Computer Graphics (CS 543)
Lecture 8a: Physically-Based Lighting Models

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BRDF Evolution

- BRDFs have evolved historically
- 1970's: Empirical models
  - Phong's illumination model
- 1980s:
  - Physically based models
  - Microfacet models (e.g. Cook Torrance model)
- 1990's
  - Physically-based appearance models of specific effects (materials, weathering, dust, etc)
- Early 2000's
  - Measurement & acquisition of static materials/lights (wood, translucence, etc)
- Late 2000's
  - Measurement & acquisition of time-varying BRDFs (ripening, etc)

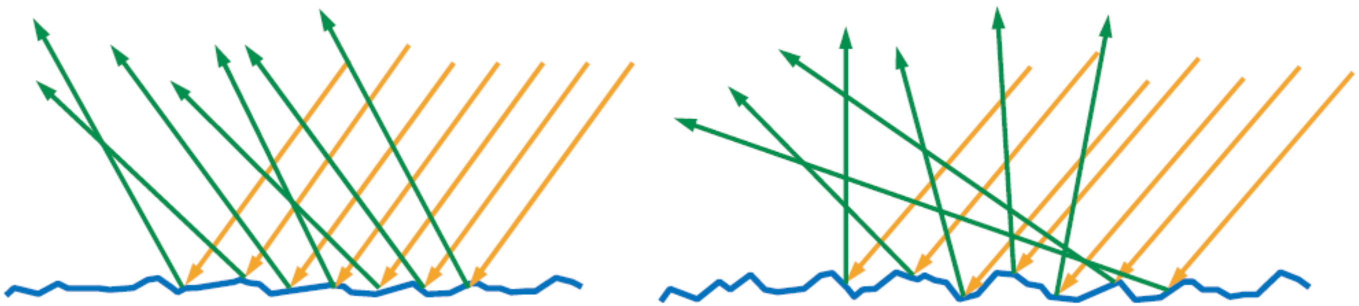
Research: 1980s
Game engines: E.g. Unity in 2014
Game engines 30 years behind research?

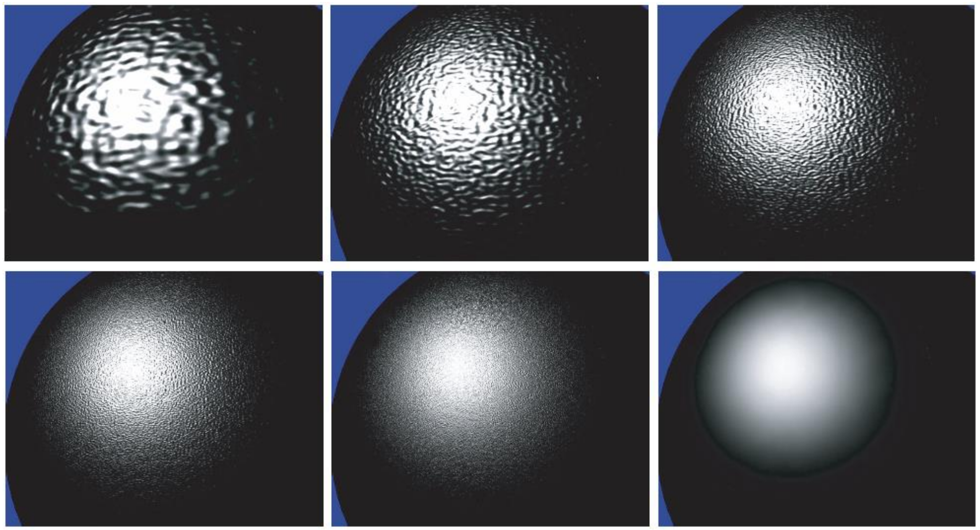
Physically-Based Lighting Models

- Phong model produces pretty pictures
- Cons: empirical (fudged?) ($cos^{\alpha}\phi$), plastic look
- Shaders can implement better lighting/shading models
- Big trend towards Physically-based lighting models
- Physically-based?
  - Based on physics of how light interacts with actual surface
  - Apply Optics/Physics theories
- Classic: Cook-Torrance shading model (TOGS 1982)

Microgeometry

- Rougher surfaces bounce light all over the place

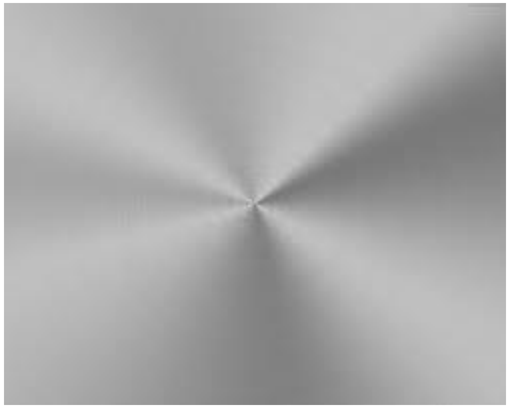




Increasing roughness

Isotropic Vs Anisotropic Surfaces

- **Isotropic:** light bounced equally in all directions
- **Anisotropic:**
  - Surface has grooves with directions. E.g. Brushed steel
  - Light bounced differently along vs across the grain.



Isotropic

Anisotropic (brushed steel)

Cook-Torrance Shading Model

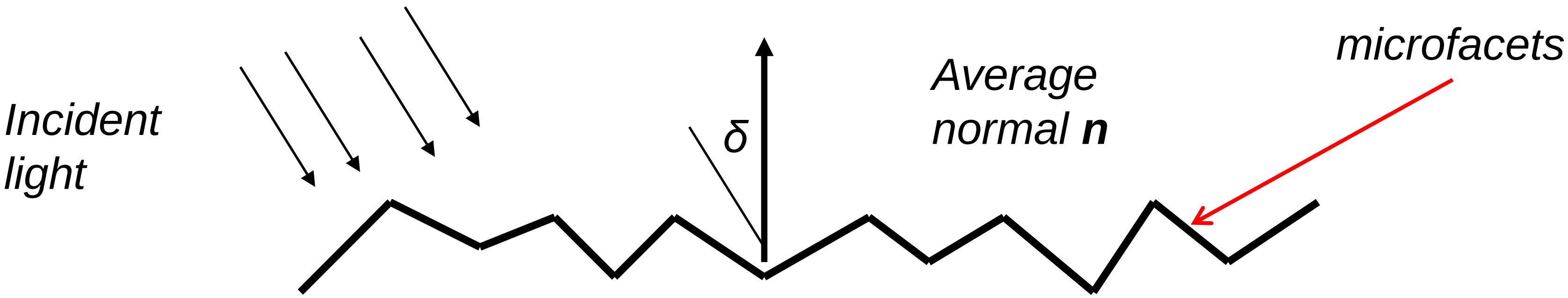
- Same ambient and diffuse terms as Phong
- New, better specular component than ($cos^{\alpha}\phi$),

$$\cos^{\alpha}\phi \rightarrow \frac{F(\phi,\eta)DG}{(\mathbf{n}\cdot\mathbf{v})}$$

- Where
  - D - Distribution term
  - G – Geometric term
  - F – Fresnel term

Distribution Term, D

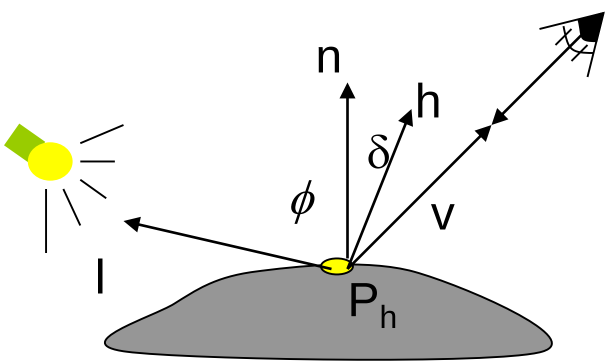
- **Idea:** surfaces consist of small V-shaped **microfacets (grooves)**

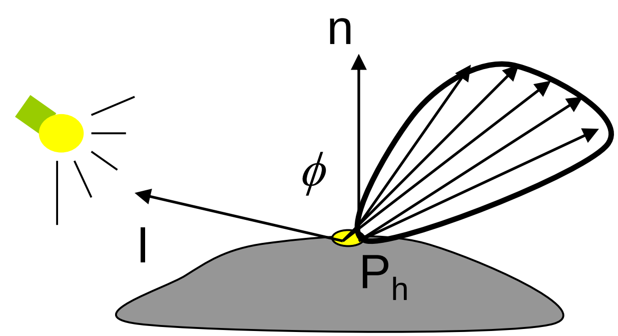


- Many grooves at each surface point
- Grooves facing a direction contribute
- D(δ) term: what fraction of grooves facing each angle δ
- E.g. half of grooves at hit point face 30 degrees, etc

Cook-Torrance Shading Model

- Define angle δ as deviation of **h** from surface normal
- Only microfacets with pointing along halfway vector, **h = s + v**, contributes





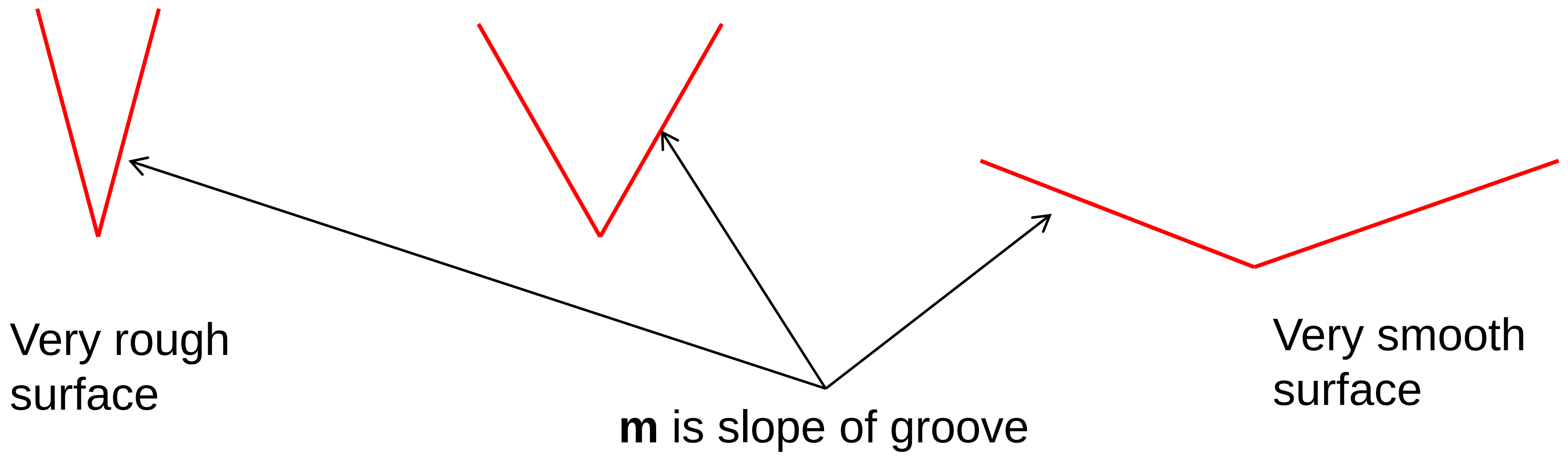
- Can use old Phong cosine ($cos^n \phi$), as D
- Use Beckmann distribution instead

$$D(\delta) = \frac{1}{4\mathbf{m}^2 \cos^4(\delta)} e^{-\left(\frac{\tan(\delta)}{\mathbf{m}}\right)^2}$$

- **m** expresses roughness of surface. How?

Cook-Torrance Shading Model

- **m** is Root-mean-square (RMS) of **slope** of V-groove
- m = 0.2 for nearly smooth
- m = 0.6 for very rough

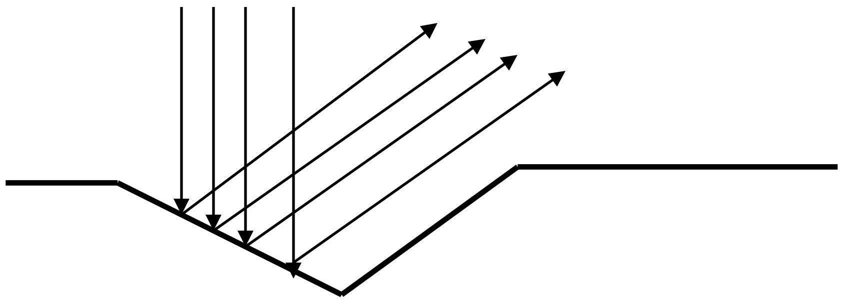


Self-Shadowing (G Term)

- Some grooves on extremely rough surface may block other grooves

Geometric Term, G

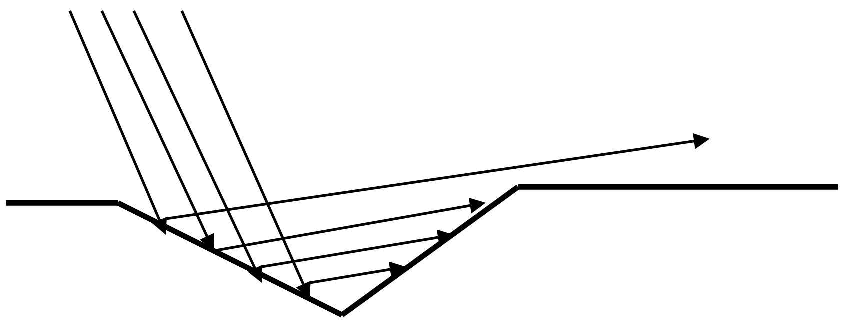
- Surface may be so rough that interior of grooves is blocked from light by edges
- Self blocking known as **shadowing** or **masking**
- Geometric term G accounts for this
- Break G into 3 cases:
- G, case a: No self-shadowing (light in-out unobstructed)



- Mathematically, G = 1

Geometric Term, G

- G_m, case b: No blocking on entry, blocking of exitting light **(masking)**



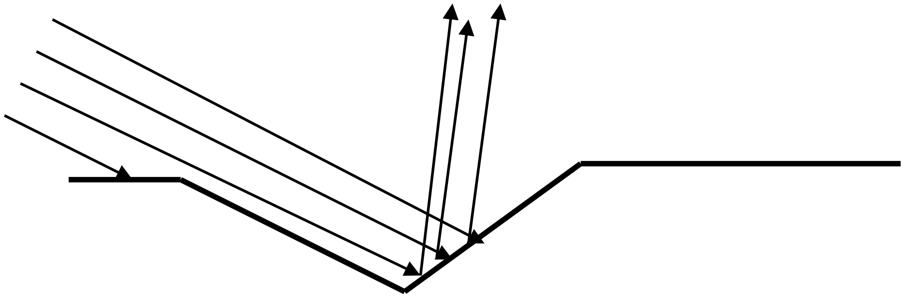
- Mathematically,

$$G_m = \frac{2(\mathbf{n} \cdot \mathbf{h})(\mathbf{n} \cdot \mathbf{s})}{\mathbf{h} \cdot \mathbf{s}}$$

Geometric Term, G

- G_s, case c: blocking of incident light, no blocking of exitting light (**shadowing)**
- Mathematically,

$$G_s = \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{\mathbf{h}\cdot\mathbf{s}}$$



- G term is minimum of 3 cases, hence

$$G = \left(1, G_m, G_s\right)$$

Fresnel Term, F

- So, again recall that specular term

$$spec = \frac{F(\phi, \eta) DG}{(\mathbf{n} \cdot \mathbf{v})}$$

- Microfacets not perfect mirrors
- F term, $F(\phi, \eta)$ gives fraction of incident light reflected

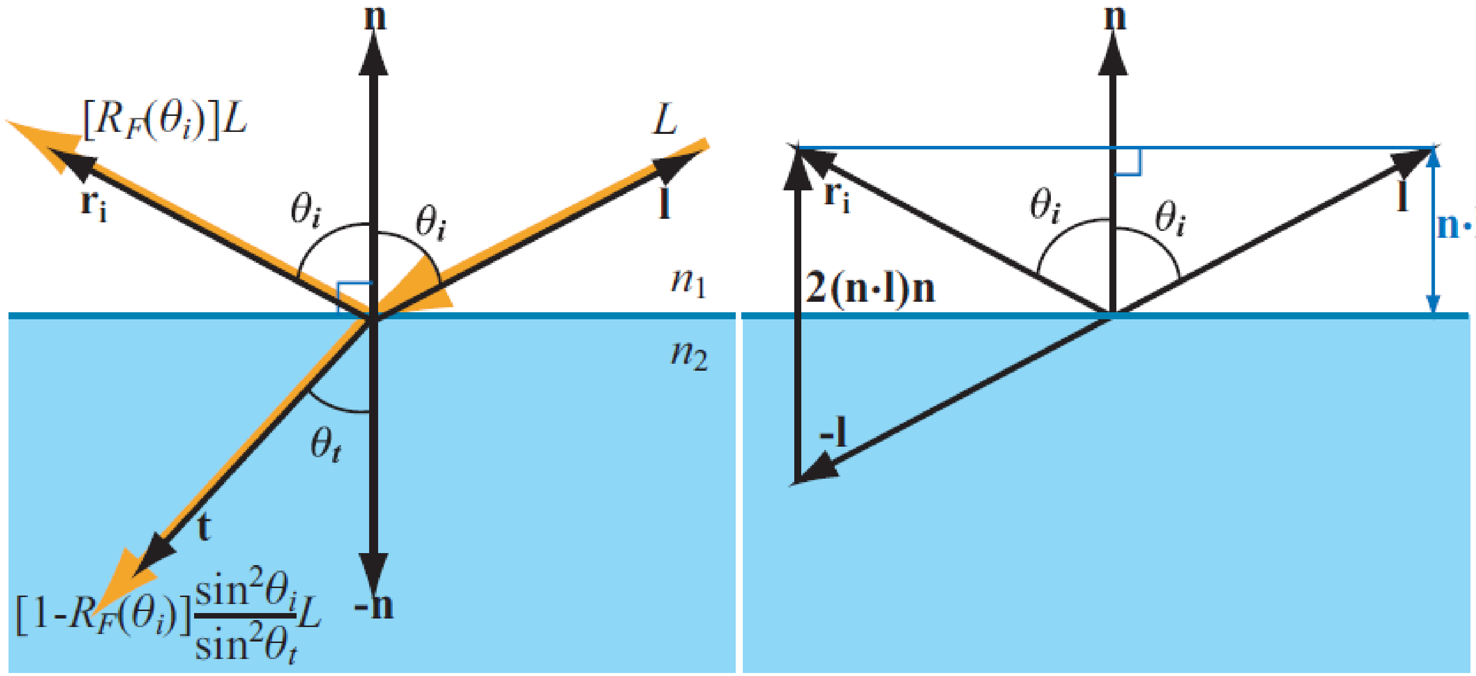
$$F = \frac{1}{2} \frac{(g-c)^2}{(g+c)^2} \left\{ 1 + \left(\frac{c(g+c)-1}{c(g-c)-1} \right)^2 \right\}$$

F is function of material and incident angle

- where c = cos(ϕ) = **n.s** and $g^2 = \eta^2 + c^2 + 1$
- ϕ is incident angle, η is refractive index of material

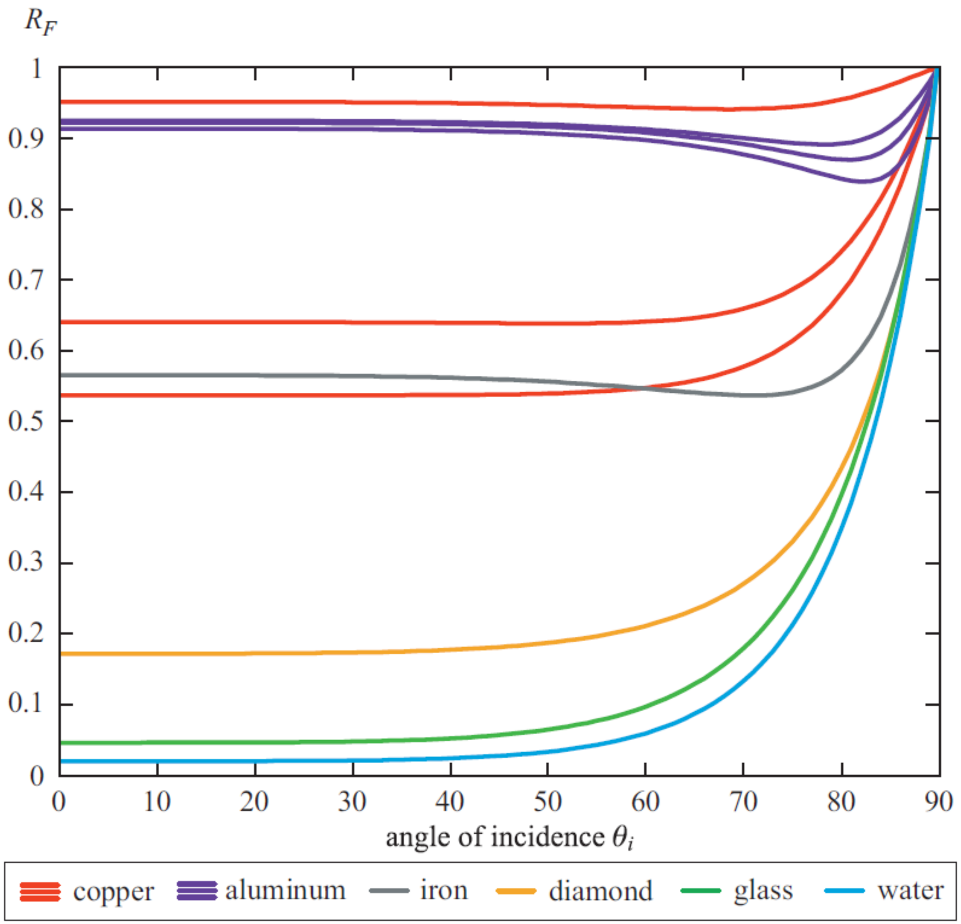
Fresnel Reflectance

- Equation that determines what fraction of incident light is reflected (and what fraction is transmitted)



Fresnel Reflectance

- Depends on angle of incidence and material



Fresnel Reflectance

- Usually, physics table for each material's fresnal reflectance at zero degrees of incidence

Material	Fresnel Value (R,G,B)
Water	0.02, 0.02, 0.02
Plastic	0.05, 0.05, 0.05
Glass	0.08, 0.08, 0.08
Diamond	0.17, 0.17, 0.17
Copper	0.95, 0.64, 0.54
Aluminum	0.91, 0.92, 0.92

- Schlick approximation to get arbitrary F

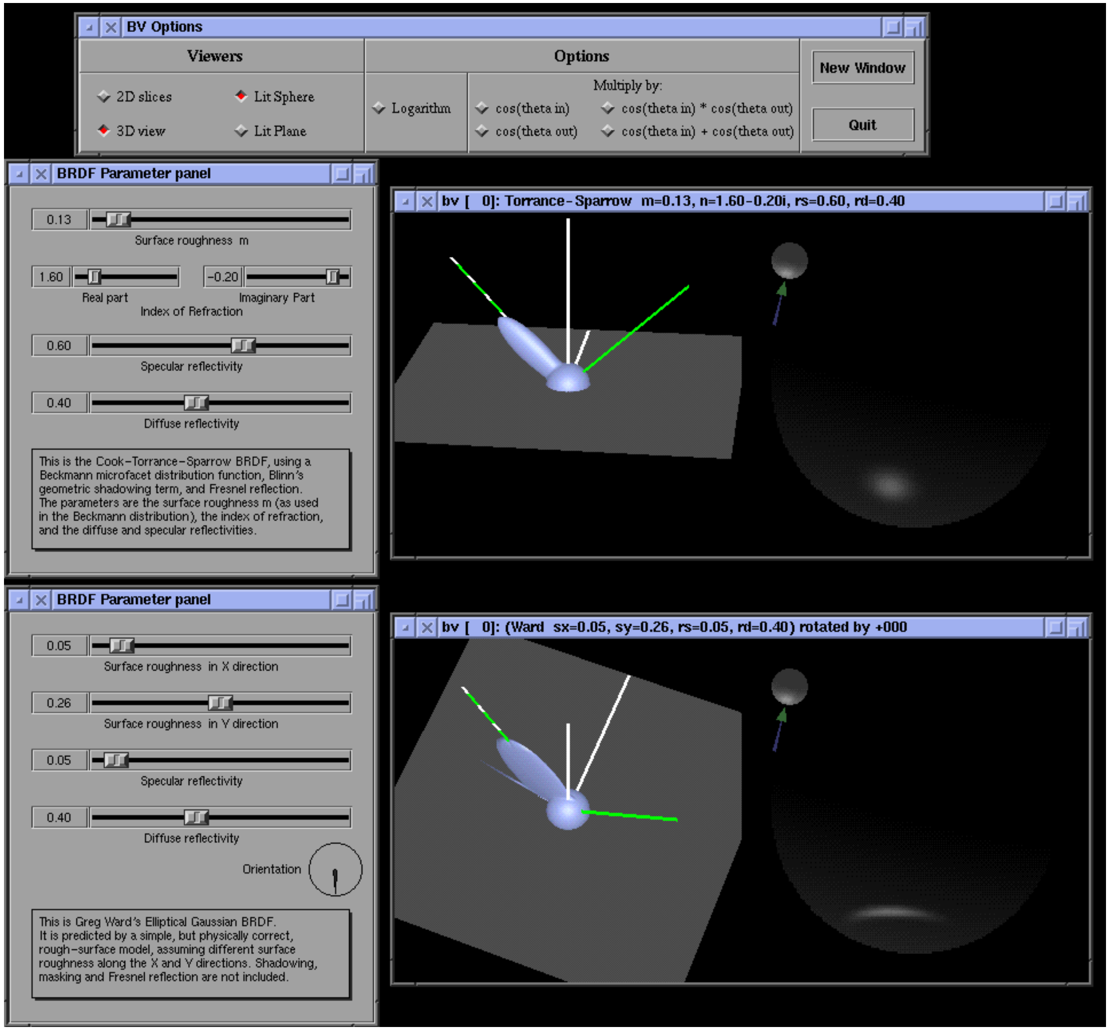
$$F(\theta) = F(0) + (1 - F(0))(1 - \cos\theta)^5$$

Other Physically-Based BRDF Models

- Oren-Nayar – Diffuse term changed not specular
- Aishikhminn-Shirley – Grooves not v-shaped. Other Shapes
- Microfacet generator (Design your own microfacet)

BV BRDF Viewer

BRDF viewer (View distribution of light bounce)



Sub-Surface Scattering

Crysis skin demo

Marble

Human Skin

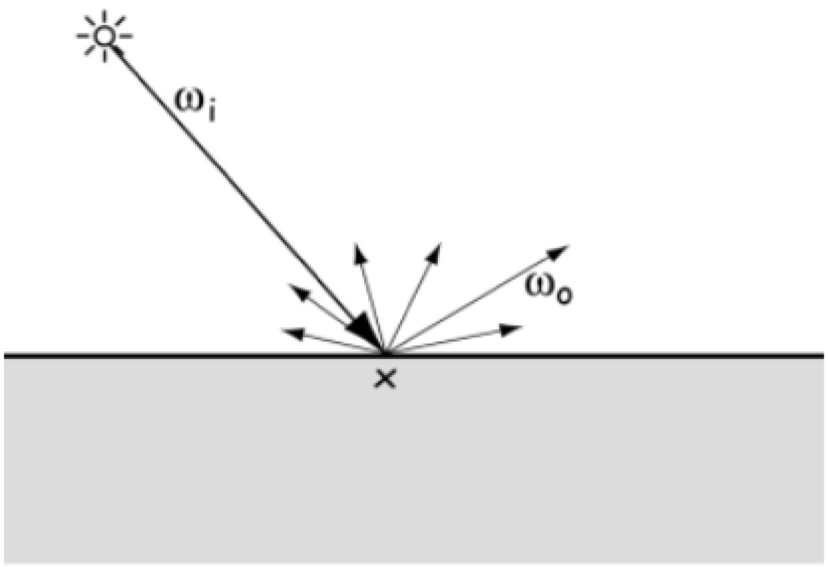
More Examples…

Leaves

Hair

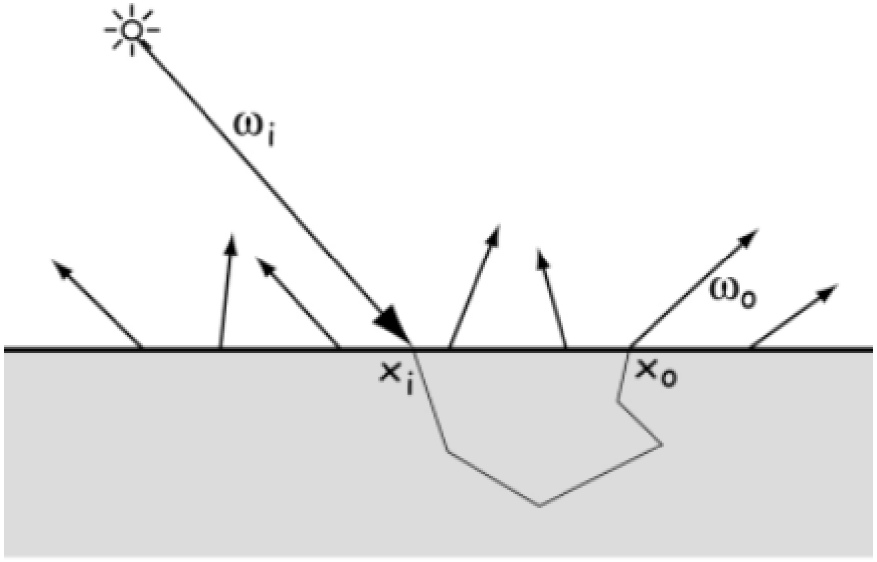
Milk

Subsurface Scattering



$$f_r(x,\omega_i,\omega_o) \equiv \frac{dL_r(x,\omega_o)}{dE_i(x,\omega_i)}$$

Reflection



$$S(x_i,\omega_i;x_o,\omega_o) \equiv \frac{dL_r(x_o,\omega_o)}{d\Phi_i(x_i,\omega_i)}$$

Subsurface Scattering

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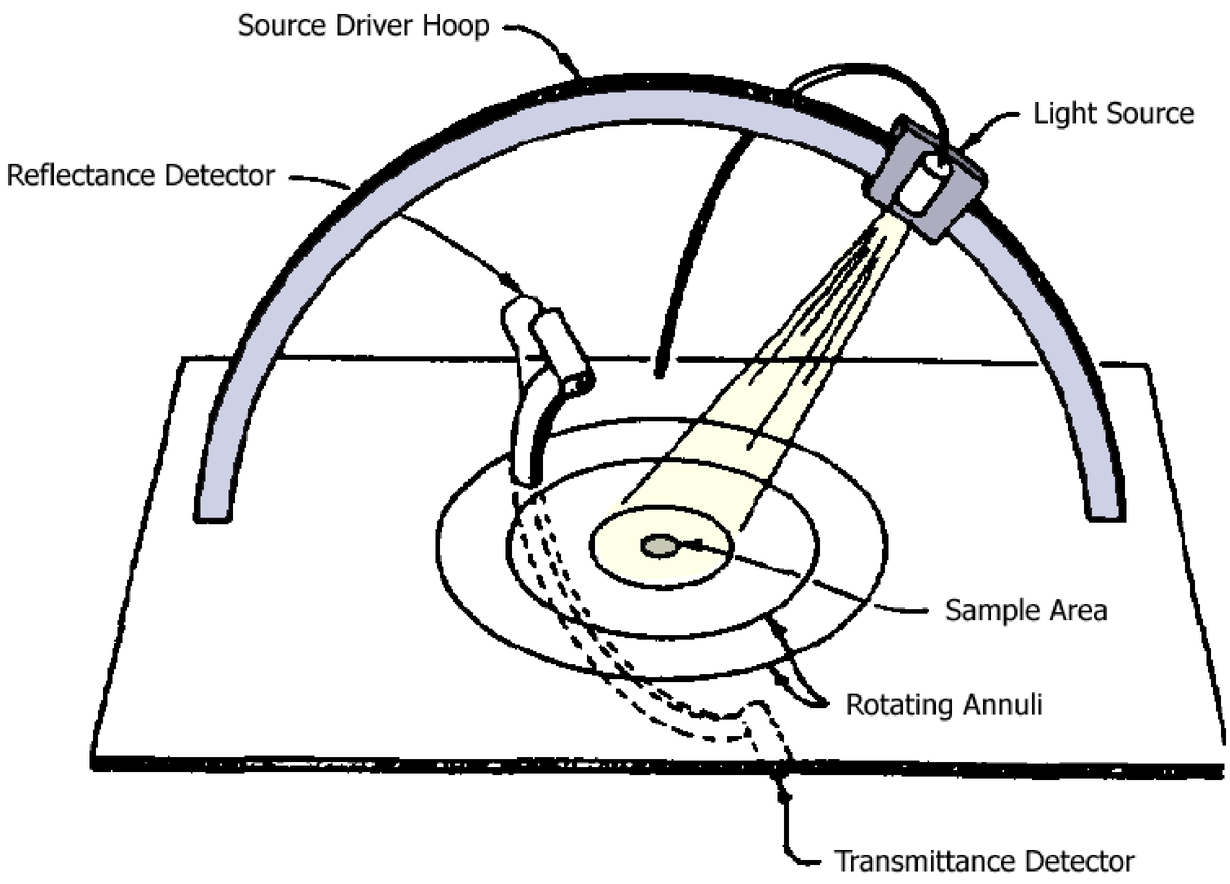
Measuring BRDFs



Murray-Coleman and Smith Gonioreflectometer. (Copied and Modified from [Ward92]).

Measured BRDF Samples

- Mitsubishi Electric Research Lab (MERL)

http://www.merl.com/brdf/

- Wojciech Matusik
- MIT PhD Thesis
- 100 Samples

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Time-varying BRDF

Ref: Wang *et al* Appearance Manifolds for Modeling Time-Variant Appearance of Materials, SIGGRAPH 2006

- BRDF: How different materials reflect light
- Time varying?: how reflectance changes over time
- Examples: weathering, ripening fruits, rust, etc [Play Video]

References

- Interactive Computer Graphics (6th edition), Angel and Shreiner
- Computer Graphics using OpenGL (3rd edition), Hill and Kelley