Reflection Models (1)

Physically-Based Illumination Models (1)

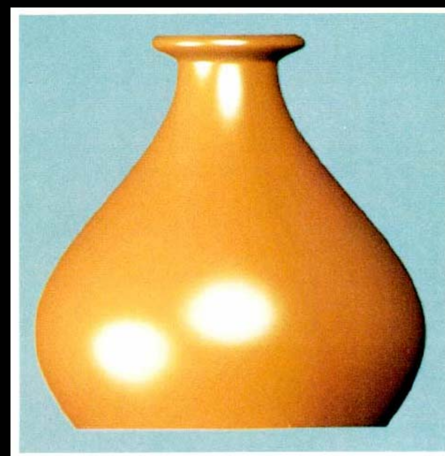
Phong's Illumination Model Revisited

$$I_{total} = k_a I_{ambient} + \sum_{i=1}^{lights} I_i \left(k_d \left(\hat{N} \cdot \hat{L} \right) + k_s \left(\hat{V} \cdot \hat{R} \right)^{n_{shiney}} \right)$$

Problems with Empirical Models:

- What are the coefficients for copper?
- What are *ka*, *ks*, and n_{shiney}?
  Are they measurable quantities?
- How does the incoming light at a point relate to the outgoing light?
  Is energy conserved?
- Just what is light intensity?
- Is my picture accurate?

Real copper vase

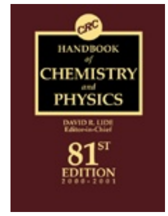


Phong's copper
(more like plastic)

Practical Surfaces

- NOT clean, optically smooth
- Rough + oxidized + contaminants!
- At the wavelengths of light such defects become important

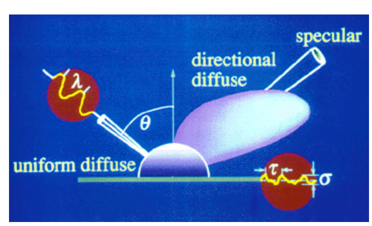
Desired Model



- A model that uses physical properties that can be looked up in the CRC Handbook of Chemistry and Physics (indices of refraction, reflectivity, conductivity, etc.)
- Parameters that that have clear physical analogies (how rough or polished a surface is)
- Models that are predictive (the simulation attempts to model the real scene)
- Models that conserve energy
- Complex surface substructures (crystals, amorphous materials, boundary-layer behavior)
- If it was easy... everyone would do it.

Better (Realistic) Local Illumination Models

- **Blinn-Torrance-Sparrow (1977)**
  - isotropic reflectors with smooth microstructure
- **Cook-Torrance (1982)**
  - wavelength dependent Fresnel term
- **Kajiya (1985)**
- **Cabral-Max,Springmeyer (1987)**
  - Anisotropic surfaces
- **Wolff (1990)**
  - adds polarization
- **He-Torrance-Sillion-Greenberg (1991)**
  - adds polarization, statistical microstructure, self-reflectance



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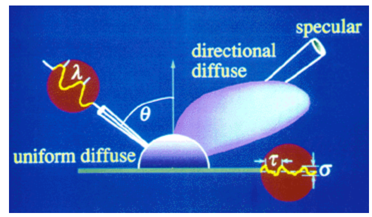

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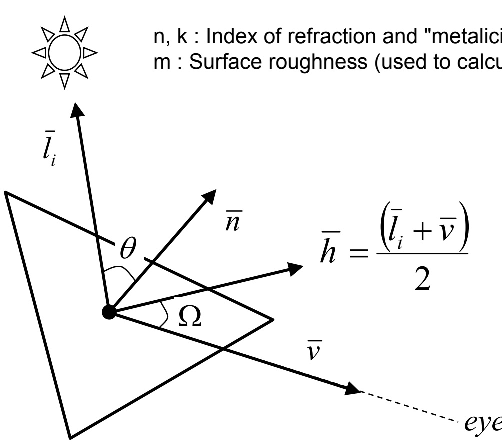
Cook-Torrance Illumination

$$double\ CT\left(vec3\ \bar{l}_i, vec3\ \bar{v}, vec3\ \bar{h}, vec3\ \bar{n}, double\ n, double\ k_s, double\ m\right)$$

n, k : Index of refraction and "metalicity" respectively (used in Fresnel Eqn.)
m : Surface roughness (used to calculate D)



Cook-Torrance Illumination

$$I_{\lambda,r} = I_{\lambda,a} k_a + \sum_{i=1}^{lights} I_{\lambda,i} \left((1 - k_a - k_s) \rho_\lambda (\bar{l}_i \cdot \bar{n}) + k_s \frac{D G F_\lambda(\theta_i)}{\pi (\bar{v} \cdot \bar{n})} \right)$$

Ambient light intensity (same old hack)

Ambient surface reflectance (hacks beget hacks)

microfacet distribution function

geometric attenuation factor

Fresnel conductance term

Luminous intensity of light source i

percentage of light reflected specularly

vector to viewer

Diffuse reflectivity

vector to light source

average surface normal at point

Microfacet Distribution Function

$$I_{\lambda,r} = I_{\lambda,a} k_a + \sum_{i=1}^{lights} I_{\lambda,i} \left((1 - k_a - k_s) \rho_\lambda (\bar{l}_i \cdot \bar{n}) + k_s \frac{D G F_\lambda(\theta_i)}{\pi (\bar{v} \cdot \bar{n})} \right)$$

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

the angle between $\bar{n}$ and $\bar{h} = \frac{(\bar{l}_i + \bar{v})}{2}$

Surface roughness

the root-mean-square slope of the microfacets

large *m* indicates steep slopes and the reflections spread out over the surface

- Statistical model of the variation in normal direction
- Based on a Beckman distribution function
- Consistent with the surface variations of rough surfaces

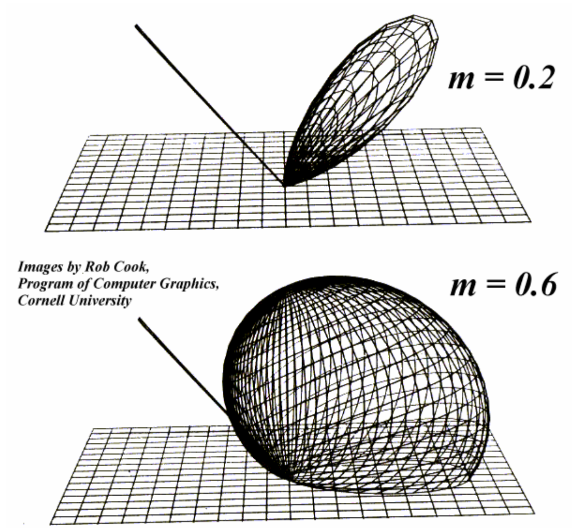
Beckman's Distribution

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

***m* = Surface roughness**

the root-mean-square slope of the microfacets

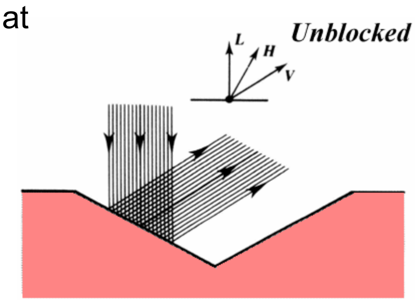
large *m* indicates steep slopes and the reflections spread out over the surface



Geometric Attenuation Factor

$$I_{\lambda,r} = I_{\lambda,a}k_a + \sum_{i=1}^{lights} I_{\lambda,i}\left((1-k_a-k_s)\rho_\lambda(\bar{l}_i\cdot\bar{n}) + k_s\frac{DGF_\lambda(\theta_i)}{\pi(\bar{v}\cdot\bar{n})}\right)$$

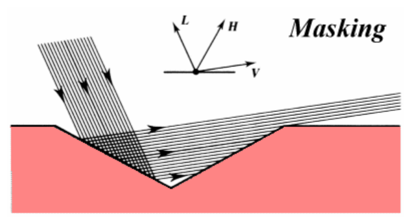
There are many different ways that an incoming beam of light can interact with the surface locally.



The entire beam can simply reflect.

Blocked Reflection

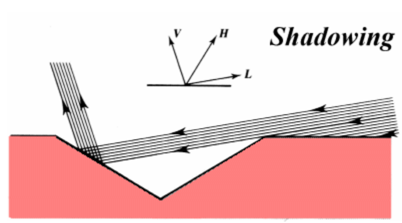
A portion of the out-going beam can be blocked.



This is called *masking*.

Blocked Beam

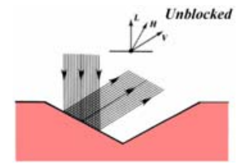
A portion of the incoming beam can be blocked.



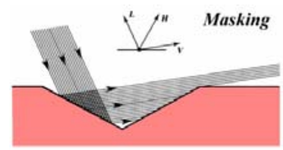
Cook called this *self-shadowing*.

Geometric Attenuation Factor

In each case, the geometric configurations can be analyzed to compute the percentage of light that actually escapes from the surface.

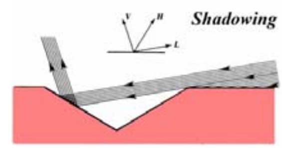


Blinn first did this analysis. The results are:



$$G = 1 - \frac{l_{blocked}}{l_{facet}}$$

$$G_{masking} = \frac{2(\overline{n} \cdot \overline{h})(\overline{n} \cdot \overline{v})}{\overline{v} \cdot \overline{h}}$$



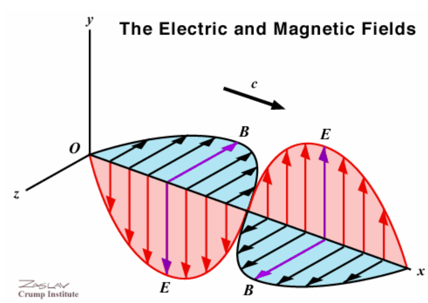
$$G_{shadowing} = \frac{2(\overline{n} \cdot \overline{h})(\overline{n} \cdot \overline{l})}{\overline{v} \cdot \overline{h}}$$

$$G = \min\{1, G_{masking}, G_{shadowing}\}$$

The geometric factor chooses the smallest amount of light that is lost as the local self-shadowing model.

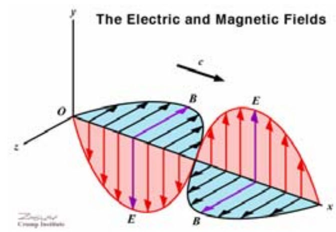
Fresnel Reflection

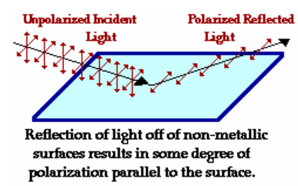
- The Fresnel term results from a complete analysis of the reflection process while considering light as an electromagnetic wave.
- The electric field of light has a magnetic field associated with it (hence the name electromagnetic).
- The magnetic field is always orthogonal to the electric field and the direction of propagation.



Fresnel Reflection

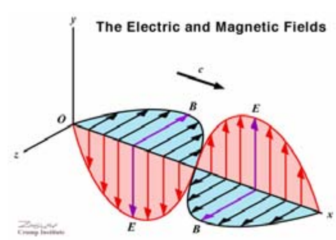
- Over time the orientation of the electric field may rotate.
- If the electric field is oriented in a particular *constant* direction it is called *polarized*.

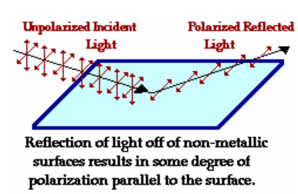




Fresnel Reflection

- The behavior of reflection depends on how the incoming electric field is oriented relative to the surface at the point where the field makes contact.
- This variation in reflectance is called the Fresnel effect.





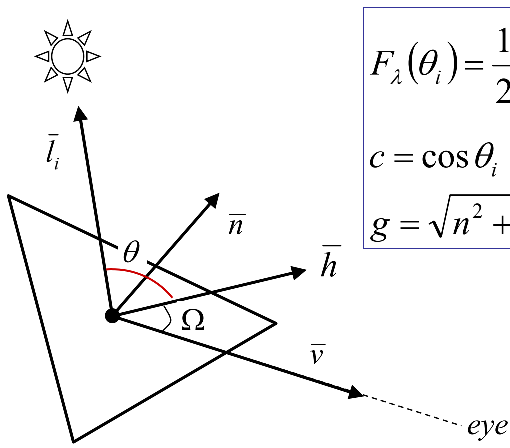
Fresnel Reflection

- The Fresnel effect is wavelength dependent.
- It behavior is determined by the index-of-refraction of the material (taken as a complex value to allow for attenuation).
- This effect explains the variation in colors seen in specular regions particular on metals (conductors).
- It also explains why most surfaces approximate mirror reflectors when the light strikes them at a grazing angle.

Fresnel Reflection

$$double\ CT\left(vec3\ \bar{l}_i, vec3\ \bar{v}, vec3\ \bar{h}, vec3\ \bar{n}, double\ n, double\ k_s, double\ m\right)$$

$$I_{\lambda,r} = I_{\lambda,a}k_a + \sum_{i=1}^{lights} I_{\lambda,i}\left((1-k_a-k_s)\rho_\lambda(\bar{l}_i \cdot \bar{n}) + k_s \frac{DGF_\lambda(\theta_i)}{\pi(\bar{v} \cdot \bar{n})}\right)$$



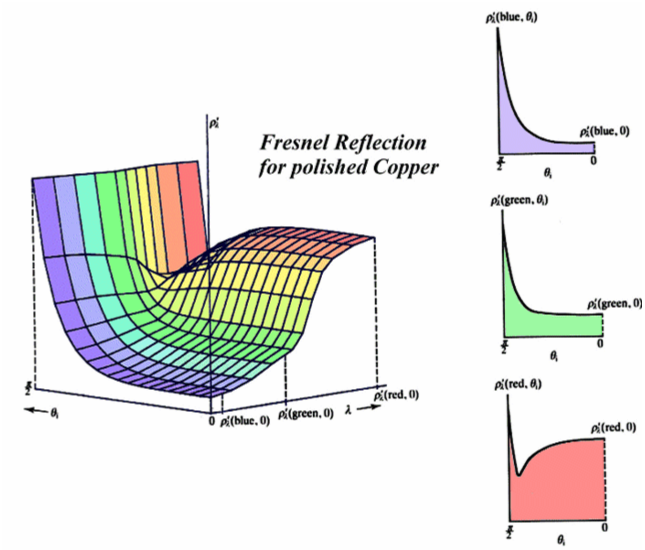
$$F_\lambda(\theta_i) = \frac{1}{2}\frac{(g-c)^2}{(g+c)^2}\left(1+\frac{(c(g+c)-1)^2}{(c(g-c)+1)^2}\right)$$

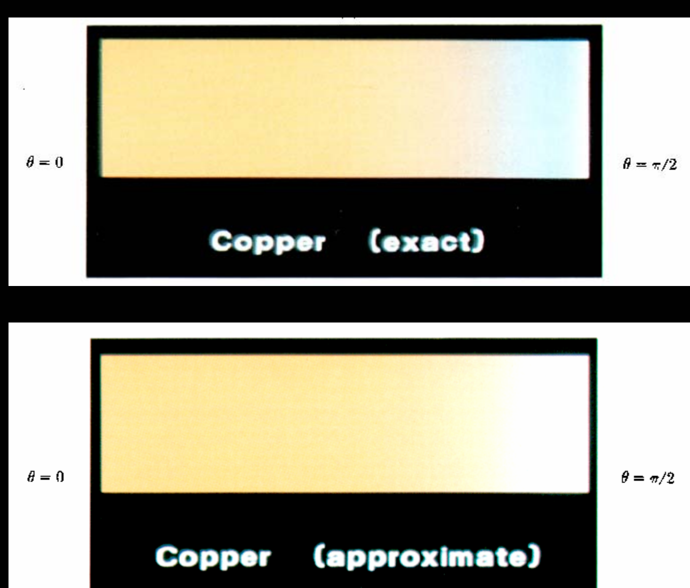
$$c = \cos\theta_i = \bar{l} \cdot \bar{h}$$

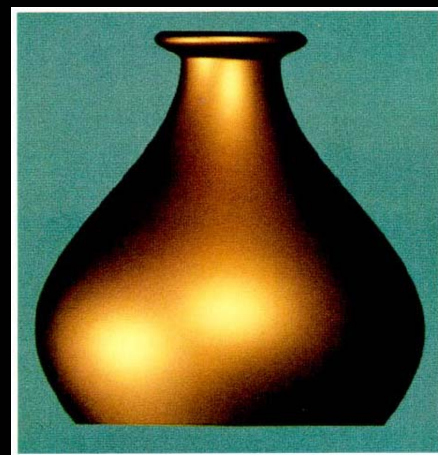
$$g = \sqrt{n^2 + c^2 - 1}$$

This version of the equation ignores the polarization of the incoming and reflected rays.

A Plot of the Fresnel Factor

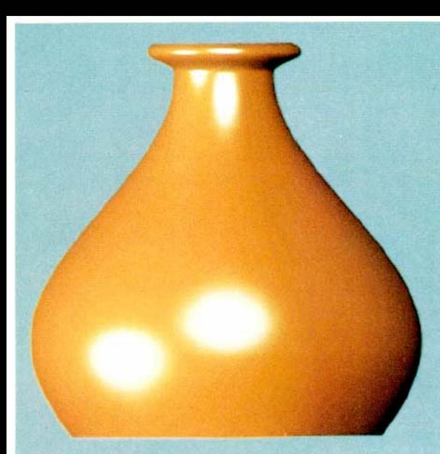


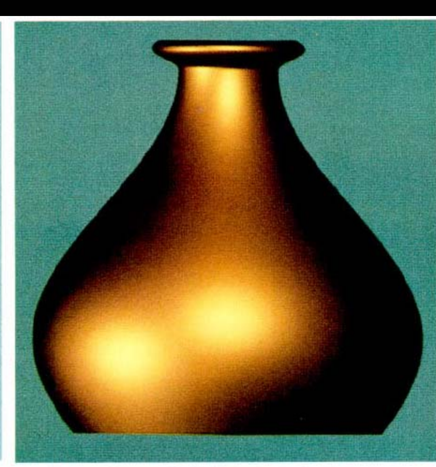




Real copper vase

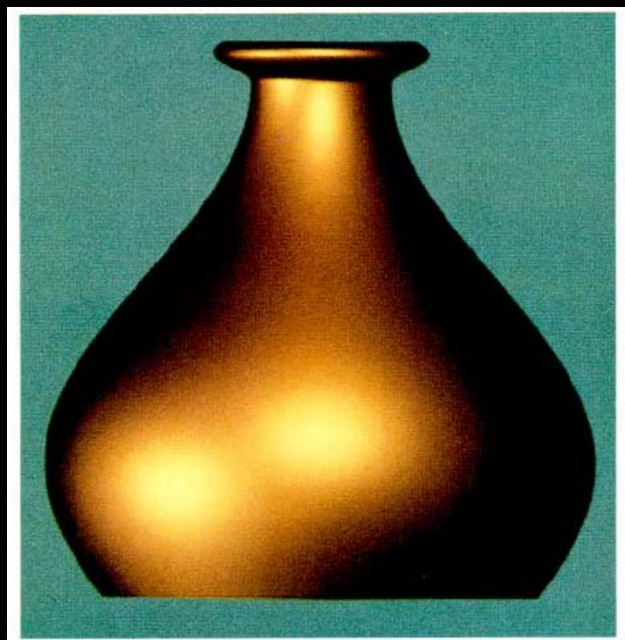
Cook-Torrance copper

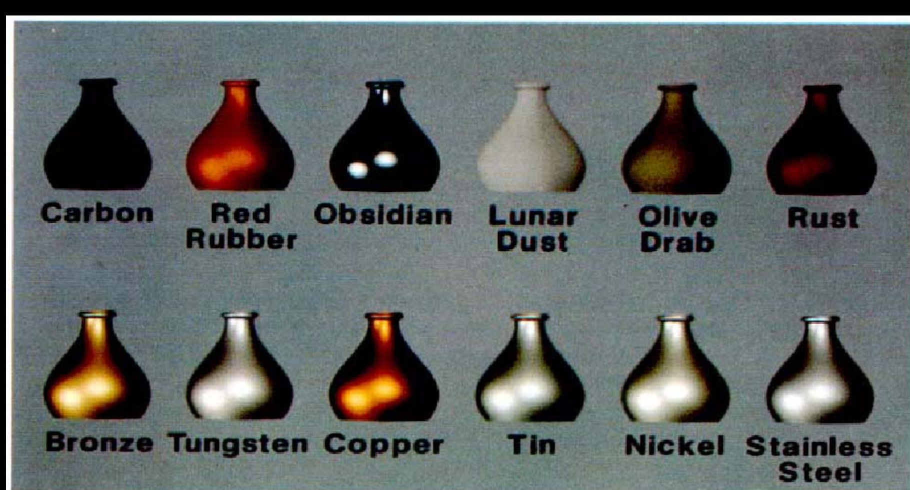




Phong's copper
(more like plastic)

Cook-Torrance copper
(more realistic)



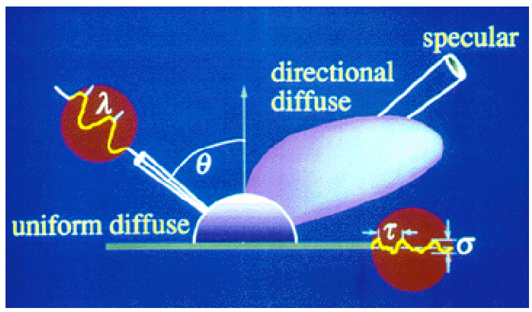


Cook-Torrance vases

Energy Conserving Approaches

There are still noticeable flaws in physically based models!

$$Light_{out} = Light_{emitted} + Light_{in} + Light_{absorbed}$$

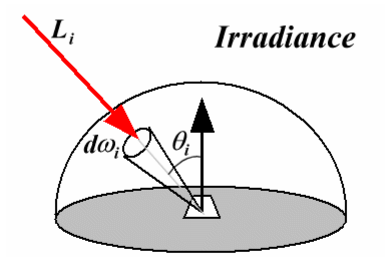


Definitions (again!)

- *Radiant flux (W)* - the rate at which light energy is emitted
- *Steradian (sr)* - a unit of solid (3D) angle (there are 4 π steradians in a sphere)
- *Radiant Intensity (W/sr)* - the rate that light energy is radiated through a given solid angle
- *Radiance ($W/(sr\ m^2)$)* - the rate of energy radiated through a given solid angle as seen reflected from a surface (i.e. the hemisphere is projected onto the surface)
- *Irradiance (W/m^2)* - the rate of incident or incoming energy at a surface point per unit surface area.

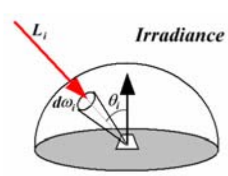
Irradiance

The irradiance function is a two dimensional function describing the incoming light energy impinging on a given point.

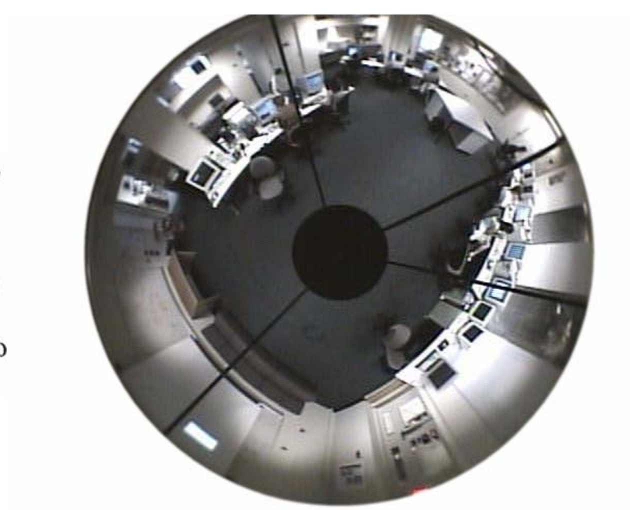


$$E_i = \int_{\Omega_i} L_i \cos\theta_i d\omega_i$$

What does Irradiance look like?

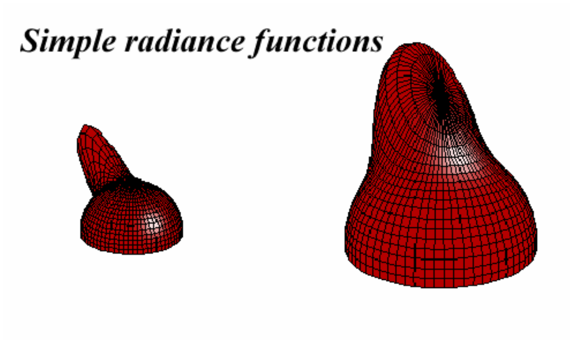


$$E_i = \int_{\Omega_i} L_i \cos\theta_i d\omega$$



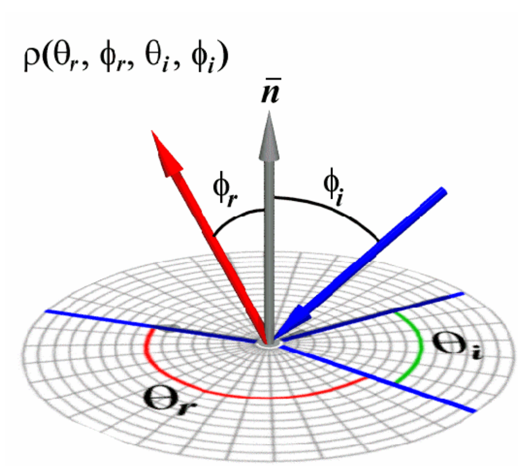
Radiance

Radiance is a two dimensional function representing the light reflected from a surface.



Combining these Functions (new stuff)

Bidirectional Reflectance Distribution Function (BRDF)



BRDF Approaches

1. Physically-based models
2. Measured BRDFs

Check slide set "BRDF-1.ppt"

Remaining Hard Problems

Reflective Diffraction Effects

- thin films
- feathers of a blue jay
- oil on water
- CDs

Anisotropy

- brushed metals
- strands pulled materials
- Satin and velvet cloths