NUSRI Summer Programme 2016

RI3004A
3D Graphics Rendering

Lecture 10
Local Reflection Models

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Photo-Realistic Rendering

- Inputs for realistic rendering
  - Camera
  - Geometry
  - Lighting
  - **Material**
- Material appearances
  - Color, intensity, glossiness, texture, etc.



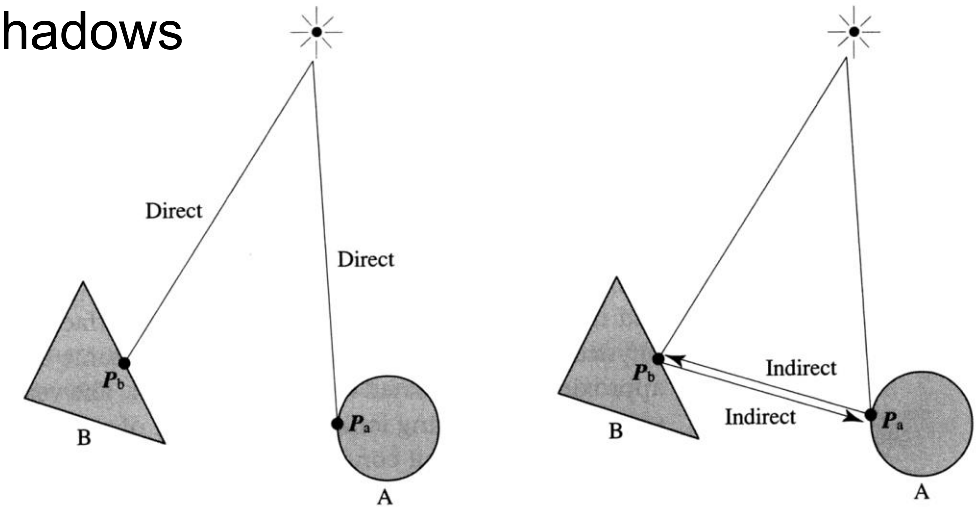

[Durand]

Material Appearances

- Material appearance is caused by the interaction of light with the object surface and reflected/transmitted from the surface
  - **Reflection** is characterized by its **BRDF** (Bi-directional Reflection Distribution Function)
  - **Transmission** is characterized by its **BTDF** (Bi-directional Transmission Distribution Function)
- Reflection may be modeled by **local reflection models**
  - Examples
    - **Phong** reflection model (**empirical**)
    - **Cook-Torrance** reflection model (**physically-based**)

Local Reflection vs Global Illumination

- Local reflection
  - Considers relationship between a **light source**, a **single surface point**, and a **view point**
  - No interaction with other objects
- Global illumination
  - Considers all light sources and surfaces
  - Inter-reflections and shadows



Radiometry

- Study of physical measurement of light / radiation energy

- Defines some fundamental radiometric quantities
  - Radiant flux / power
  - Irradiance
  - Radiant exitance / radiosity
  - Radiance

Radiometric Quantities (1)

- **Radiant Power** or **Radiant Flux**
  - Total energy flows from/to/through a surface per unit time
  - Expressed in watts (W)
  - Usually denoted as Φ
- **Irradiance**
  - Incident (incoming) radiant power on a surface per unit surface area
  - Expressed in W/m^2
  - Usually denoted as E

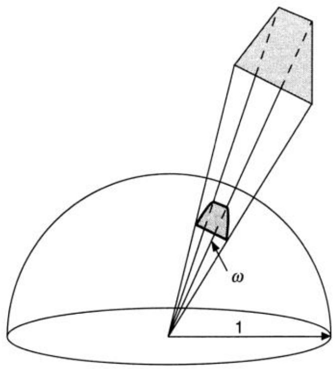
$$\boxed{E = \frac{d\Phi}{dA}}$$

- **Radiant Exitance** or **Radiosity**
  - Exitant (outgoing) radiant power from a surface per unit surface area
  - Expressed in W/m^2
  - Usually denoted as M (radiant exitance) and B (radiosity)

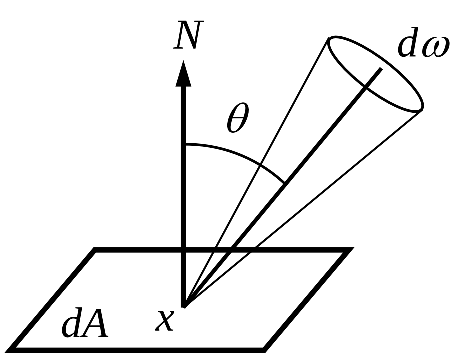
$$\boxed{M = B = \frac{d\Phi}{dA}}$$

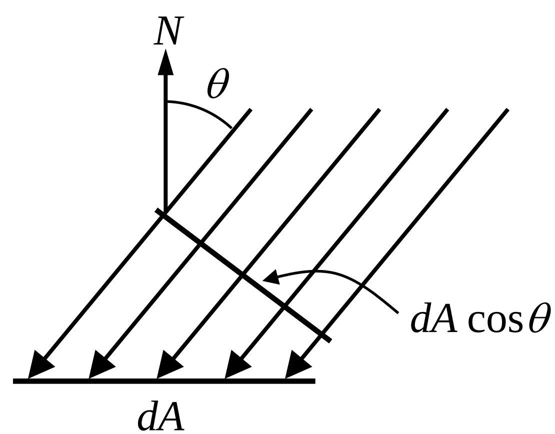
Radiometric Quantities (2)

- **Radiance**
  - Radiant power per unit <u>projected surface area</u> per unit <u>solid angle</u>
    - **Solid angle** — measured in <u>steradian</u> (sr), where a steradian is the sphere surface area intercepted by a cone divided by the square of the sphere's radius r
      - A hemisphere has solid angle of $2\pi r^2/r^2 = 2\pi$ sr
    - **Projected surface area** = surface area × cos θ
  - Expressed in $W/(sr.m^2)$
  - Usually denoted as L



$$\boxed{L = \frac{d^2\Phi}{d\omega \cdot dA\cos\theta}}$$





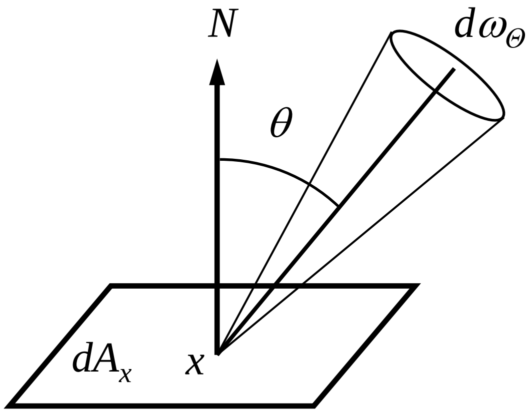
Radiometric Quantities (3)

- Radiance
  - Most important quantity in global illumination algorithms
  - Corresponds to light "intensity"
  - Relationship with other quantities

$$\text{Radiant Power, } \Phi = \int_A \int_\Omega L(x \to \Theta) \cos\theta \, d\omega_\Theta \, dA_x$$

$$\text{Irradiance, } E(x) = \int_\Omega L(x \leftarrow \Theta) \cos\theta \, d\omega_\Theta$$

$$\text{Radiosity, } B(x) = \int_\Omega L(x \to \Theta) \cos\theta \, d\omega_\Theta$$



Radiometric Quantities (4)

- Radiometric quantities can vary with wavelength
- Radiometric quantities are perception independent

Example

- Diffuse emitter
  - Emits equal radiance, L, in all directions

$$\text{Radiosity}, B(x) = \int_{\Omega} L(x \rightarrow \Theta) \cos\theta \, d\omega_{\Theta}$$

$$= L \int_{\Omega} \cos\theta \, d\omega_{\Theta}$$

$$= L \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \cos\theta \sin\theta \, d\theta \, d\phi$$

$$= L\pi$$

Properties of Radiance

- **Property (1):** Radiance is invariant along straight paths
  - Radiance leaving point x directed towards point y is equal to radiance arriving at point y from point x
    - Assuming no participating medium
- **Property (2):** Sensors (such as cameras and human eyes) are sensitive to radiance
  - Response of sensors is proportional to radiance incident upon them
- (1)+(2) explain why perceived color or brightness of an object does not change with distance

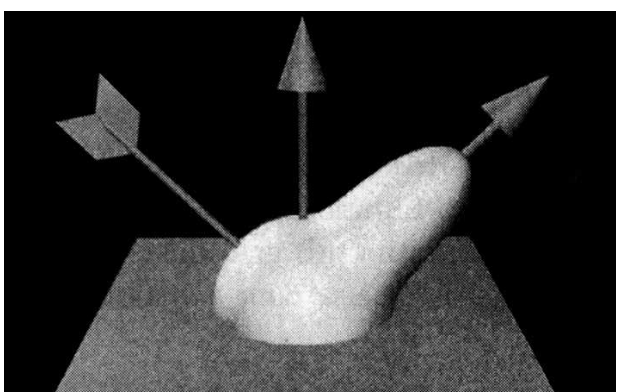
BRDF

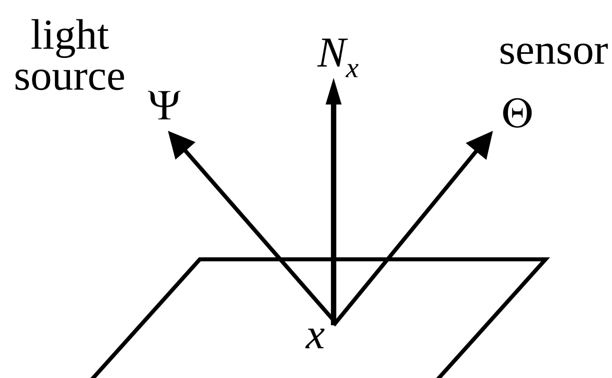
- **B**i-directional **R**eflection **D**istribution **F**unction
- Describes the "amount" of incident light reflected in an exitant direction

$$\text{BRDF}, \; f_r(x, \Psi \to \Theta) = \frac{dL(x \to \Theta)}{dE(x \leftarrow \Psi)}$$

$$= \frac{dL(x \to \Theta)}{L(x \leftarrow \Psi)(N_x \bullet \Psi)\, d\omega_\Psi}$$

Example BRDF.
It shows the BRDF for only one incident direction.





BRDF

- Assumptions
  - Frequency of light unchanged (no fluorescence)
  - Light reflected instantaneously (no phosphorescence)
  - No subsurface scattering
- Range of function
  - BRDF can give any **non-negative** value (even infinity)
- Dimension
  - 4D
  - If BRDF varies on a surface (spatially-varying material), it is described by a BTF (bi-directional texture function) (6D)
  - BRDF is dependent on wavelength of light, therefore, strictly speaking, it is 5D

BRDF

- Helmholtz Reciprocity
  - BRDF is symmetric with respect to the incident and reflected directions

$$f_r(x, \Psi \to \Theta) = f_r(x, \Theta \to \Psi)$$

- Energy conservation
  - Total power reflected in all directions must be equal or less than incident power
    - For any incident direction Ψ

$$\int_{\Omega_x} f_r(x, \Psi \to \Theta)(N_x \bullet \Theta)\, d\omega_\Theta \le 1$$

Example BRDFs

- Diffuse surface / reflector
  - BRDF is constant for all values of Ψ and Θ

$$f_r(x, \Psi \leftrightarrow \Theta) = \frac{\rho_d}{\pi}$$

where reflectance (albedo) ρ_d varies from 0 to 1

- Perfect mirror reflector
  - BRDF is 0 for all exitant directions, except the mirror reflection direction, where BRDF is infinite

$$\int_{\Omega_x} f_r(x, \Psi \rightarrow \Theta)(N_x \bullet \Theta)\, d\omega_\Theta = 1$$

Shading Models

- Lambert's model

$$f_r(x, \Psi \leftrightarrow \Theta) = k_d = \frac{\rho_d}{\pi}$$

- Phong model

$$f_r(x, \Psi \leftrightarrow \Theta) = k_s \frac{(R \bullet \Theta)^n}{N \bullet \Psi} + k_d$$

where R is the mirror reflection direction of Ψ

  - Not energy conserving
  - Not satisfying Helmhotz Reciprocity

Shading Models

- Blinn-Phong model

$$f_r(x, \Psi \leftrightarrow \Theta) = k_s \frac{(N \bullet H)^n}{N \bullet \Psi} + k_d$$

  where H is the halfway vector between Ψ and Θ

  - Not energy conserving
  - Not satisfying Helmhotz Reciprocity

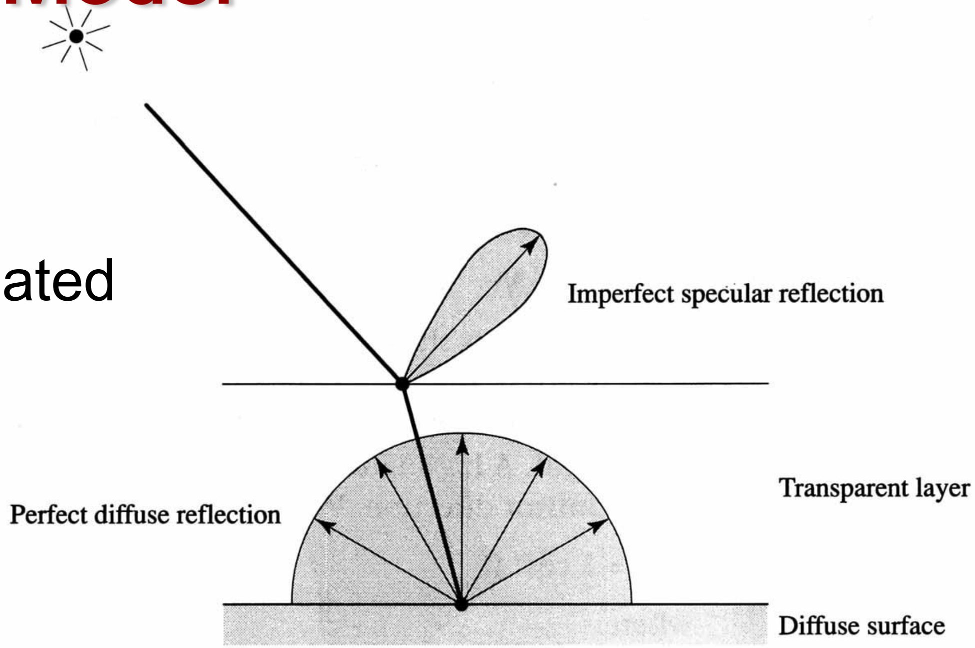
- Modified Blinn-Phong model

$$f_r(x, \Psi \leftrightarrow \Theta) = k_s (N \bullet H)^n + k_d$$

  - Energy conserving?
  - Satisfy Helmhotz Reciprocity?

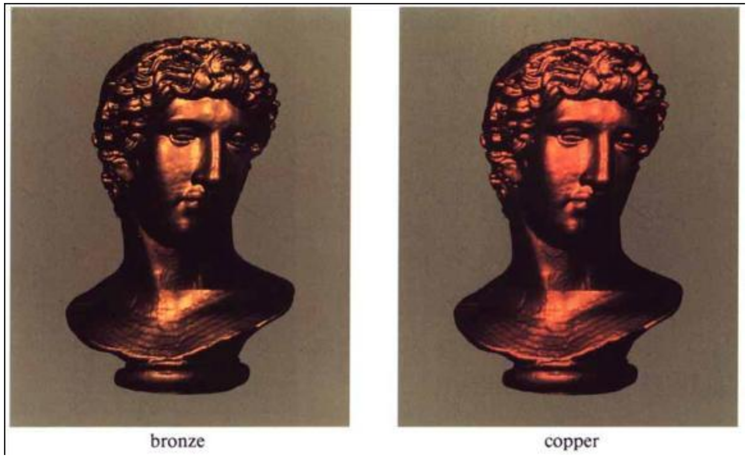
Limitations of Phong Model

- Objects have plastic-like appearance
  - As if diffuse surface is coated with a layer of lacquer
    - E.g. billiard balls



- Cannot simulate metallic appearance
  - The intensity and color of the specular highlights depend on the angle of incoming light

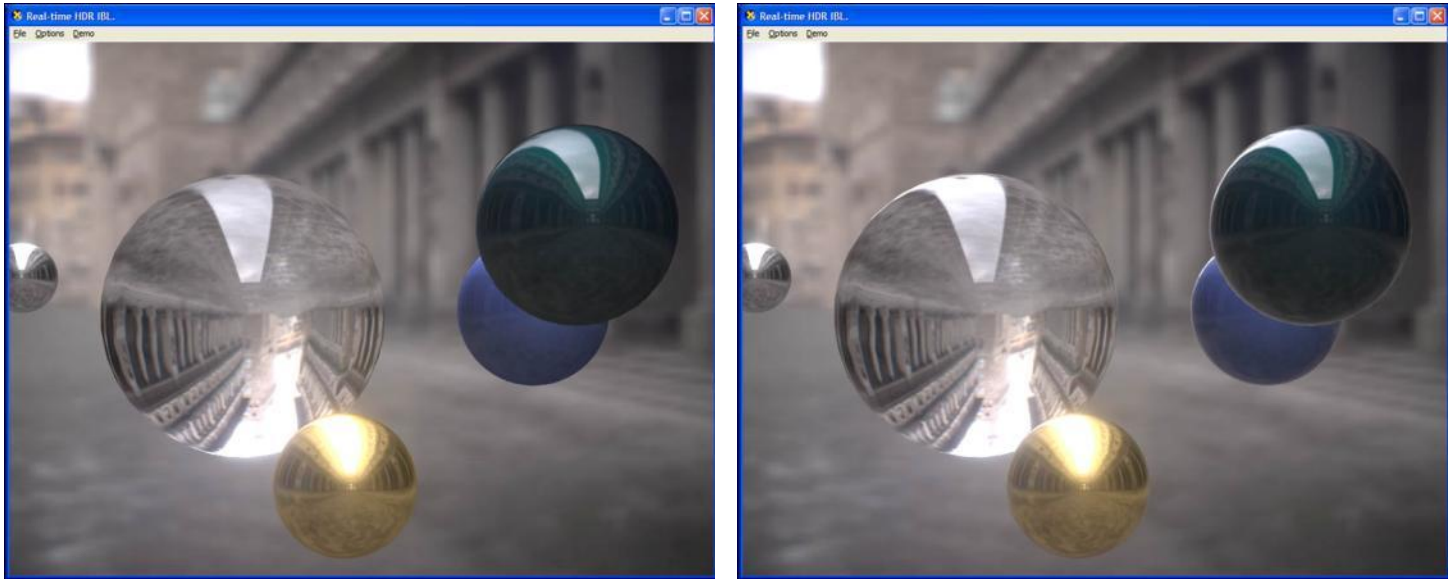
Bronze Copper



Limitations of Phong Model

- No simulation of Fresnel effects

[Lafortune et al. 97]

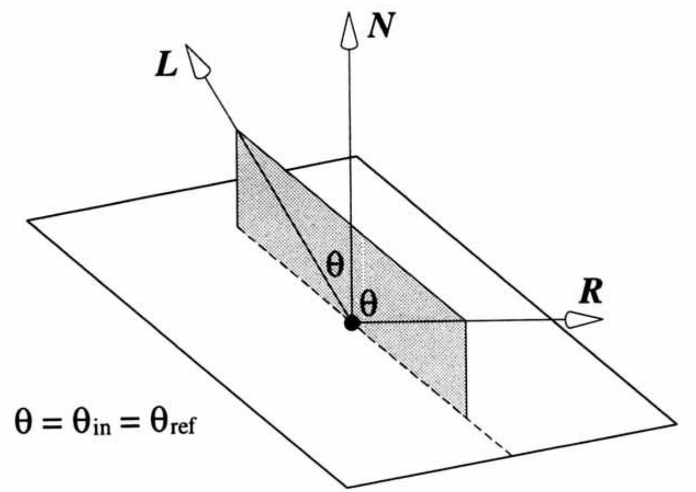


Example Materials Not Modeled By Phong Model

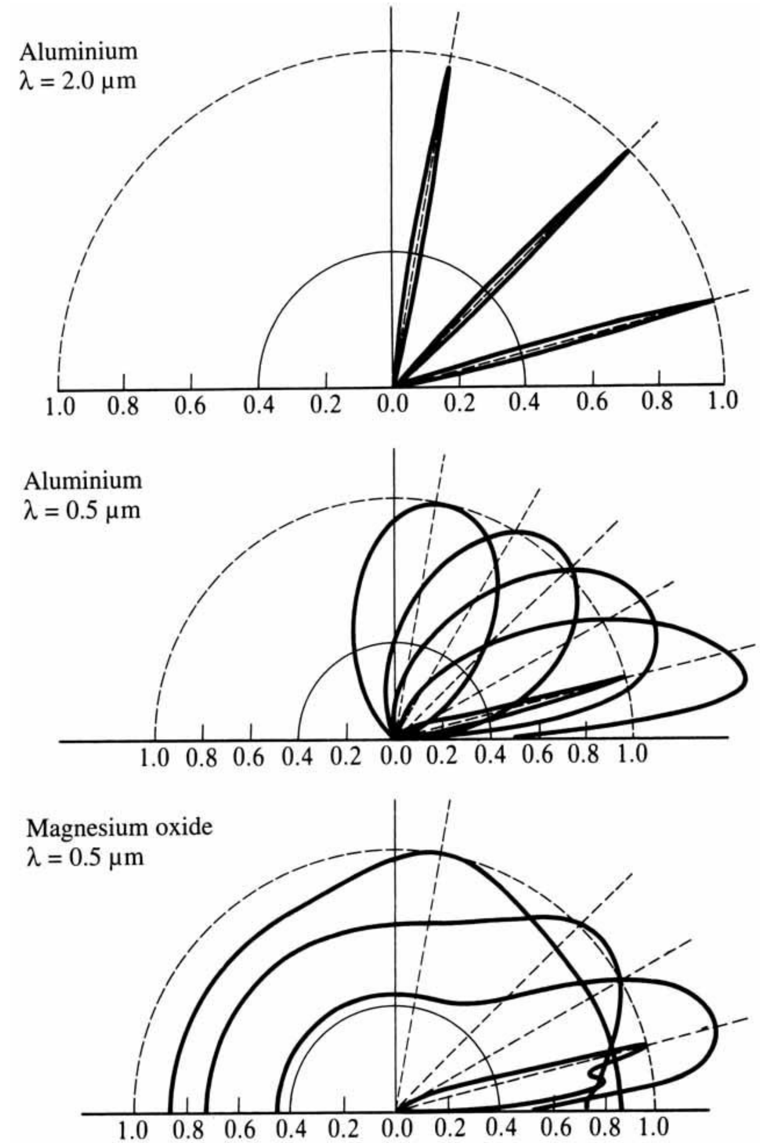
self-illuminating Lambertian sphere | illuminated spherical Lambertian reflector | moon no Lambertian reflector!

[Peter Eisert]

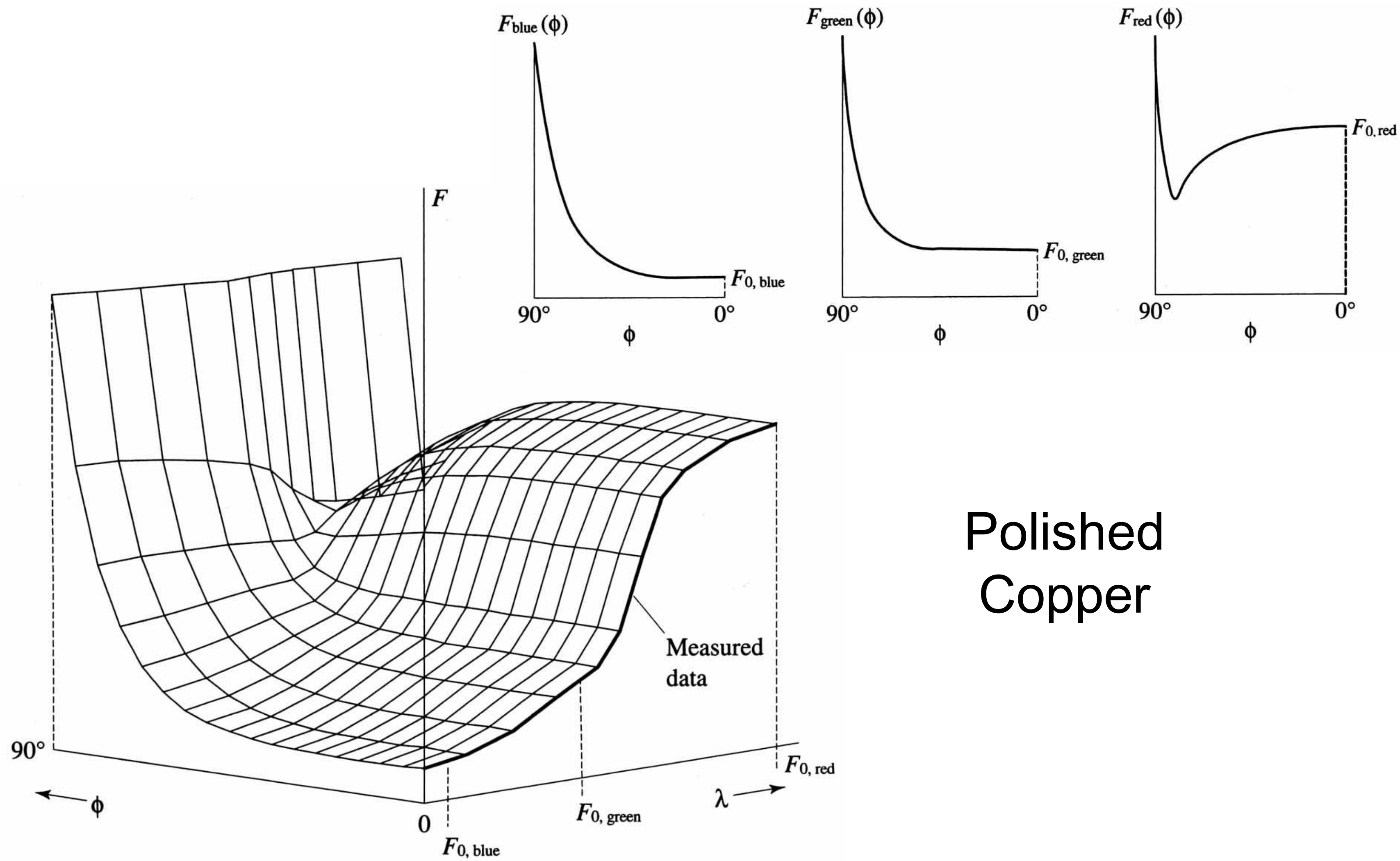
Example Materials Not Modeled By Phong Model



Plane containing ***L*** and ***R*** the mirror direction



Example Materials Not Modeled By Phong Model



Polished Copper

Fresnel Equation

- Determines the ratio of reflected and transmitted light energy from a perfect surface

$$F = \frac{1}{2}\left\{\frac{\sin^2(\phi-\theta)}{\sin^2(\phi+\theta)} + \frac{\tan^2(\phi-\theta)}{\tan^2(\phi+\theta)}\right\}$$

where:

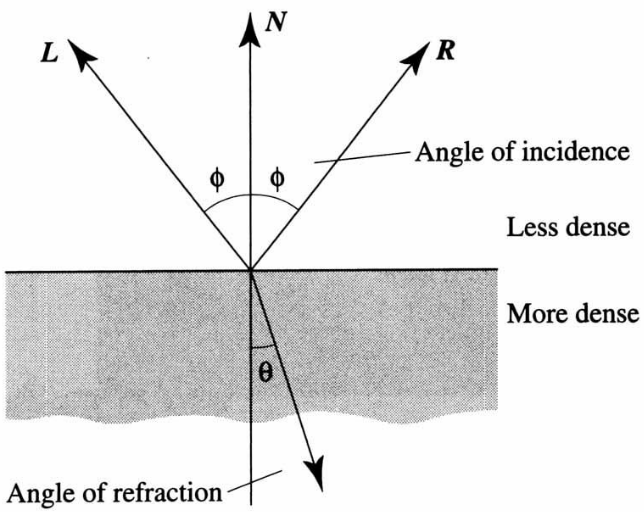
ϕ is the angle of incidence

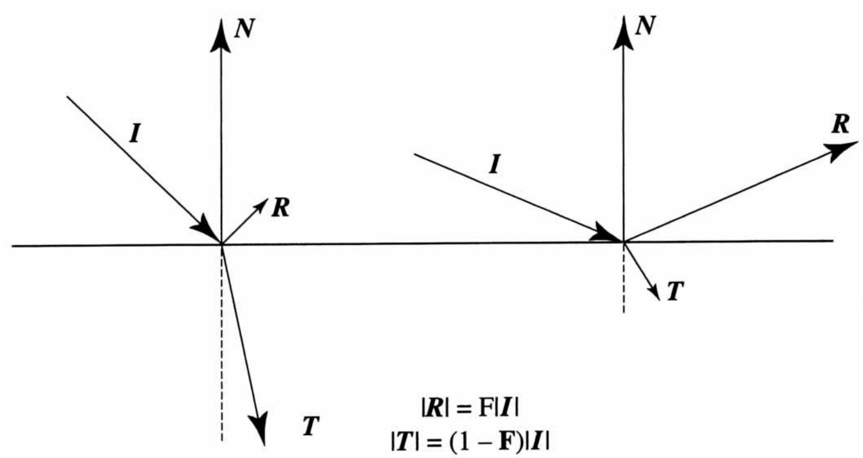
θ is the angle of refraction

$\sin\theta = \sin\phi/\mu$ (where μ is the refractive index of the material)

Assumes incoming light is unpolarized, and surface is dielectric (non-conducting).

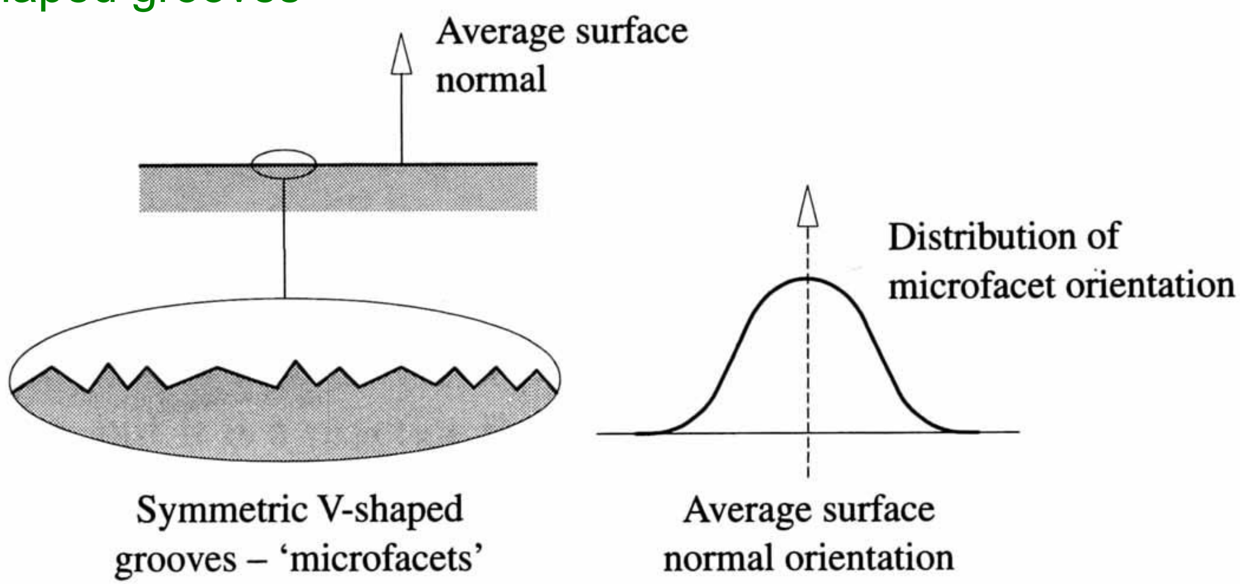
Refractive index is wavelength dependent.





Cook-Torrance Reflection Model

- Also called **Torrance-Sparrow Reflection Model**
- Physically-based specular reflection
  - Based on the micro-geometry theory
    - Imperfect surfaces are made up of a collection of microfacets, where each is a perfect surface
    - For simplicity, microfacet model is assumed to consist of symmetric V-shaped grooves



Cook-Torrance Reflection Model

- Model only the specular component
  - Diffuse component is computed separately as before
  - They are combined as $sR_s + dR_d$, where $s + d = 1$

- The simulation of specular highlights has four components

  (1) Statistical distribution of the orientation of the microfacets

  (2) Shadowing and masking effects

  (3) Glare effect

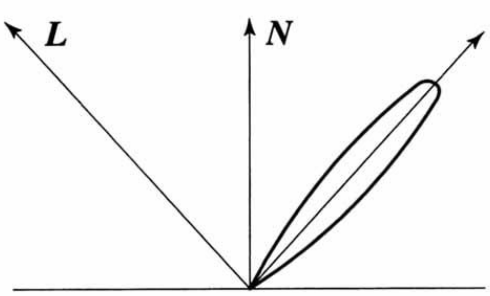
  (4) The Fresnel term

Cook-Torrance Reflection Model

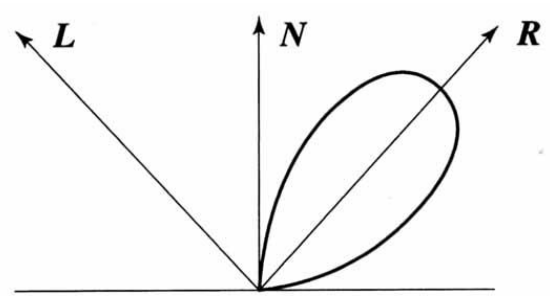
- (1) Statistical distribution of the orientation of the microfacets
  - So we can estimate the proportion of microfacets that face a given direction
  - A simple Gaussian (normal distribution) can be used

$$D(\alpha) = k \exp[-(\alpha/m)^2]$$

    - α is the angle between $\boldsymbol{N}$ and $\boldsymbol{H}$
    - $D(\alpha)$ gives the proportion of microfacets that mirror reflect the light in direction $\boldsymbol{V}$
    - m is the standard distribution; controls mean surface's roughness



Gaussian, $m = 0.2$



Gaussian, $m = 0.6$

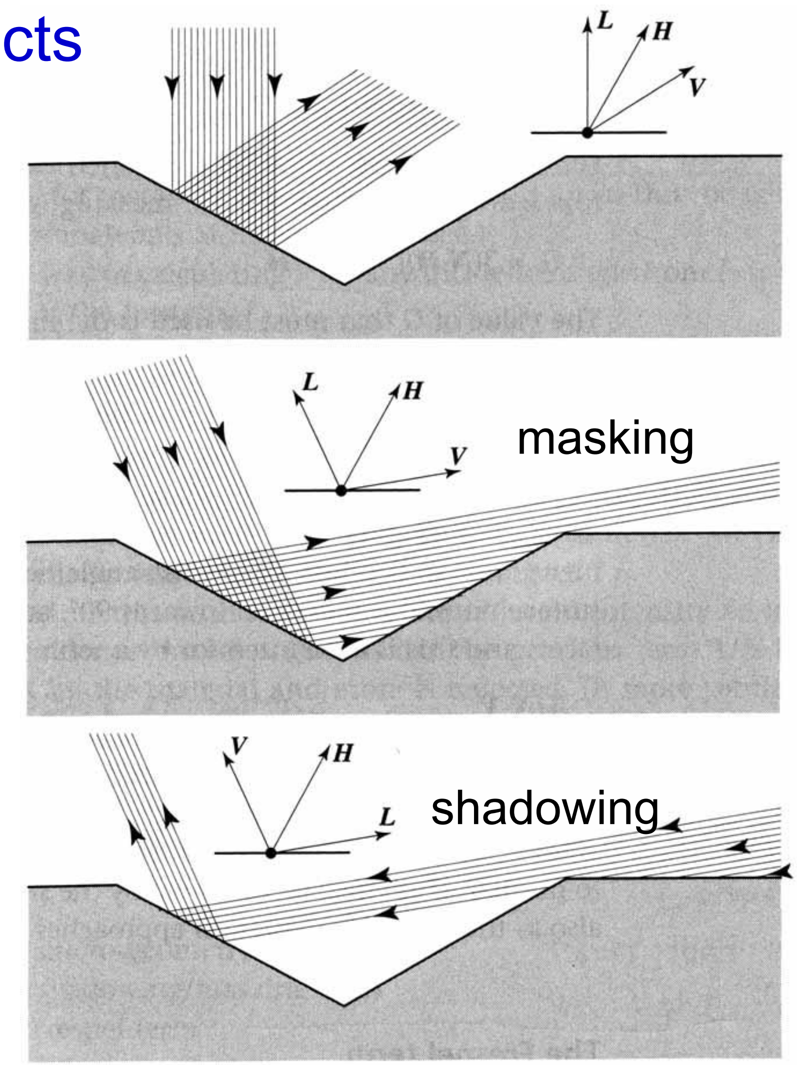
Cook-Torrance Reflection Model

- (2) Shadowing and masking effects
  - Some light is trapped or intercepted
  - The degree of shadowing and masking can be computed as

$$G_m = 2(\mathbf{N}\cdot\boldsymbol{H})(\mathbf{N}\cdot\mathbf{V})/\boldsymbol{V}\cdot\boldsymbol{H}$$

$$G_s = 2(\mathbf{N}\cdot\boldsymbol{H})(\mathbf{N}\cdot\boldsymbol{L})/\boldsymbol{V}\cdot\boldsymbol{H}$$

$$G = \min\{1, G_s, G_m\}$$



Cook-Torrance Reflection Model

- (3) Glare effect
  - When angle between the view vector and the mean surface normal increases, an observer sees more microfacets
  - Accounted for by the term $1\ /\ \boldsymbol{N}\cdot\boldsymbol{V}$

- Countered by the masking effect if the viewing direction getting parallel to mean surface

Cook-Torrance Reflection Model

- (4) The Fresnel term
  - Estimate the fraction of light that is reflected as opposed to being absorbed
  - Each microfacet is assumed a perfect mirror
  - Dependent on wavelength of light, refractive index of surface, and angle of incidence of incoming light w.r.t. the microfacet orientation

$$F = \frac{1}{2}\left\{\frac{\sin^2(\phi - \theta)}{\sin^2(\phi + \theta)} + \frac{\tan^2(\phi - \theta)}{\tan^2(\phi + \theta)}\right\}$$

where:

ϕ is the angle of incidence

θ is the angle of refraction

$\sin\theta = \sin\phi/\mu$ (where μ is the refractive index of the material)

Cook-Torrance Reflection Model

- Final specular term = $D(\alpha) \cdot G \cdot F \,/\, (\boldsymbol{N} \cdot \boldsymbol{V})$
  - $D(\alpha)$ is the micro-geometry term
  - G is the shadowing/masking term
  - F is the Fresnel term
  - $(\boldsymbol{N} \cdot \boldsymbol{V})$ is the glare effect term

- Final BRDF

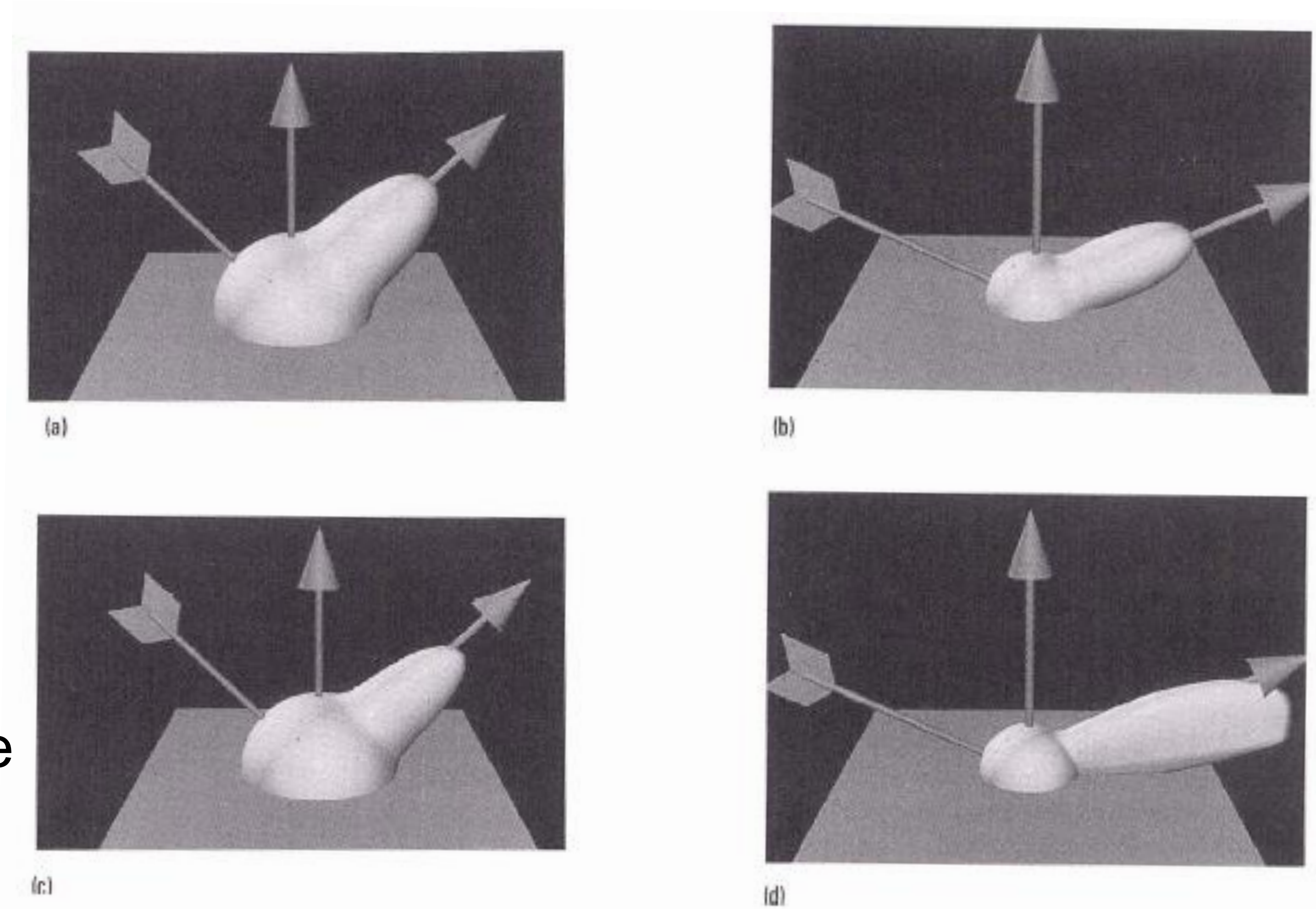
$$f_r(x, \Psi \leftrightarrow \Theta) = \frac{F}{\pi} \cdot \frac{D(\alpha) G}{(N \bullet \Psi)(N \bullet \Theta)} + k_d$$

where $\Psi = \boldsymbol{L}$ and $\Theta = \boldsymbol{V}$

Phong vs. Cook-Torrance

Phong

Cook-
Torrance



Limitations of Cook-Torrance Model

- Assume microfacets are perfectly clean

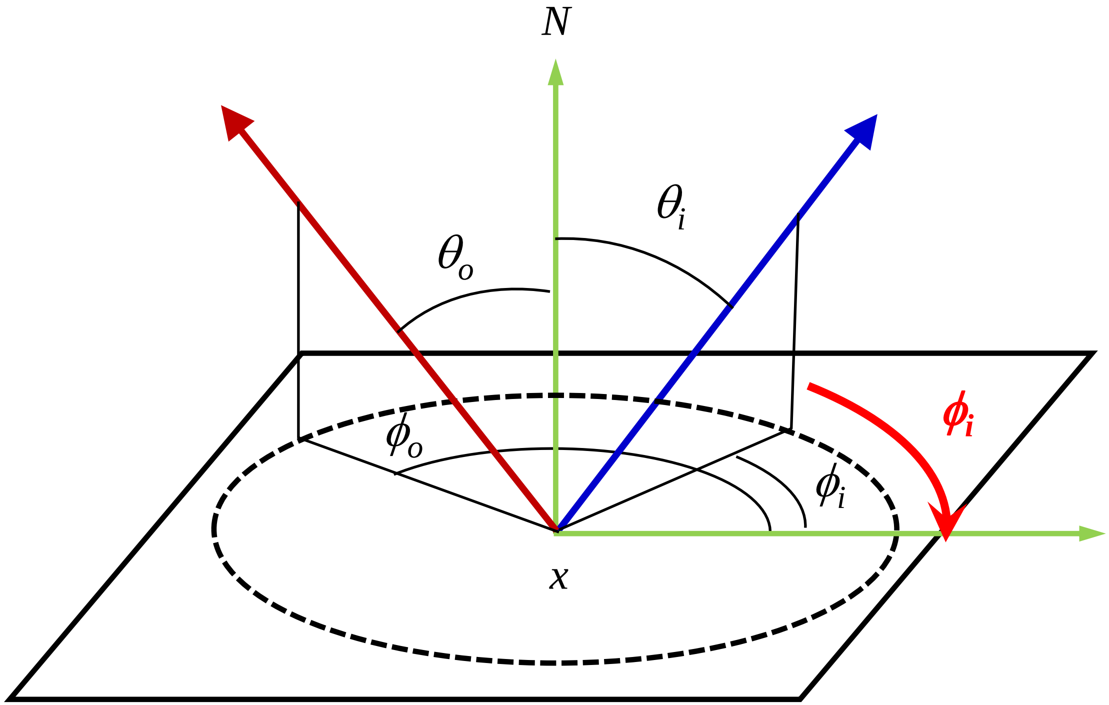
- The BRDF produced is independent of the azimuth angle (ϕ) of the incident light
  - **Isotropic**
  - Many interesting surfaces exhibit **anisotropic** BRDF
    - Surfaces are made up of strongly oriented micro-geometry elements
    - Examples
      - brushed metals
      - cloth, fur, hair

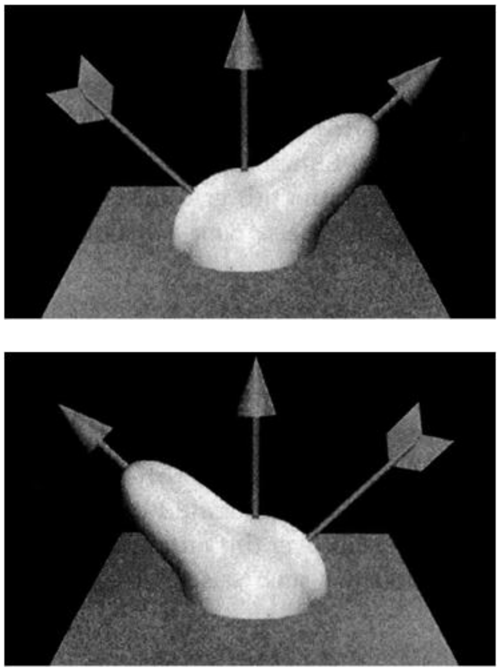
[Pantene, China]

Isotropic BRDF

- If a BRDF is isotropic, then

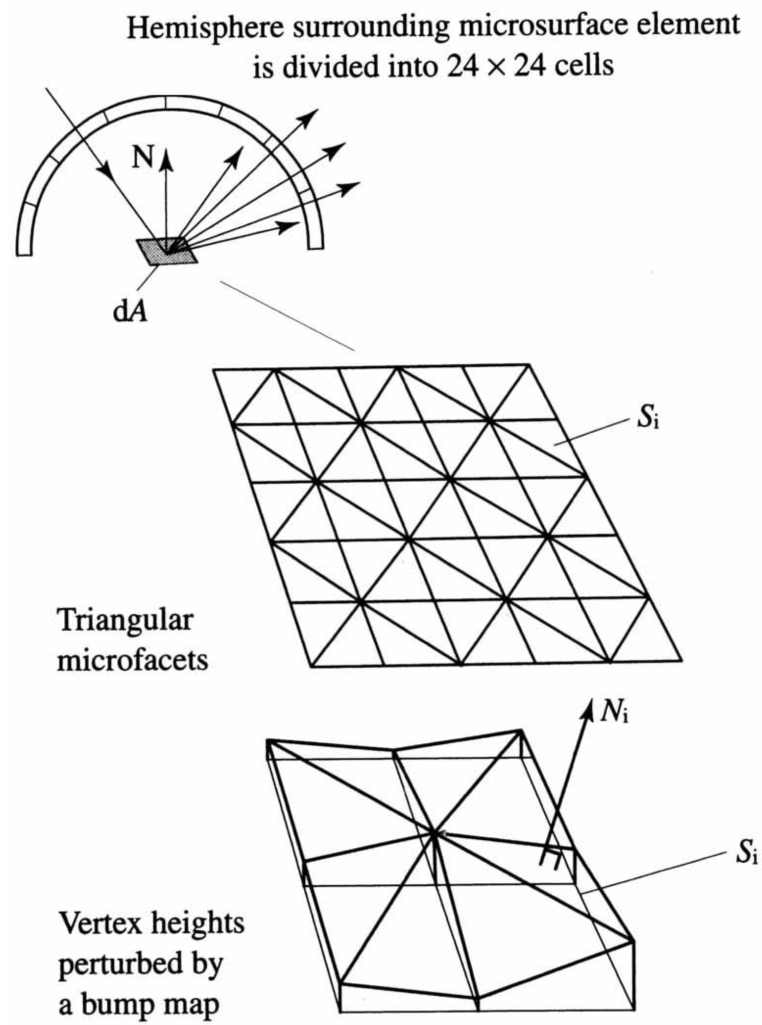
$$f_r\left(x,(\theta_i,\phi_i)\leftrightarrow(\theta_o,\phi_o)\right)=f_r\left(x,(\theta_i,0)\leftrightarrow(\theta_o,\phi_o-\phi_i)\right)$$





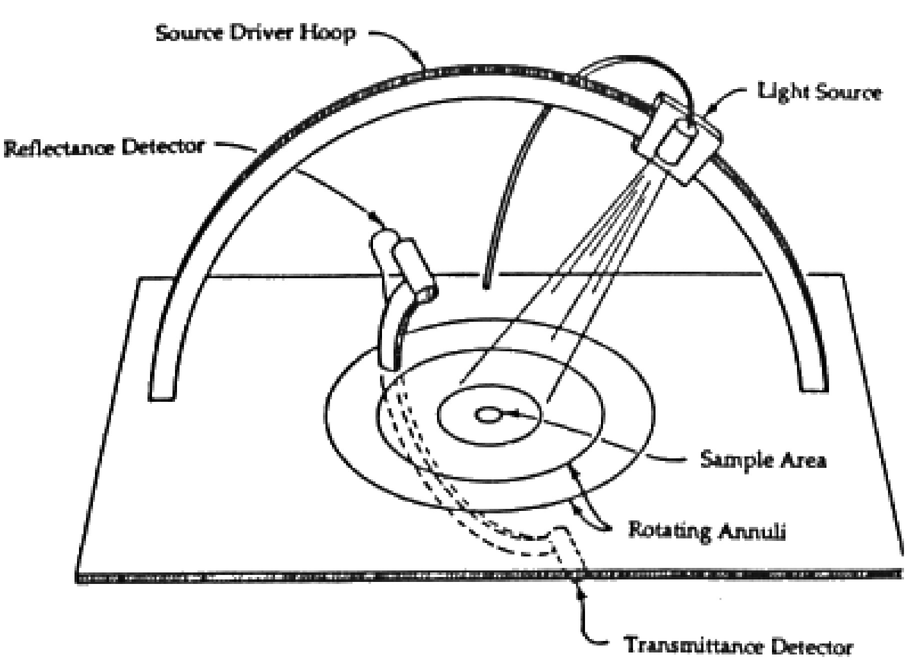
Pre-Computing BRDFs

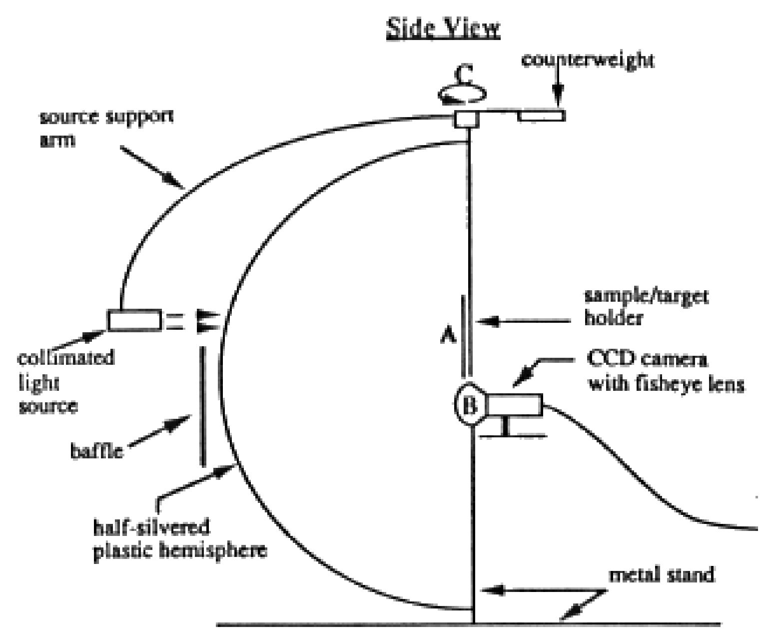
- Surface element is modeled by a grid of triangular microfacets
  - The geometry can be specified using a bump map
  - No restriction on the small-scale geometry
- BRDF is calculated by firing rays from each incoming direction (on a hemisphere), and ray-tracing the reflected rays to a receiving hemisphere
  - Both hemispheres are divided into cells or bins
- The sampled BRDF is stored and can be used later in rendering
- Can simulate anisotropic BRDF



Measuring BRDFs

- Generally difficult
  - BRDF is 4D, light source & camera instability, variation in surface geometry, inter-reflection within measuring device
  - See http://www.cs.princeton.edu/~smr/cs348c-97/surveypaper.html
- Greg Ward. "Measuring and Modeling Anisotropic Reflection", SIGGRAPH 1992





Measuring BRDFs

- Measurement of BRDFs for film production
  - See http://www.virtualcinematography.org/publications/acrobat/BRDF-s2003.pdf

real | computer generated | real | computer generated

End of Lecture 10