Lec 17 - 材质和外观 Materials and Appearances

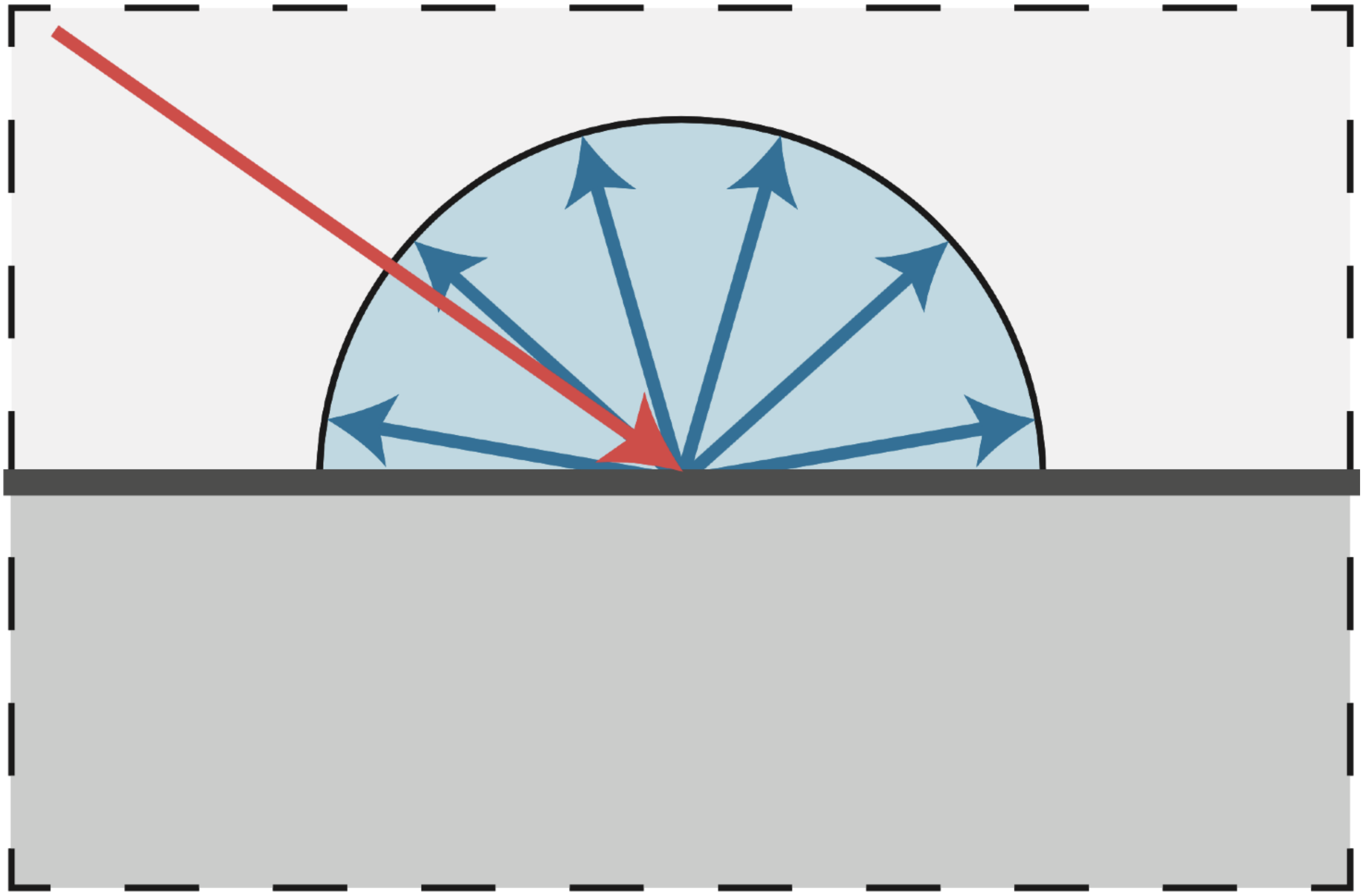
Manuka | Weta Digital 渲染器Renderer，支持40种材质。

以前只有Blinn Phong的时候，通过非物理的方式模拟出各种材质。

Material == BRDF 决定光如何被反射

漫反射、镜面反射、折射材质

- Diffuse / Lambertian Material (BRDF) 漫反射材质



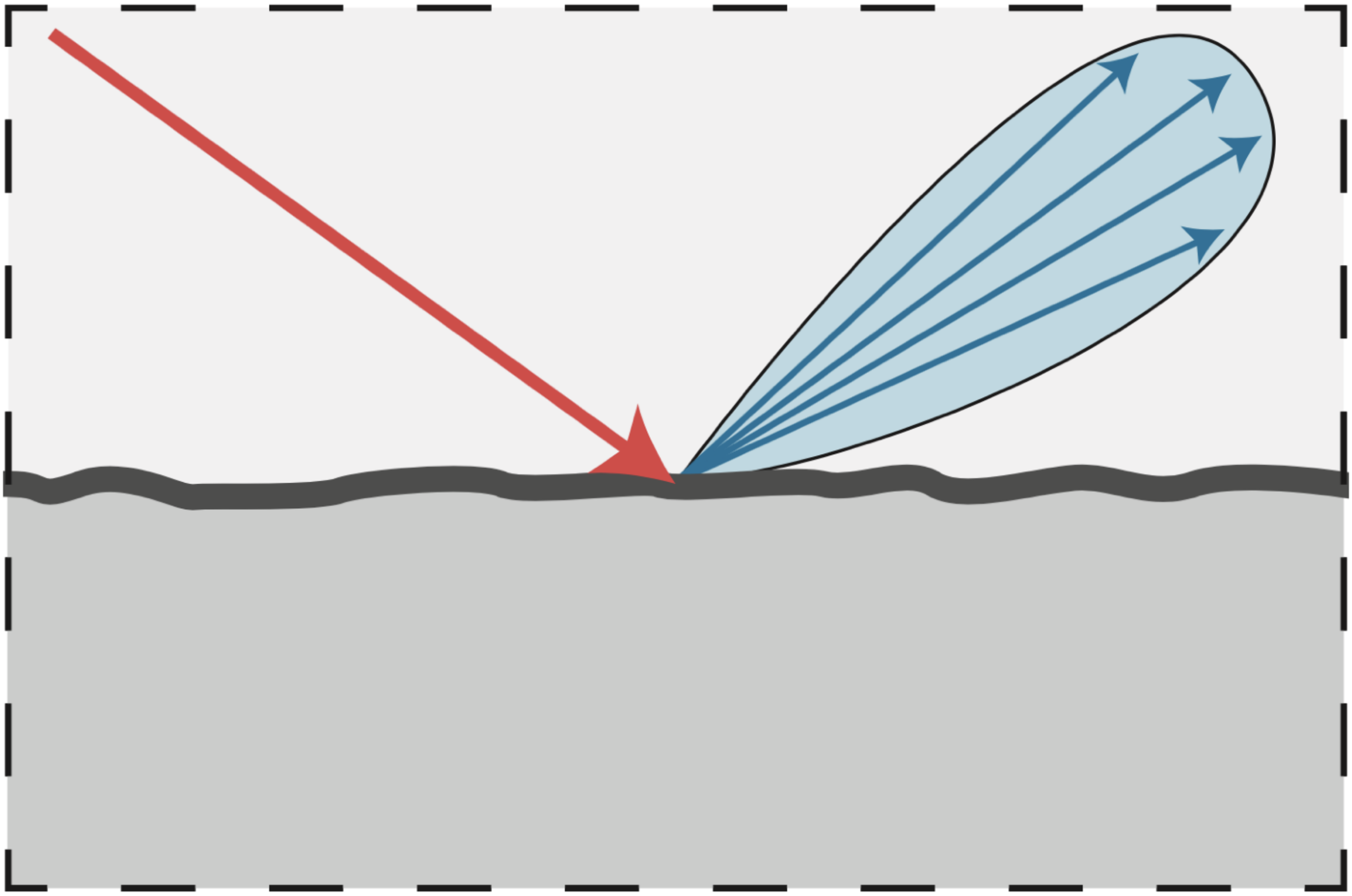
$$
\begin{aligned}
L_o\left(\omega_o\right) &= \int_{H^2} f_r L_i\left(\omega_i\right) \cos\theta_i \mathrm{d}\omega_i \\
&= f_r L_i \int_{H^2} \cos\theta_i \mathrm{d}\omega_i \\
&= \pi f_r L_i
\end{aligned}
$$

  - 能量守恒：进出的irradiance相同（总量）
  - 漫反射：出的radiance均匀→ $f_r = c$ （常量）
  - 假设入射光和出射光都是均匀的→ $L_i = L_o$

$$f_r = \frac{\rho}{\pi}$$

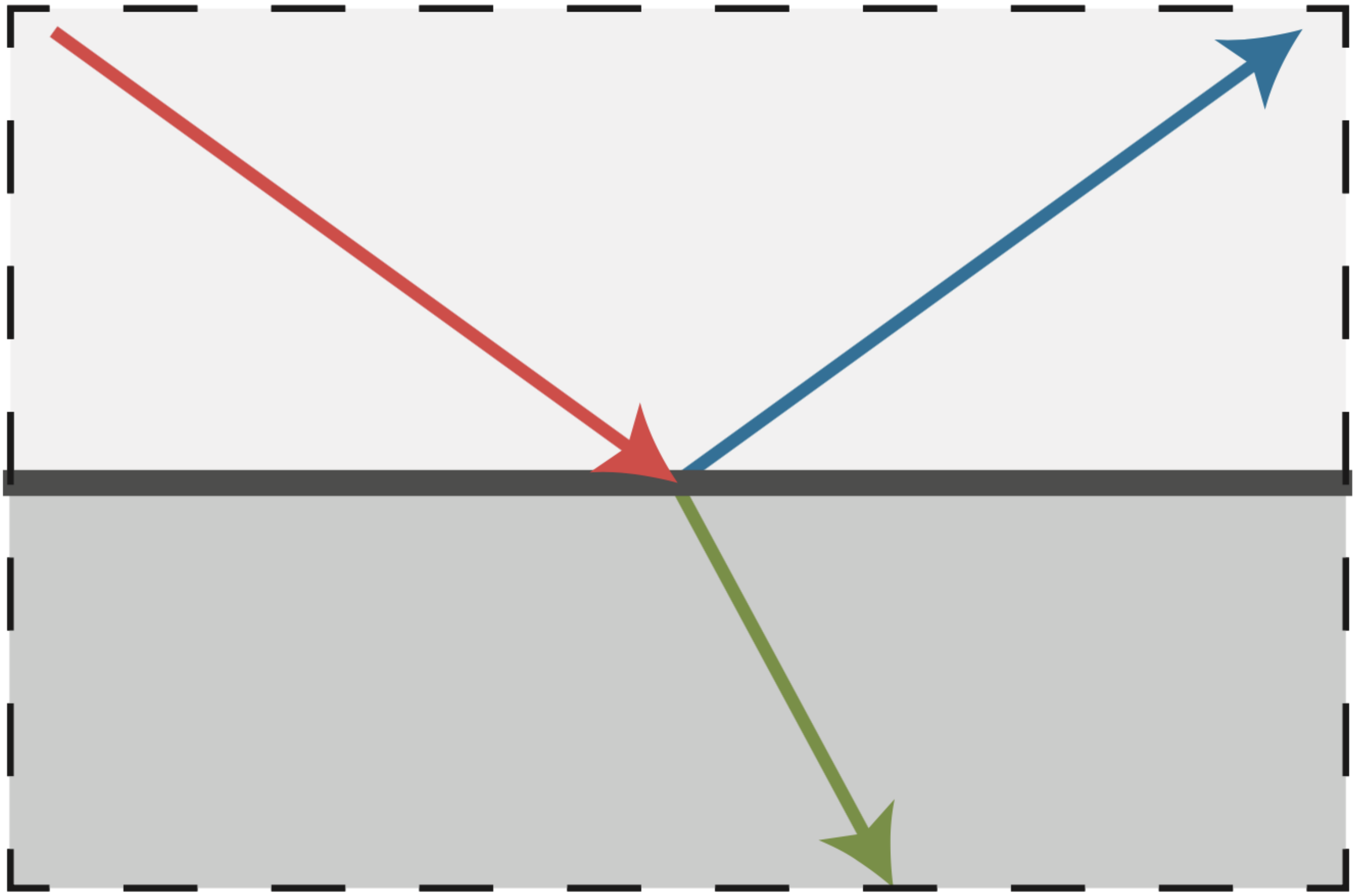
  - ρ: albedo(反射率), 0~1（完全不吸收能量）

- Glossy material (BRDF)



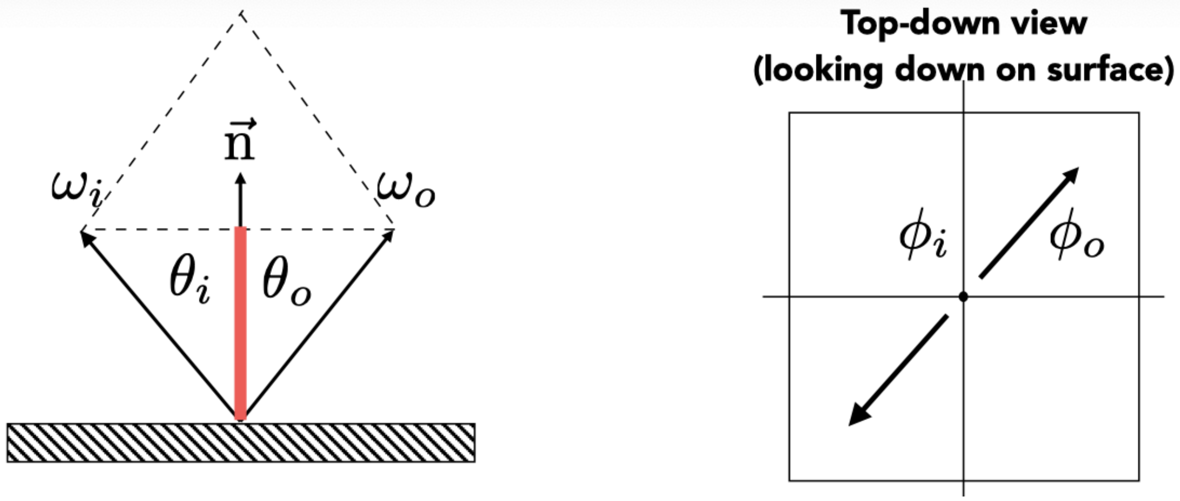
  - Copper, Aluminum

- Ideal reflective / refractive material (BSDF *)



- 玻璃、水……

- 折射光可被部分吸收
    - 反射定律：



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

方位角：

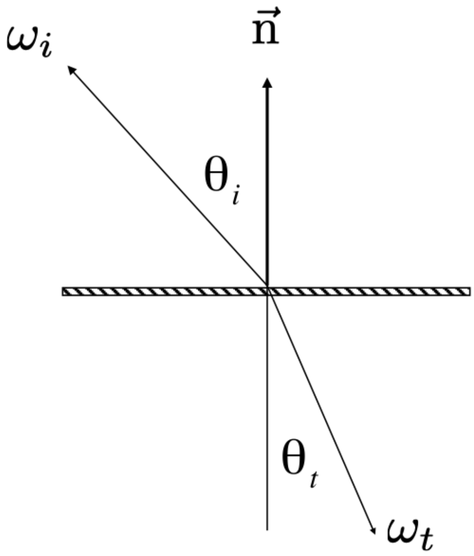
$$\phi_o = (\phi_i + \pi) \bmod 2\pi$$

总结：

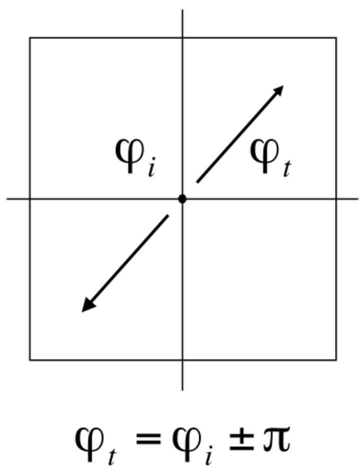
$$\begin{aligned} &\omega_o + \omega_i = 2\cos\theta\vec{n} = 2\left(\omega_i \cdot \vec{n}\right)\vec{n} \\ &\omega_o = -\omega_i + 2\left(\omega_i \cdot \vec{n}\right)\vec{n} \end{aligned}$$

- Specular Refraction折射
    - 白光分解成彩虹：折射率不同
    - Caustics (不合适的翻译：焦散，因为只有聚焦才能被看到)
    - 折射定律（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

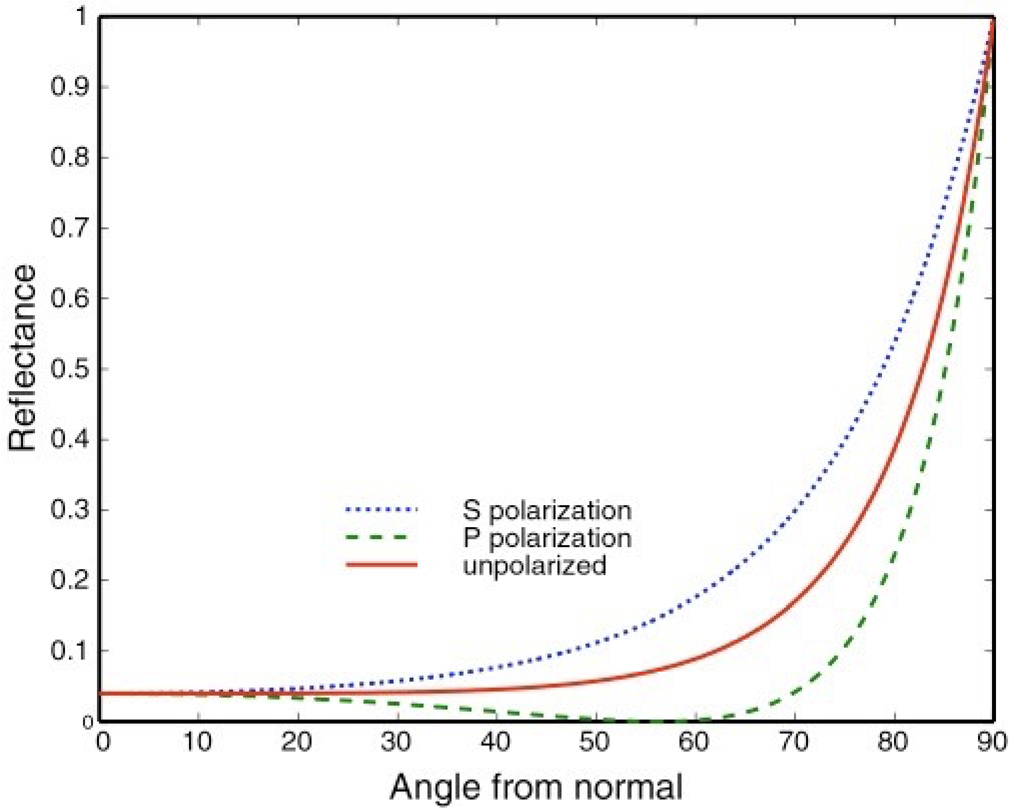
* index of refraction is wavelength dependent (these are averages)

- 全反射：折射不可能发生的情况下，当入射介质折射率>出射介质折射率时可能发生。
    - Snell's Window / Circle: 在水下往上看只能看到锥形的一片区域有光

- BSDF（散射） = BRDF（反射） + BTDF（折射）

- Fresnel Reflection / Term （菲涅耳项）

    - Reflectance depends on incident angle (and polarization of light)
    - 和normal法线方向越接近，越少光被反射



    - 精确计算：需要考虑极化情况
    - 近似：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 微表面材质

基于如下假设：离得足够远的时候，微小的东西往往看不见，看见的是最后汇聚起来总体的样子

Rough surface

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

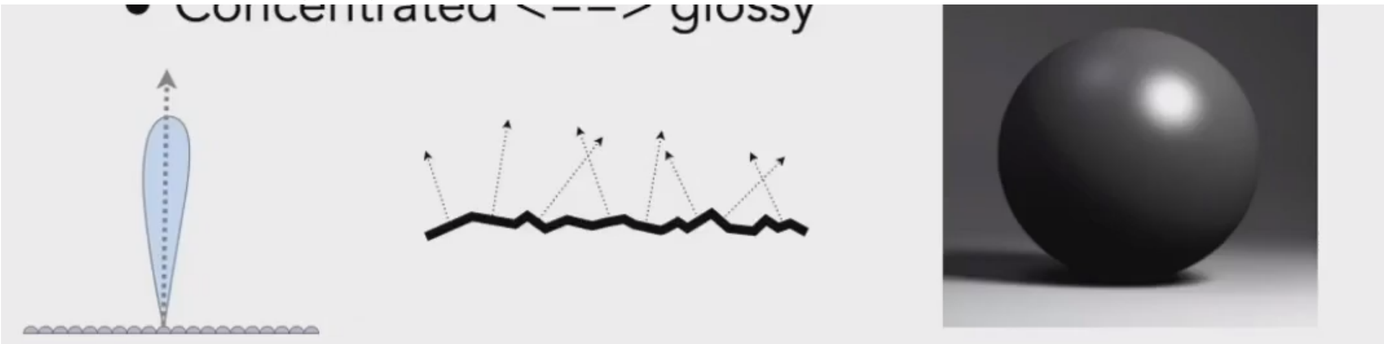
Individual elements of surface act like mirrors

- Known as Microfacets
- Each microfacet has its own normal

Microfacet BRDF 微表面模型

- the distribution of microfacets' normals 法线

- Concentrated <==> glossy



- Spread <==> diffuse

- BRDF计算：

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

  - $\mathbf{F}(\mathbf{i},\mathbf{h})$: Fresnel term
  - $\mathbf{G}(\mathbf{i},\mathbf{o},\mathbf{h})$: shadowing-masking term，微表面互相遮挡的损耗
    - 几乎和表面平行的光线方向：Grazing Angle，损耗很大
  - $\mathbf{D}(\mathbf{h})$: 基于h的法线Distribution, h是half vector，

- 效果十分强大

- State-of-the-art

- PBR：Physically Based Rendering / Shading

- 缺点

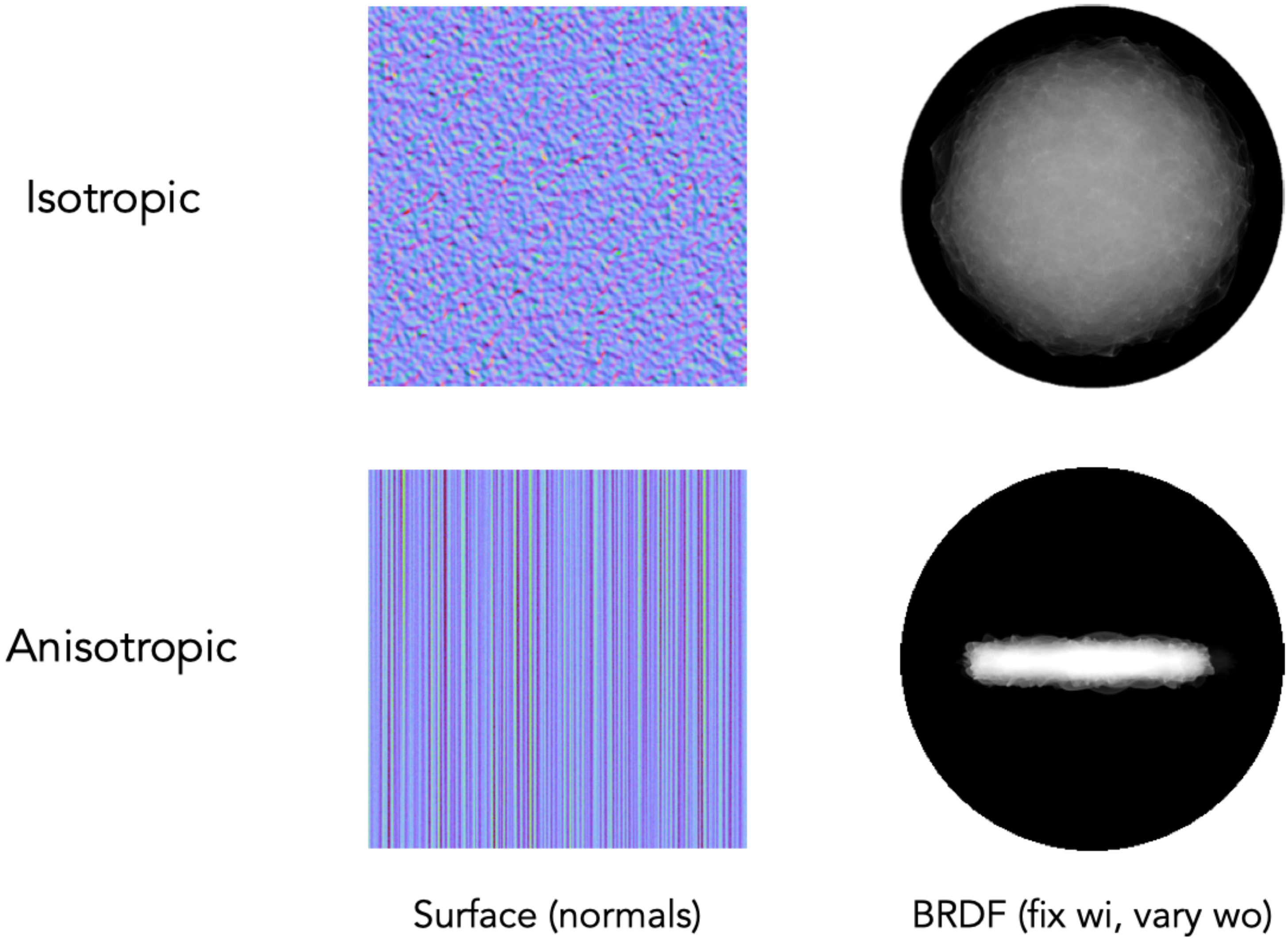
  - Diffuse比较少，有时需要手动加

- 是统称，有很多不同的模型

Isotropic(各向同性) / Anisotropic Materials (BRDFs)

电梯间的条状高光→磨过的表面，各向异性Anisotropic

- 关键区别**Key: directionality of underlying surface**



反映到BRDF上，各向异性的BRDF有如下性质：

$$f_r\left(\theta_i, \phi_i ; \theta_r, \phi_r\right) \neq f_r\left(\theta_i, \theta_r, \phi_r-\phi_i\right)$$

- 方位角不一样时，BRDF不保持一致(Reflection depends on azimuthal angle)
- 锅底 → 辐射状高光
- Nylon（编织），Velvet（天鹅绒，可以人为造成各向异性）

BRDF的属性：

- 非负Non-negativity：描述能量分布
- 线性Linearity：可加，组合
- 可逆性(Reciprocity principle)：交换入射和出射，结果一致
- 能量守恒Energy conservation：能量要么一致，要么变小（被吸收），收敛
- 各向同性：

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

  从可逆性可得：

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

  于是不用考虑方位角的绝对值，便于储存

Measuring BRDFs

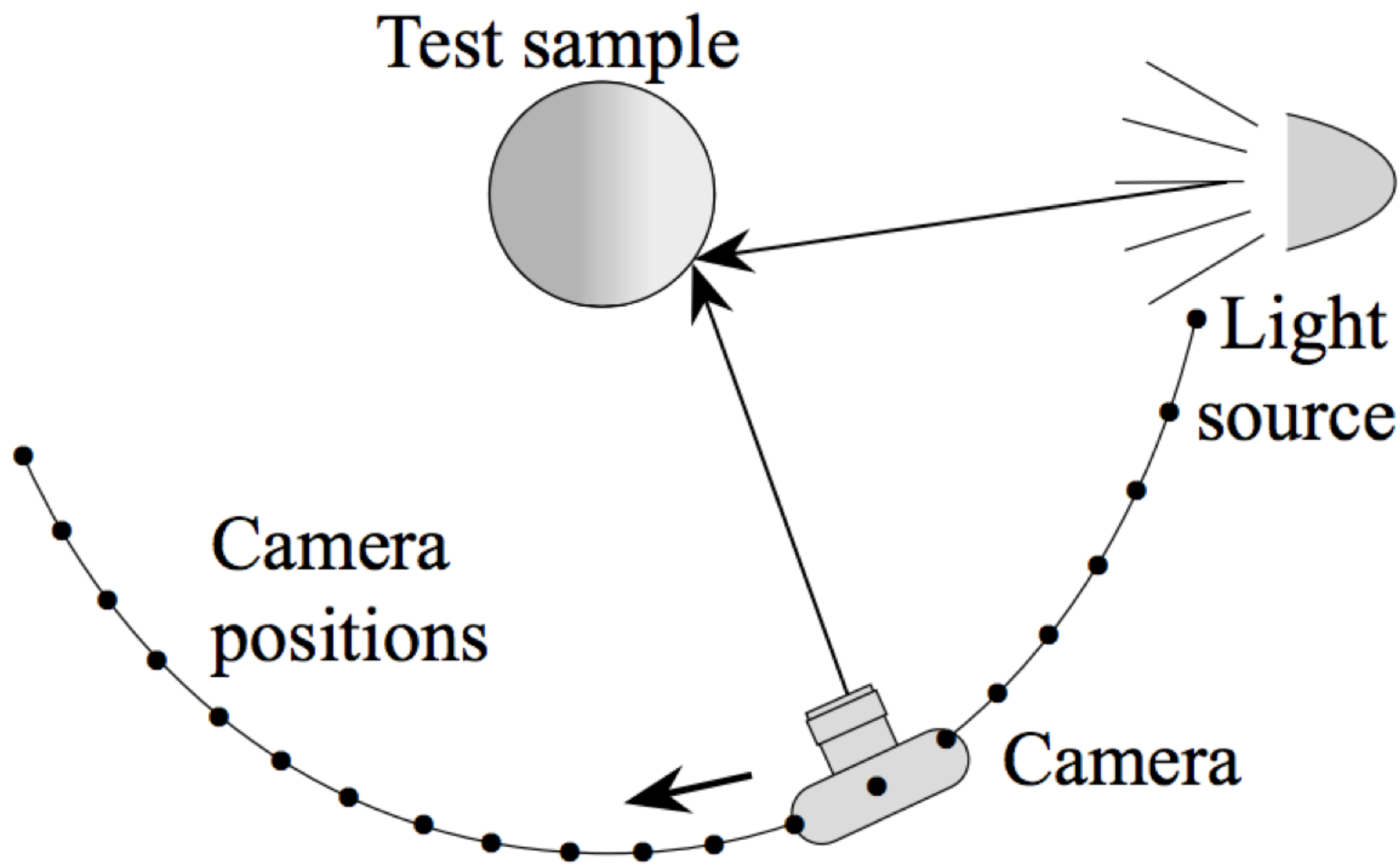
Motivation:

- Avoid need to develop / derive models 不用费力推模型
  - Automatically includes all of the scattering effects present
- Can accurately render with real-world materials
  - Useful for product design, special effects, ...
- 实际和推算出来的经常会有很大差距

方法：

- Image-Based BRDF Measurement

  给定入射出射，参数十分精确，直接测量，枚举



[Marschner et al. 1999]

- 实际存在：UCSD的gonioreflectometer
- 四维，维度爆炸 → 各向同性：三维 → 可逆性：砍掉一半
- 或者采样部分，剩余插值（猜测）
- 挑战：
  - 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,

存储 BRDF

Desirable qualities

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

一种方式：Tabular Representation

- Store regularly-spaced samples in $(\theta_i, \theta_r, |\phi_r - \phi_i|)$
- Better: reparameterize angles to better match specularities
- Generally need to resample measured values to table
- Very high storage requirements
- 实例：MERL BRDF Database [Matusik et al. 2004] 90 *90* 180 measurements