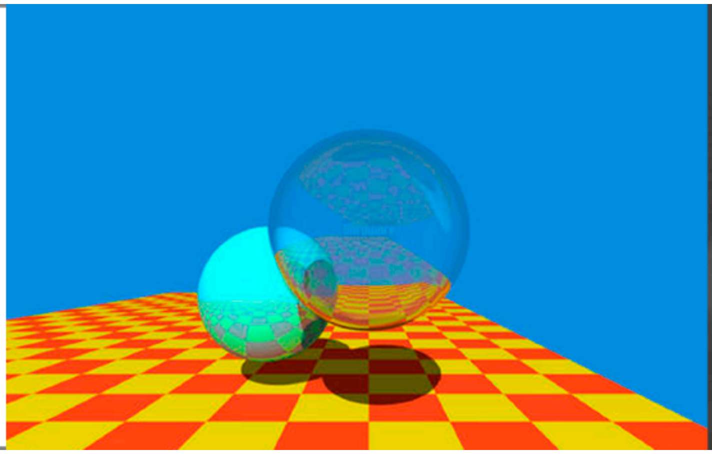
Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 17:
Materials and Appearances






http://www.cs.ucsb.edu/~lingqi/teaching/games101.html

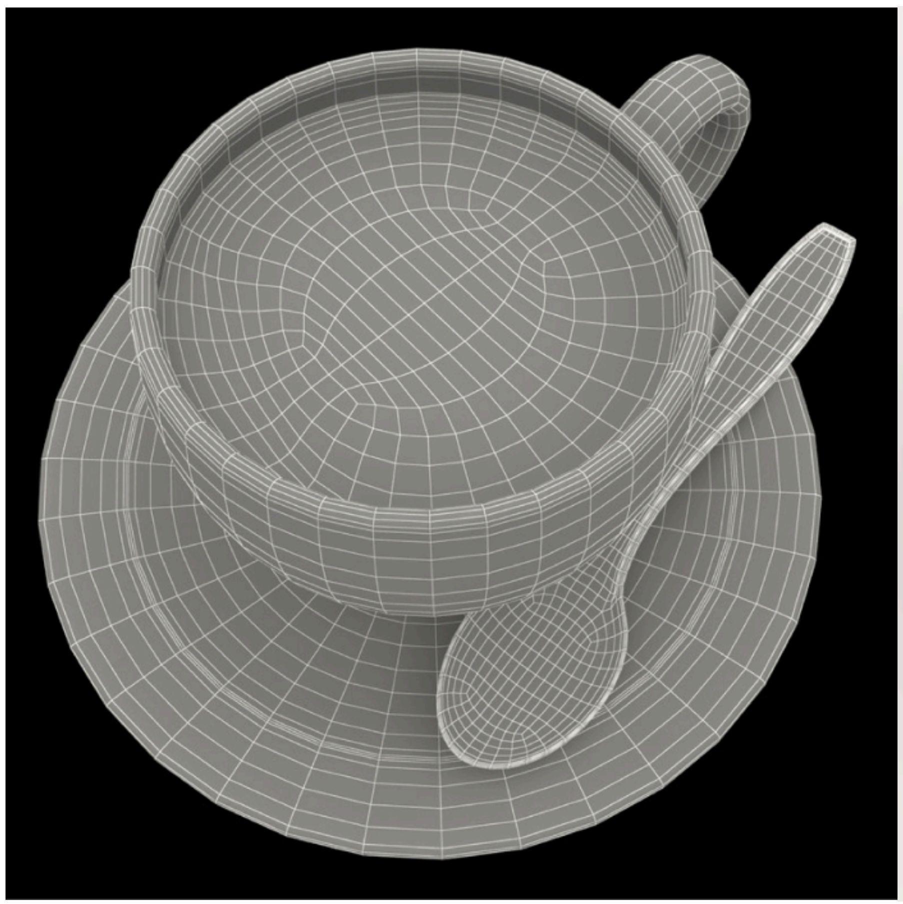
Announcements

- Homework 6: 82 submissions so far (note: 1.5 weeks for it)
- New assignment on path tracing has been worked out!
  - Followed the pseudocode in the last lecture as much as possible
  - Will be released this Friday
- Final project ideas: to be released soon
- From today: the lectures will be much easier!

The Appearance of Natural Materials

[Courtesy of Prof. Henrik Wann Jensen, UCSD]

What is Material in Computer Graphics?



3D coffee mug model

Rendered

Rendered

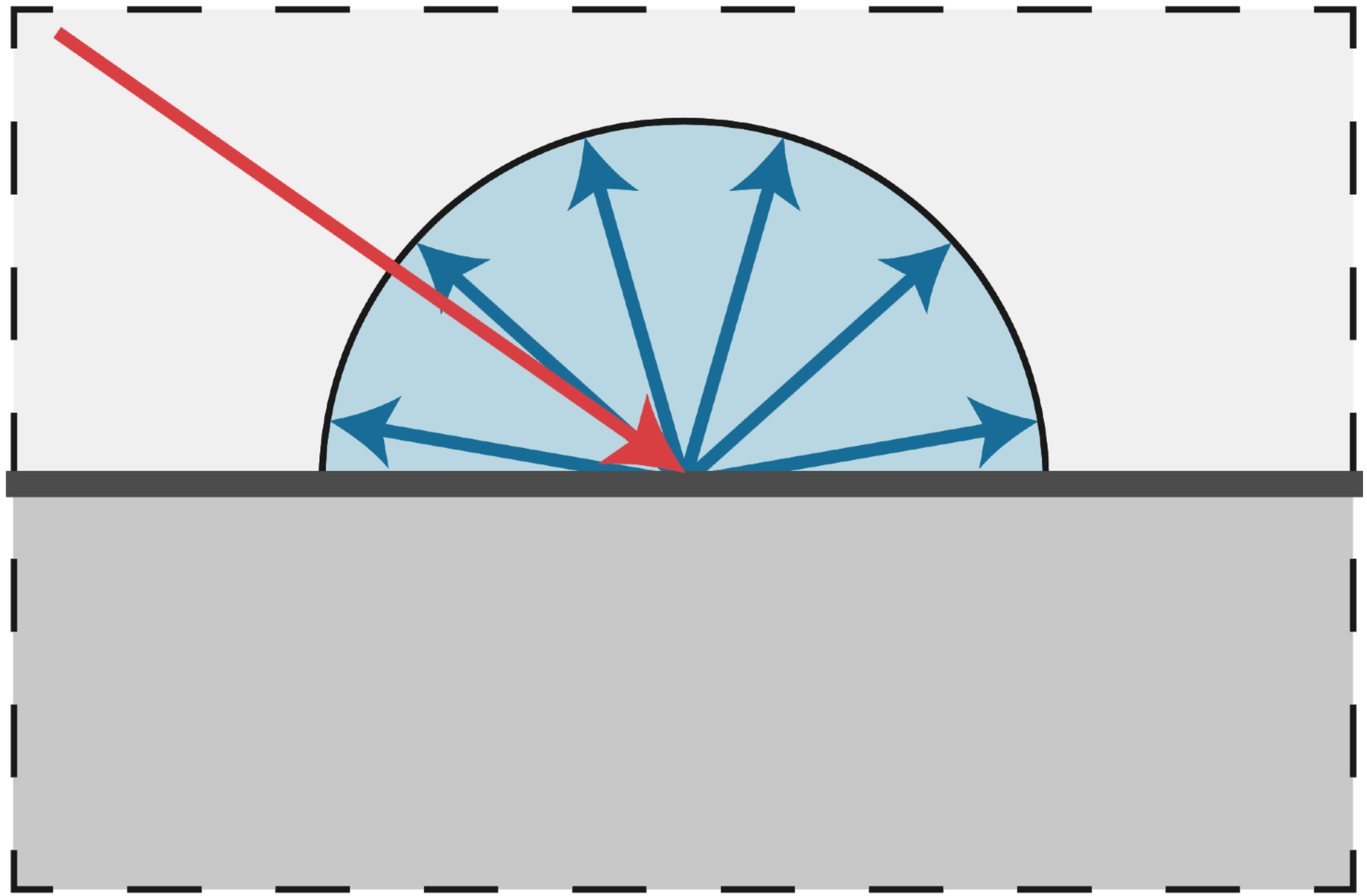
[From TurboSquid, created by artist 3dror]

Material == BRDF

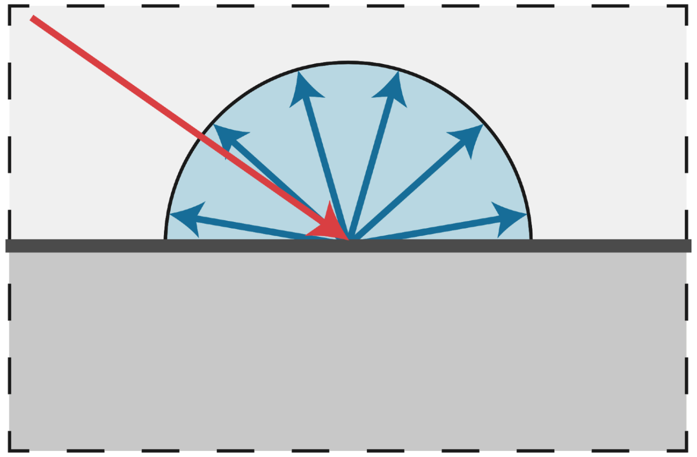
描述反射的分布函数被称为双向反射分布函数（BRDF）
描述折射也需要一种分布函数 这种分布函数被称为双向折射(透射)分布函数（BTDF）
BRDF和BTDF统称为双向散射分布函数（BSDF）

fs = fr + ft

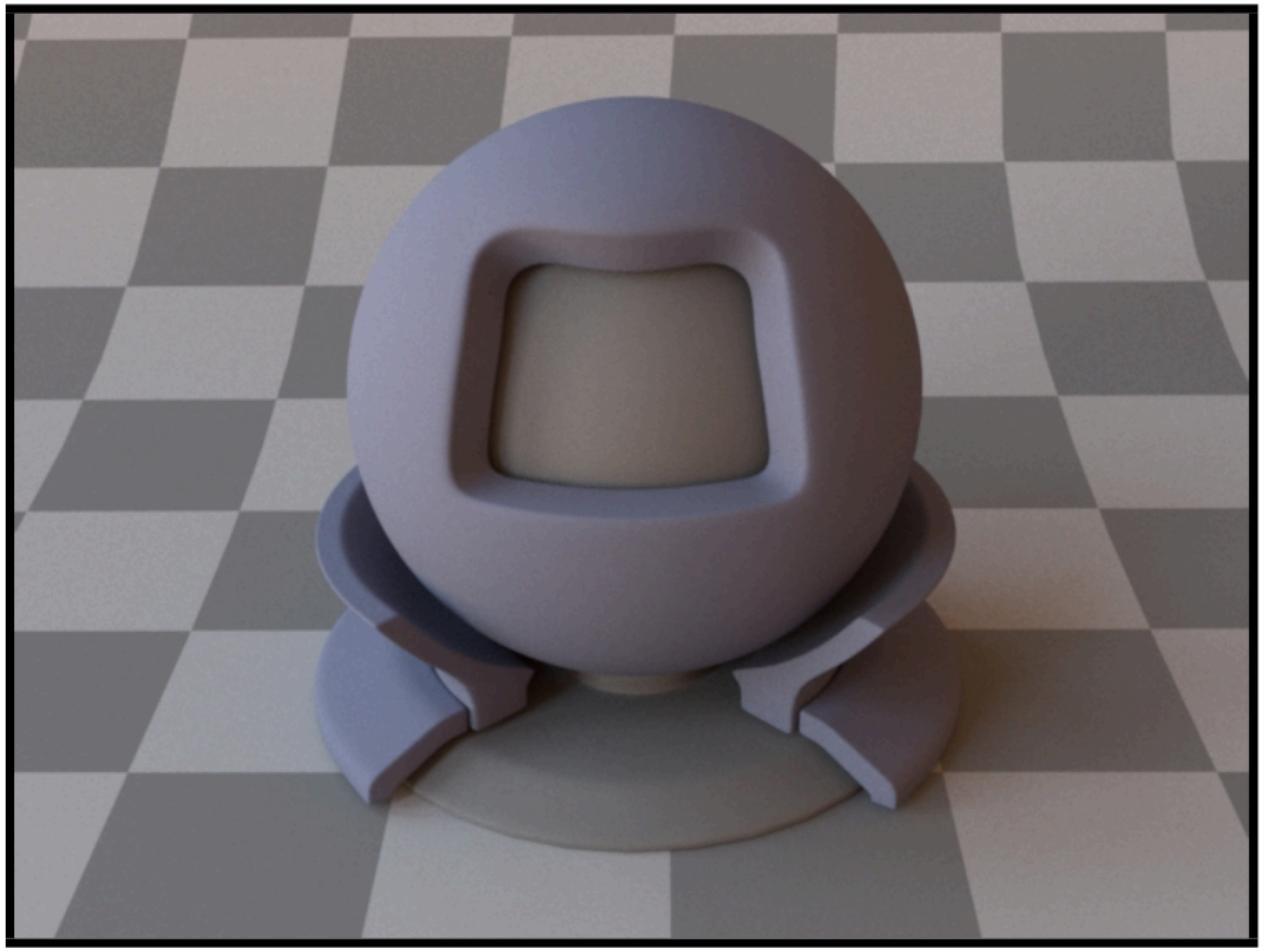
What is this material?



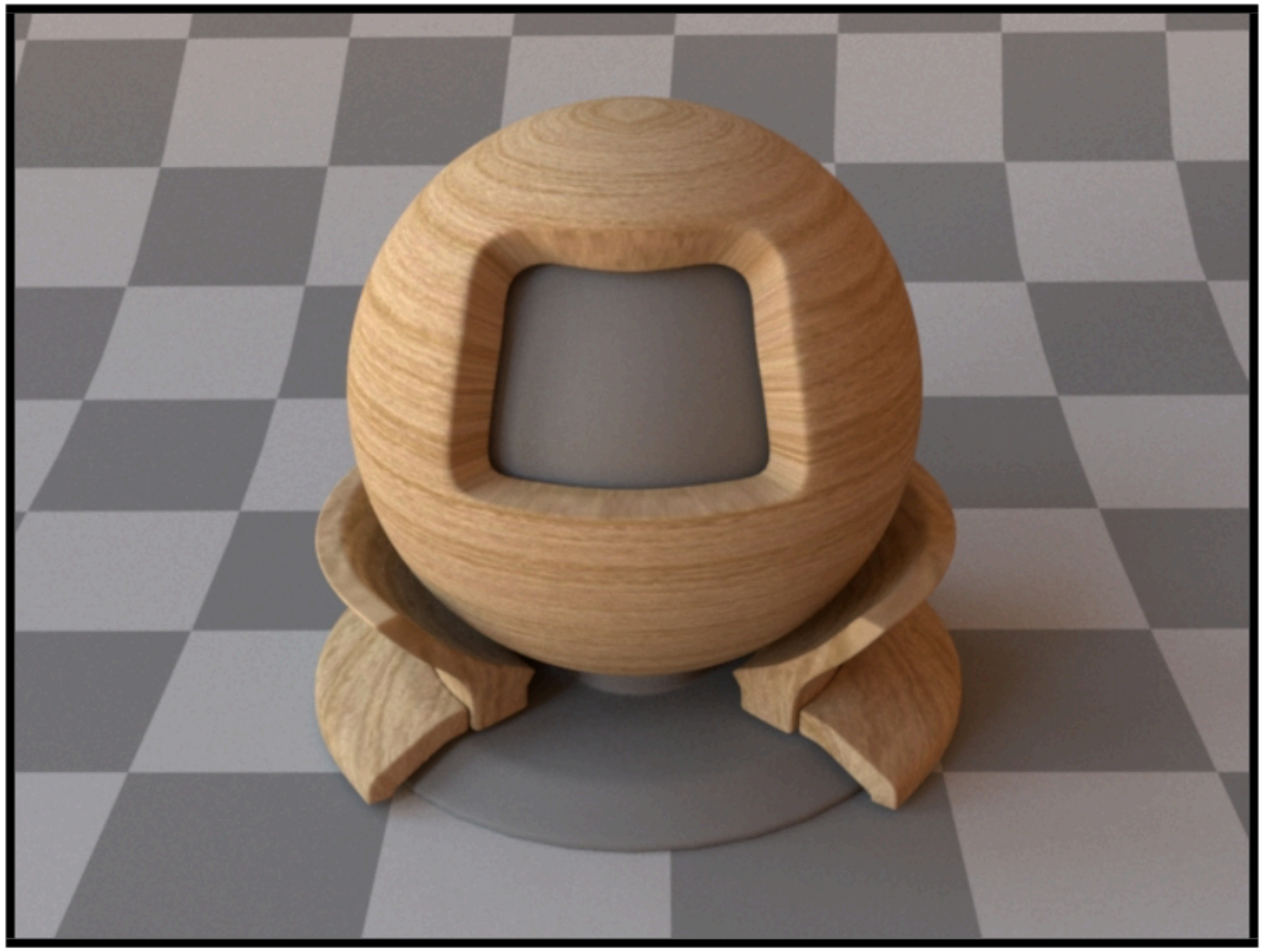
Diffuse / Lambertian Material (BRDF)



[Mitsuba renderer, Wenzel Jakob, 2010]



Uniform colored diffuse BRDF

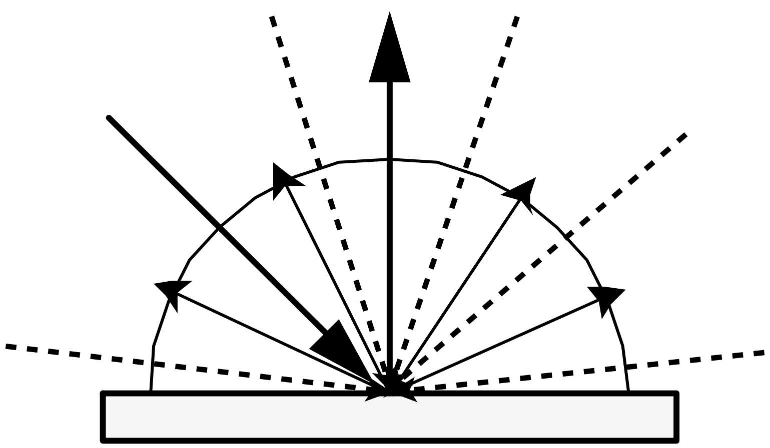


Textured diffuse BRDF

Diffuse / Lambertian Material

Light is equally reflected in each output direction

假设任意方向的入射光和出射光的Radiance和Irradiance都相等，着色点不吸收任何能量，且自发光项为0



$$f_r = c$$

Suppose the incident lighting is uniform:

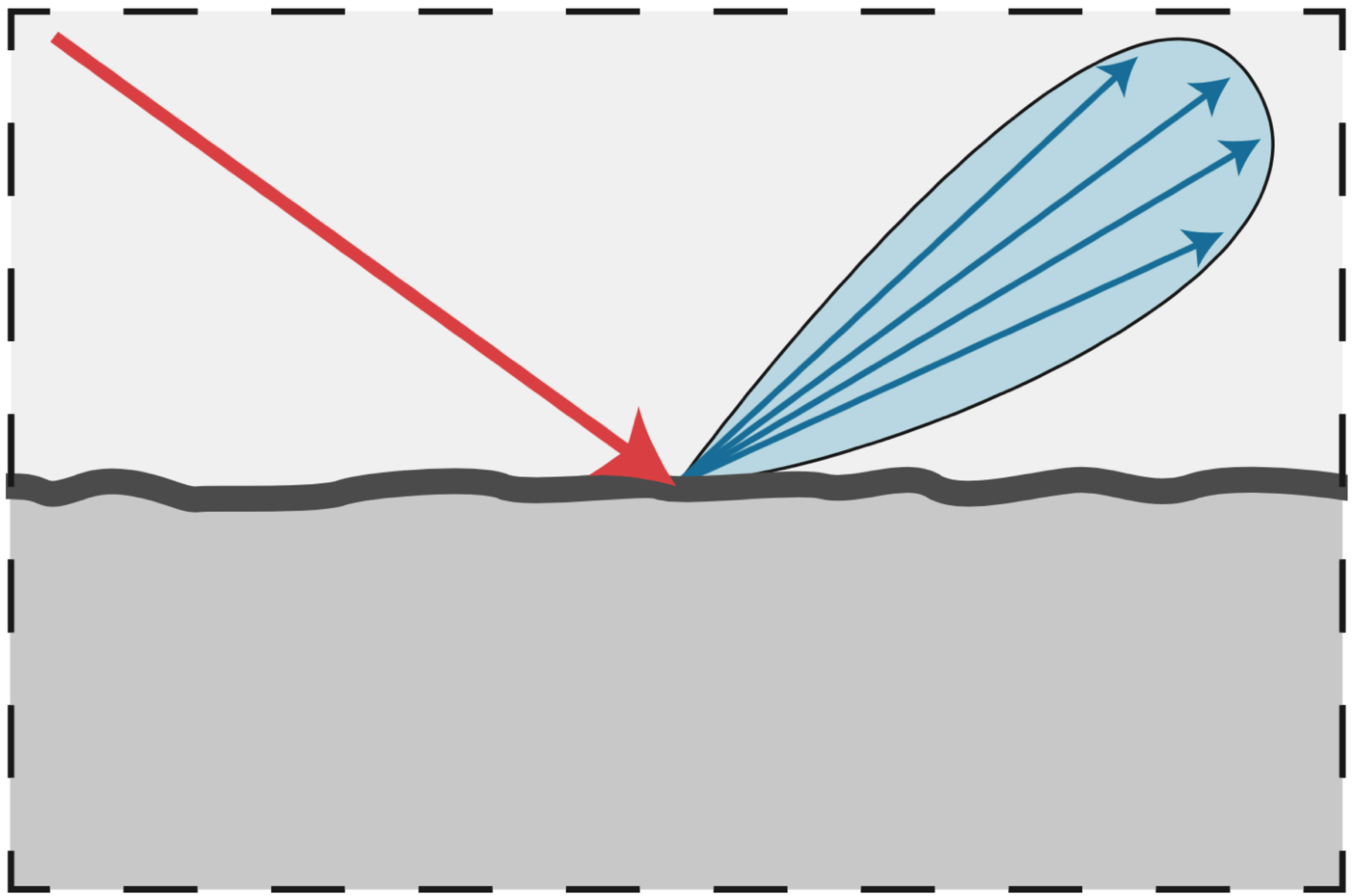
$$\begin{aligned} L_o(\omega_o) &= \int_{H^2} f_r L_i(\omega_i) \cos\theta_i \, \mathrm{d}\omega_i \\ &= f_r L_i \int_{H^2} \cancel{(\omega_i)} \cos\theta_i \, \mathrm{d}\omega_i \\ &= \pi f_r L_i \end{aligned}$$

L_o = L_i

定义一个反射率（albedo）ρ ∈ [0,1]与 fr 相乘，于是通过fr就可以控制材质的颜色变化

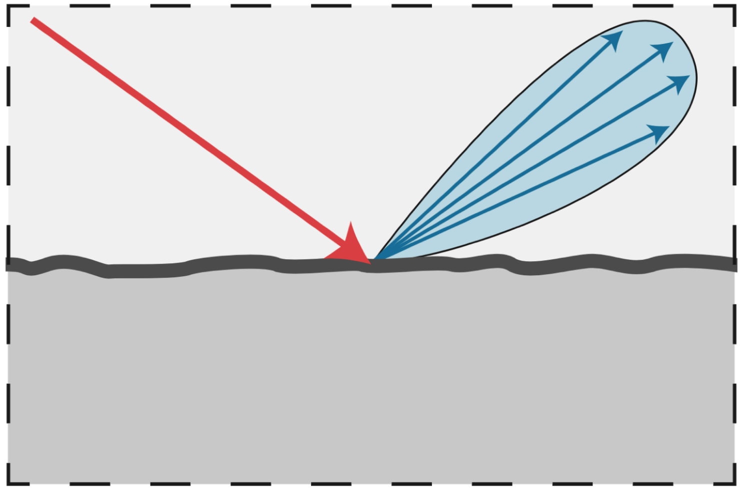
$$f_r = \frac{\rho}{\pi}$$ — albedo (color)

What is this material?

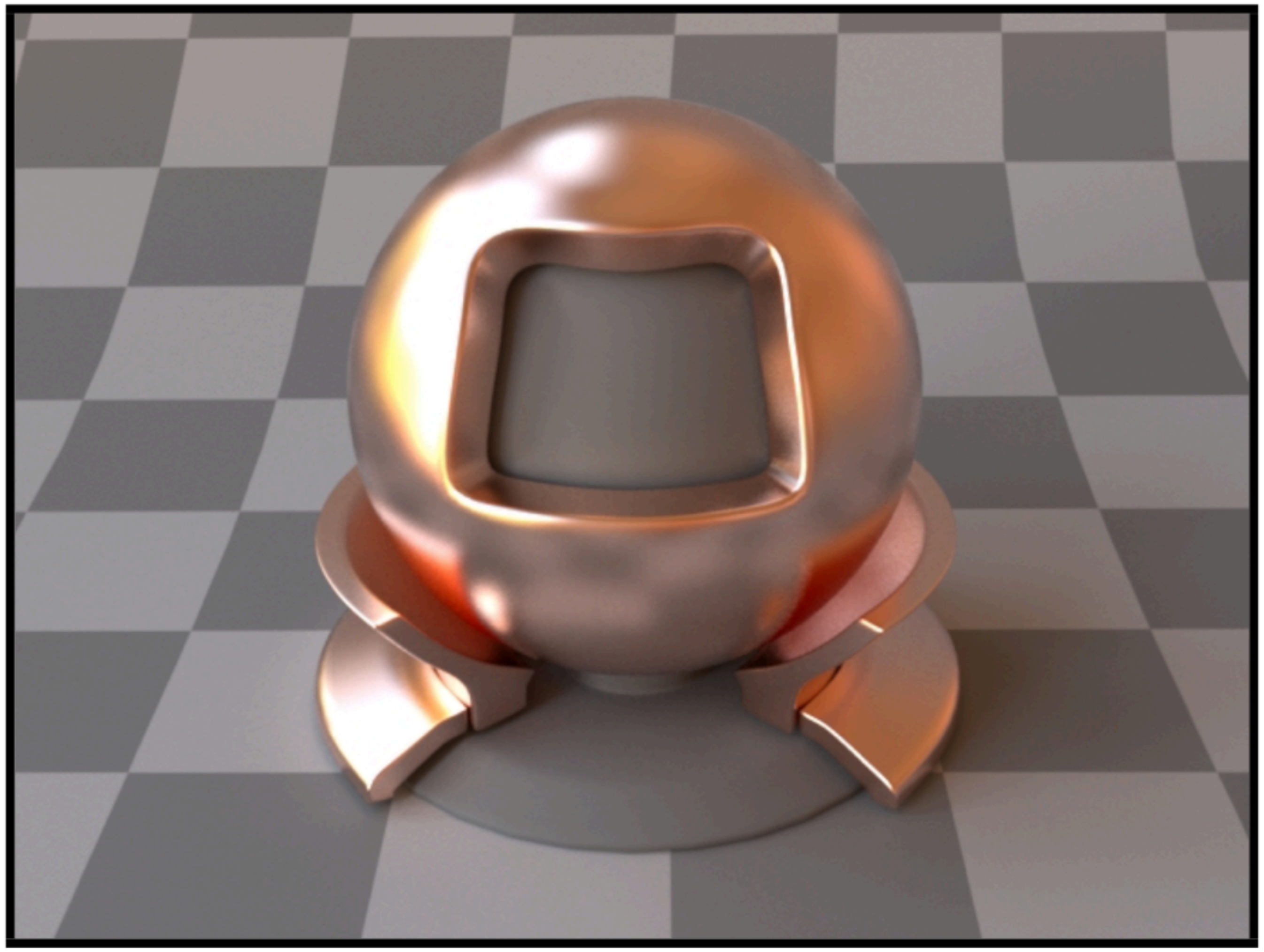


Glossy material (BRDF)

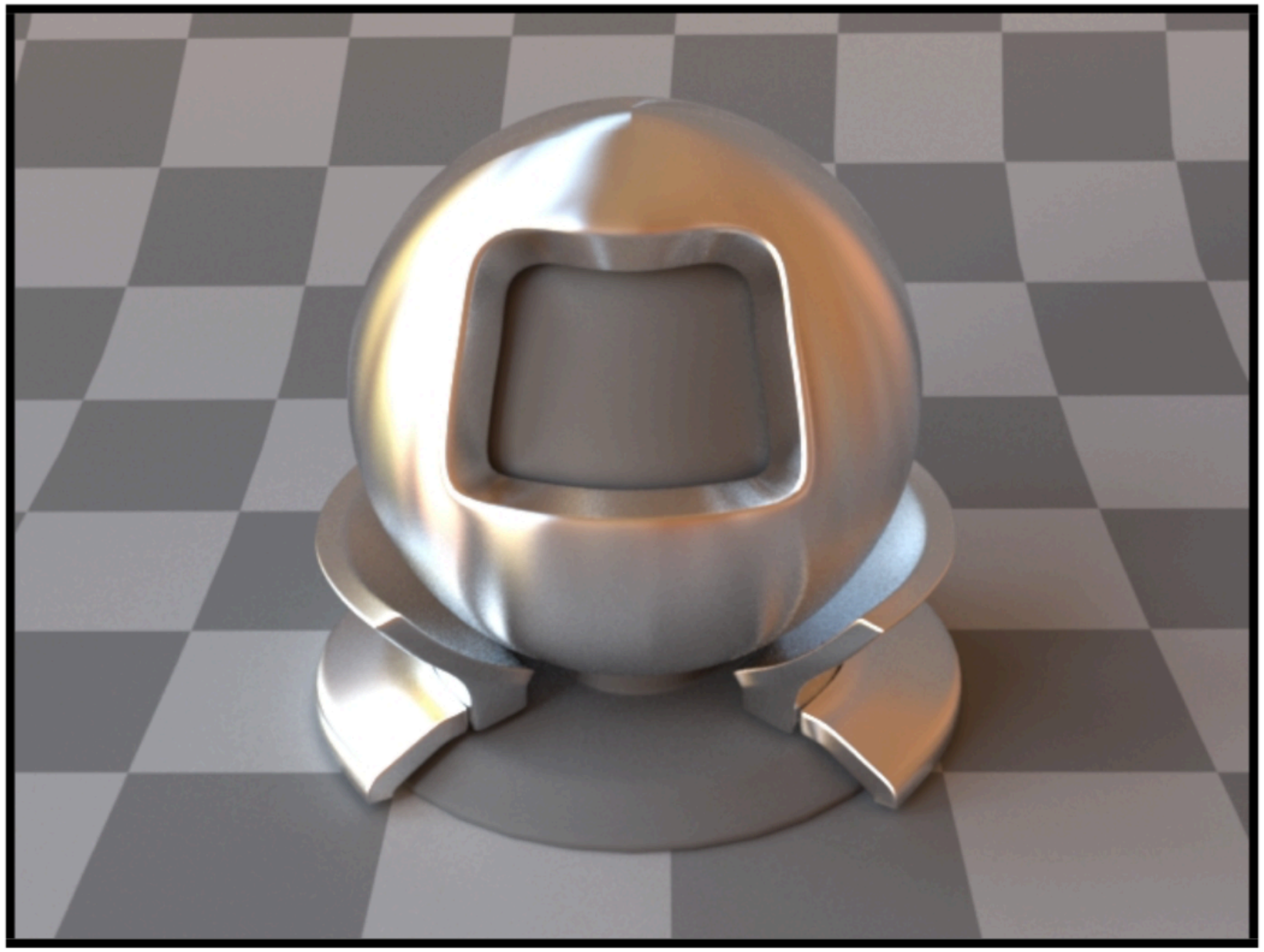
光泽材质是介于漫反射材质与理想镜面反射材质之间的一种材质，光线的反射方向集中在一个小范围内生活中的光泽材质有如打磨过的铜镜或者其他的一些金属材质



[Mitsuba renderer, Wenzel Jakob, 2010]

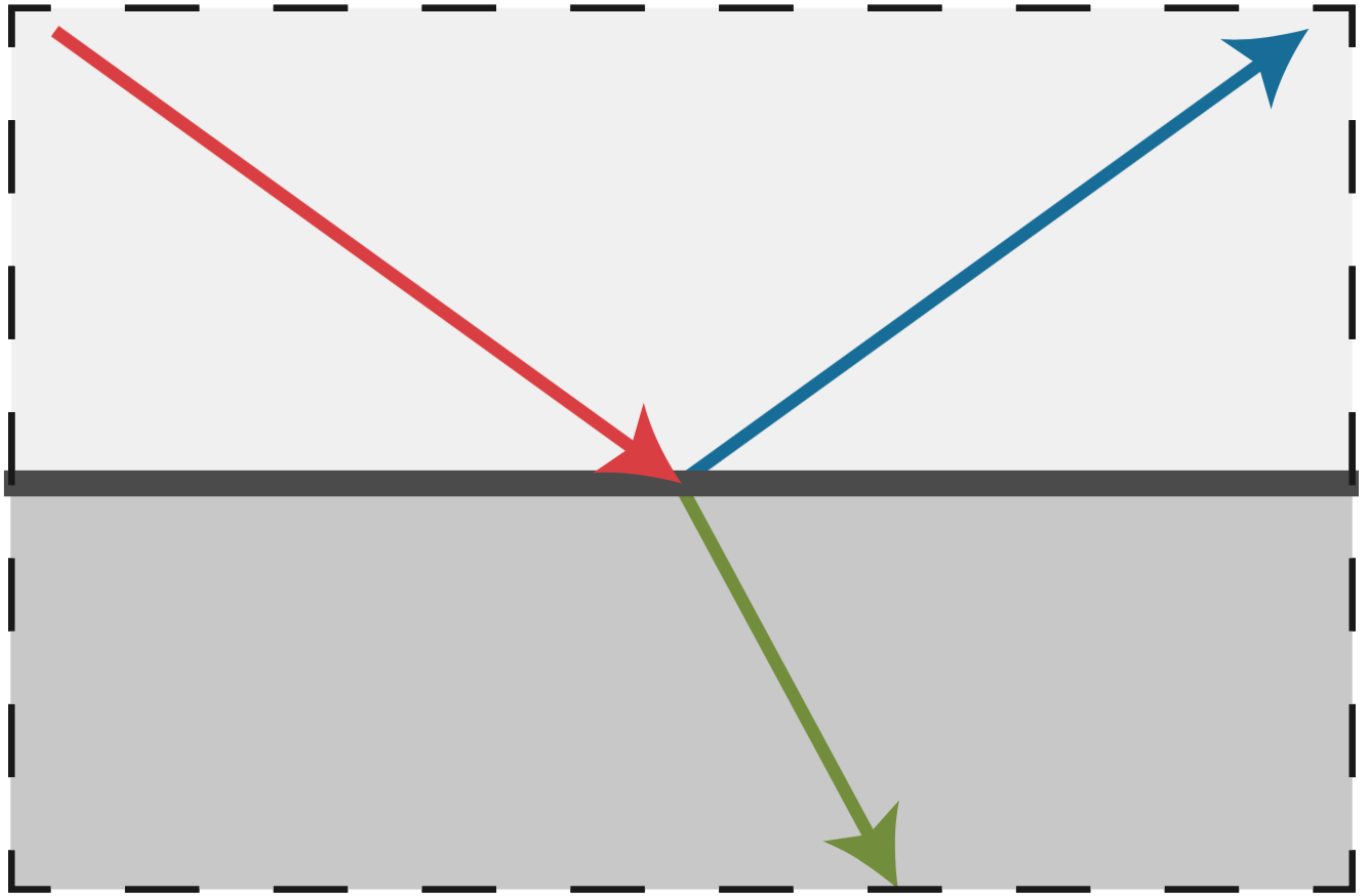


Copper



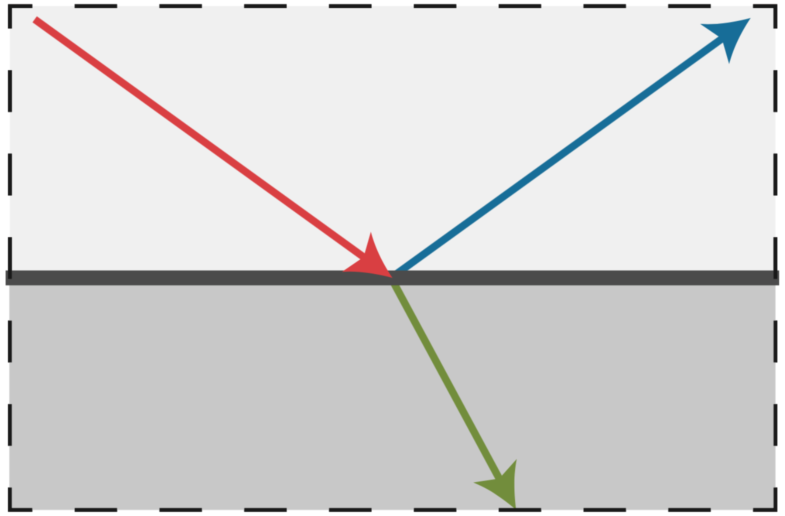
Aluminum

What is this material?

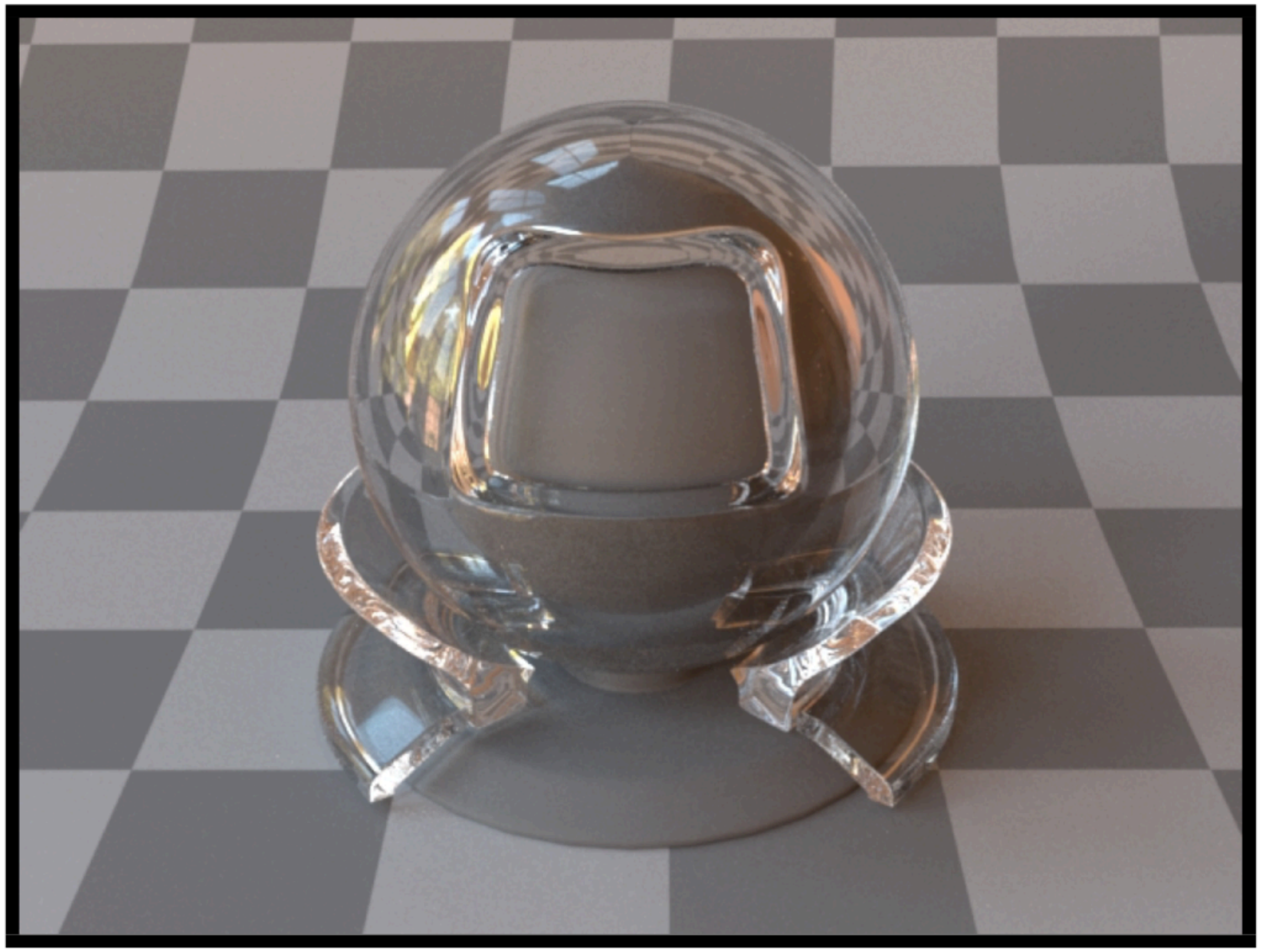


Ideal reflective / refractive material (BSDF*)

理想反射/折射材质

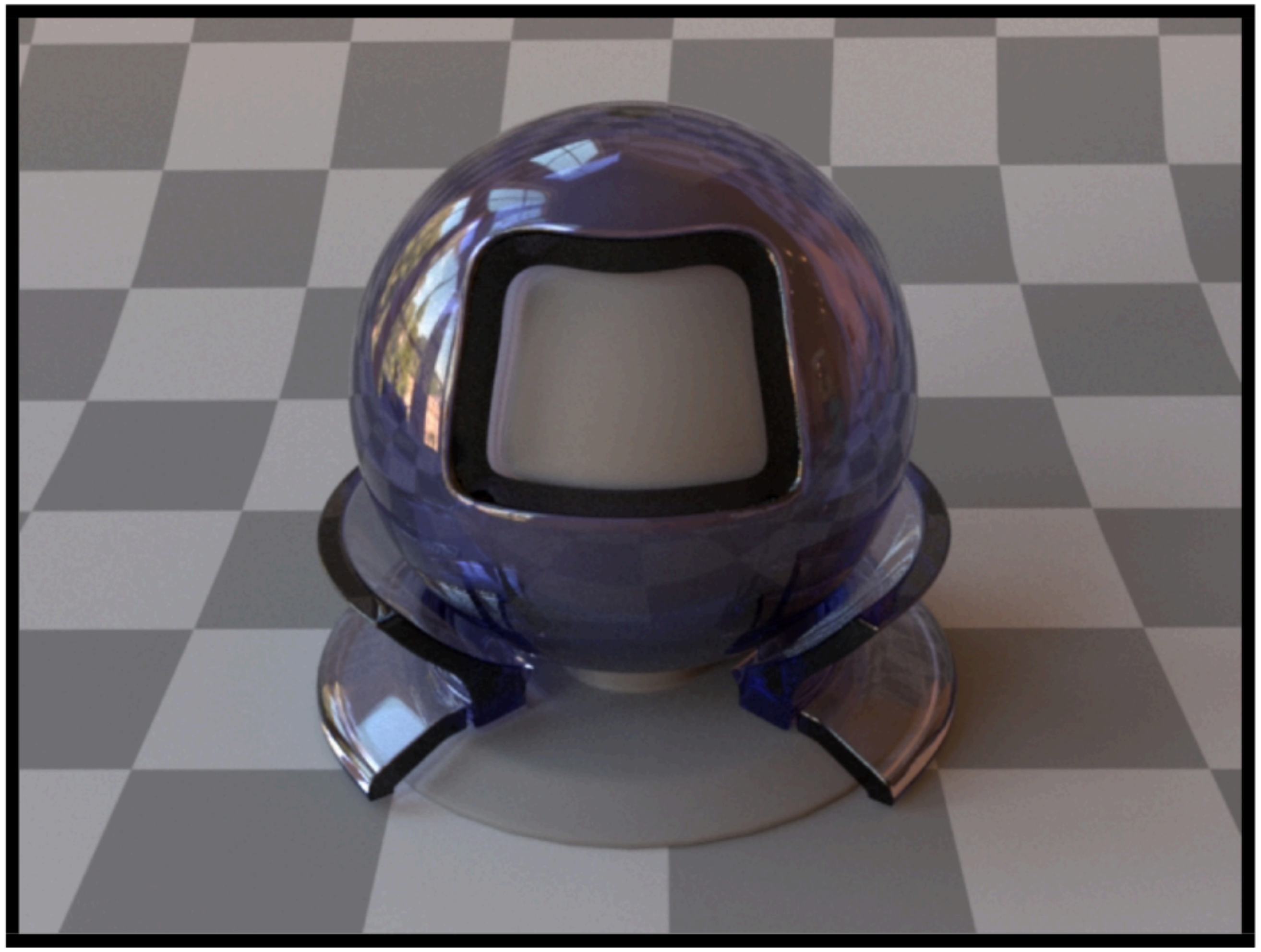


[Mitsuba renderer, Wenzel Jakob, 2010]



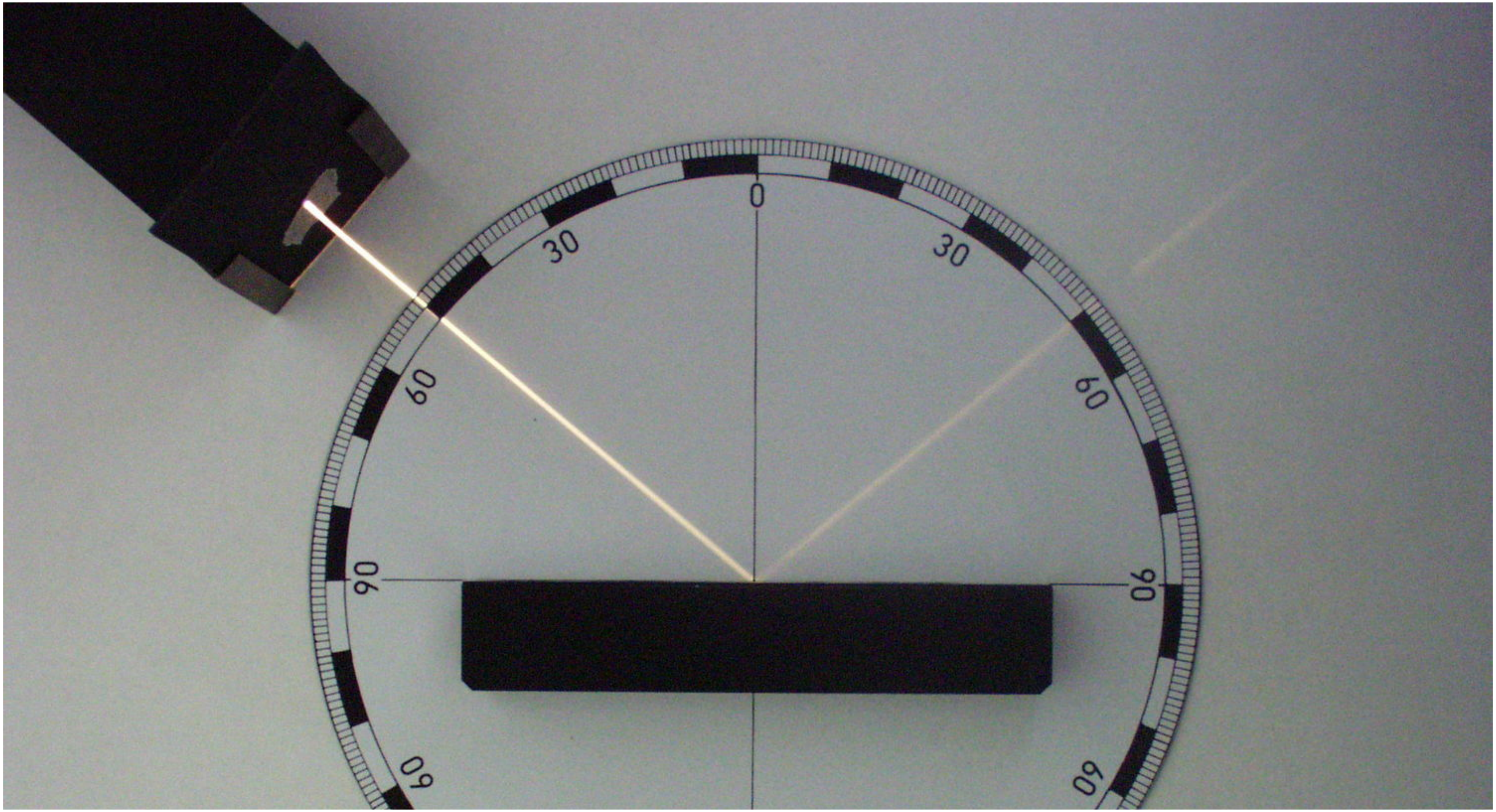
Air <-> water interface

光线到达材质表面被吸收一部分，同时发生镜面反射和镜面折射



Air <-> glass interface
(with absorption)

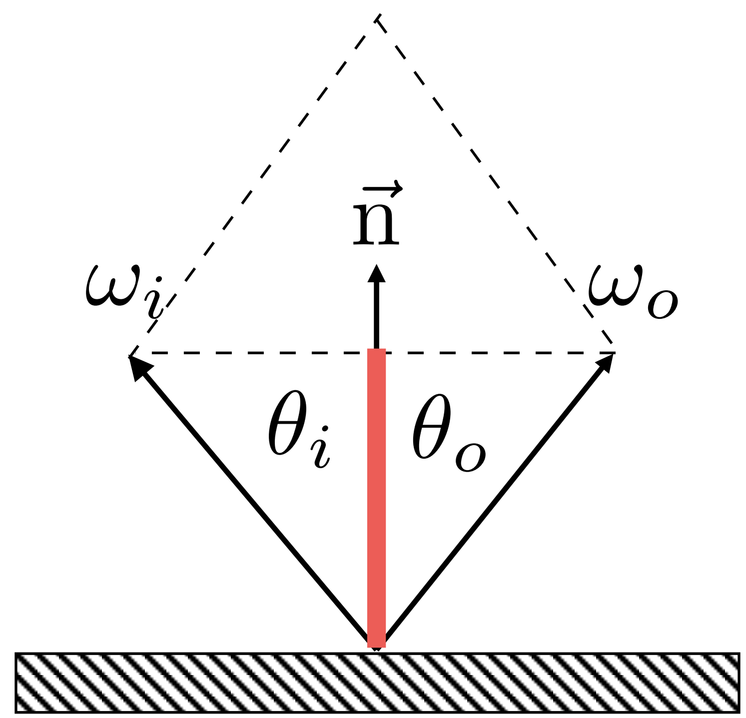
Perfect Specular Reflection



[Zátonyi Sándor]

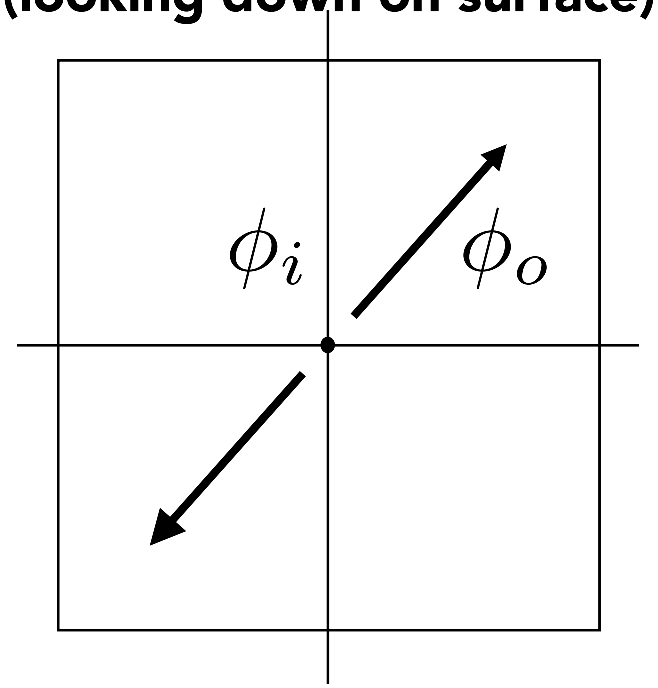
Perfect Specular Reflection

（完美）镜面反射



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

Top-down view
(looking down on surface)



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

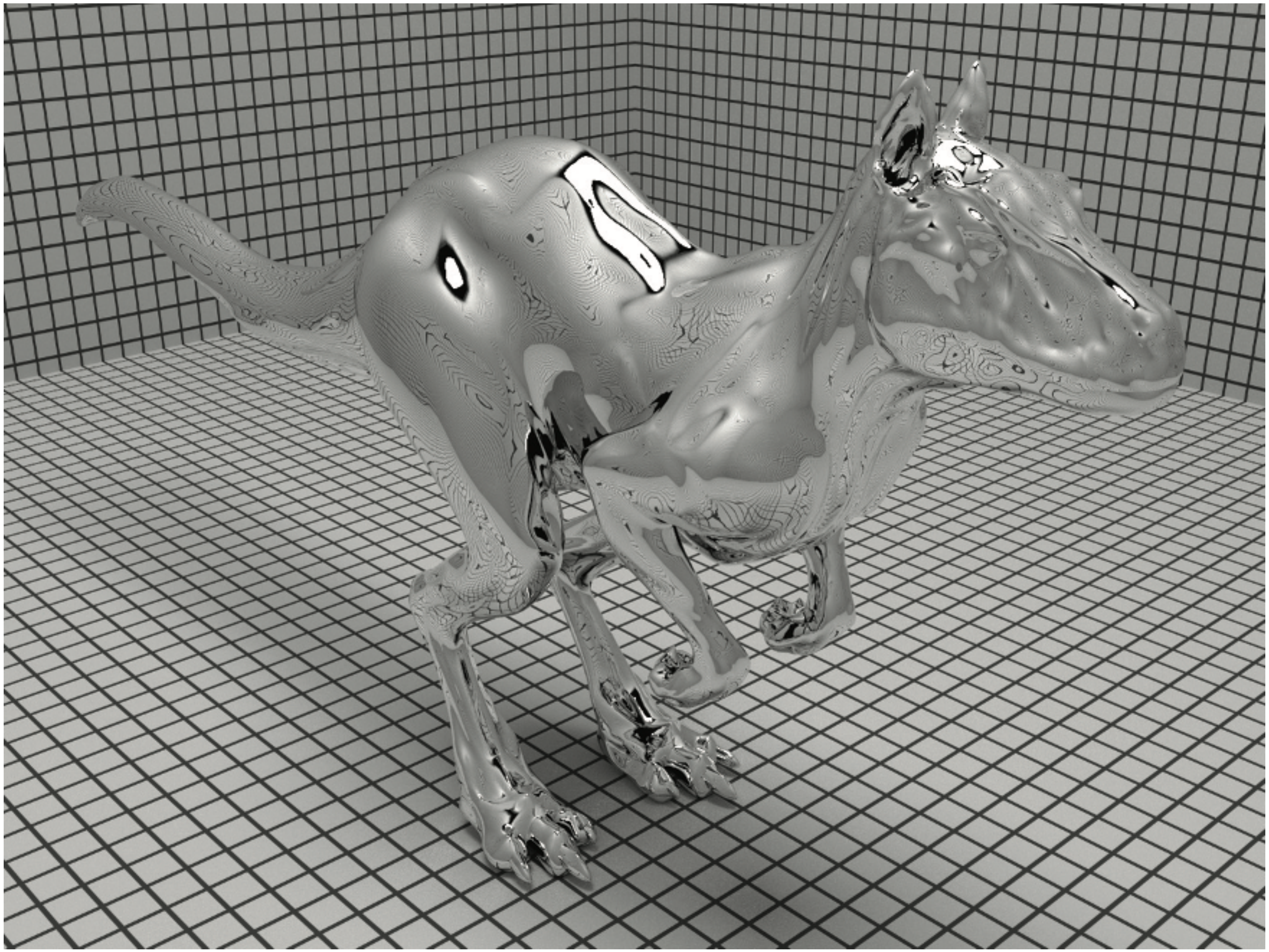
左图（正视图）观察入射角和出射角，右图（俯视图）观察方位角

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

写出正确的完美镜面反射BRDF方程需要用到δ函数

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

Perfect Specular Reflection BRDF



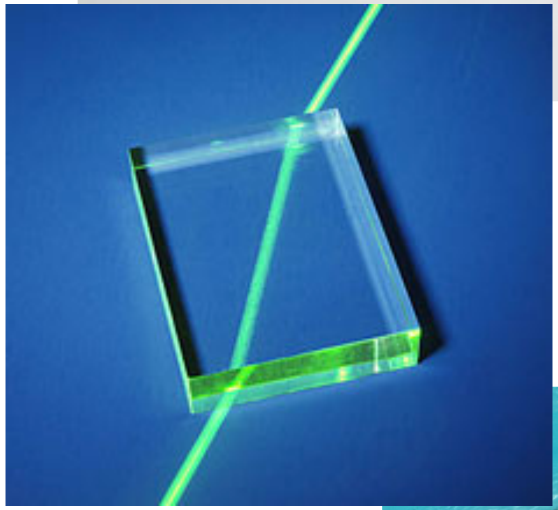
PBRT

Specular Refraction

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

Light refracts when it enters a new medium.

光从一种透明介质斜射入另一种透明介质时，由于光在两种介质中传播速度不同而使传播方向发生偏转的现象称为折射



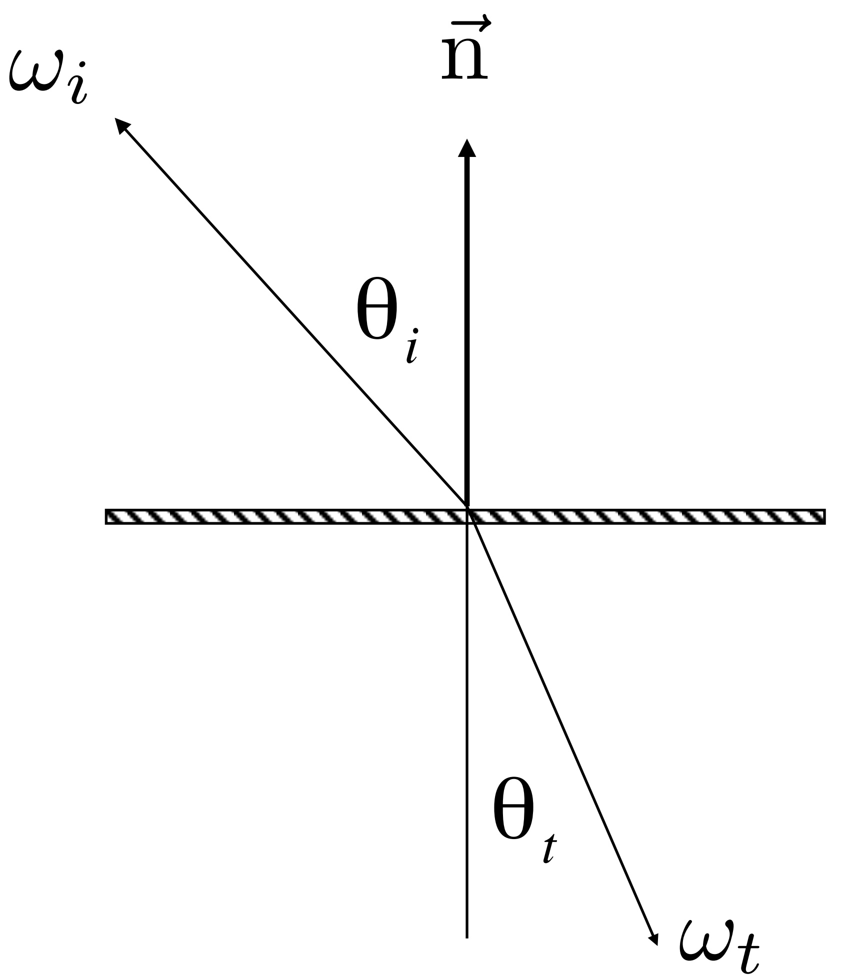
Snell's Law

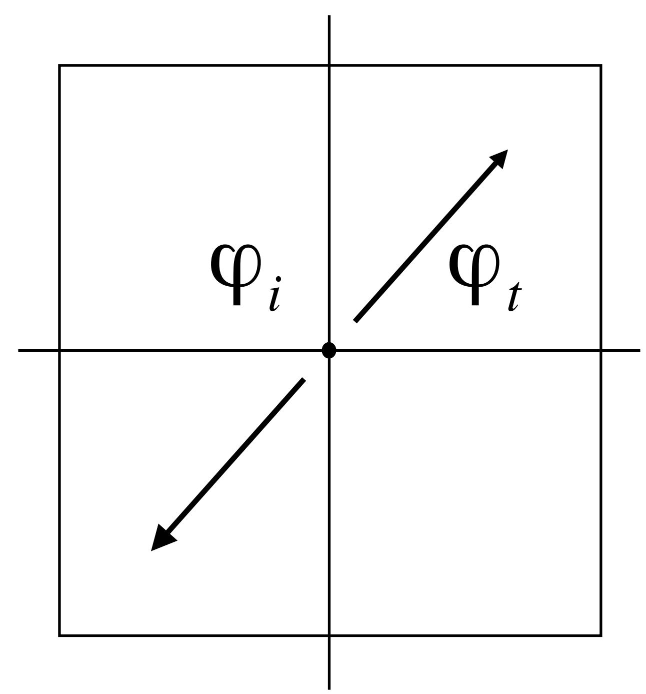
入射材质折射率 × 入射角正弦 = 出射材质折射率 × 折射角正弦

Transmitted angle depends on

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

由图侧常见折射率，钻石折射率较大，这就意味着光线通过钻石发生的偏转幅度比较大，这也是为什么钻石闪闪发光的原因





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

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

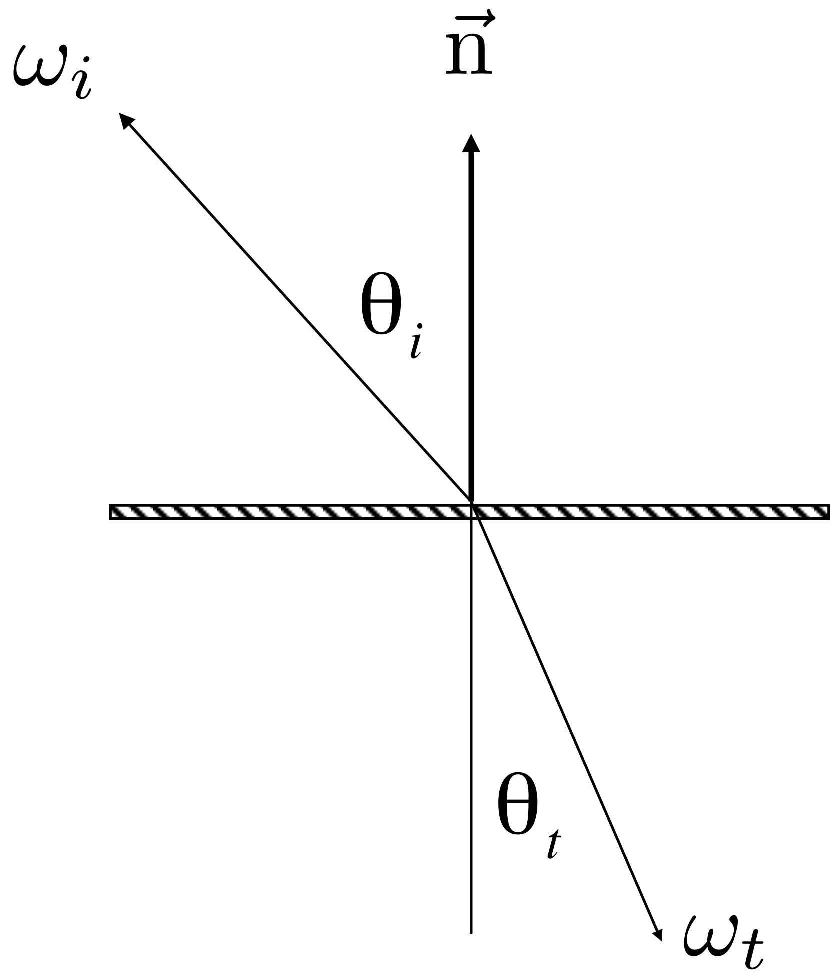
Medium	η*
Vacuum	1.0
Air (sea level)	1.00029
Water (20°C)	1.333
Glass	1.5-1.6
Diamond	2.42

* index of refraction is wavelength dependent (these are averages)

Law of Refraction

折射的发生条件是入射材质的折射率小于出射材质折射率，一旦大于，就会发生全反射现象

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



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

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

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

Total internal reflection:

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

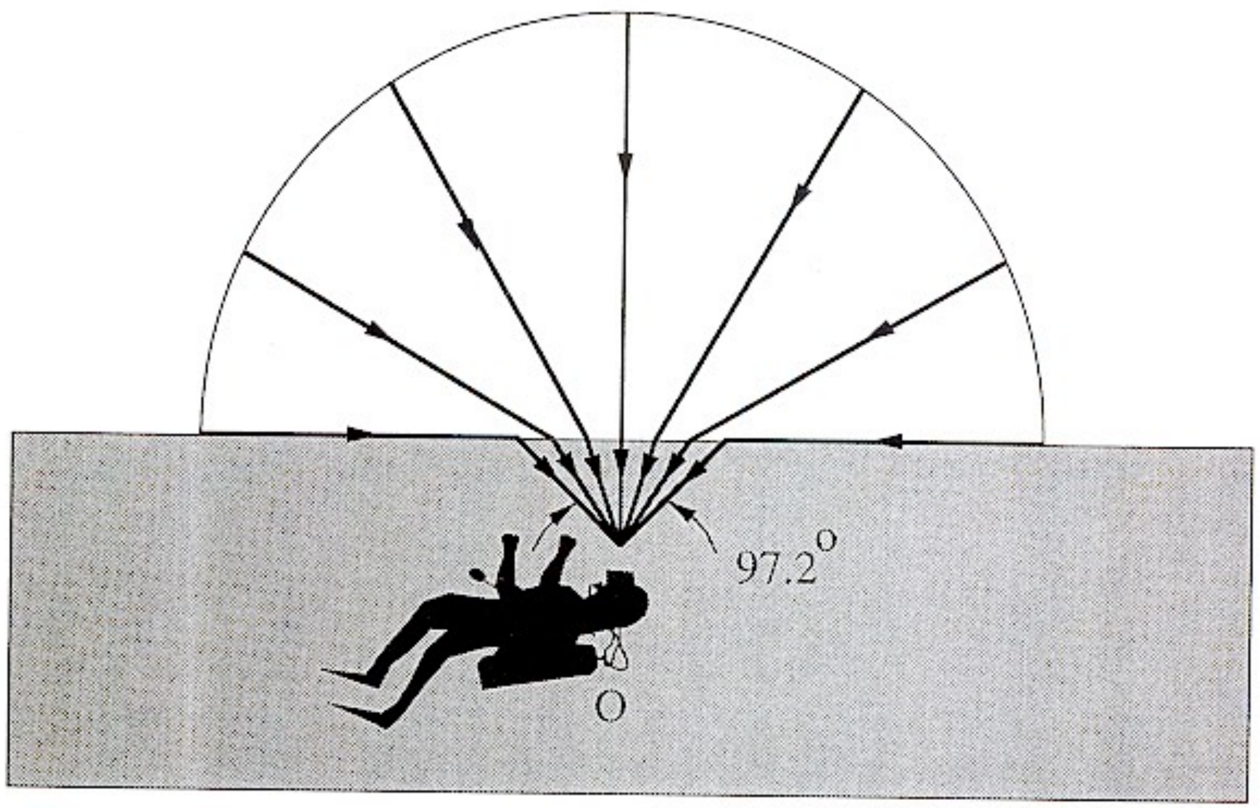
When light is moving from a more optically dense medium to a less optically dense medium: $\frac{\eta_i}{\eta_t} > 1$

Light incident on boundary from large enough angle will not exit medium.

Snell’s Window / Circle

人在水底只能看到锥形视野范围内的光，也是因为折射，相关现象被称为斯涅耳耳窗

Total internal reflection



[Livingston and Lynch]

Fresnel Reflection / Term

(菲涅耳项)

Reflectance depends on incident angle (and polarization of light)

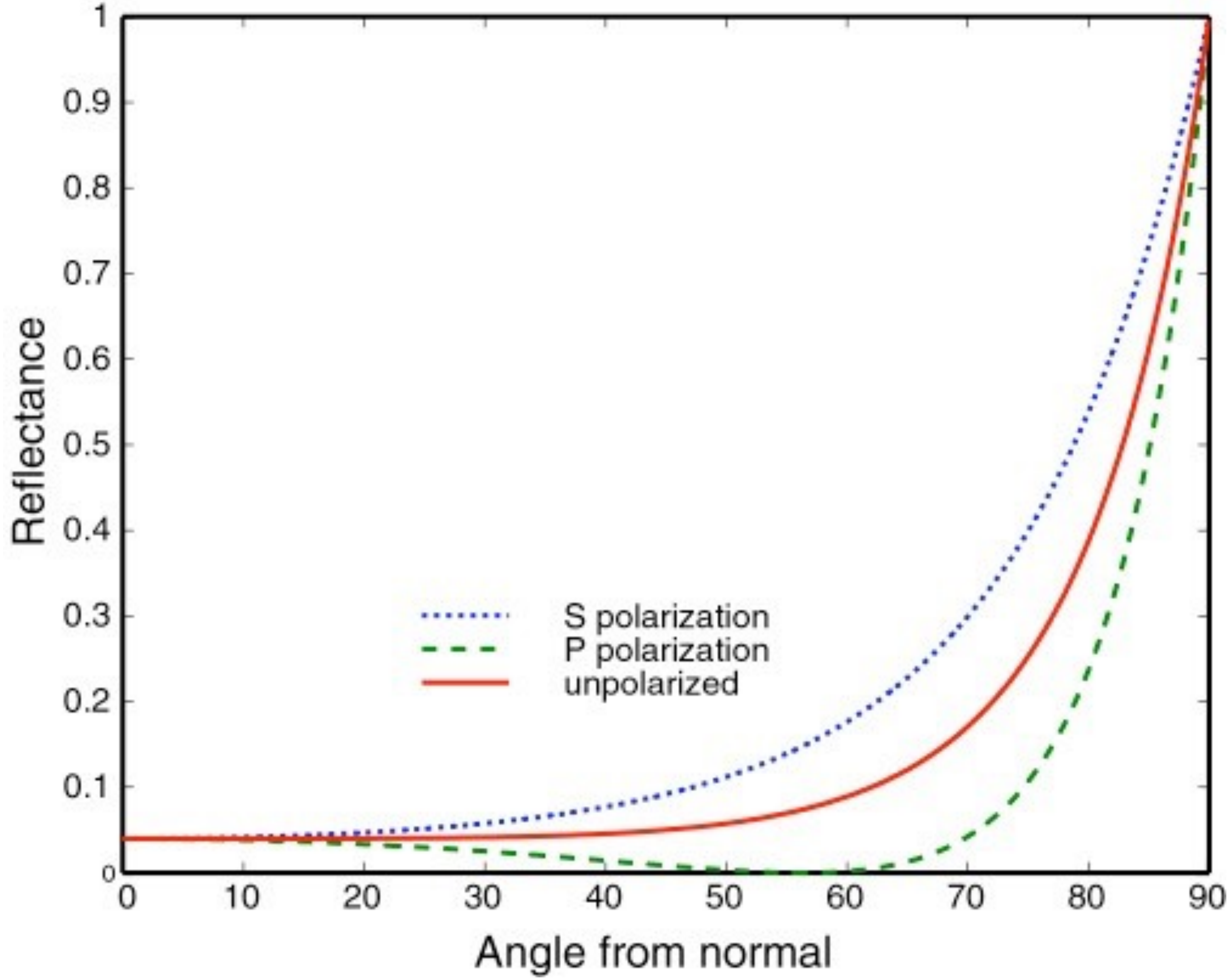
This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

当我们用几乎垂直的视角看下去，基本看不到什么反射，而当我们的视角几乎水平时，反射结果特别明显

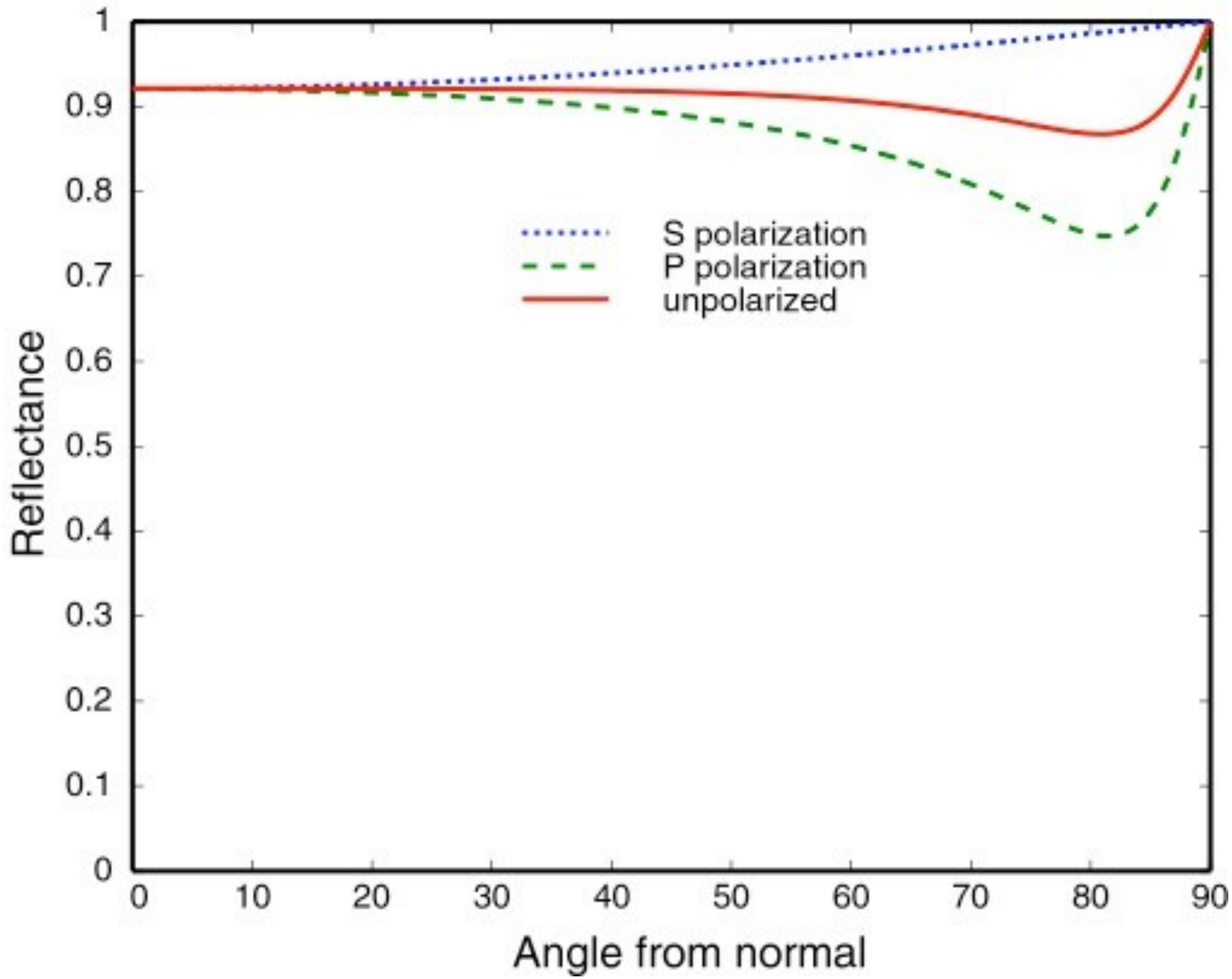
Fresnel Term (Dielectric, $\eta = 1.5$)

另外两条虚线表示光的极化性质，即光只沿一个方向振动情况下的菲涅尔项，现在的渲染器很少考虑这种情况



Fresnel Term (Conductor)

金属的反射率一直都很高，所以我们习惯用镀银的玻璃作为镜子而不是用玻璃



Fresnel Term — Formulae

为了计算菲涅尔项，有非常复杂的公式，通过极化的菲涅尔数据做平均得到结果

Accurate: need to consider polarization

$$R_{\mathrm{s}} = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \cos\theta_{\mathrm{t}}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \cos\theta_{\mathrm{t}}} \right|^2 = \left| \frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}}{n_1 \cos\theta_{\mathrm{i}} + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2}} \right|^2,$$

$$R_{\mathrm{p}} = \left| \frac{n_1 \cos\theta_{\mathrm{t}} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \cos\theta_{\mathrm{t}} + n_2 \cos\theta_{\mathrm{i}}} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} - n_2 \cos\theta_{\mathrm{i}}}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_{\mathrm{i}}\right)^2} + n_2 \cos\theta_{\mathrm{i}}} \right|^2.$$

$$R_{\mathrm{eff}} = \frac{1}{2}\left(R_{\mathrm{s}} + R_{\mathrm{p}}\right).$$

Approximate: Schlick's approximation

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos\theta)^5$$

$$R_0 = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

Microfacet Material

微表面模型

Microfacet Material: Motivation

从理论上来说，地球表面是凹凸不平的，具有沙漠山丘等复杂地形，但在非常远的距离下拍摄，如下图所示的卫星图，我们却看到了如同在光滑球面上一样的高光

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

Microfacet Theory

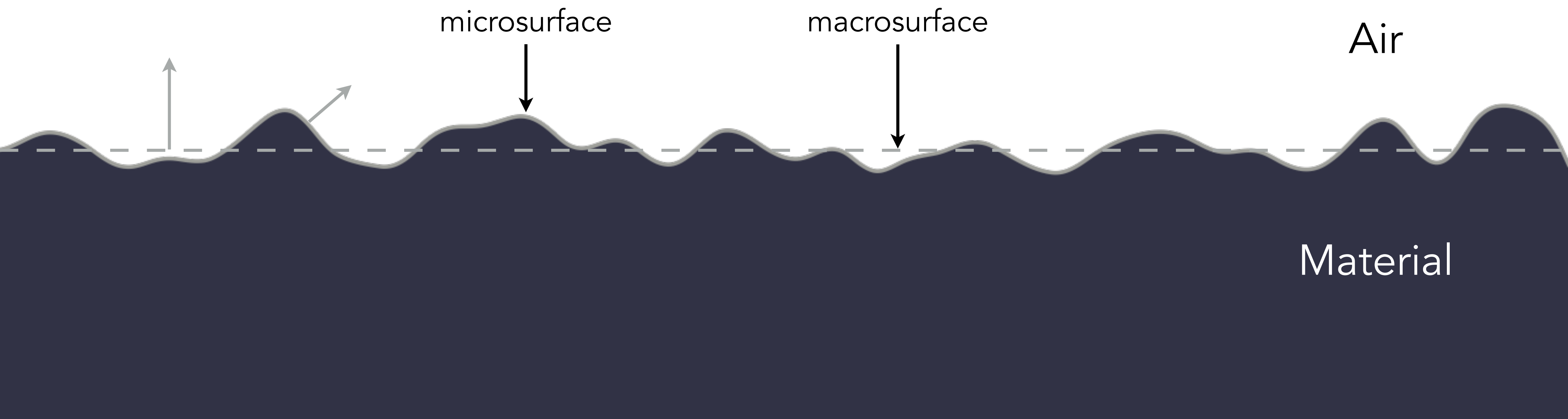
由此我们提出微表面模型，假设离得足够远的时候，微观表面可以被忽略，而最后看到一个宏观的结果，用微表面理论解释漫反射，即从微观看漫反射表面，每个微元表面都是完美镜面反射，都有各自的法线（微观上看是几何），我们可以通过研究这些法线的分布来描述物体表面的粗糙程度

Rough surface

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

Individual elements of surface act like mirrors

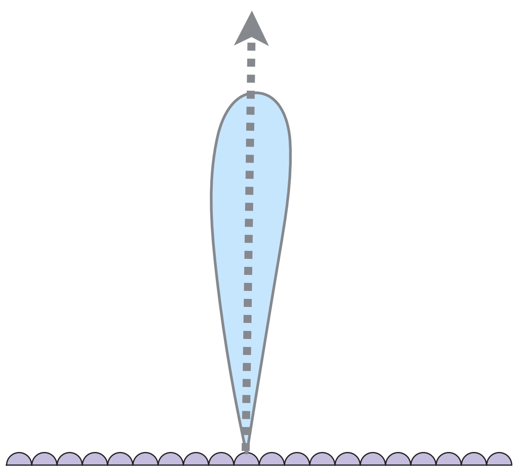
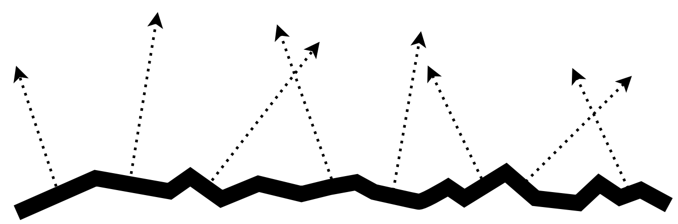
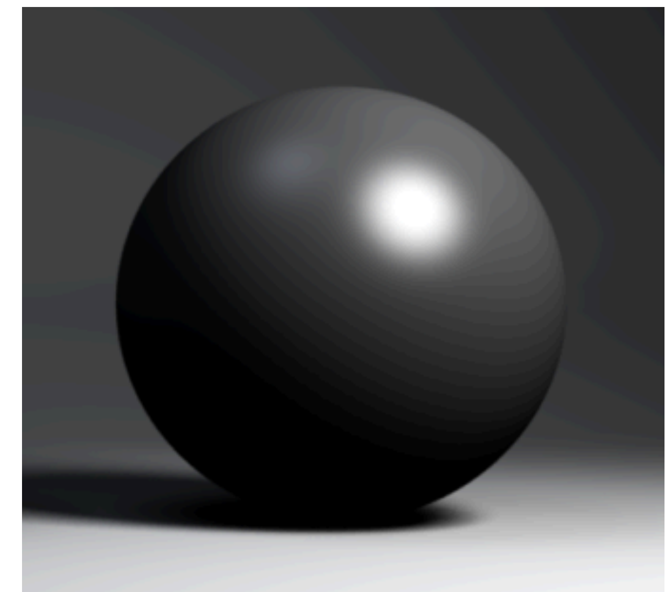
- Known as Microfacets
- Each microfacet has its own normal



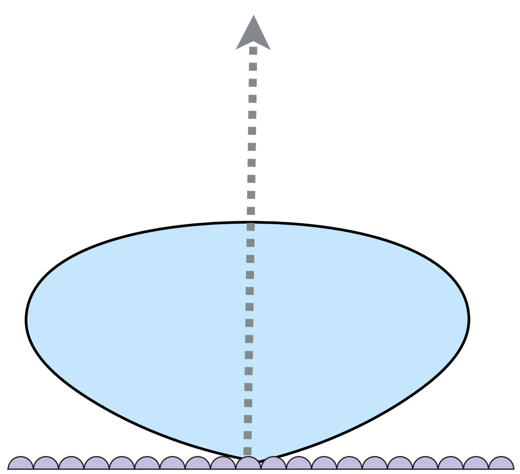
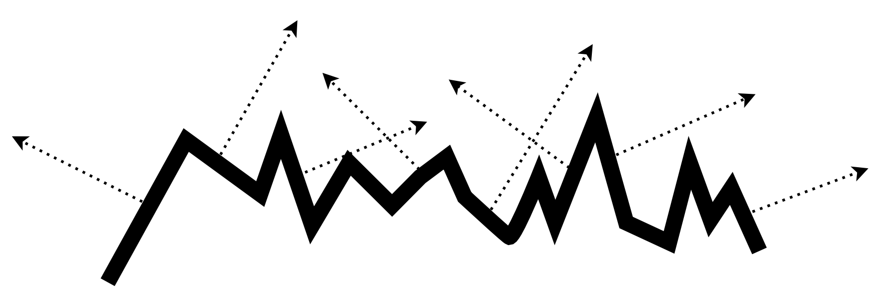
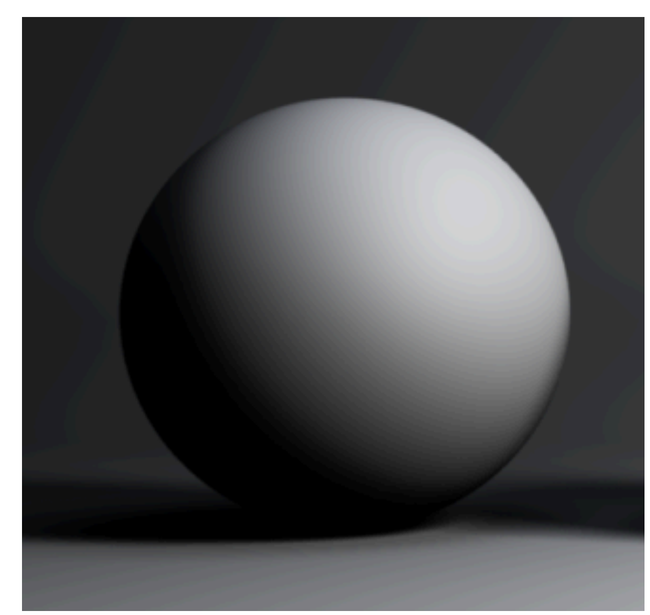
Microfacet BRDF

镜面反射的法线方向分布比较集中，而漫反射表面的法线分布比较分散

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

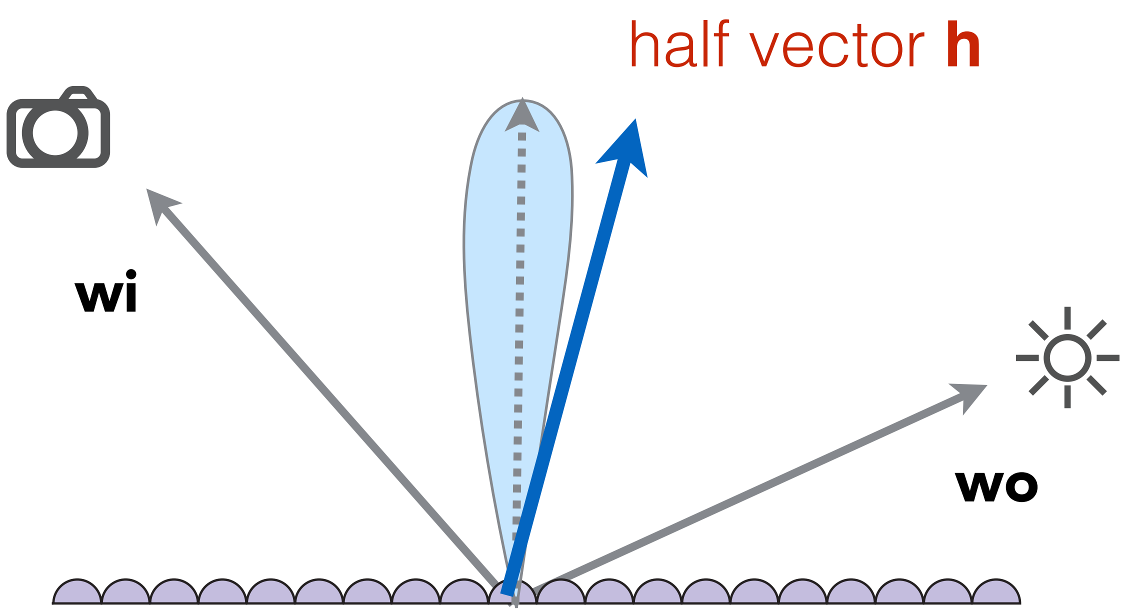
  - Spread <==> diffuse

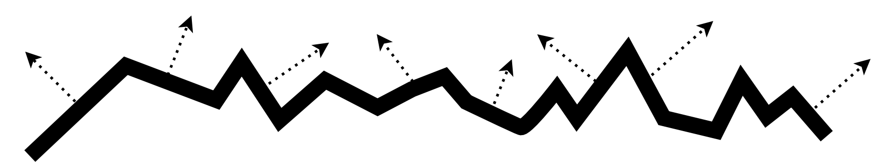




Microfacet BRDF

如图，F为菲涅尔项；D为法线分布，查询半程向量是否在法线分布内；G为几何项，由于在微表面上，对于那些几乎和表面平行的入射光，很容易发生互相遮挡的现象，从而使得部分微表面失去作用，我们把这种光线角度称为掠射角度（Grazing Angle），在这种角度下的着色会非常亮，G项就起到了一定的修正作用

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





Fresnel term

shadowing-masking term

distribution of normals

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

Microfacet BRDF: Examples

[Autodesk Fusion 360]

Isotropic / Anisotropic Materials (BRDFs)

各向同性/各向异性材质

各向同性（IsotropicMaterials）：微表面不存在方向性
各向异性（Anisotropic Materials）：微表面存在方向

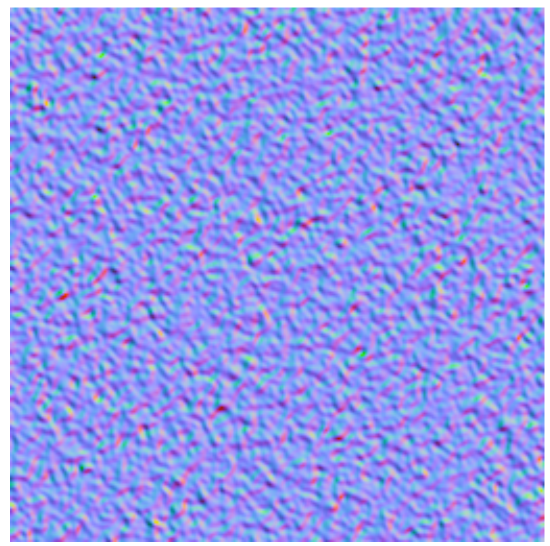
Inside an elevator

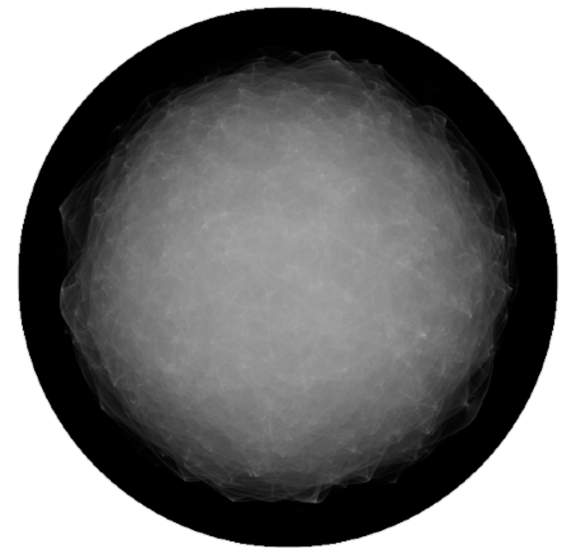
Slide courtesy of Prof. Ren Ng, UC Berkeley

Isotropic / Anisotropic Materials (BRDFs)

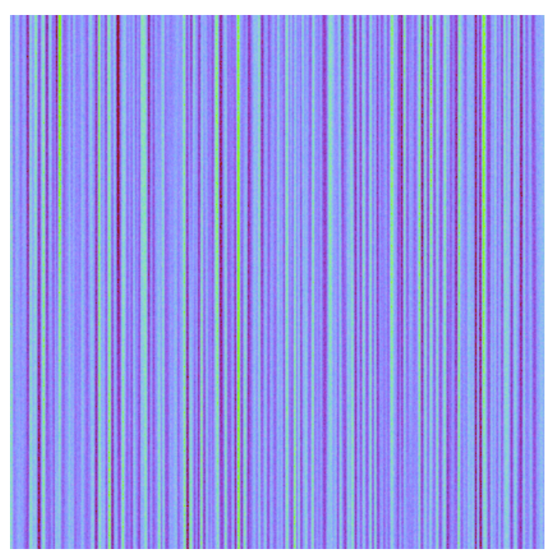
- Key: directionality of underlying surface

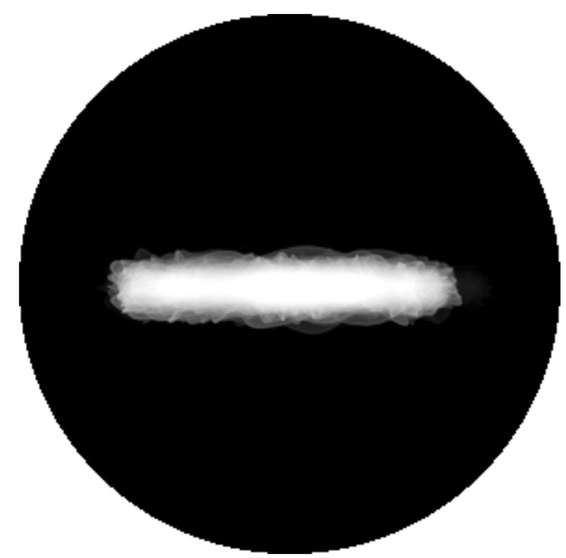
Isotropic





Anisotropic





Surface (normals)

BRDF (fix wi, vary wo)

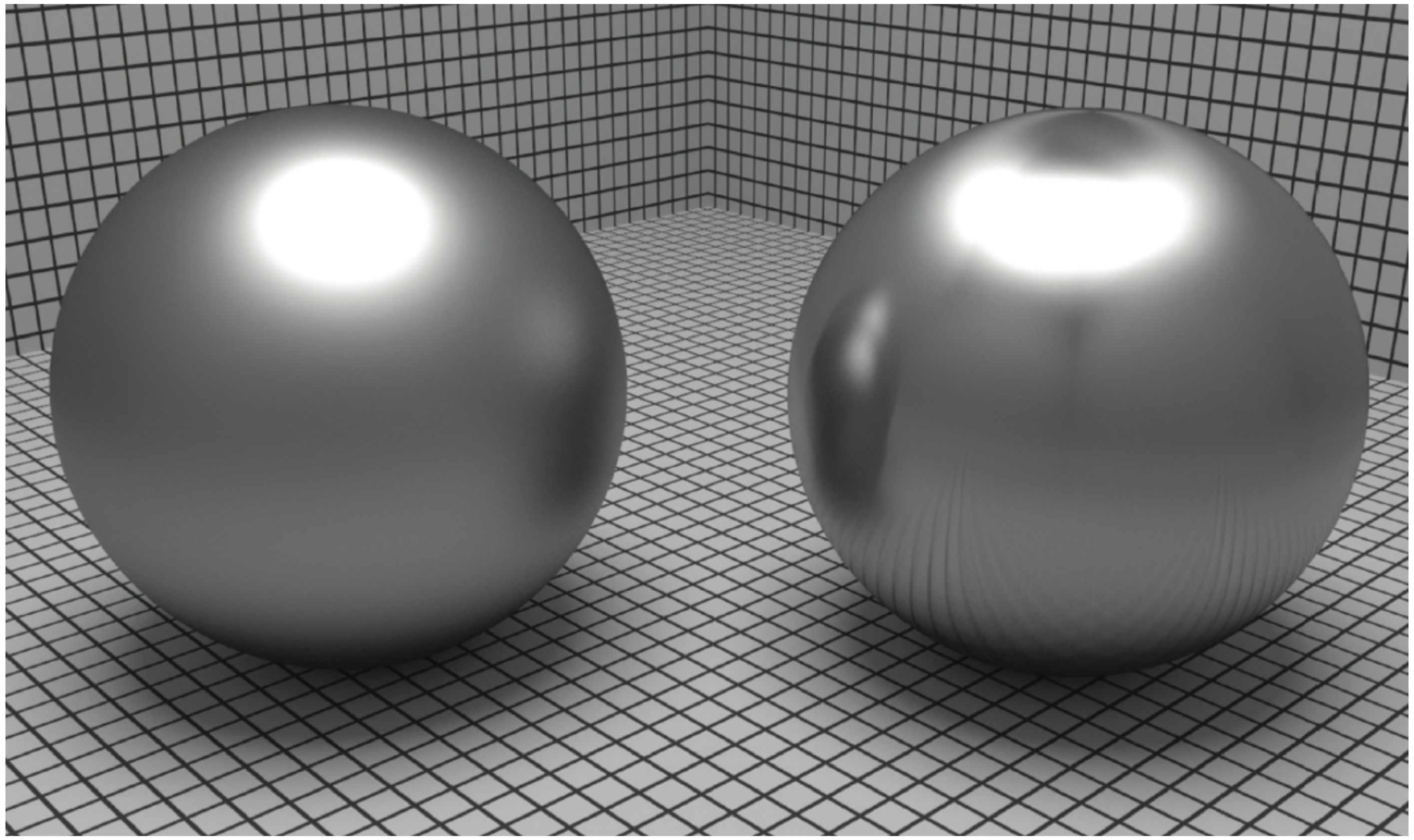
Anisotropic BRDFs

对于BRDF来说，这里所说的方向性就是指，如果入射光和出射光做一定方位角的旋转前后，BRDF方程不变，那么这种材质就是各向同性的，反之则为各向异性

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



Anisotropic BRDF: Brushed Metal

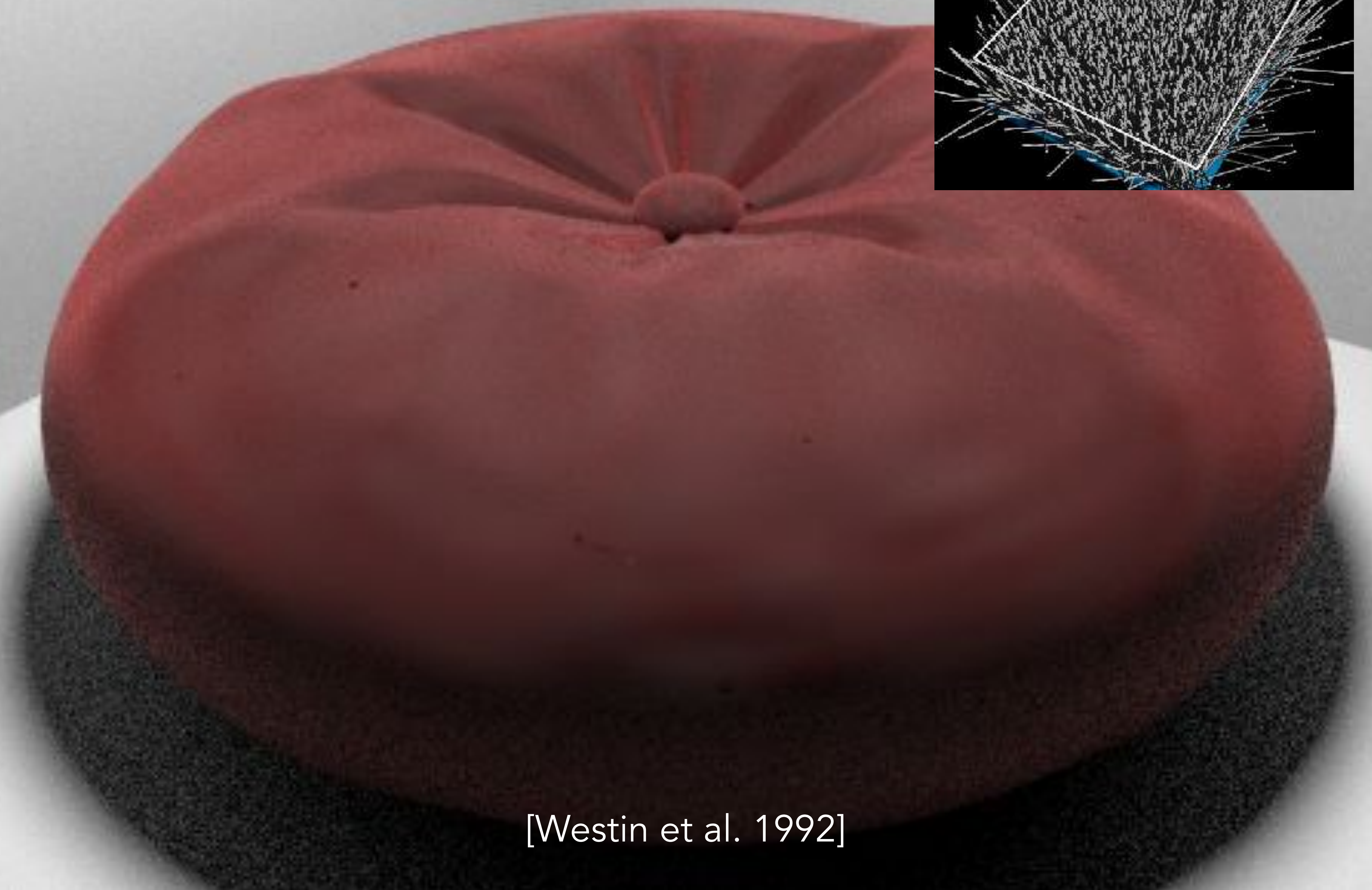
- How is the pan brushed?

[VRay renderer]

Anisotropic BRDF: Nylon

[Westin et al. 1992]

Anisotropic BRDF: Velvet



[Westin et al. 1992]

Anisotropic BRDF: Velvet

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

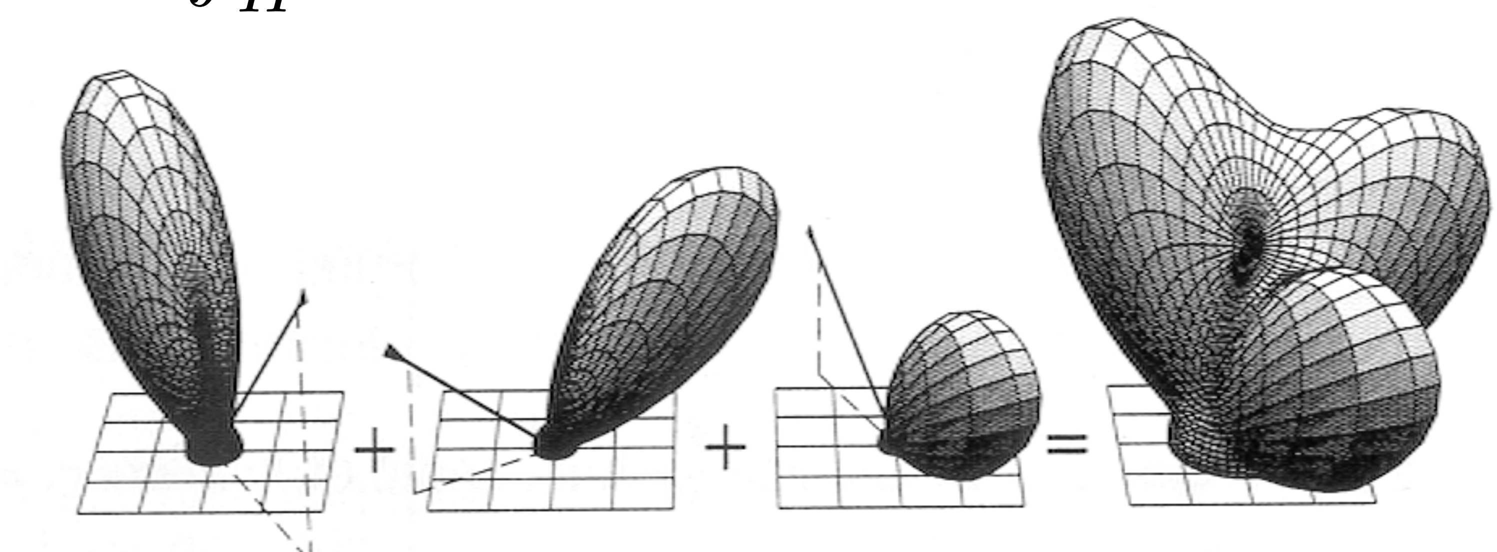
Properties of BRDFs

- Non-negativity
  - 非负性：描述能量分布

$$f_r(\omega_i \to \omega_r) \geq 0$$

- Linearity
  - 线性性：可以被拆分成不同项的线性组合（ambient，diffuse，specular）

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

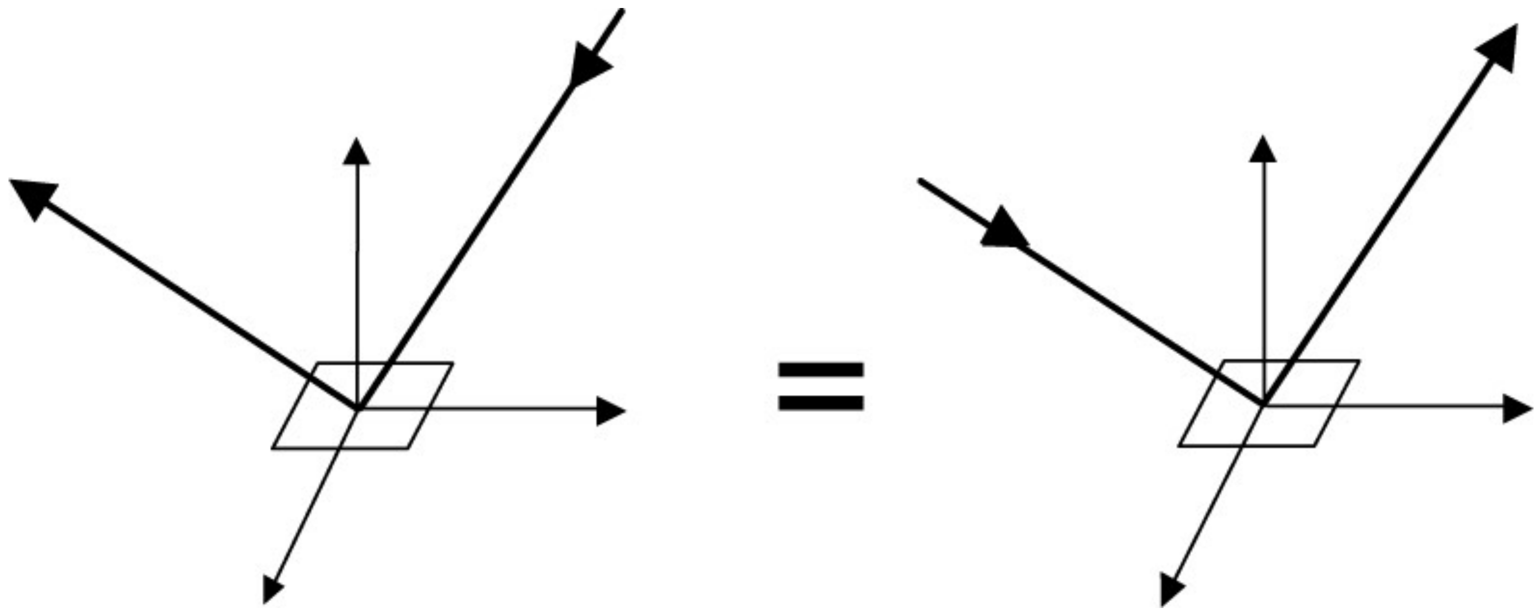


[Sillion et al. 1990]

Properties of BRDFs

- Reciprocity principle
  - 可逆性：调换入射出射方向，BRDF渲染结果严格不变

$$f_r(\omega_r \to \omega_i) = f_r(\omega_i \to \omega_r)$$



- Energy conservation
  - 能量守恒：出射光线的能量永远不能超过入射光线的能量

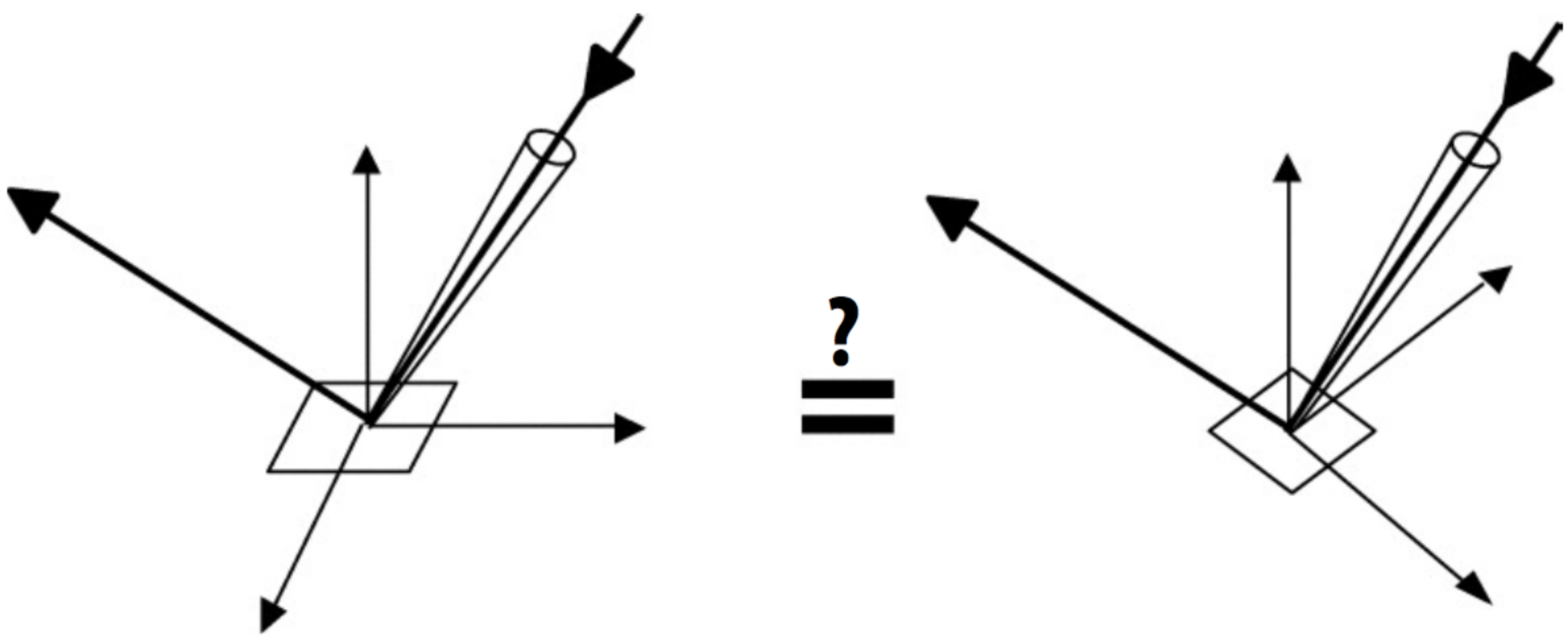
$$\forall \omega_r \int_{H^2} f_r(\omega_i \to \omega_r) \cos\theta_i \, \mathrm{d}\omega_i \leq 1$$

Properties of BRDFs

各向同/异性：如果是各项同性材质，则BRDF值只和相对方位角有关，四维的BRDF材质可以被降维为三维，
并且根据可逆性，结果不需要考虑方位角的正负

- Isotropic vs. anisotropic
  - If isotropic, $f_r(\theta_i, \phi_i; \theta_r, \phi_r) = f_r(\theta_i, \theta_r, \phi_r - \phi_i)$
  - Then, from reciprocity,

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



Measuring BRDFs

Measuring BRDFs: Motivation

如图，推算出来的菲涅尔项和实际测量出来的往往会有很大差距，更不用说BRDF了

Avoid need to develop / derive models

- Automatically includes all of the scattering effects present

Can accurately render with real-world materials

- Useful for product design, special effects, ...

Theory vs. practice:

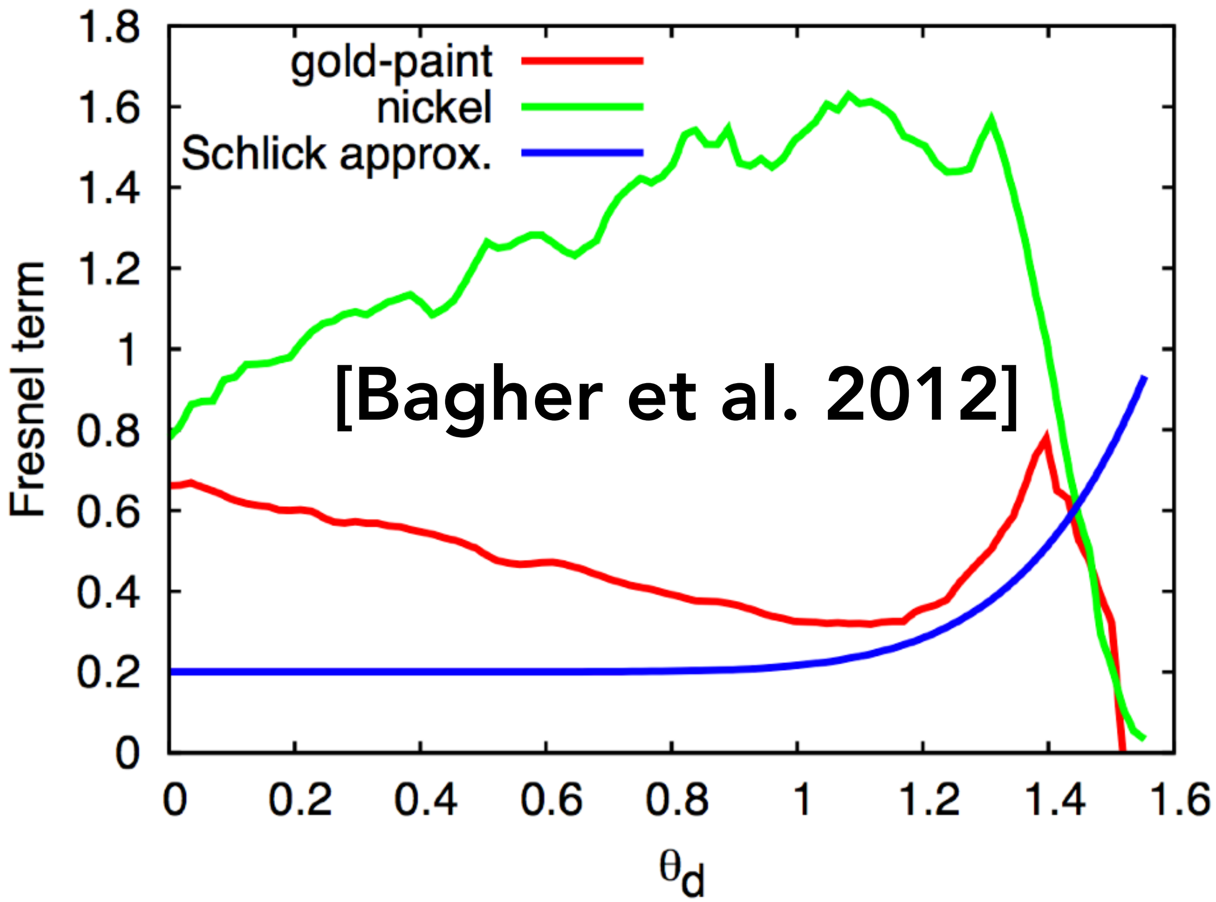
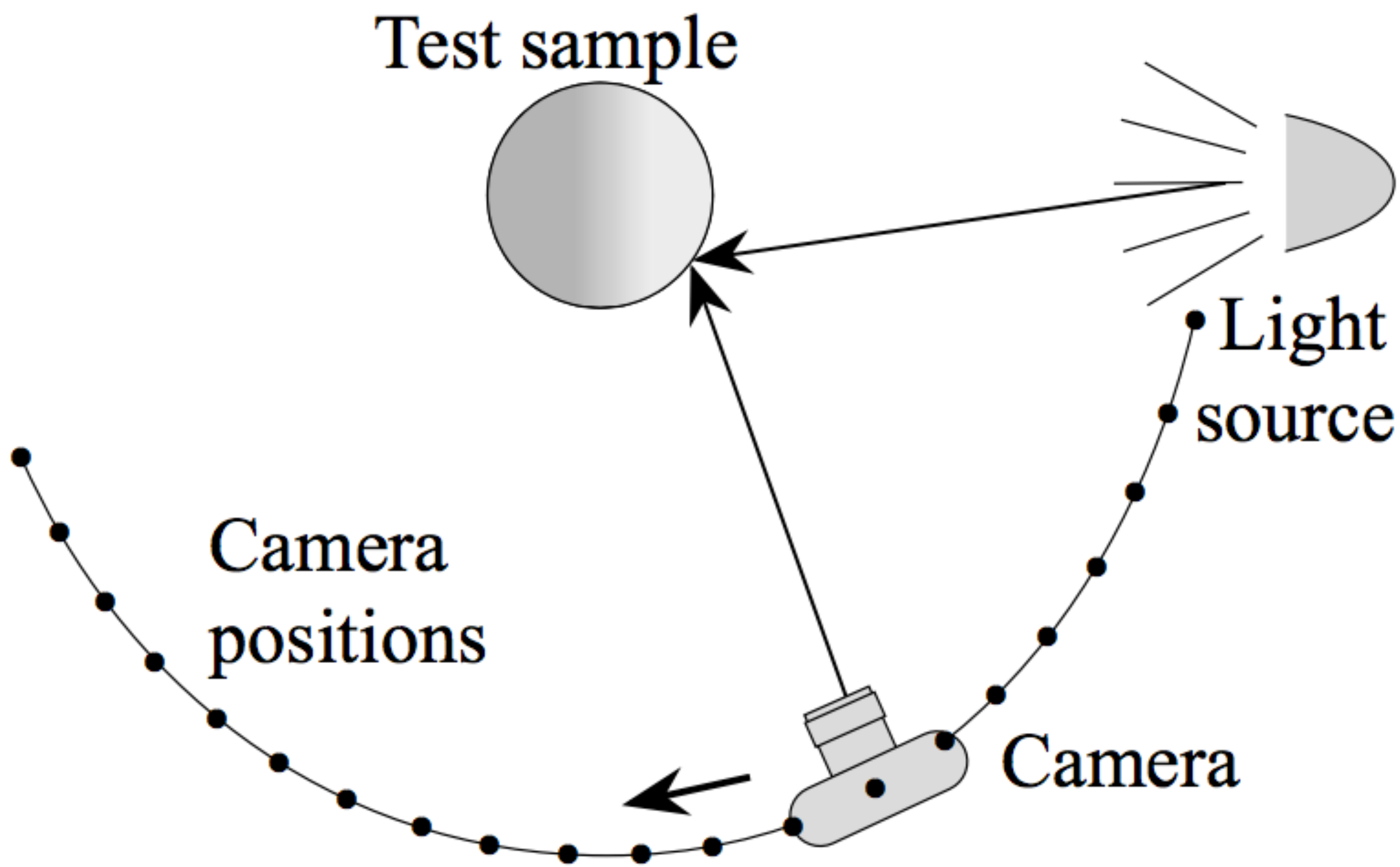
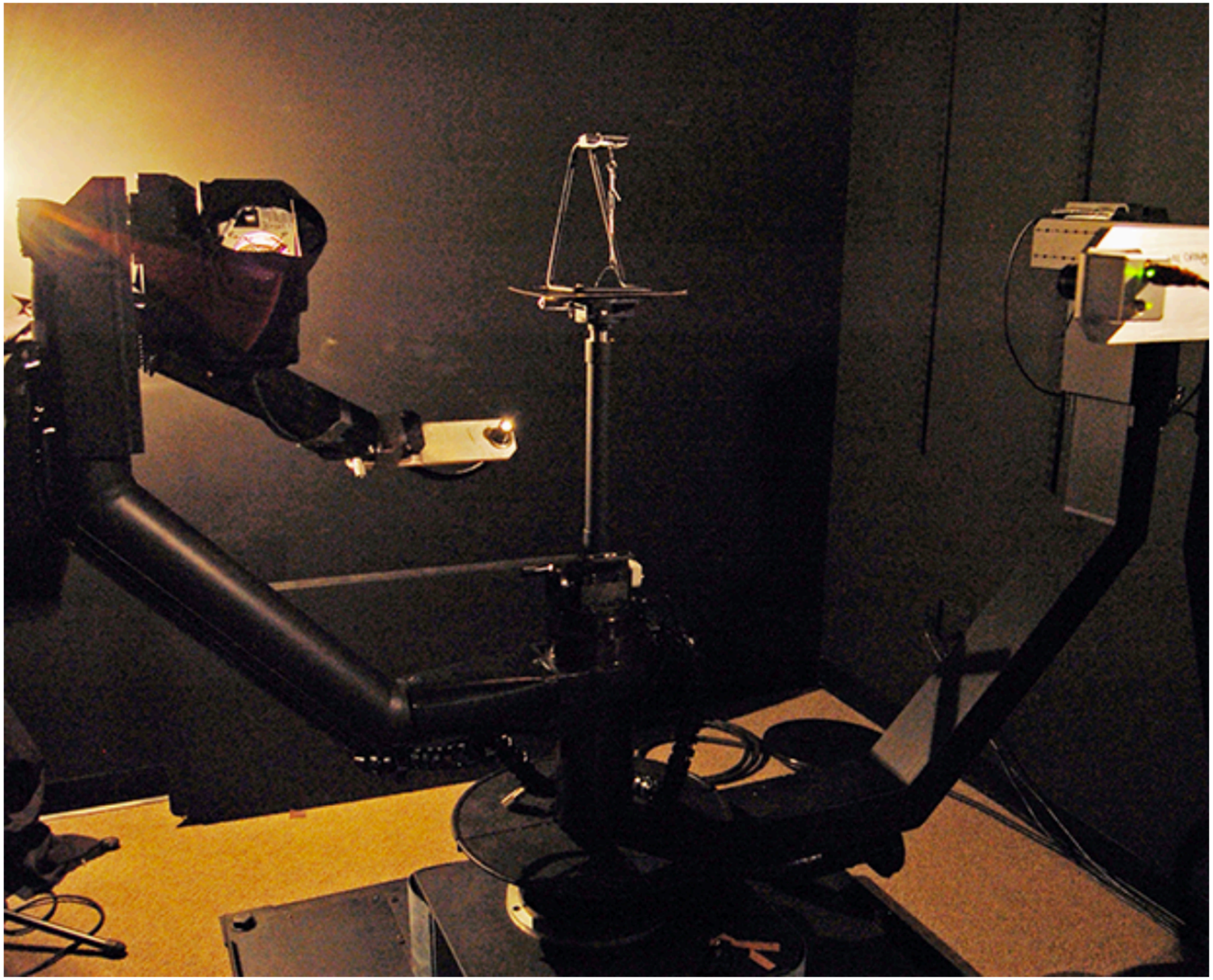


Image-Based BRDF Measurement



[Marschner et al. 1999]

Measuring BRDFs: gonioreflectometer



Spherical gantry at UCSD

Measuring BRDFs

General approach: 给定一个着色点，通过改变入射和出射的角度（改变光源与相机位置）进行测量

```
foreach outgoing direction wo
    move light to illuminate surface with a thin beam from wo
    for each incoming direction wi
        move sensor to be at direction wi from surface
        measure incident radiance
```

Improving efficiency:

- Isotropic surfaces reduce dimensionality from 4D to 3D
- Reciprocity reduces # of measurements by half
- Clever optical systems…

Challenges in Measuring BRDFs

- Accurate measurements at grazing angles
  - Important due to Fresnel effects
- Measuring with dense enough sampling to capture high frequency specularities
- Retro-reflection
- Spatially-varying reflectance, …

为了提高效率，我们可以尽量让材质呈各向同性
就像之前说的，这不仅可以让BRDF从四维降至三维，还能由光路可逆性再砍去一半的测量
最后，关于BRDF的储存，有一个著名的库 MERL BRDF Database，是三菱电子实验室和MIT合作的项目

Representing Measured BRDFs

Desirable qualities

- Compact representation
- Accurate representation of measured data
- Efficient evaluation for arbitrary pairs of directions
- Good distributions available for importance sampling

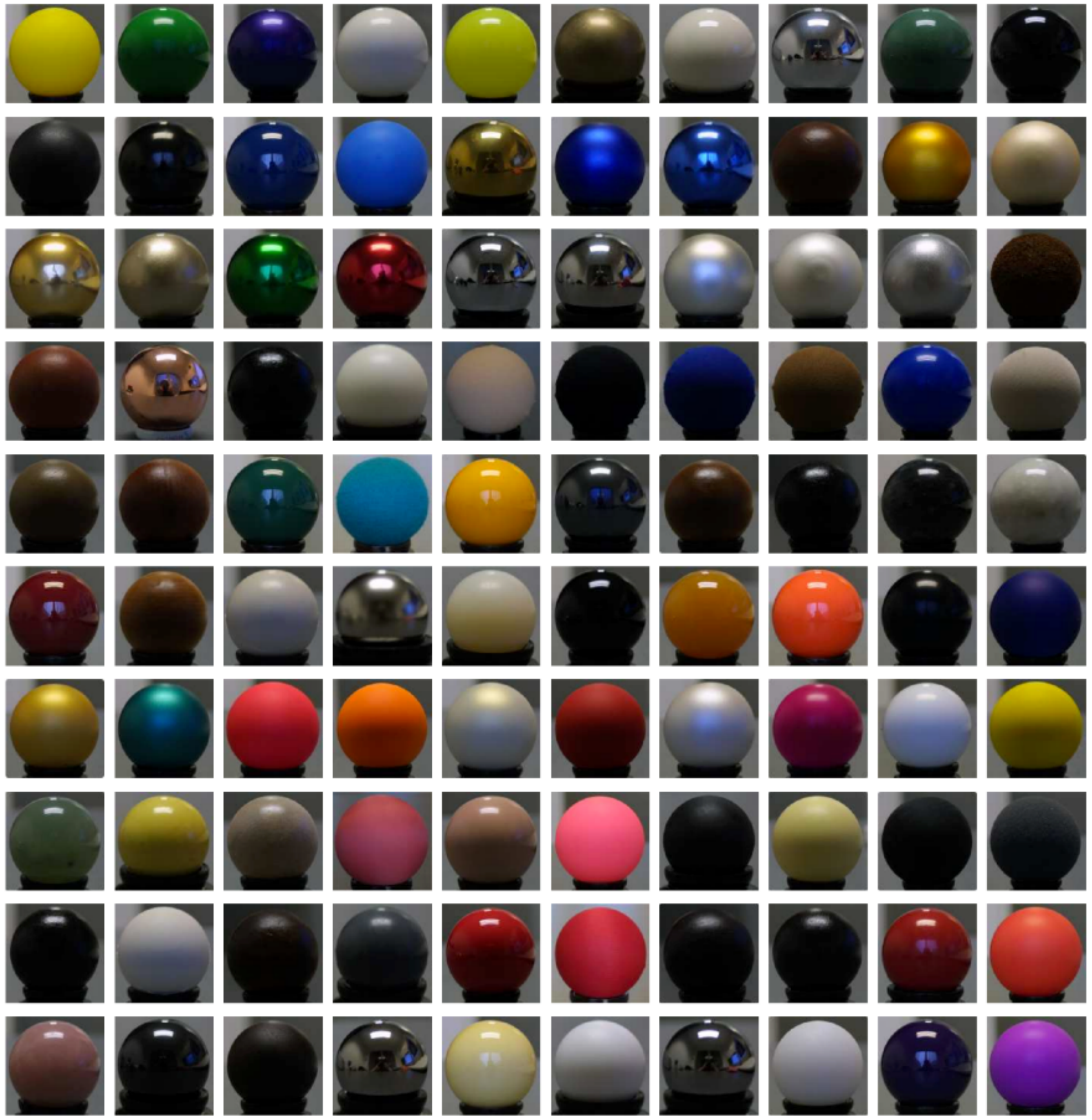
Tabular Representation

Store regularly-spaced samples in $(\theta_i, \theta_o, |\phi_i - \phi_o|)$

- 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

Thank you!

(And thank Prof. Ravi Ramamoorthi and Prof. Ren Ng for many of the slides!)