5CM507 Graphics

Lecture 06 Physically-based lighting

Dr Youbing Zhao

November 20, 2025

Last Week

- Basic Lighting Models : Ambient + Diffuse + Specular
  - Specular
    - Phong - reflection vector r : $k_s(\boldsymbol{v} \cdot \boldsymbol{r})^{\alpha}$
    - Blinn-Phong - half vector h :$k_s(\boldsymbol{n} \cdot \boldsymbol{h})^{\beta}$
  - Diffuse - Cosine law : $k_d(n \cdot l)$
- Basic Shading Models
  - Flat : polygon-based, normal and colour per polygon
  - Gouraud: vertex-based, normal per vertex, colour interpolation
  - Phong: pixel-based, interpolation of vertex normals, normal per vertex

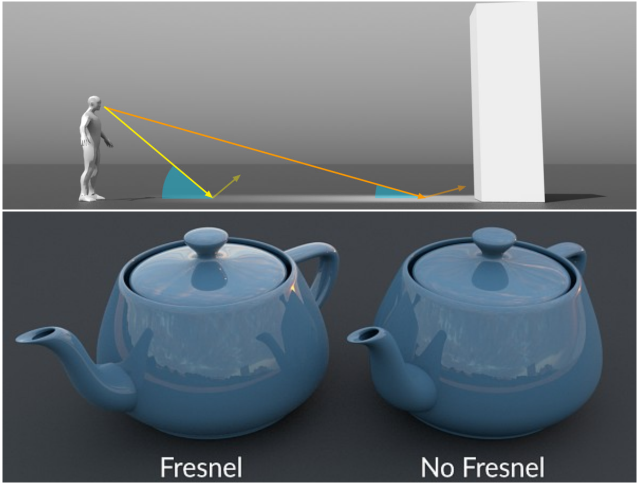
Contents

- Physically based Rendering (PBR)
  - Approximation of physical light transmission laws
  - Balance between fidelity and computing complexity
- In this lecturer:
  - Microfacet Illumintation model GGX
  - Bidirectional Reflection Distribution Function (BRDF)

Physically-based Rendering: the Microfacet Model

The Fresnel Reflectance

- Stronger reflection when the viewing angle is smaller.



Hongkong Intl. Airport

The Fresnel Reflectance

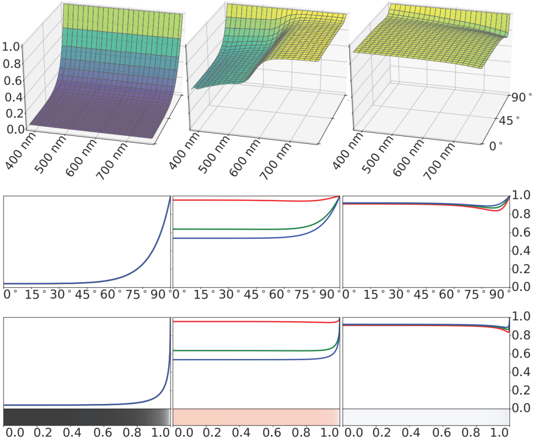
Schlick's approximation

$$F = F_0 + (1 - F_0) * (1 - (\vec{l} \cdot \vec{h}))^5$$

Right term: stronger fresnel reflectance if angle $\widehat{\mathbf{l}\,\mathbf{h}} = \widehat{\mathbf{v}\,\mathbf{h}}$ is close to $90°$.

$F_0 \approx \frac{(n-1)^2}{(n+1)^2}$ n: index of refraction

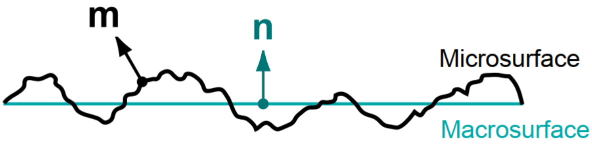
- Metal: $0.54 \sim 1.0$
- Water: 0.02
- Plastics, glass : $0.02 \sim 0.05$
- Skin: 0.028
- Hair: 0.046
- Stone: $0.035 \sim 0.056$



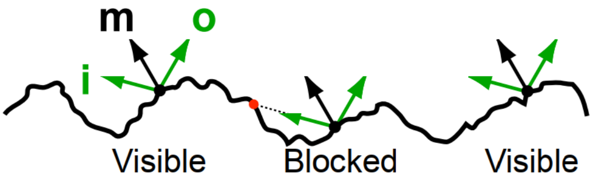
Fresnel Reflection from glass, copper and aluminum (Real-time Rendering)

The Microfacet Model

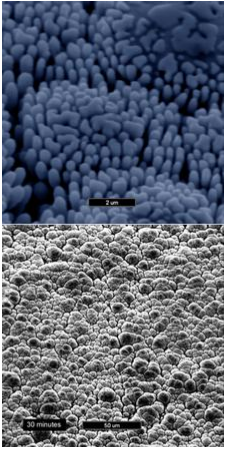
Normals of microfacets are modelled as distributions.



Micro vs. macro surface



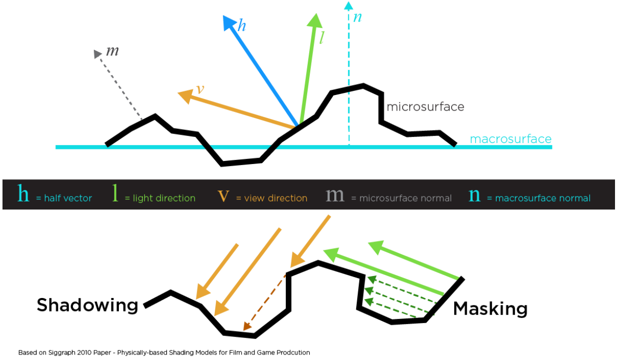
Shadowing-masking geometry



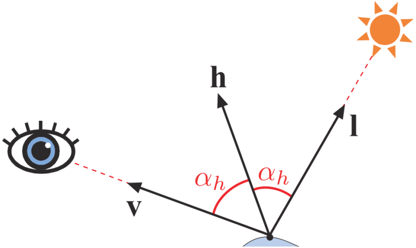
Microscopic view of nickel coatings

The Microfacet Model

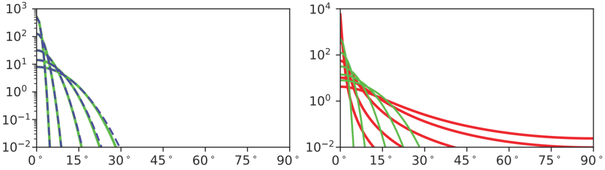
- Distribution of microfacet normals
- Microfacet masking
- Microfacet shadowing

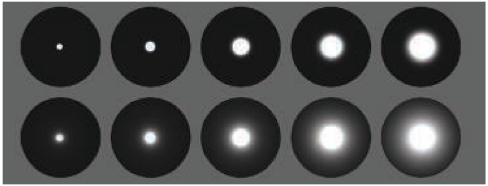


The Normal Distribution Function (NDF)



- Only consider microfacets with normals close to $h = \frac{l+v}{2}$.
- GGX
  - $D(h) = \frac{\alpha^2}{\pi[(n \cdot h)^2(\alpha^2-1)+1]^2}$
  - $\alpha = roughness^2$
  - With longer tails.





Blinn-Phong (dashed blue), Beckmann (green), GGX (red) NDFs (Source: Real-time Rendering)

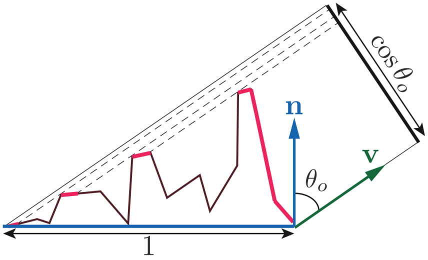
Joint Masking-Shadowing Function

The simplest form: Separable Masking and Shadowing

- Assume masking and shadowing uncorrelated.
- May cause over-darkening.
  $G_2(n, l, v) = G_1(n \cdot l) G_1(n \cdot v)$
- Smith masking function $G_1(n \cdot v) = \frac{1}{1+\Lambda(v)}$

The Λ (lambda) function differs for each NDF.

E.g., in GGX model, $\Lambda(v) = \frac{-1+\sqrt{1+\alpha^2 \tan^2 \theta_v}}{2}$



Source: Real-time Rendering

Torrance–Sparrow BRDF for Specular Reflection (1967)

A compound of the already known functions F, G and D:

$$f\left(l, v\right) = \frac{D(h)F(l,h)G(l,v,h)}{4|n\cdot l||n\cdot v|}$$

l : incident light vector, v : viewing direction vector, h : half vector

$D(h)$: Normal Distribution Function.

$F(l, h)$: Fresnel term

$G(l, v, h)$: Geometry (Joint Masking-shadowing) function.

$|n \cdot l|$: How much of the macroscopic surface is visible to the light source

$|n \cdot v|$: How much of the macroscopic surface is visible to the viewer

The GGX Model (2007)

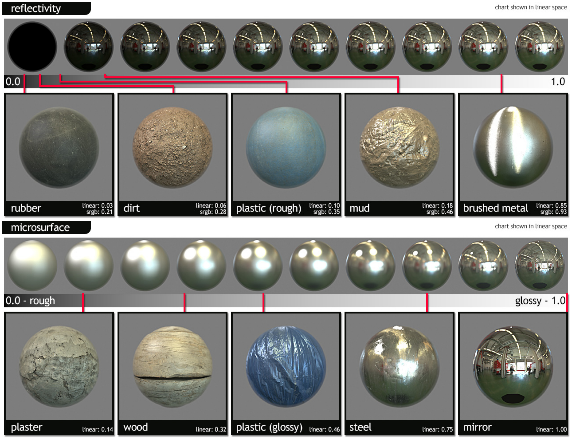
- Widely used specular BRDF in practice
- $D(h) = \frac{\alpha^2}{\pi[(n \cdot h)^2(\alpha^2 - 1) + 1]^2}$
- Fresnel term $F(l, h) = F_0 + (1 - F_0) * (1 - (v \cdot h))^5 \quad F_0 = \frac{(n-1)^2}{(n+1)^2}$
- Geometry (Smith Joint Masking-Shdowing) G_2 :

$$G_2(n, l, v) = G_1(n \cdot l) G_1(n \cdot v)$$

$$G_1(n \cdot v) = \frac{2}{1 + \sqrt{1 + \alpha^2 \tan^2 \theta_v}} = \frac{2(n \cdot v)}{n \cdot v + \sqrt{\alpha^2 + (1 - \alpha^2)(n \cdot v)^2}}.$$

Metalness and Roughness

- Metalness: relates to F_0; roughness: relates to α



Source: https://marmoset.co/

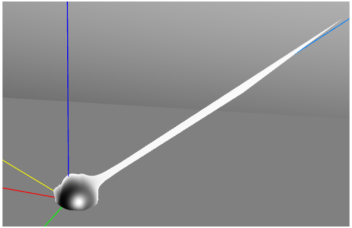
Bidirectional Reflectance Distribution Function (BRDF)

Bidirectional Reflectance Distribution Function (BRDF)

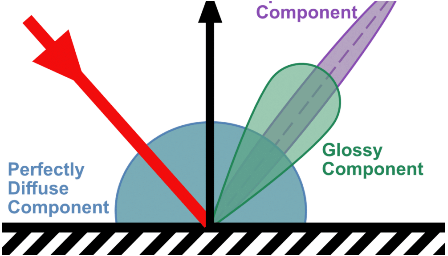
Lighting models such as Phong or Blinn-Phong are approximations to real reflections.

We can measure elevations (1D) and show them on a relief globe.

When the incident light direction is fixed, can we measure reflections from all directions?



The BRDF of white acrylic



BRDF

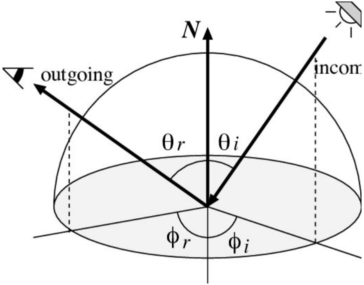
For each incident light direction $\boldsymbol{l}$, measure reflections from all directions $\boldsymbol{v}$.

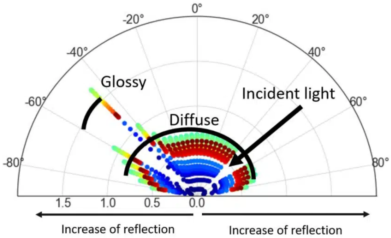
BRDF can be described by a huge look-up table or function with parameters in

- Vector form: $f(\boldsymbol{l}, \boldsymbol{v})$
- Angle form (4D): $f(\theta_i, \phi_i; \theta_r, \phi_r)$

BRDF Functions

- 4D Lookup tables from sampling : images of images
- Parameterised: such as Phong, or shader-based





BRDF

- Analytical: Phong, Blinn-Phong, Cook-Torrence, GGX, etc.
- Data-Driven
  - MERL 100 database, 2003, Mitsubishi Electric Research Laboratories, https://www.merl.com/research/downloads/BRDF
  - EPFL BRDF Database, 2018, https://rgl.epfl.ch/pages/lab/material-database
  - OpenSVBRDF, 1000+, 2023,https://opensvbrdf.github.io/
- BRDF viewer: https://patapom.com/topics/WebGL/BRDF/

BRDF: Isotropic vs Anisotropic

When the sample rotates about its normal, light reflections

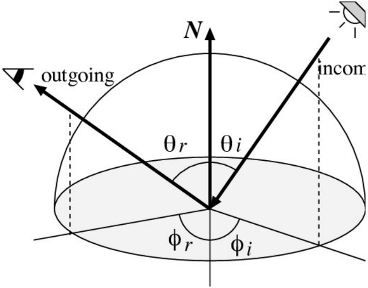
- Anisotropic : change, such as brushed stainless steel.
- Isotropic : no change

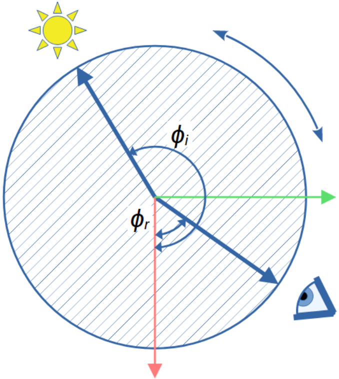
Brushed vs unbrushed [boroughkitchen.com]

BRDF: Isotropic vs Anisotropic

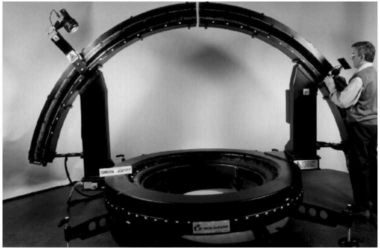
When the sample rotates about its normal, light reflections

- Anisotropic : change, such as brushed stainless steel.
- Isotropic : no change, BRDF reduced to 3D: $f(\theta_i, \theta_r, \phi_i - \phi_r)$

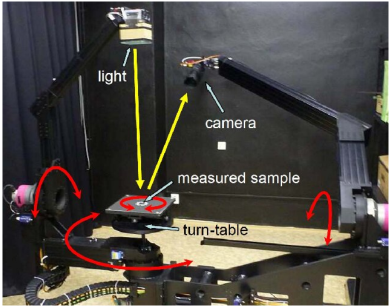




BRDF Measurement: Gonioreflectometer



The BRDF measurement device of ONERA/DOTA, 1999



The UTIA gonioreflectometer, 2013

The Robotic Optical Scatter Instrument (ROSI), NIST, 2018

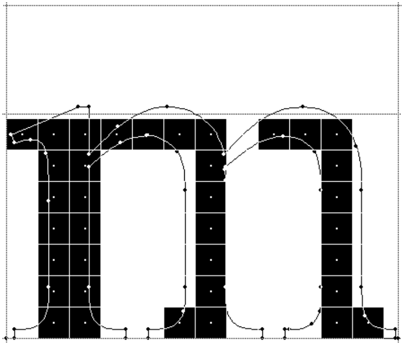
Analytical BRDF Models

Data-Driven BRDF:

- High Storage and Processing
- Difficult Integration with Texture Mapping

Analytical models: approximations of BRDF in parametic forms

- Phong (1975)
- Blinn-Phong (1977)
- Cook-Torrance (1981)
- GGX (Walter 2007)



An analogy of font parameterisation

Summary

- Physically-based lighting models:
  - Microfacet models, GGX model
- Bidirectional Reflectance Distribution Function (BRDF)
  - Isotropic(3D), Anisotropic(4D)

Diffuse in PBR? Bidirectional Scattering Distribution Function (BSDF), e.g., Oren-Nayar model.

Further Reading:

- Allegorithmic PBR Guide, Part 1 (Easy)
- GSN Composer Video Tutorial (Highly recommened)
- (Hard) Chapter 9, Physically based Shading, Real-time Rendering 4th Edition. (available online in the library)