = \underbrace{k_a}_{\text{ambient coefficient}} \, I_a$$

Let's make a material — **Blinn-Phong**

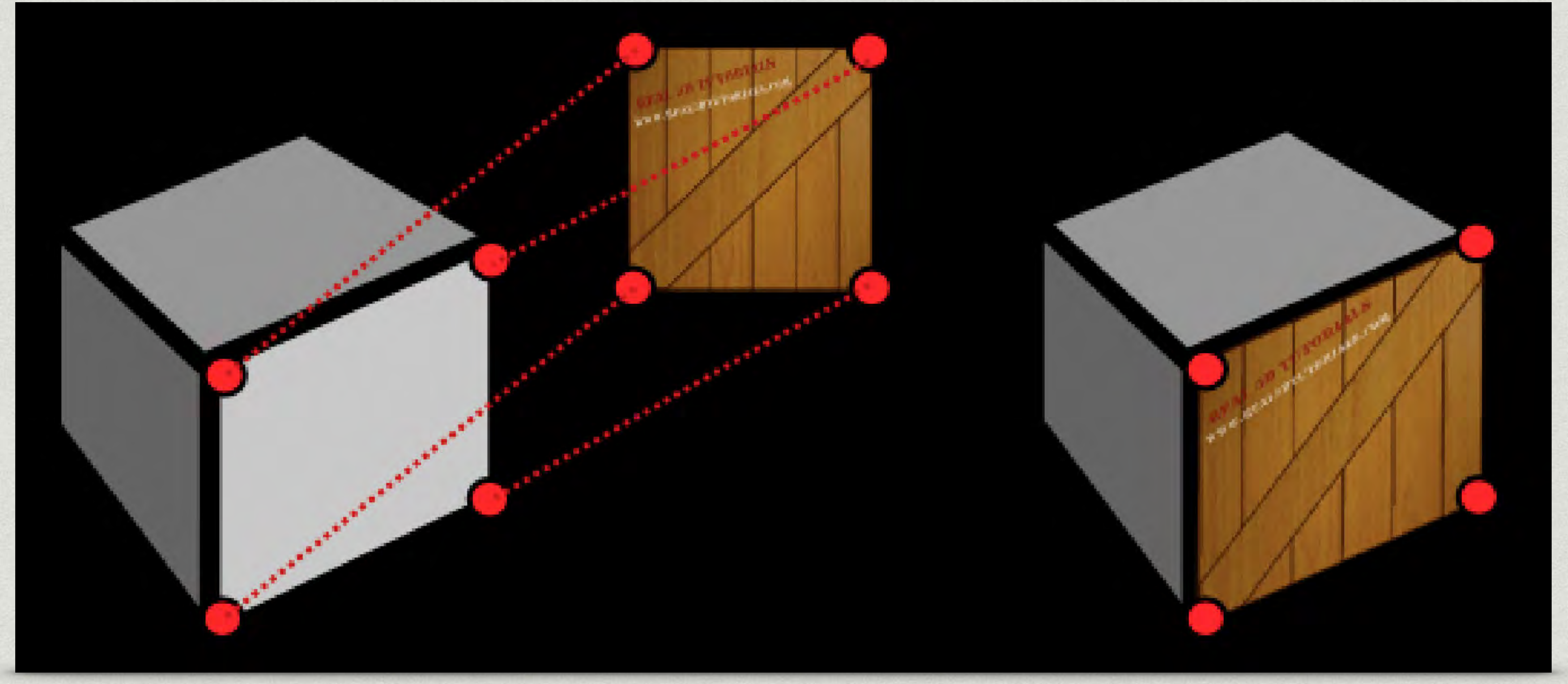


Ambient + Diffuse + Specular = **Blinn-Phong Model**

$$
\begin{aligned}
L &= L_a + L_d + L_s \\
&= k_a\, I_a + k_d\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l}) + k_s\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p
\end{aligned}
$$

Add some color — texture mapping

- A texture is an image that specifies spatially-varying colors (Kd).



Applying the material

Shading

- In Merriam-Webster Dictionary

  shad·ing, [ˈʃeɪdɪŋ], noun

  The darkening or coloring of an illustration or diagram with parallel lines or a block of color.

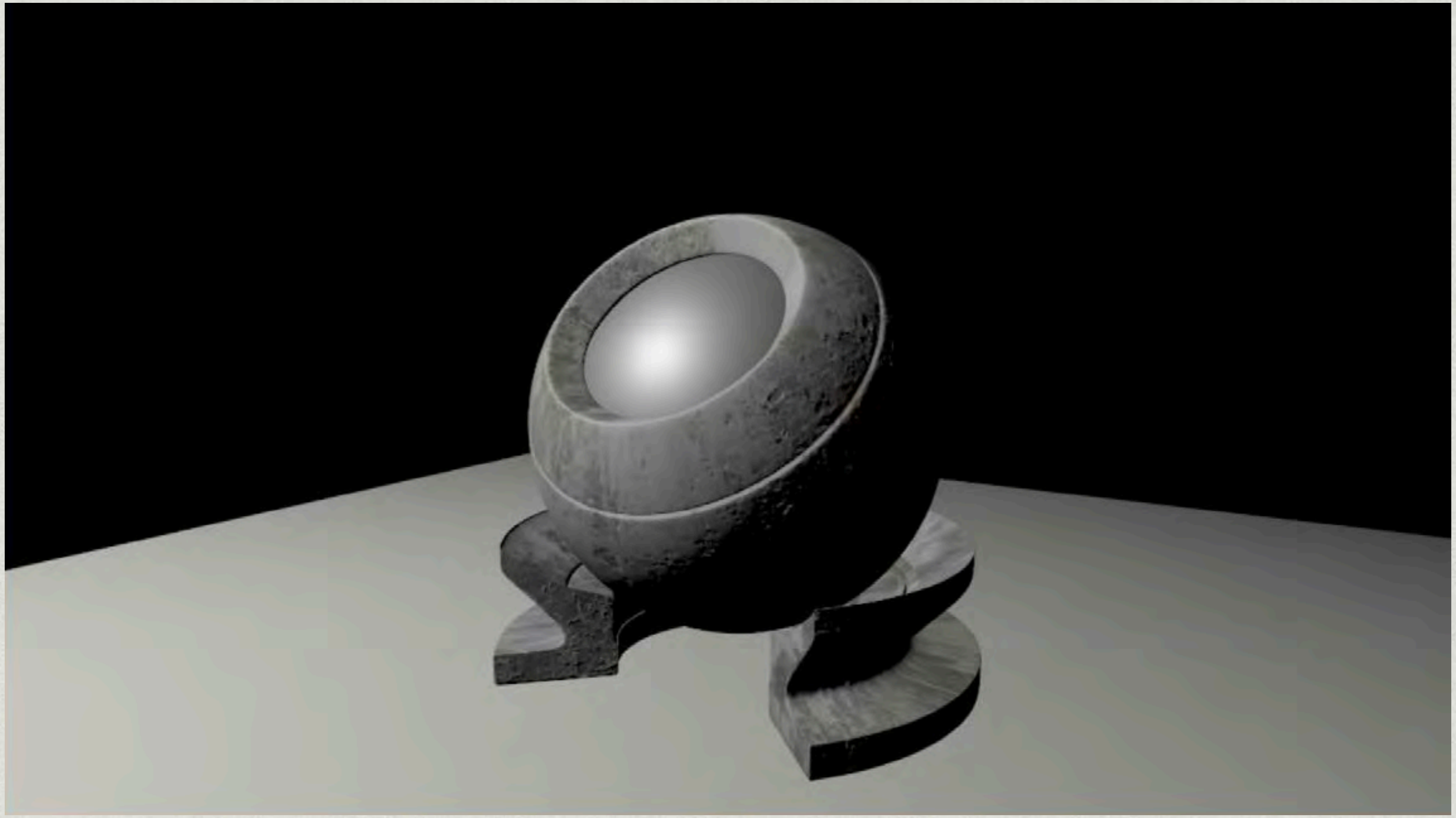
- By Lingqi

  (1) The process of applying a material to an object.

  (2) The process of **local** rendering.

Shading == local rendering

No shadows, no indirect illumination



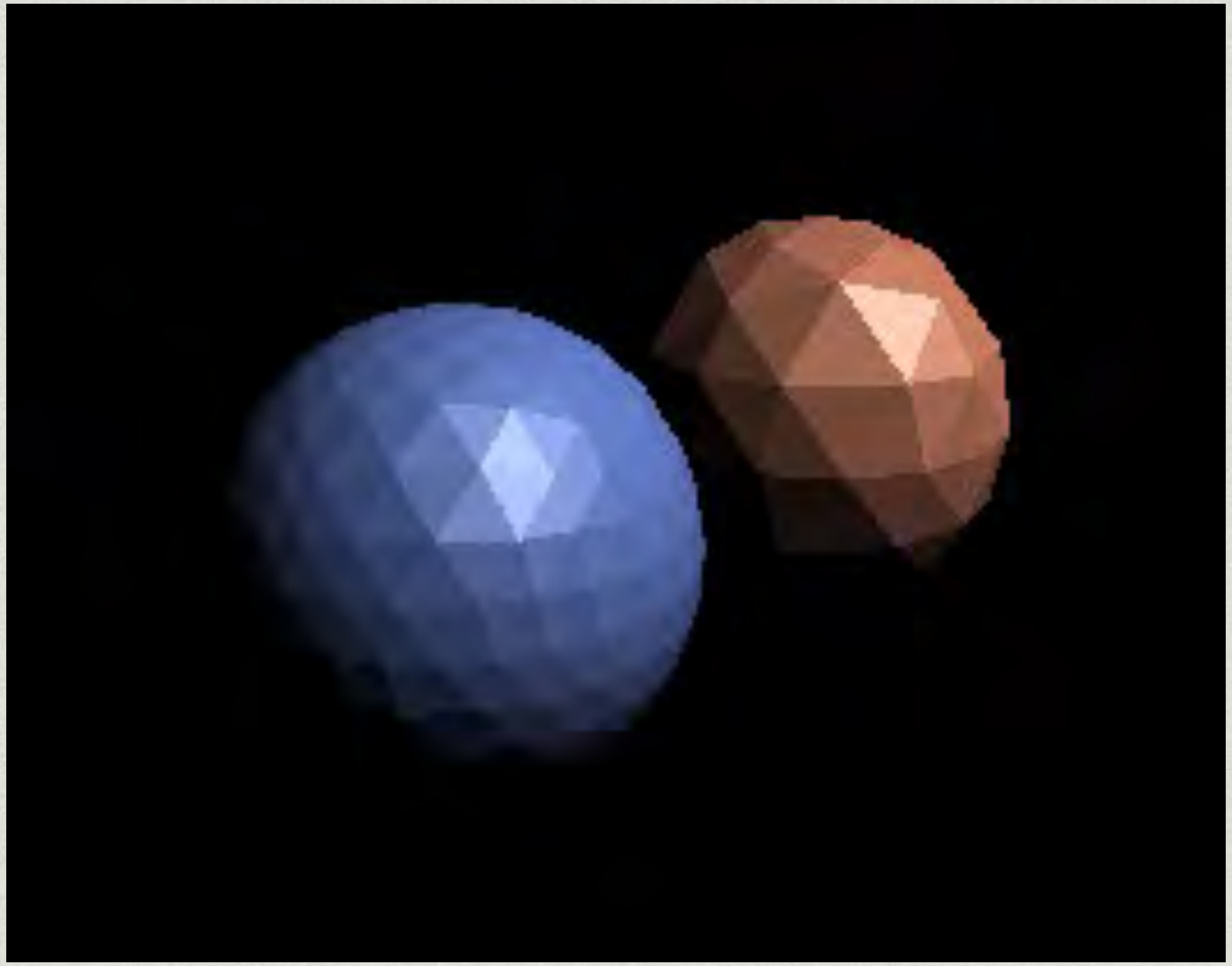
Shading methods

What caused the shading difference?

Shade each triangle (flat shading)

flat shading

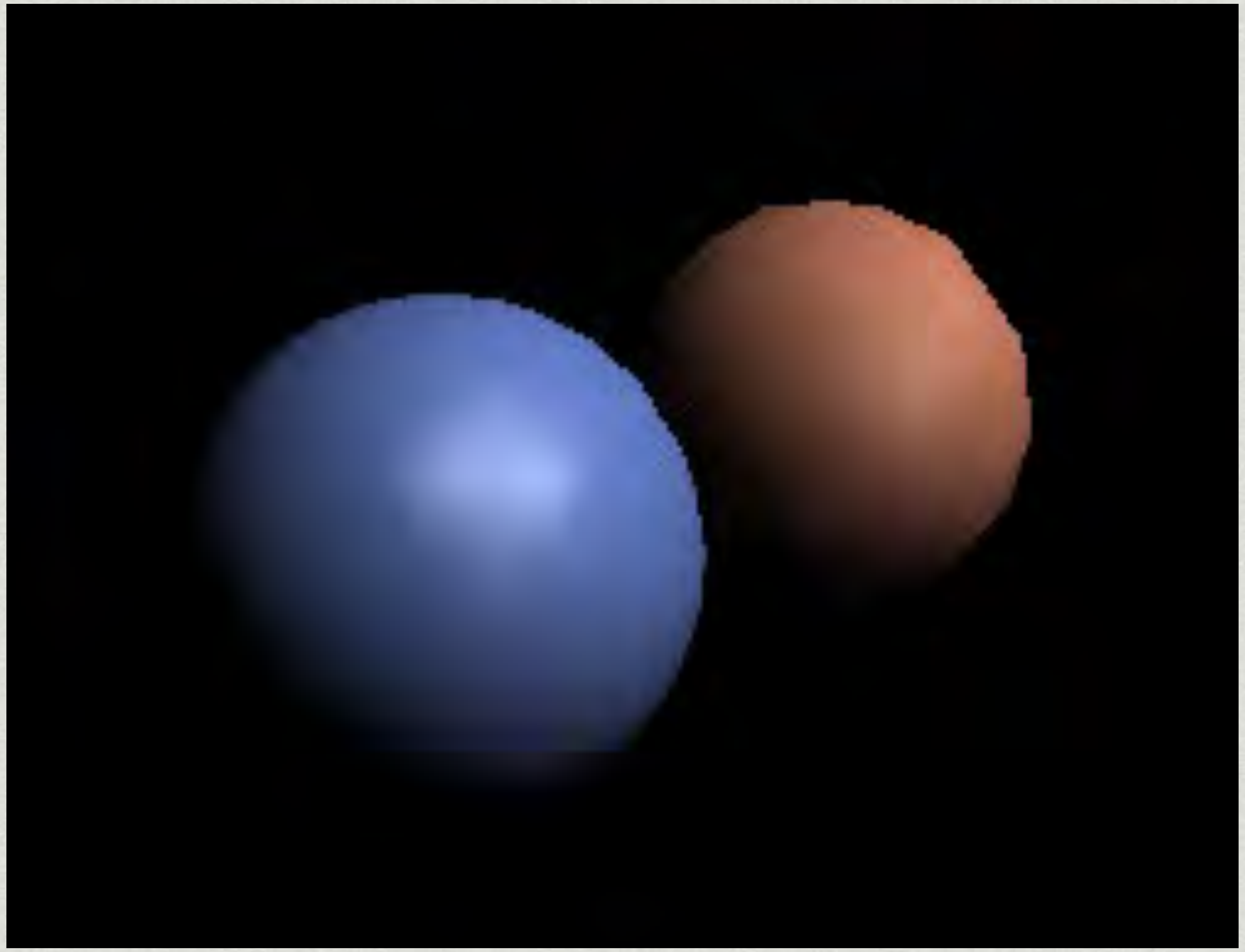
- Triangle face is flat — one normal vector
- Not good for smooth surfaces



Shade each vertex (Gouraud shading)

Gouraud shading

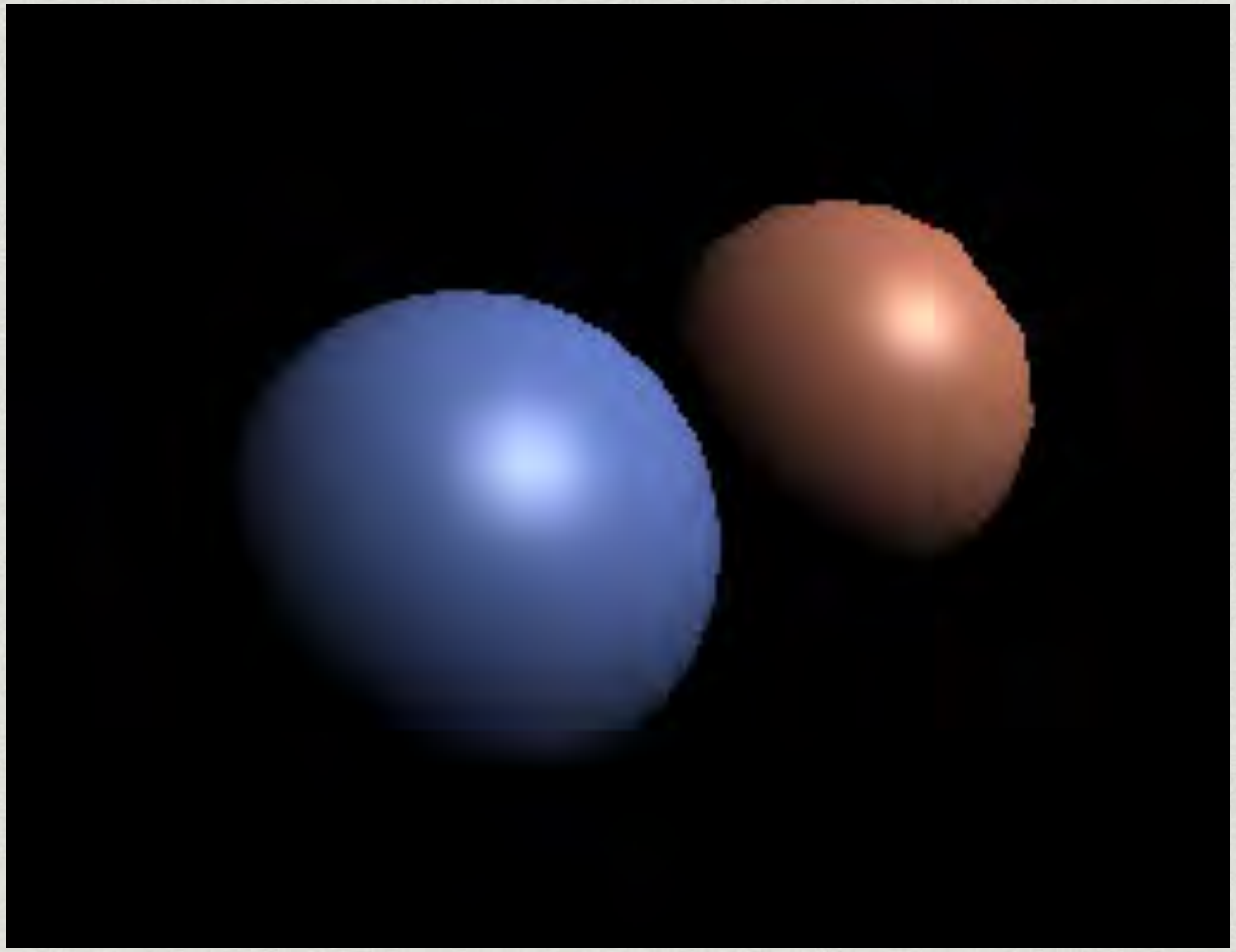
- Interpolate colors from vertices across triangle
- Each vertex has a normal vector



Shade each pixel (Phong shading)

Phong shading

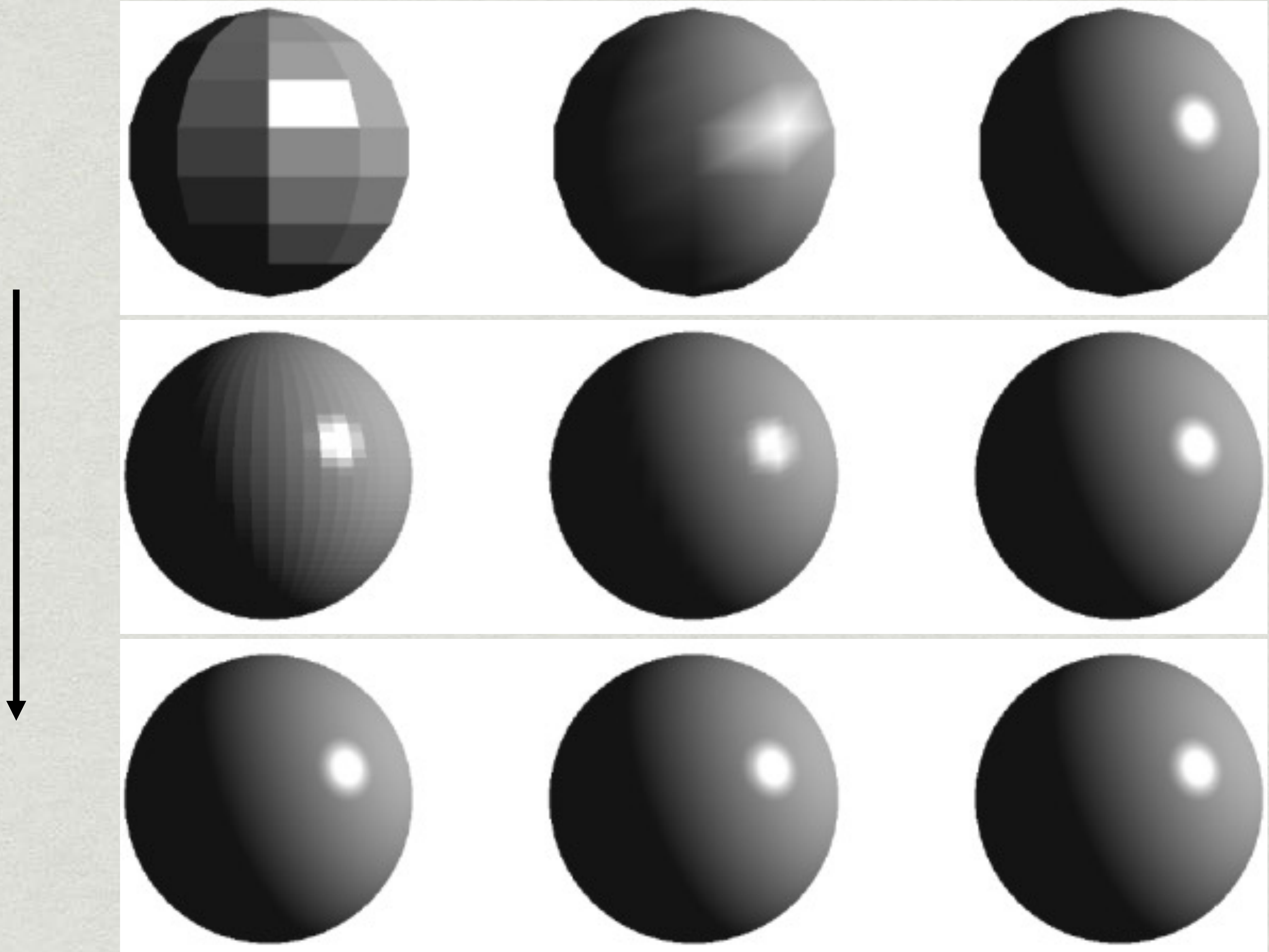
- Interpolate normal vectors across each triangle
- Compute full shading model at each pixel
- Not Phong material model



In fact…

- As long as there are enough faces / vertices, any shading method works fine.

Num
Vertices



Face
Flat

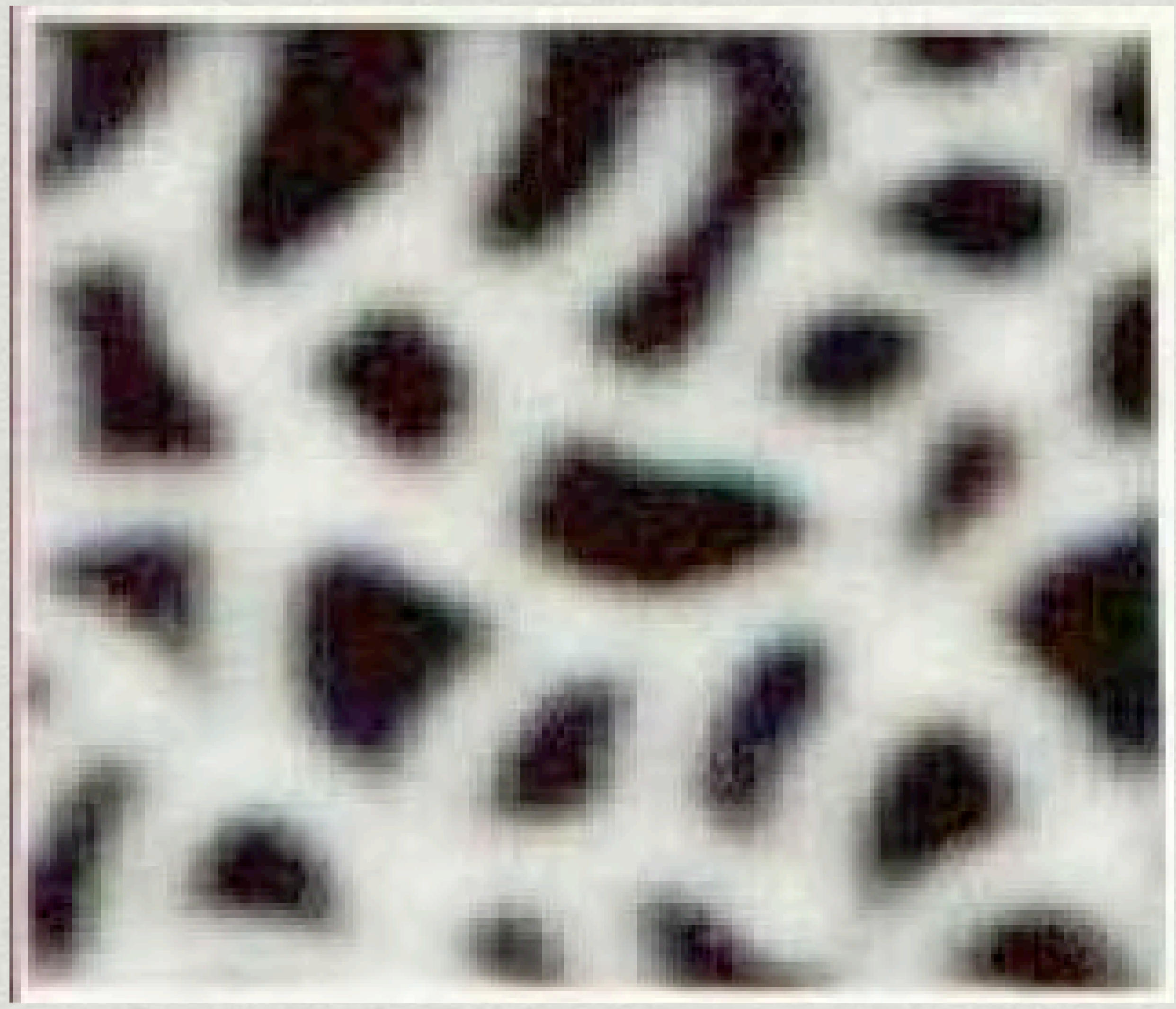
Vertex
Gouraud

Pixel
Phong

Textures can affect shading!

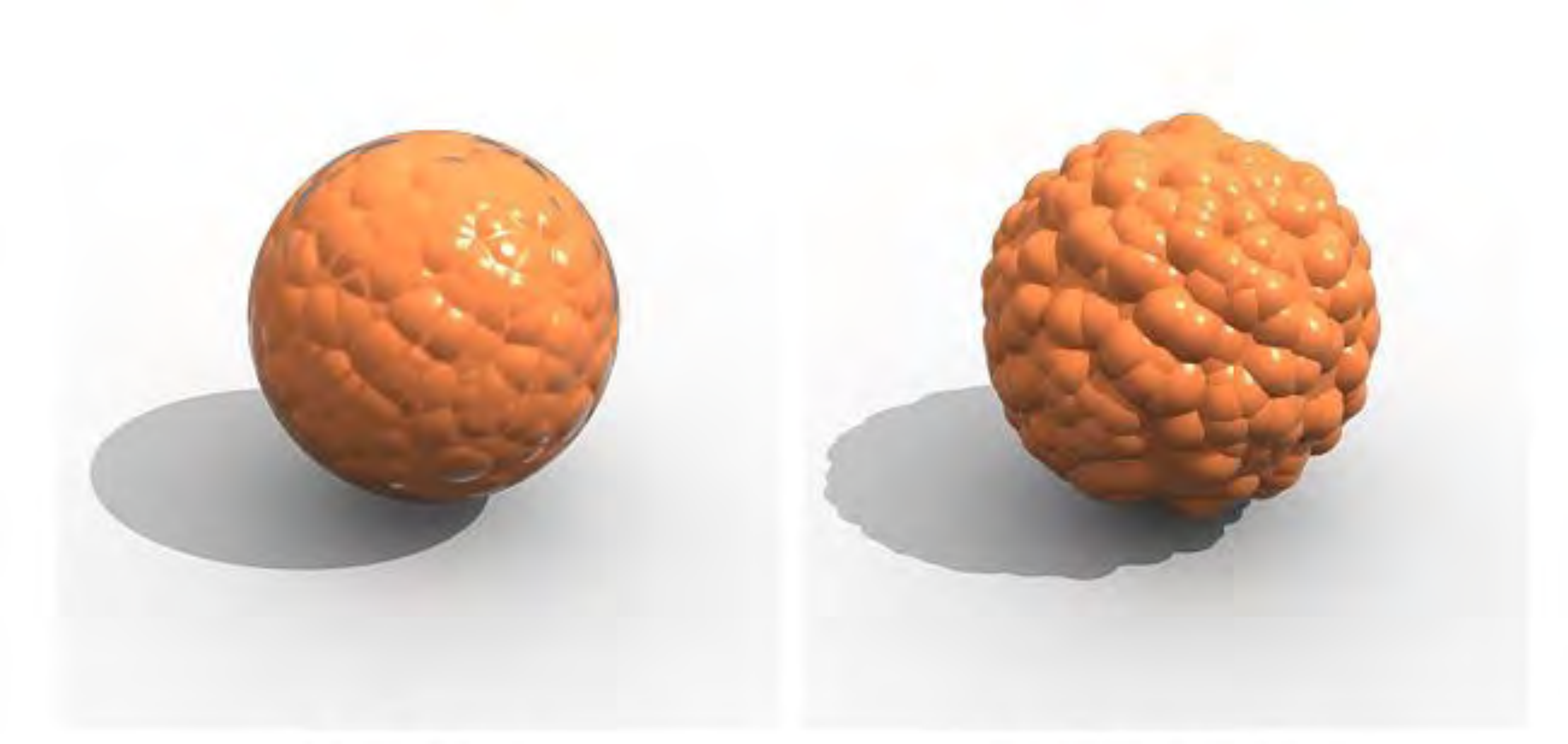
- Textures doesn't have to only represent colors
  - What if it stores the height / normal?
  - Bump / normal mapping
  - **Fake** the detailed geometry

Relative height to the underlying surface



Textures can affect shading!

- Displacement mapping — a more advanced approach
  - Actually subdivides the mesh and **modify** the geometry



Bump/normal mapping Displacement mapping

Physically-based materials

What is material?

- Recap: the Rendering Equation

$$L_o(x,\omega_o) = L_e(x,\omega_o) + \int_{H^2} L_i(x,\omega_i) f_r(x,\omega_i \rightarrow \omega_o) \cos\theta_i d\omega_i$$

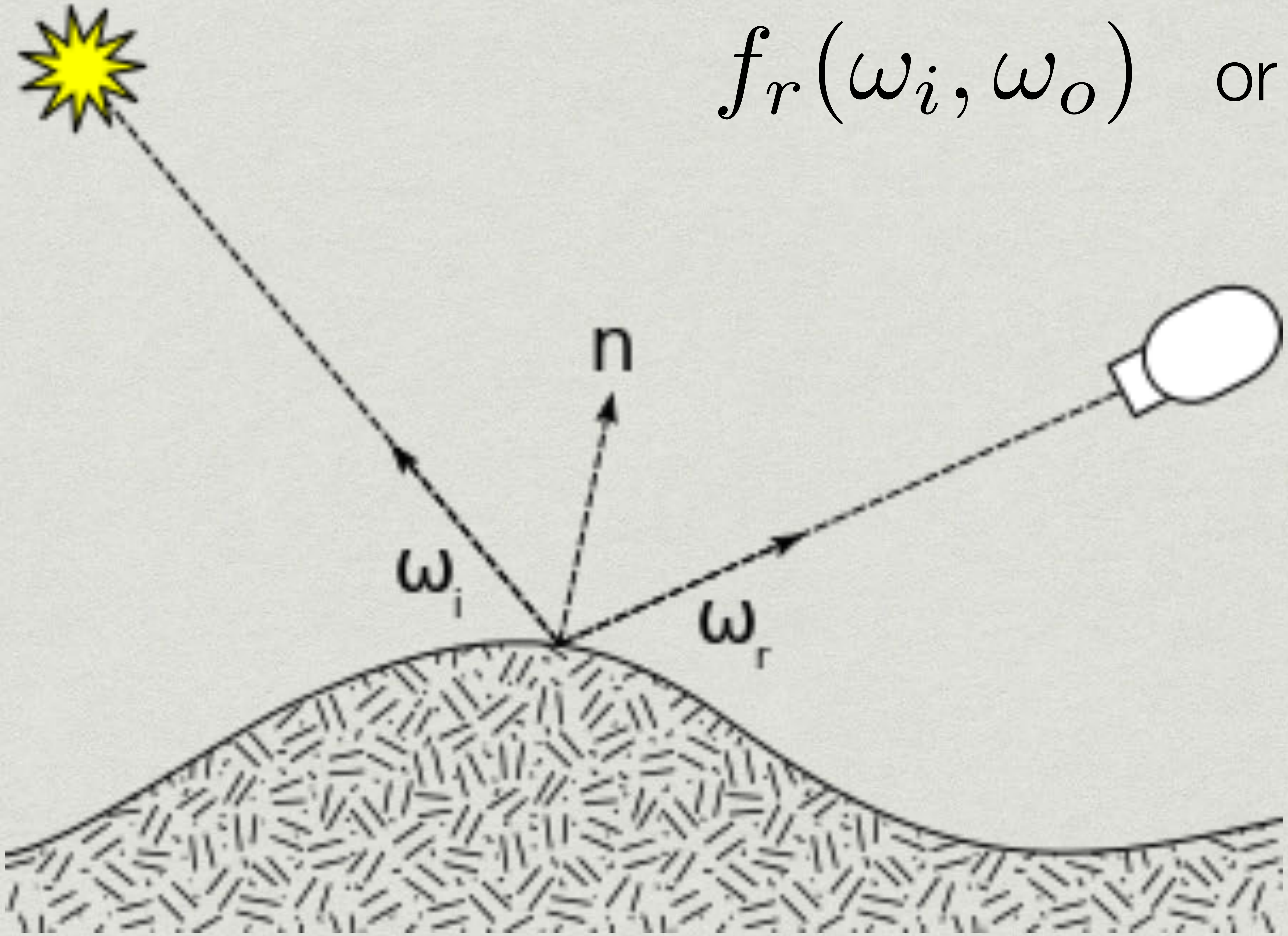
outgoing radiance

emission

incident radiance

BRDF (Bidirectional Reflection Distribution Function)

BRDF (Bidirectional Reflection Distribution Function)



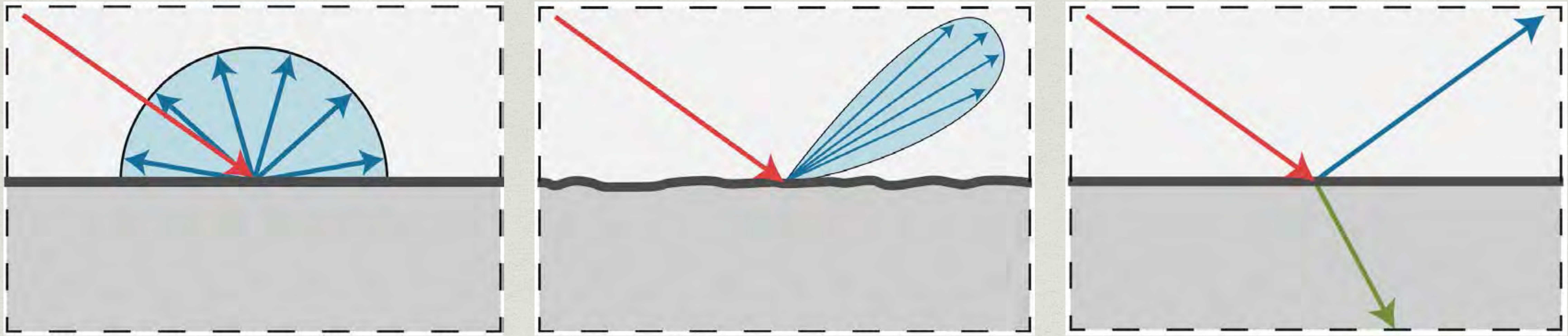
$$f_r(\omega_i, \omega_o) \quad \text{or} \quad f_r(\theta_i, \phi_i, \theta_o, \phi_o)$$

- At any position, it represents how much light is reflected into each outgoing direction from each incoming direction
- 4D function
  2D for incoming direction
  2D for outgoing direction

Material == BRDF

Material == BRDF

- Because BRDF defines **how the light interacts objects**



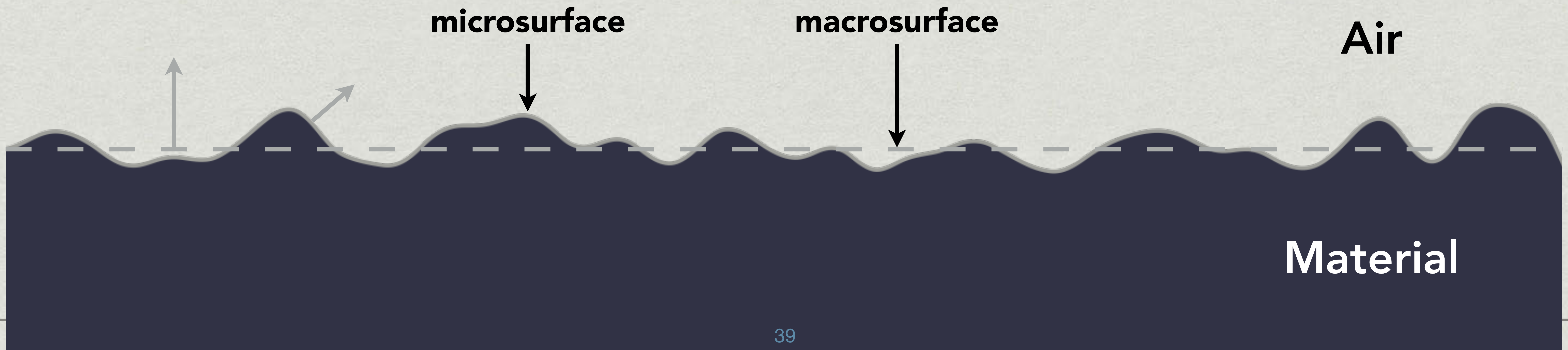
Diffuse Glossy Specular

Microfacet BRDF

Microfacet model in the real world

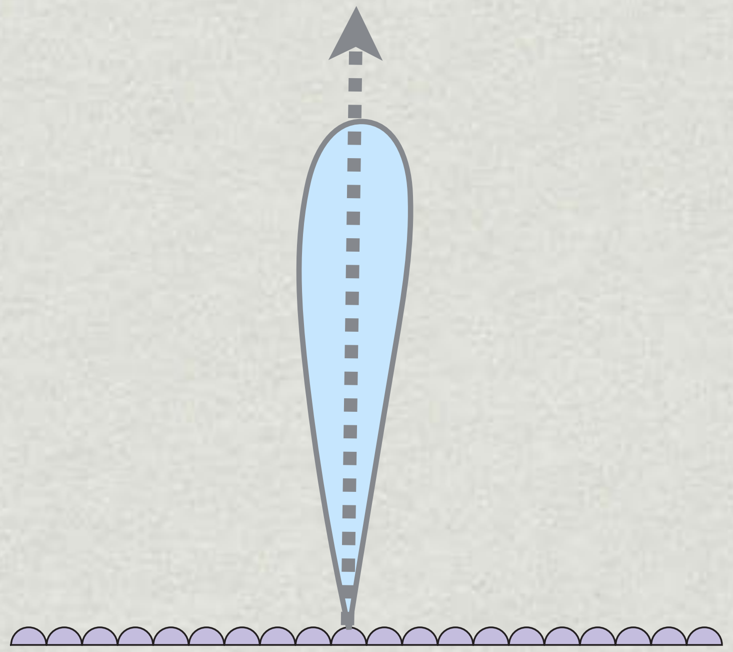
Microfacet Theory

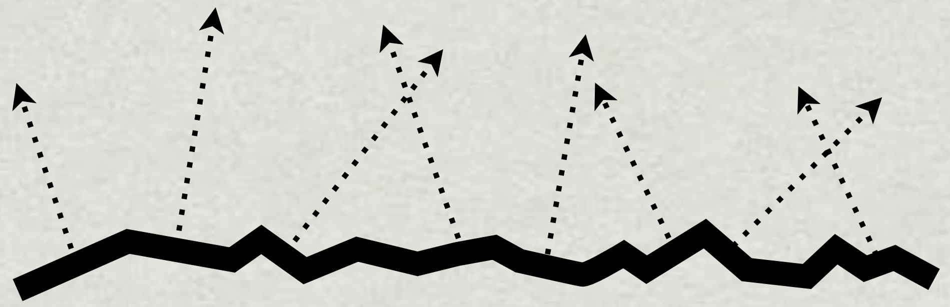
- Rough surface
  - Macroscale: flat & rough
  - Microscale: bumpy & specular
- Individual elements of surface act like mirrors
  - Known as Microfacets
  - Each microfacet has its own normal

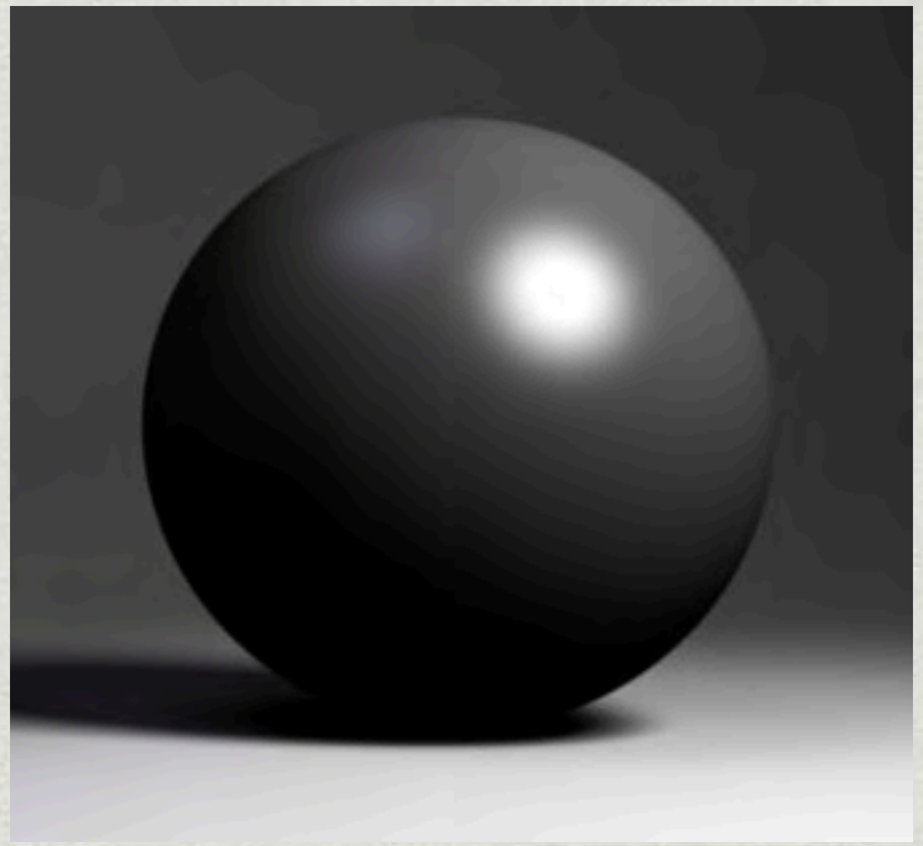


Microfacet BRDF

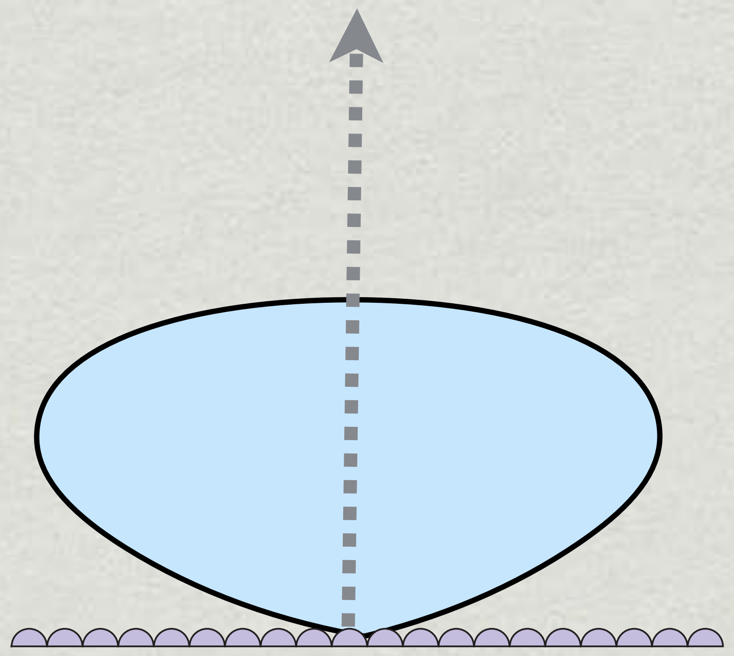
- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

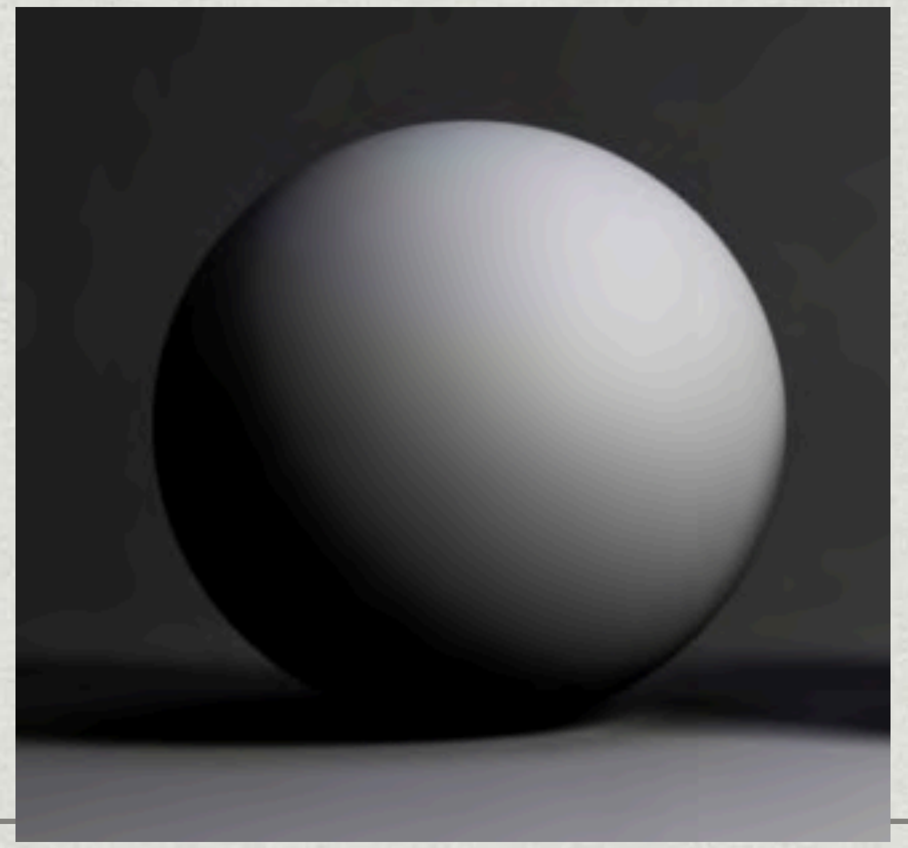






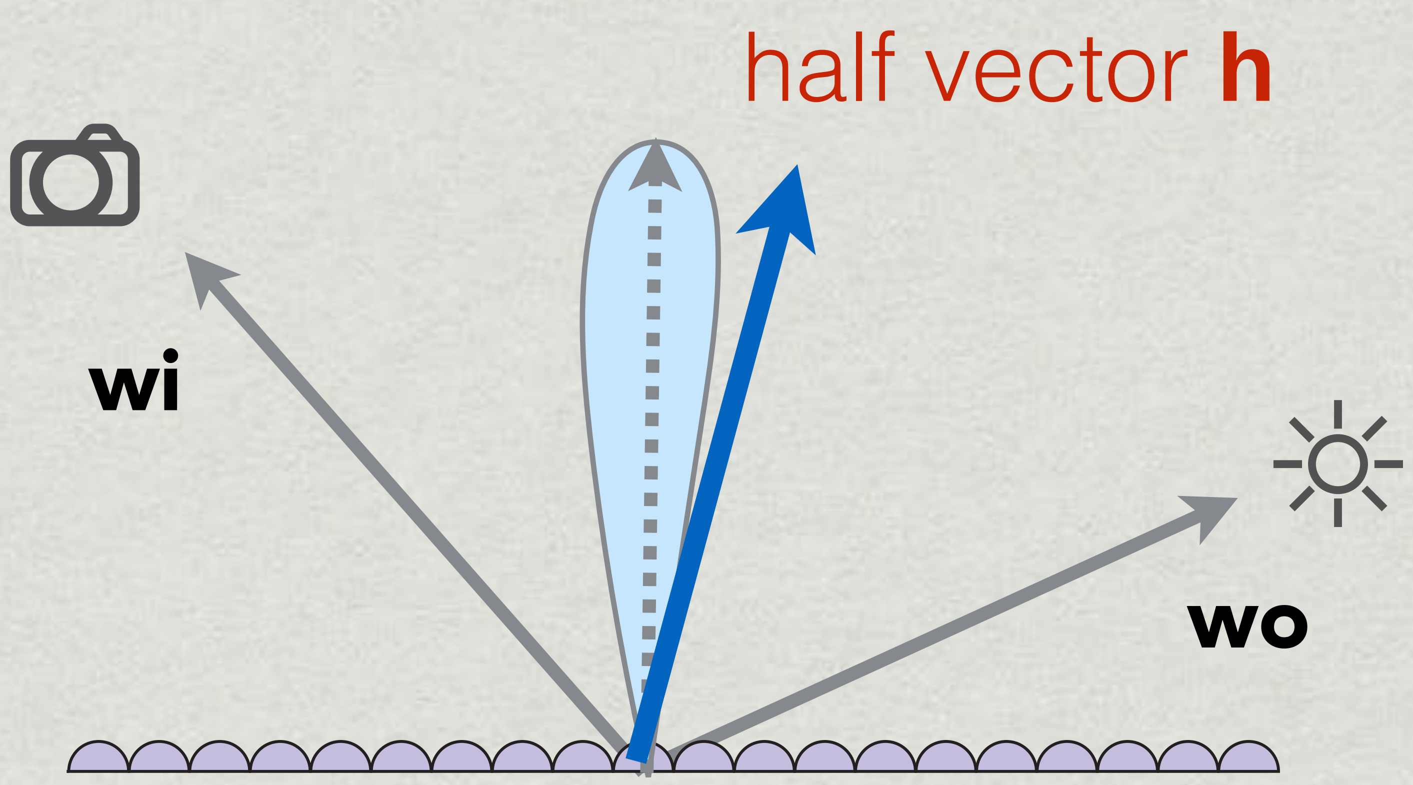
  - Spread <==> diffuse





Microfacet BRDF

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



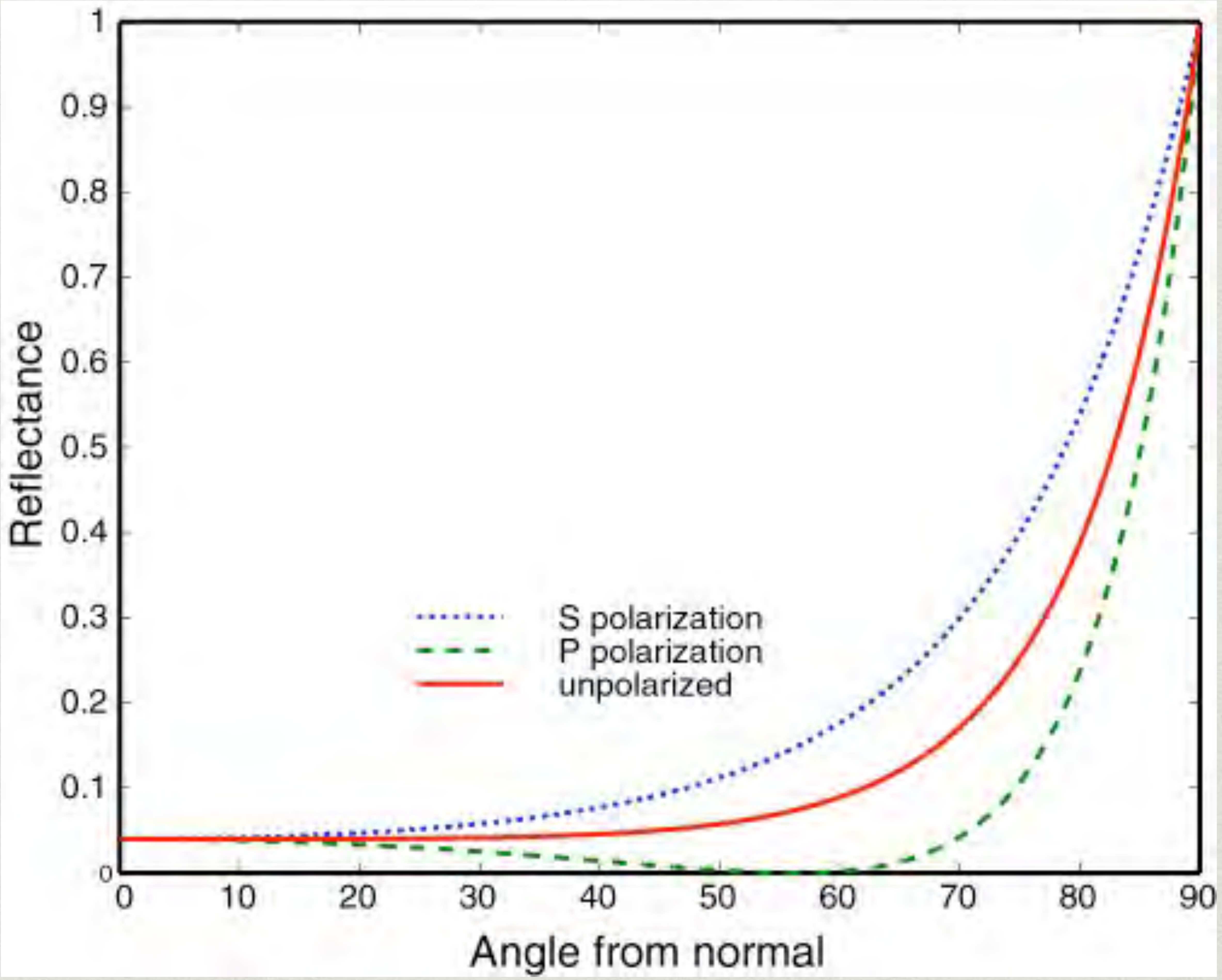
$$f(\mathbf{i},\mathbf{o}) = \frac{\underbrace{\boxed{\mathbf{F}(\mathbf{i},\mathbf{h})}}_{\text{Fresnel term}}\;\underbrace{\boxed{\mathbf{G}(\mathbf{i},\mathbf{o},\mathbf{h})}}_{\text{shadowing-masking term}}\;\underbrace{\boxed{\mathbf{D}(\mathbf{h})}}_{\textbf{distribution of normals}}}{4(\mathbf{n},\mathbf{i})(\mathbf{n},\mathbf{o})}$$

Fresnel Reflection / Term

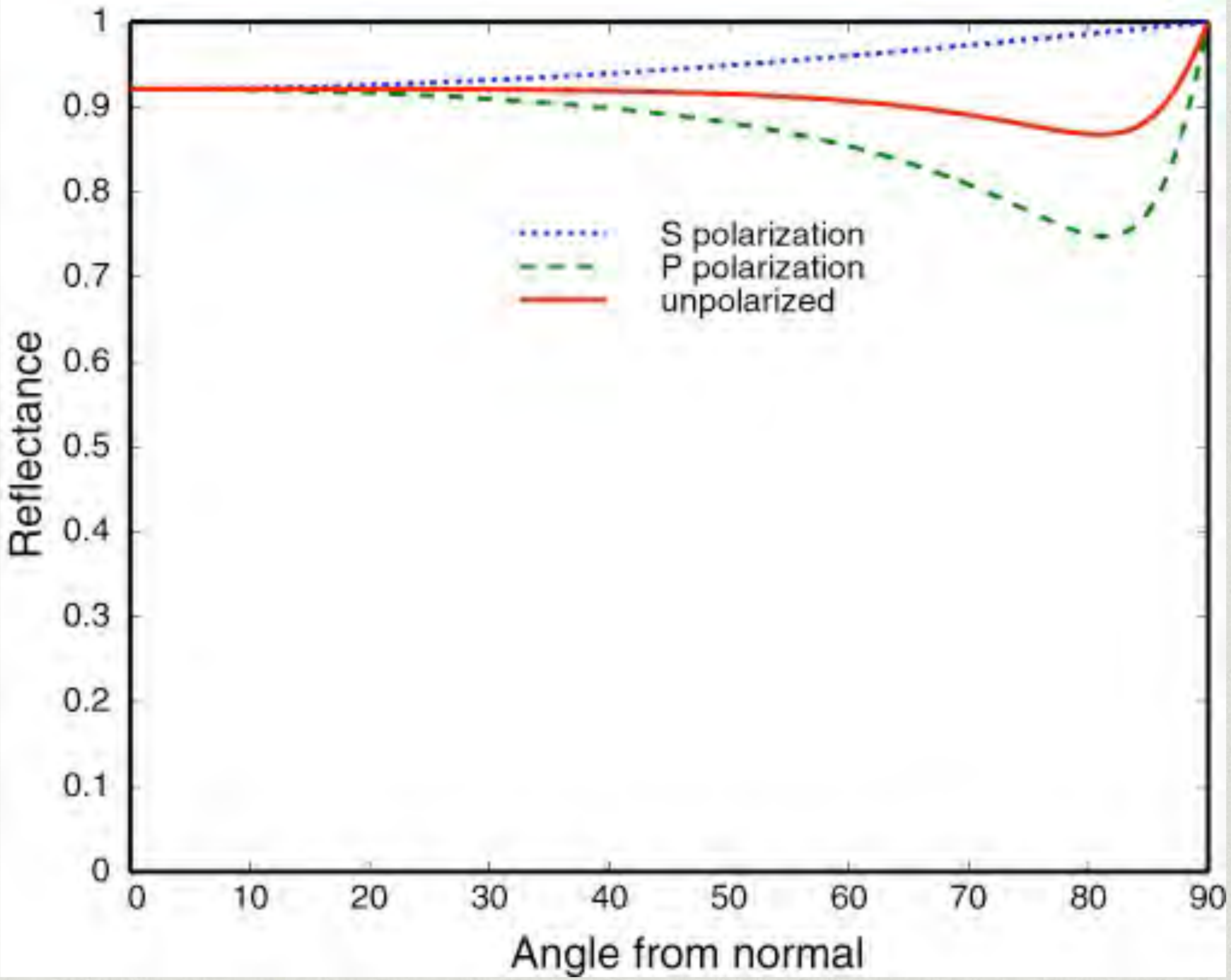
Reflectance depends on incident angle (and polarization of light)

This example: reflectance increases with grazing angle

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



Fresnel Term (Conductor)



Microfacet BRDF: Examples

[Autodesk Fusion 360]

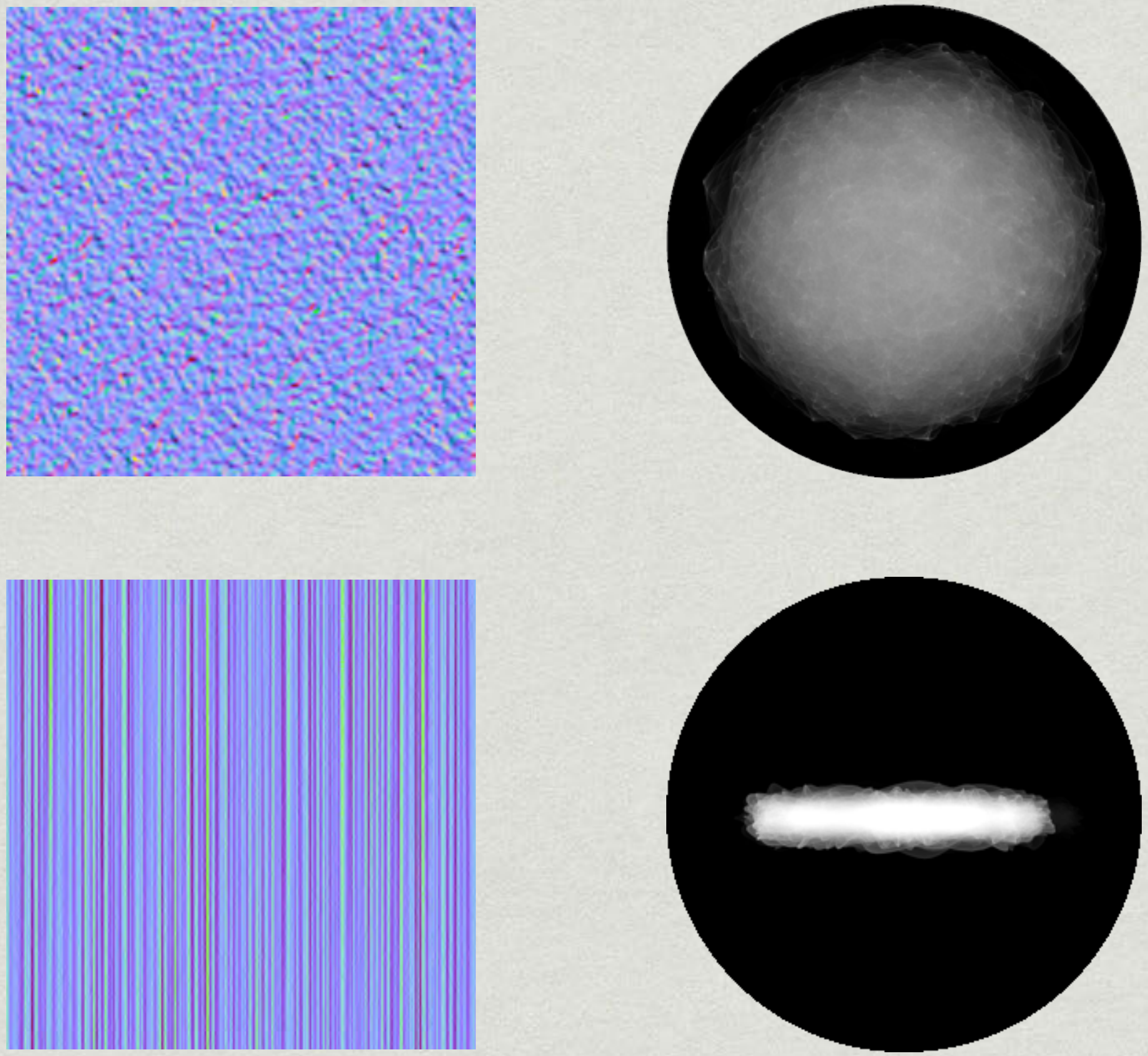
Isotropic / Anisotropic Materials (BRDFs)

- So far, Point light + Metal = Round / Elliptical highlight
- What can we see inside an elevator?

Inside an elevator

Isotropic / Anisotropic Materials (BRDFs)

- Key: directionality of underlying surface



Isotropic

Anisotropic

Surface (normals)

BRDF (fix wi, vary wo)

Anisotropic BRDF: Brushed Metal

- How is the pan brushed?

[VRay renderer]

Anisotropic BRDF: Nylon

[Westin et al. 1992]

Anisotropic BRDF: Velvet

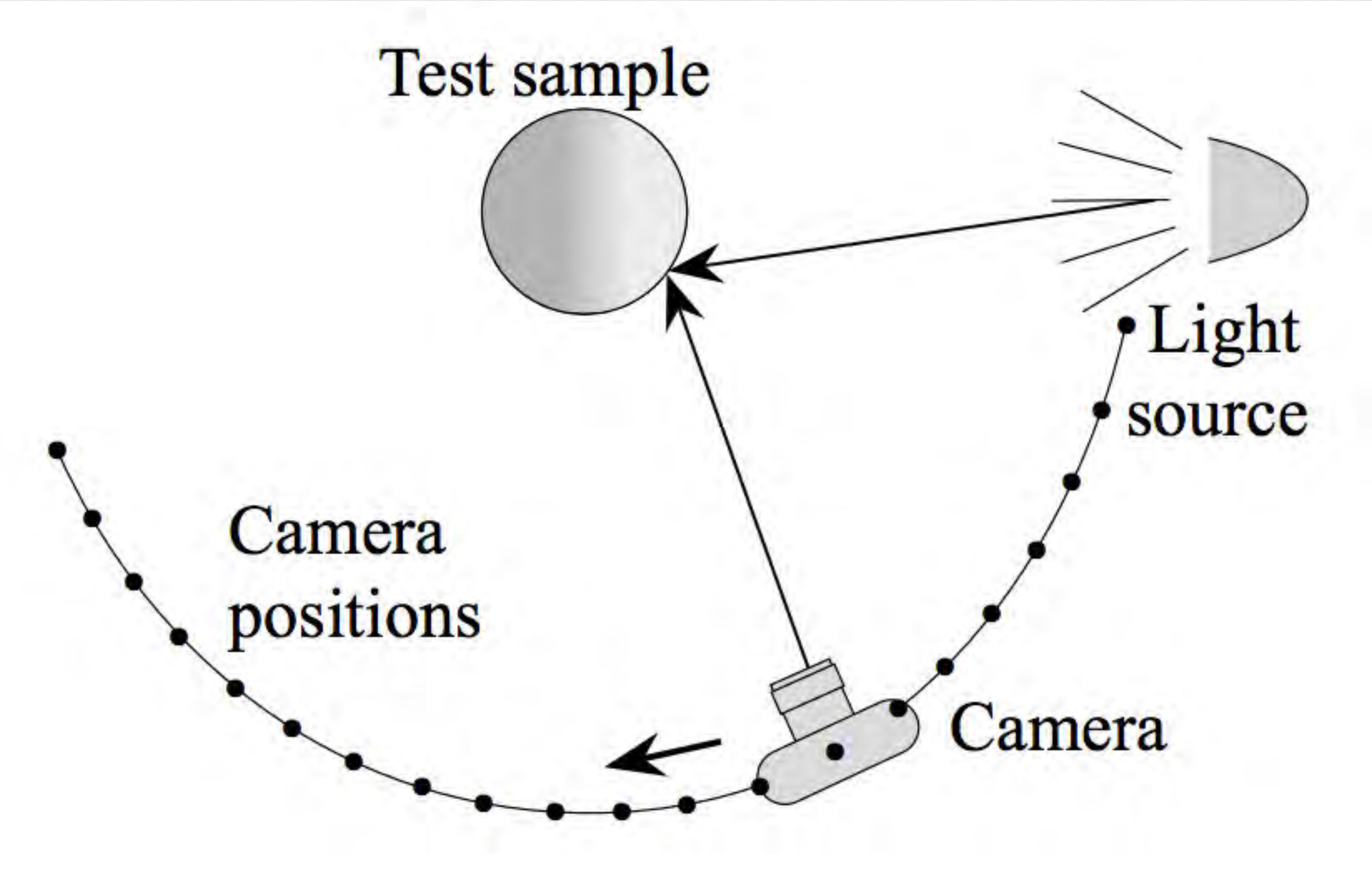
[Westin et al. 1992]

Anisotropic BRDF: Velvet

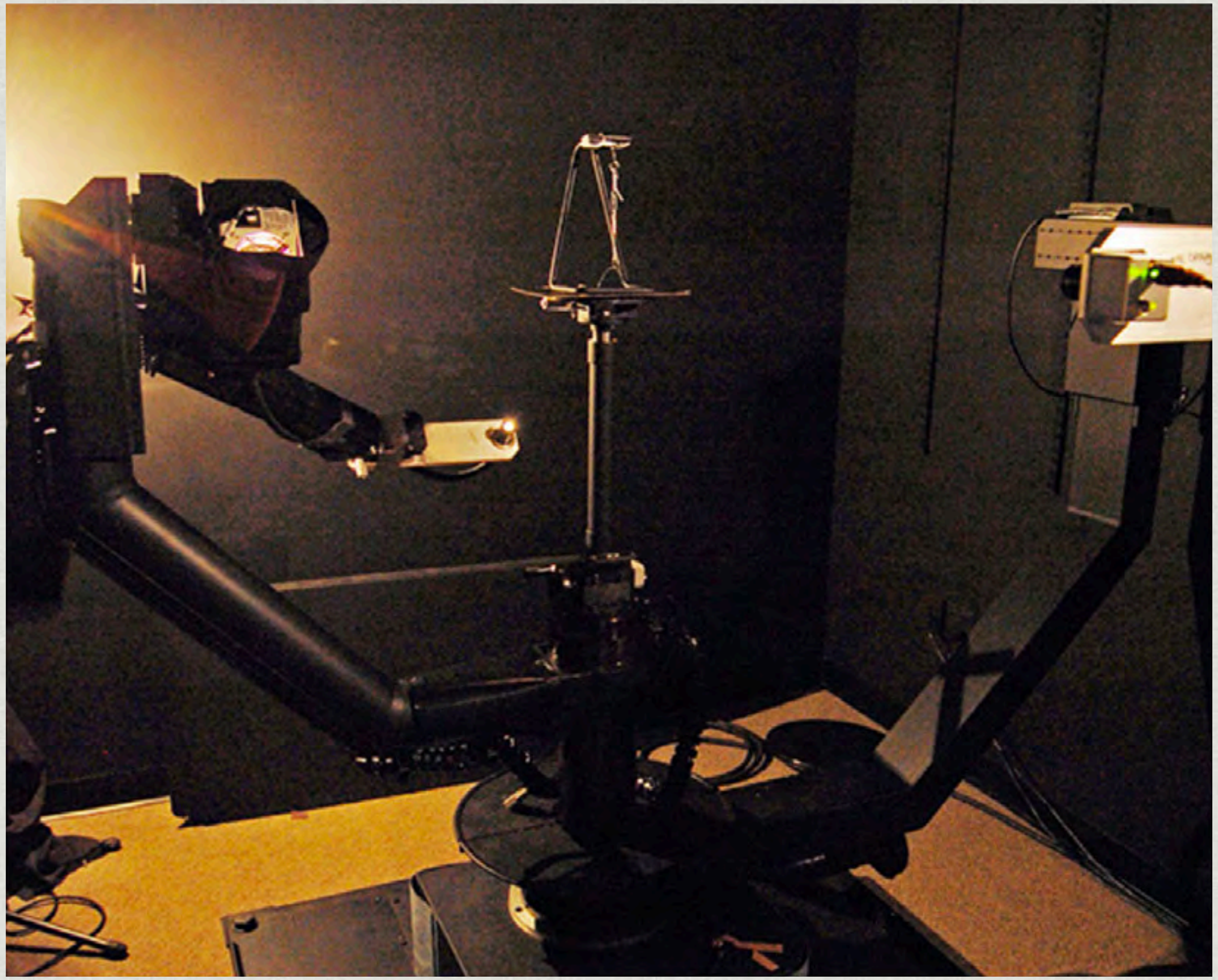
Material Capture

(BRDF measurement)

Image-Based BRDF Measurement



Measuring BRDFs: gonioreflectometer

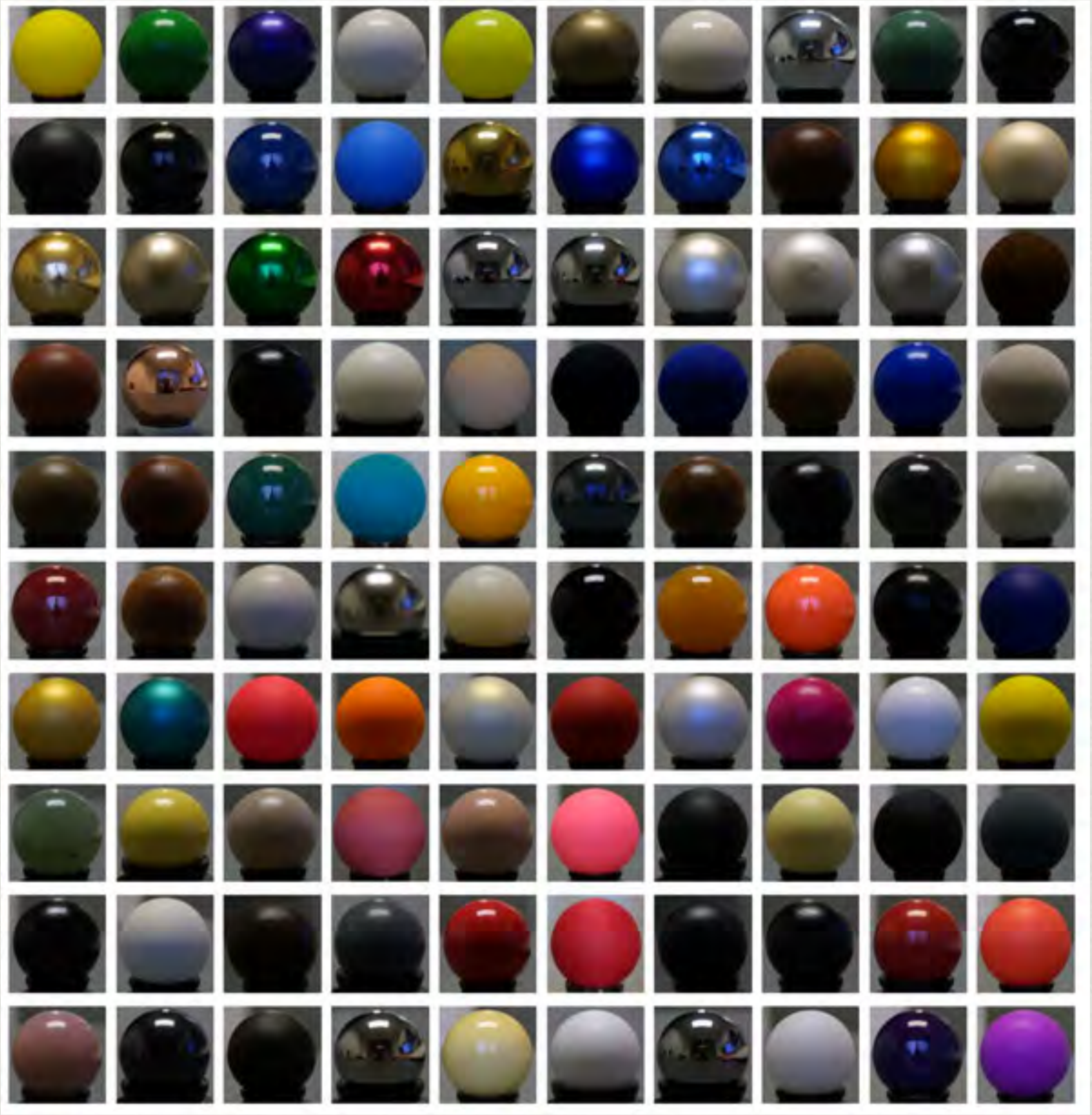


Spherical gantry at UC San Diego

Tabular Representation

$$(\theta_i, \theta_o, |\phi_i - \phi_o|)$$

- Store regularly-spaced samples in
  - Better: reparameterize angles to better match specularities
- Generally need to resample measured values to table
- Very high storage requirements



MERL BRDF Database
[Matusik et al. 2004]
90*90*180 measurements

Before we proceed

* A brief summary
    * Material == BRDF
        * [Non-physically-based] Blinn-Phong material
        * [Physically-based] Microfacet material
        * Material acquisition / measurement
    * Shading methods
        * Flat (triangle) / Gouraud (vertex) / Phong (pixel)
    * Texture mapping, bump/normal/displacement mapping

Advanced materials
(including state of the art research)

- Detailed / glinty material (non-statistical BRDF)
- Hair / fur (BCSDF)
- Participating media
- Translucent material (BSSRDF)
- Cloth
- Granular material
- Procedural appearance
- ...

Detailed / Glinty material

Motivation

[Car rendered in NVIDIA Iray]

[Mouse rendered in Autodesk 3DS Max]

Real world is more complicated

[Real photograph of a car]

[Real video of a mouse]

Why details?

Microfacet model

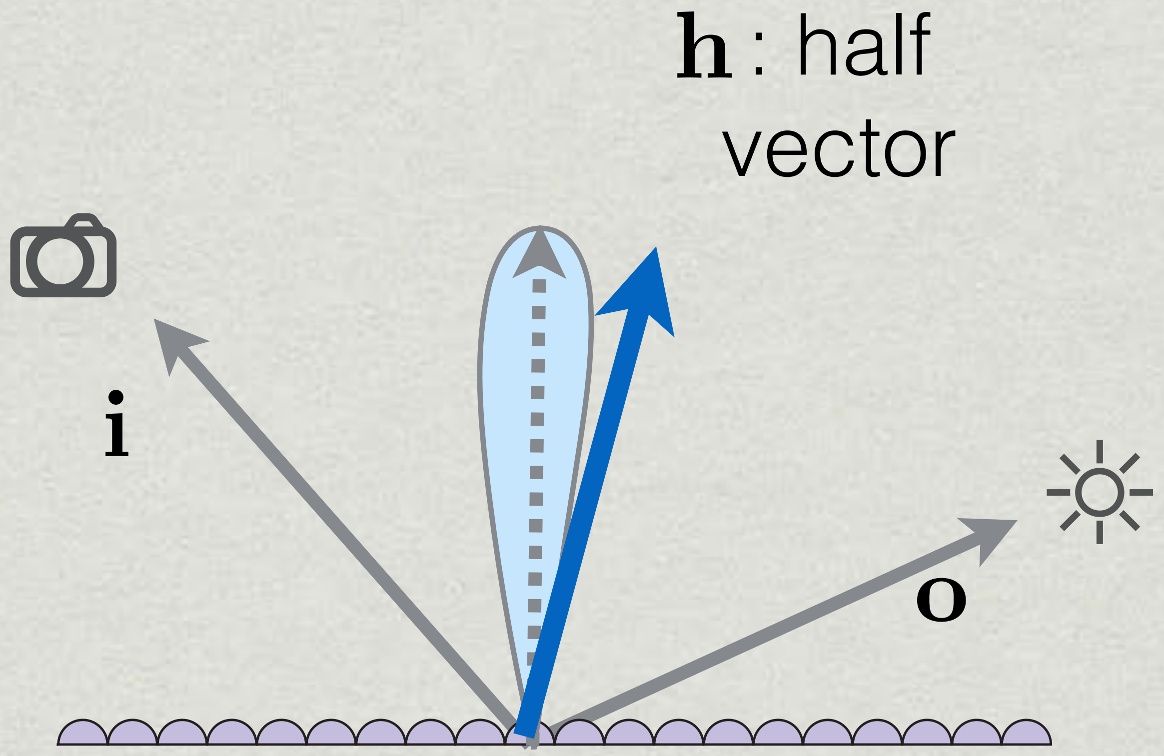
Why details?

[Yan et al. 2014, 2016]

Why details?

[Yan et al. 2014, 2016]

Recap: Microfacet BRDF



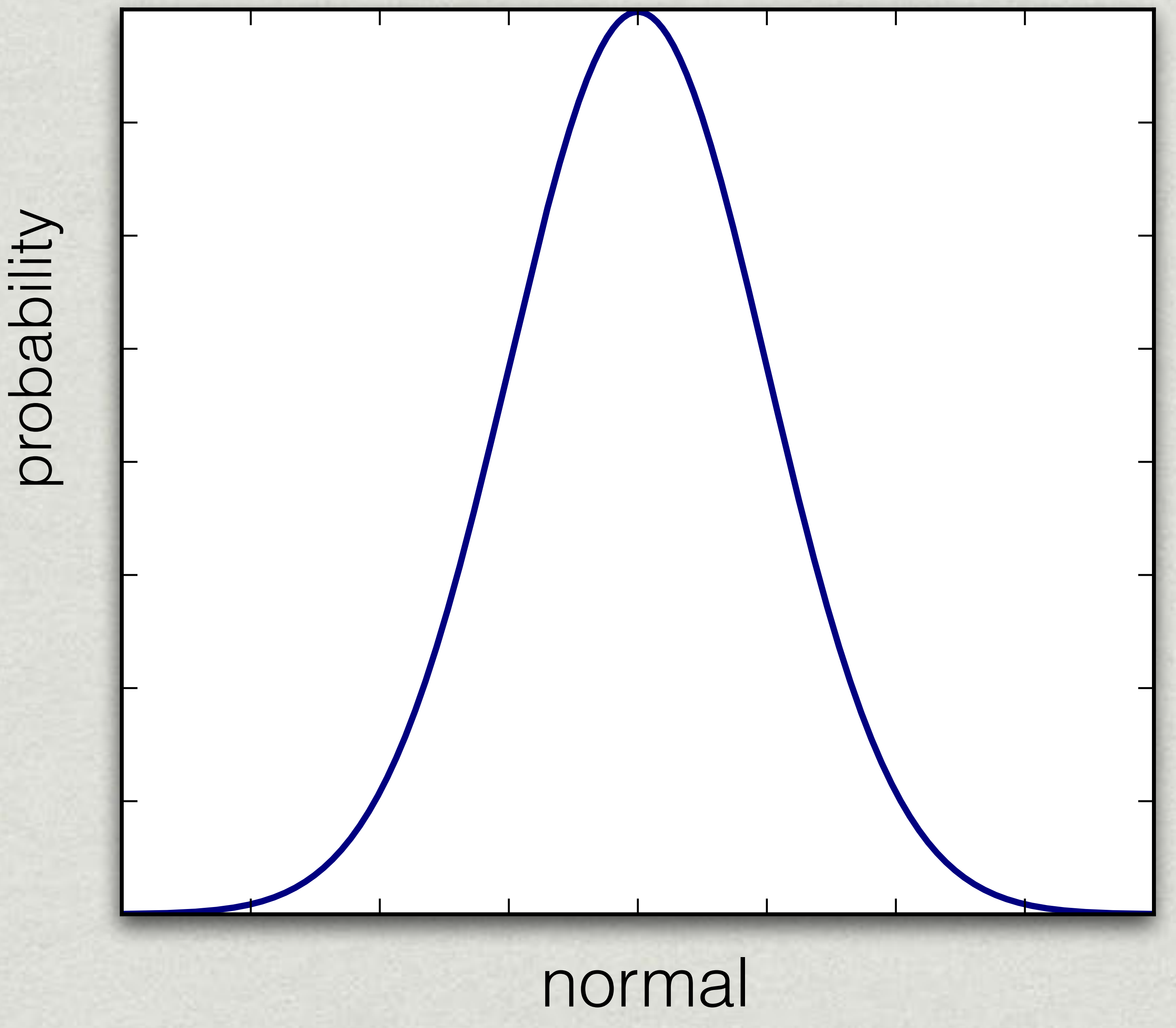
Surface = Specular microfacets + statistical normals

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

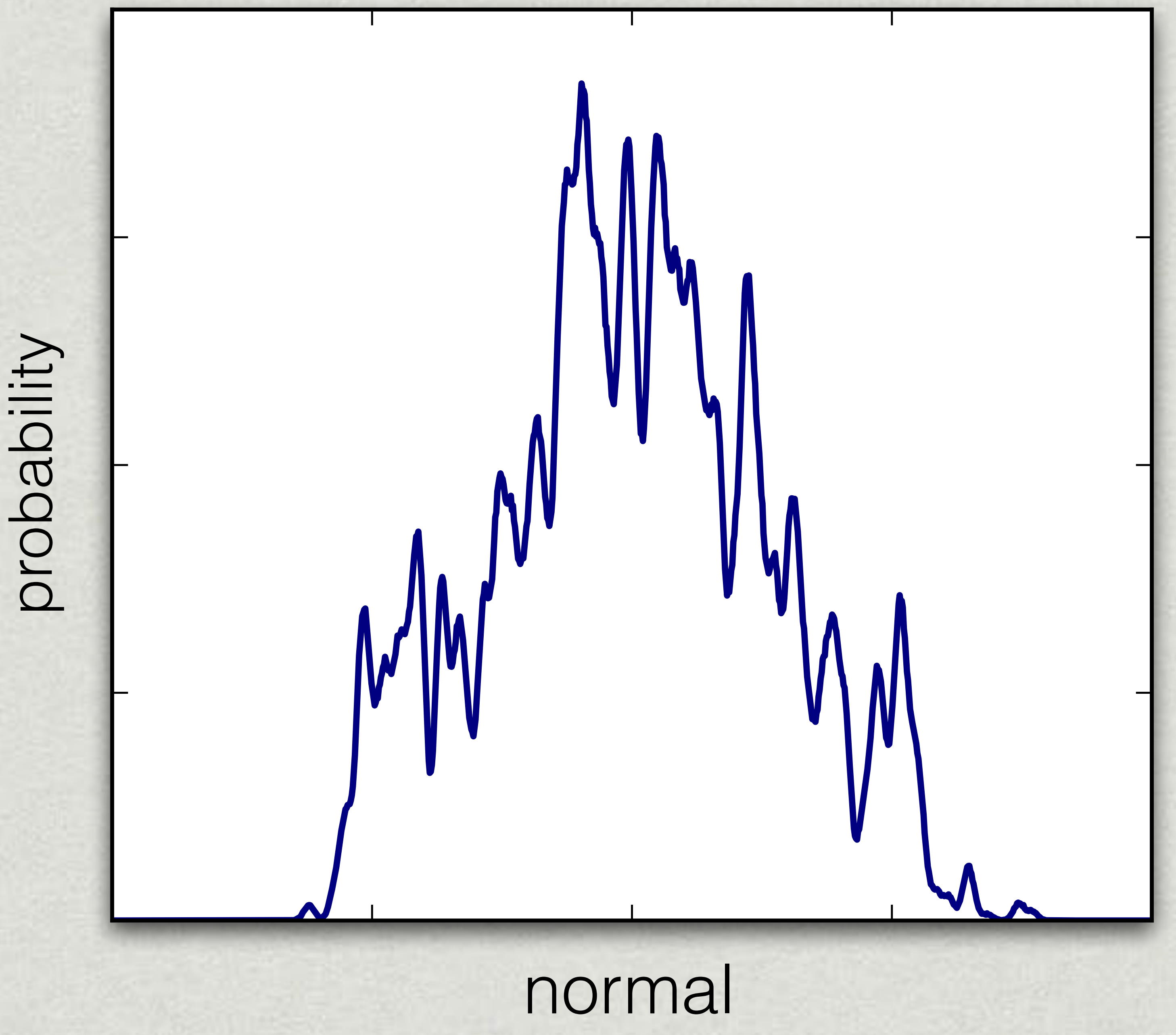
NDF: Normal Distribution Function

Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

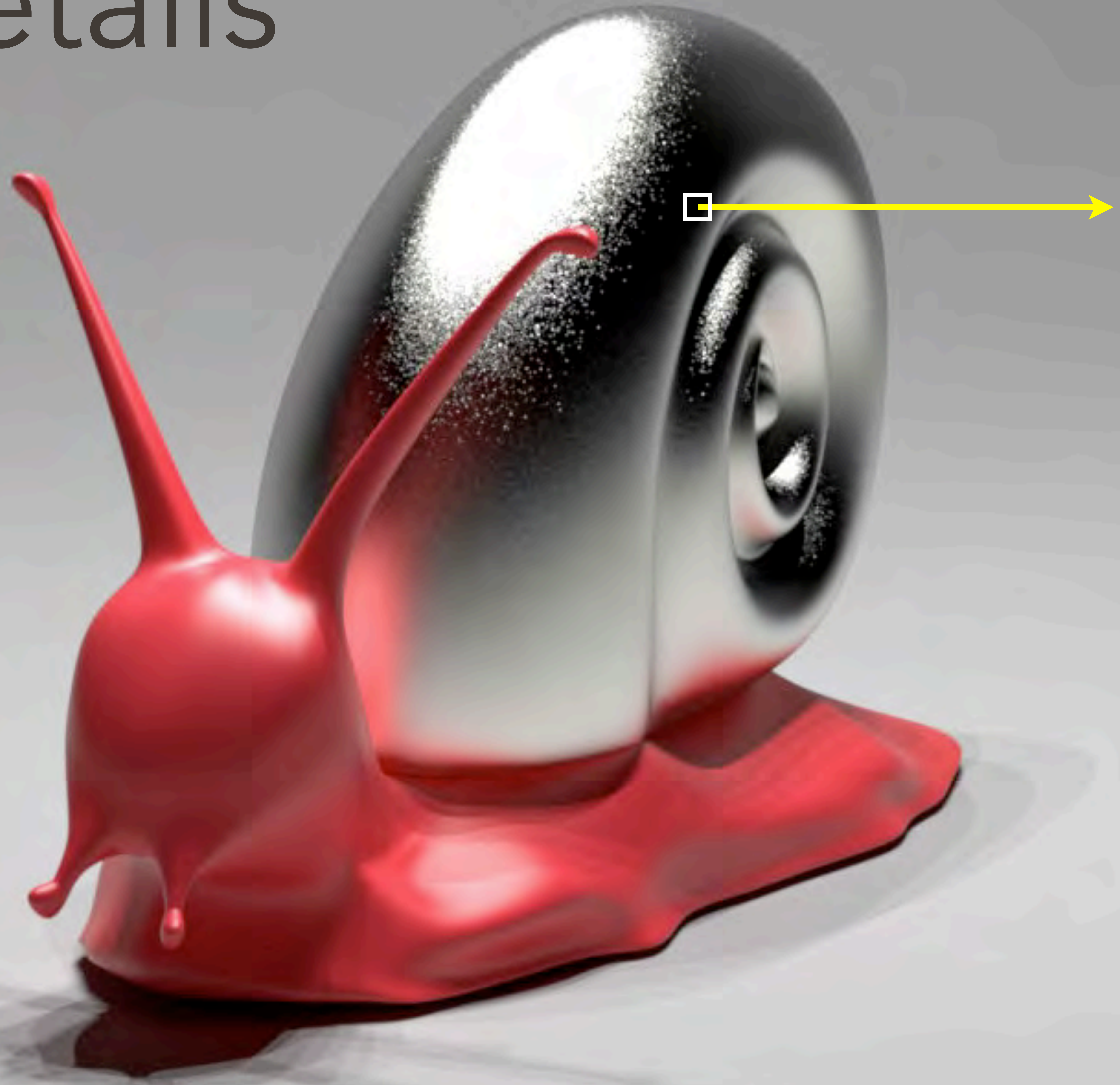


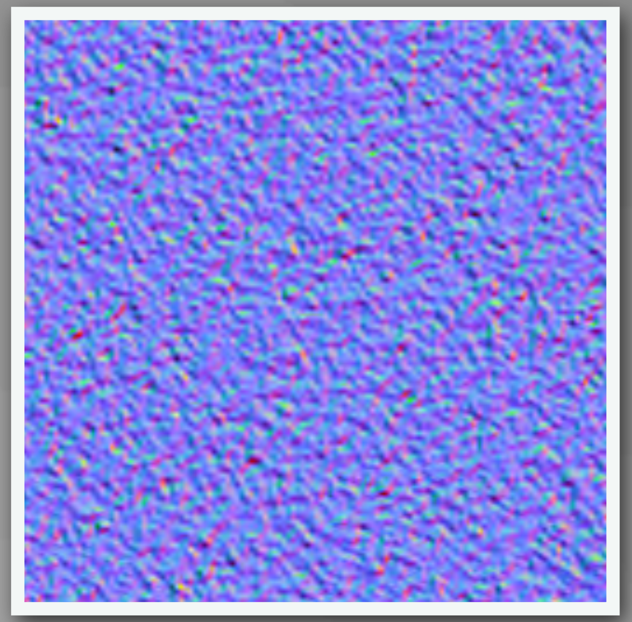
What we have
(microfacet — statistical)



What we want

Define details



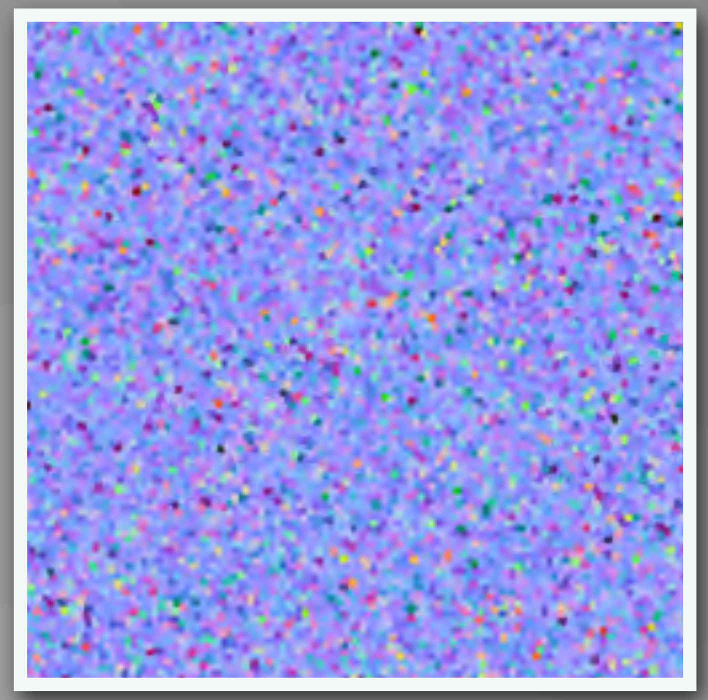


isotropic noise
normal map

Normal map
resolution:
≈ 200K x 200K

Define details

Different details



Metallic flakes

Ocean waves

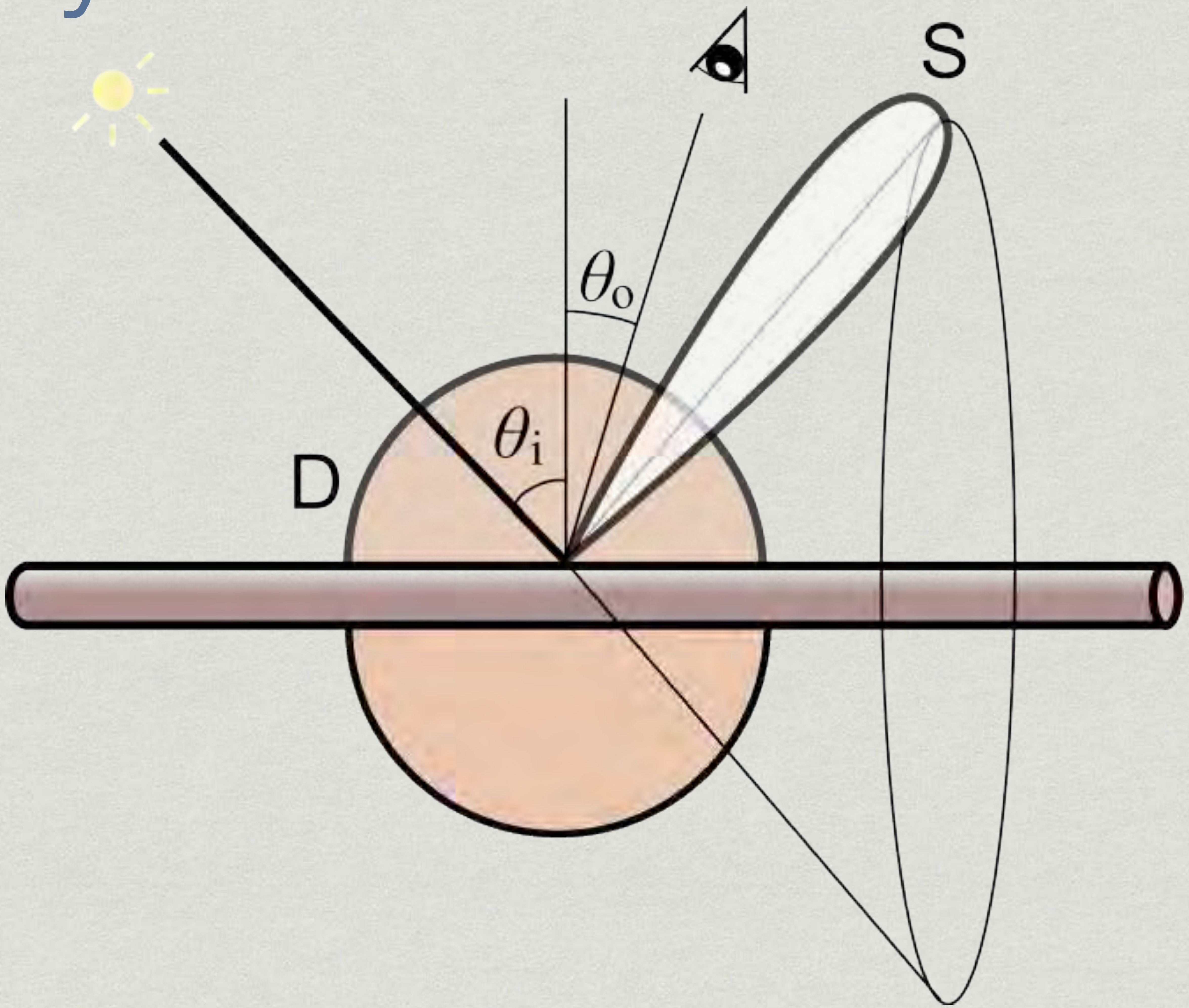
Detailed / Glinty Material: Application

[Rise of the Tomb Raider. 2016 Square Enix]

Hair and fur

Hair Appearance

Kajiya-Kay Model

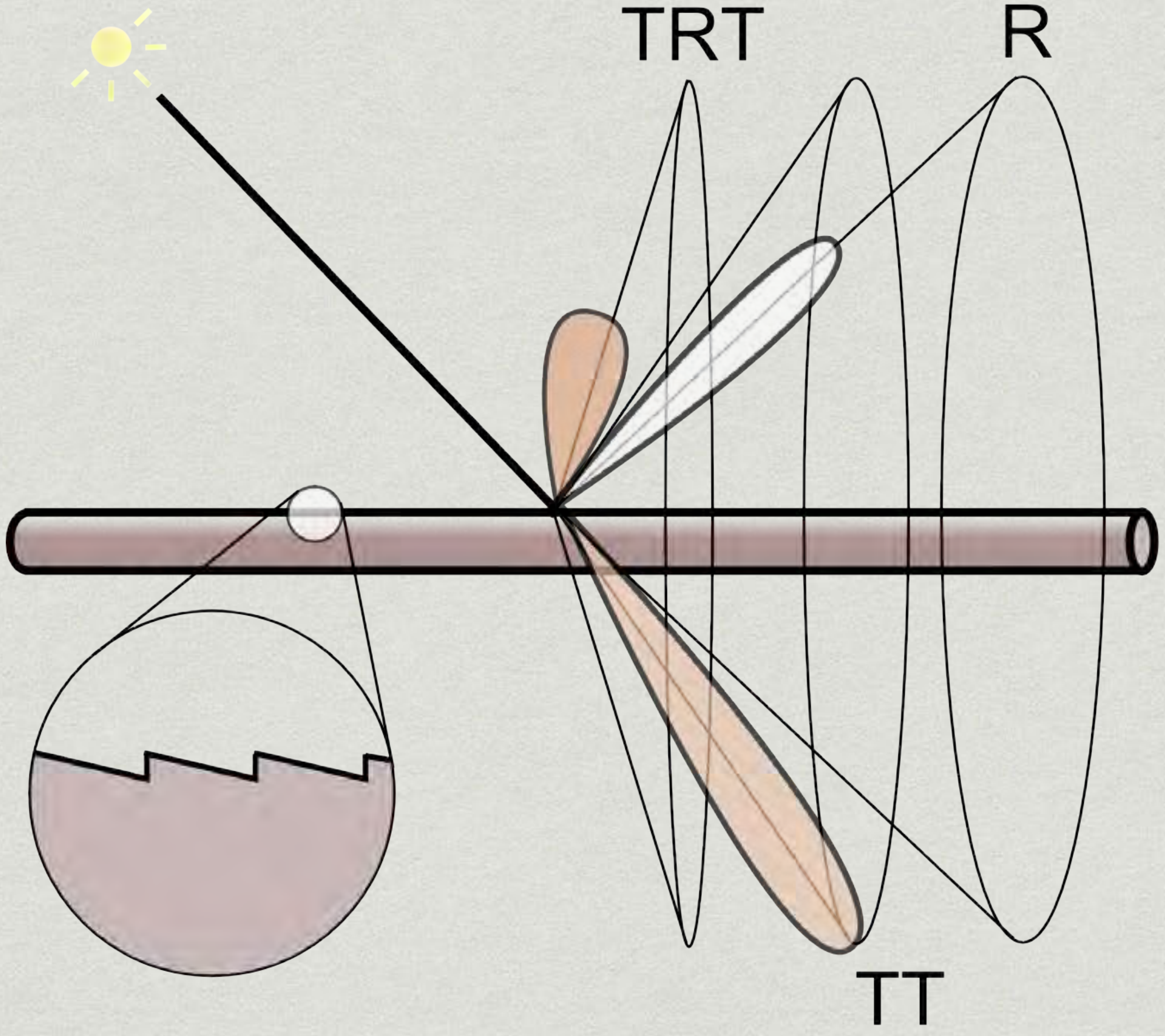


[Image courtesy of Chiwei Tseng]

Kajiya-Kay Model

[Yuksel et al. 2008]

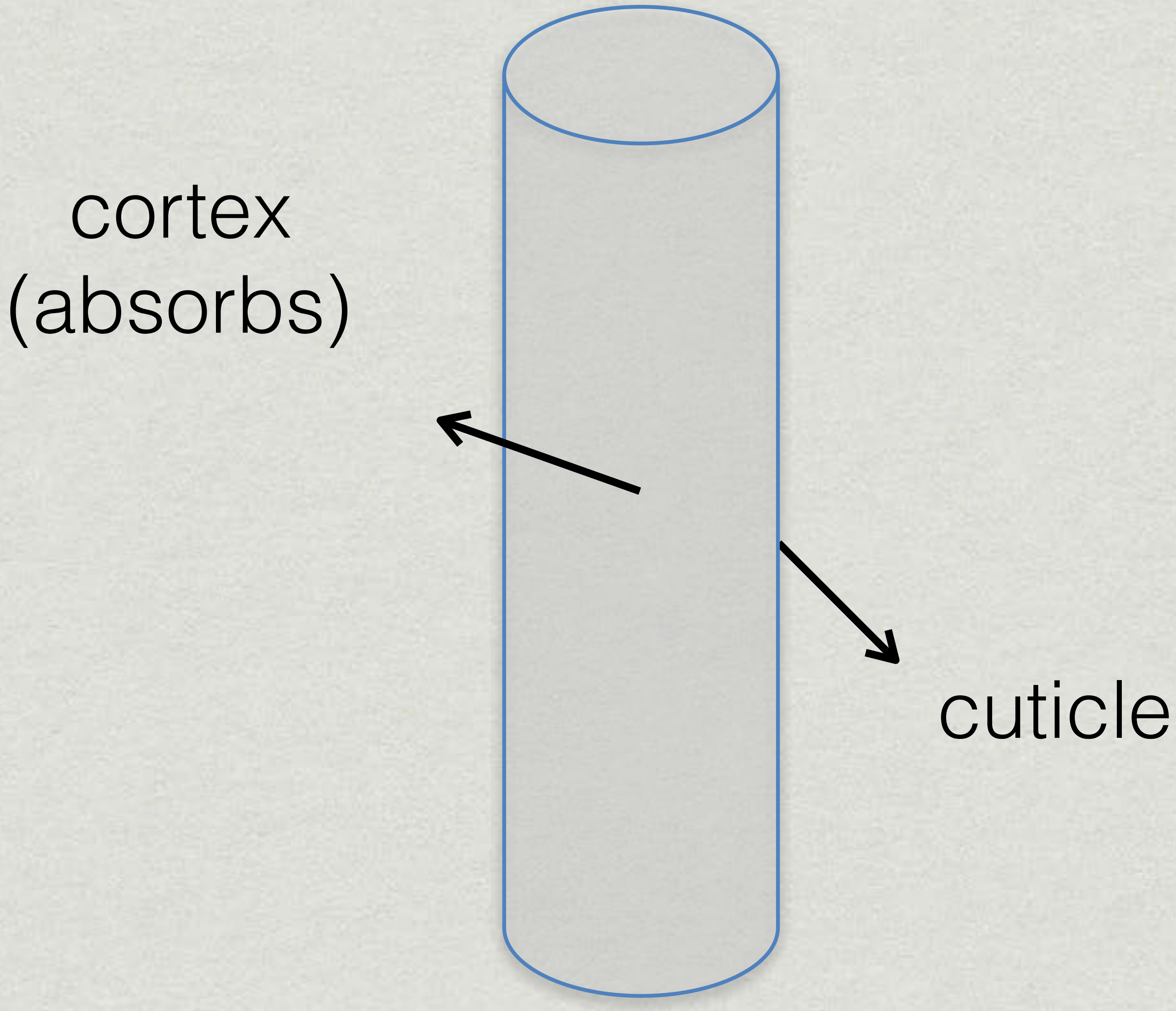
Marschner Model



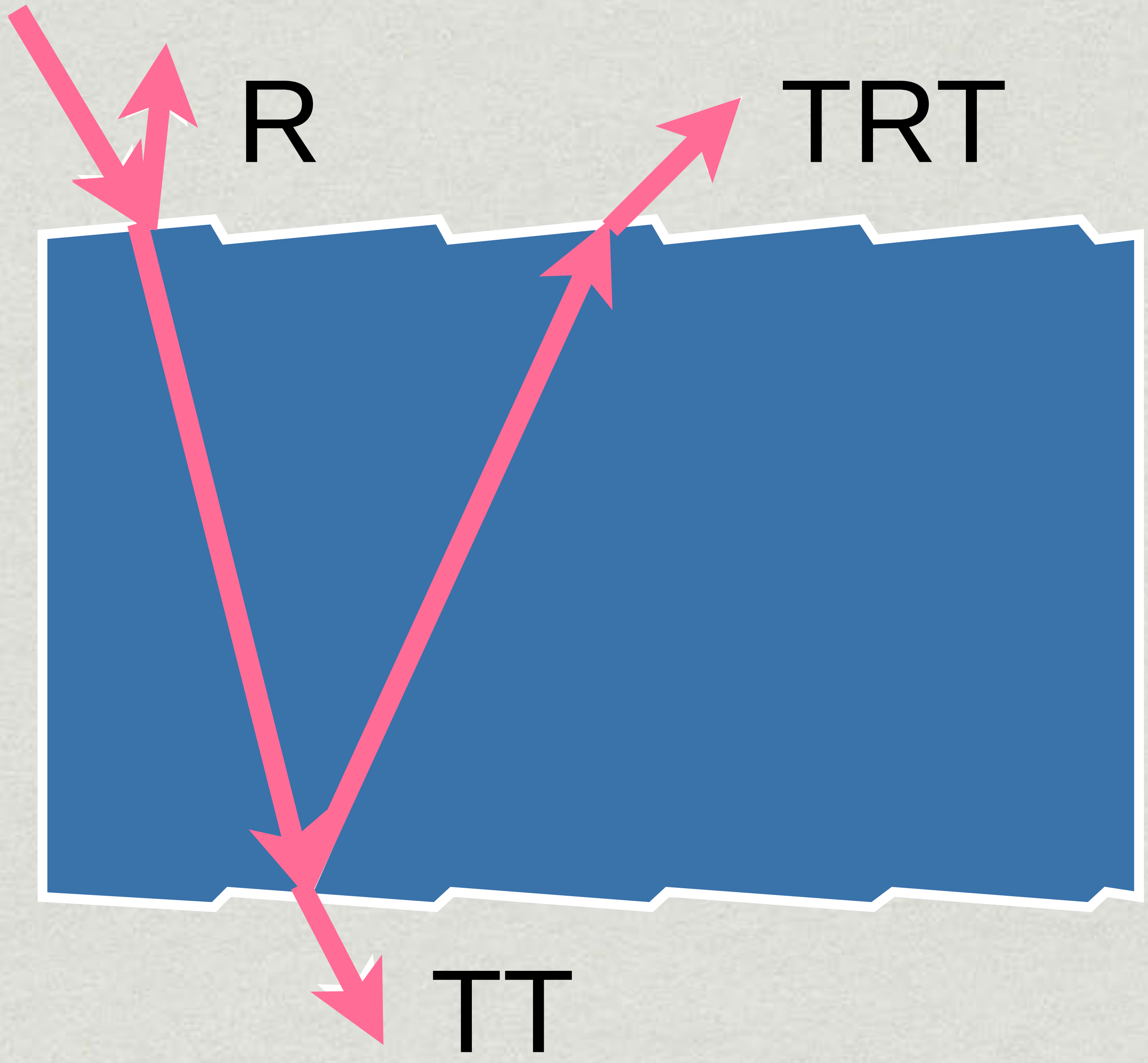
[Image courtesy of Chiwei Tseng]

Marschner Model

- Glass-like cylinder



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



[Marschner et al. 2003]

Marschner model

[Marschner et al. 2003]

[d'Eon et al. 2011]

Hair Appearance Model: Application

[Final Fantasy XV. 2 uare Eni

Hair Appearance Model: Application

[Zootopia. 2016 Disney]

Even more advanced: Double Cylinder Model

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

Participating Media

Participating Media: Fog

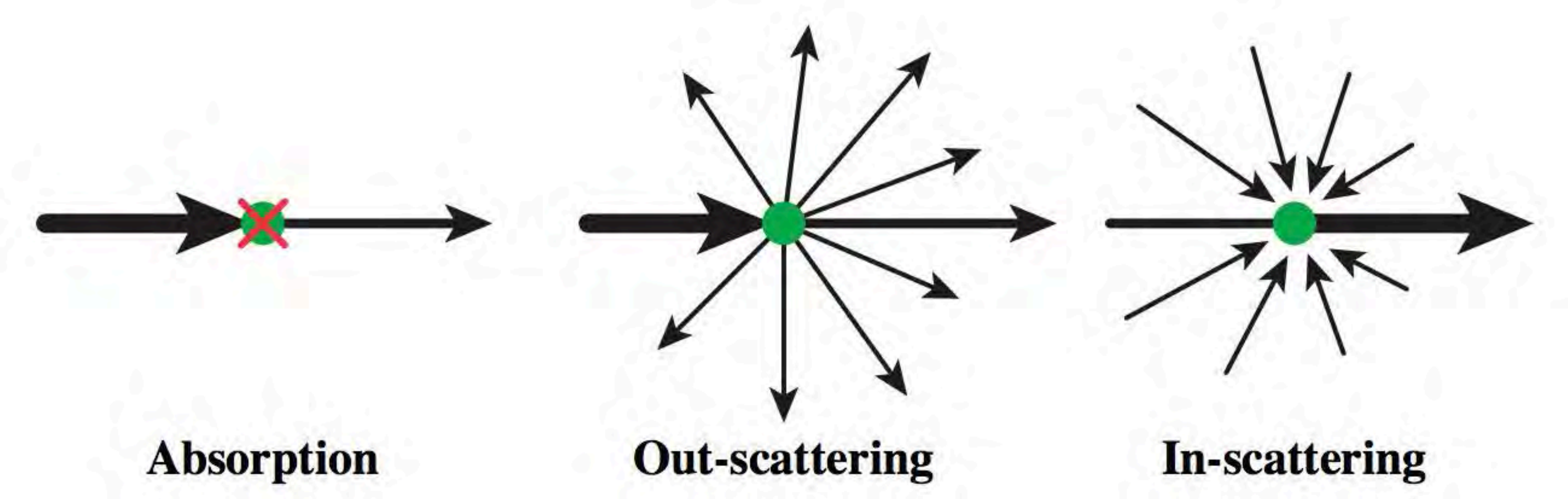
[Novák et al. 2012]

Participating Media: Cloud

[by thephotographer0]

Participating Media

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



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

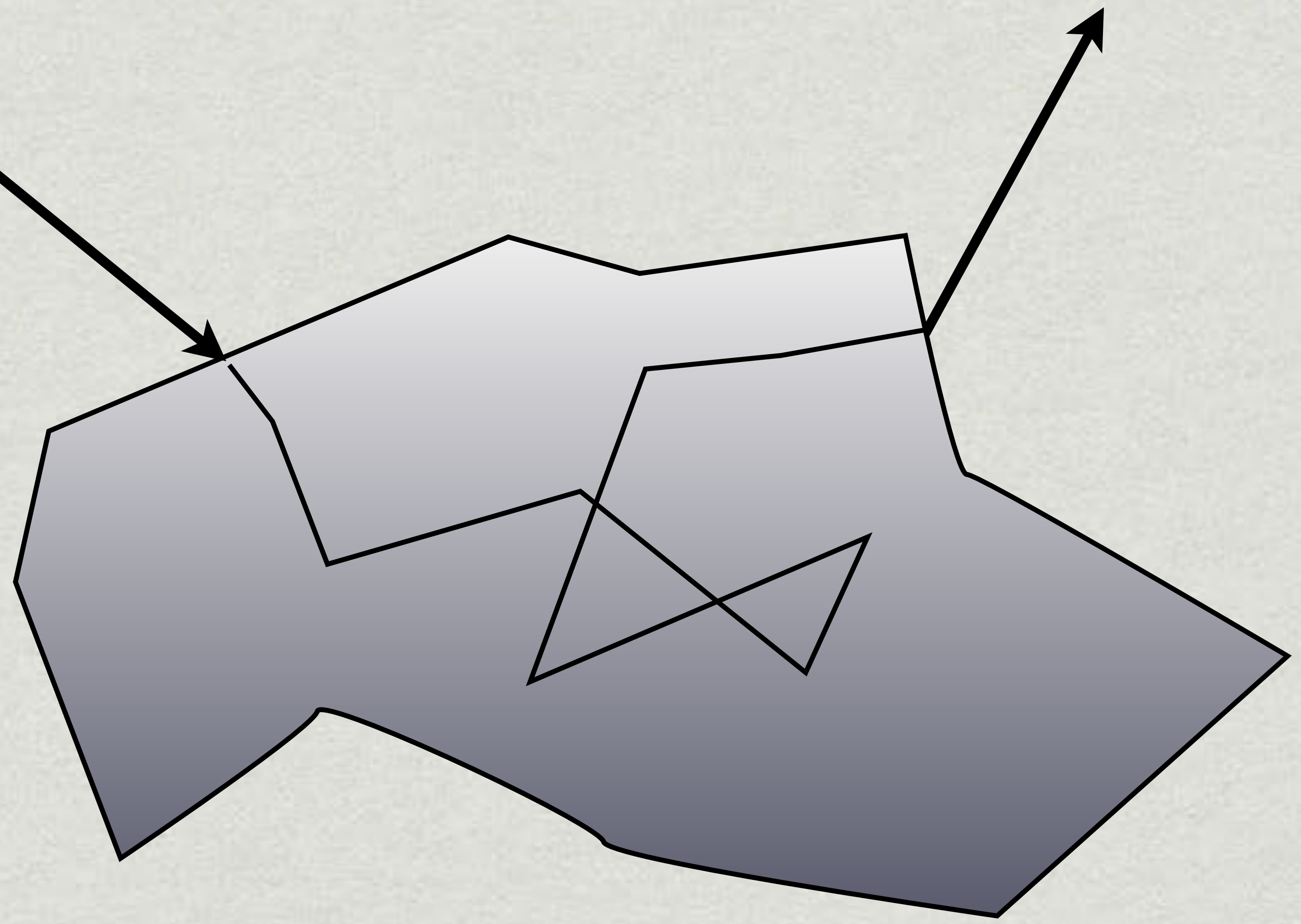
(a specific participating medium)

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]

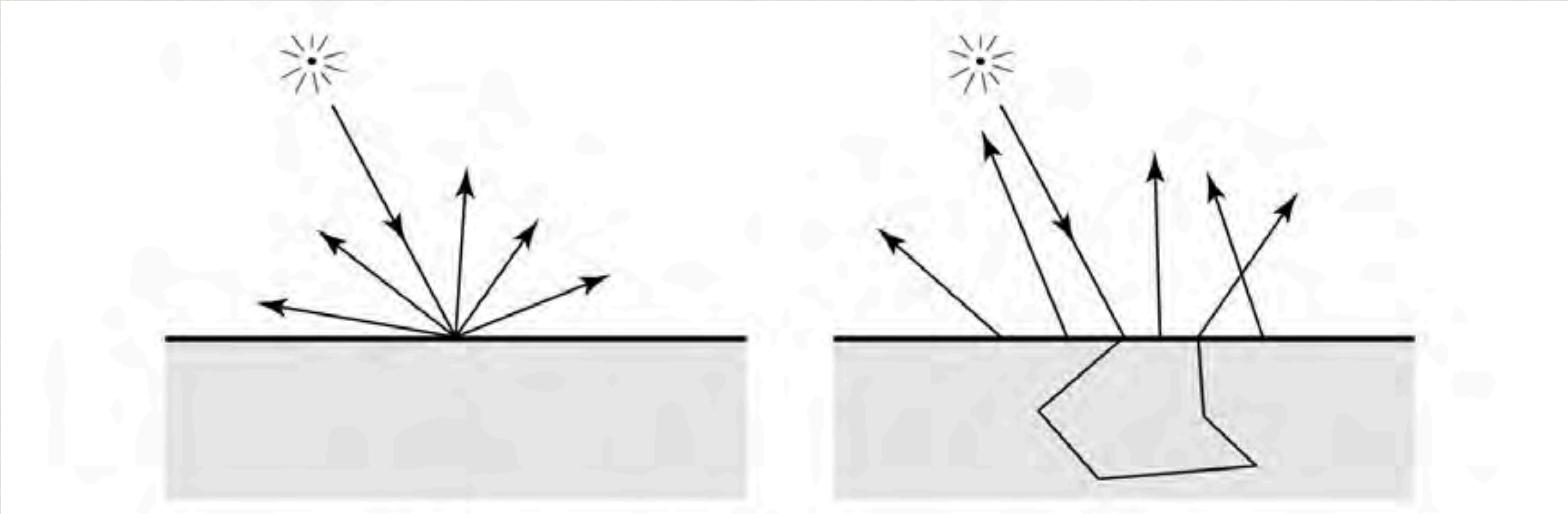
Scattering Functions

- 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]

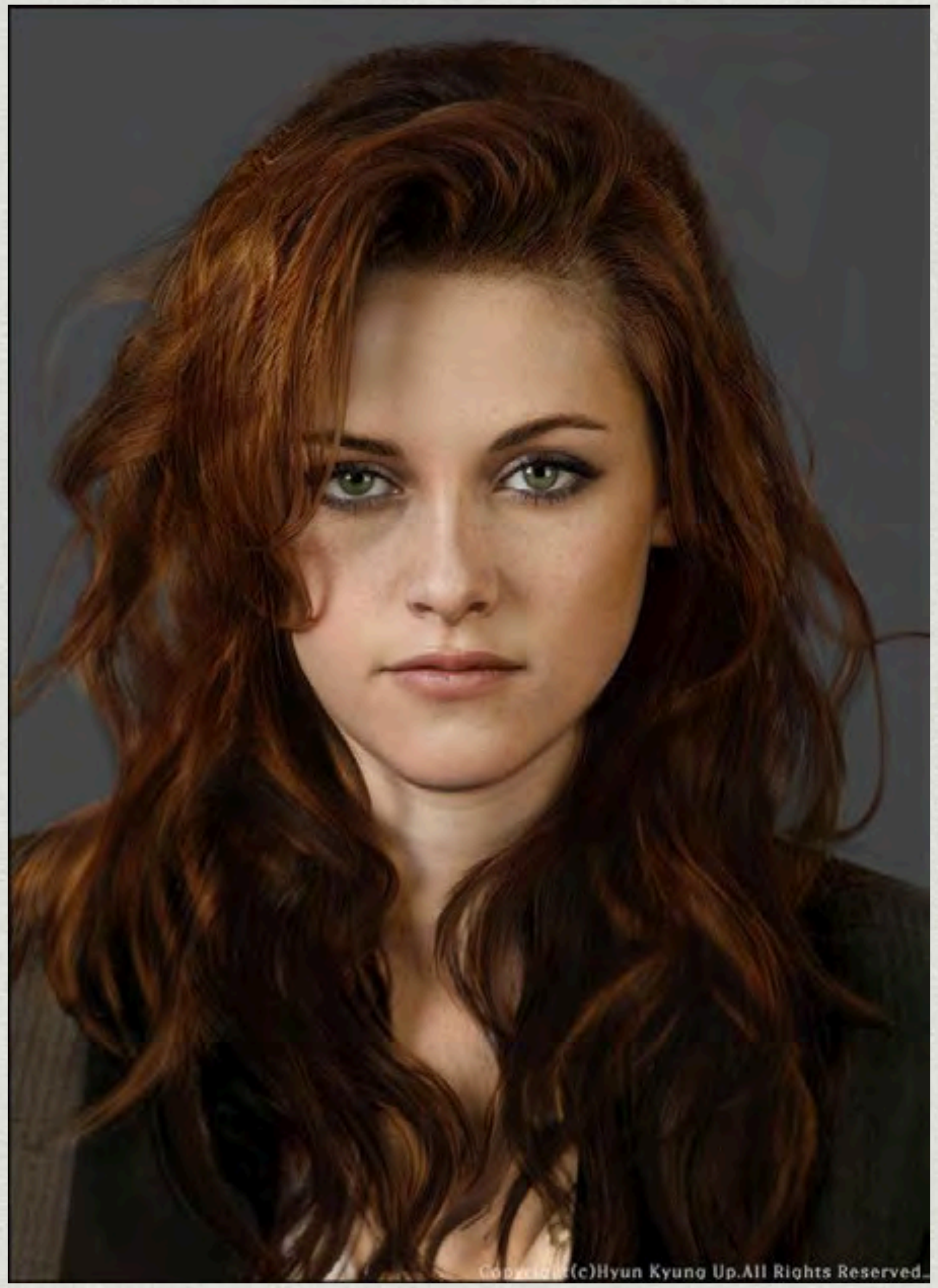
BRDF vs BSSRDF

BRDF BSSRDF

[Jensen et al. 2001]

BSSRDF: Application

[Artist: Teruyuki and Yuka]



[Artist: Hyun Kyung]

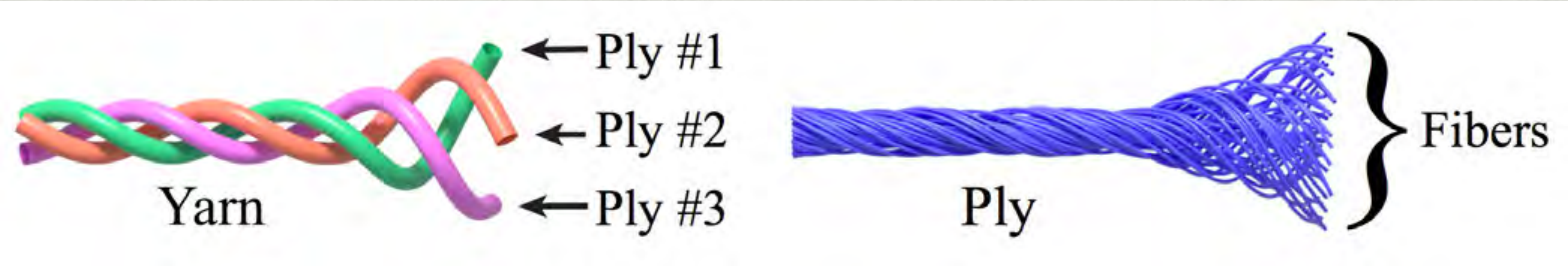
[Artist: Dan Roarty]

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

Cloth

Cloth

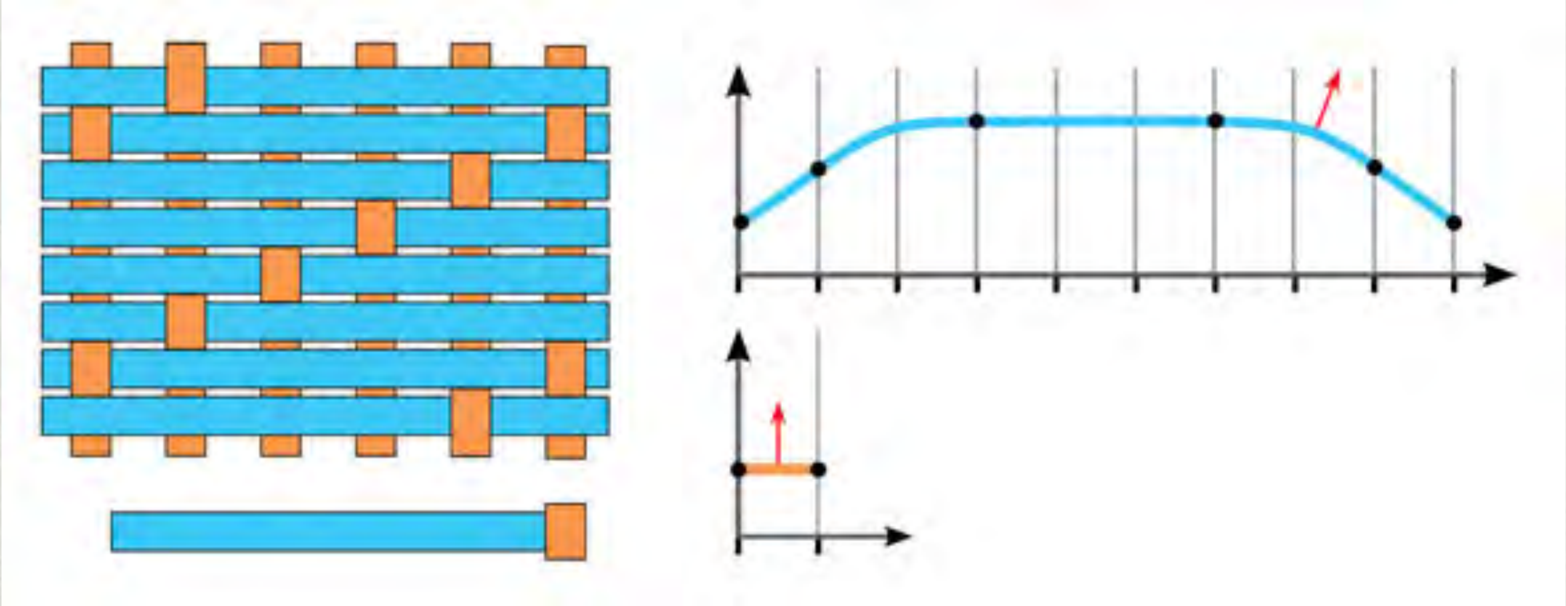
- A collection of twisted fibers!
- Two levels of twist

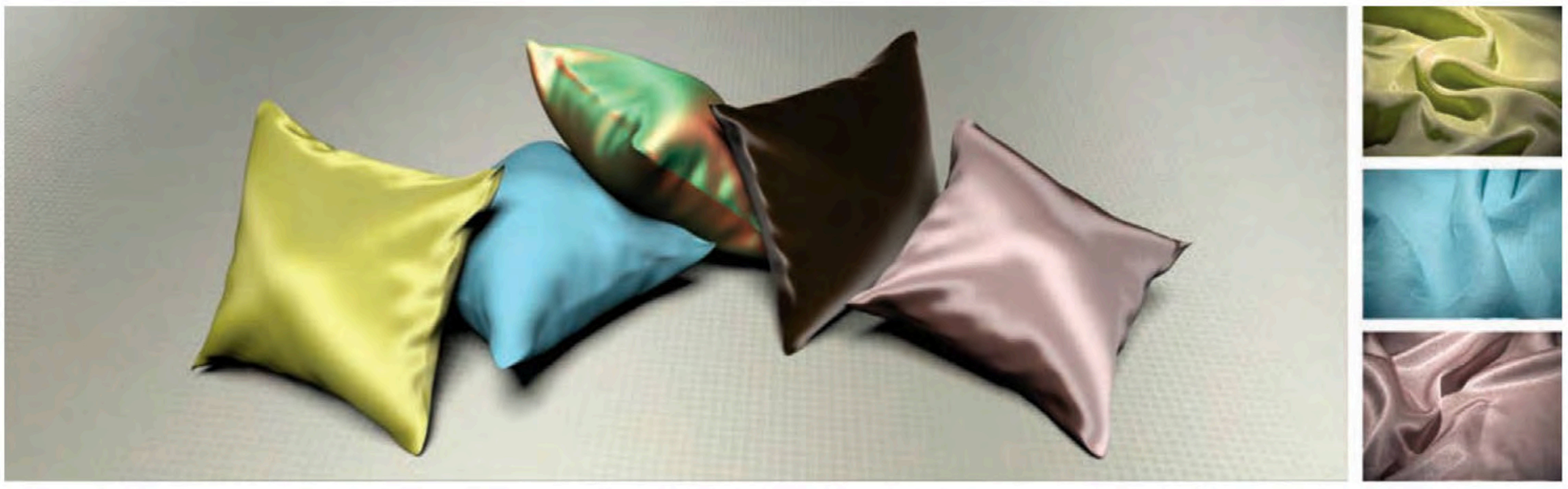


- Woven or knitted

Cloth: Render as Surface

- Given the weaving pattern, calculate the overall behavior
- Render using a BRDF



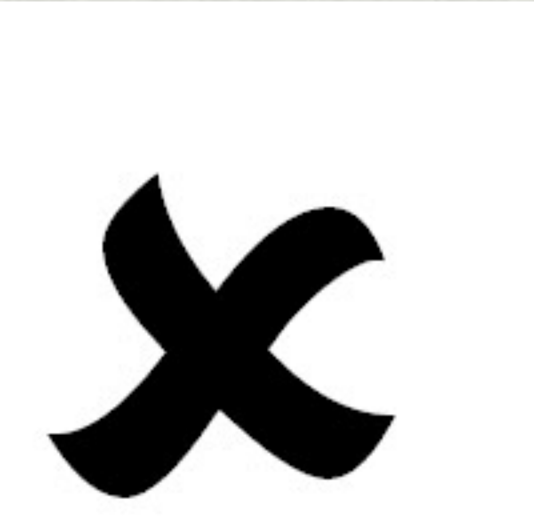
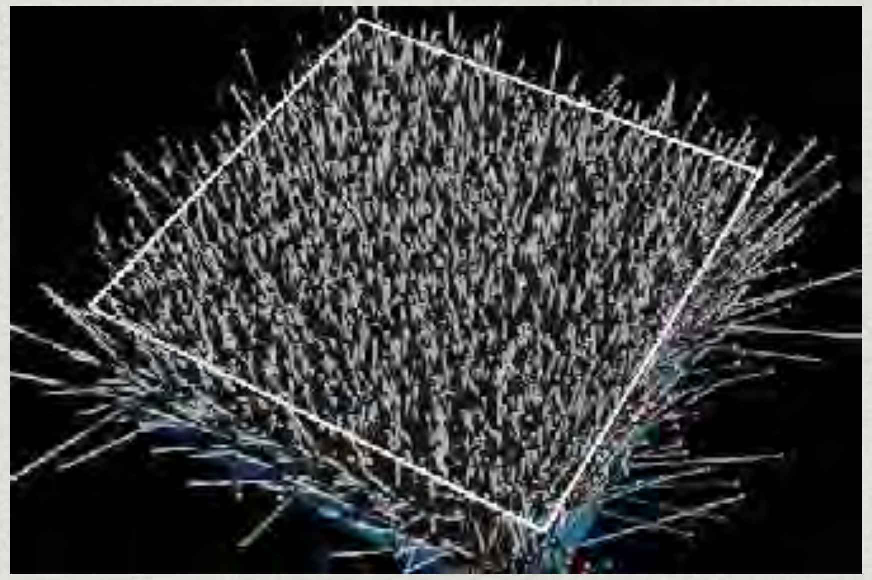


[Sadeghi et al. 2013]

Render as Surface — Limitation


[Westin et al. 1992]



Cloth: Render as Participating Media

- Properties of individual fibers & their distribution -> scattering parameters
- Render as a participating medium

[Jakob et al. 2010]

[Schroder et al. 2011]

Cloth: Render as Actual Fibers

- Render every fiber explicitly!

[Kai Schroder]

Cloth: Application

[The BFG. 2016 Disney]

Granular Material

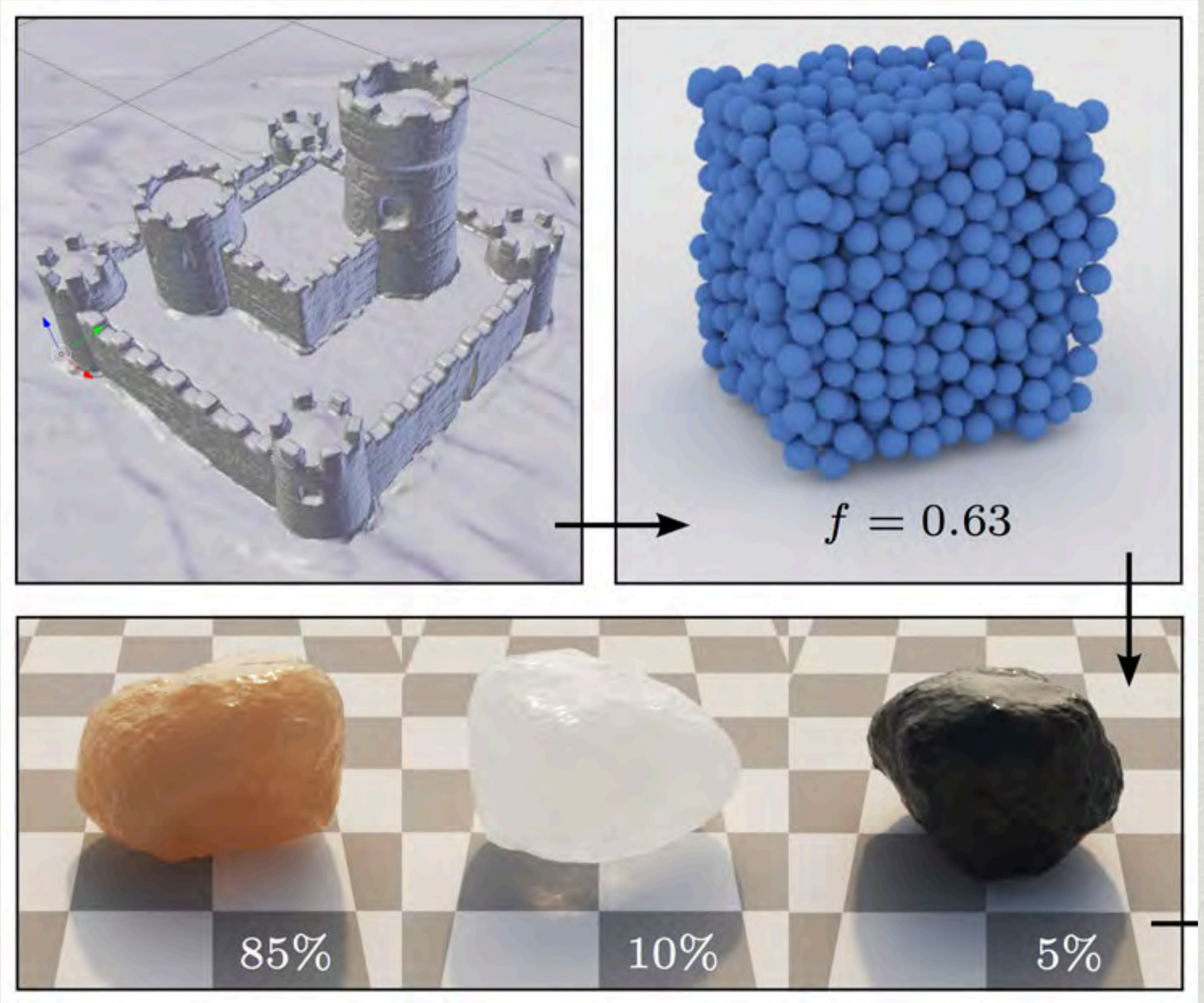
Granular Material

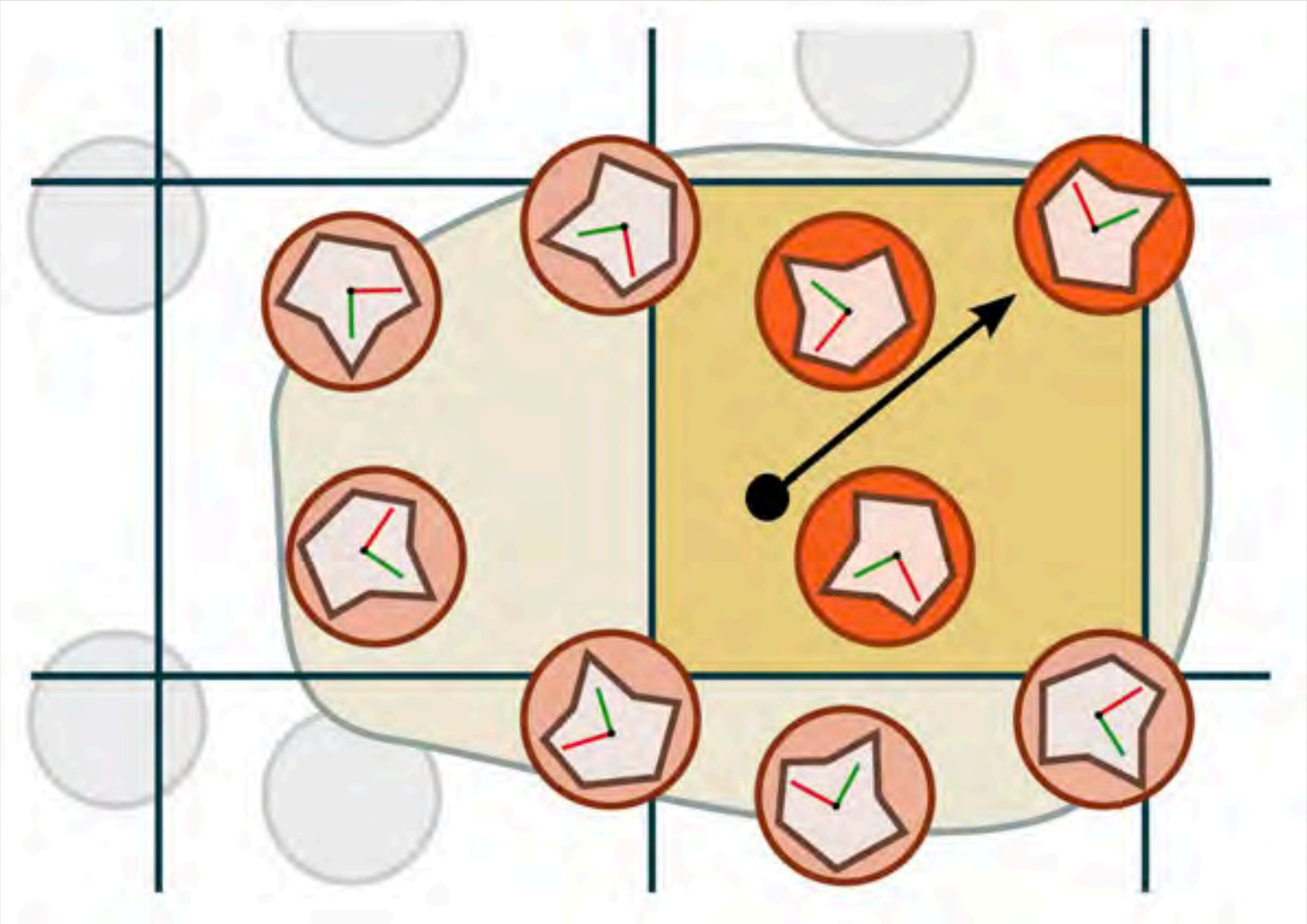
- What is granular material?

[Meng et al. 2015]

Granular Material

- Can we avoid explicit modeling of all granules?
  - Yes with procedural definition.





[Meng et al. 2015]

Granular Material

[Meng et al. 2015]

Granular Material: Application

[Piper. 2016 Pixar]

Procedural Material

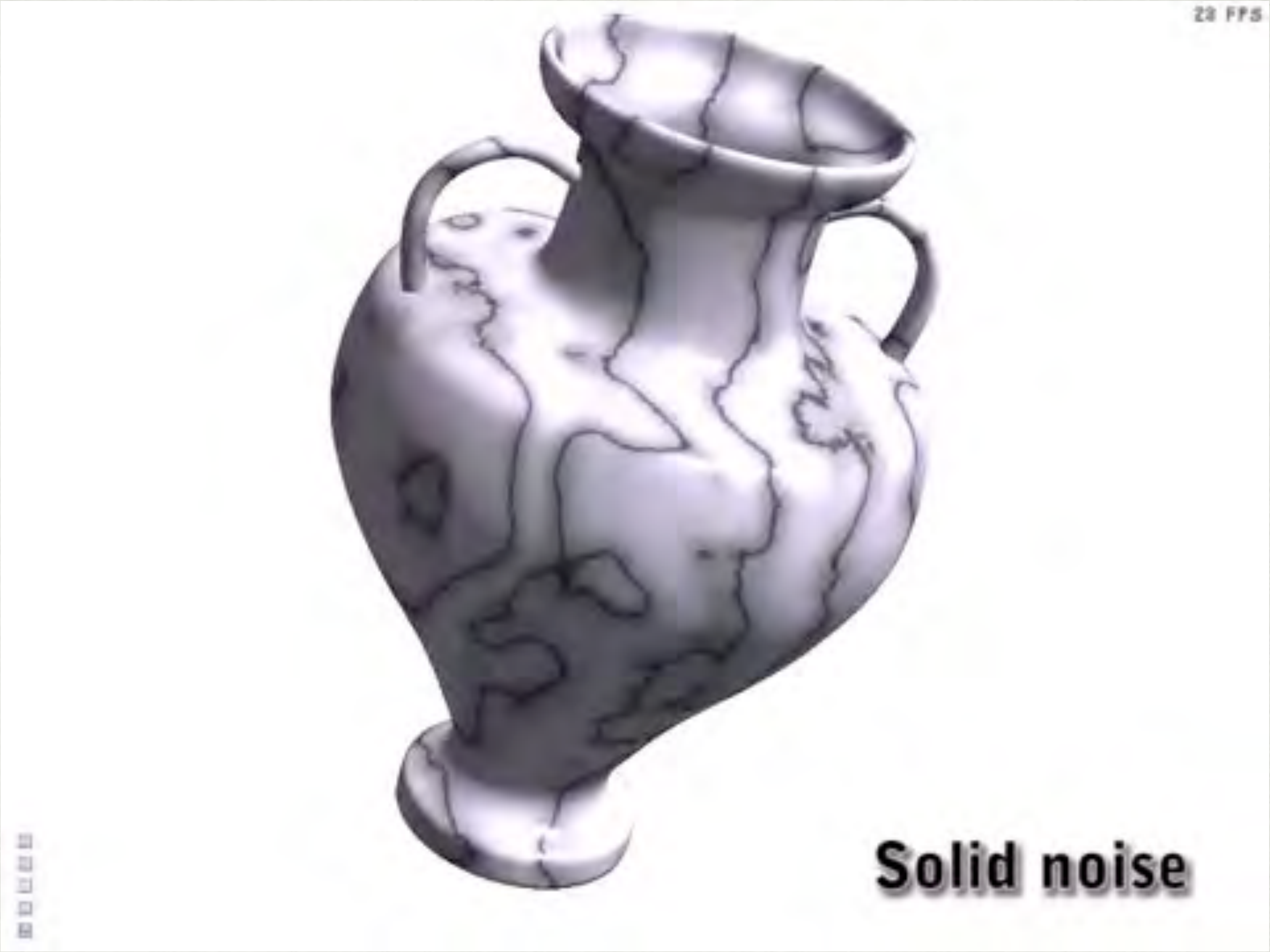
Procedural Model

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

[Lagae et al. 2009]

Procedural Model

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - 3D noise -> internal structure if cut or broken



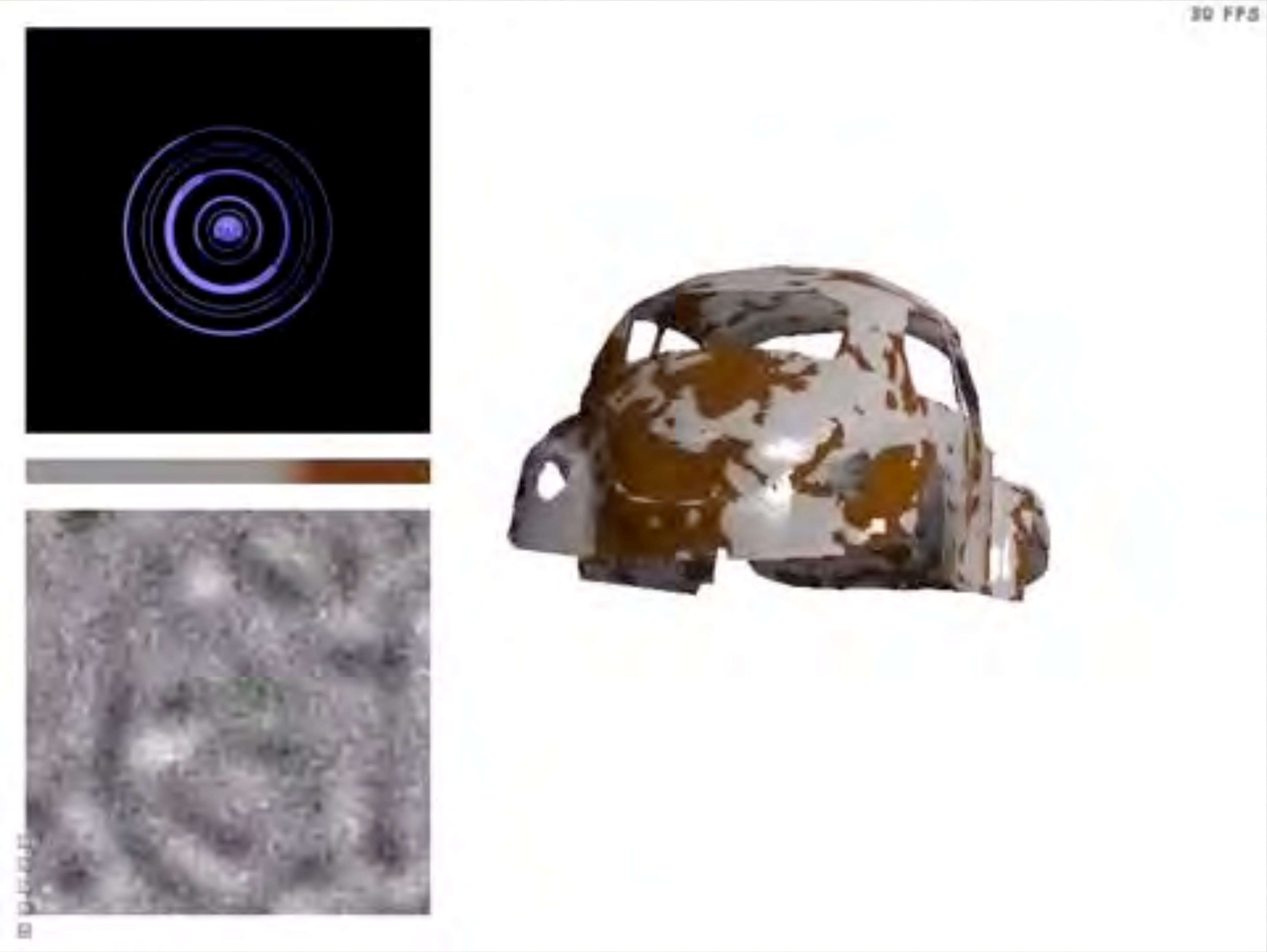
[Lagae et al. 2009]

Procedural Model

- Can we define details without textures?
  - Yes! Compute a noise function on the fly.
  - Thresholding
    (noise -> binary noise)

  Example:

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



[Lagae et al. 2009]

Procedural Model

- Complex noise functions can be very powerful.

Procedural Model

- Complex noise functions can be very powerful.

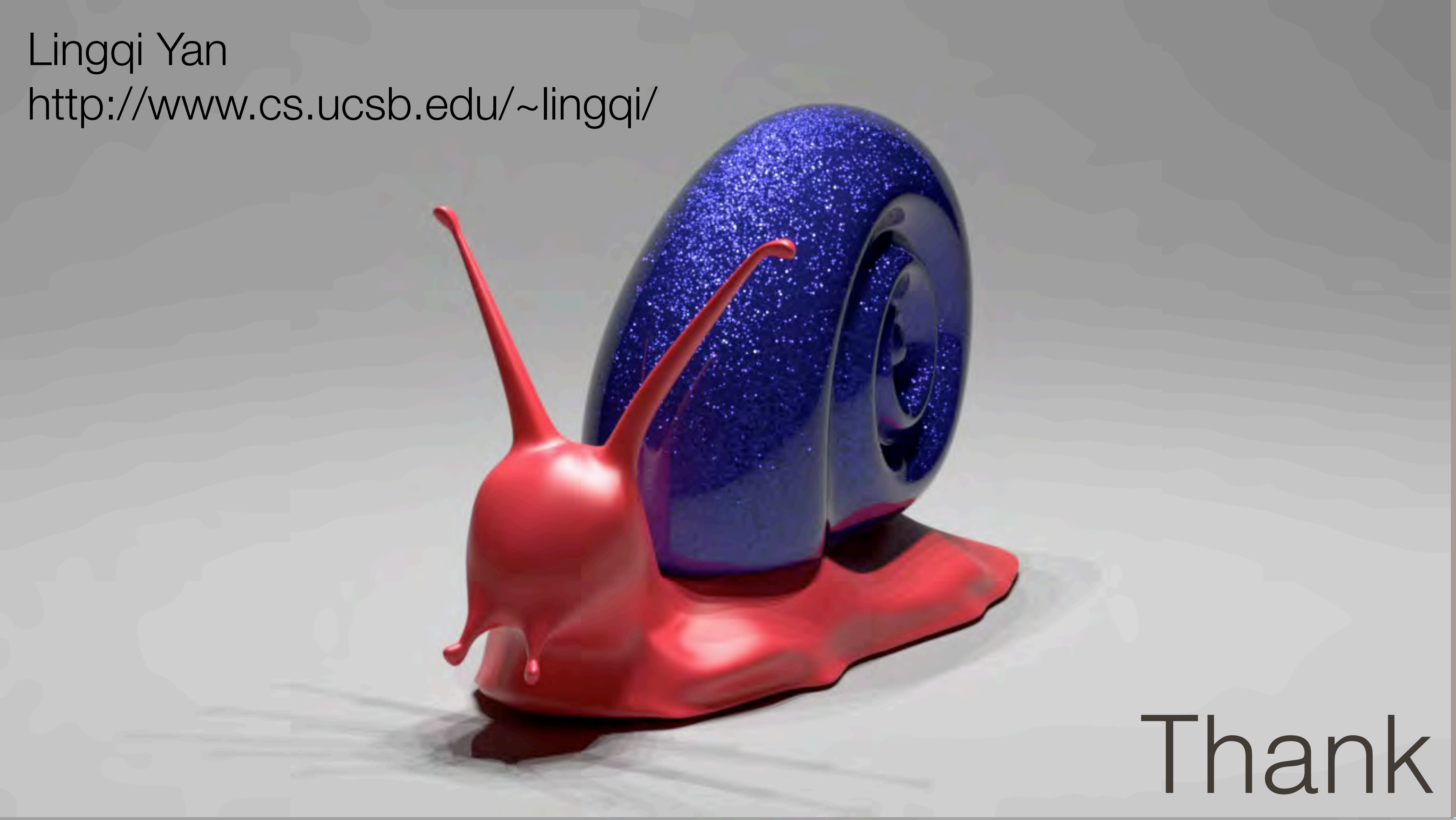
Procedural Model

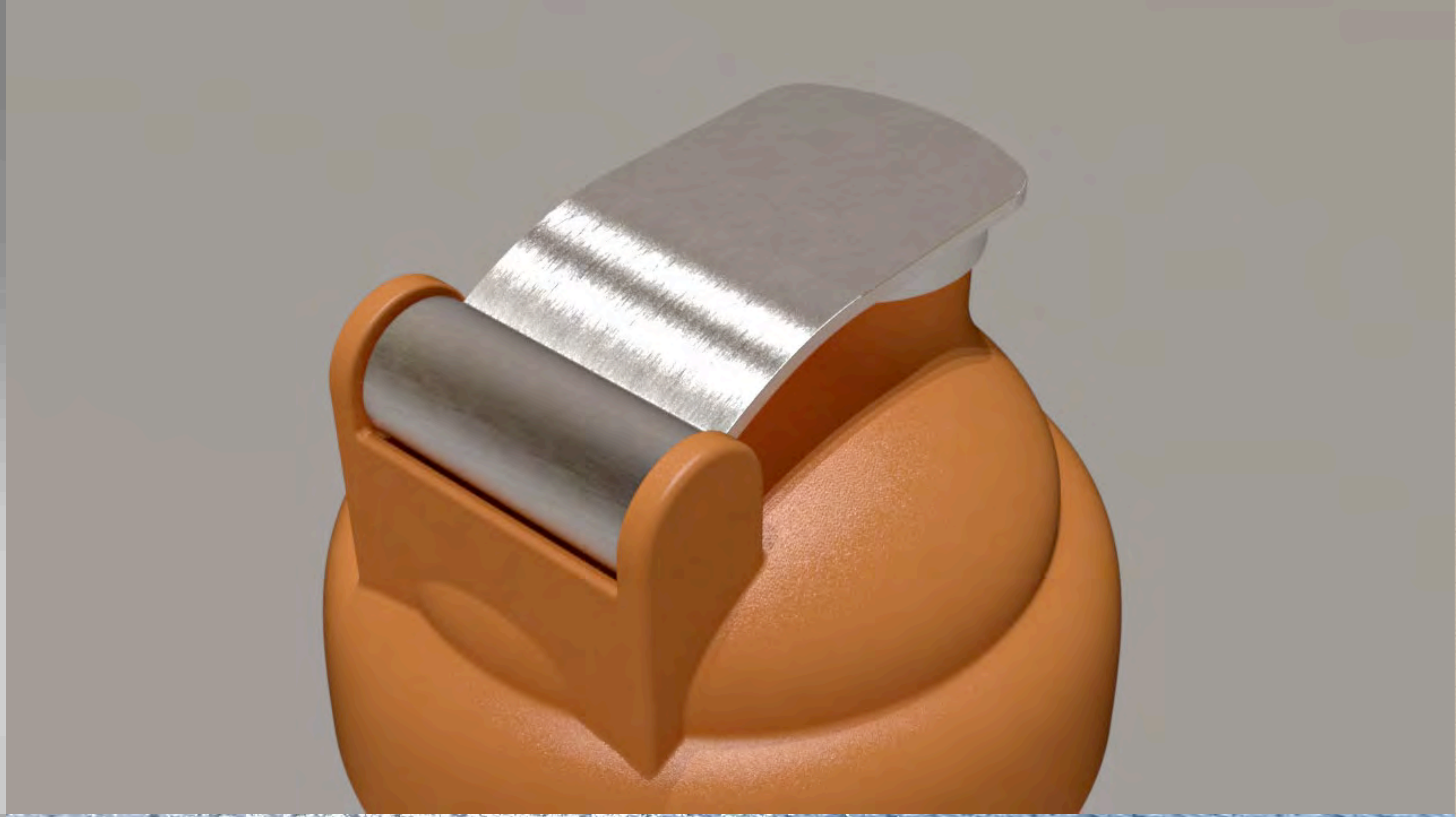
- Complex noise functions can be very powerful.

Procedural Model

- Complex noise functions can be very powerful.

Lingqi Yan
http://www.cs.ucsb.edu/~lingqi/





Thank you!