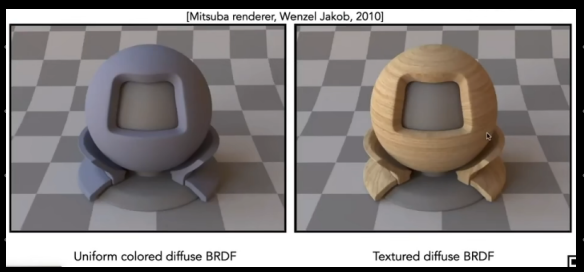
光照与材质密切相关

"最强渲染器" Manuka 支持的各种材质

Material == BRDF

漫反射 Diffuse / Lambertian



漫反射 BRDF 常数

Light is equally reflected in each output direction

入射光照强度常数 <Irradiance>

Suppose the incident lighting is uniform:

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

$$= f_r L_i \int_{H^2} (\omega_i) \cos\theta_i \, d\omega_i$$

$$= \pi f_r L_i \quad \Rightarrow f_r = \frac{1}{\pi}$$

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

$f_r = c$

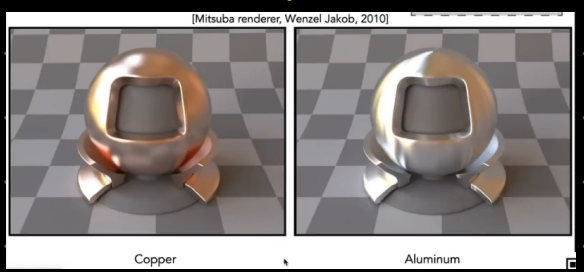
半球立体角积分 $= 2\pi$

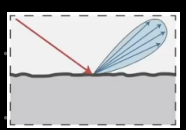
$\cos\theta$ 积分 $= \pi$

能量守恒 入射 == 出射

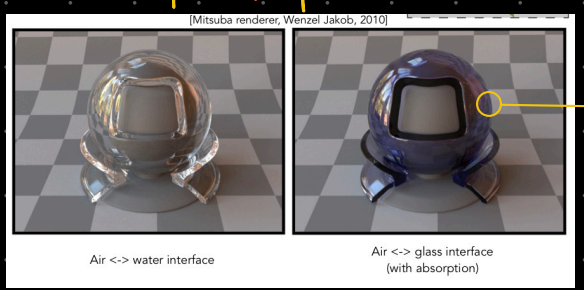
L_i $L_o(\omega_o)$

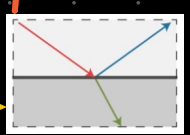
高面反射 Glossy Material BRDF





Ideal reflective/refractive material BSDF

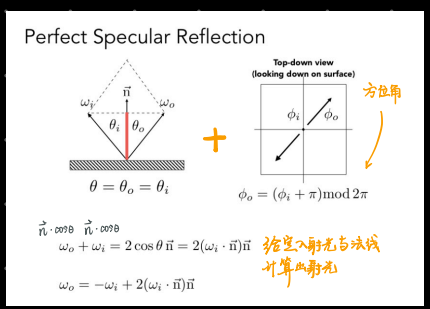


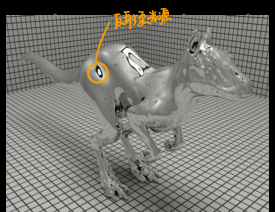


能量发生破坏

完美反射：
入射与出射方向中间为法线

镜面反射 perfect specular reflection BRDF





难点：如何用 BRDF 描述镜面反射

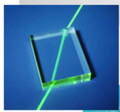
折射 Specular refraction BTDF + BRDF = BSDF

transmit scattering

Specular Refraction

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

Light refracts when it enters a new medium.



caustics

聚焦

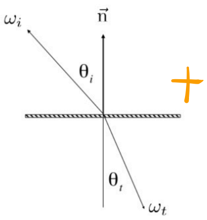
翻译为焦散 ×

Snell's Law 斯内尔定律〈折射定律〉

Transmitted angle depends on

index of refraction (IOR) for incident ray

index of refraction (IOR) for exiting ray



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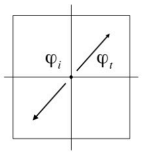


$\varphi_t = \varphi_i \pm \pi$

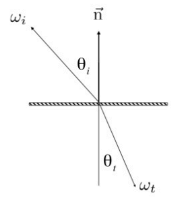
$\eta_i \sin\theta_i = \eta_t \sin\theta_t$

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

不同波长的光的区别在折射中体现

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

Law of Refraction



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

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

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

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

Total internal reflection:

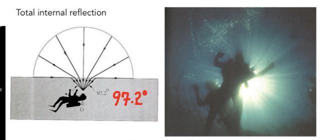
When light is moving from a more optically dense medium to a less optically dense medium: $\frac{\eta_i}{\eta_t} > 1$

Light incident on boundary from large enough angle will not exit medium. 全反射现象

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

不可能大于 1

Snell's Window / Circle



[Livingston and Lynch]

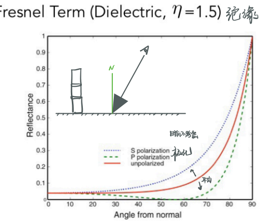
菲涅尔项 Fresnel Reflection / Term

Reflectance depends on incident angle (and polarization of light)

This example: reflectance increases with grazing angle

[Lafortune et al. 1997]

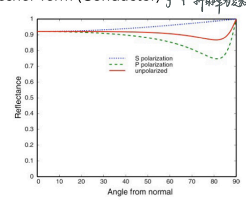
Fresnel Term (Dielectric, η=1.5) 绝缘



Fresnel Term (Conductor) 导体

n & k

折射率为复数



Fresnel Term — Formulae

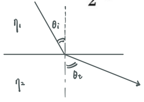
Accurate: need to consider polarization

$$R_s = \left|\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right|^2 = \left|\frac{n_1\cos\theta_i - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1\cos\theta_i + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}\right|^2,$$

$$R_p = \left|\frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2\cos\theta_i}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2\cos\theta_i}\right|^2.$$

有多少能量会被反射〈0,1〉

$$R_{eff} = \frac{1}{2}(R_s + R_p).$$



对材质要一

Approximate: Schlick's approximation

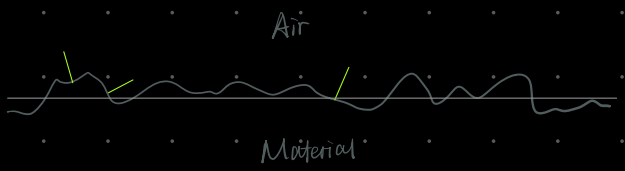
基准反射率〈0°时〉

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

0°时 = R_0，90°时 = 1

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

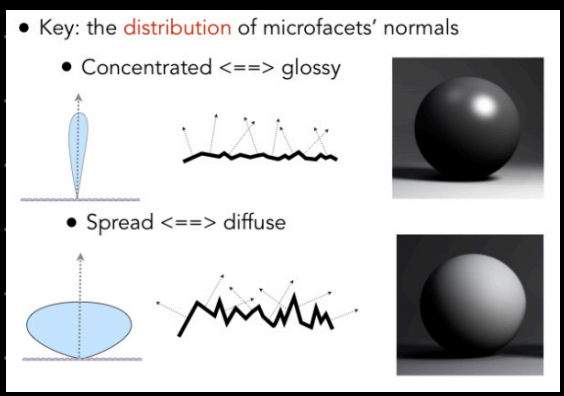
微表面模型 Microfacet Material

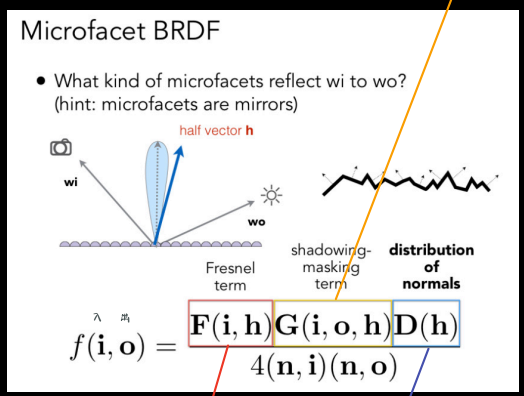


Rough surface
- Macroscale: flat & rough 远
- Microscale: bumpy & specular 近

Individual elements of surface act like mirrors
- Known as Microfacets
- Each microfacet has its own normal

Microfacet BRDF 可用于表现各种材质之表面 [用于 PBR]



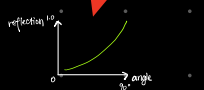


自遮挡 使一些微表面失去反射作用

grazing angle 时平行

修正边界过亮问题

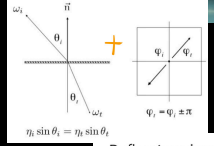
微观表面 vs 宏观表面 通过法线分布表示

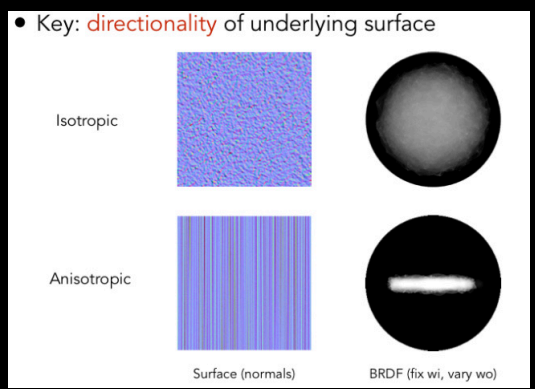


总共有多少能量进入

法线集中度 ☆ 决定性参数

各向同性 各向异性 Isotropic / Anisotropic Materials BRDFs

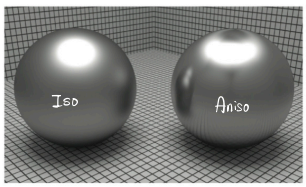


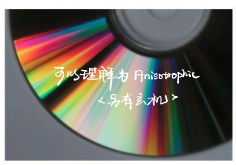


Reflection depends on azimuthal angle ϕ

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

Results from oriented microstructure of surface, e.g., brushed metal





Properties of BRDFs

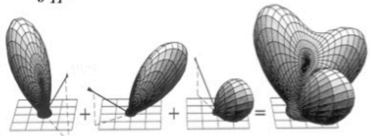
- Non-negativity

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

表示能量分布，非负

- Linearity

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



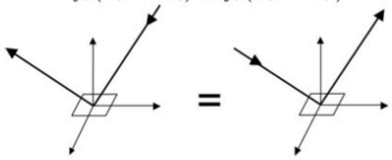
[Sillion et al. 1990]

将各运算部分先拆，再算，后组合

→ 结果不变

- Reciprocity principle

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



可逆性

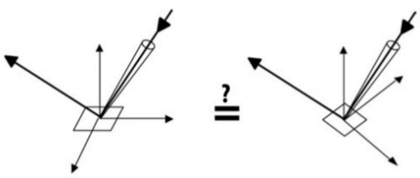
- Energy conservation

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

能量守恒

- 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,

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



仅与相对方位角差值有关

不必考虑谁大谁小

Measuring BRDFs

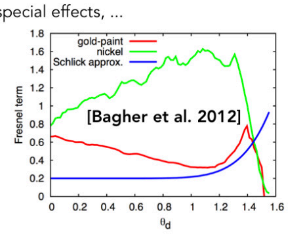
Avoid need to develop / derive models

- Automatically includes all of the scattering effects present

Can accurately render with real-world materials

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

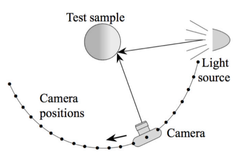
Theory vs. practice:



菲涅尔项之复杂性

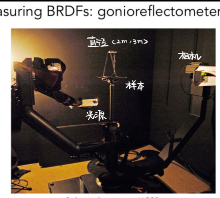
⇒ 难以近似，模拟

Image-Based BRDF Measurement



[Marschner et al. 1999]

Measuring BRDFs: gonioreflectometer



Spherical gantry at UCSD

General approach:

```
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: curse of dimentionality

- Isotropic surfaces reduce dimensionality from 4D to 3D
- Reciprocity reduces # of measurements by half 可逆
- Clever optical systems… ↑↗ 只采样特定方向，猜剩下

Challenges

- 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, ...

Representing / Storing BRDF data

Desirable qualities

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

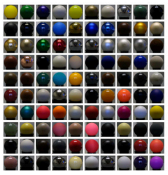
Tabular Representation

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

MERL BRDF DATABASA