

5CM507 Graphics

Lecture 06 Physically-based lighting

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Last Week

- ▶ Basic Lighting Models : Ambient + Diffuse + Specular
 - ▶ Specular
 - ▶ Phong - reflection vector $r : k_s(\mathbf{v} \cdot \mathbf{r})^\alpha$
 - ▶ Blinn-Phong - half vector $h : k_s(\mathbf{n} \cdot \mathbf{h})^\beta$
 - ▶ Diffuse - Cosine law : $k_d(\mathbf{n} \cdot \mathbf{l})$
- ▶ 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

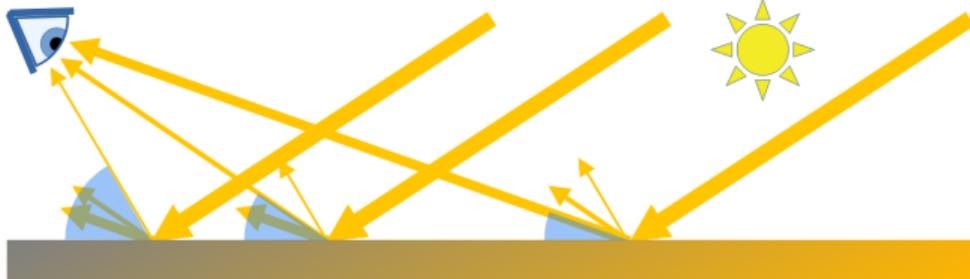
Contents

- ▶ Physically based Rendering (PBR)
 - ▶ Approximation of physical light transmission laws
 - ▶ Balance between fidelity and computing complexity
- ▶ In this lecture:
 - ▶ Fresnel Reflectance
 - ▶ Microfacet Reflectance Model
 - ▶ Torrance-Sparrow Microfacet Model
 - ▶ GGX Model
 - ▶ Bidirectional Reflection Distribution Function (BRDF)

Physically-based Rendering: the Fresnel Reflectance

The Fresnel Reflectance

Materials become more reflective at grazing angles.



The Fresnel Reflectance

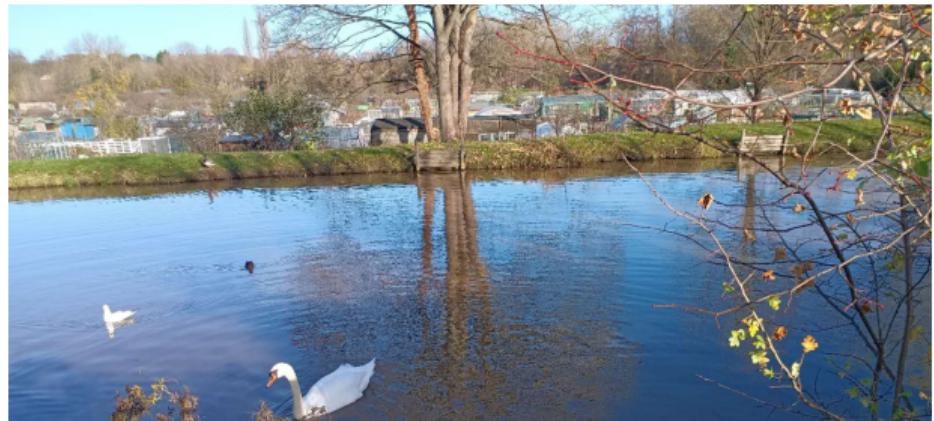
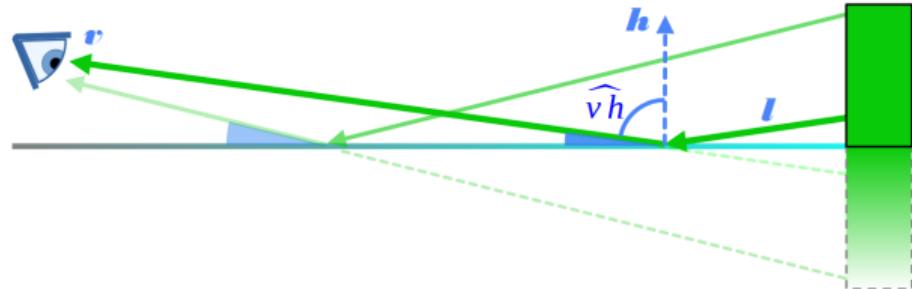
Fresnel reflectance equation

- ▶ Light as electromagnetic waves
- ▶ Polarisation
- ▶ Interface between two media

Schlick's approximation

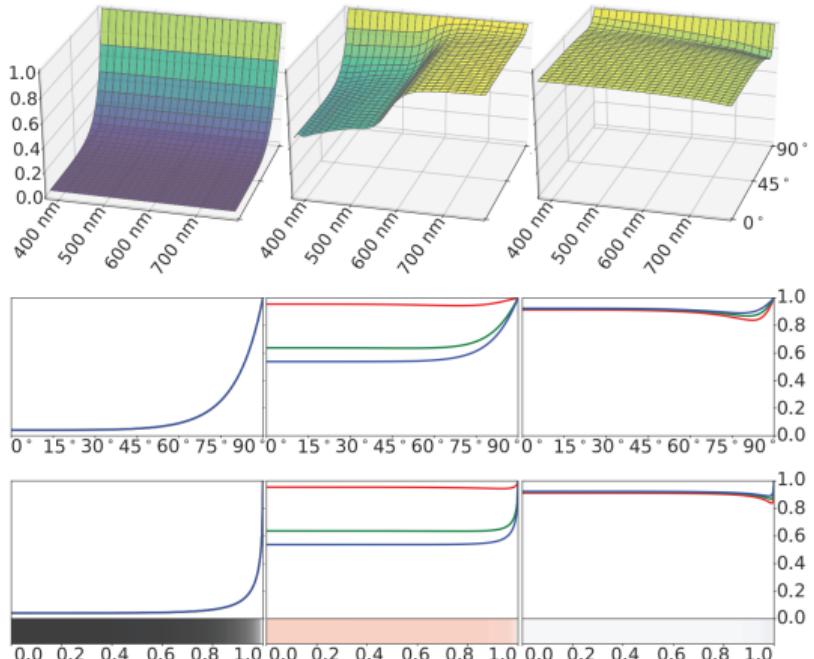
$$F \approx F_0 + \underbrace{(1 - F_0) * \overbrace{(1 - (\mathbf{l} \cdot \mathbf{h}))}^{\rightarrow 1 \text{ if } \hat{\mathbf{l}} \cdot \mathbf{h} \rightarrow 90^\circ}}_{\text{Grazing angle reflectance}}^5$$

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



Fresnel F_0 of Materials

- ▶ Metal: $0.5 \sim 1.0$
 - ▶ Gold (1.0, 0.782, 0.344)
 - ▶ Silver (0.972, 0.960, 0.915)
 - ▶ Aluminum (0.913, 0.922, 0.924)
 - ▶ Copper (0.955, 0.638, 0.538)
 - ▶ Nickel (0.660, 0.609, 0.526)
 - ▶ Chromium (0.549, 0.556, 0.554)
 - ▶ Iron (0.562, 0.565, 0.578)
- ▶ Water: 0.02
- ▶ Plastics, glass : $0.04 \sim 0.05$
- ▶ Skin: 0.028
- ▶ Hair: 0.046
- ▶ Stone: $0.035 \sim 0.056$

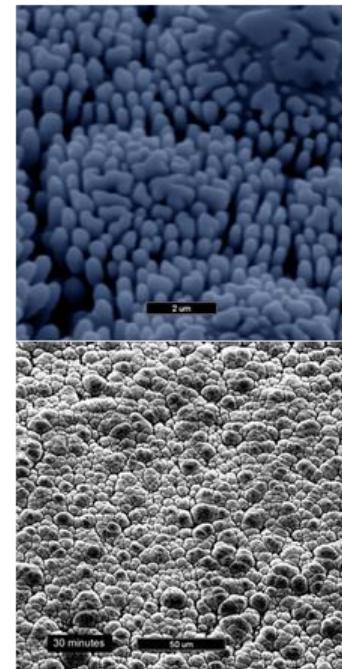
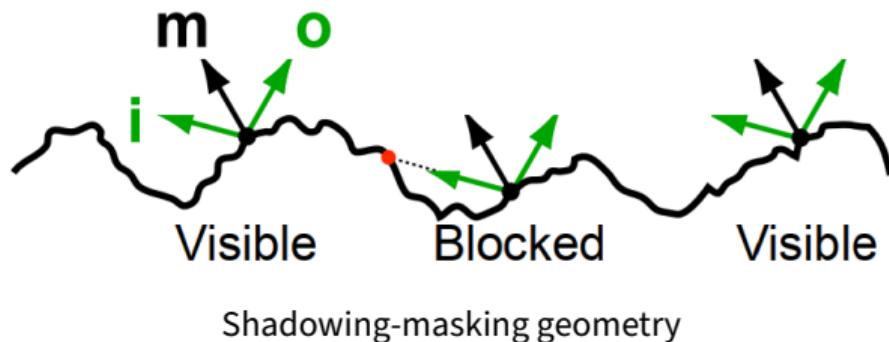
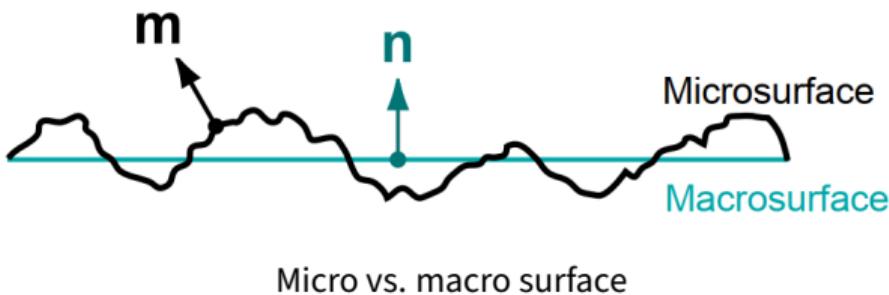


Fresnel Reflection from glass, copper and aluminum (Real-time Rendering)

Physically-based Rendering: the Microfacet Reflectance Model

The Microfacet Reflectance Model

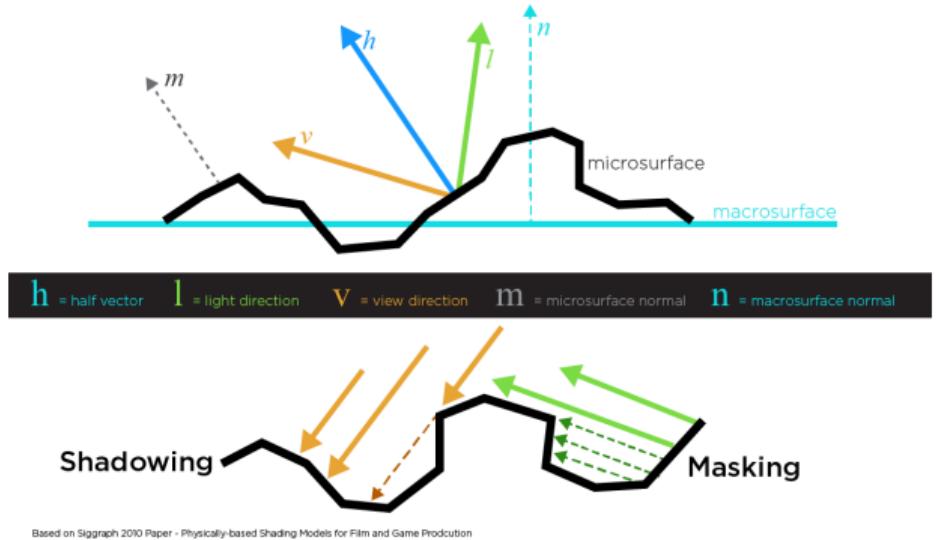
Normals of microfacets are modelled as distributions.



Microscopic view of nickel coatings

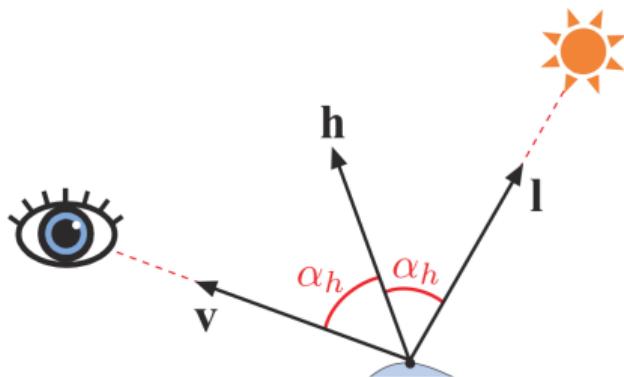
The Microfacet Model

- ▶ Distribution of microfacet normals
- ▶ Microfacet masking
- ▶ Microfacet shadowing

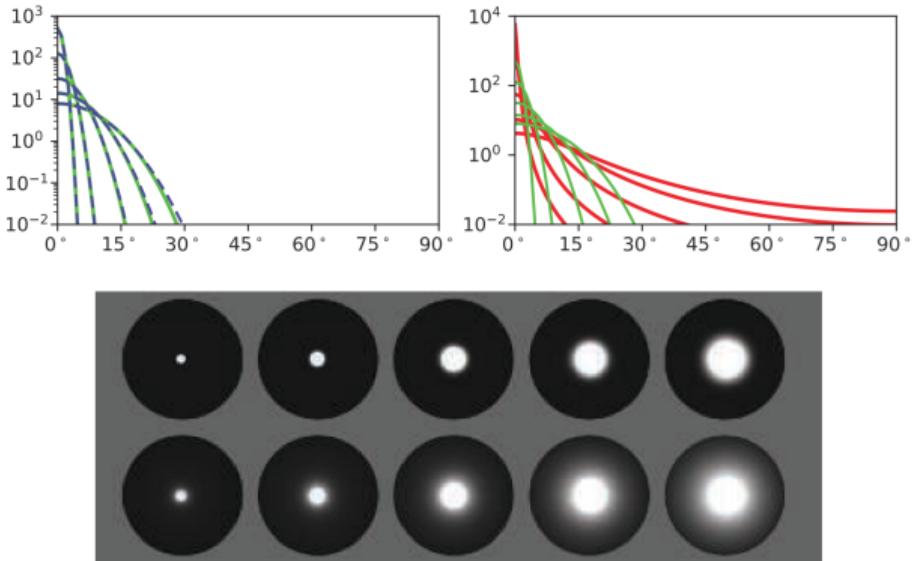


Based on Siggraph 2010 Paper - Physically-based Shading Models for Film and Game Production

The Normal Distribution Function (NDF)



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

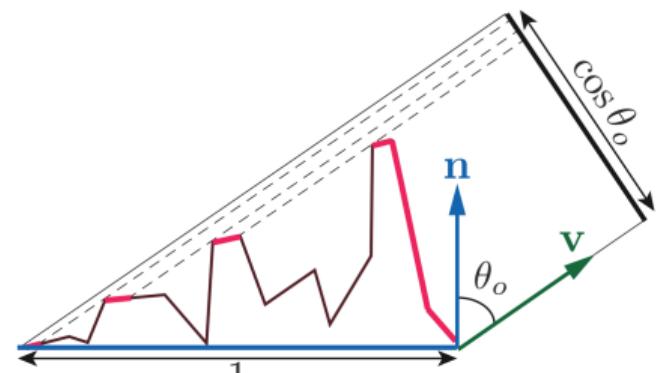
- ▶ May cause over-darkening.

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

- ▶ 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 Model for Specular Reflection (1967)



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

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

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 $F(l, h) = F_0 + (1 - F_0) * (1 - (v \cdot h))^5$ $F_0 = \frac{(n-1)^2}{(n+1)^2}$
- ▶ 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/>

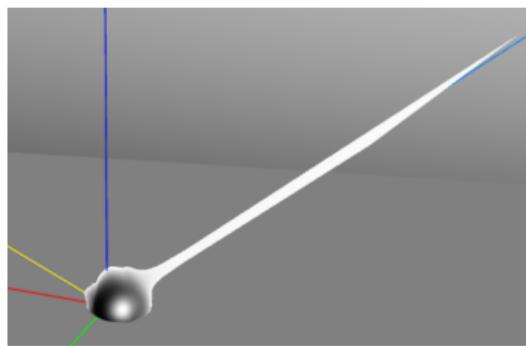
Bidirectional Reflectance Distribution Function (BRDF)

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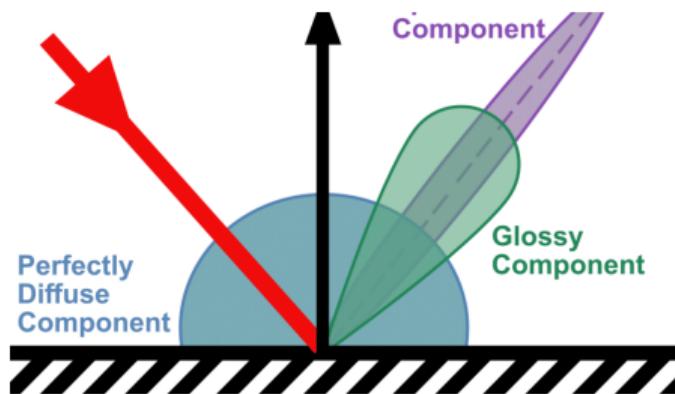
Lighting models such as Phong or Blinn-Phong are approximations to real reflections.

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

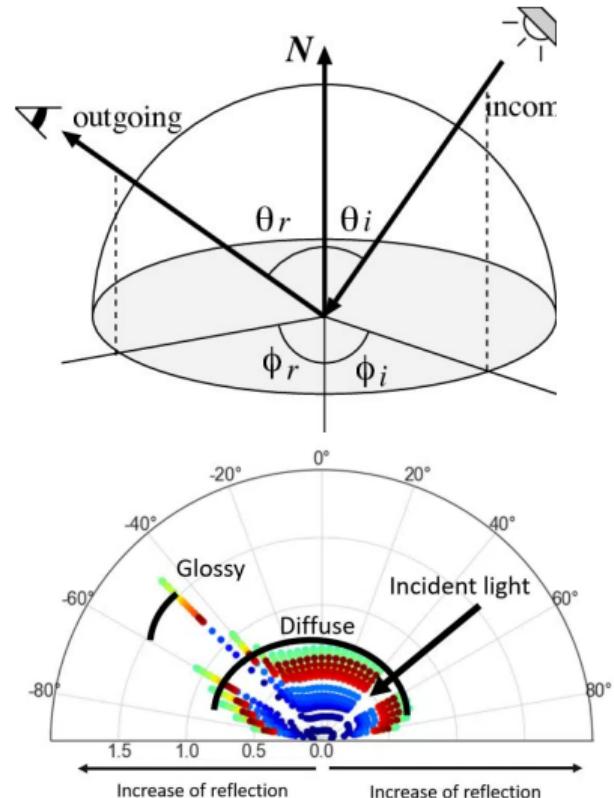
For each incident light direction \mathbf{l} , measure reflections from all directions \mathbf{v} .

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

- ▶ Vector form: $f(\mathbf{l}, \mathbf{v})$
- ▶ 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

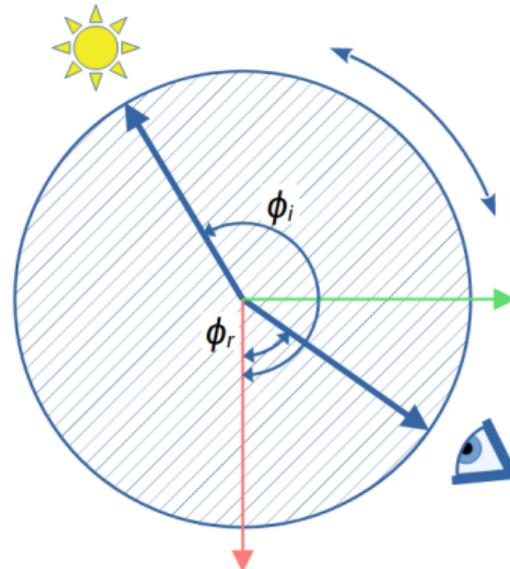
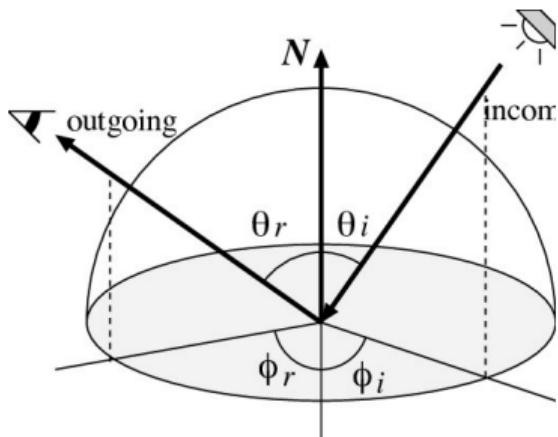


Brushed vs unbrushed [boroughkitchen.com]

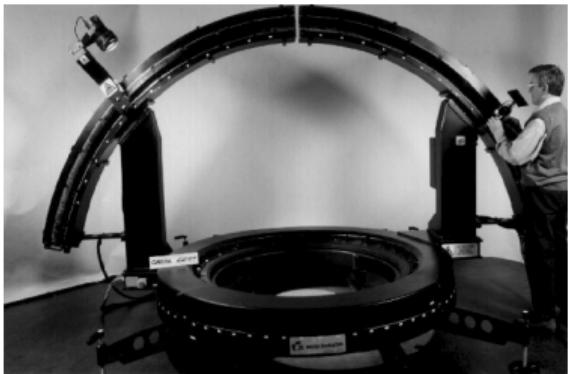
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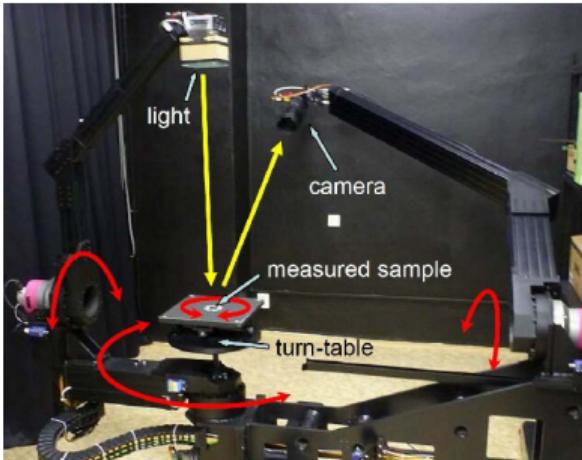
- ▶ Anisotropic : change, such as brushed stainless steel.
- ▶ Isotropic : no change, BRDF reduced to 3D: $f(\theta_i, \theta_r, \phi_i - \phi_r)$



BRDF Measurement: Gonioreflectometer



The BRDF measurement device of
ONERA/DOTA, 1999



The UTIA gonioreflectometer, 2013



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

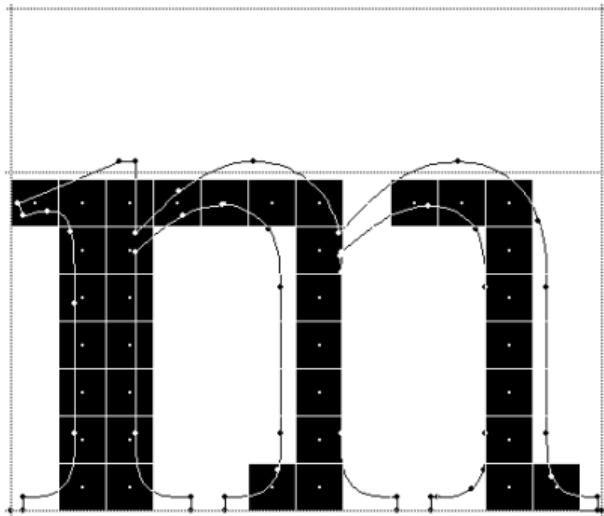
Analytical BRDF Models

Data-Driven BRDF:

- ▶ High Storage and Processing
- ▶ Difficult Integration with Texture Mapping

Analytical models: approximations of BRDF in parametric 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 \(Highly recommended\)](#)
- ▶ (Hard) Chapter 9, Physically based Shading, Real-time Rendering 4th Edition. (available online in the library)