Surface Scattering

Surface Scattering

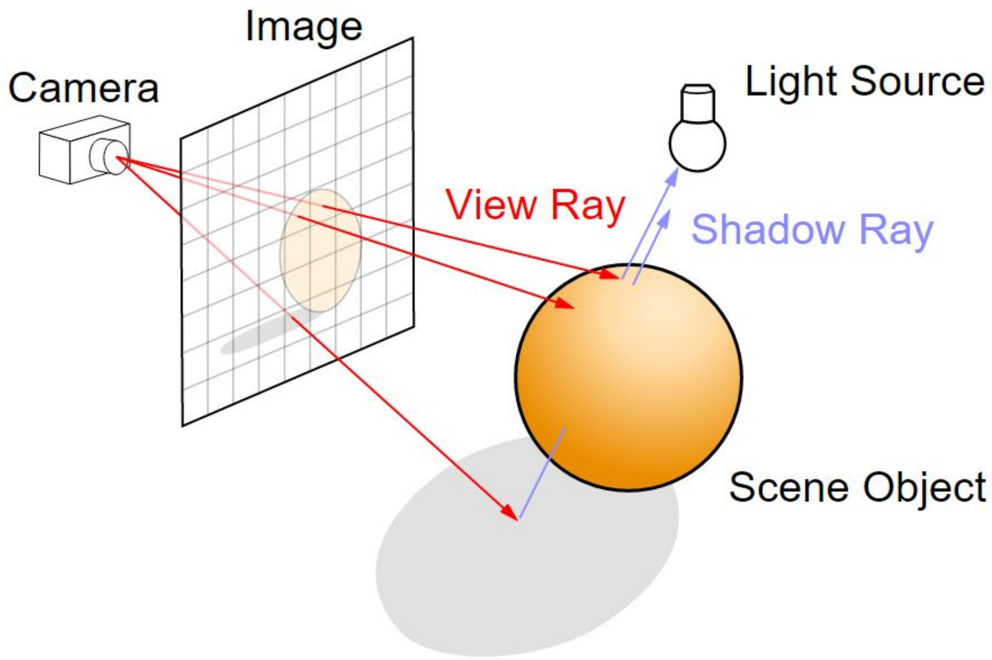
(not **sub**surface scattering)

Surface Scattering

- Ray tracing
- Materials
- BxDF Models
  - **B**i-directional **x** **D**istribution **F**unction
  - BRDF: Reflectance
  - BTDF: Transmission
  - BSDF: Scattering (= BRDF + BTDF)
  - BSSRDF - Scattering-surface reflectance
    - Subsurface scattering

Ray Tracing

- Trace rays through plane
- Camera effects
- Sampling schemes
- Speed-up techniques



Ray Tracing

- Spheres
- Diffuse, specular, (glossy)
- Reflection, refraction
- (Textures)

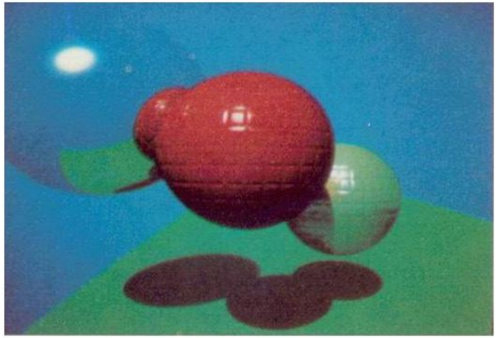


Figure 5

Figure 7

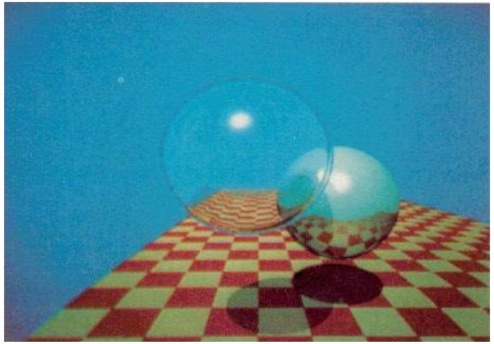


Figure 6

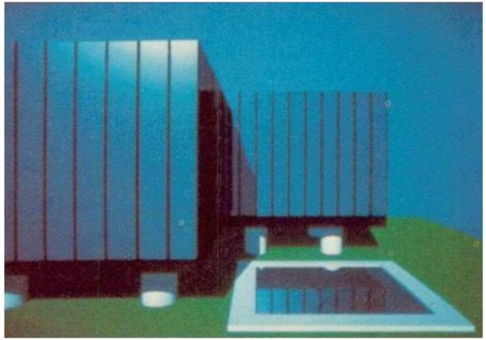


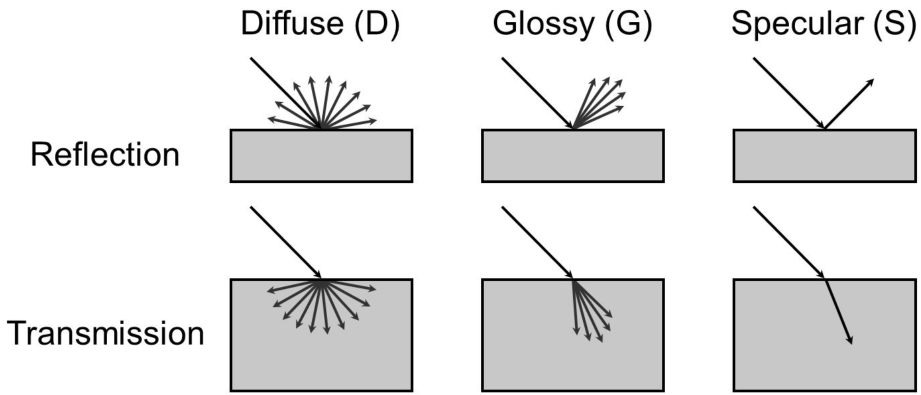
Figure 8

Turner Whitted (1980)
“An improved illumination model for shaded display”

Figure 5: Jim Blinn (1978)
“Simulation of wrinkled surfaces” (Bump mapping)

Ray Tracing

- Diffuse (or “Lambertian”)
    - Uniform sampling
- Specular
    - Perfect reflection
- (Glossy)
    - “glossiness” parameter



Scale

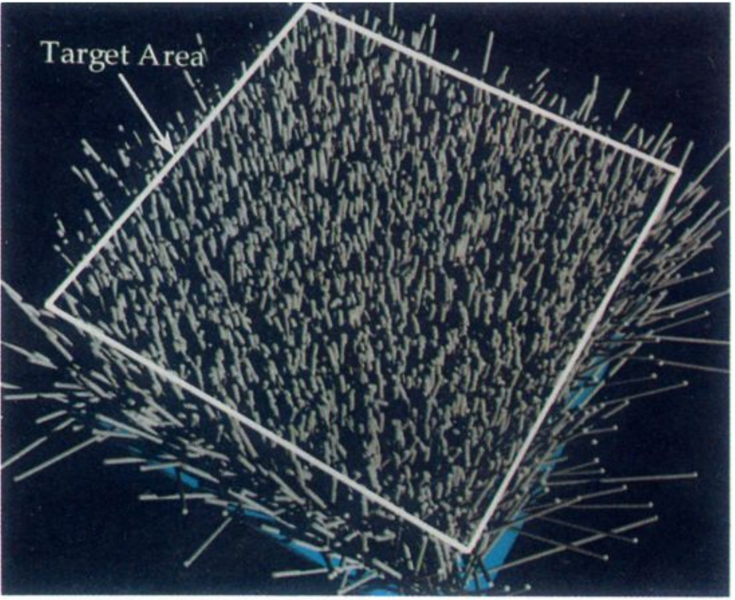


Figure 11: Microscale Geometry for Velvet

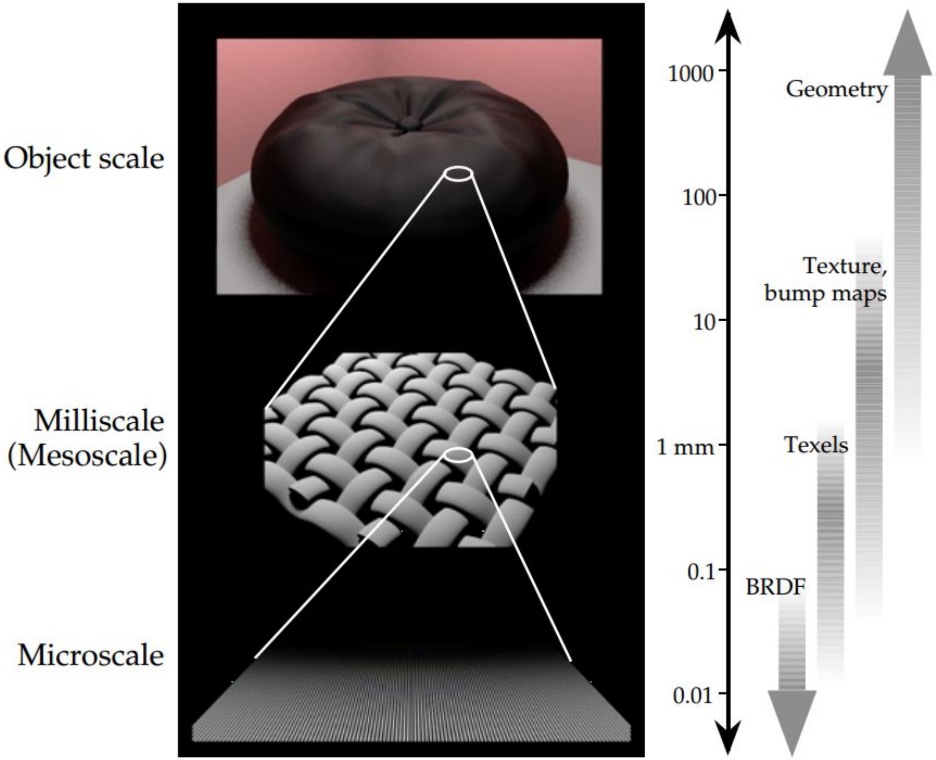
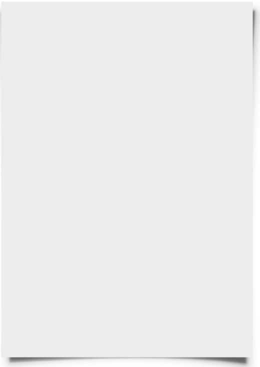
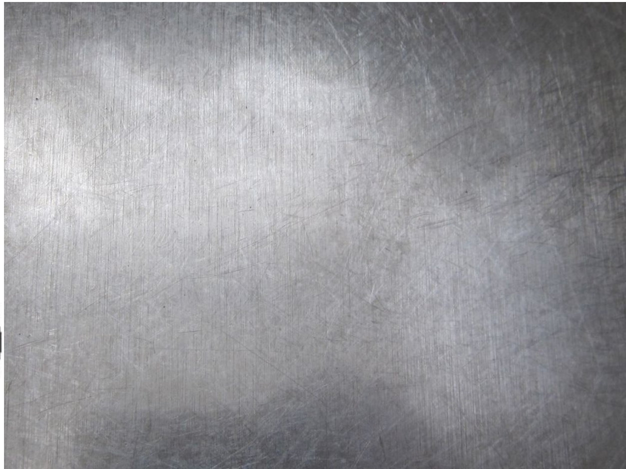


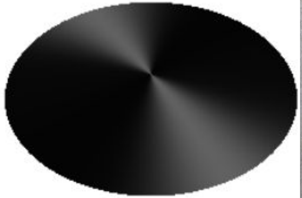
Figure 1: Applicability of Techniques

Materials



- Isotropic
  - Reflectance invariant of rotation about the surface normal
  - Paints, papers, plastics, (sandblasted) metals
- Anisotropic
  - Not isotropic
  - Roughness **biased** in some direction
  - Materials with grains, fibers, grooves, crystalline structures
  - Wood, brushed metal, marble

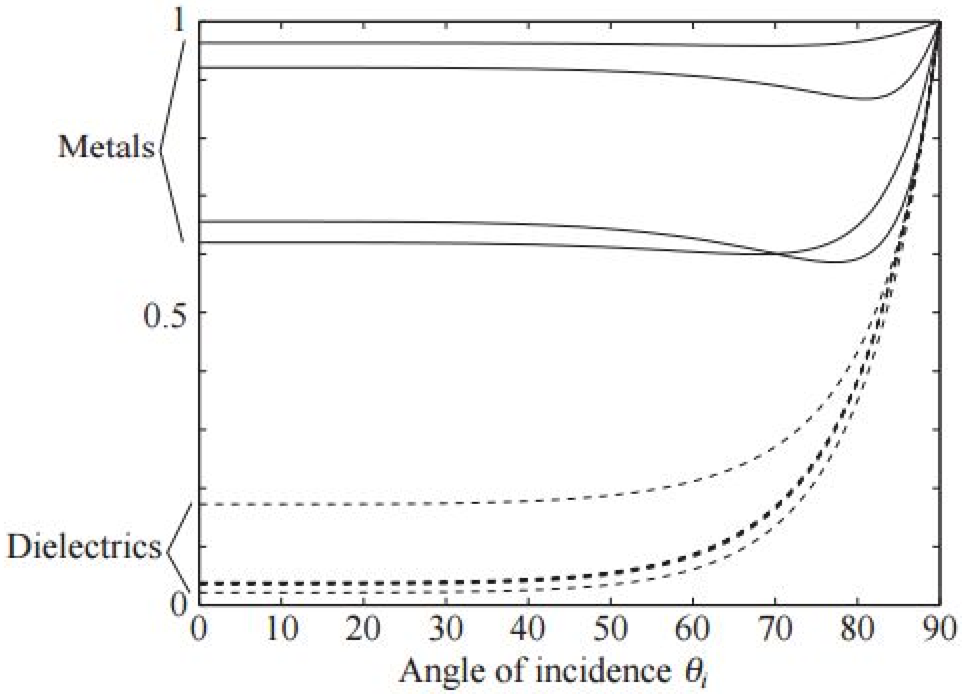




[Heidrich-Seidel]
Efficient Rendering of Anisotropic Surfaces Using Computer Graphics Hardware (1998)

Materials

- Metals
  - Conductors
- Dielectrics
  - Insulators
  - Glass, plastic…
- (Semiconductors)
  - Rare in practice, often ignored



Specular reflectance by angle of incidence.
Perfectly smooth surfaces.

Materials

- Metals
  - Prevents subsurface scattering
  - Absorbs all energy within a fraction of one wavelength
- Dielectrics
  - **Black dielectrics** absorb all energy, but over a longer distance
  - Other dielectrics reflect significant energy by subsurface scattering
  - "**All non-metallic materials are translucent to some degree**" - Henrik Wann Jensen

Materials

Wave property of light vs. Surface roughness

- X-rays (0.01-20 nm)
- Ultraviolet light (100-400 nm)
- ➢ Visible light (400-700 nm)
- Infrared (800-1000 nm)
- microwave (1-1000 mm)

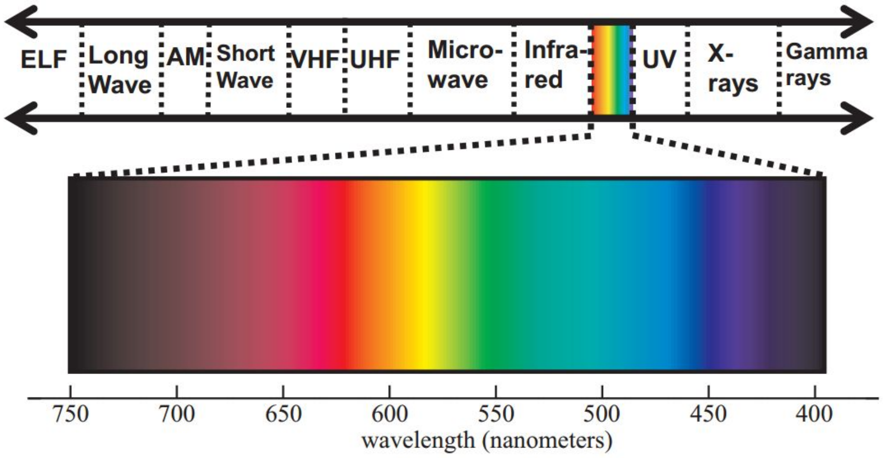


Figure 2: The visible spectrum.

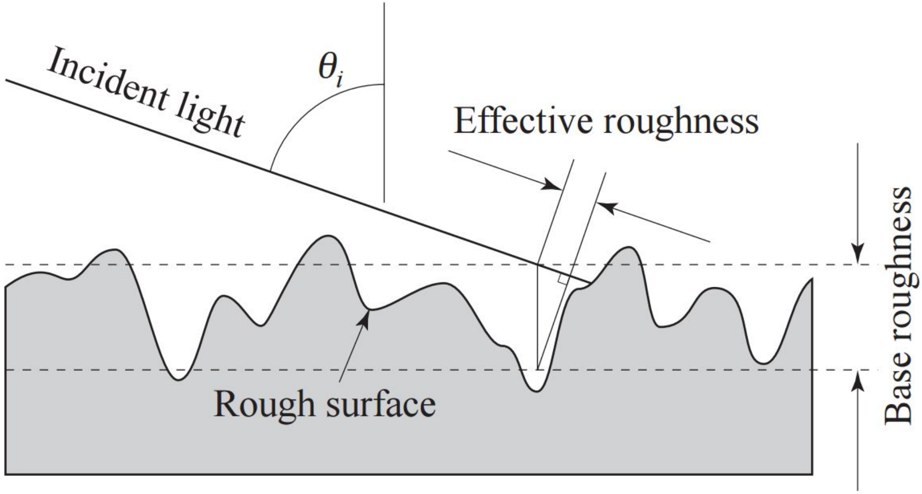
H Davies
The reflection of electromagnetic waves from a rough surface (1954)

Materials: Smooth surfaces

$$\rho \approx F e^{-\left(4\pi \frac{\sigma}{\lambda} \cos\theta_i\right)^2}$$

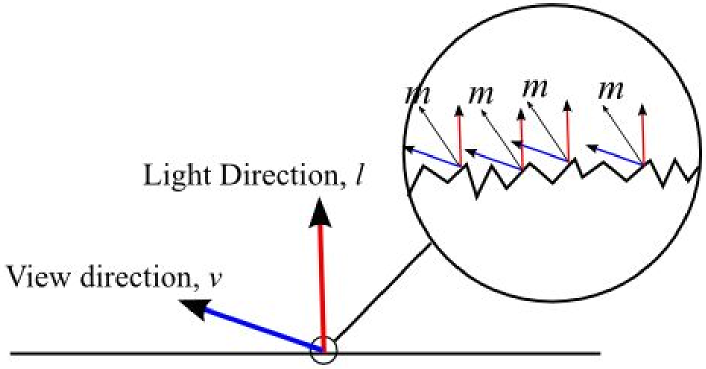
- Surfaces with low roughness:
- ρ: specular reflectance
- F - ρ: non-specular reflectance
- As the exponent approaches 0, all energy becomes specular reflectance

- Rough surfaces can look smooth
  - Effective roughness ≈ 0



Materials: Rough surfaces

- Roughness much greater than wavelength
- Rough surfaces:
  - “A set of faces with different slopes” or “microfacets”
  - Detectable with visible light (**millimeter** scale)
- Rough surface models
  - Phong, 1975
  - Cook & Torrance, 1982
  - Ward, 1992
  - Oren-Nayar, 1994



Michael Oren, Shree K. Nayar
Generalization of Lambert's Reflectance Model (1994)

Reflectance models

- Lambertian (*diffusely reflecting*):

$$L_r = \frac{\rho}{\pi} \cos(\theta_i) E_0$$

- Oren-Nayar:

$$L_r = \frac{\rho}{\pi} \cos(\theta_i) S E_0$$

$$S = A + (B\, max[0, \cos(\phi_i - \phi_r)] \sin\alpha \tan\beta)$$

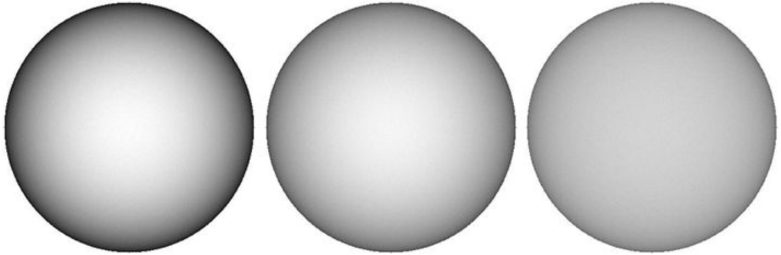
$$A = 1 - 0.5 \frac{\sigma^2}{\sigma^2 + 0.57}$$

$$B = 0.45 \frac{\sigma^2}{\sigma^2 + 0.09}$$

$$\alpha = max(\theta_i, \theta_r)$$

$$\beta = min(\theta_i, \theta_r)$$

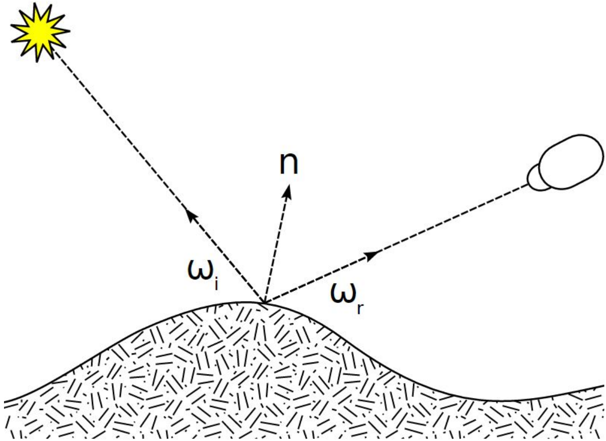
Real Image Lambertian Model Oren-Nayar Model



$\sigma = 0$ $\sigma = 0.1$ $\sigma = 0.3$

Models: BRDF

- BRDF (Bidirectional reflectance distribution function)
  - Assumes that light enters and leaves at the same point
  - Incoming direction $\mathbf{w_i}$, outgoing direction $\mathbf{w_o}$
  - BRDF: Ratio of reflected radiance exiting along $\mathbf{w_o}$ to the irradiance incident to $\mathbf{w_i}$
- Physically plausible if…
  - Always positive
  - Reciprocal: w_i, w_o can be swapped for the same result
  - Energy-conserving: sum over the hemisphere is **one or less**.*
- Part of the rendering equation (…)



* Error in reading material: "Σ f ≥ 1"

The Rendering Equation

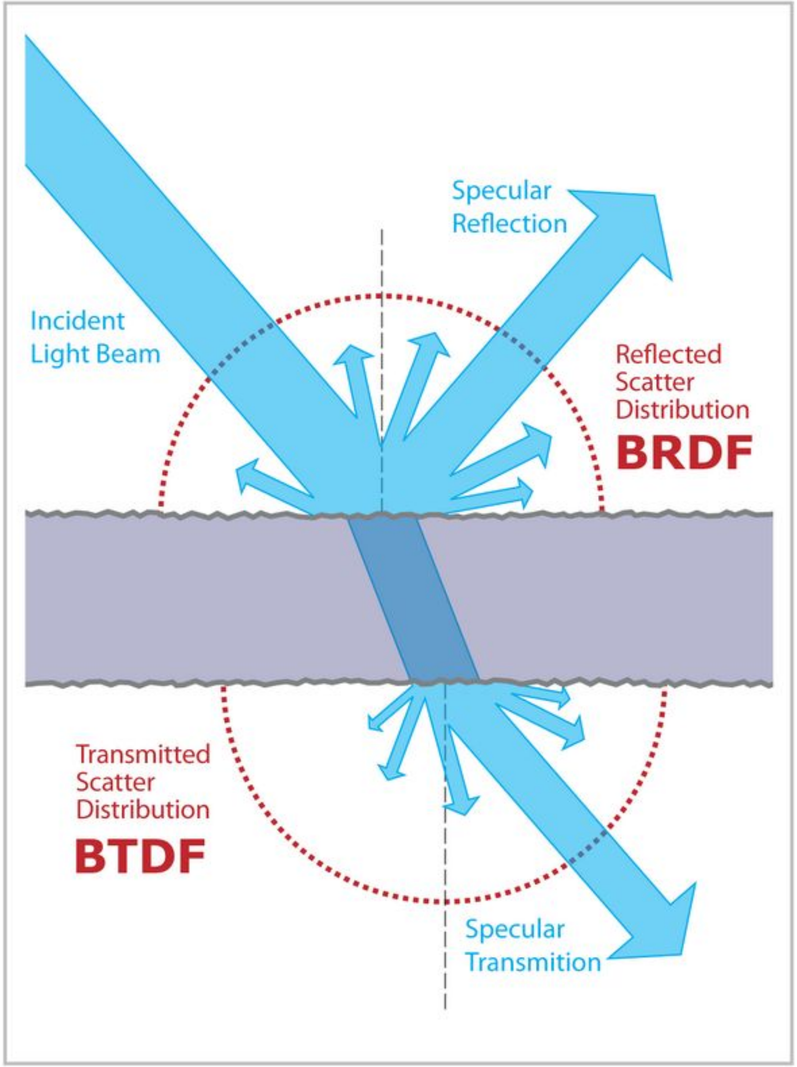
- The radiance is…
  - **Emitted** radiance, plus
  - **Reflected** radiance, over all incoming directions $\mathbf{w_i}$ of the hemisphere $\mathbf{\Omega}$ along $\mathbf{w_o}$

$$L_o(\boldsymbol{x}, \boldsymbol{\omega}_o, \lambda) = L_e(\boldsymbol{x}, \boldsymbol{\omega}_o, \lambda)$$

$$+ \int_\Omega \underline{f(\boldsymbol{x}, \boldsymbol{\omega}_i, \boldsymbol{\omega}_o, \lambda)} L_i(\boldsymbol{x}, \boldsymbol{\omega}_i, \lambda) \cos\theta d\boldsymbol{\omega}_i$$

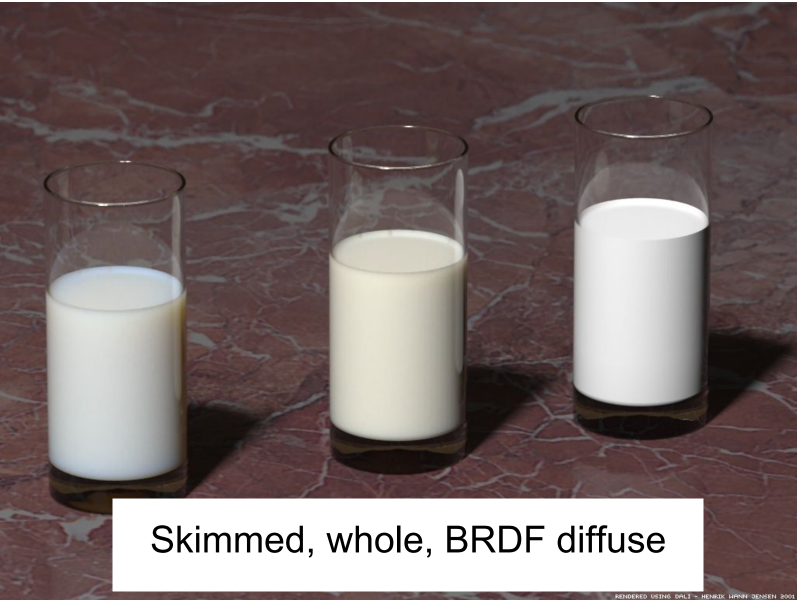
Models: BTDF, BSDF

- BTDF: Transmission
- BSDF: BRDF + BTDF

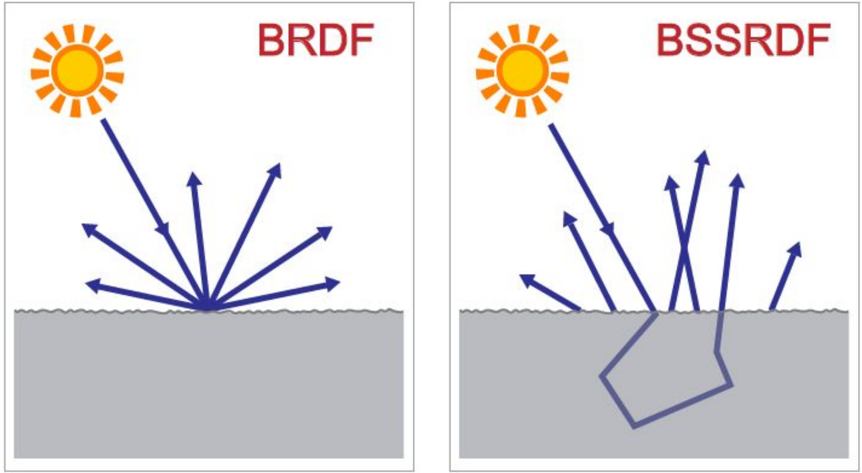


Models: BSSRDF

- BSSRDF (Bidirectional reflectance distribution function)
  - General case of BRDF
  - Entry and exit point do not have to be the same
  - Same laws (energy conservation, reciprocity)



Skimmed, whole, BRDF diffuse



Subsurface Scattering

- Not obvious to take into account
- Obvious when the effect is missing



Subsurface Scattering

- Translucent materials
  - Wax, milk, marble
- Different shapes and colors inside
  - Leaves, skin
- Light enters, scatters within, and exits
- Some light may be absorbed

Subsurface Scattering

- Single scattering approximation
  - A single bounce
  - Estimate number of photons reflected toward camera

- Depth map approximation
- Texture space diffusion
  - “General blurring of the diffuse lighting”

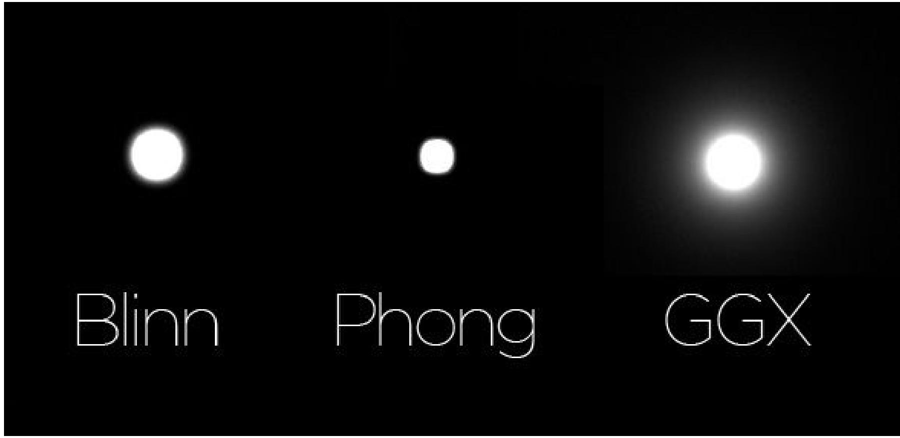
Subsurface Scattering - Multiple Layers

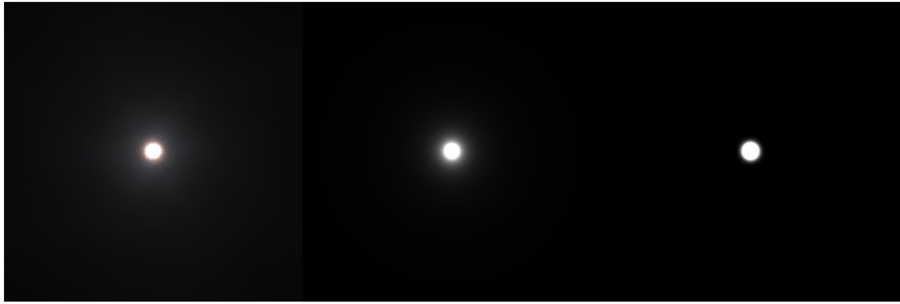
- Light Diffusion in Multi-Layered Translucent Materials (2005)
  - The skin is composed of **three layers**: epidermis, dermis, and the bloody dermis.
  - Scattering parameters for the layers are from **measured data** in medical literature.
  - The multilayered model gives the skin a **less waxy look** compared to the standard BSSRDF
- Reflectance and transmittance over radial distance
- Unique functions per layer

Figure 5: *A buddha statuette sprayed with a thin layer of white paint. The first and third images are front-lit, the second and fourth back-lit.*

Models: BRDF

- Many models
  - Difference in highlights
  - Size, fall-off
- Physically plausible
  - Cook-Torrance (1982)
  - GGX (2007)
  - Schlick (1994)
  - Oren-Nayar (non-simplified; 1994)



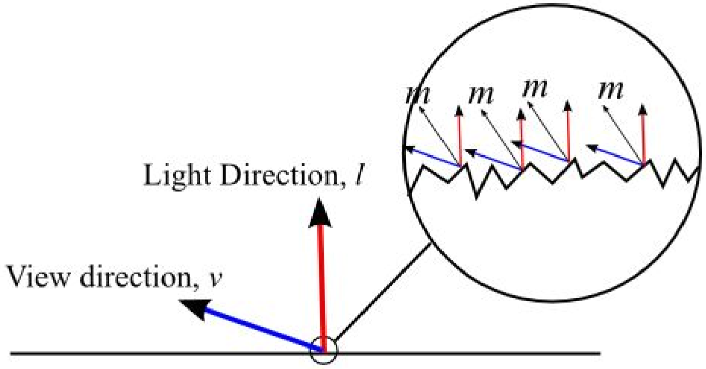


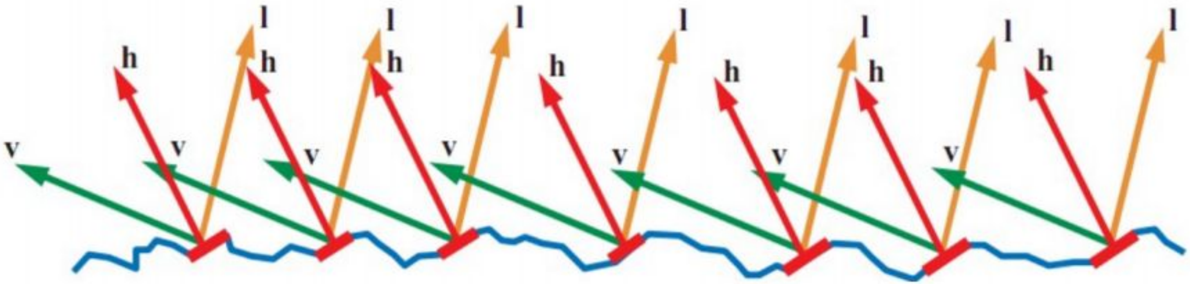
Chrome, GGX, Beckmann
Source: *Physically-Based Shading at Disney* (2012)

Cook-Torrance

Paper:
A Reflectance Graphics Model for Computer Graphics (1982)

- Two components
  - $\mathbf{f} = d\mathbf{f}_{\mathbf{diff}} + s\mathbf{f}_{\mathbf{spec}}$
  - Weights: d + s = 1
- Diffuse
  - “Body reflectance”
  - Independent of viewing angle; constant term
  - (Approximates subsurface scattering)
- Specular
  - “Surface reflectance”
  - Models **microfacets**
  - h = normalize(l + v)
  - Contributes if h = n





Cook-Torrance: Microfacet phenomena

- Shadowing
  - Light-occlusion by microgeometry
  - “Self-shadowing”
- Masking
  - Visibility-occlusion by microgeometry
  - “Self-occlusion”
- Interreflections
  - When facets reflect onto other facets
  - <u>Not</u> taken into account

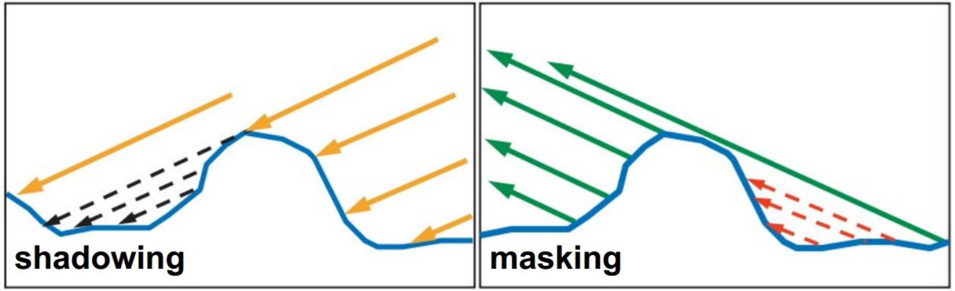


Figure 2: On the left, occlusion of light source by microgeometry (shadowing). On the right, visibility occlusion of microgeometry (masking). Source: [1]

Cook-Torrance: $f_{\text{spec}}(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \frac{F}{\pi} \frac{GD}{(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)(\boldsymbol{n} \cdot \boldsymbol{\omega}_o)}$

- Reflectance: $\mathbf{f} = d\mathbf{f}_{\mathbf{diff}} + s\mathbf{f}_{\mathbf{spec}}$
  - d + s = 1
  - $\mathbf{f}_{\mathbf{diff}}$ is constant (e.g. Lambertian)
- f_{spec}
  - F: Fresnel term
  - G: Geometric attenuation (shadowing, masking)
  - D: Normal distribution of facets oriented along **h**

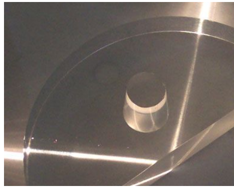
Cook-Torrance: $$f_{\text{spec}}(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \frac{F}{\pi} \frac{GD}{(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)(\boldsymbol{n} \cdot \boldsymbol{\omega}_o)}$$

Fresnel term F

$$F(\theta) = \frac{1}{2} \frac{(g-c)^2}{(g+c)^2} \left(1 + \frac{(c(g+c)-1)^2}{(c(g-c)+1)^2}\right)$$

$$c = \cos\theta = \boldsymbol{v} \cdot \boldsymbol{h}$$

$$g = \sqrt{\eta^2 + c^2 - 1}$$



Geometric attenuation G

$$G(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \min\left\{1, \frac{2(\boldsymbol{n} \cdot \boldsymbol{h})(\boldsymbol{n} \cdot \boldsymbol{\omega}_o)}{(\boldsymbol{\omega}_o \cdot \boldsymbol{h})}, \frac{2(\boldsymbol{n} \cdot \boldsymbol{h})(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)}{(\boldsymbol{\omega}_o \cdot \boldsymbol{h})}\right\}$$

Normal distribution D - (fraction of facets with normal = h) : (Phong, Heidrich-Seidel, GGX…)

Beckmann (rough surfaces):

$$D_{Beckmann} = \frac{1}{m^2 \cos^4 \alpha} e^{-[(\tan\alpha/m]^2}$$

Gaussian:

$$D_{Gaussian} = c\, e^{-\left(\frac{\alpha}{m^2}\right)}$$

GGX

- Microfacet distribution model **D**
- Improvement over Beckmann distribution
    - Better fit to measured data (for some surfaces)
    - Derived from geometry term **G**
- BSDF
    - Handles transmittance

Paper:
Microfacet Models for Refraction through Rough Surfaces (2007)

GGX

Cook-Torrance specular BRDF:

$$f_{\text{spec}}(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \frac{F}{\pi} \frac{GD}{(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)(\boldsymbol{n} \cdot \boldsymbol{\omega}_o)}$$

GGX BRDF:

$$f(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \frac{FGD}{4(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)(\boldsymbol{n} \cdot \boldsymbol{\omega}_o)}$$

GGX

Beckmann D (used in Cook-Torrance):

$$D_{Beckmann} = \frac{1}{m^2 \cos^4 \alpha} e^{-[(\tan \alpha / m]^2}$$

GGX D:

$$D = \frac{\alpha_g^2 \chi^+(\boldsymbol{h} \cdot \boldsymbol{n})}{\pi \cos^4 \theta_h (\alpha_g^2 + \tan^2 \theta_h)^2}$$

GGX

Cook-Torrance G:

$$G(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) = \min\left\{1, \frac{2(\boldsymbol{n}\cdot\boldsymbol{h})(\boldsymbol{n}\cdot\boldsymbol{\omega}_o)}{(\boldsymbol{\omega}_o\cdot\boldsymbol{h})}, \frac{2(\boldsymbol{n}\cdot\boldsymbol{h})(\boldsymbol{n}\cdot\boldsymbol{\omega}_i)}{(\boldsymbol{\omega}_o\cdot\boldsymbol{h})}\right\}$$

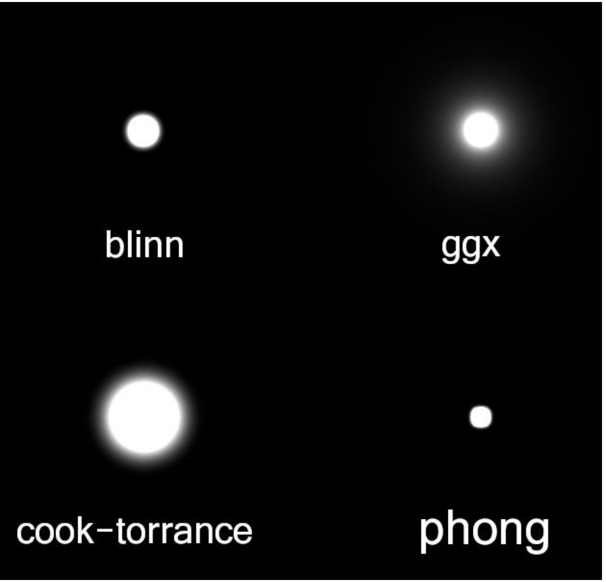
GGX G (Smith):

$$G(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o) \approx G_1(\boldsymbol{\omega}_i) G_1(\boldsymbol{\omega}_o)$$

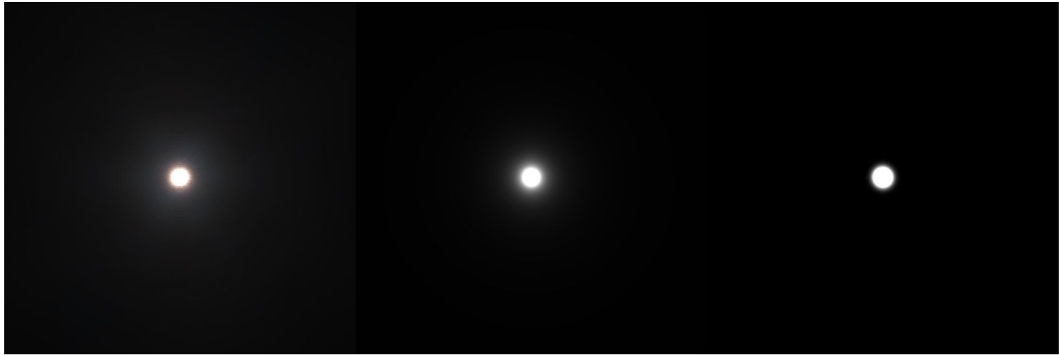
$$G_1(\boldsymbol{v}) = \chi^+\left(\frac{\boldsymbol{v}\cdot\boldsymbol{h}}{\boldsymbol{v}\cdot\boldsymbol{n}}\right)\frac{2}{1+\sqrt{1+\alpha_g^2\tan^2\theta_v}}$$

GGX: Result

- Bigger tail
- Closer to real surfaces



(Measured chrome), GGX, Beckmann



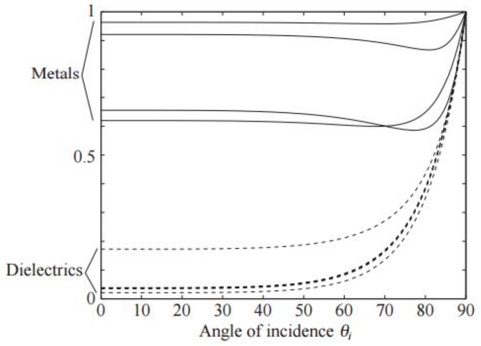
Schlick

Paper by Christophe Schlick:
An Inexpensive BRDF Model for Physically-based Rendering (1994)

Problems with BRDF models:

- Linear combination of specular, diffuse
  - Constant weights (Cook-Torrance: $\mathbf{f} = d\mathbf{f}_{\mathbf{diff}} + s\mathbf{f}_{\mathbf{spec}}$)
  - Instead, **f** should be a function of incident angle
- **G** only models reflection toward light
  - **G**: the fraction of light **not obstructed** by microgeometry
  - Problem: the (unabsorbed) obstructed light (**1 - G**) is reflected elsewhere in reality
  - Existing models do not account for this “re-emission” of light
- Physically plausible models are expensive
  - Schlick’s approximation

Schlick: Approximations

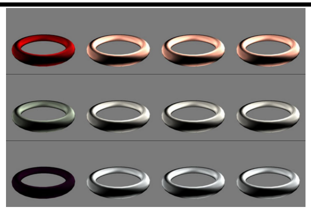


Fresnel term F (Cook-Torrance):

$$F(\theta) = f_0 + (1 - f_0)(1 - \cos\theta)^5 \qquad f_0 = \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}\right)^2$$

* Paper:
Fresnel term approximations for Metals (2005)

$$\boxed{F^*(n, k, \cos\theta) := \frac{(n-1)^2 + 4n(1-\cos\theta)^5 + k^2}{(n+1)^2 + k^2}}$$



Geometrical attenuation G (Smith):

$$G(v) = \frac{v}{v - kv + k} \quad \text{with} \quad k = \sqrt{\frac{2m^2}{\pi}}$$

Distribution D (Beckmann):

$$\forall t \in [1-m, 1] \quad D(t) = \frac{m^3 x}{t\,(mx^2 - x^2 + m^2)^2} \quad \text{with} \quad x = t + m - 1$$

Schlick

- Approximations → faster Cook-Torrance
- Two new BRDF models:
  - Homogeneous
    - metal, glass, paper, cotton
  - Heterogeneous (two layers)
    - opaque layer + translucent layer
    - varnished wood, lacquered glass
- Layer properties
  - All values in [0, 1]:
  - C_λ: Reflection factor at wavelength λ
  - r: Roughness factor (0: perfectly specular; 1: perfectly diffuse)
  - p: Isotropy factor (0: perfectly anisotropic; 1: perfectly isotropic)

Summary: Cook-Torrance, GGX, Schlick

- Physically plausible?
  - Reciprocal: **All**
  - Energy-conserving: **GGX**, **Schlick**
  - **Cook-Torrance**: not energy-conserving under all angles

Summary: Cook-Torrance, GGX, Schlick

- **Cook-Torrance**
  - **Suitable for**: plastics, metals.
  - “Not as intuitive parameters. Experimentation required”
  - **F, D, G** are independent and can be replaced.
- **GGX**
  - **Suitable for**: developed for transmittance through rough surfaces (etched glass)
  - In general, “improved Cook-Torrance”
  - Many different versions of **D, G**
- **Schlick**
  - **Suitable for**: heterogeneous materials (translucent + opaque)
  - Continuums for isotropy, specular/diffuse
  - “Intuitive parameters”

Overview

Models	Physical	Plausible	Fresnel Eq.	Anisotrotopic	Sampling	Rel.Cost (cycles)	Material Type
Ideal Specular	★	★	▼	▼	★	x	perfect specular
Ideal Diffuse	★	★	▼	▼	★	x	perfect diffuse
Minnaert	▼	···	▼	▼	▼	$5.35x$	Moon surf.
Torrance-Sparrow	★	▼	★	★	▼	···	rough surf.
Beard-Maxwell	★	▼	★	▼	▼	$397x$	painted surf.
Blinn-Phong	▼	▼	▼	▼	★	$9.18x$	rough surf.
Cook-Torrance	★	★	★	▼	▼	$16.9x$	metal,plastic
Kajiya	★	▼	★	★	▼	···	metal,plastic
Poulin-Fournier	★	▼	▼	★	▼	$67x$	clothes
Strauss	▼	···	★	▼	▼	$14.88x$	metal,plastic
He et al.	★	★	★	▼	▼	$120x$	metal
Ward	▼	▼	▼	★	★	$7.9x$	wood
Westin	★	···	★	★	▼	···	metal
Lewis	▼	★	▼	▼	★	$10.73x$	mats
Schlick	▼	★	★	★	▼	$26.95x$	heterogeneous
Hanrahan	★	···	★	▼	▼	···	human skin
Oren-Nayar	★	★	▼	▼	★	$10.98x$	matte, dirty.
Neumann	▼	★	▼	★	★	···	metal,plastic
Lafortune	▼	★	▼	★	★	$5.43x$	rough surf.
Coupled	★	★	★	▼	★	$17.65x$	polished surf.
Ashikhmin-Shirley	★	▼	★	★	★	$79.6x$	polished surf.
Granier-Heidrich	★	···	★	▼	▼	···	old-dirty metal

Table 1: *Brief summary of the properties exhibited by the reviewed BRDFs. Legend: (★) if the BRDF has this property; (▼) if the BRDF does not; (···) unknown value.*

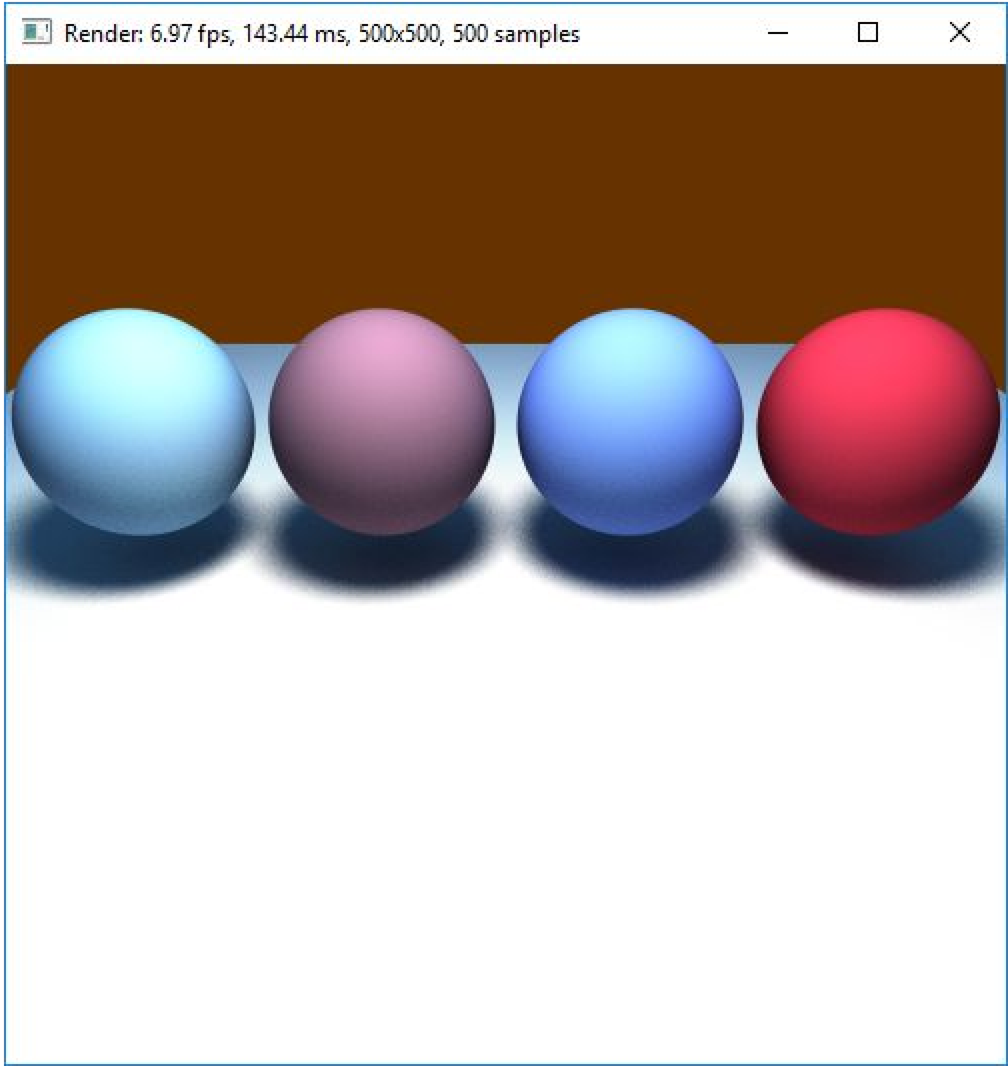
Paper:
An Overview of BRDF Models (2012)

Demo

Lambertian, Oren-Nayar

Roughness:

0 → 0.1 → 0.5 → 0.9

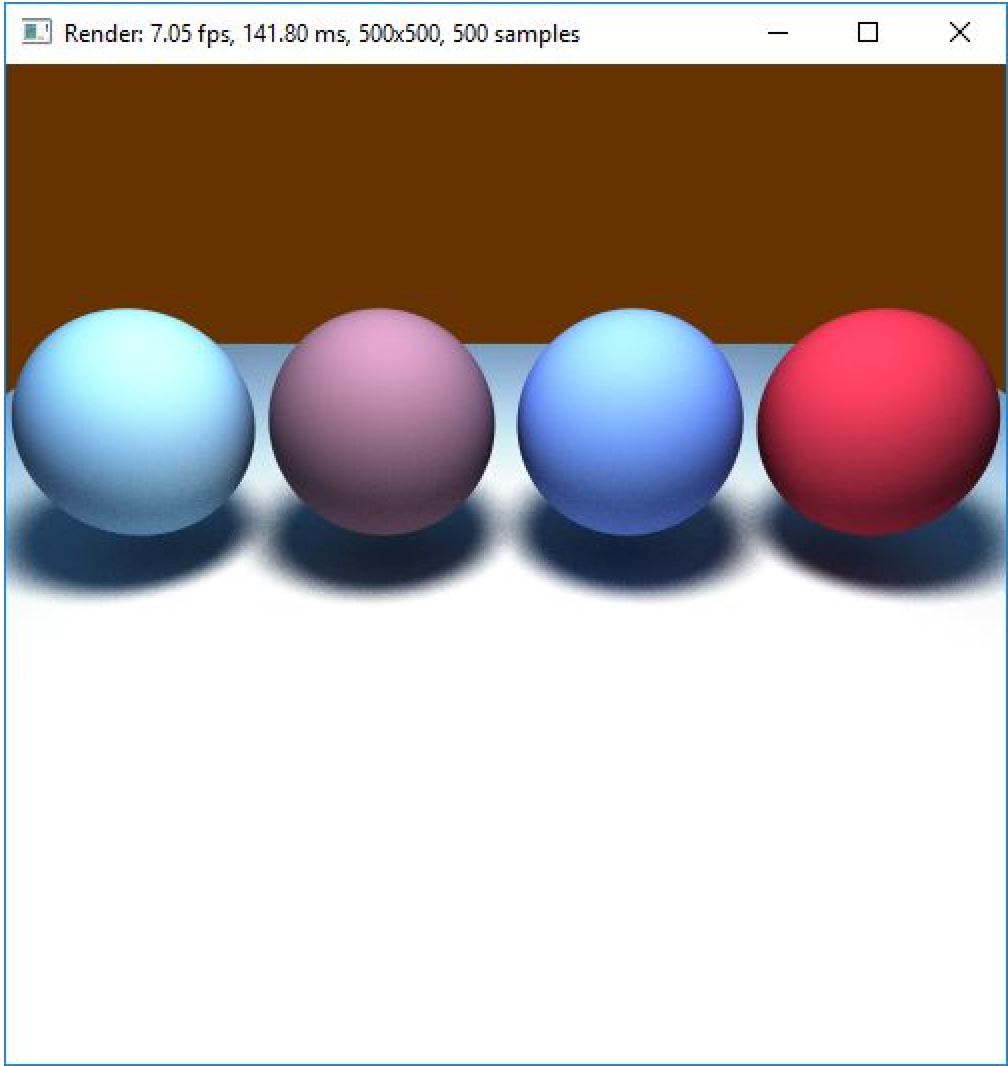


Demo

Lambertian, Oren-Nayar

Roughness:

0 → 0.1 → 0.5 → 0.9

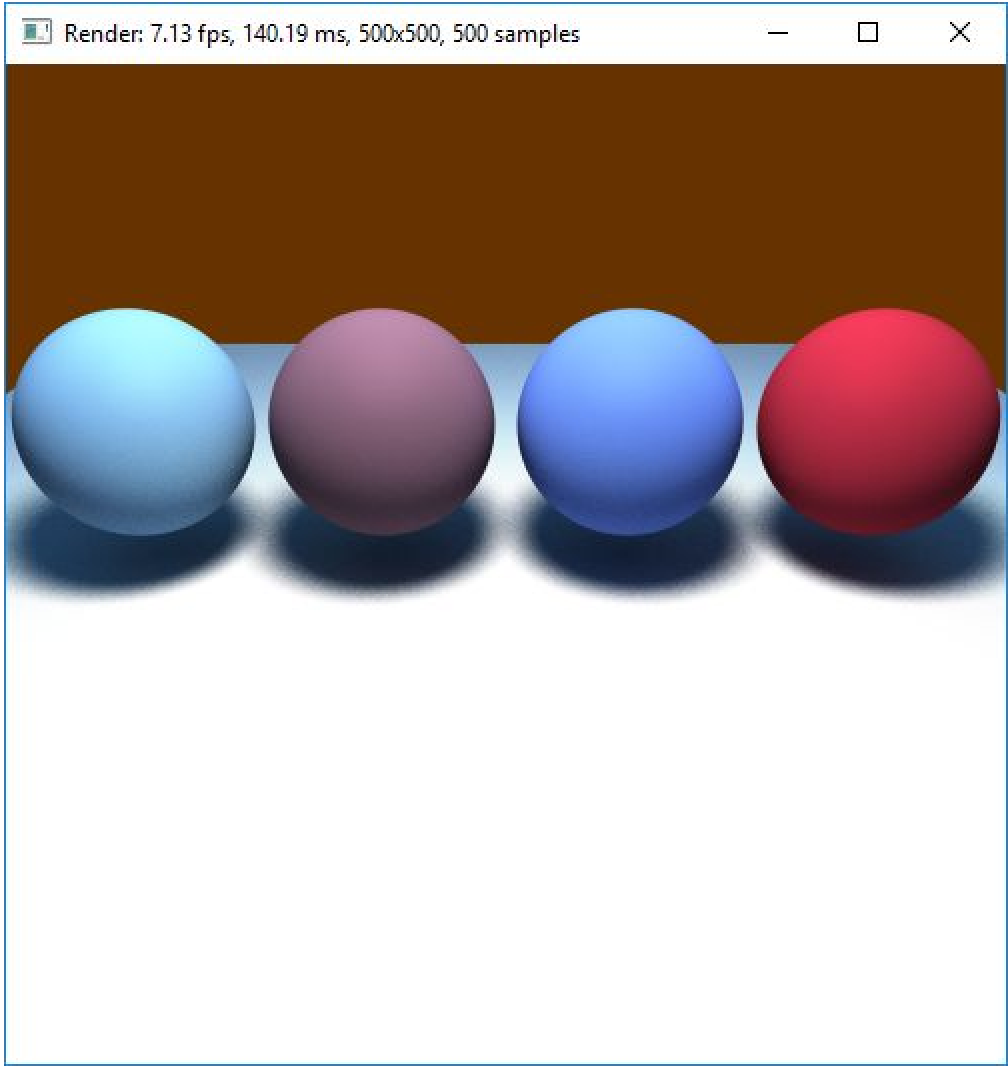


Demo

Lambertian, Oren-Nayar

Roughness:

0 → 0.1 → 0.5 → 0.9

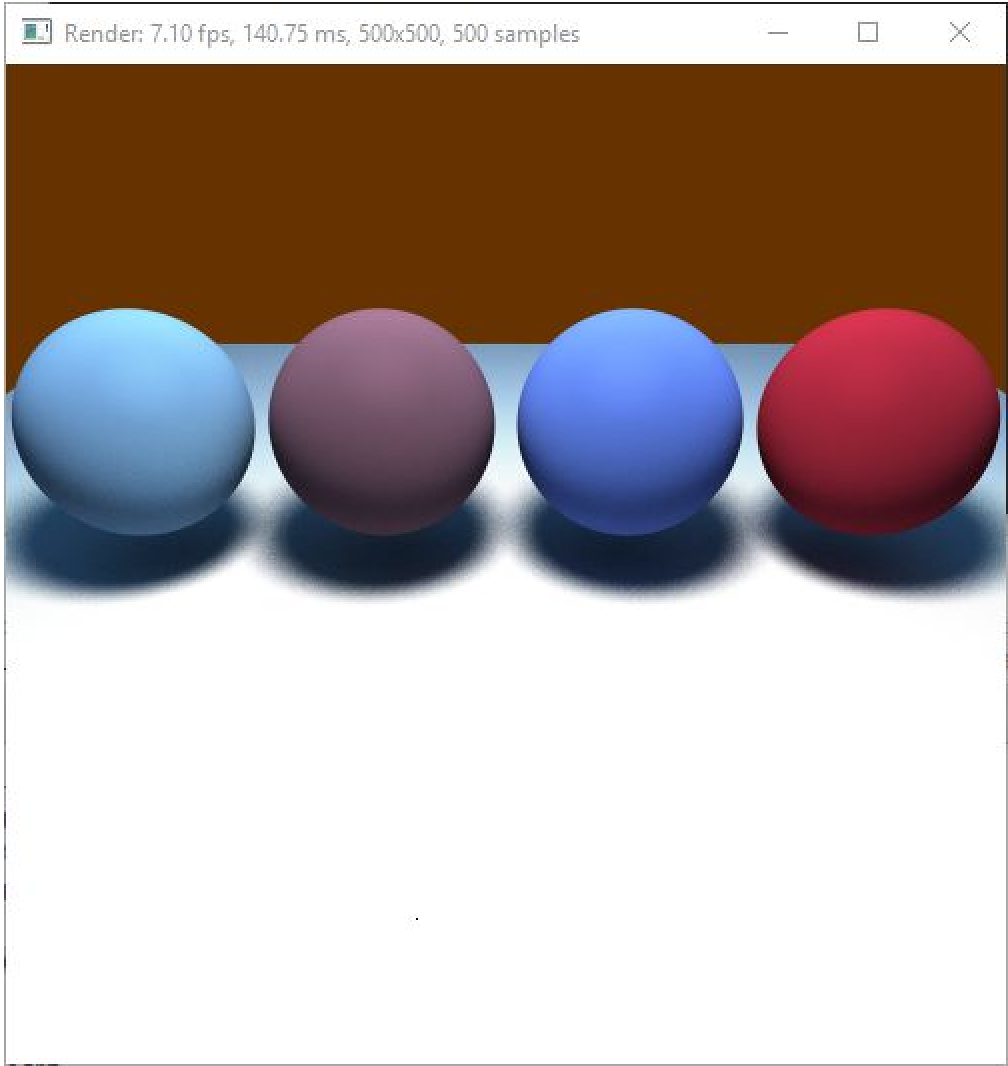


Demo

Lambertian, Oren-Nayar

Roughness:

0 → 0.1 → 0.5 → 0.9



Demo

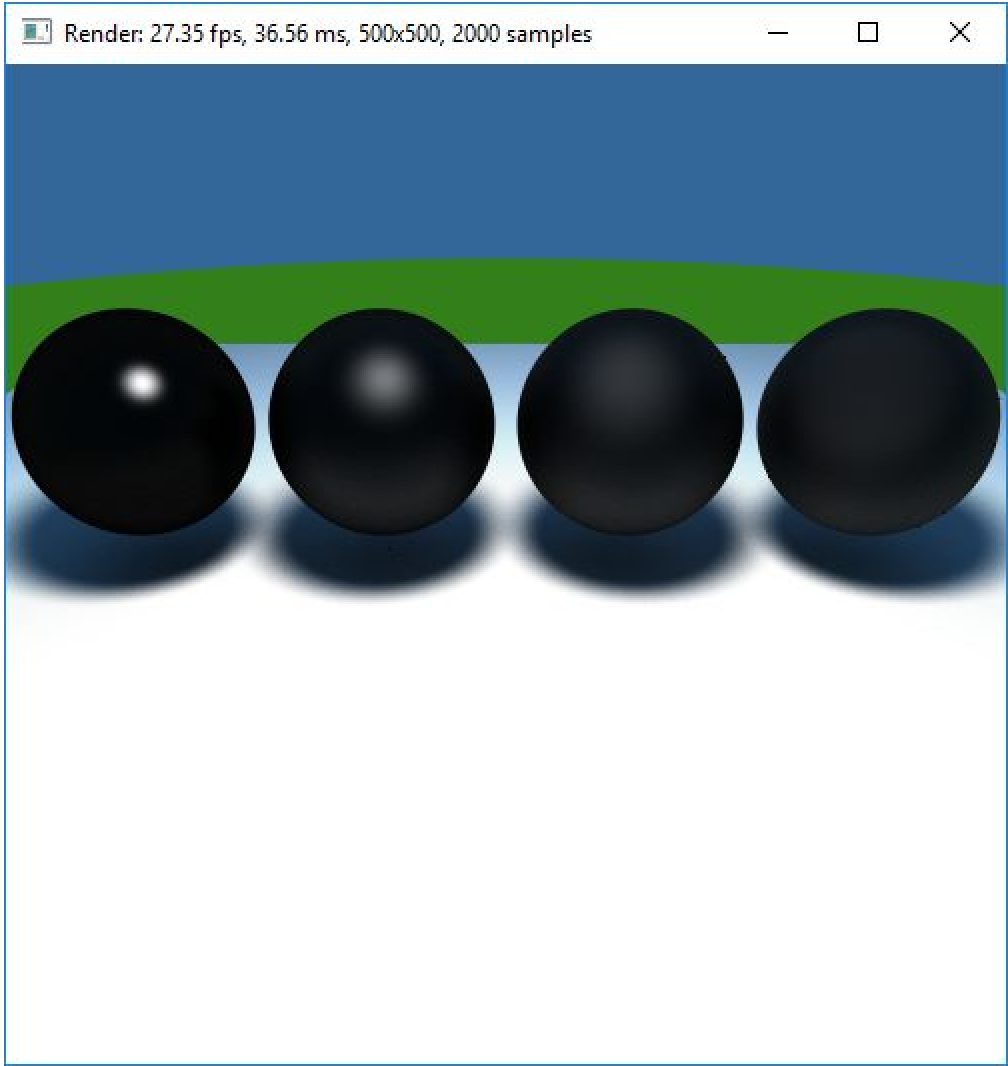
Cook-Torrance (specular only)

ior = 1.5 (typical glass)

($\Rightarrow f_0 = 0.04$)

Roughness:

0.10 → 0.25 → 0.40 → 0.55



Demo

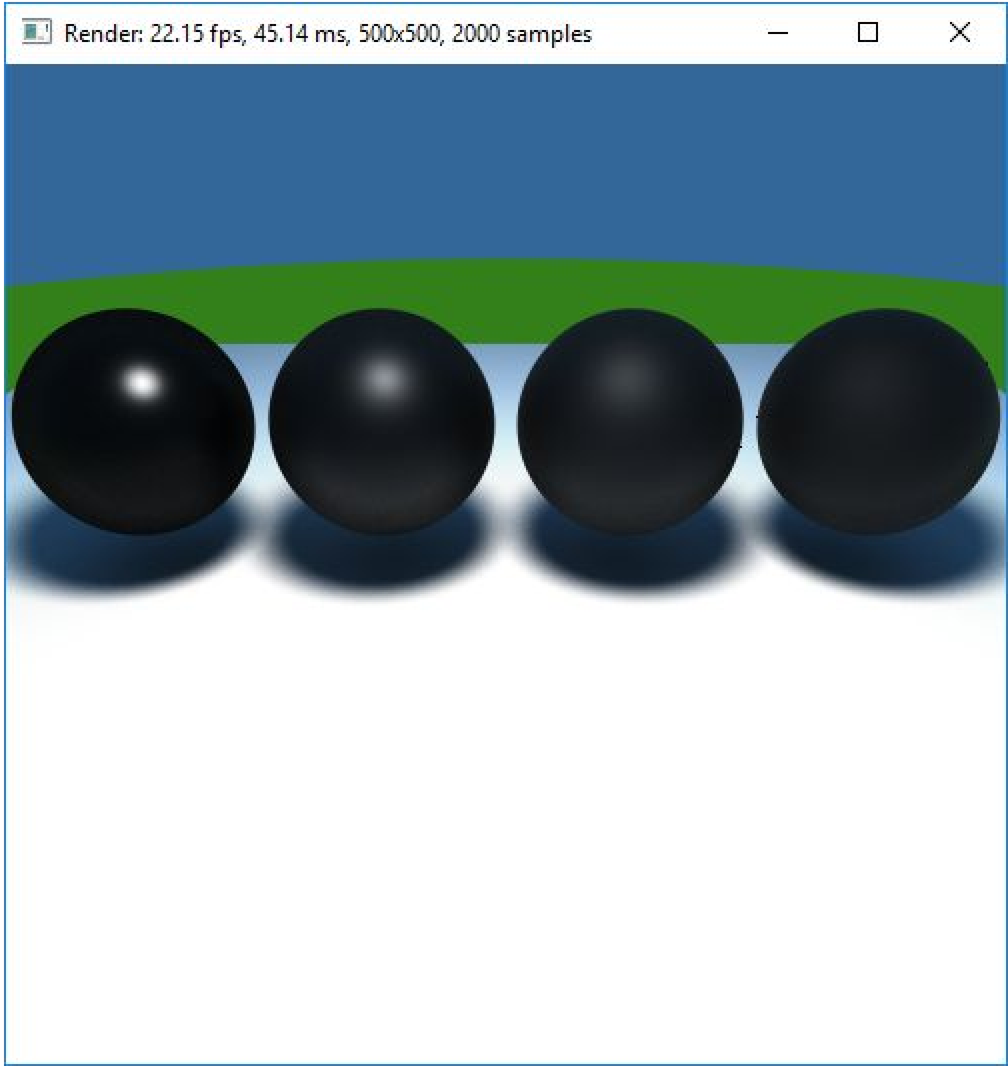
GGX (specular only)

ior = 1.5 (typical glass)

($\Rightarrow f_0 = 0.04$)

Roughness:

0.10 → 0.25 → 0.40 → 0.55



Demo

Cook-Torrance (specular only)

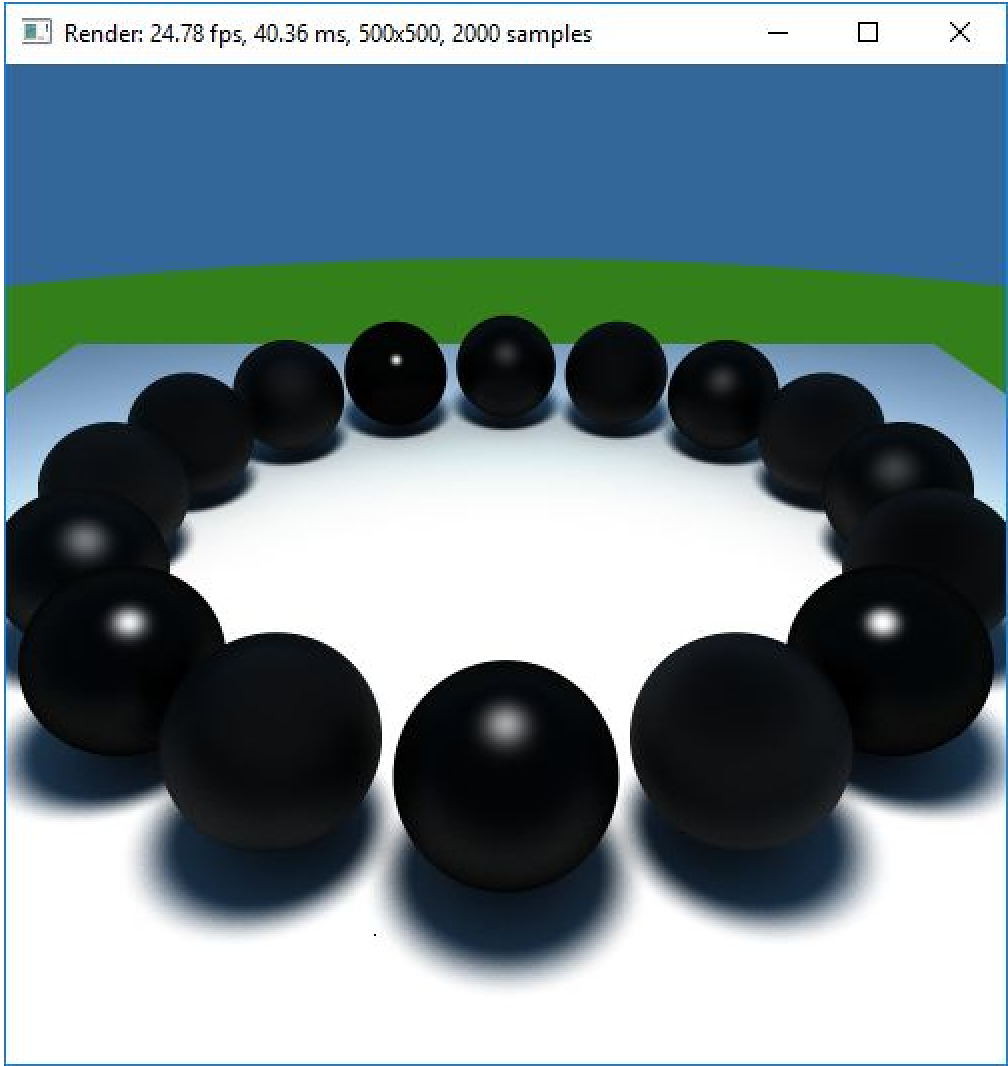
Random parameters:

f0 in [0.02, 0.05]

(⇒ ior in ~[1.33, 1.58])

α in [0, 1]

white specular color



Demo

GGX (specular only)

Random parameters:

f0 in [0.02, 0.05]

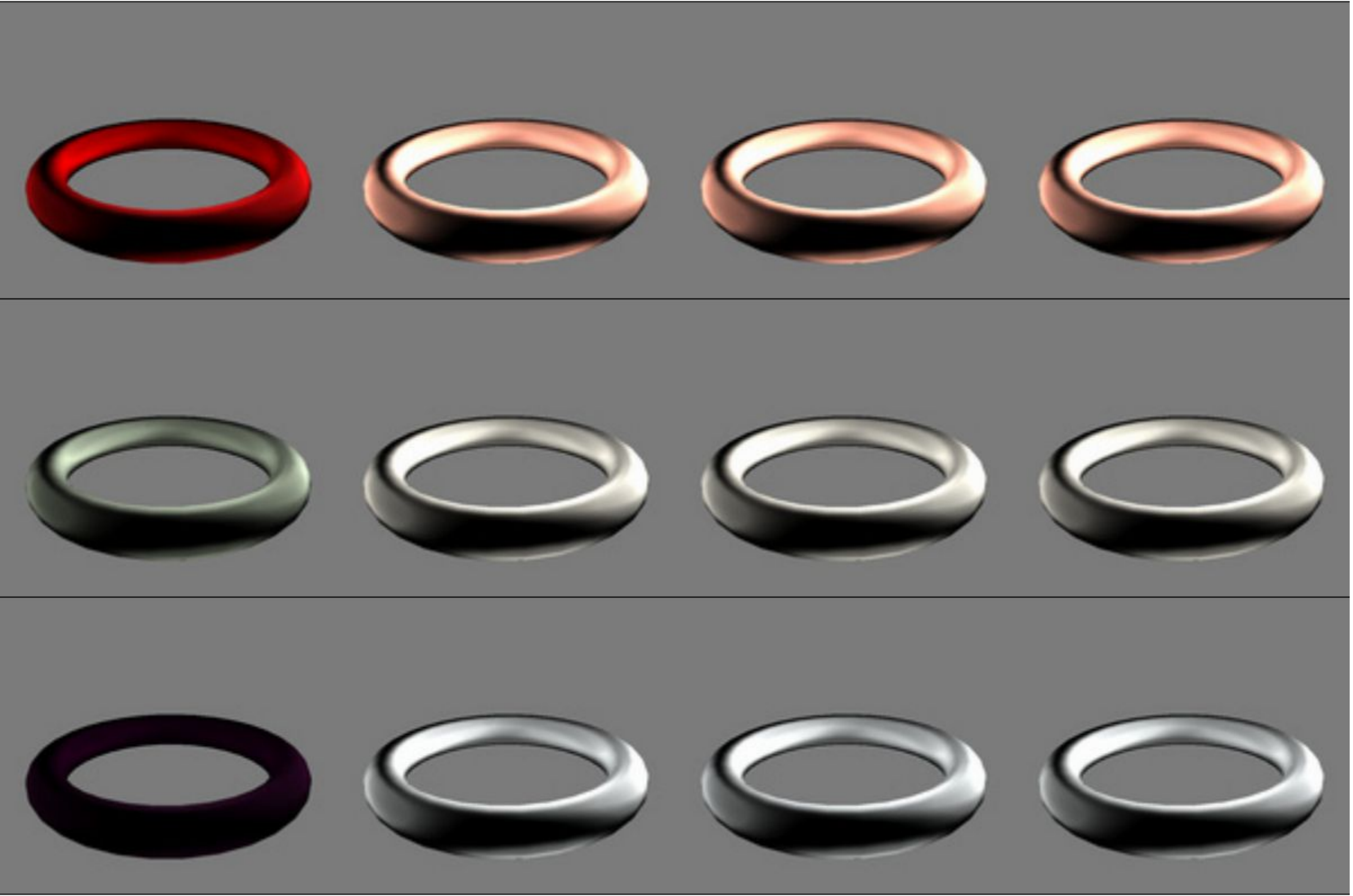
(⇒ ior in ~[1.33, 1.58])

α in [0, 1]

white specular color

The End

Extra



Microfacet distributions visualised

- Experimental Analysis of BRDF Models
  - http://people.csail.mit.edu/addy/research/ngan05_brdf_eval.pdf

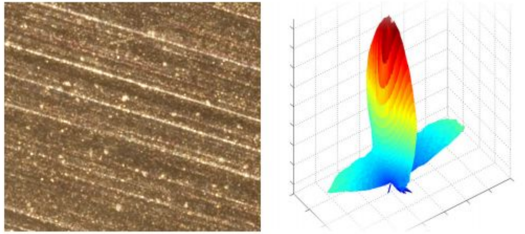


Figure 11: *Left: Brushed aluminium macro photograph. Right: deduced microfacet distribution (log plot).*

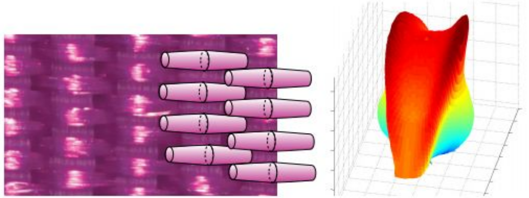


Figure 12: *Left: Purple satin macro photograph with sketched double cones. Right: deduced microfacet distribution (log plot).*

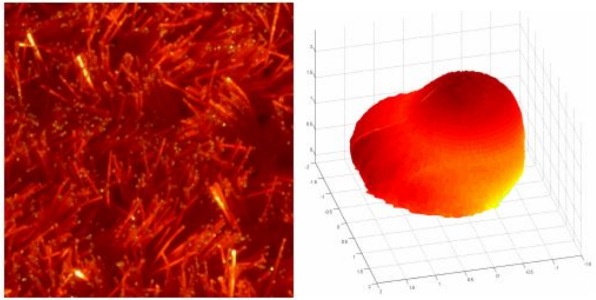


Figure 13: *Left: Red velvet macro photograph. Right: deduced microfacet distribution (log plot).*

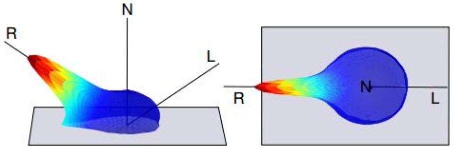


Figure 8: *Side and top-down view of the measured "PVC" BRDF, at 55° incidence. (Cubic root is applied to the BRDF for visualization.) Its specular lobe exhibits a similar asymmetry to the $H \cdot N$ lobe.*