Physically-Based Rendering

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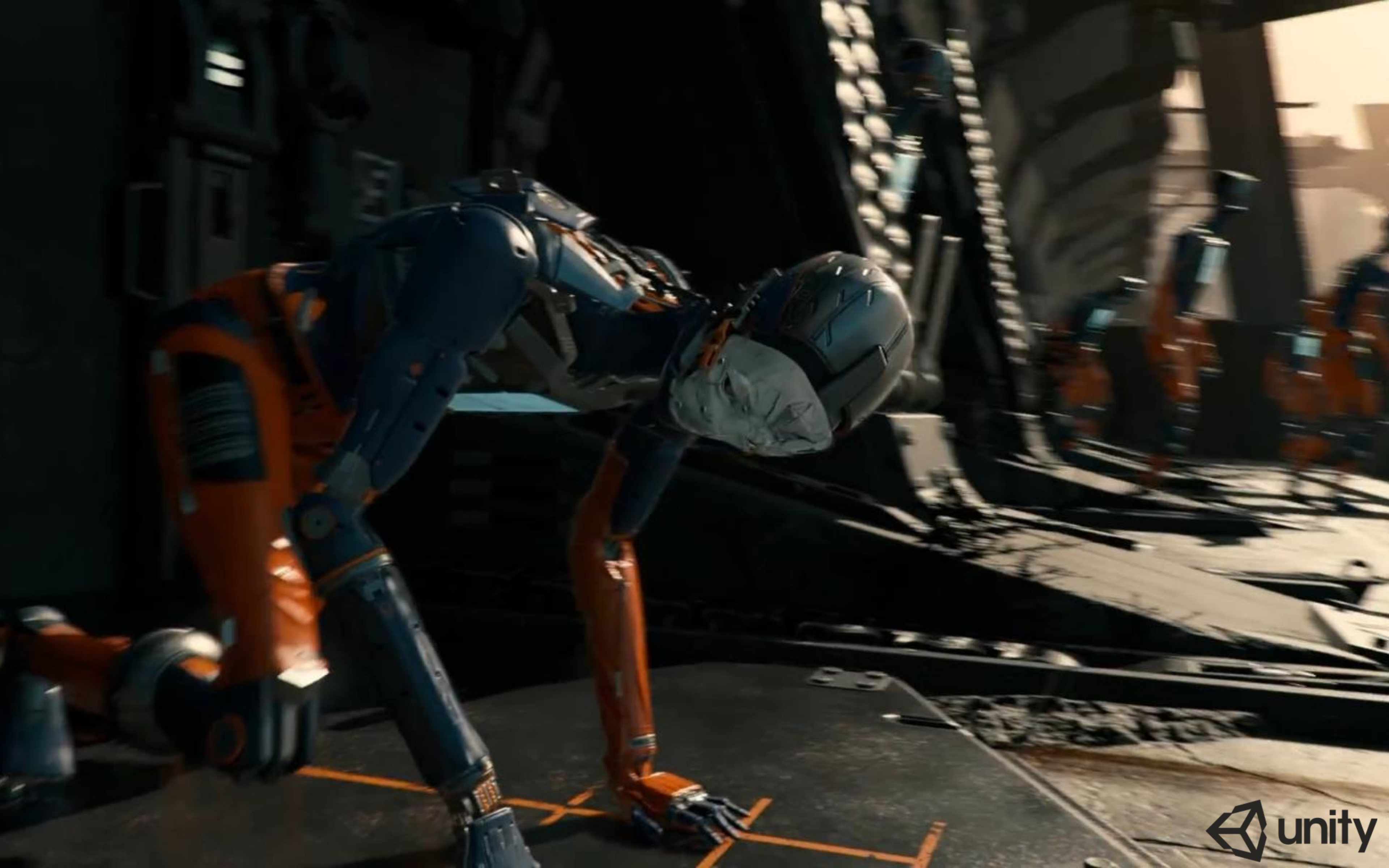
What is PBR?


unity


UNREAL
ENGINE

SOLIDANGLE

The Chemical Brothers - Wide Open, The Mill

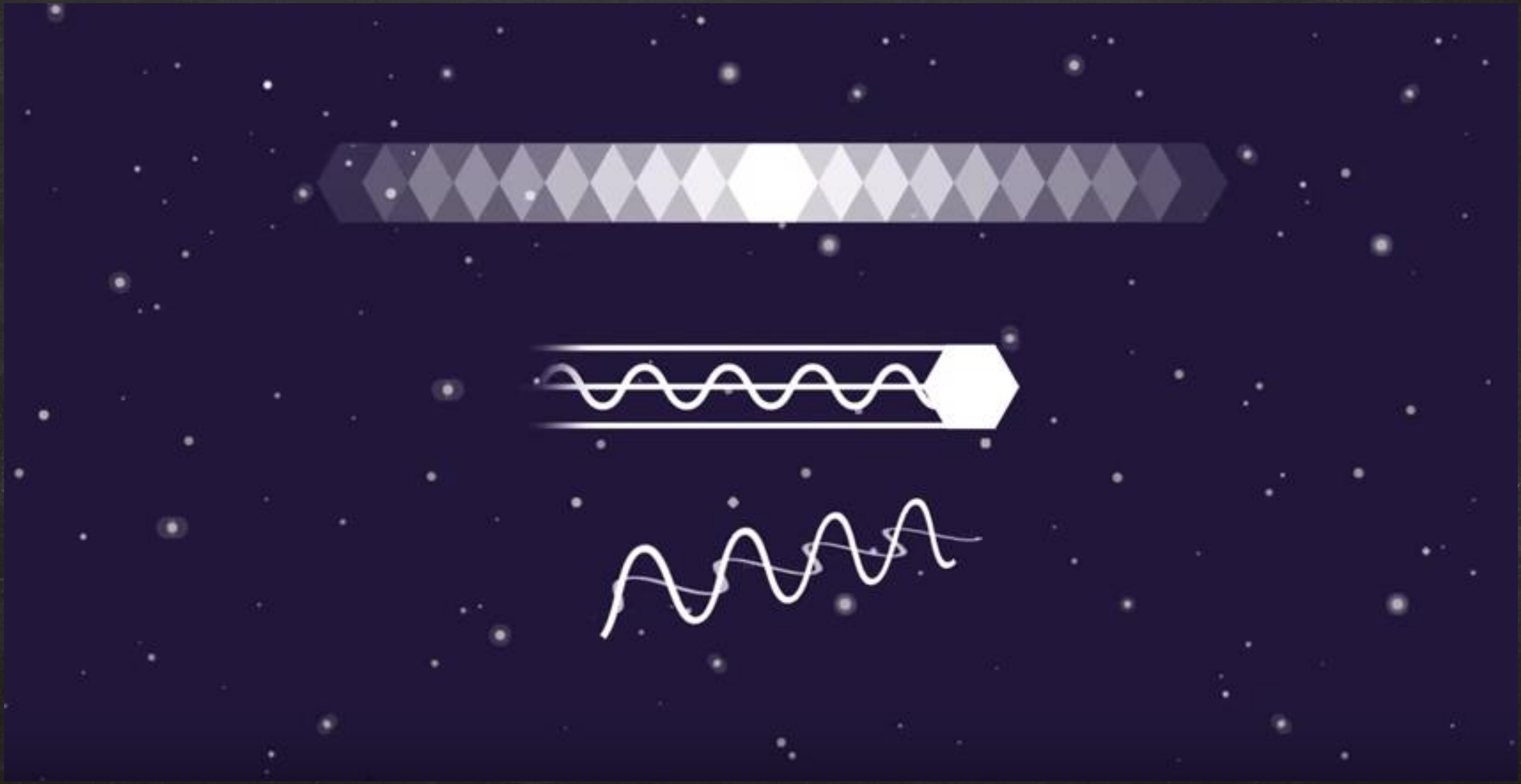
Physically **B**ased **R**endering

Simulate materials and lights based on physical laws or observations of real world more accurately.

Stages of Photorealistic Rendering

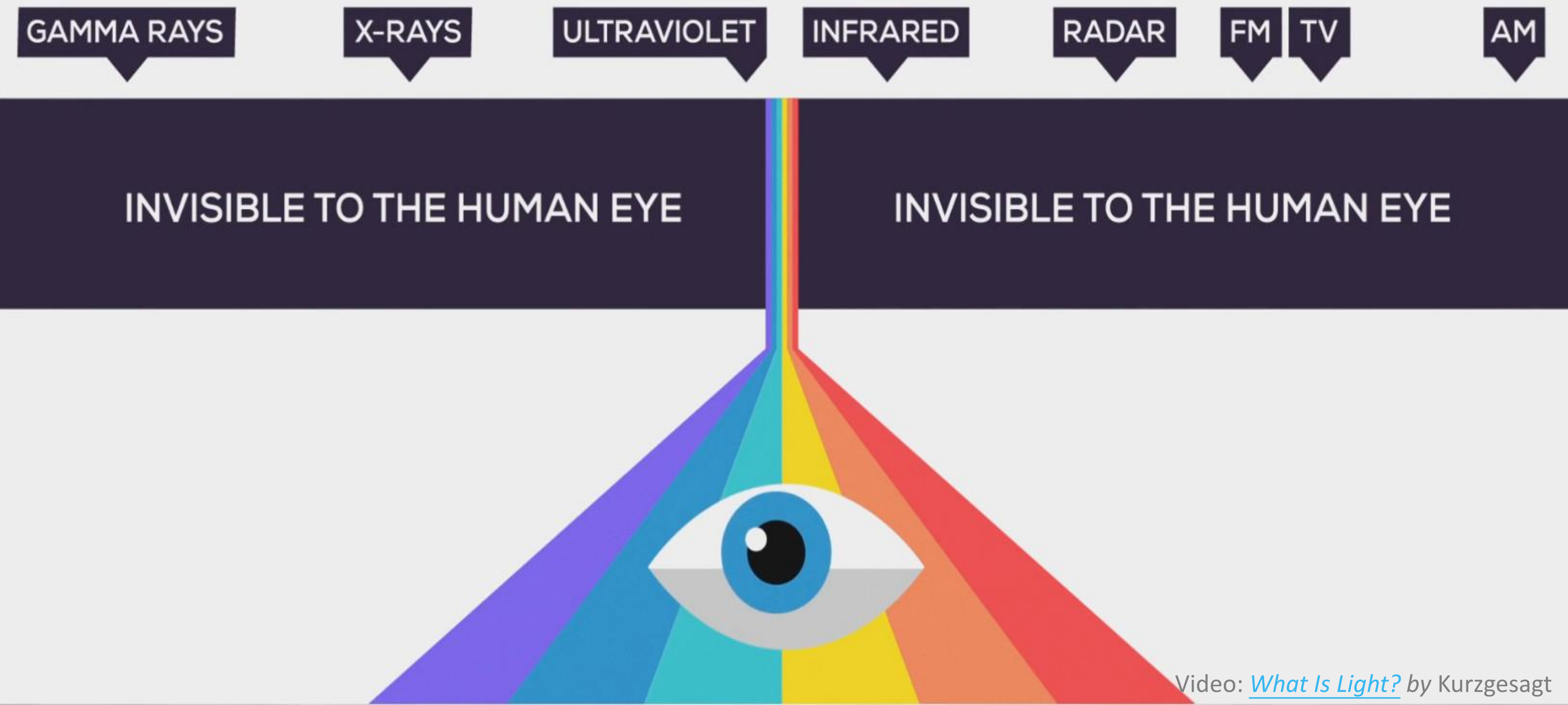
1. Measurement and acquisition of scene data
   – BRDF, BSSRDF, BTF, etc.
2. Light transport simulation
   – Ray tracing, photon-mapping, radiosity, etc.
3. Visual display
   – Tone mapping

What Is Light?



Video: *What Is Light?* *by* Kurzgesagt

ELECTROMAGNETIC SPECTRUM

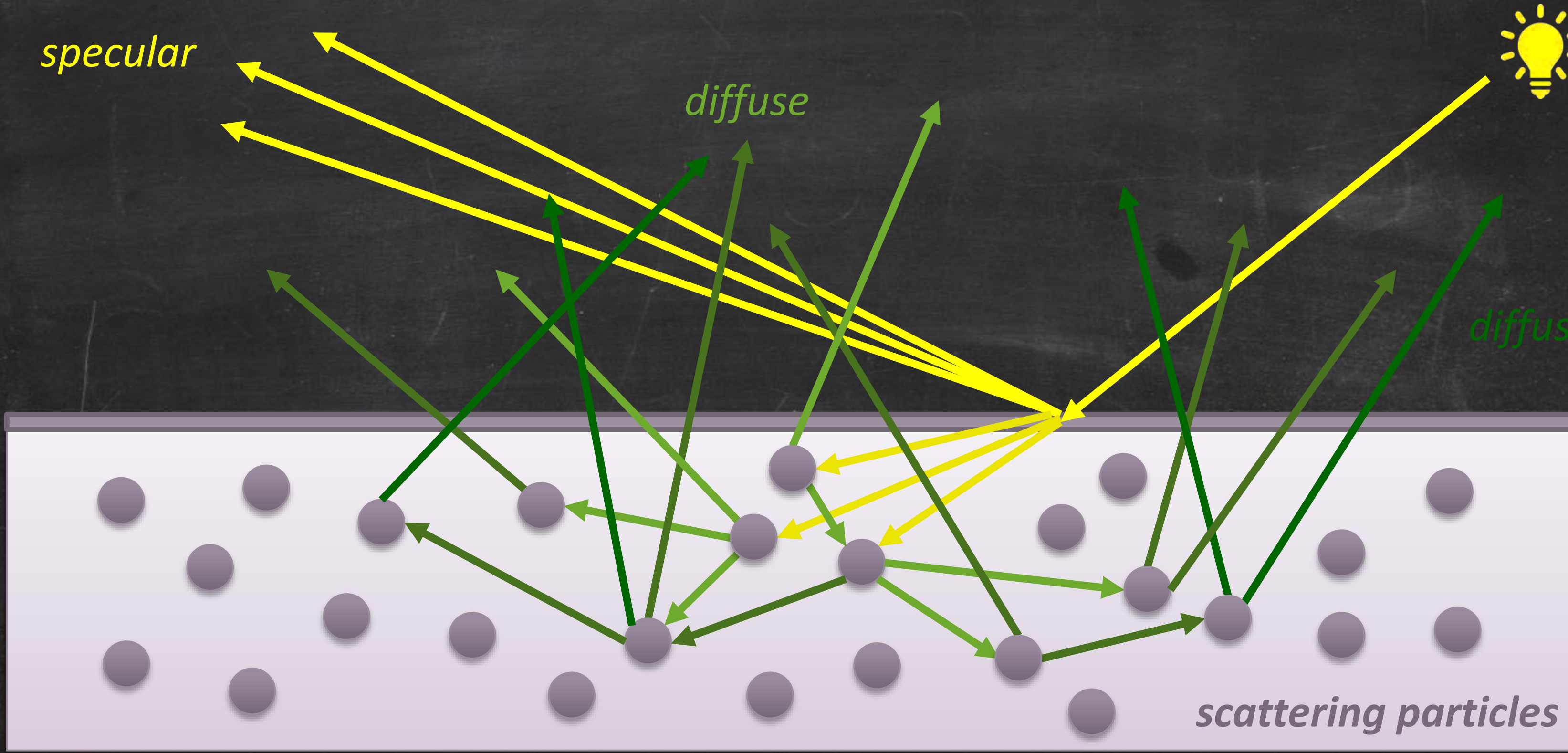


Video: *What Is Light?* *by* Kurzgesagt

Geometric Optics

- Assumption: the wavelength of light is much smaller than the scale of interacted object
- Light travels
  - in straight lines
  - instantaneously through a medium
- Light is not influenced by gravity or magnetic fields
  - No diffraction, dispersion
  - But the movie “Interstellar” does simulate the light bent by gravity!!

Light Matter Interaction



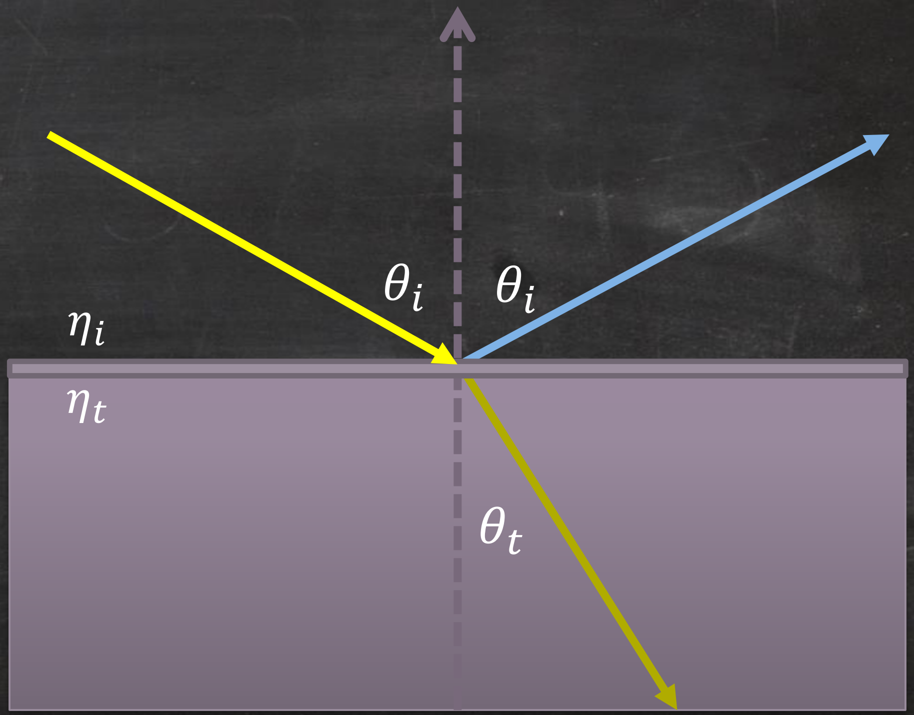
Snell’s Law

Photo by Gabriel Gurrola

Snell's Law

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

Index of Refraction (IOR): η



https://en.wikipedia.org/wiki/Snell%27s_law#/media/File:Snells_law_wavefronts.gif

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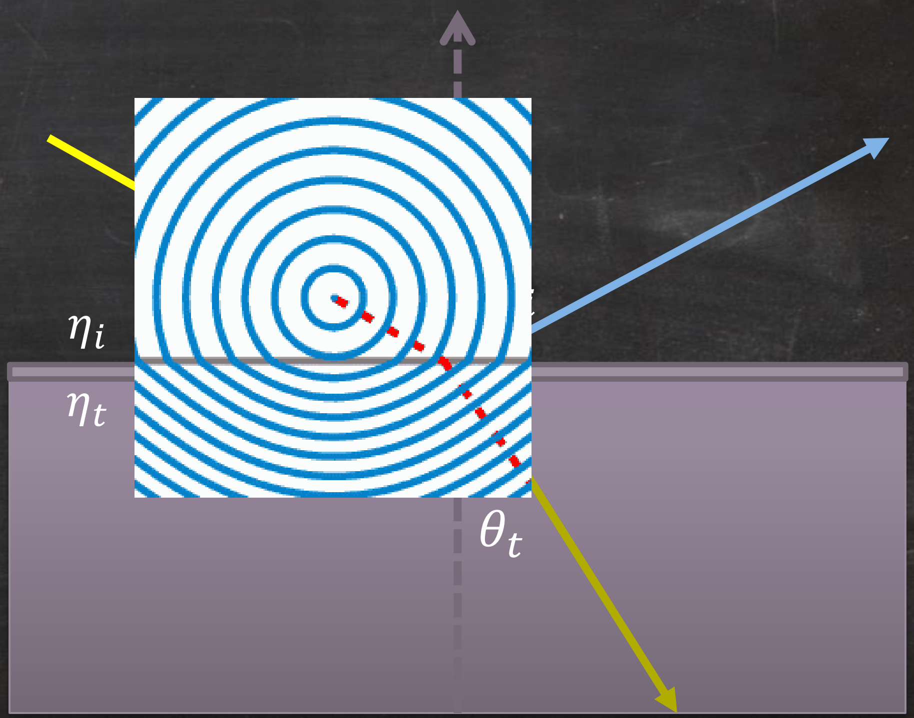

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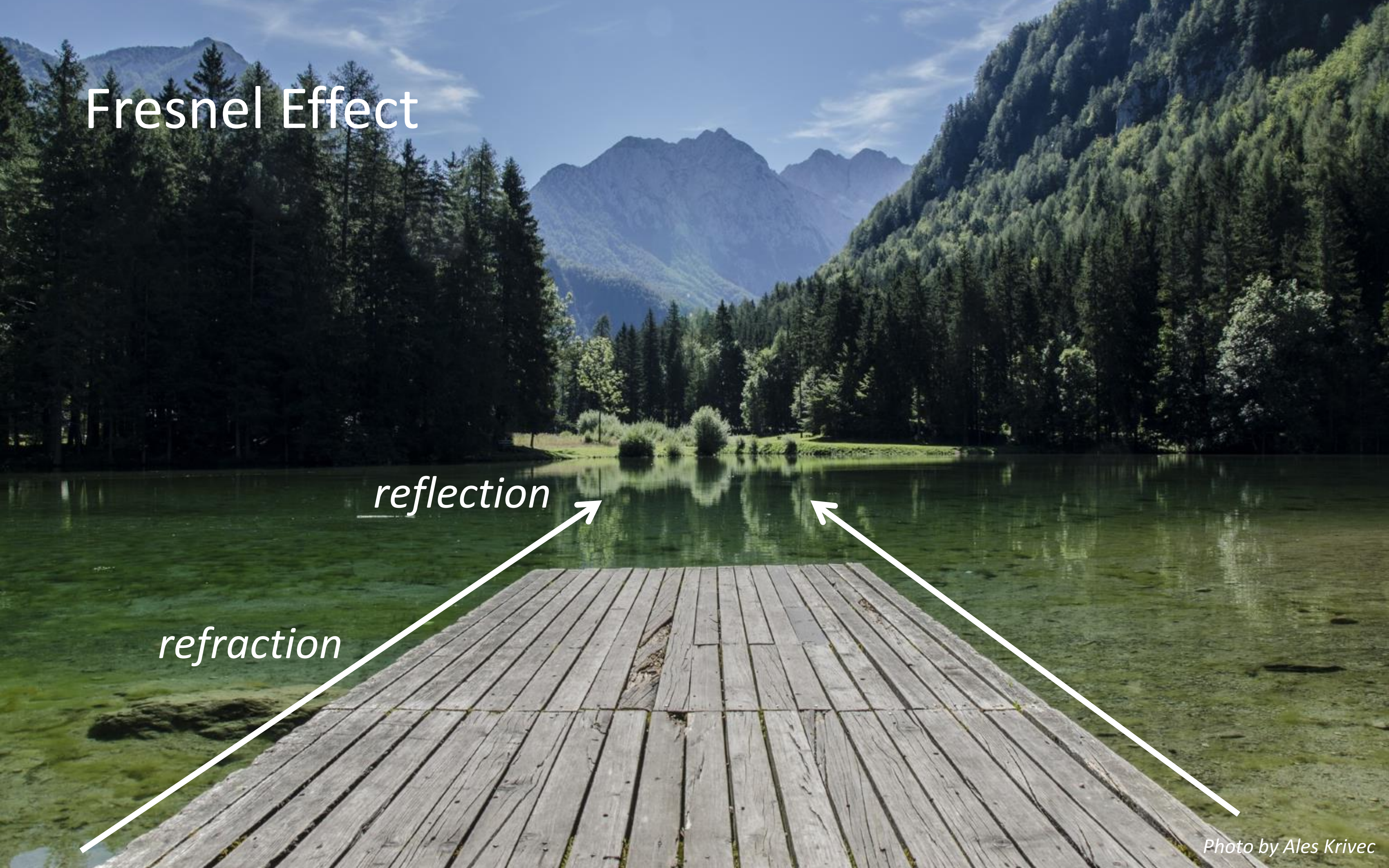

Fresnel Effect
reflection
refraction
Photo by Ales Krivec

Fresnel Effect

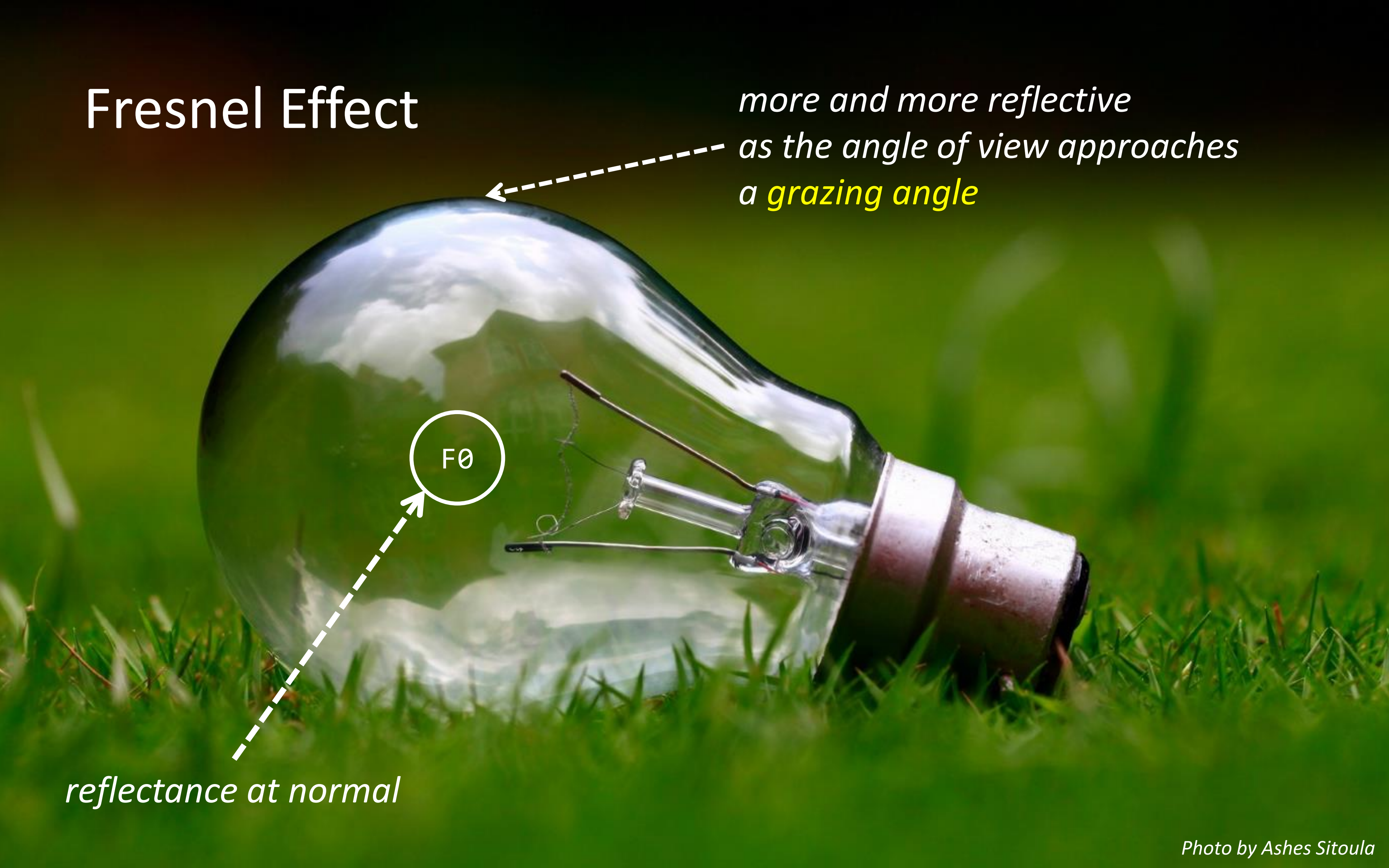


Photo by Ashes Sitoula

Fresnel

- Fresnel reflectance
  - the amount of reflected light w.r.t. the viewing angle
- Relates the ratio of reflected and transmitted energy as a function of
  - Incident direction
  - Polarization
  - Materials’ properties

Material Properties

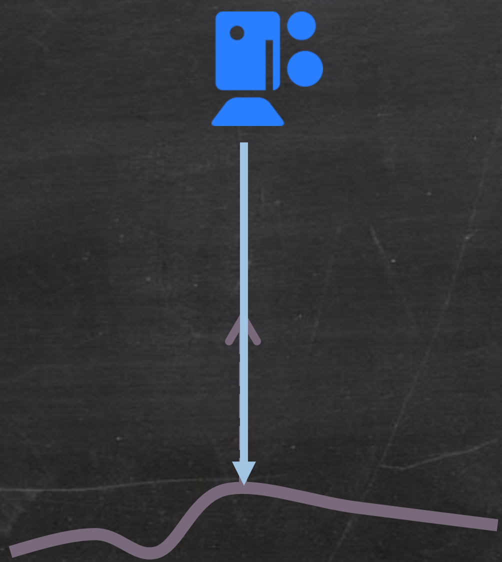
Non-metal (dielectrics)

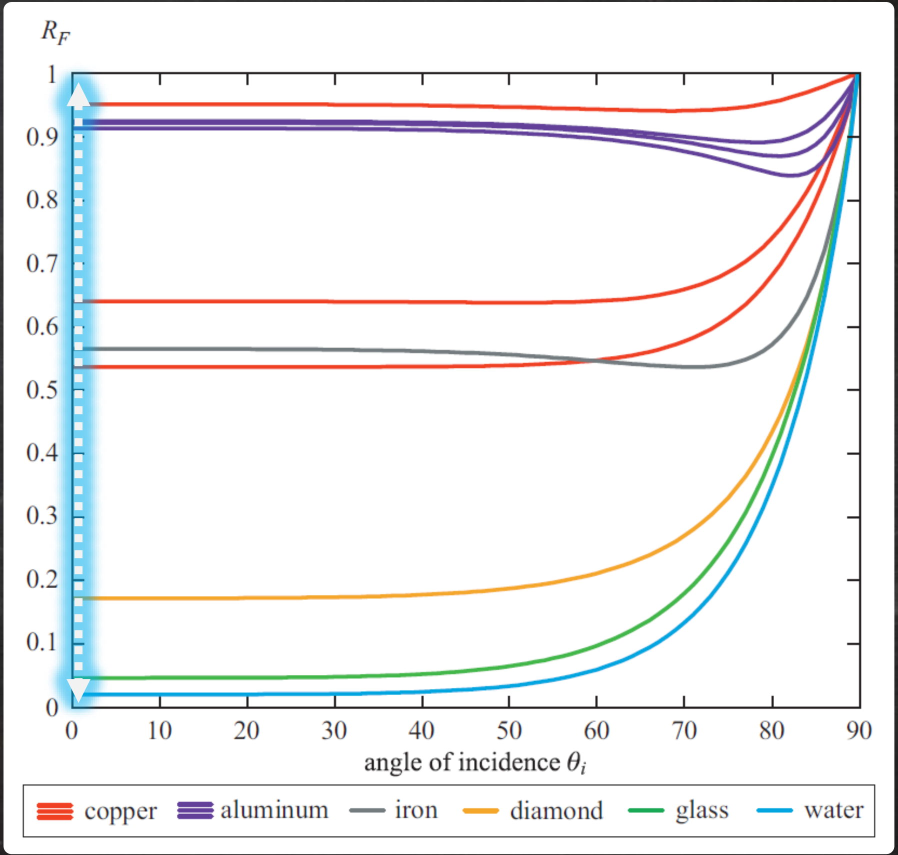
- Only reflect 4~10% of incoming light in average
- The reflection intensity is independent on the wavelength
- No energy is absorbed during reflection
  - but might be absorbed during subsurface scattering

Metal

- IOR strongly depends on the wavelength
- Immediately absorbs refracted lights (i.e. no refraction)
  - The reflected lights would change their color

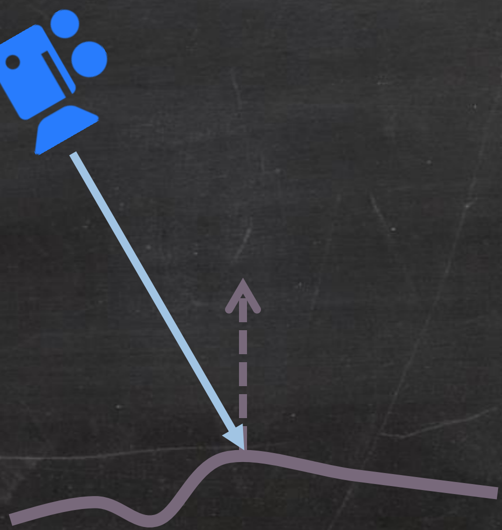
Fresnel Reflectance

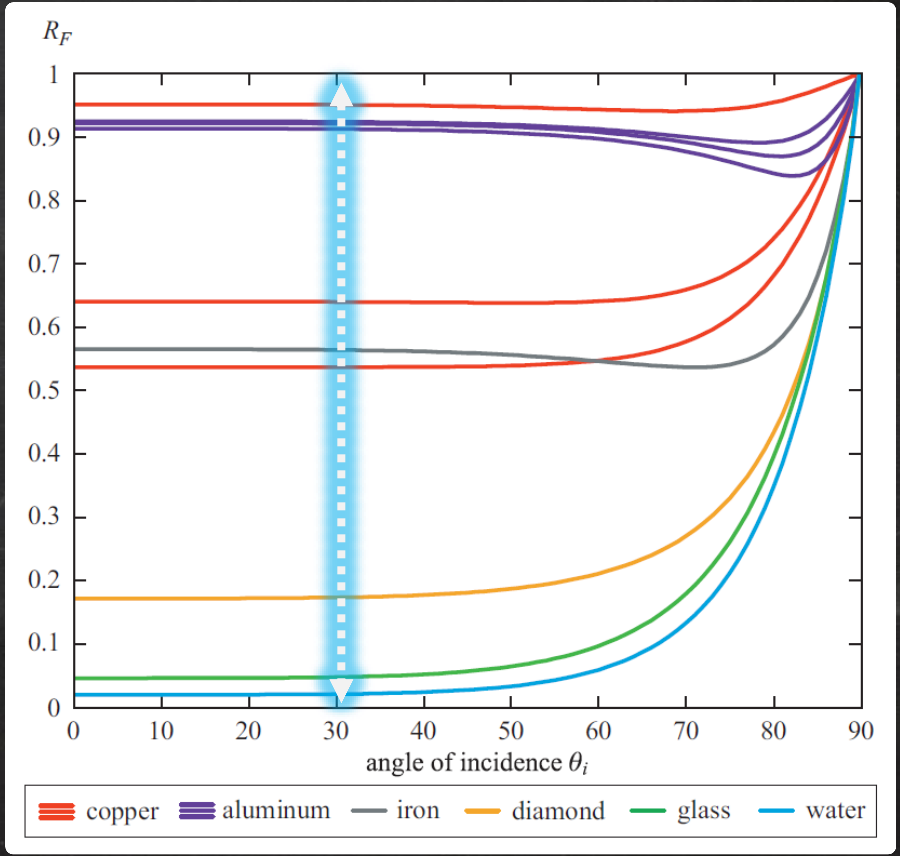




[*Real-time Rendering*, 3/e, A K Peters 2008]

Fresnel Reflectance





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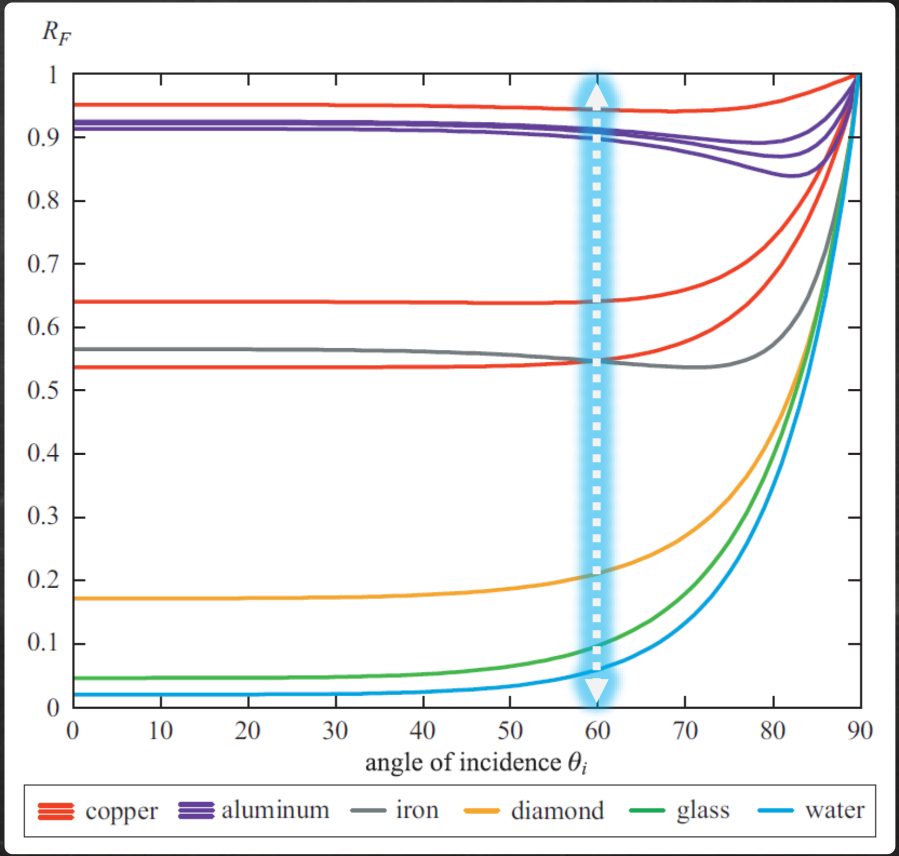
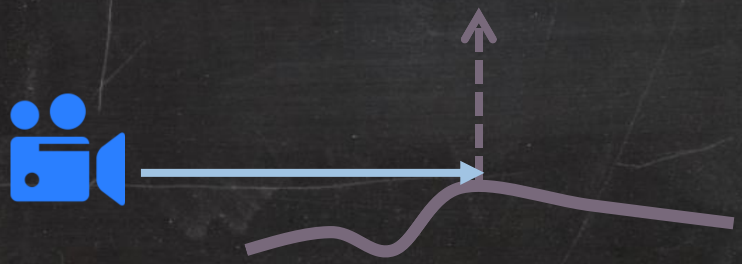
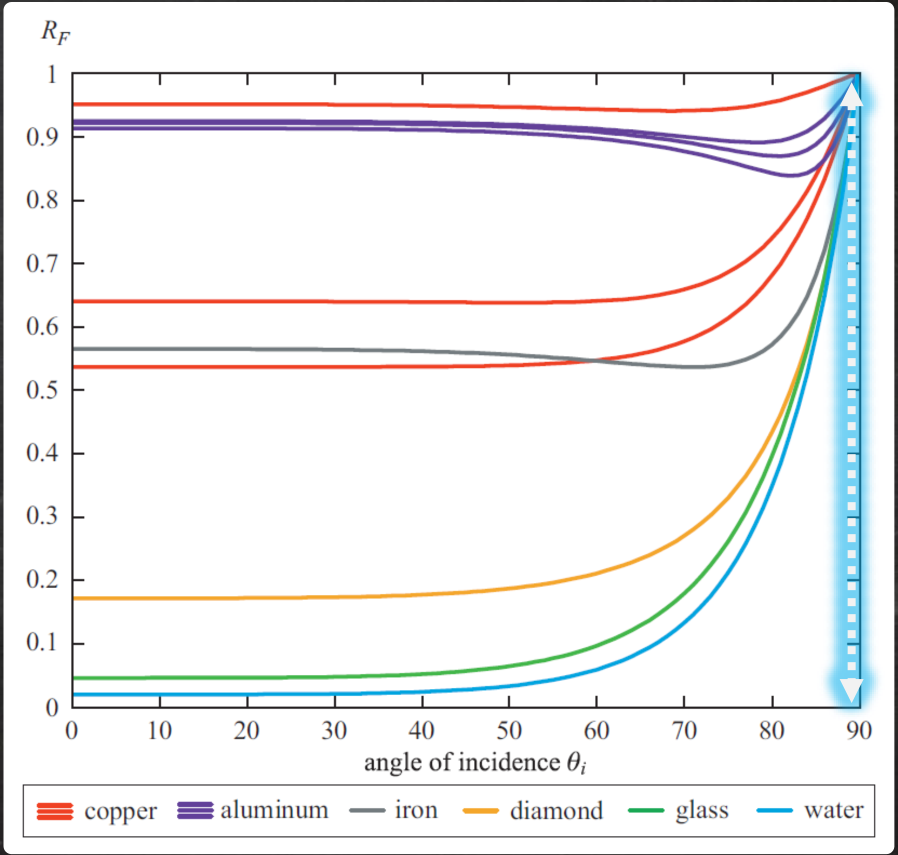
Fresnel Reflectance



[*Real-time Rendering*, 3/e, A K Peters 2008]

Fresnel Reflectance

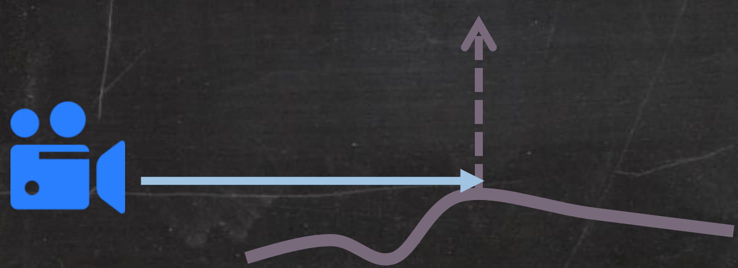


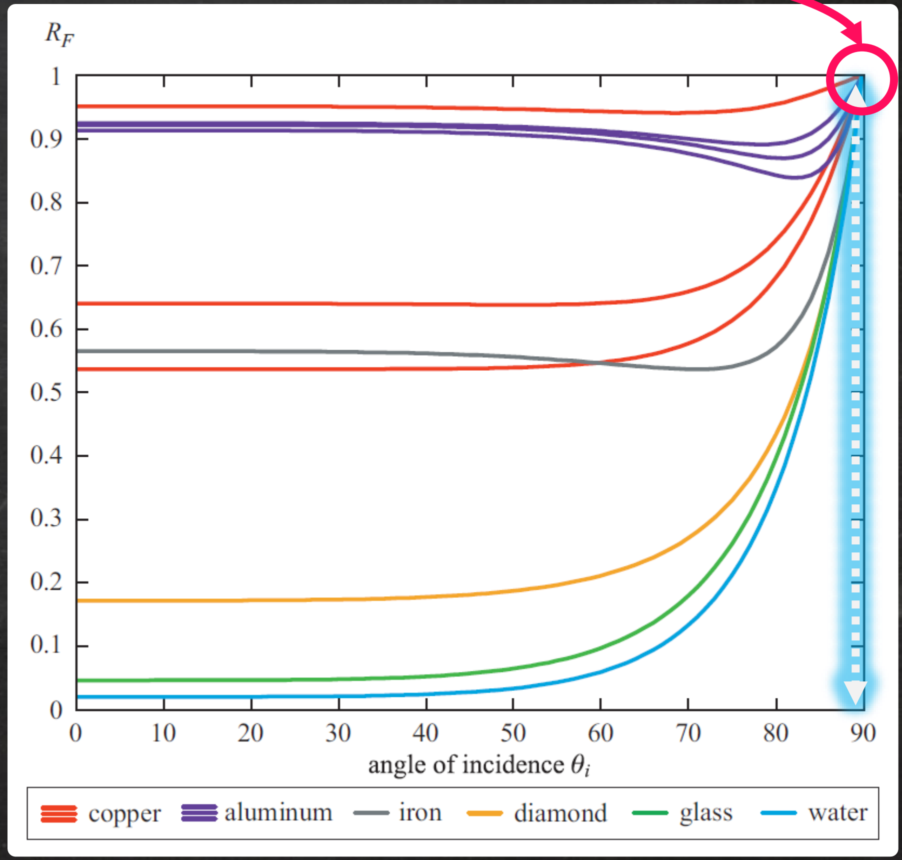


[Real-time Rendering, 3/e, A K Peters 2008]

Fresnel Reflectance

*Reflection goes to **100%** at grazing angle!*





[*Real-time Rendering*, 3/e, A K Peters 2008]

Fresnel

for unpolarized light

$$F_r = \frac{1}{2}\left(r_\parallel^2 + r_\perp^2\right)$$

Dielectric

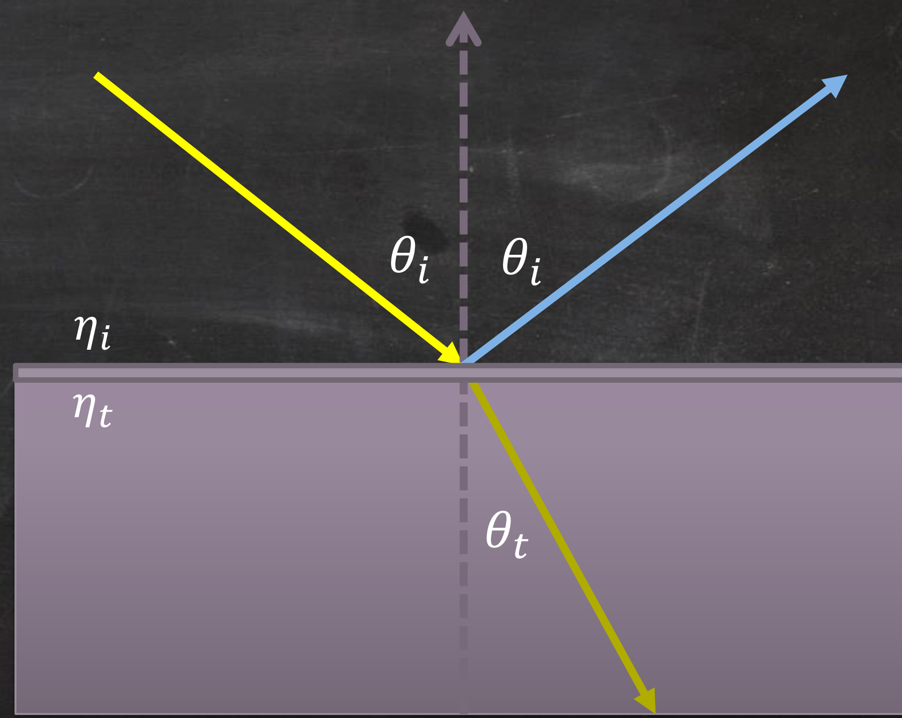
$$r_\parallel = \frac{\eta_t \cos\theta_i - \eta_i \cos\theta_t}{\eta_t \cos\theta_i + \eta_i \cos\theta_t}$$

$$r_\perp = \frac{\eta_i \cos\theta_i - \eta_t \cos\theta_t}{\eta_i \cos\theta_i + \eta_t \cos\theta_t}$$

Conductor

$$r_\parallel^2 = \frac{(\eta^2 + k^2)\cos^2\theta_i - 2\eta\cos\theta_i + 1}{(\eta^2 + k^2)\cos^2\theta_i + 2\eta\cos\theta_i + 1}$$

$$r_\perp^2 = \frac{(\eta^2 + k^2) - 2\eta\cos\theta_i + \cos^2\theta_i}{(\eta^2 + k^2) + 2\eta\cos\theta_i + \cos^2\theta_i}$$

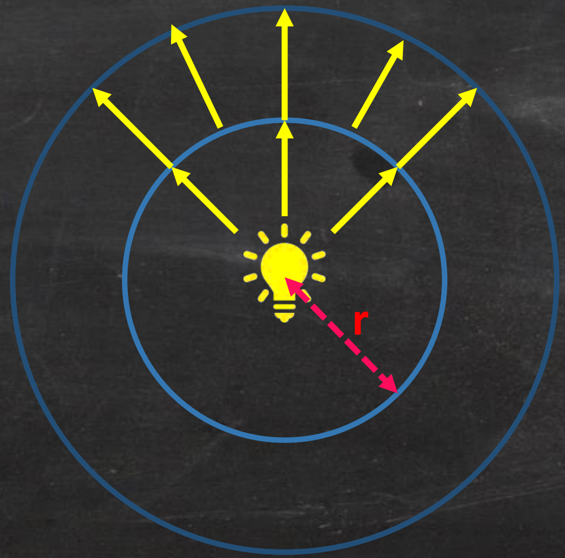


Radiometry

the total amount Φ measured
*at **inner** and **outer** sphere is **the same***
(equals to the radiant flux of the point light)

Radiant flux $\Phi = \frac{\mathrm{dQ}}{\mathrm{dt}}$ (J/sec)

The total amount of energy passing through a region of surface per unit time



$$E = \frac{\Phi}{4\pi r^2}$$

Irradiance $E = \frac{d\Phi}{dA}$

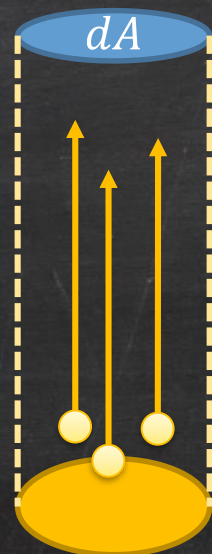
Pre area incoming flux at a surface

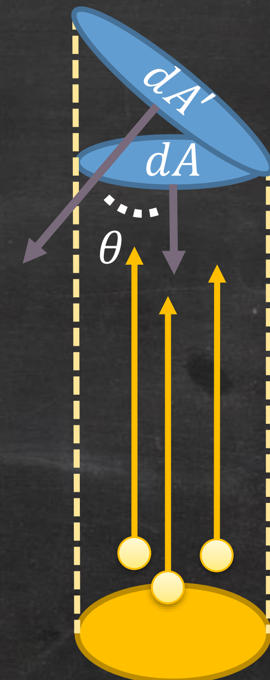
Radiant Exitance or Radiosity

$$M = B = \frac{d\Phi}{dA}$$

Lambert's Cosine Law

$$E = \frac{d\Phi}{dA}$$





$$dA = dA' \cos\theta$$

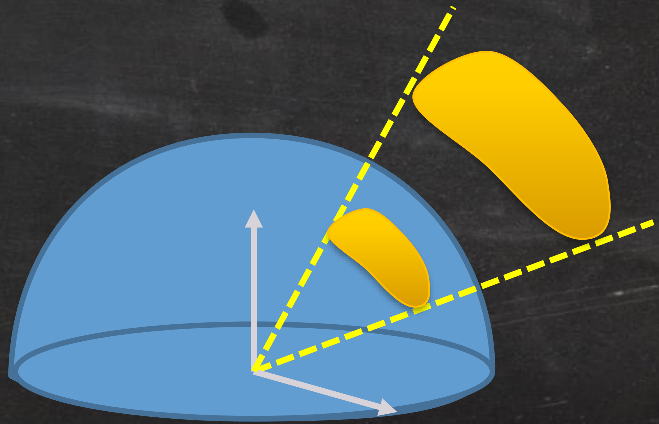
$$E_1 = \frac{d\Phi}{dA}$$

$$E_2 = \frac{d\Phi}{dA'} = \frac{\cos\theta \, d\Phi}{dA} = E_1 \cos\theta$$

Solidangle

$$\Omega = \frac{A}{r^2}$$

– The total area on a unit sphere subtended by the object
– A set of *directions*
– Measured in steradians (sr)
– Often denoted as ω



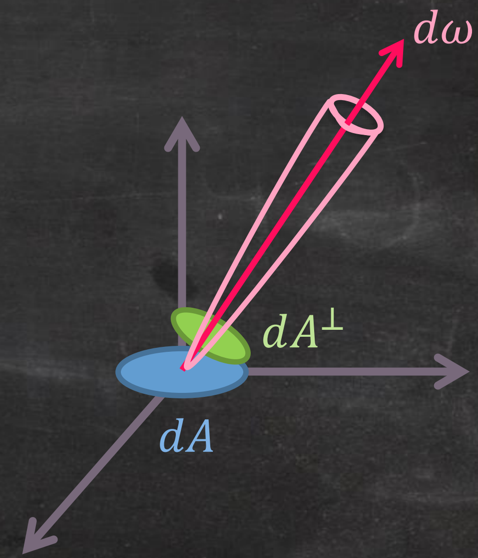
★Radiance

flux

$$L = \frac{d^2\Phi}{d\omega dA^{\perp}} = \frac{d^2\Phi}{d\omega dA\cos\theta}$$

solidangle

projected area



The density of photons passing near x and traveling in directions near ω

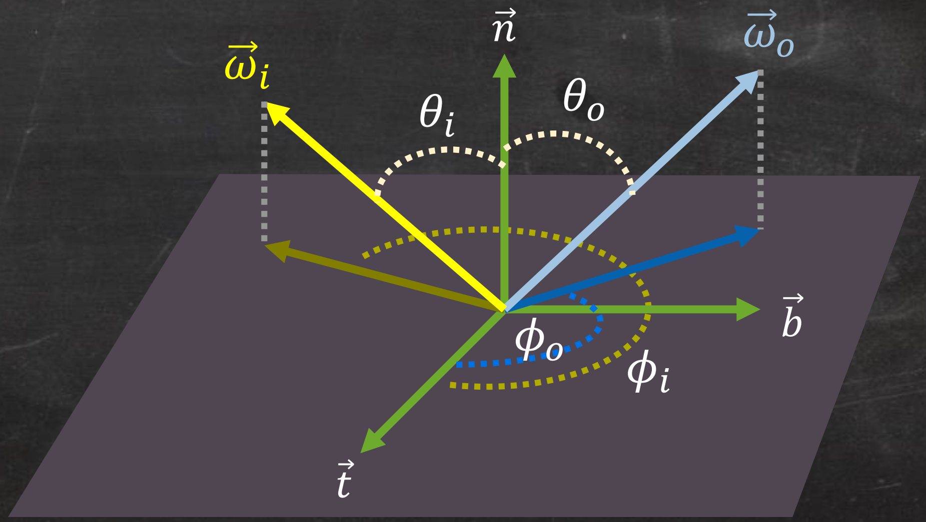
Bidirectional

Reflection

Distribution

Function

$$f(\theta_i, \phi_i, \theta_o, \phi_o) = f(\vec{\omega}_i, \vec{\omega}_o)$$



BRDF Definition

outgoing radiance

$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{dL_r(\vec{\omega}_o)}{dE_i(\vec{\omega}_i)} = \frac{dL_r(\vec{\omega}_o)}{L_i(\vec{\omega}_i)\cos\theta_i \, d\omega_i}$$

incoming irradiance

BRDF Definition

$$\frac{spending}{income}$$

outgoing radiance

$$f(\vec{\omega}_i, \vec{\omega}_o) = \frac{dL_r(\vec{\omega}_o)}{dE_i(\vec{\omega}_i)} = \frac{dL_r(\vec{\omega}_o)}{L_i(\vec{\omega}_i)\cos\theta_i\, d\omega_i}$$

incoming irradiance

Properties of BRDFs

- Helmholtz reciprocity
  - symmetric surface reflectance

$$f(\vec{\omega}_i, \vec{\omega}_o) = f(\vec{\omega}_o, \vec{\omega}_i)$$

- Positivity

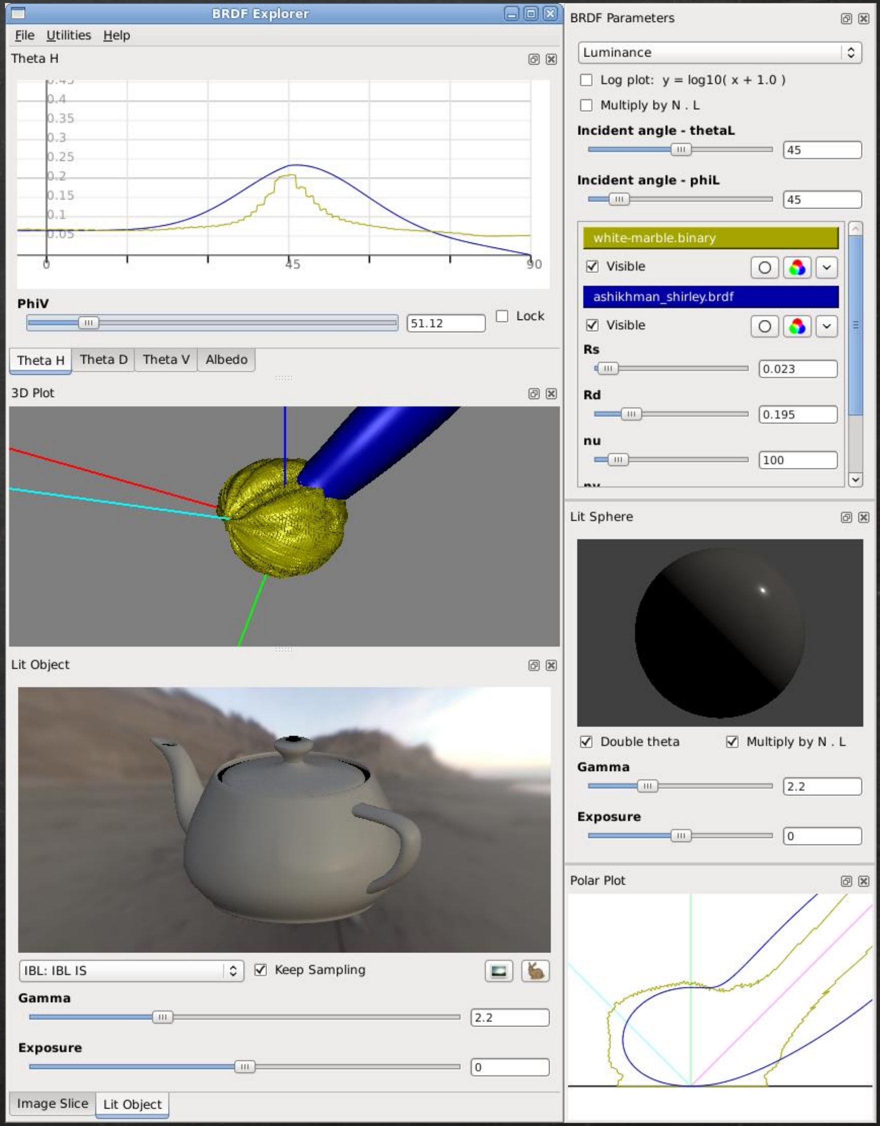
$$f(\vec{\omega}_i, \vec{\omega}_o) \geq 0$$

- Energy conservation
  - Total amount of outgoing energy must be *less than or equal to* the incoming energy

BRDF Explorer

from Disney Animation

http://www.disneyanimation.com/technology/brdf.html

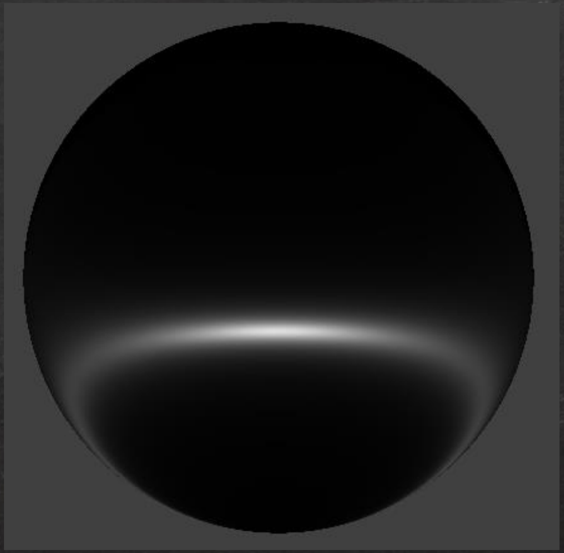


[*Image courtesy of Disney.*]

Isotropic vs. Anisotropic

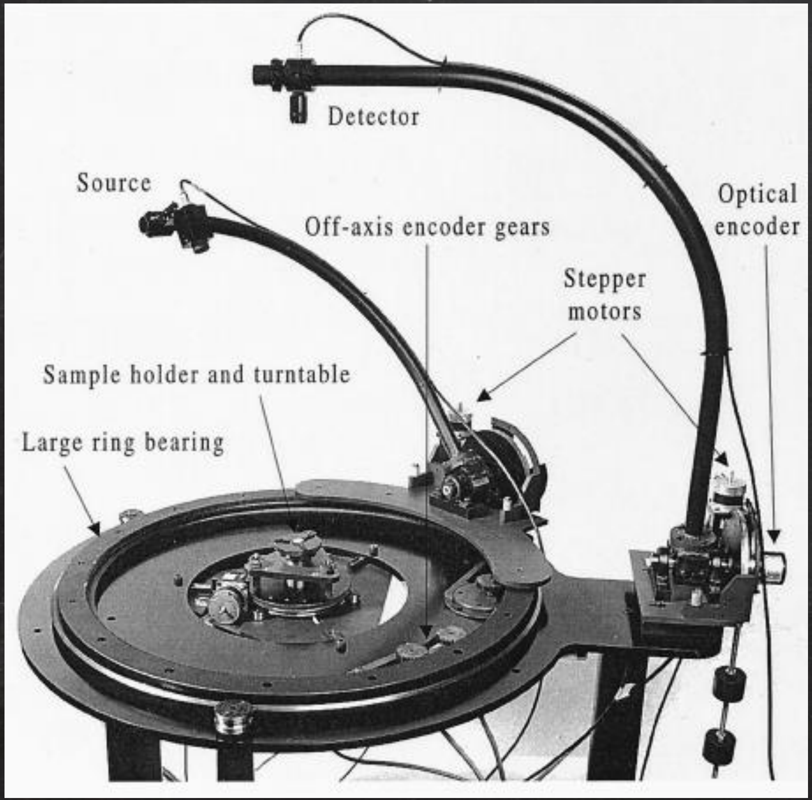
- Isotropic BRDFs are independent of incident azimuth angle ϕ

isotropic

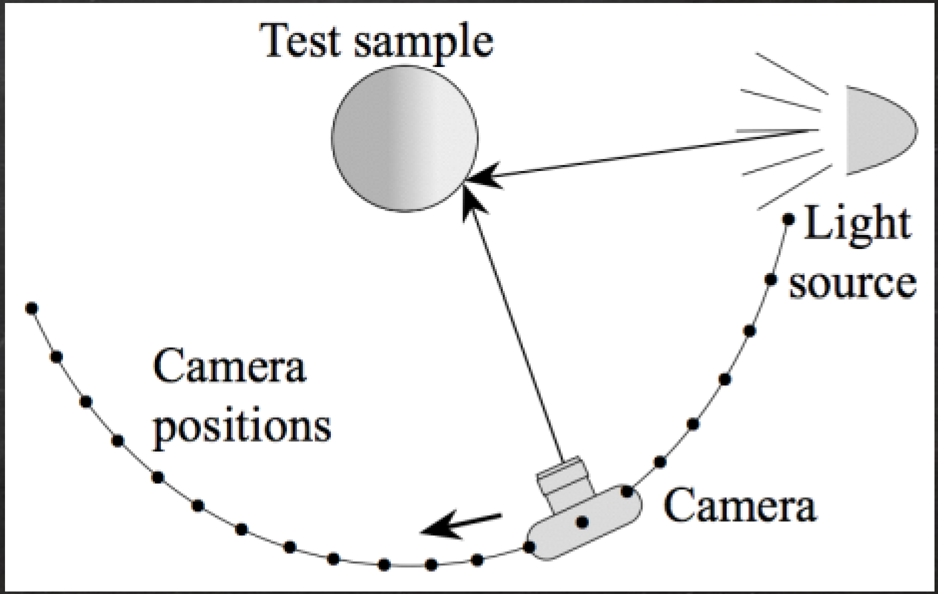


anisotropic

BRDF Acquisition



[White et al, JAO 98]

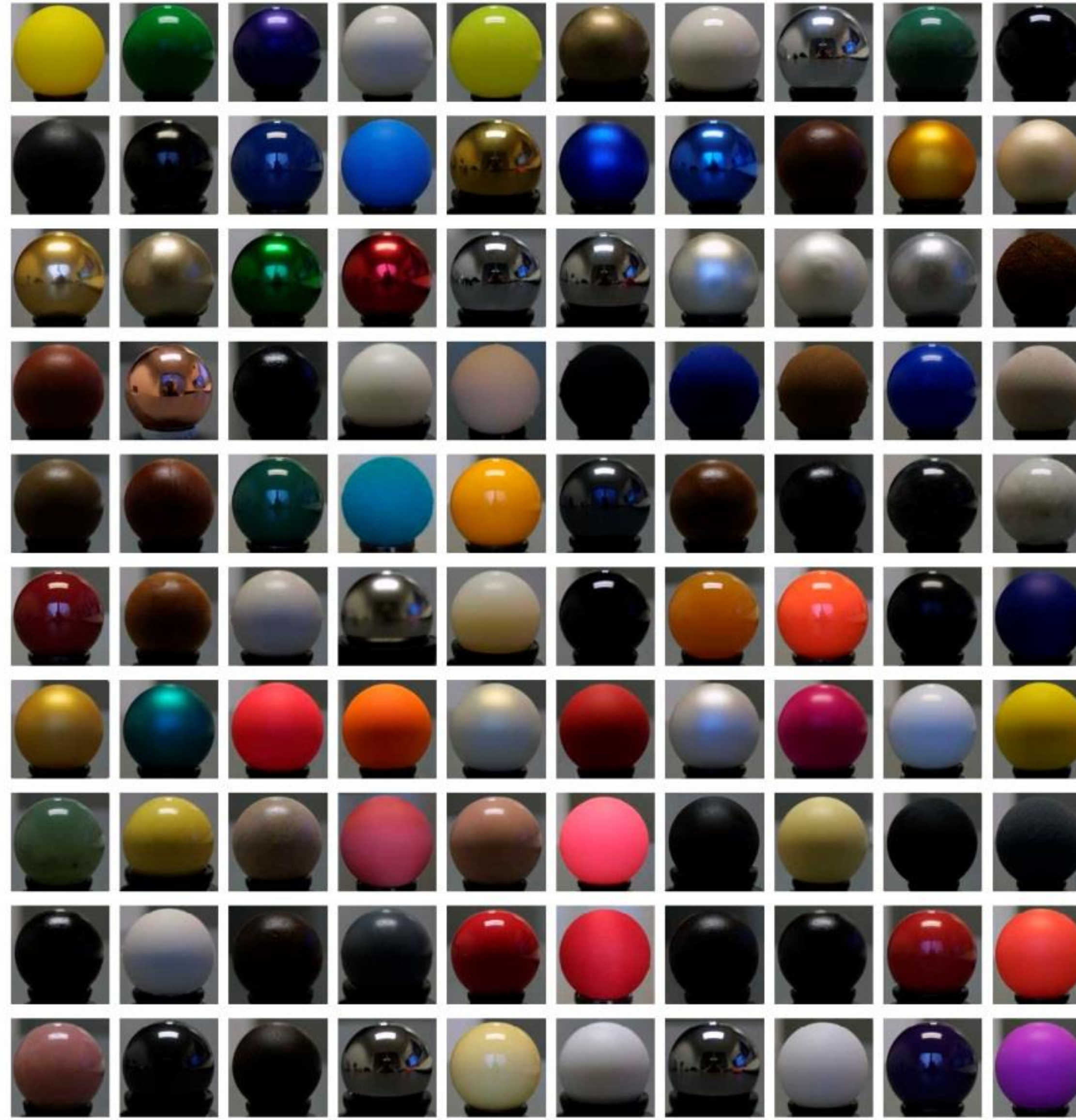


[Marschner et al. 1999]

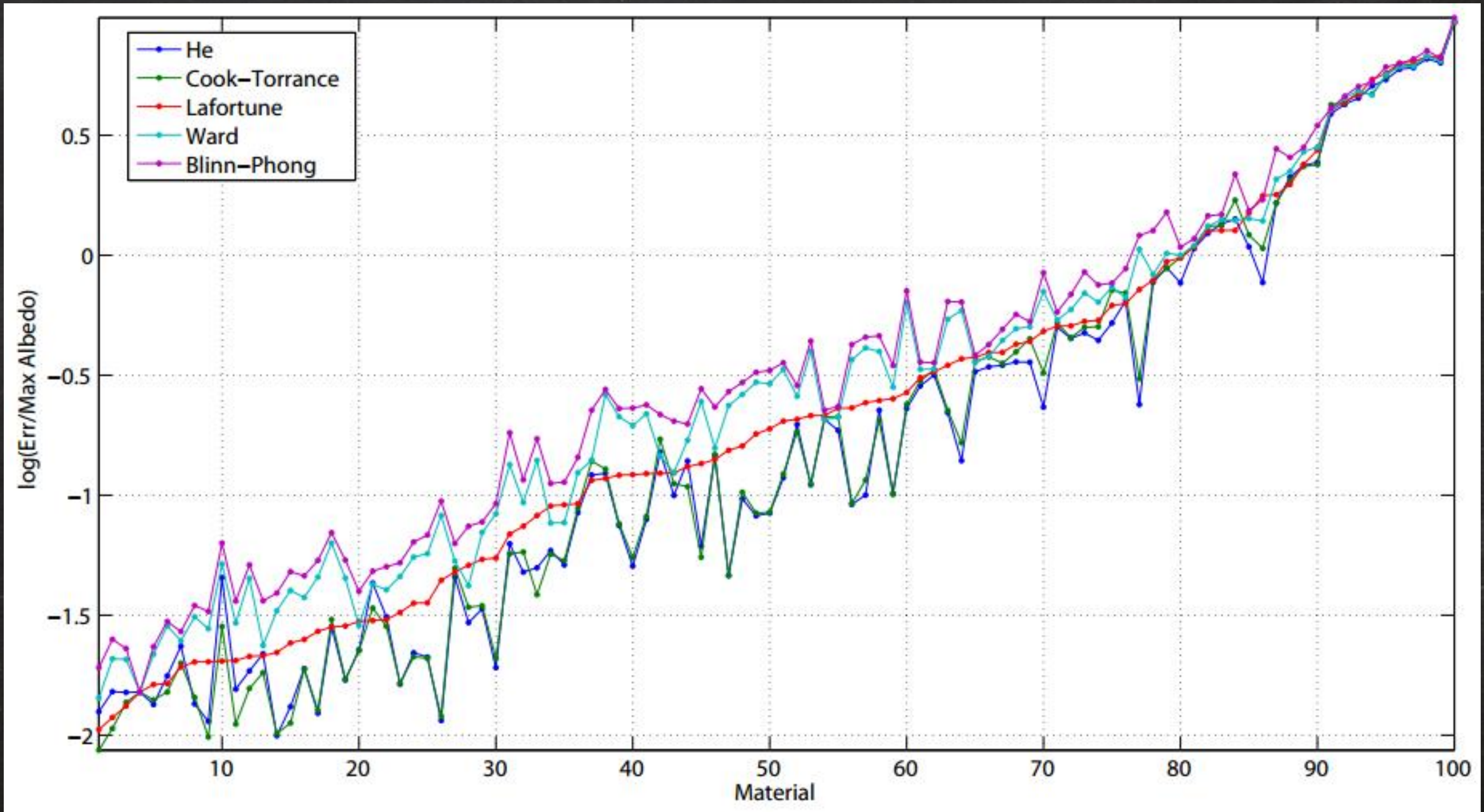
MERL 100

http://www.merl.com/brdf/

"A Data-Driven Reflectance Model",
Matusik et al., SIG'03



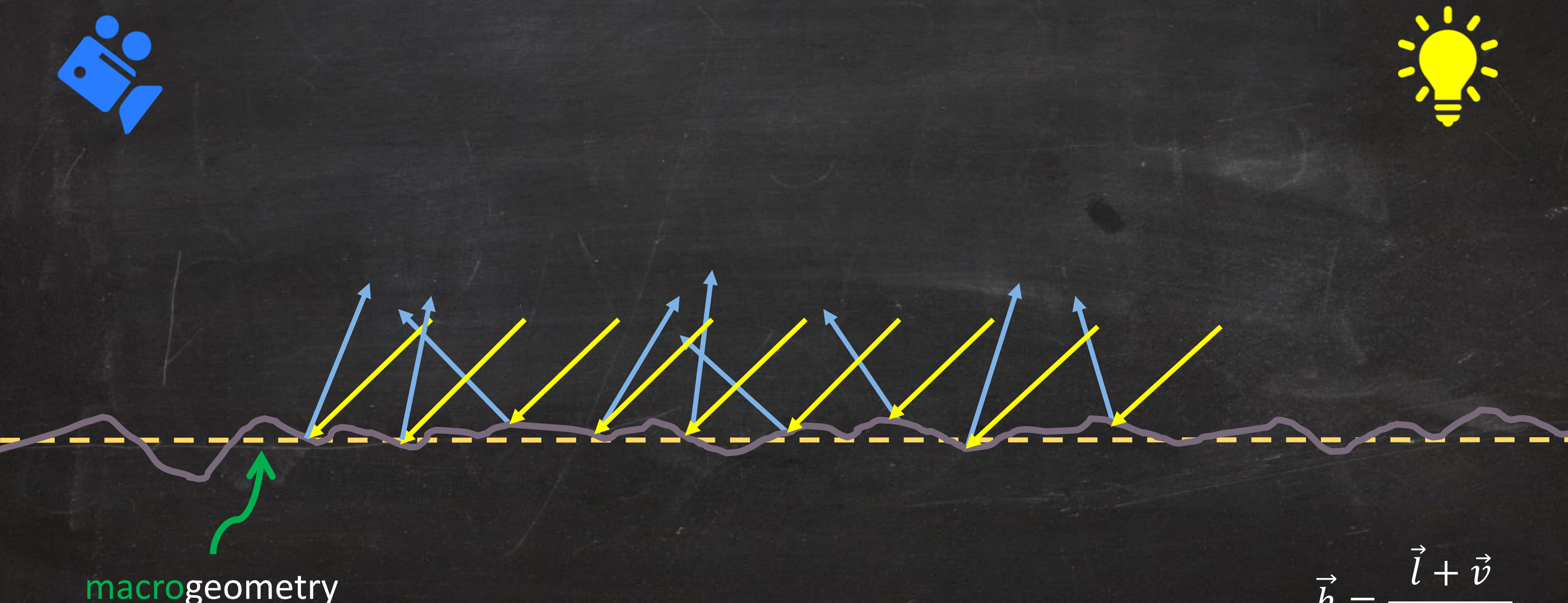
BRDF Data Fitting



[Ngan et al., 2005]

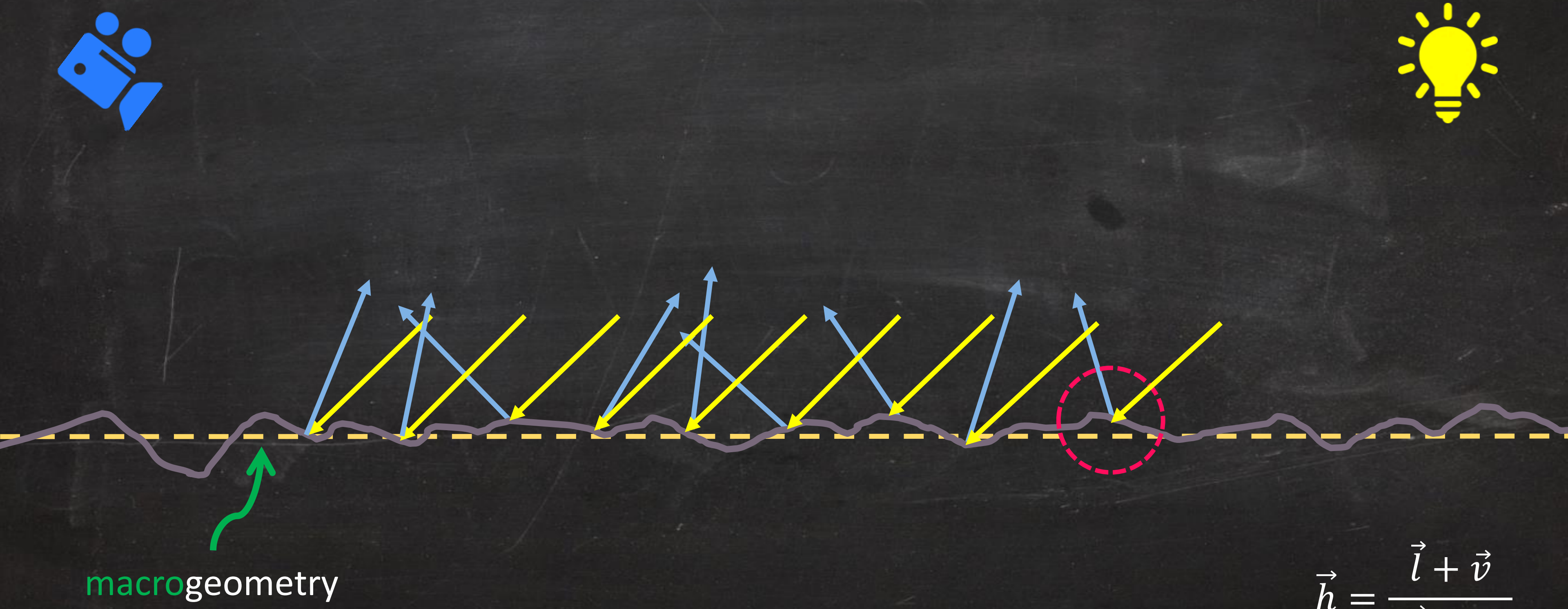
Microfacet Model

Microfacet Model



$$\vec{h} = \frac{\vec{l} + \vec{v}}{\|\vec{l} + \vec{v}\|}$$

Microfacet Model



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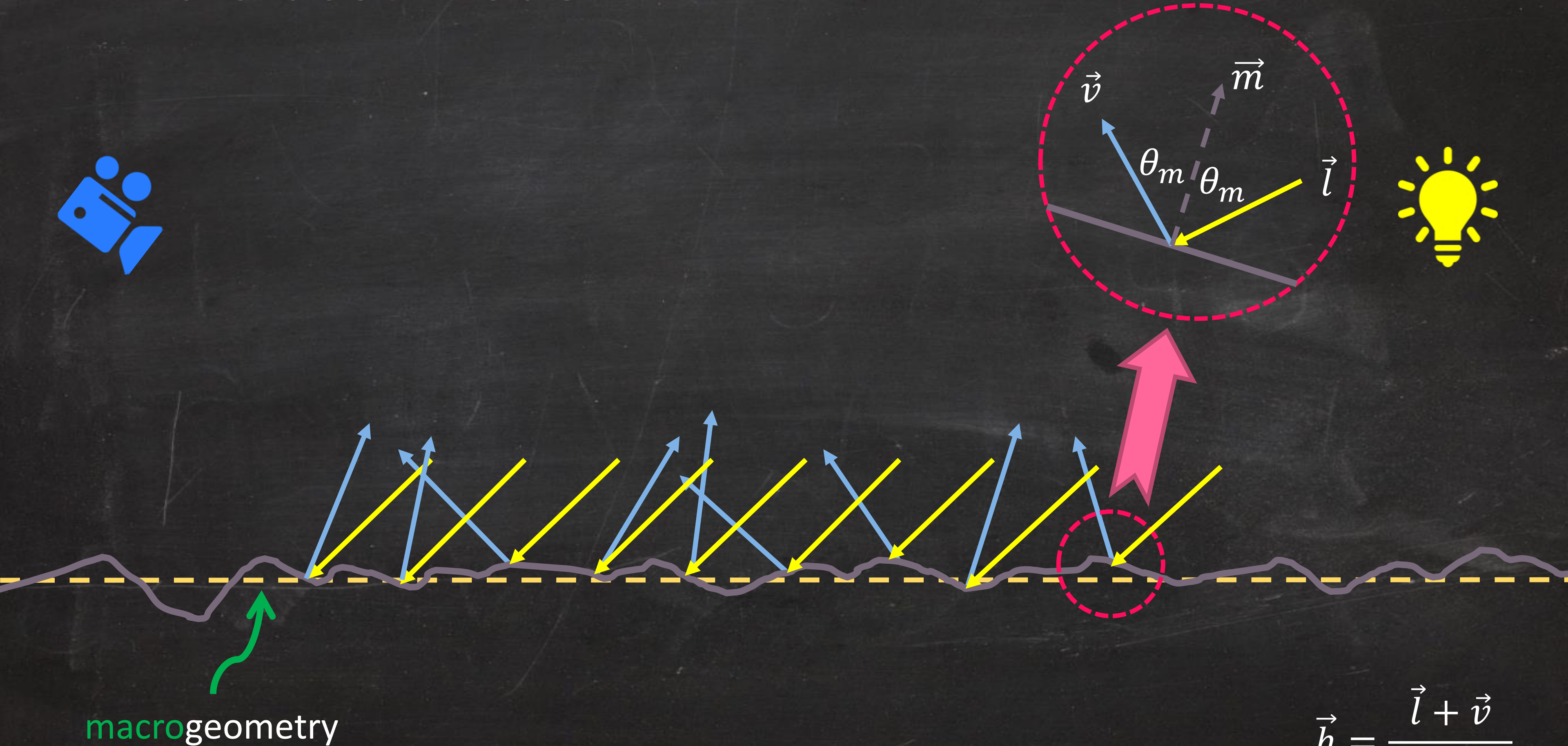
Microfacet Model



$$\vec{h} = \frac{\vec{l} + \vec{v}}{\|\vec{l} + \vec{v}\|}$$

General Microfacet BRDF

Normal Distribution Function (NDF)

Fresnel reflectance

Geometric Term

$$f_r(\vec{l}, \vec{v}) = diffuse + \frac{D(\theta_h)F(\theta_d)G(\theta_l, \theta_v)}{4 \cos\theta_l \cos\theta_v}$$

The ratio of micro-surface area visible to the light, viewer

θ_l, θ_v: angle between $\vec{l}, \vec{v}$ and normal
θ_h: angle between normal and $\vec{h}$
θ_d: difference between $\vec{l}$ $(or\ \vec{v})$ and $\vec{h}$

Fresnel

- Schlick's approximation

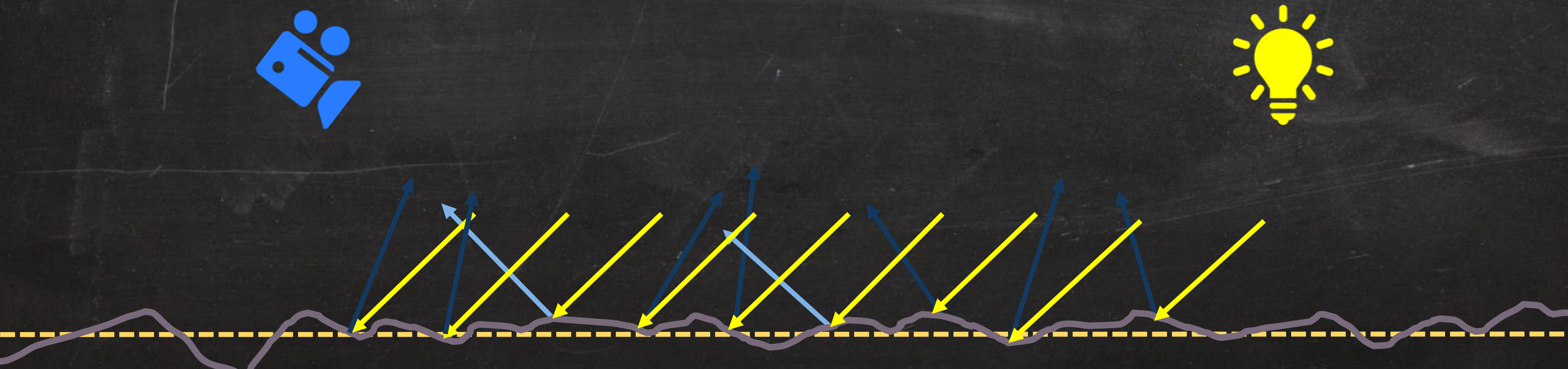
$$F_{Schlick} = F_0 + (1 - F_0)(1 - \overline{\cos\theta_i})^5$$

  – Where $\mathrm{F}_0 = \left(\frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}\right)^2$
    - a.k.a. reflectance at normal, normal reflectance, etc.

  ? What if $\eta_2 = \eta_1$
    - F should be zero but $F_{Schlick} = (1 - \overline{\cos\theta_i})^5 \neq 0$

NDF (Normal Distribution Function)

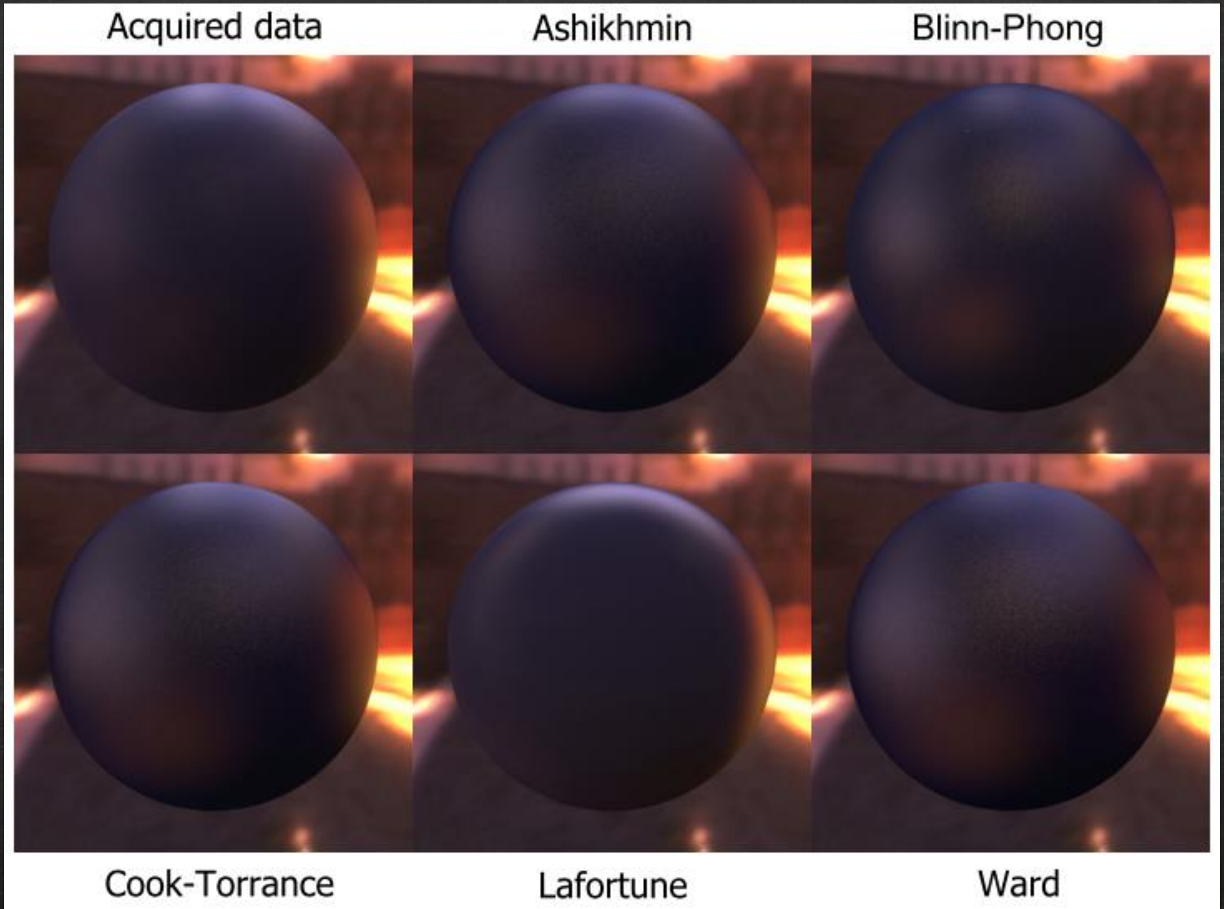
- Half vector $\vec{h} = \frac{\vec{l}+\vec{v}}{\|\vec{l}+\vec{v}\|}$
- As for perfect mirror microfacets, we can only see those facets whose normal vector $\vec{m} = \vec{h}$



Highlights at Grazing Angles

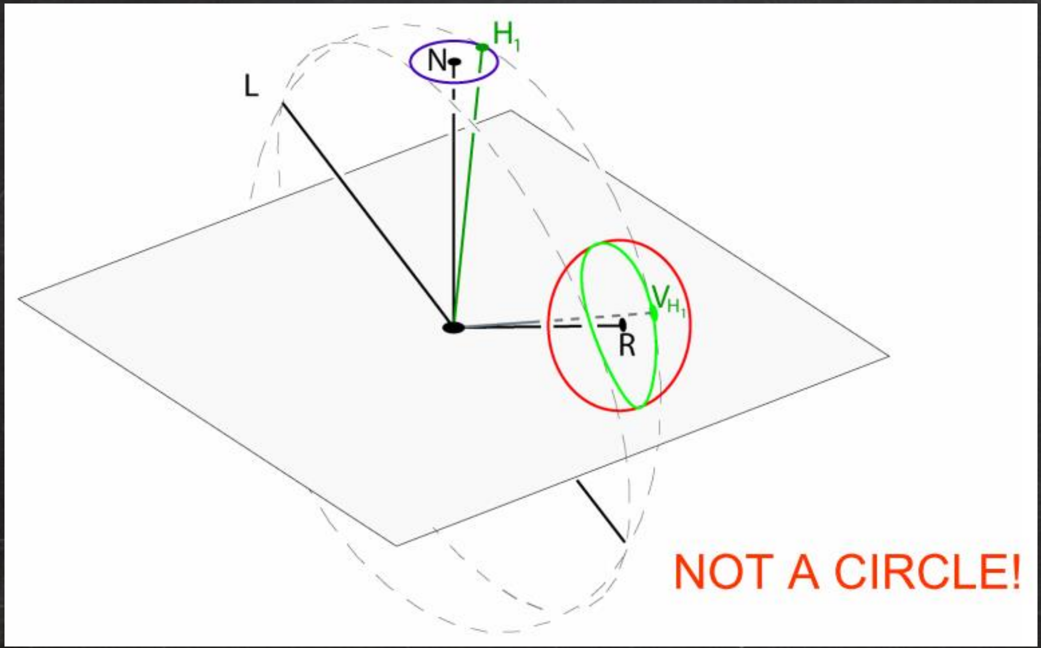
Photo by Liu Zai Hou

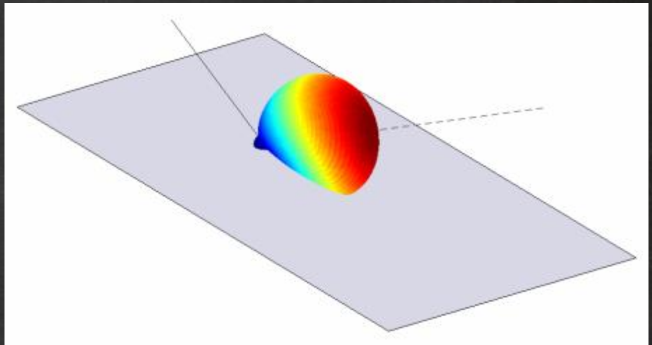
Data Fitting of Acquired Data



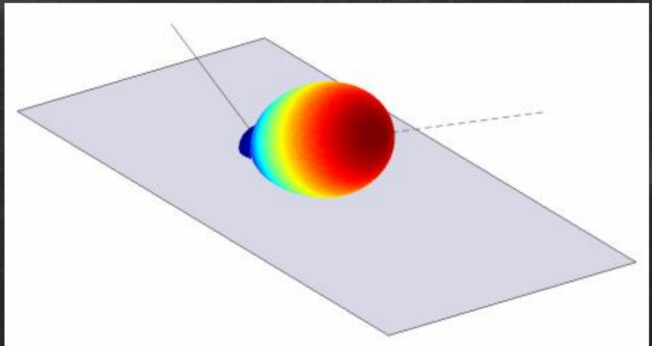
[Ngan et al., SIG'04]

Highlights at Grazing Angles





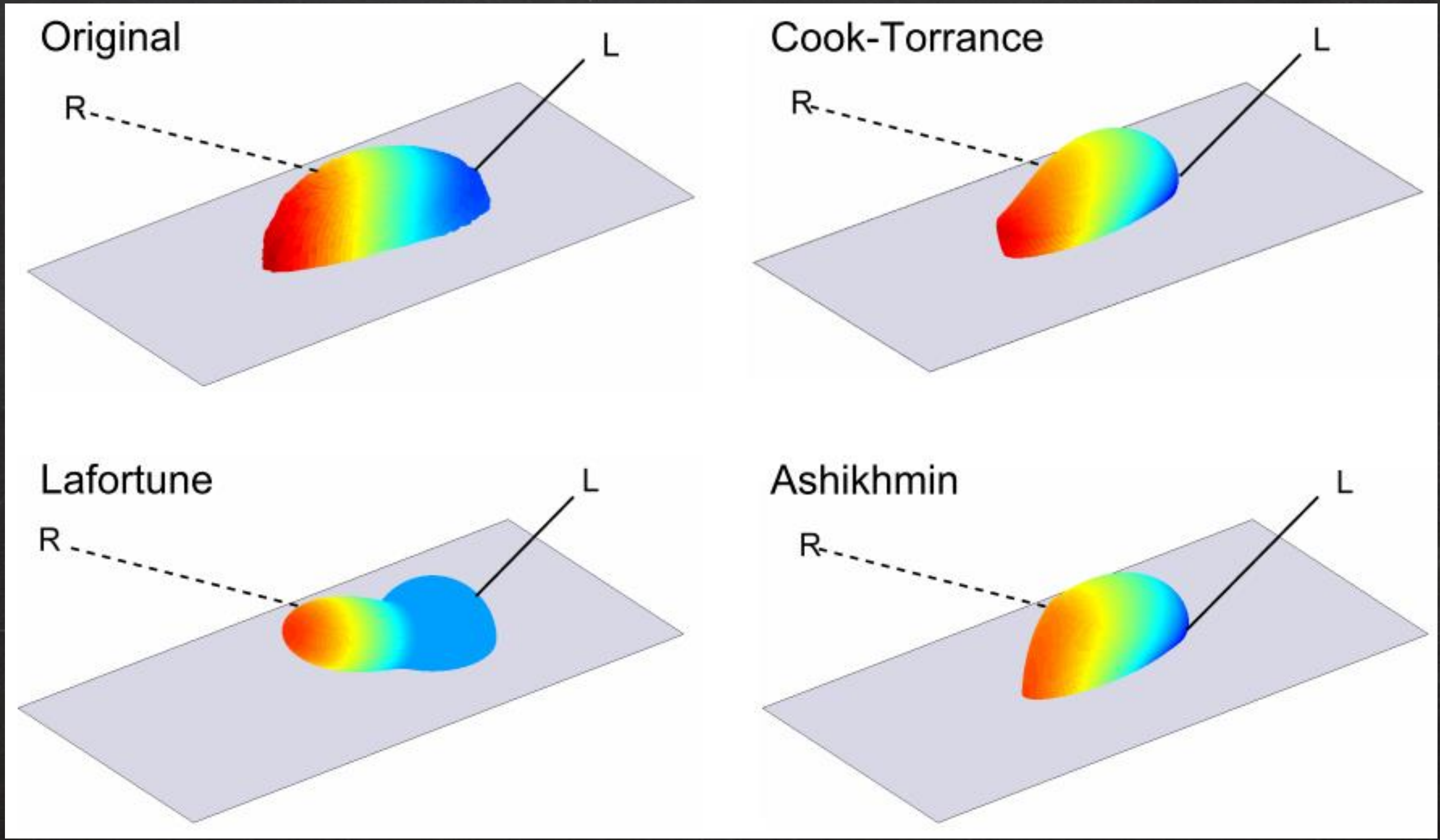
Half vector lobe



Mirror lobe

[Ngan et al., SIG'04]

Data Fitting of Acquired Data (Cont'd)

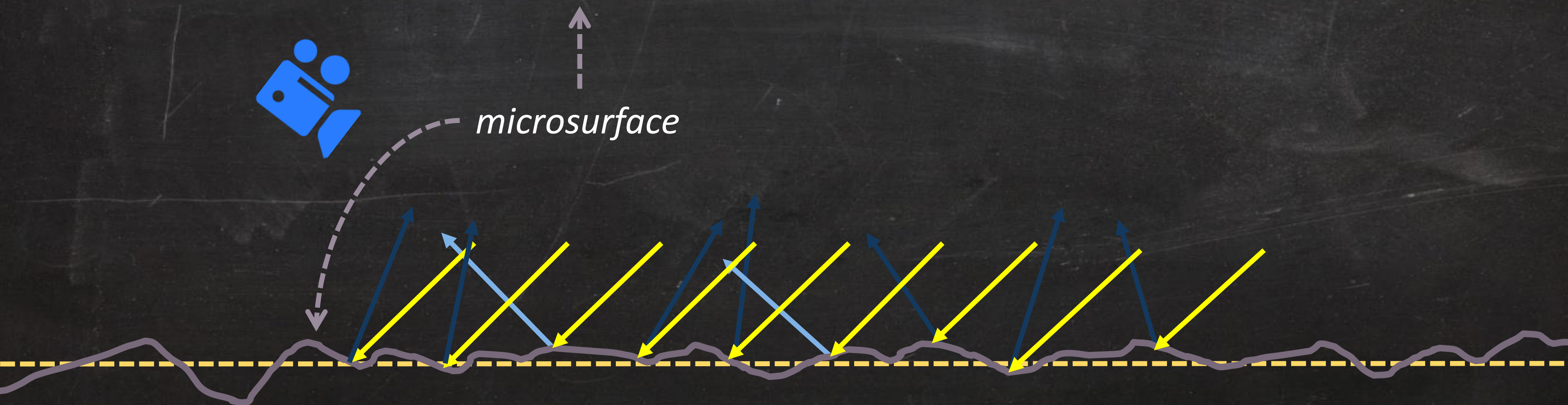


[Ngan et al., SIG'04]

NDF (Cont'd)

- Measures **area density** of microsurface with respect to microsurface **normal**

$$D(\omega) = \int_{\mathcal{M}} \delta_{\omega}(\omega_m(p_m))\,dp_m$$



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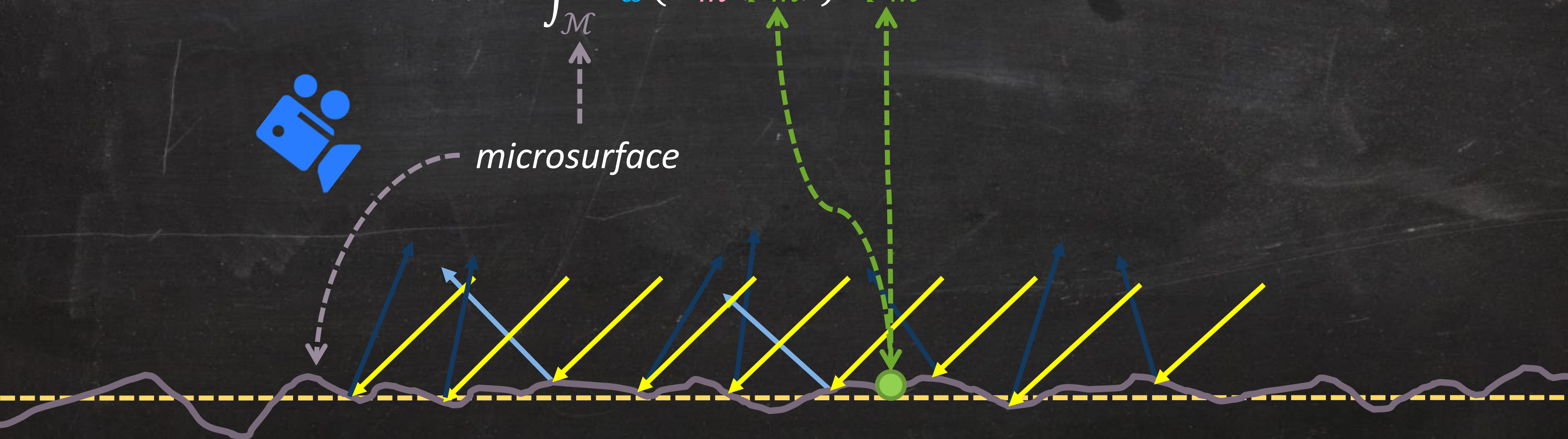

NDF (Cont'd)

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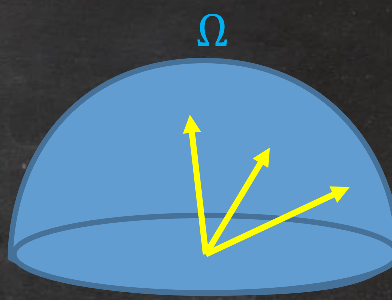

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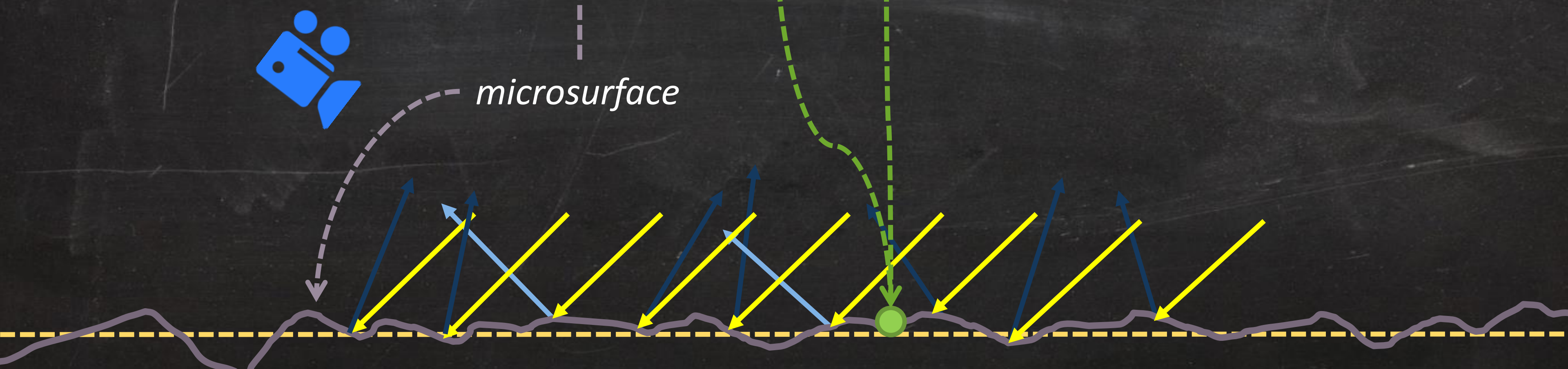

NDF (Cont'd)

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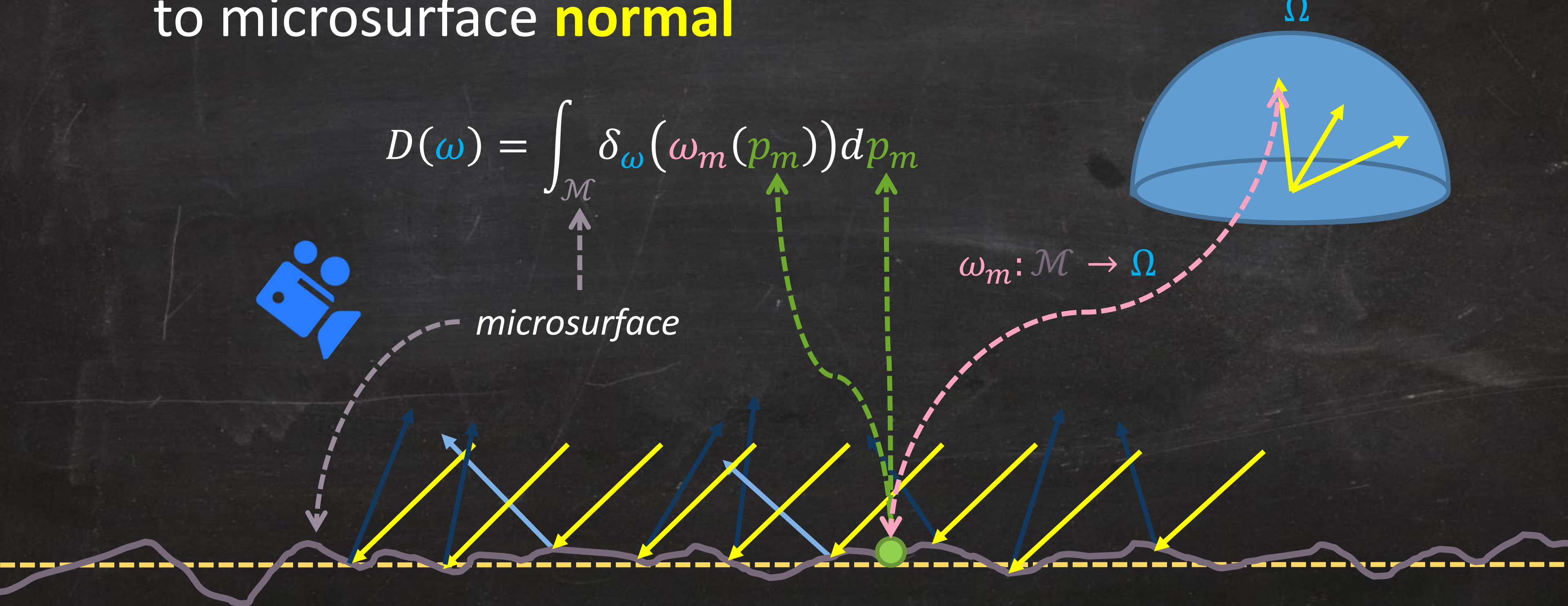
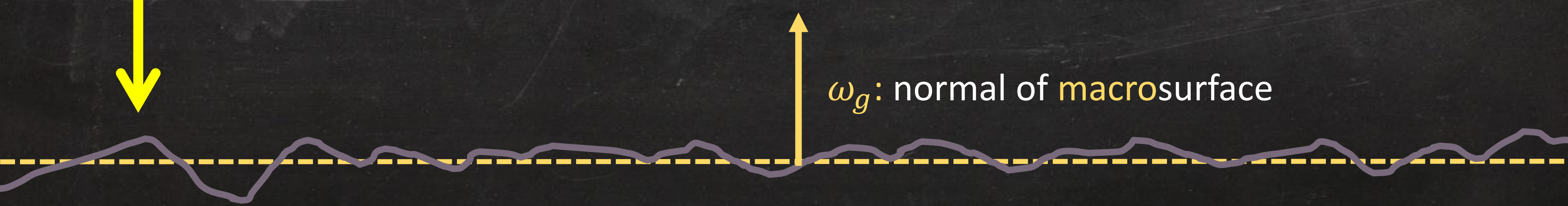


NDF (Cont'd)

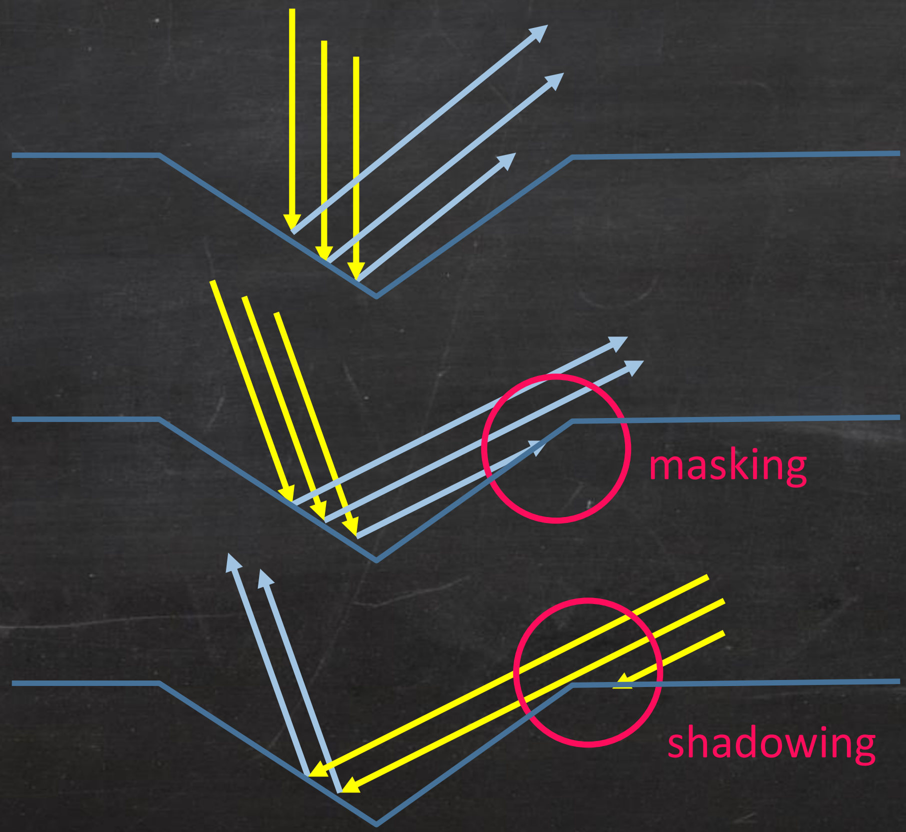
$$microsurface\ area = \int_{\mathcal{M}} dp_m = \int_{\Omega} D(\omega_m)d\omega_m$$

$$projected\ microsurface\ area = \int_{\Omega} (\omega_m \cdot \omega_g)D(\omega_m)d\omega_m$$

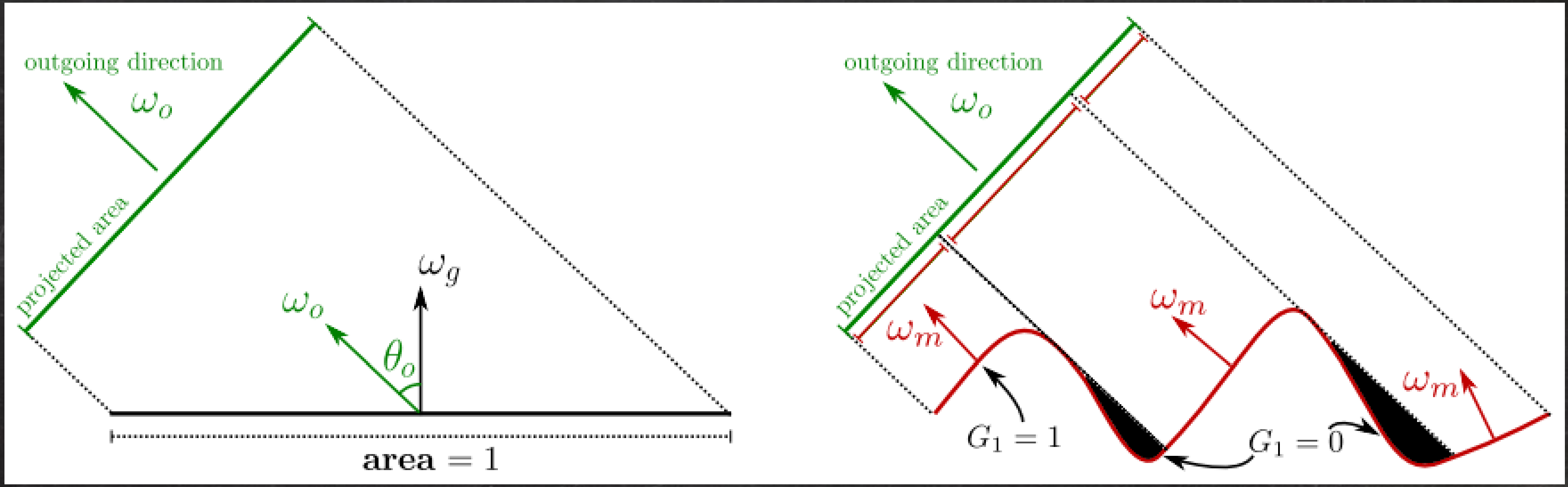
projection



Masking/Shadowing



Conservation of Projected Area

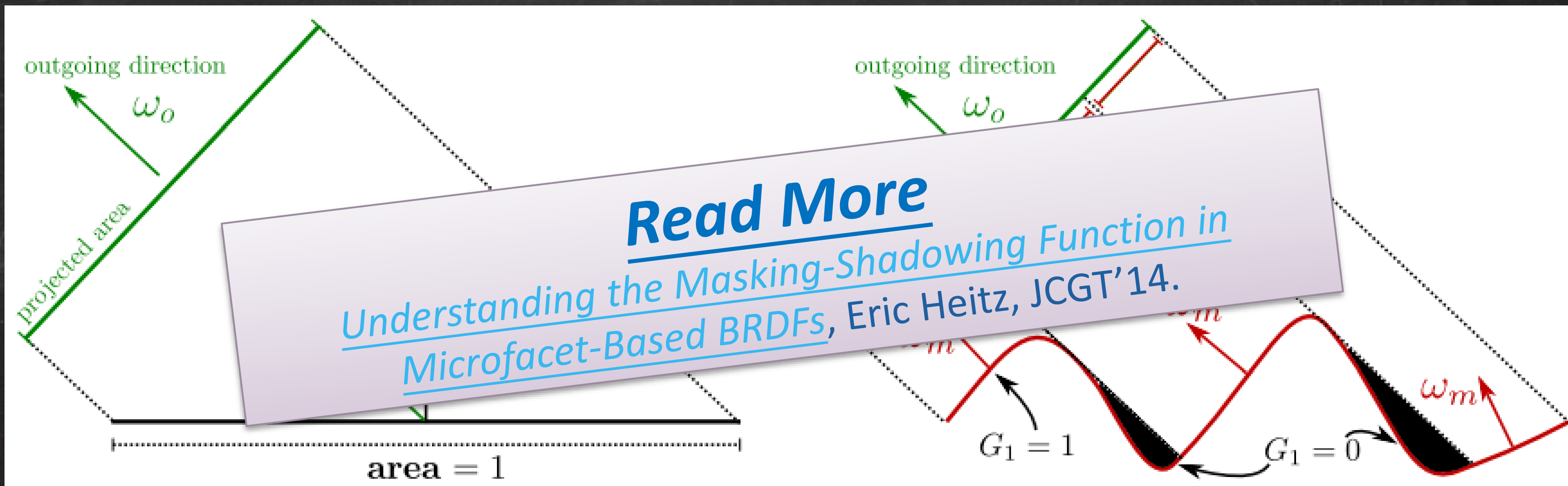


[Heitz '14]

$$\cos\theta_o = \int_\Omega G_1(\omega_o, \omega_m)\langle\omega_o, \omega_m\rangle D(\omega_m) d\omega_m$$

masking function

Conservation of Projected Area



Read More

Understanding the Masking-Shadowing Function in Microfacet-Based BRDFs, Eric Heitz, JCGT'14.

[Heitz '14]

$$\cos\theta_o = \int_\Omega G_1(\omega_o, \omega_m)\langle\omega_o, \omega_m\rangle D(\omega_m)d\omega_m$$

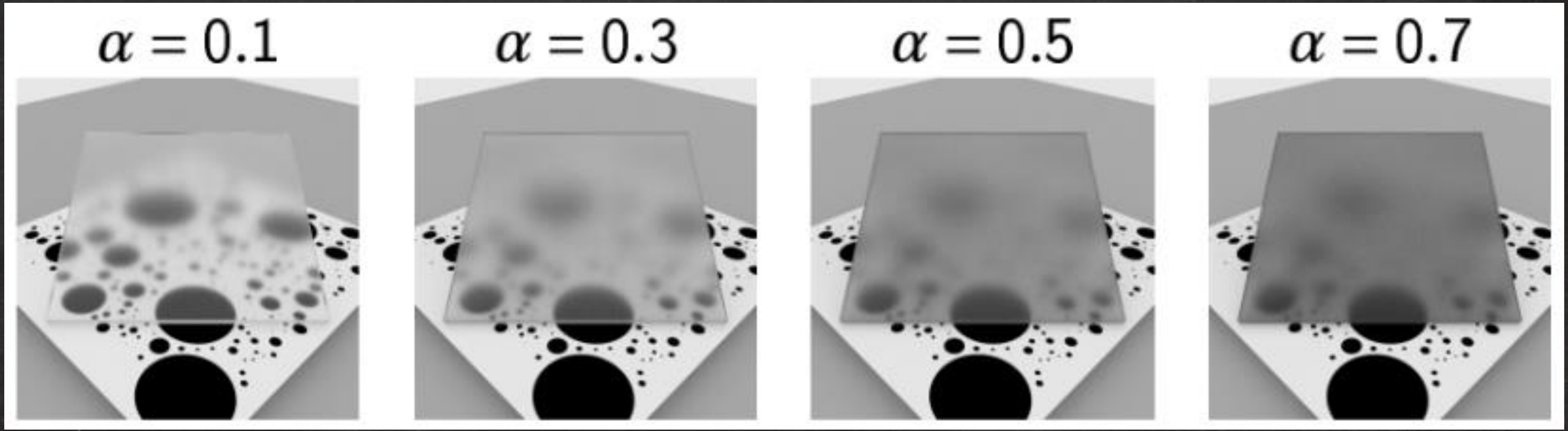
masking function

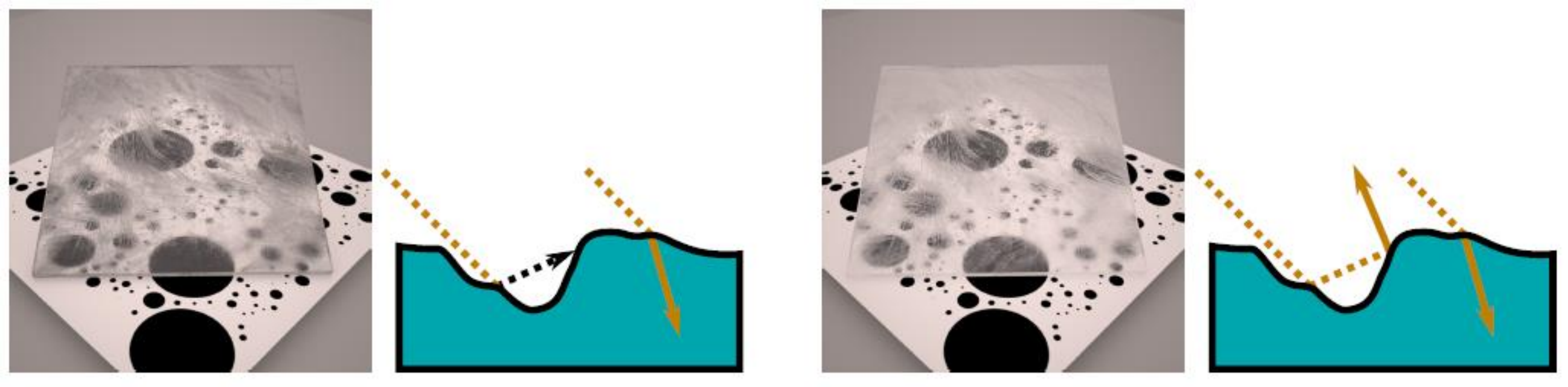
BRDF Validation

- What makes it physically-based?
  1. Reciprocity: $\mathrm{f}(\mathrm{l}, \mathrm{v}) = \mathrm{f}(\mathrm{v}, \mathrm{l})$
  2. Positivity: $\mathrm{f}(\mathrm{l}, \mathrm{v}) > 0$
  3. Energy conservation: $\int_\Omega f(l, v) \cos\theta_i \, d\omega_i \leq 1$

What do we miss?

Multiple Surface Bounces?





[Heitz, 2015]

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