BRDFs and Materials

Computer Graphics and Imaging
UC Berkeley CS184
Summer 2020

Overview

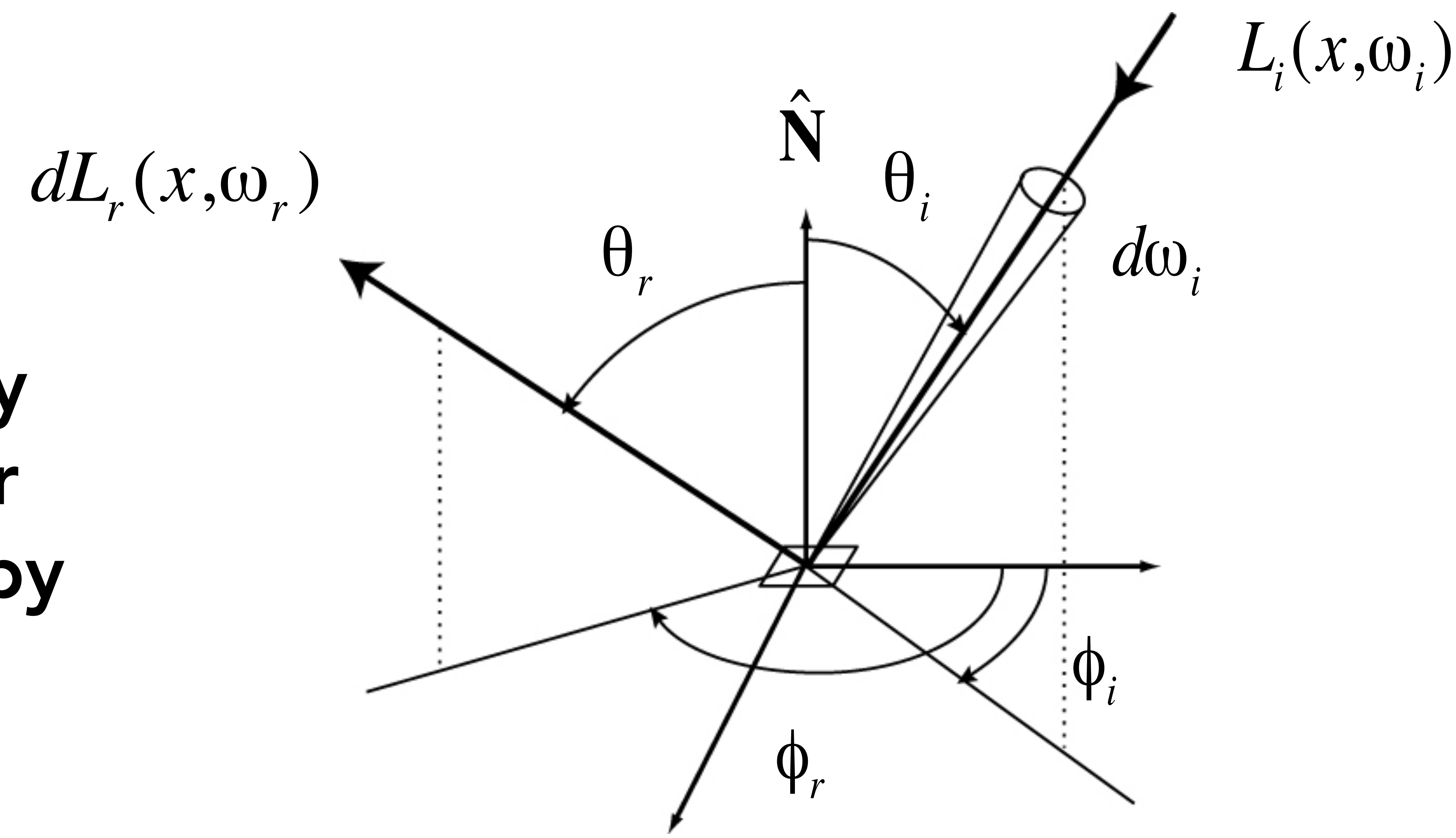
- BRDF definition
- Materials
  - Ideal diffuse
  - Ideal specular (reflection and refraction)
  - Microfacet models
  - Isotropic vs anisotropic
- Importance sampling
- The Disney BRDF
- Demo

BRDF

BRDF

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

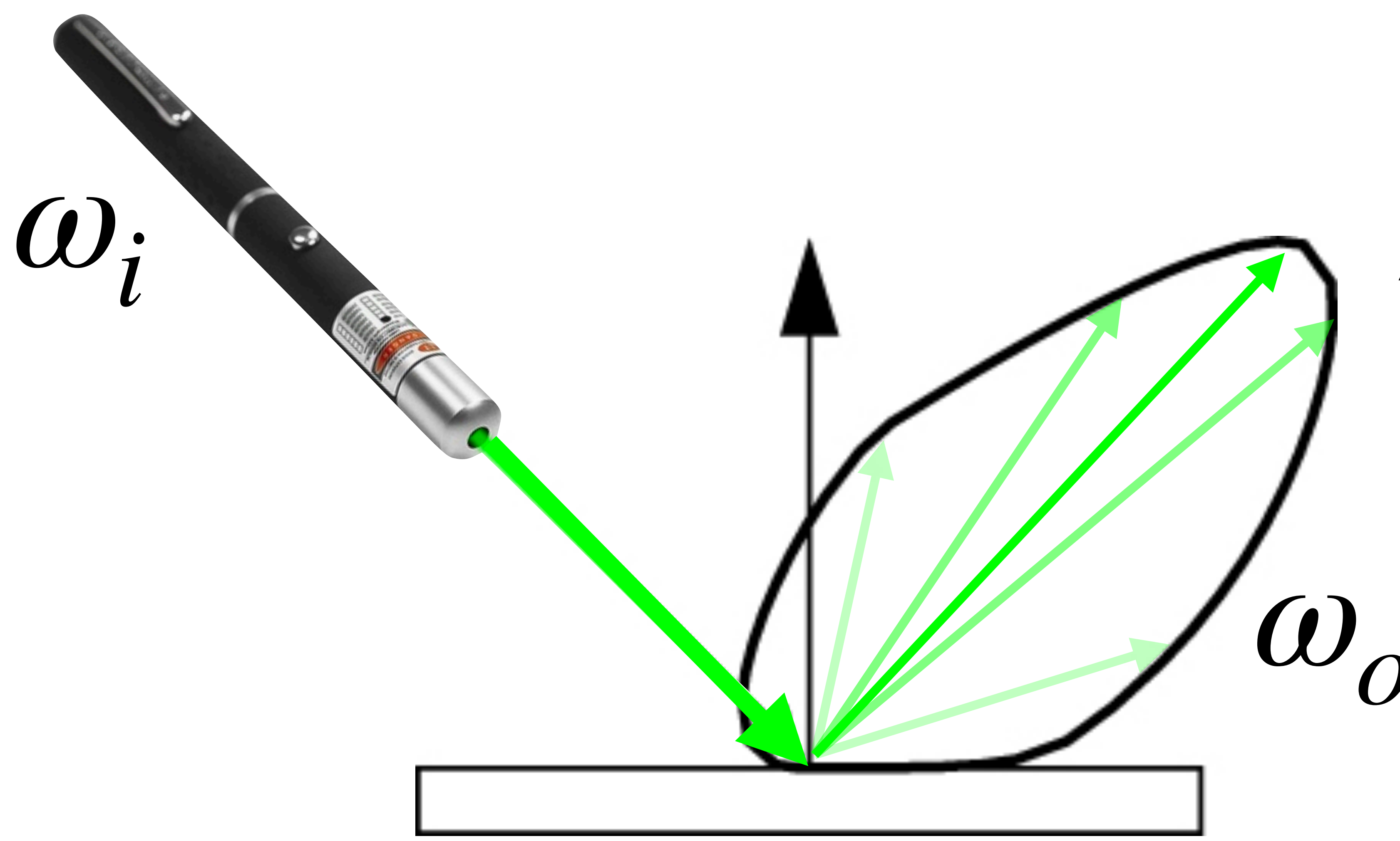
NB: ω_i points away from surface rather than into surface, by convention.



$$f_r(\omega_i \to \omega_r) = \frac{\mathrm{d}L_r(\omega_r)}{\mathrm{d}E_i(\omega_i)} = \frac{\mathrm{d}L_r(\omega_r)}{L_i(\omega_i)\cos\theta_i\,\mathrm{d}\omega_i} \quad \left[\frac{1}{\mathrm{sr}}\right]$$

What is a BRDF?

Imagine shining a laser pointer at a specific point on a surface

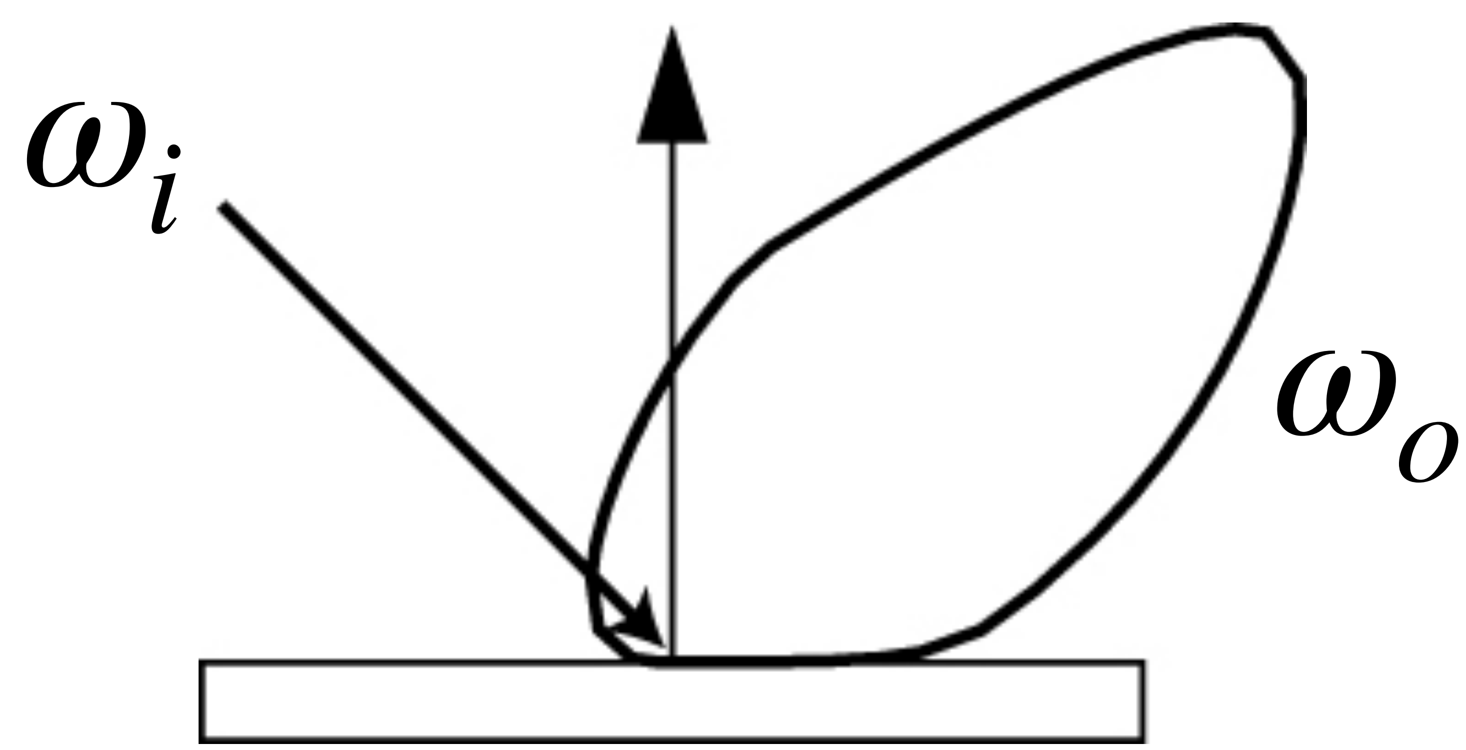


And observing the reflected light in all directions

What is a BRDF?

That's how you read "lobe" diagrams:

Length of lobe = amount of incoming light reflected in that direction



Important properties

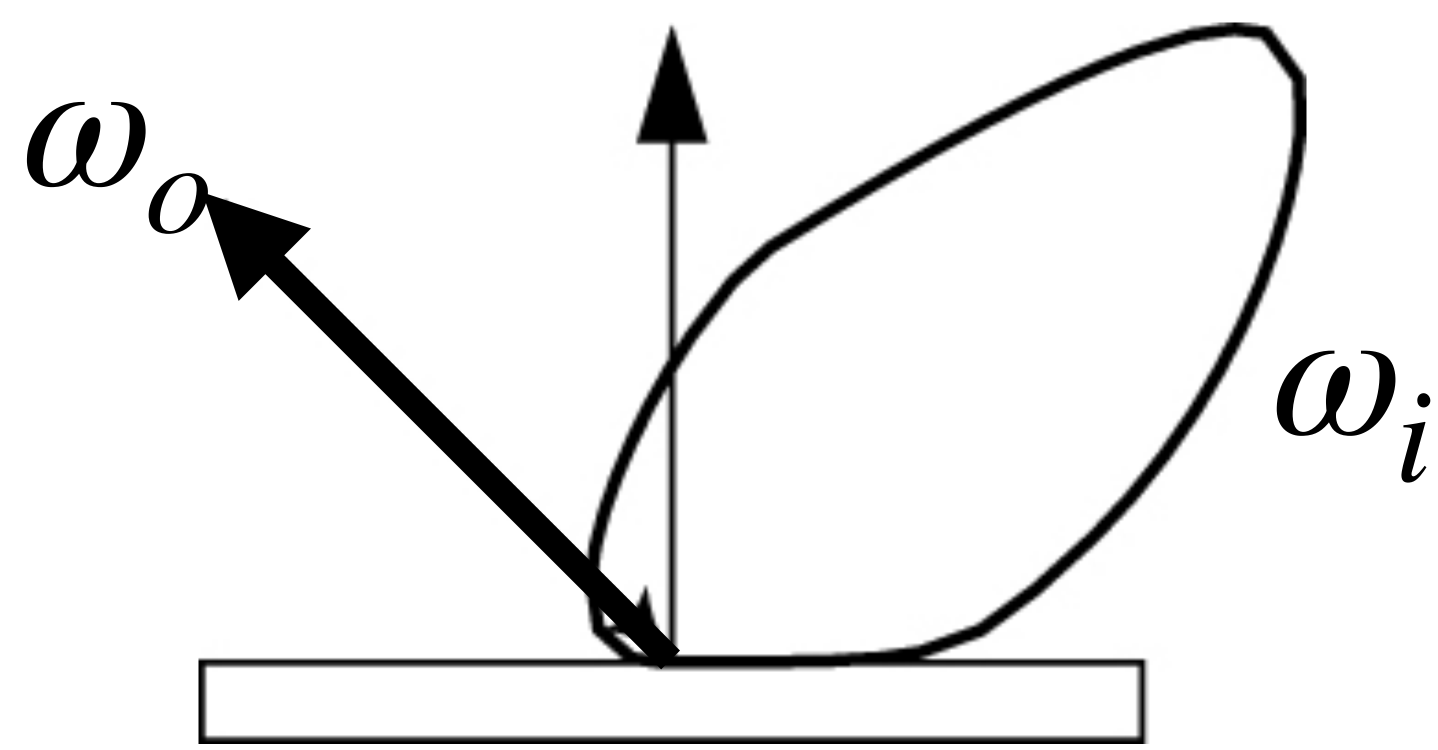
- Positivity (self explanatory)

$$f(\omega_i, \omega_o) \geq 0$$

Important properties

- Reciprocity (can trace light paths either direction)

$$f(\omega_i, \omega_o) = f(\omega_o, \omega_i)$$

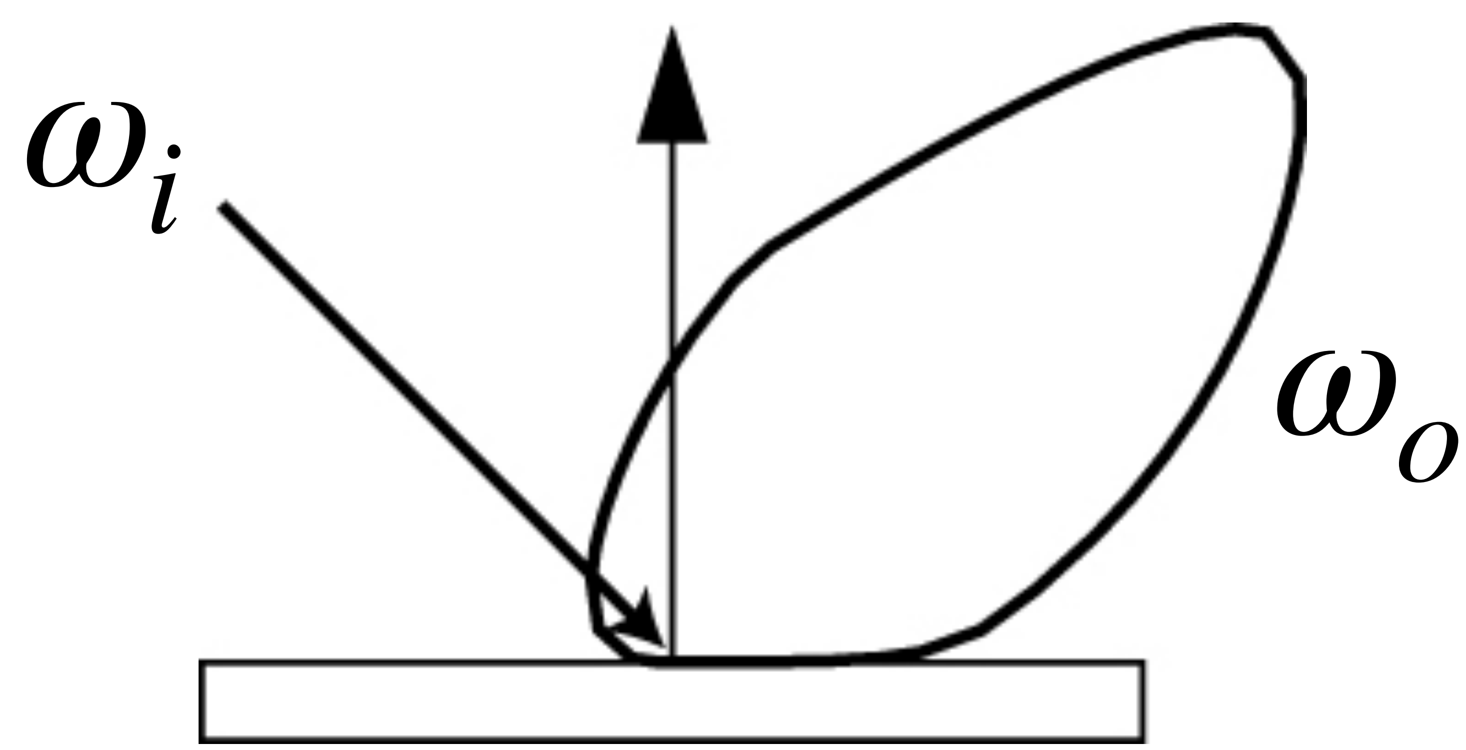


Means you can swap the labels in this diagram

Important properties

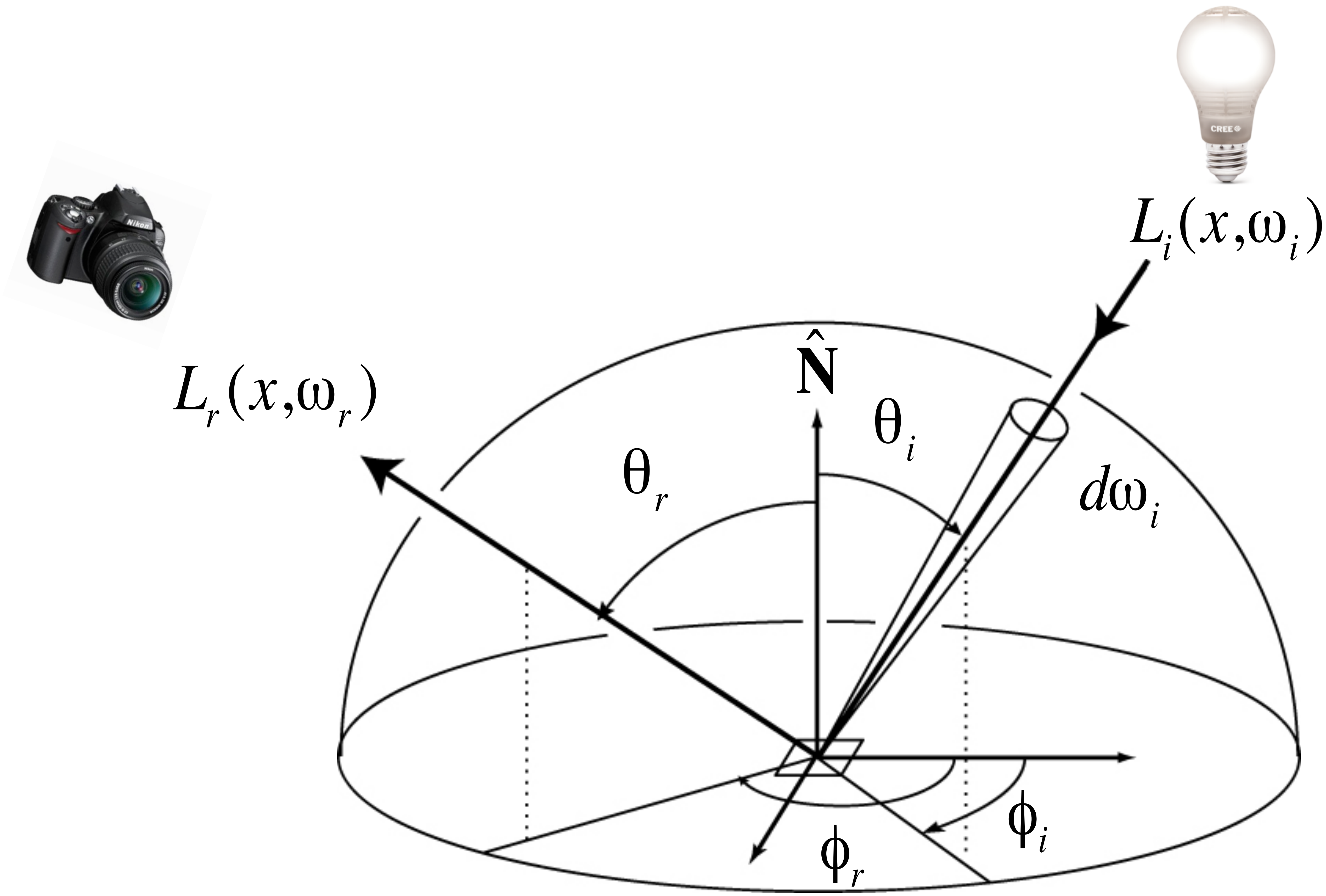
- Conservation of energy (can't reflect > 100%)

$$\int_{\Omega} f(\omega_i, \omega_o) \cos\theta_o d\omega_o \leq 1$$



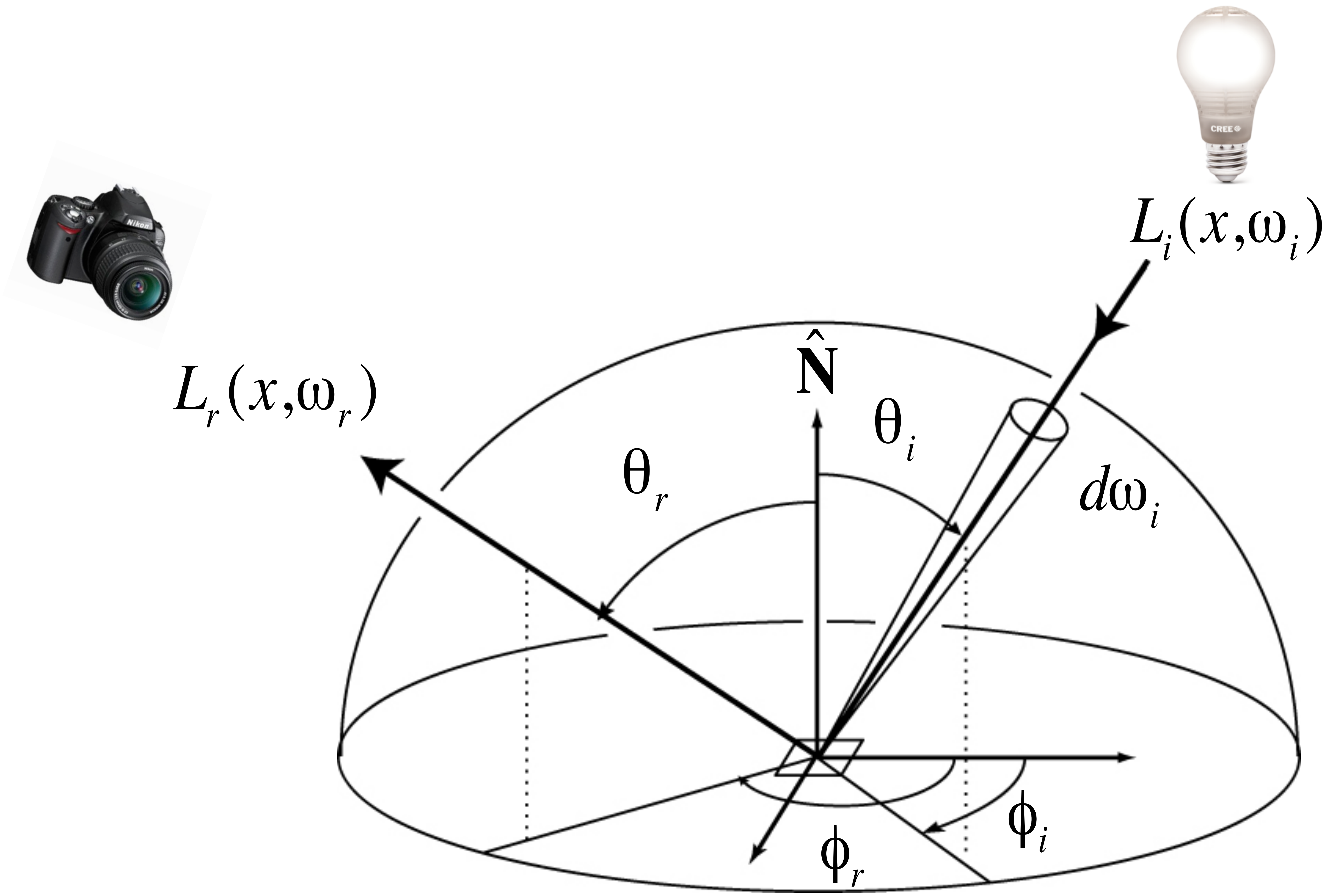
If you add up all the radiance
in the "lobe" it can't exceed 1,
given 1 unit of input radiance

How you use a BRDF: reflection equation



$$L_r(\mathrm{p}, \omega_r) = \int_{H^2} f_r(\mathrm{p}, \omega_i \rightarrow \omega_r)\, L_i(\mathrm{p}, \omega_i)\, \cos\theta_i \, \mathrm{d}\omega_i$$

How you use a BRDF: reflection equation



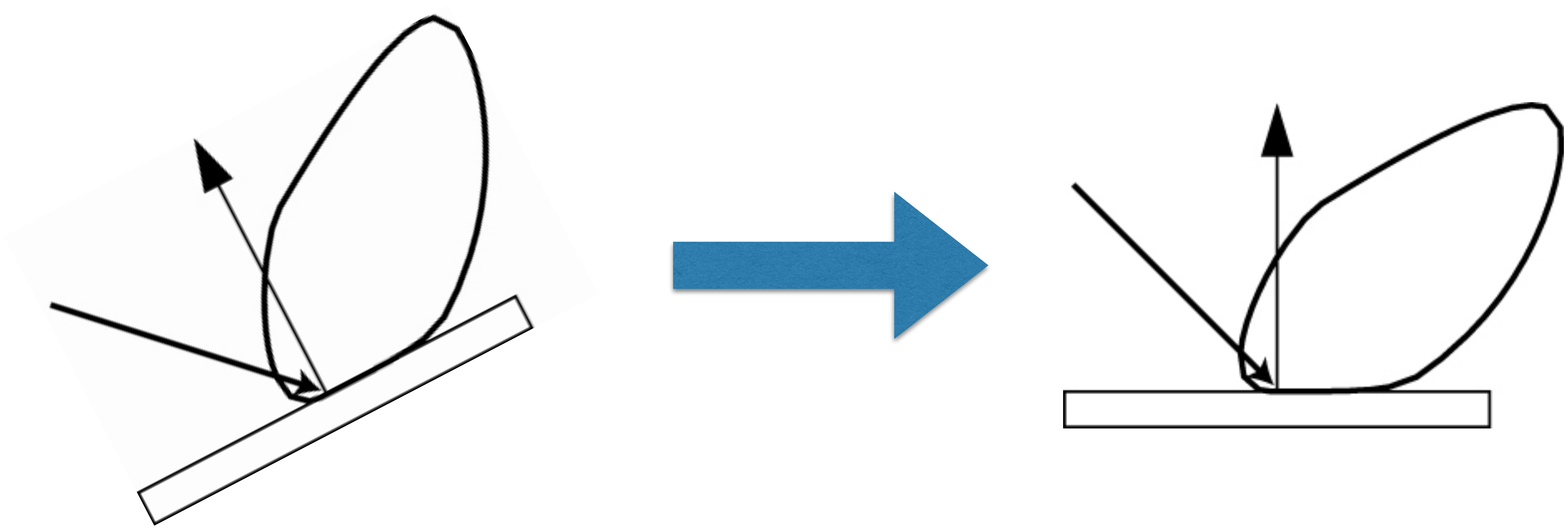
For a given fixed output direction ω_r , add up all the radiance reflected from incoming light over all directions of the hemisphere

Points of clarification: terminology

- BRDF, BTDF, BSDF, BxDF, B*DF
  - R = reflection, T = transmission, S = scattering
  - x, * = catch-all
  - "BSDF" used in project 3 since it covers refraction
- Direction vectors: ω_r and ω_o are the same, subscript is short for "reflected" or "outgoing"
- BRDF sometimes written as $f(\theta_i, \phi_i, \theta_o, \phi_o)$, in terms of spherical coordinates for the two input directions

BRDF "coordinate system" in assignment

- Aligns the normal with the *z* axis (0,0,1)
- This simplifies some BRDF evaluation math
- ONLY valid for a single point on object! Not the same as "object space"



World-space orientation of surface

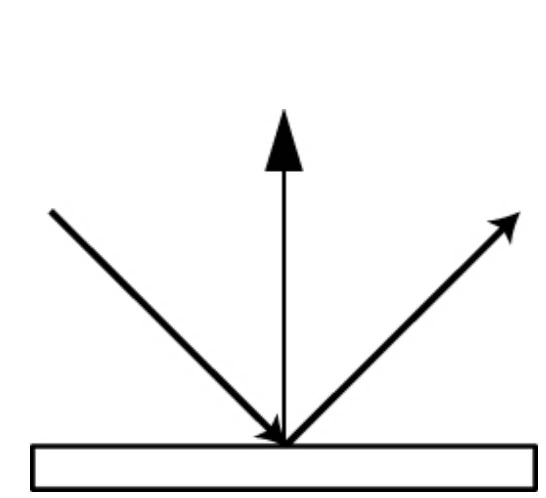
Local BRDF-space defined by normal vector

Types of materials

Categories of Reflection Functions

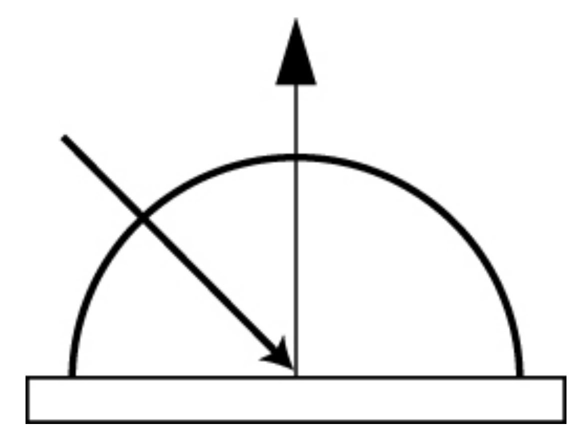
Ideal specular

- Perfect mirror reflection



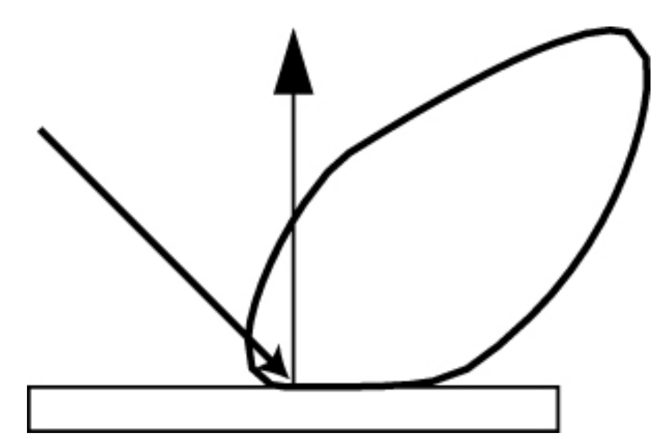
Ideal diffuse

- Equal reflection in all directions



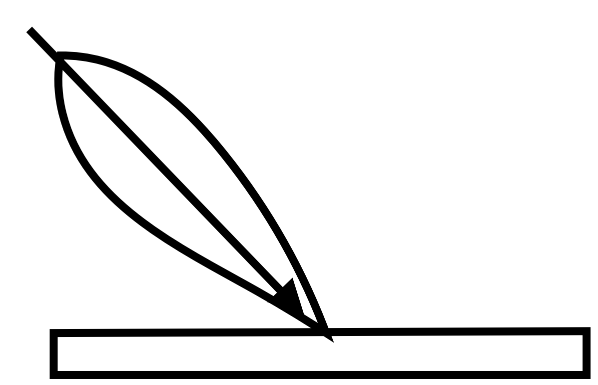

Glossy specular

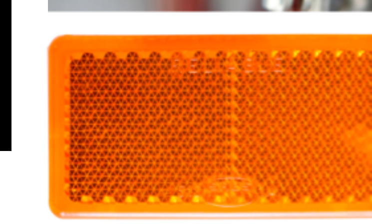
- Majority of light reflected near mirror direction



Retro-reflective

- Light reflected back towards light source

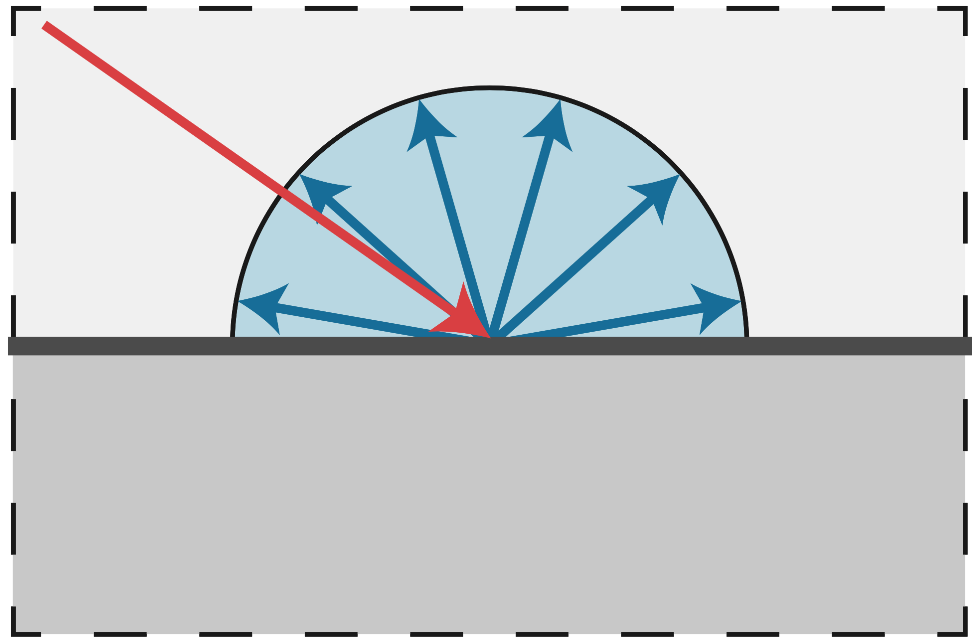


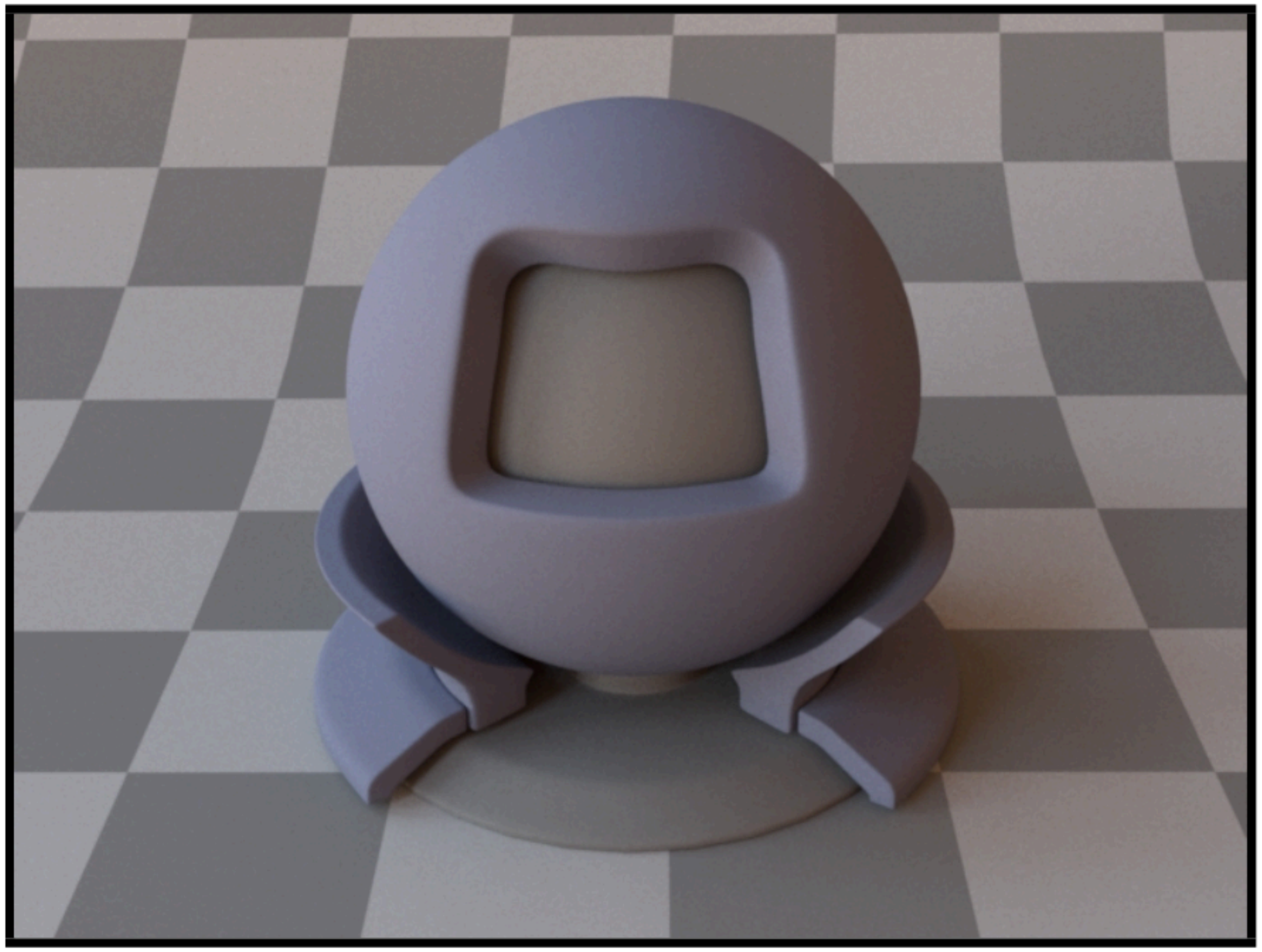



Diagrams illustrate how light from incoming direction is reflected in various outgoing directions.

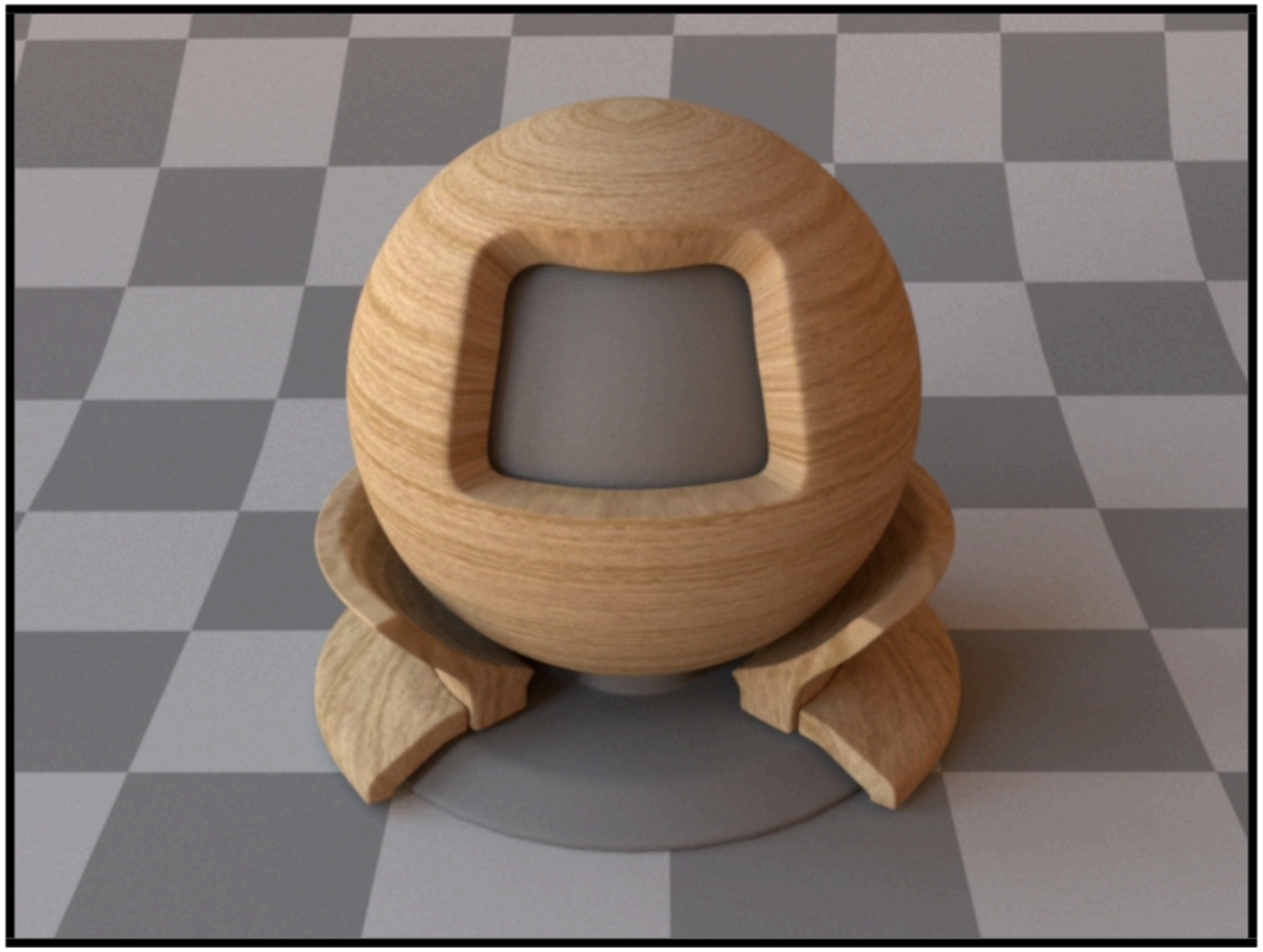
Basic BRDFs

Diffuse / Lambertian Material (BRDF)





Uniform colored diffuse BRDF

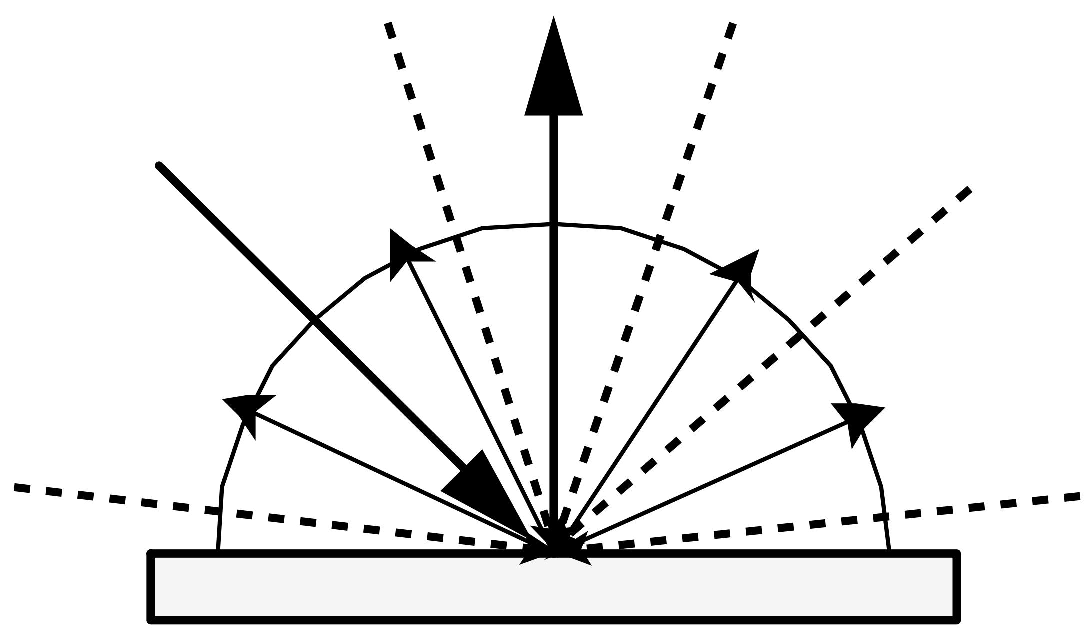


Textured diffuse BRDF

[Mitsuba renderer, Wenzel Jakob, 2010]

Diffuse / Lambertian Material

Light is equally reflected in each output direction



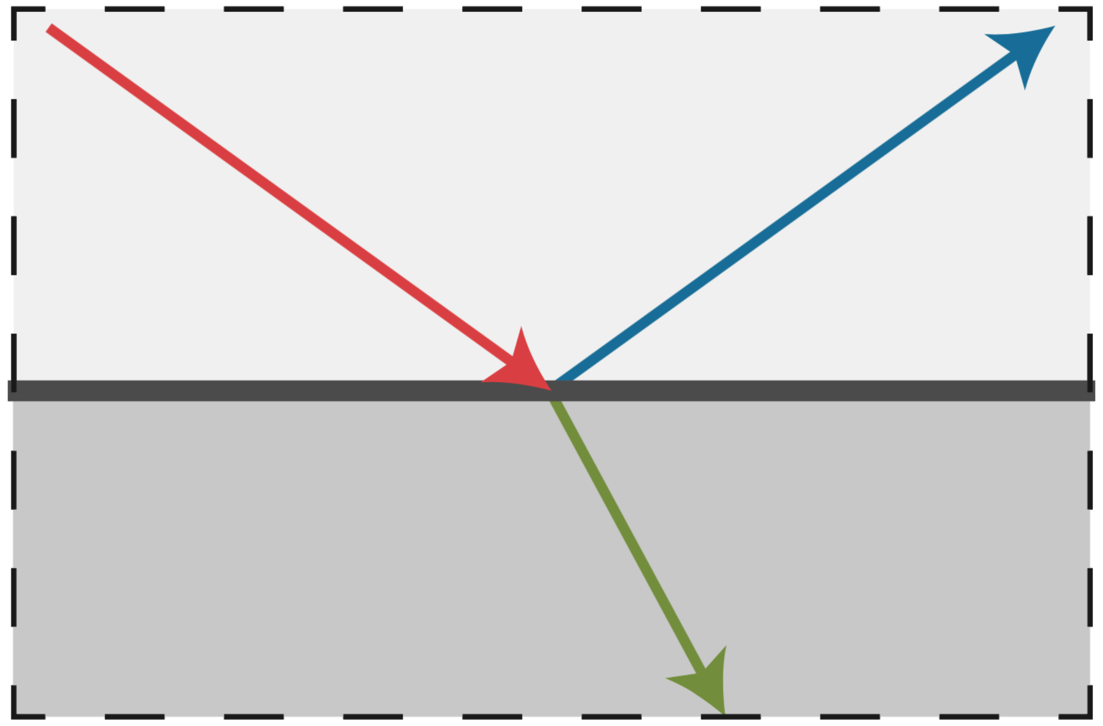
$$f_r = c$$

Suppose the incident lighting is uniform:

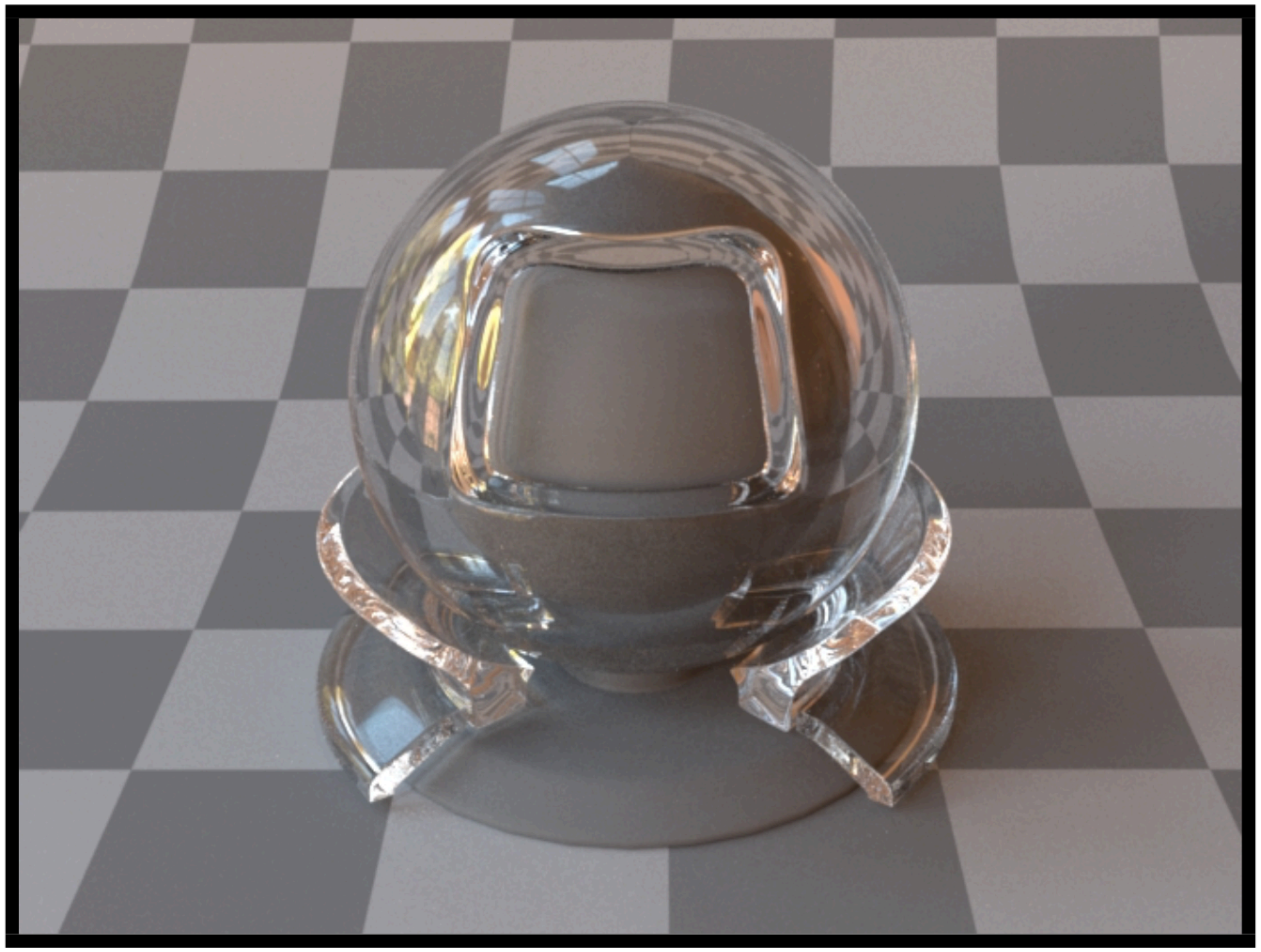
$$\begin{aligned} L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos\theta_i \, \mathrm{d}\omega_i \\ &= f_r L_i \int_{H^2} \cancel{(\omega_i)} \cos\theta_i \, \mathrm{d}\omega_i \\ &= \pi f_r L_i \end{aligned}$$

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

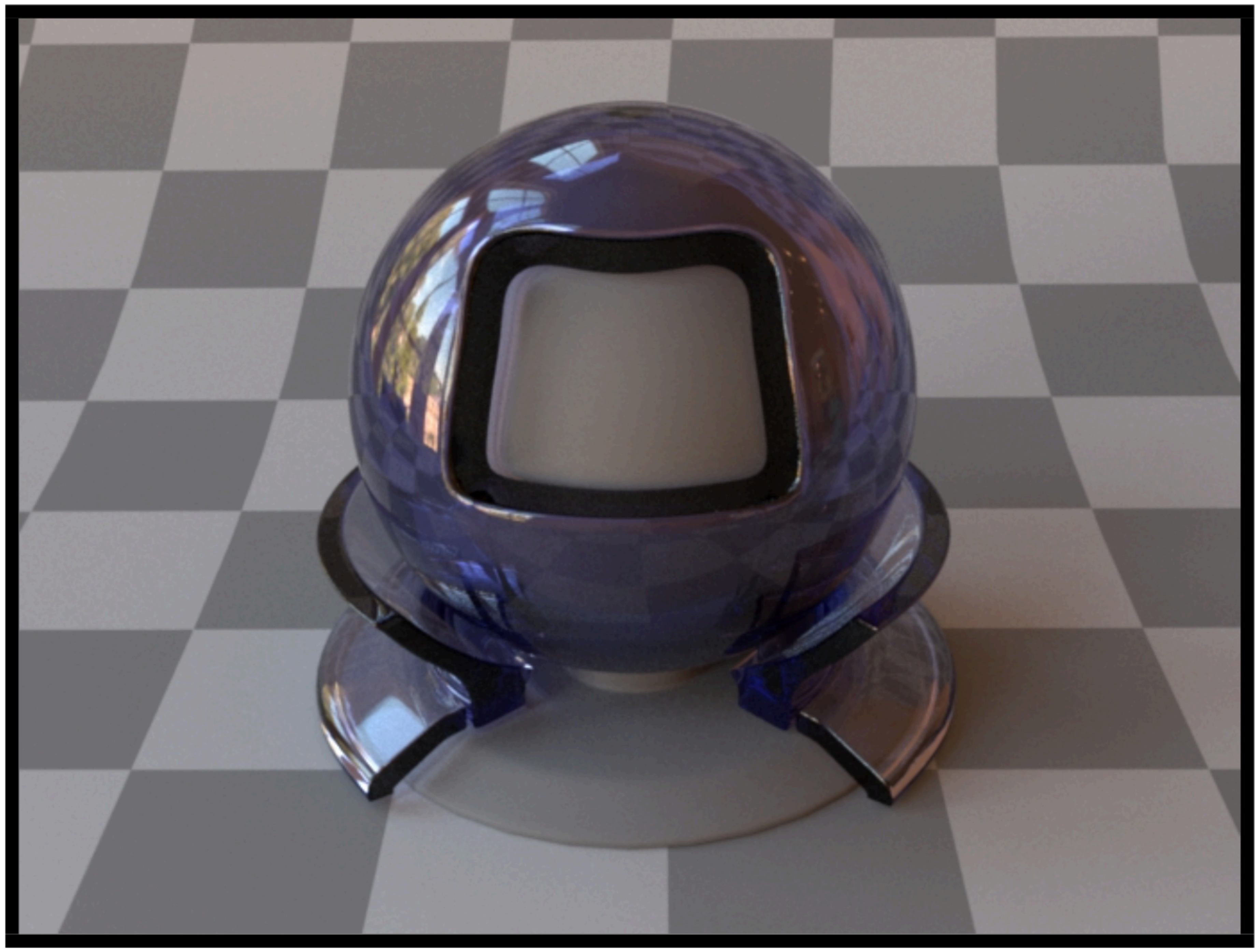
Ideal reflective / refractive material (BSDF*)



[Mitsuba renderer, Wenzel Jakob, 2010]

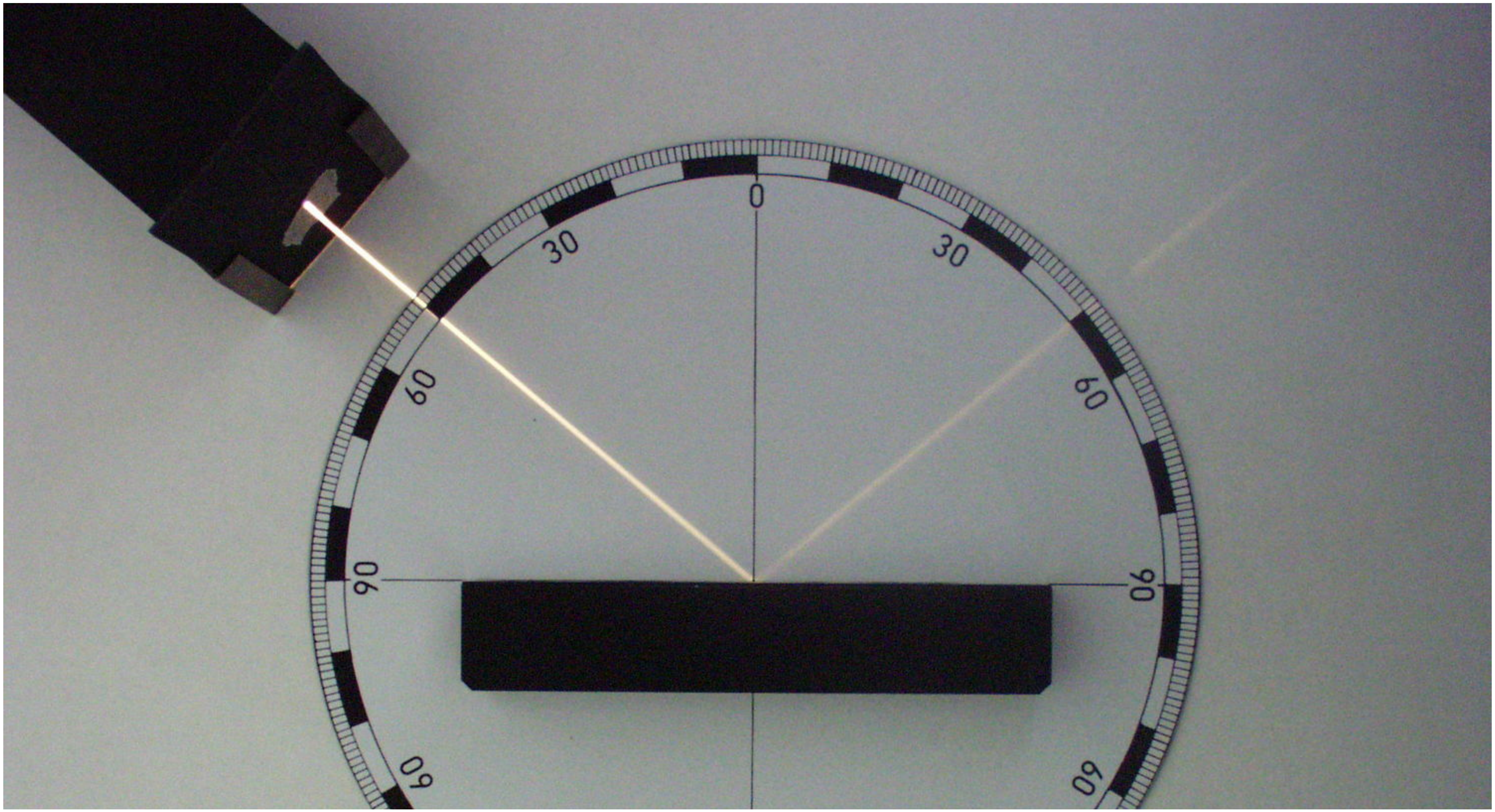


Air <-> water interface



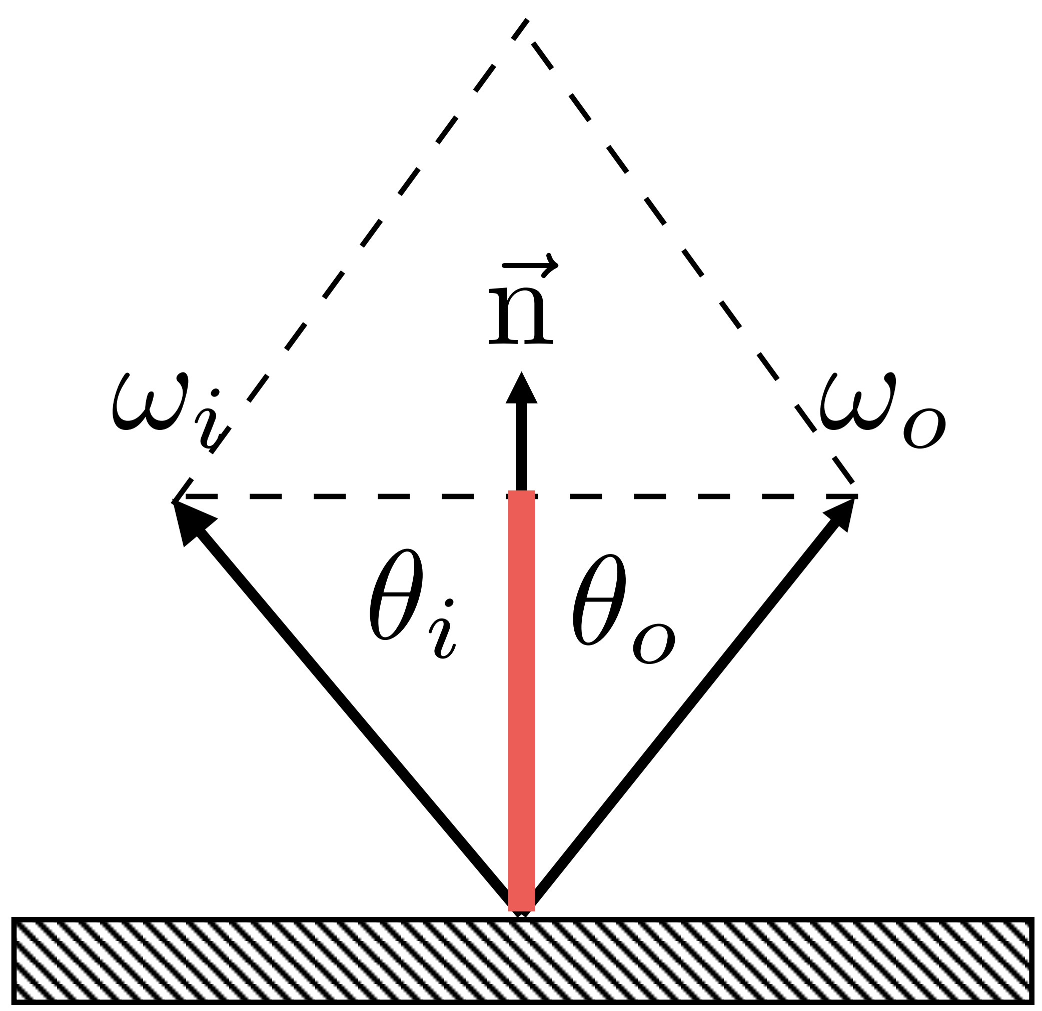
Air <-> glass interface
(with absorption)

Perfect Specular Reflection



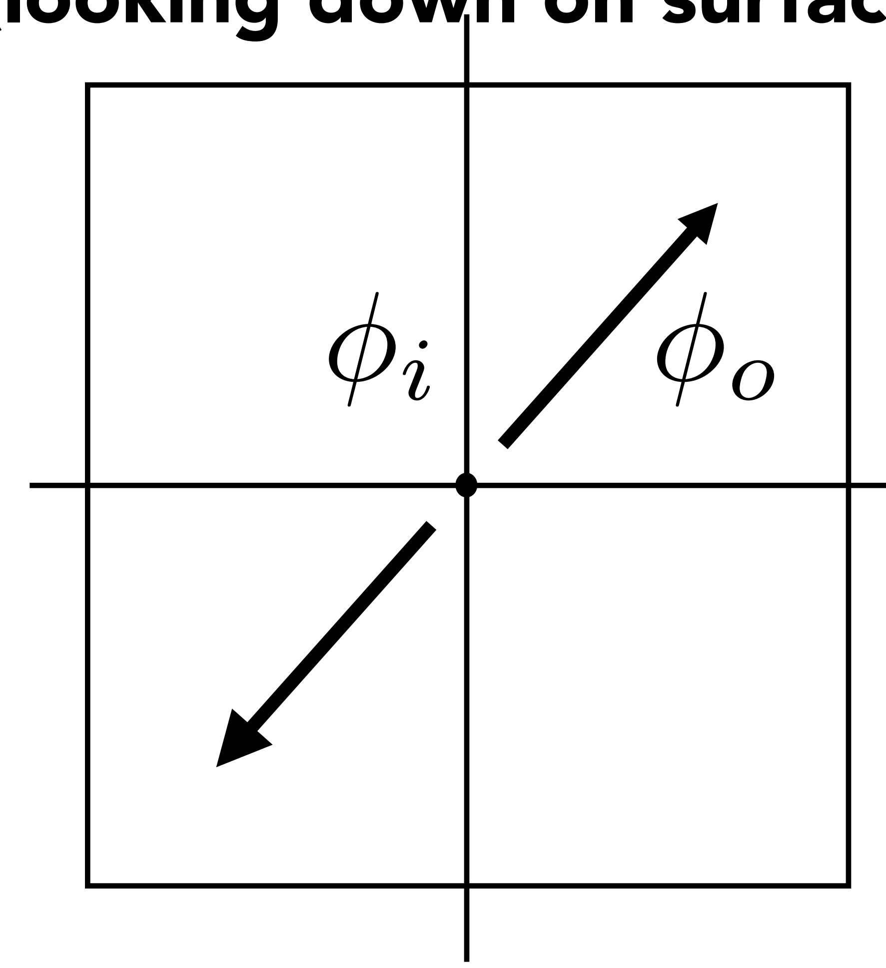
[Zátonyi Sándor]

How to compute bounce?



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

Top-down view
(looking down on surface)



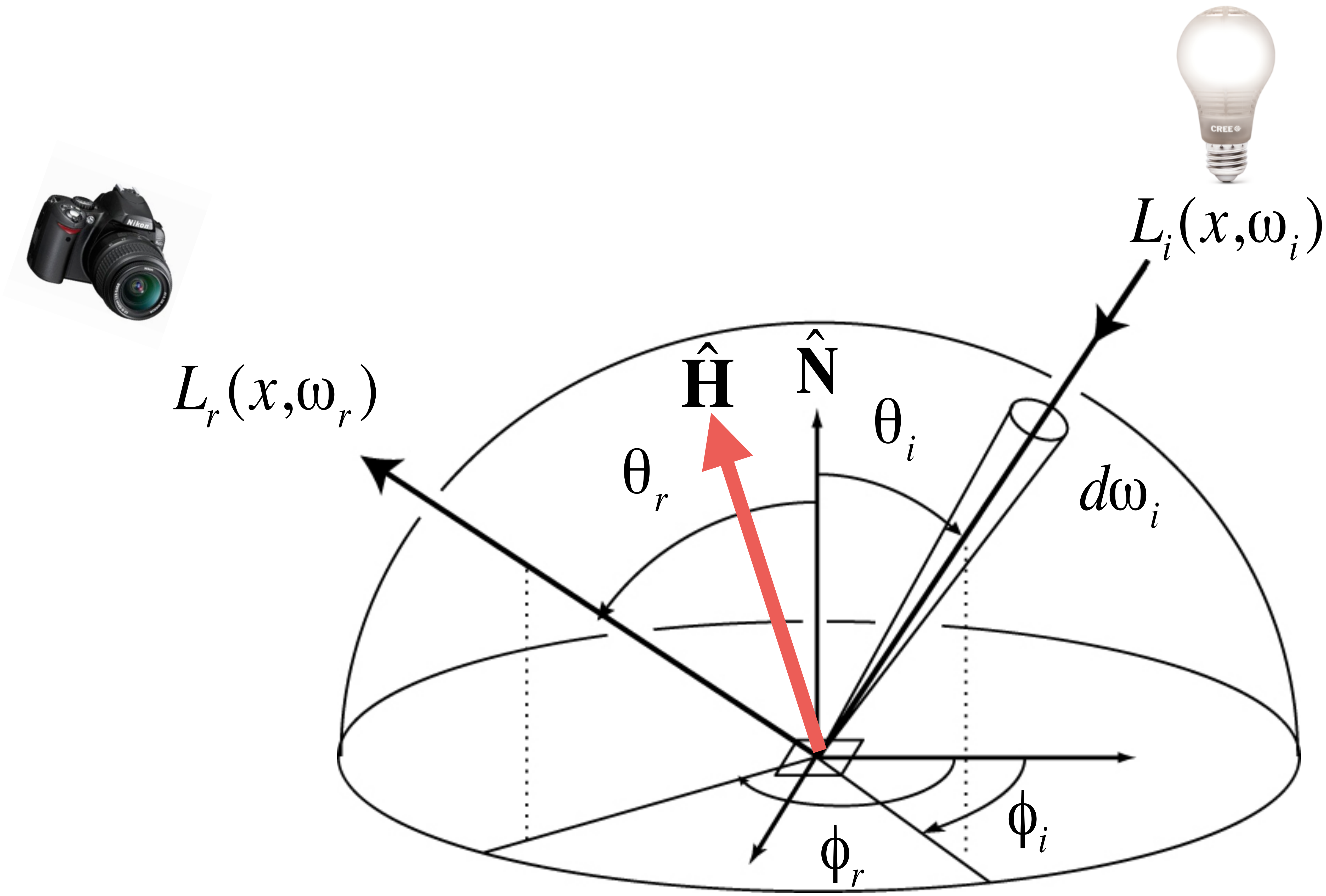
$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

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

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

Ren Ng

Important concept: the "half angle"



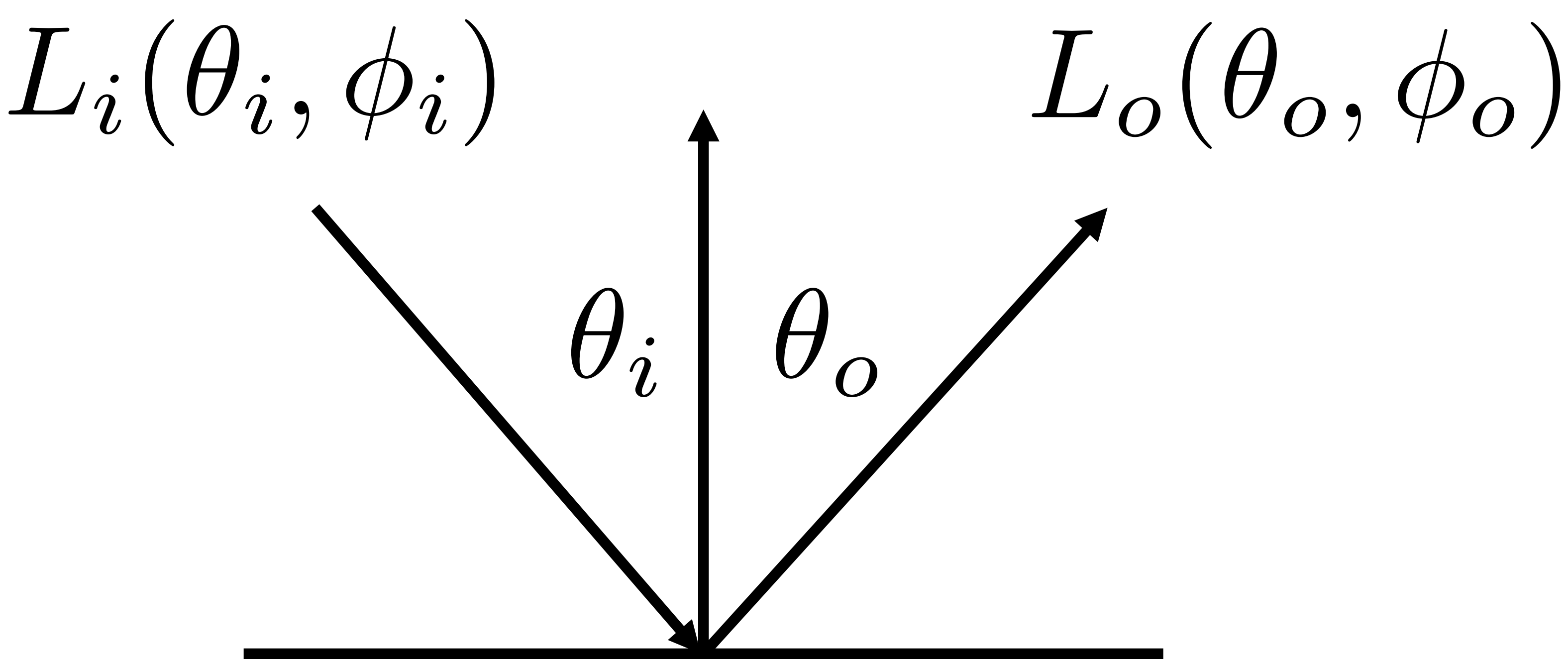
$$\hat{\mathbf{H}} = \text{normalize}(\omega_r + \omega_i)$$

Perfect specular reflection occurs when $\hat{\mathbf{H}} = \hat{\mathbf{N}}$

Glossy BRDFs often written as a function of $\hat{\mathbf{H}} \cdot \hat{\mathbf{N}}$

Ren Ng

How does this work with reflection integral?



$$L_o(\theta_o, \phi_o) = L_i(\theta_i, \phi_i \pm \pi)$$

$$f_r(\theta_i, \phi_i; \theta_o, \phi_o) = \frac{\delta(\cos\theta_i - \cos\theta_o)}{\boxed{\cos\theta_i}} \delta(\phi_i - \phi_o \pm \pi)$$

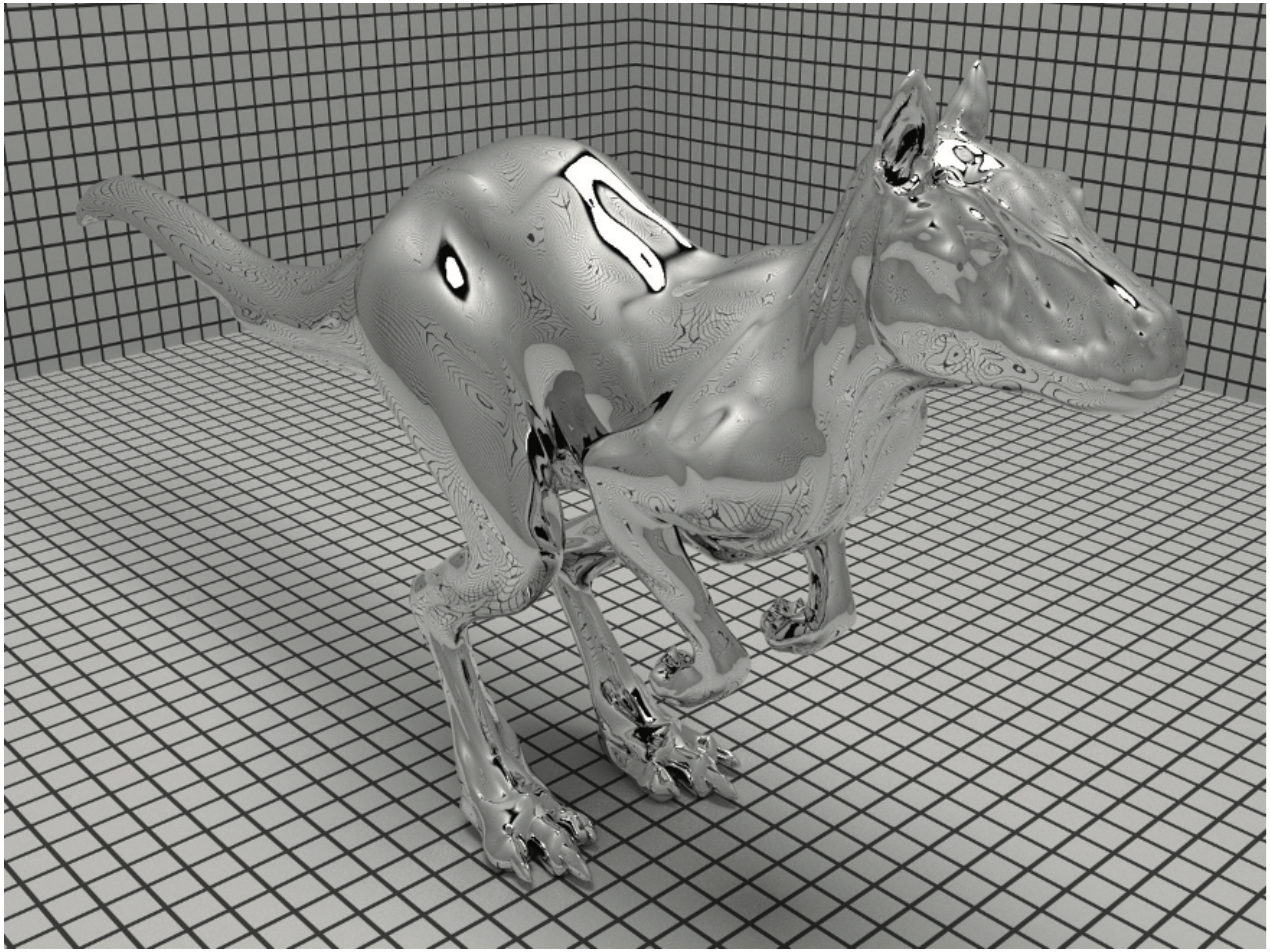
- **Why $\cos\theta_i$?**

$$L_o(\theta_o, \phi_o) = \int f_r(\theta_i, \phi_i; \theta_o, \phi_o)\, L_i(\theta_i, \phi_i) \boxed{\cos\theta_i}\, \mathrm{d}\cos\theta_i\, \mathrm{d}\phi_i$$

$$= \int \frac{\delta(\cos\theta_i - \cos\theta_o)}{\cos\theta_i} \delta(\phi_i - \phi_o \pm \pi)\, L_i(\theta_i, \phi_i)\, \cos\theta_i\, \mathrm{d}\cos\theta_i\, \mathrm{d}\phi_i$$

$$= L_i(\theta_r, \phi_r \pm \pi)$$

Perfect Specular Reflection BRDF

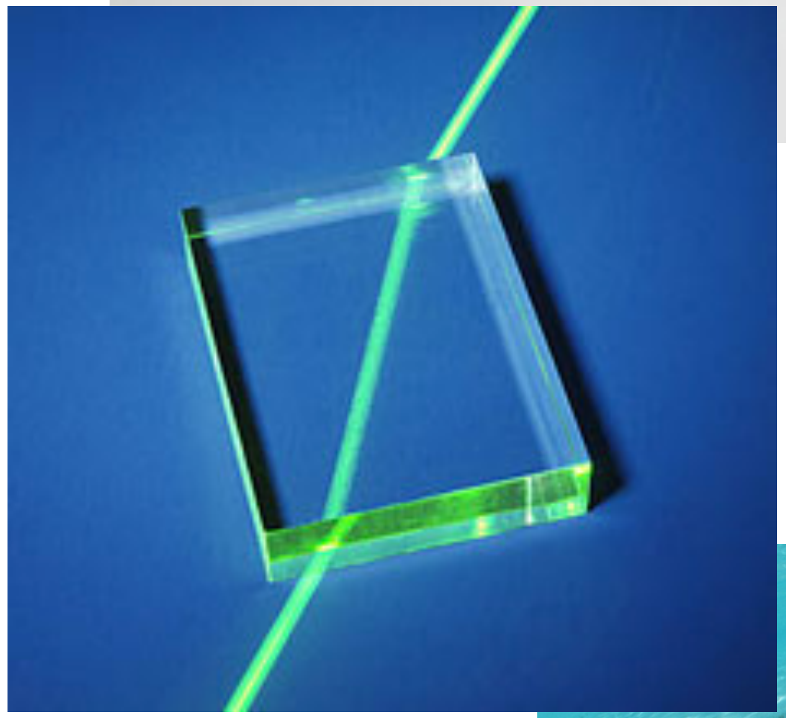


PBRT

Specular Refraction

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

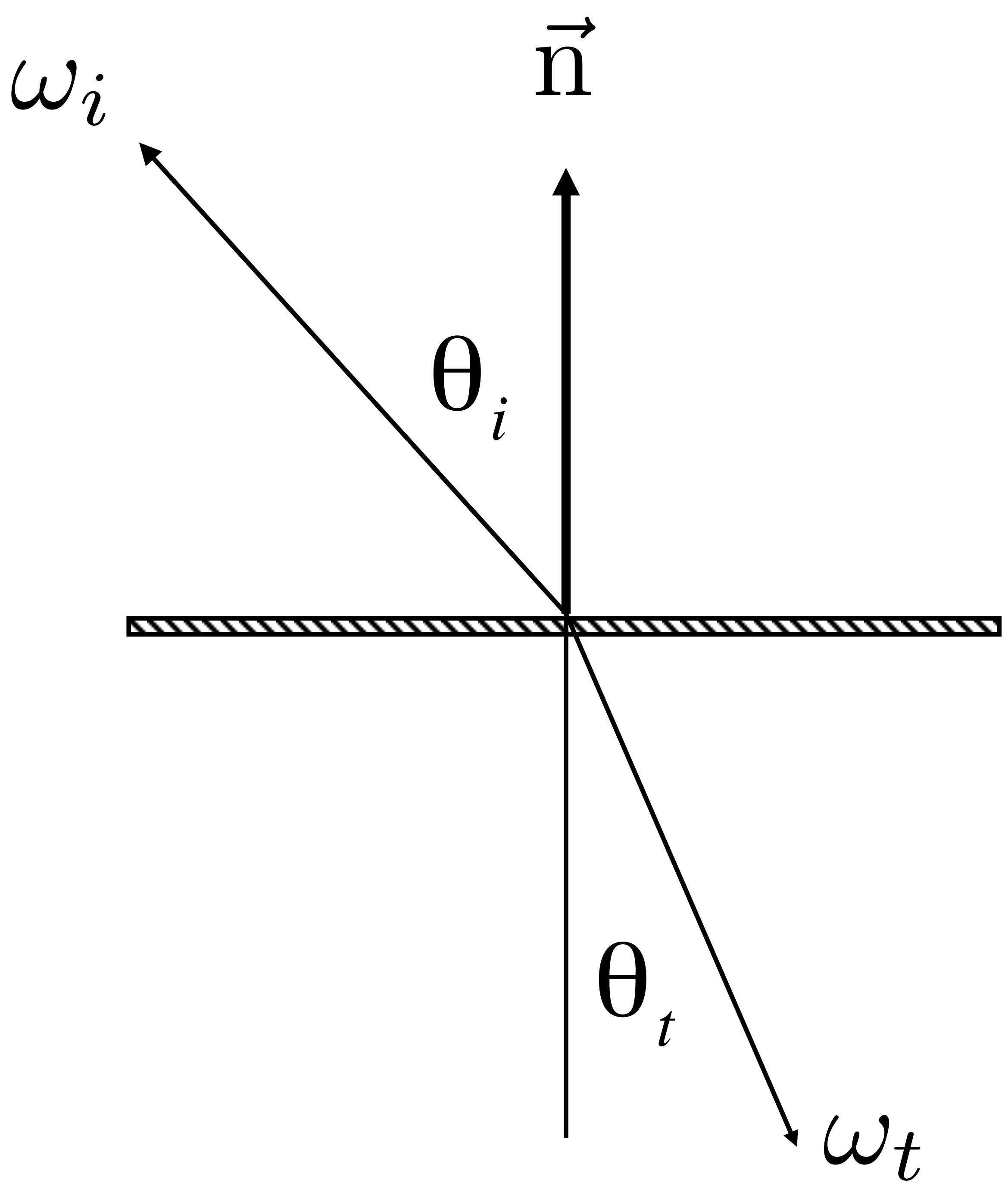
Light refracts when it enters a new medium.



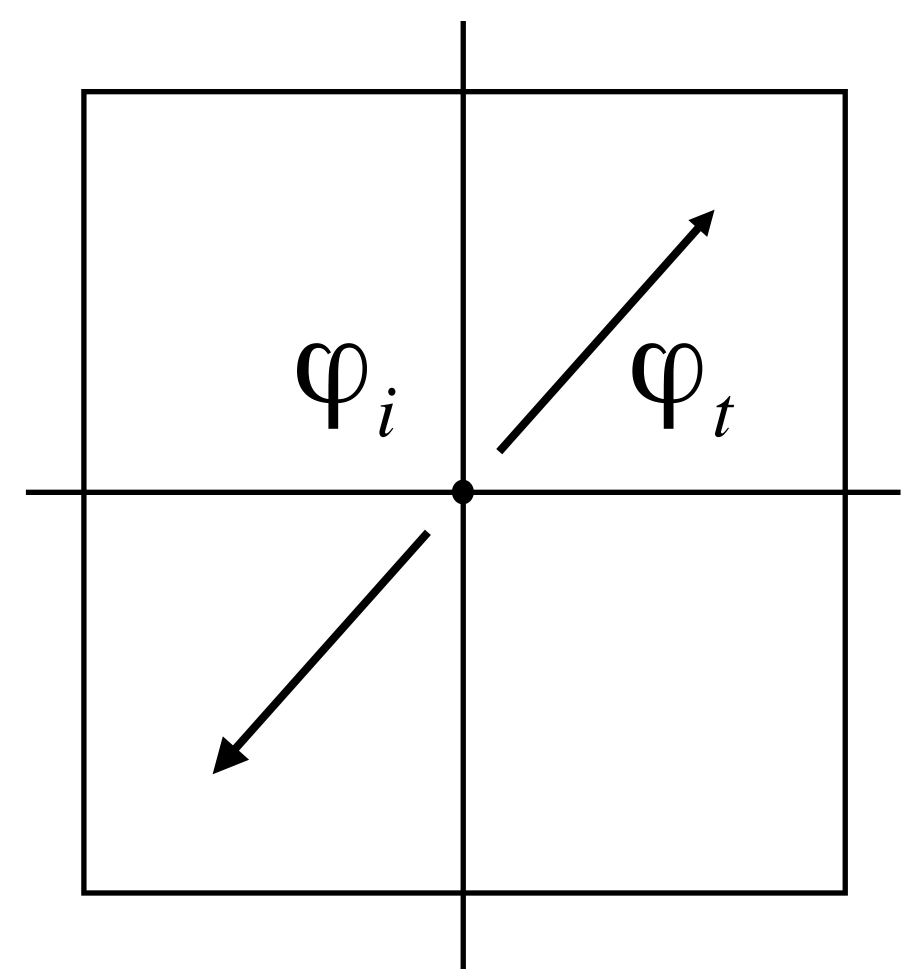
Snell's Law

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	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)

Microfacet BRDFs

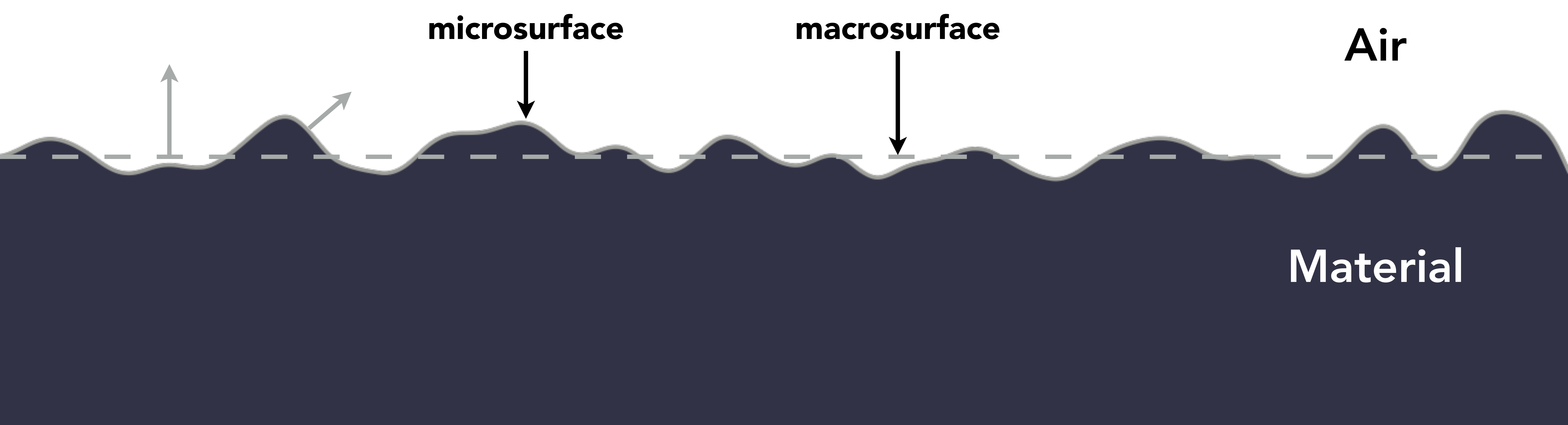
Microfacet Theory

Rough surface

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

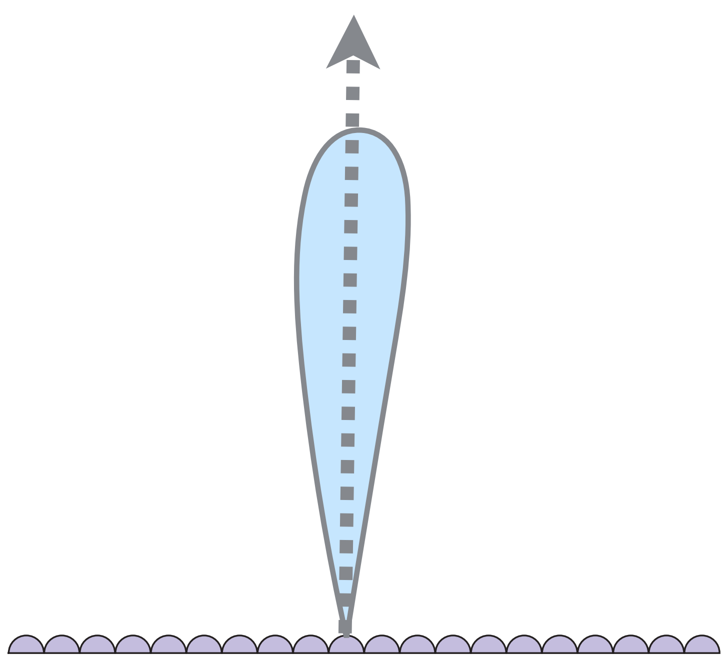
Individual elements of surface act like mirrors

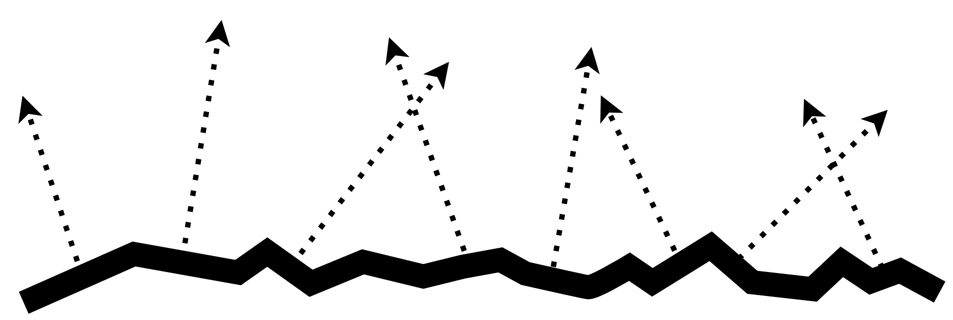
- Known as Microfacets
- Each microfacet has its own normal

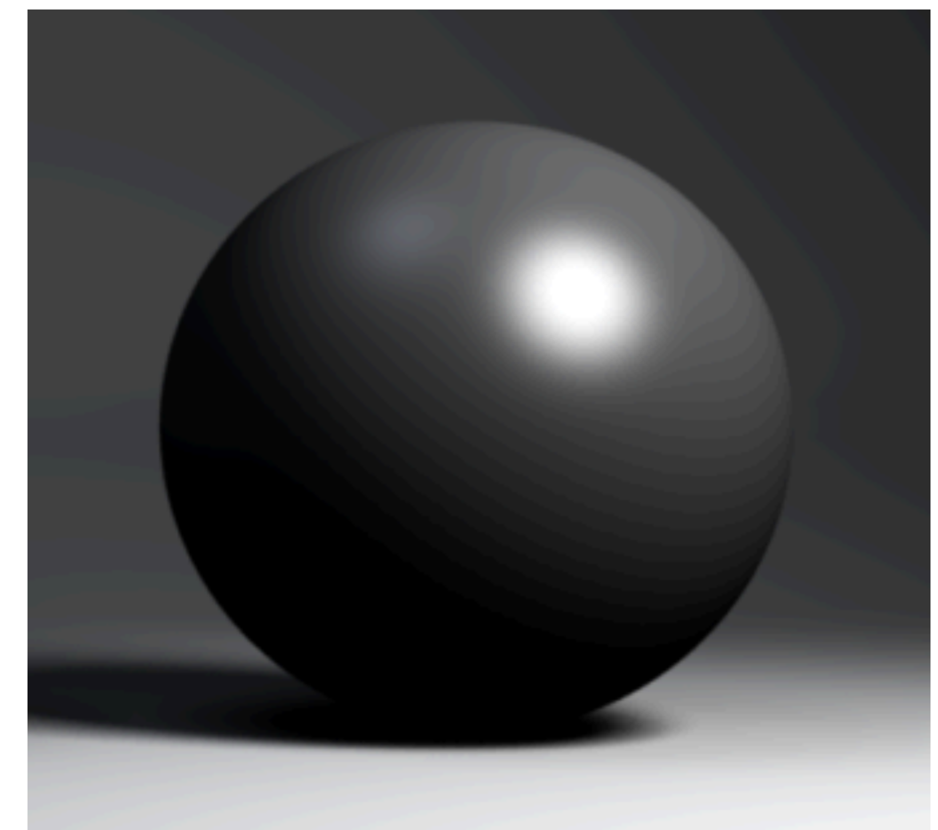


Microfacet BRDF

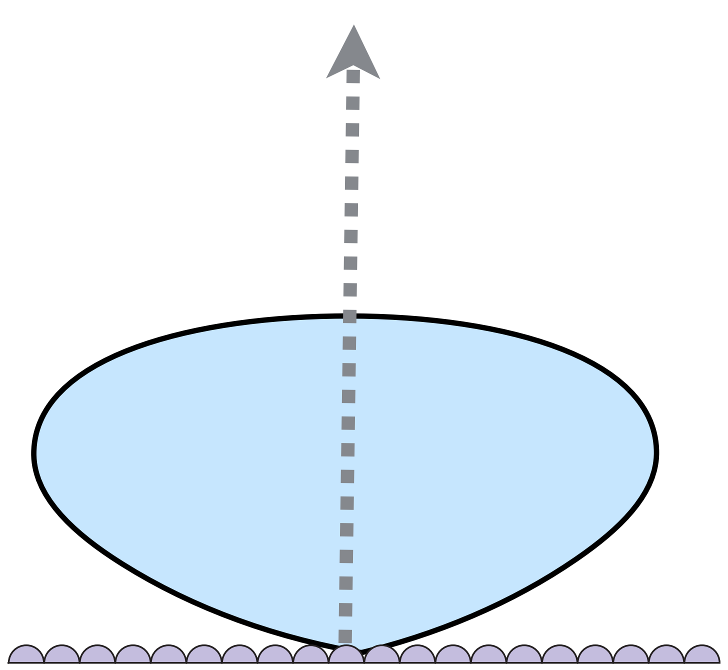
- Key: the distribution of microfacets' normals
  - Concentrated <==> glossy

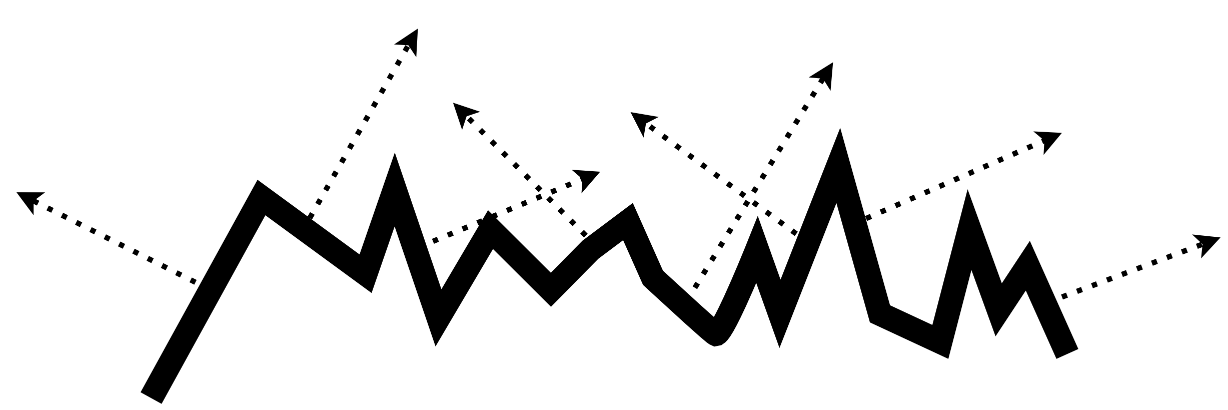


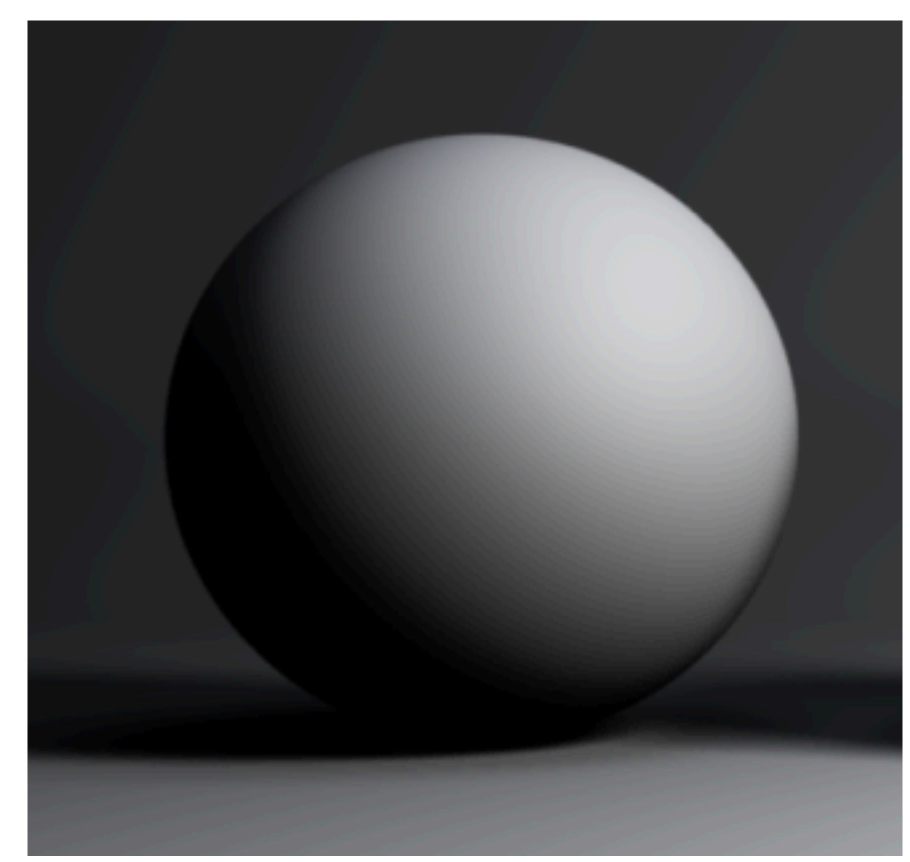




  - Spread <==> diffuse

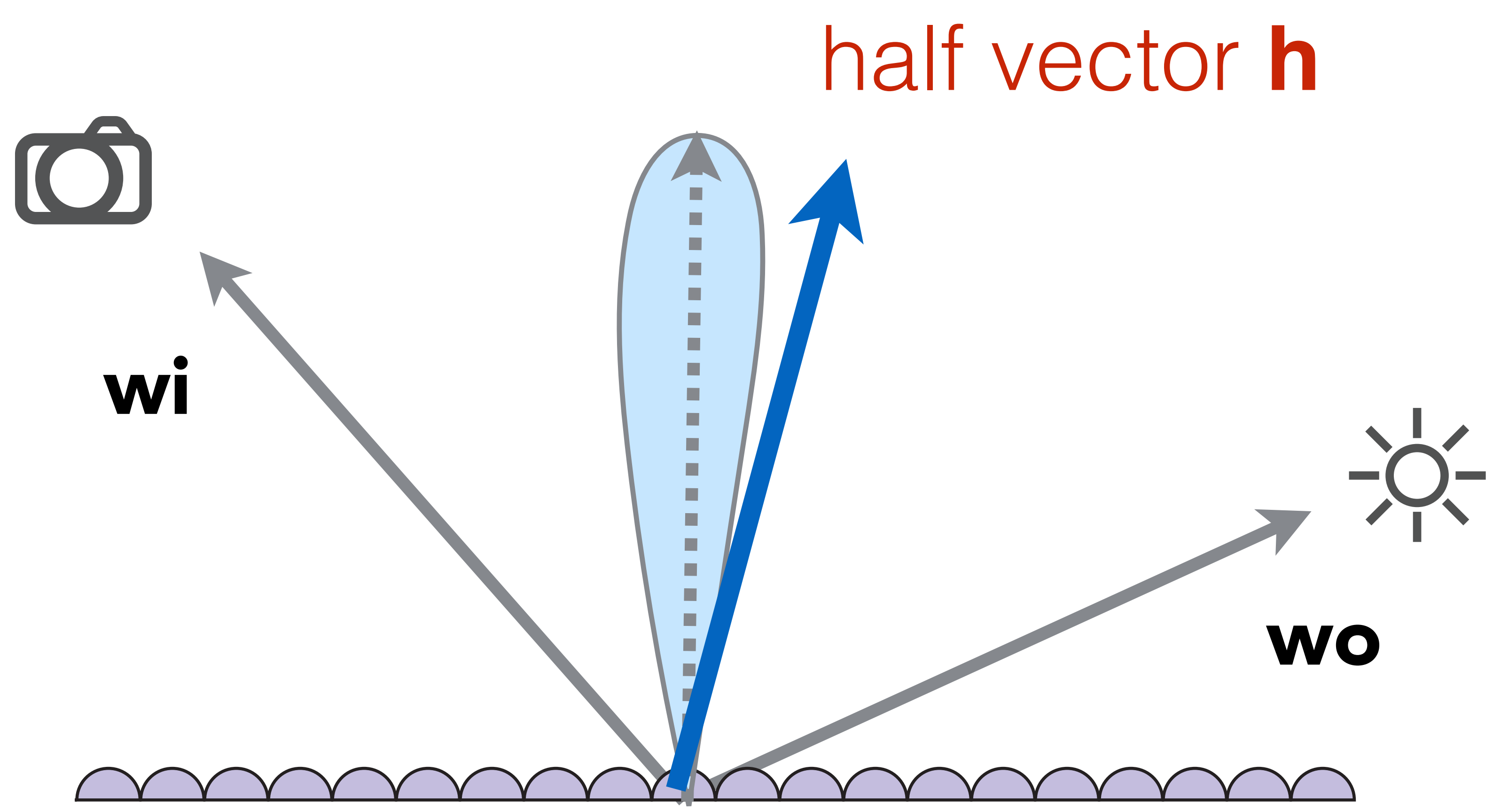


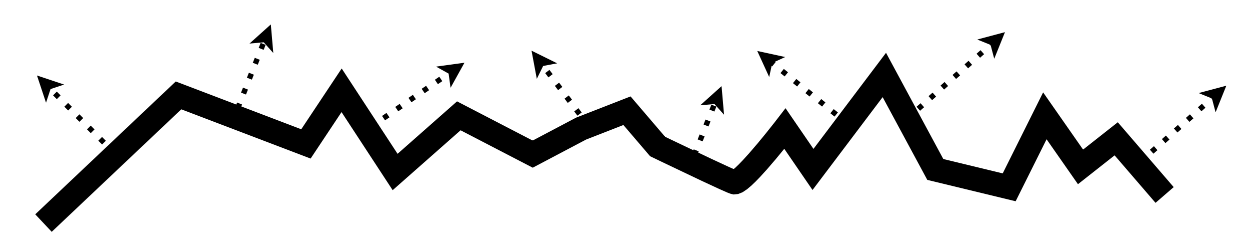




Microfacet BRDF

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





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

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

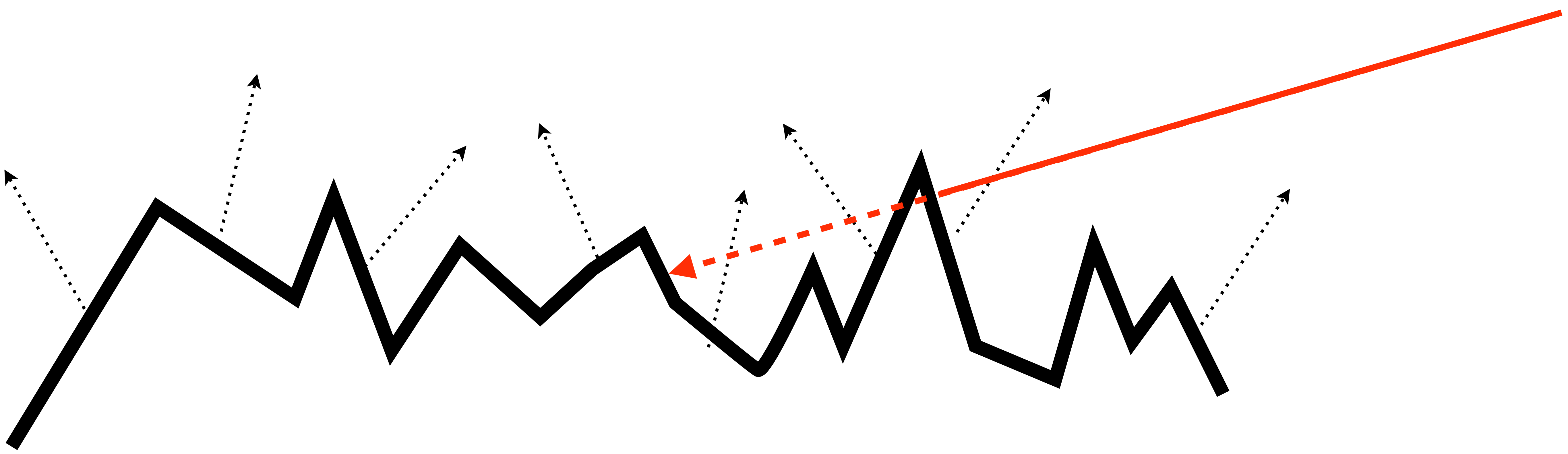
Fresnel Reflection / Term

Reflectance depends on incident angle (and polarization of light)

This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

Shadowing/masking term



At grazing incoming light angles, some microfacets will block light from reaching other parts of surface

Microfacet BRDF: Examples

[Autodesk Fusion 360]

Anisotropic materials

Isotropic / Anisotropic Materials (BRDFs)

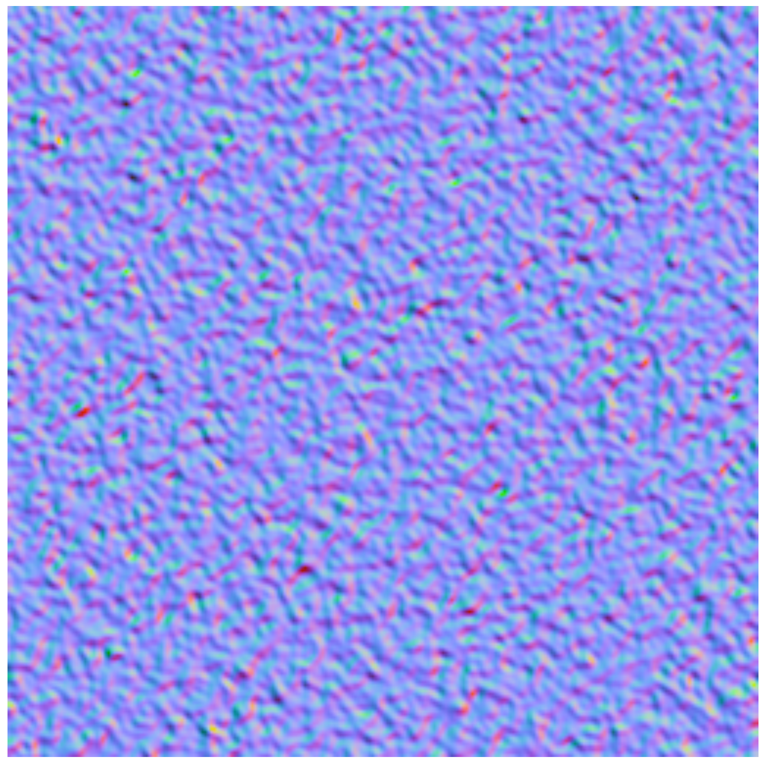
- So far, Point light + Metal = Round / Elliptical highlight
- What can we see inside an elevator?

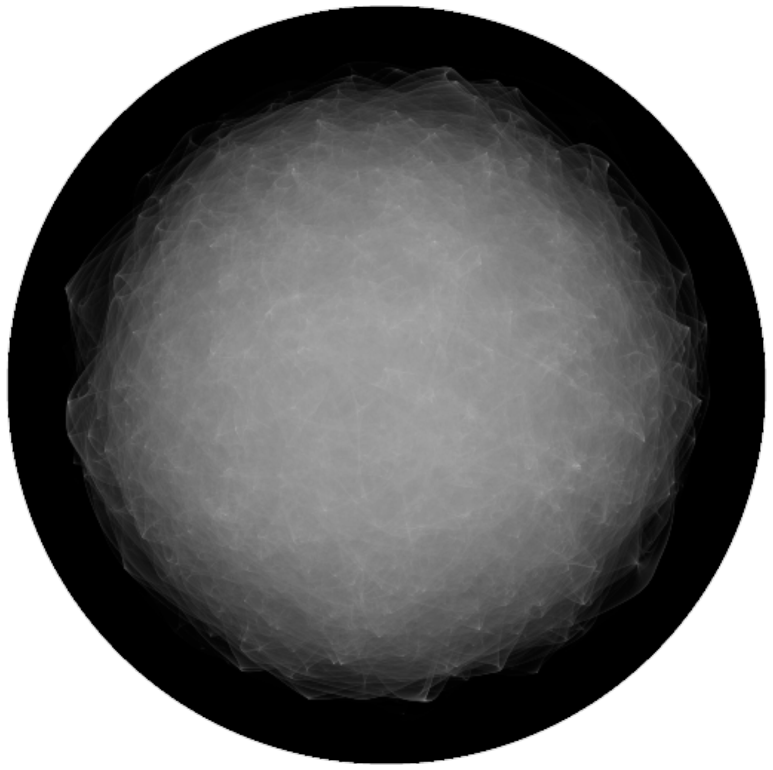
Inside an elevator

Isotropic / Anisotropic Materials (BRDFs)

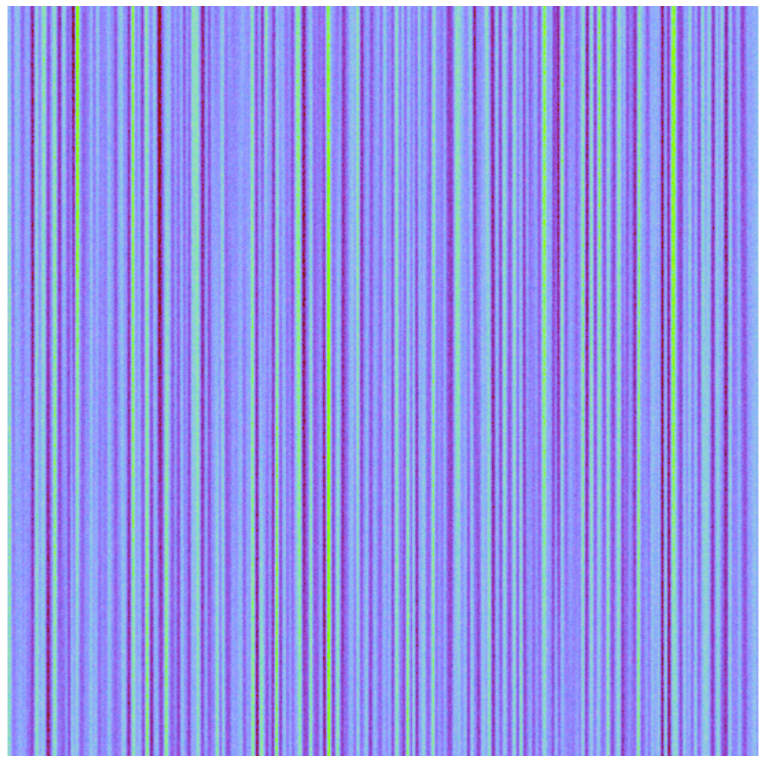
- Key: directionality of underlying surface

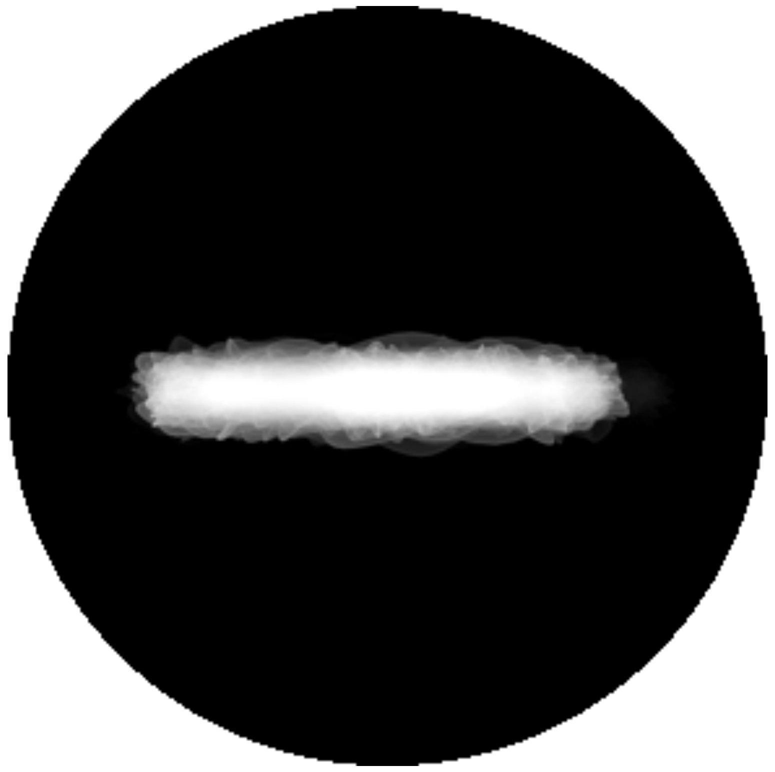
Isotropic





Anisotropic





Surface (normals)

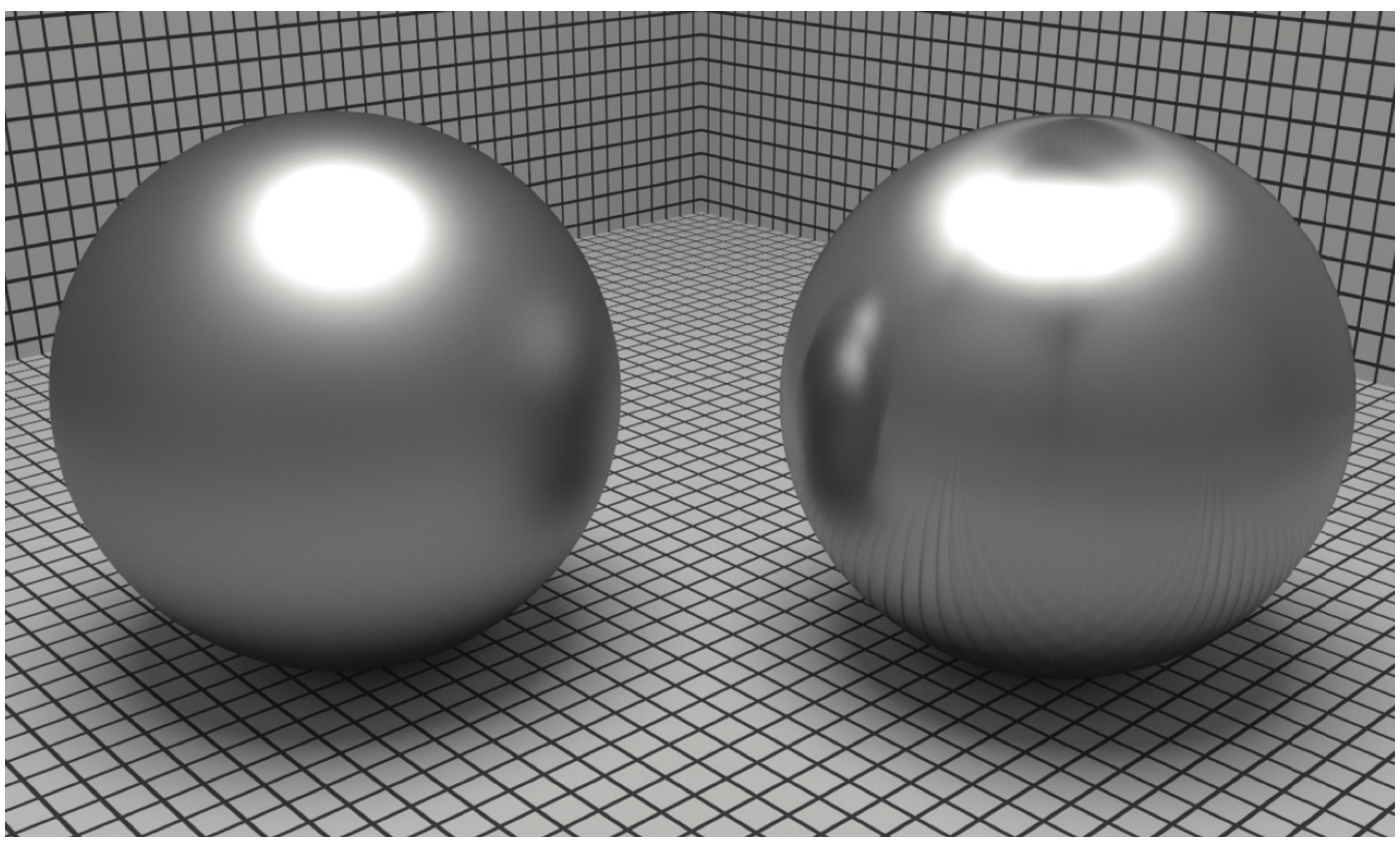
BRDF (fix wi, vary wo)

Anisotropic 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



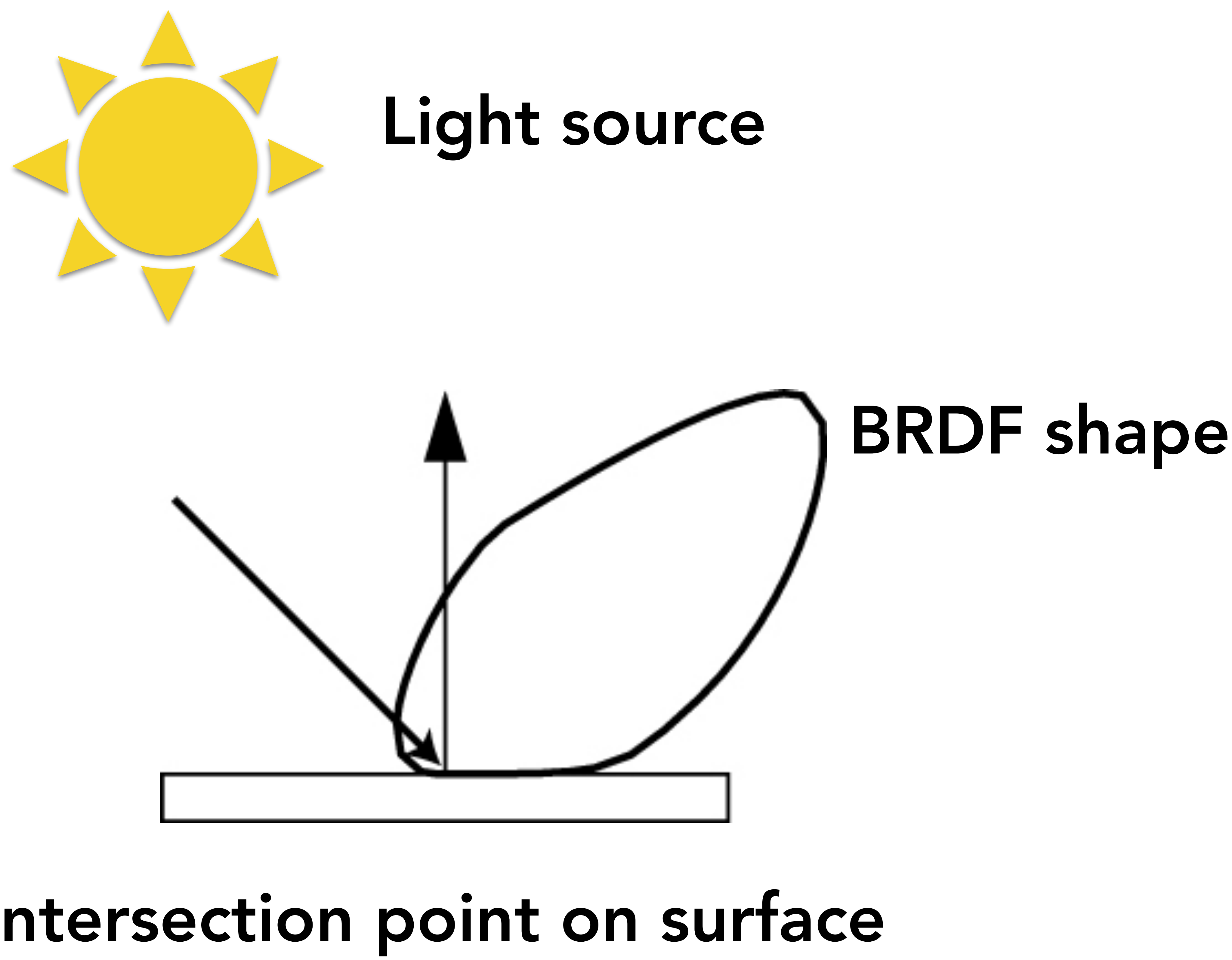
Isotropic vs Anisotropic Reflection

Isotropic

Anisotropic

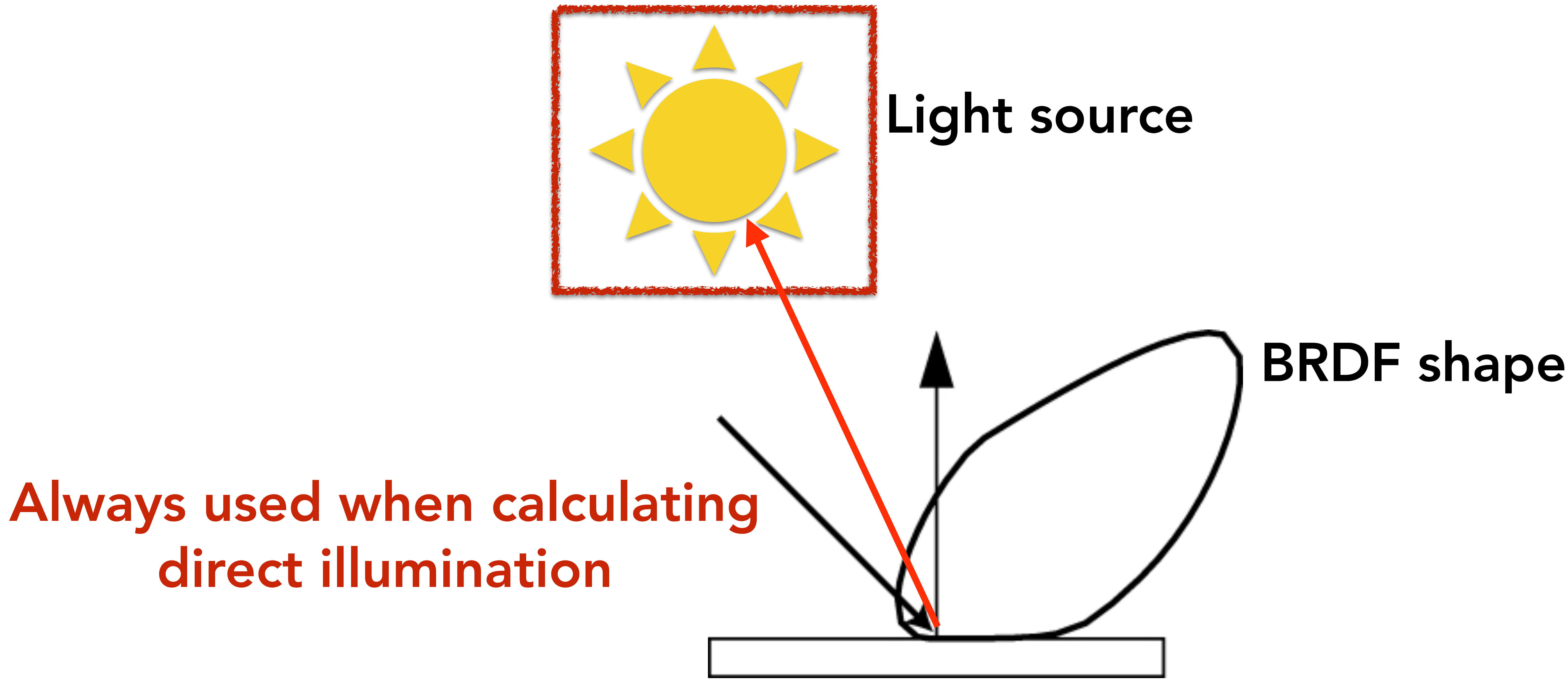
Importance sampling

Importance sampling: lights and BRDF



$$L_r(\mathrm{p}, \omega_r) = \int_{H^2} f_r(\mathrm{p}, \omega_i \to \omega_r)\, L_i(\mathrm{p}, \omega_i)\, \cos\theta_i \, \mathrm{d}\omega_i$$

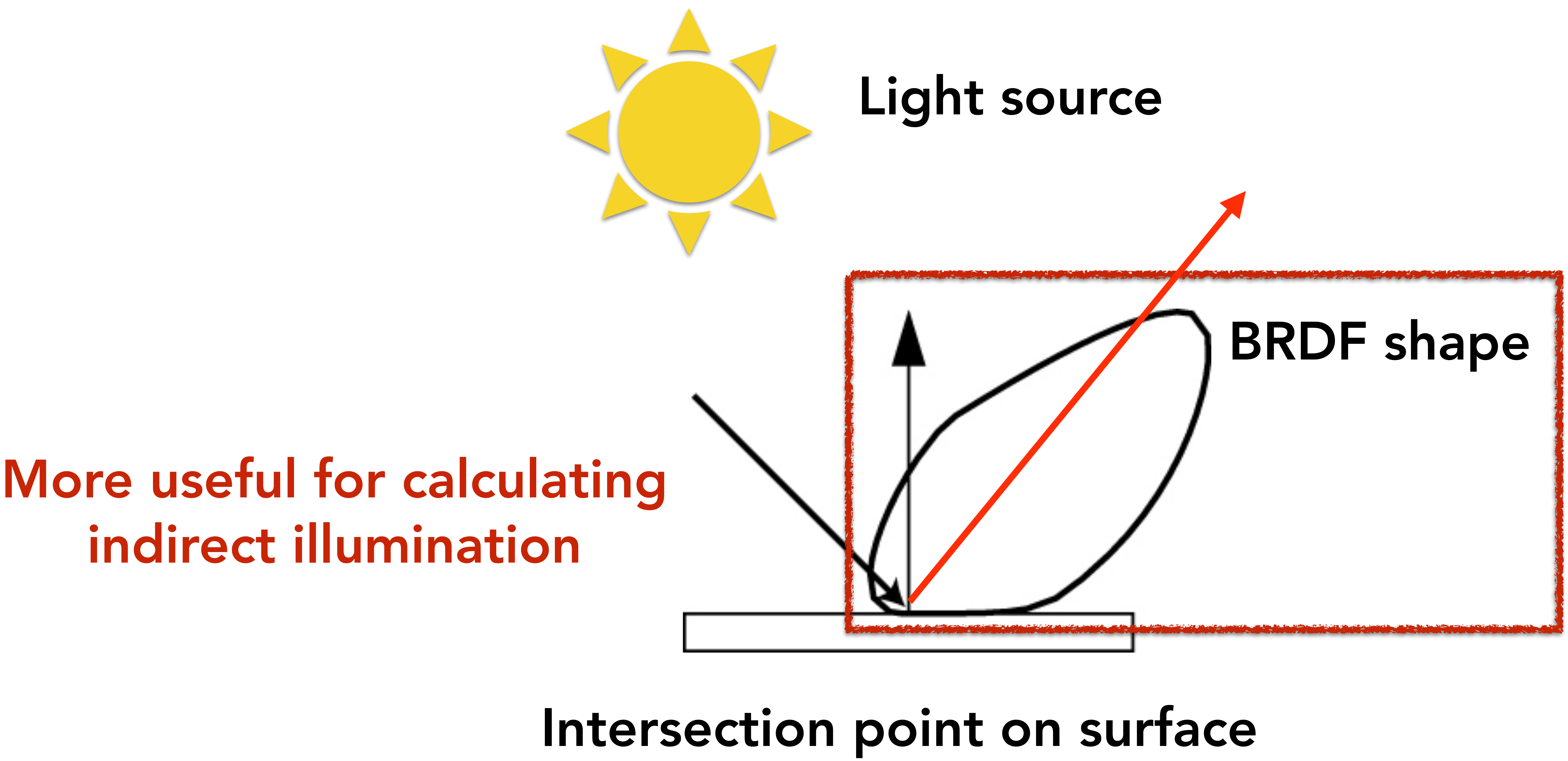
Shoot rays toward random point on light surface



Intersection point on surface

$$L_r(\mathrm{p}, \omega_r) = \int_{H^2} f_r(\mathrm{p}, \omega_i \to \omega_r)\, L_i(\mathrm{p}, \omega_i) \cos\theta_i \, \mathrm{d}\omega_i$$

Shoot rays in proportion to BRDF strength



$$L_r(\mathrm{p}, \omega_r) = \int_{H^2} f_r(\mathrm{p}, \omega_i \to \omega_r)\, L_i(\mathrm{p}, \omega_i)\, \cos\theta_i \, \mathrm{d}\omega_i$$

Importance sampling diffuse BRDF

$$L_o(\omega_o) = \frac{\rho}{\pi} \int L_i(\omega_i) \cos\theta_i \mathrm{d}\omega_i$$

The BRDF factors out of the reflectance integral since it's constant

Can just use cosine-weighted random samples on hemisphere

Importance sampling microfacet BRDF

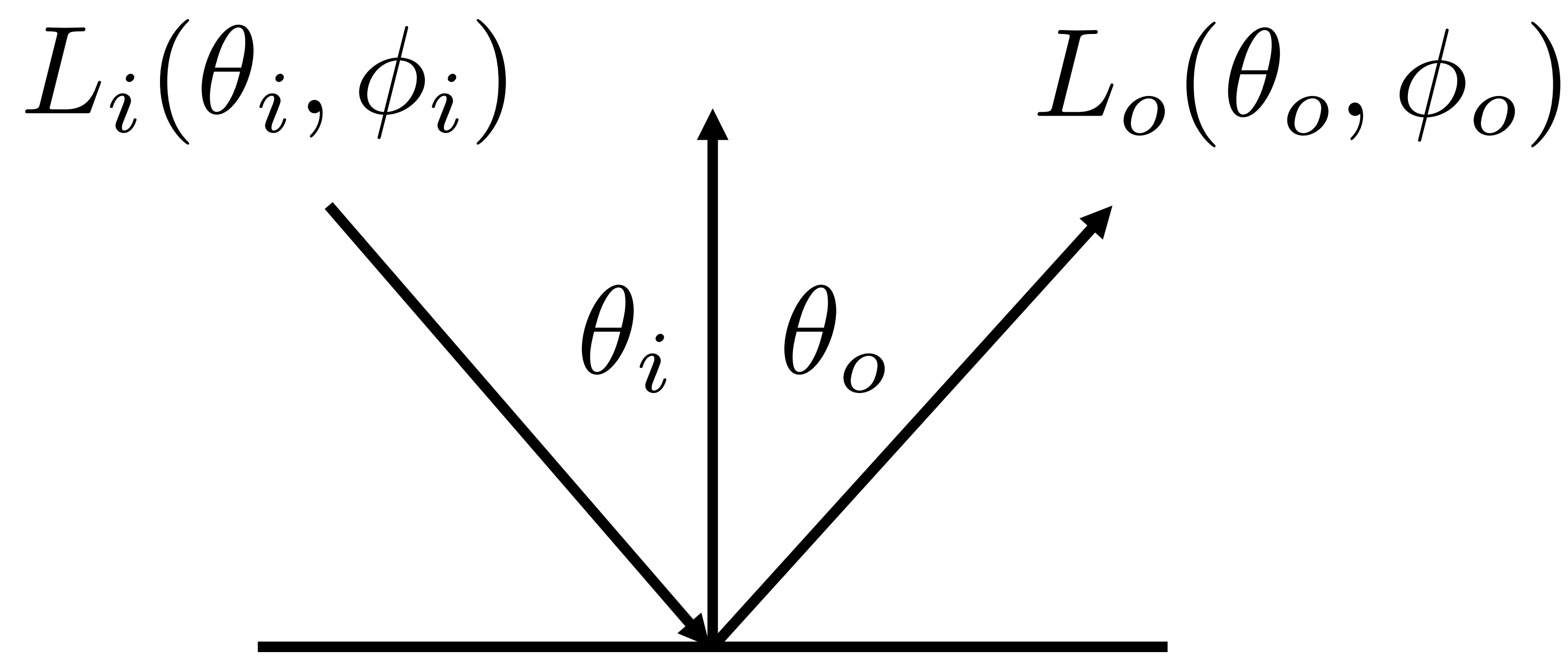
distribution of normals

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

They come with a probability distribution built right in!

Sampling a half-angle from $\mathbf{D}$ works well to match specular lobe

“Importance sampling” perfect specular BRDFs



$$L_o(\theta_o, \phi_o) = L_i(\theta_i, \phi_i \pm \pi)$$

$$f_r(\theta_i, \phi_i; \theta_o, \phi_o) = \frac{\delta(\cos\theta_i - \cos\theta_o)}{\cos\theta_i}\delta(\phi_i - \phi_o \pm \pi)$$

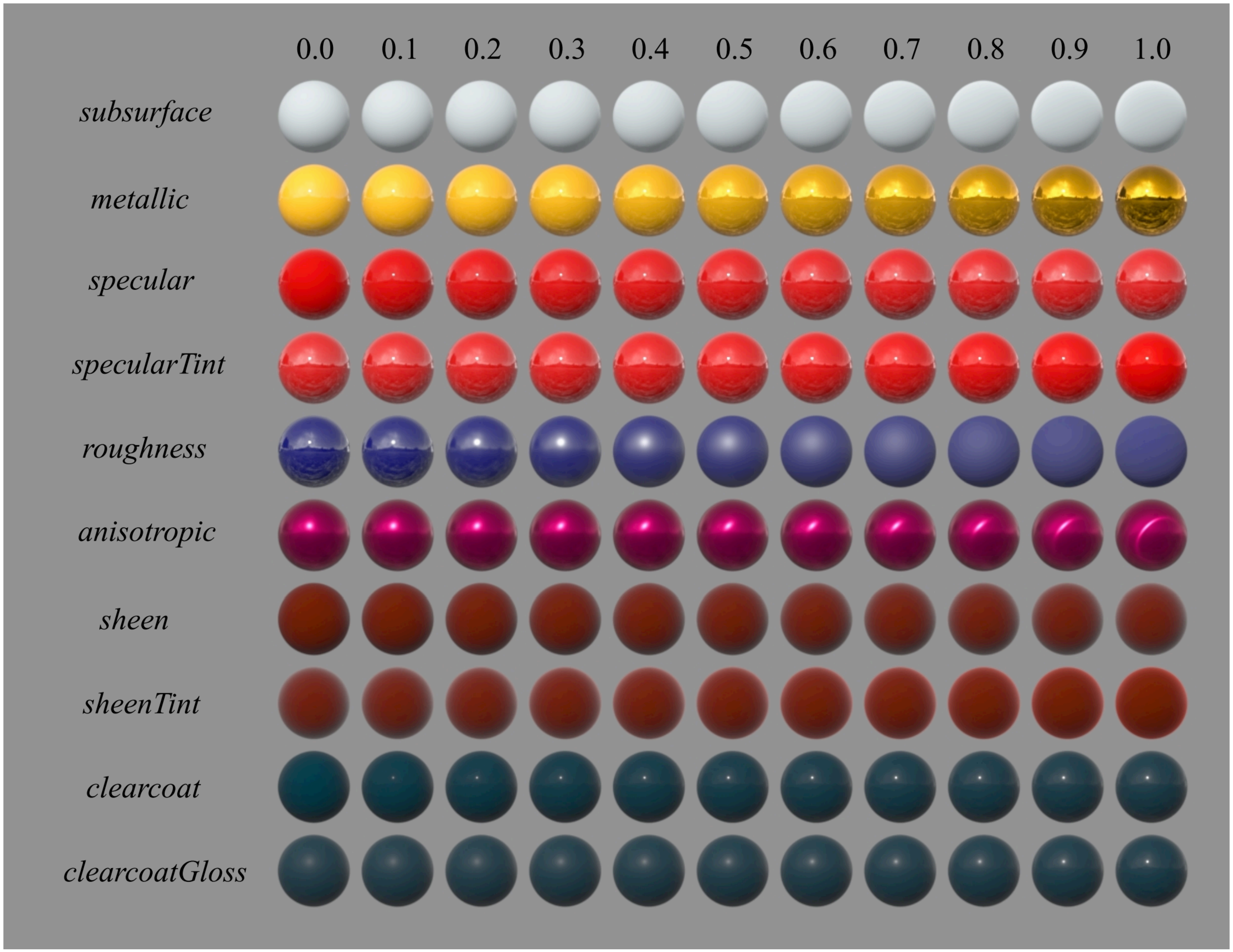
In the case of a perfect specularity, the BRDF is a “delta function”

No energy will bounce from ANY other direction

Importance sampling lights is useless here

Disney BRDF

Disney BRDF: flexible model used in production



Physically Based Shading at Disney, 2012

Disney BRDF: flexible model used in production

- "Our philosophy has been to develop a 'principled' model rather than a strictly physical one. These were the principles [used] when implementing our model:
  - Intuitive rather than physical parameters should be used.
  - There should be as few parameters as possible.
  - Parameters should be zero to one over their plausible range.
  - Parameters should be allowed to be pushed beyond their plausible range where it makes sense.
  - All combinations of parameters should be as robust and plausible as possible."

Physically Based Shading at Disney, 2012

Disney BRDF: flexible model used in production

All materials (except hair) defined using a single BRDF!

Physically Based Shading at Disney, 2012

Disney BRDF: flexible model used in production

- Deployed for Wreck-It Ralph (2012)
- Ended up simplifying artist workflow!
  - Interpolating parameters works (use texture "masks" to switch between param vals)
  - Area lights work (cannot use point lights any more since specular highlights won't show up)
- Overall, a very interesting look inside the technical work that goes on in 3D movie production
  https://blog.selfshadow.com/publications/s2012-shading-course/burley/s2012_pbs_disney_brdf_notes_v3.pdf

Physically Based Shading at Disney, 2012

Demo