Advanced Computer Graphics (Fall 2010)

CS 283, Lecture 9: Illumination and Reflection

http://inst.eecs.berkeley.edu/~cs283/fa10

Many slides courtesy Pat Hanrahan

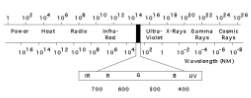
Overview

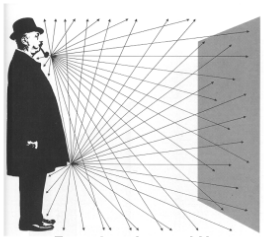
- Moving from geometry to rendering and appearance
- Major part of course: 10 lectures
  - Includes discussion of current research topics
  - Assignments 2 and 3
- First couple of lectures recap of 184 for those in it
  - Formal illumination, reflection, global illumination
  - But quickly move to new and advanced material
- Remember Mesh Assignment due Oct 7

Light

Visible electromagnetic radiation

Power spectrum





From London and Upton

Polarization

Photon (quantum effects)

Wave (interference, diffraction)

Radiometry

- Physical measurement of electromagnetic energy
- *Measure spatial (and angular) properties of light*
  - *Radiance, Irradiance*
  - Reflection functions: Bi-Directional Reflectance Distribution Function or BRDF
  - Reflection Equation
  - Simple BRDF models
- Environment Maps

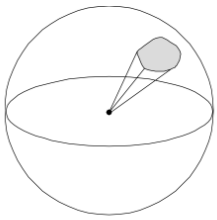
Angles and Solid Angles

- **Angle** $\theta = \frac{l}{r}$

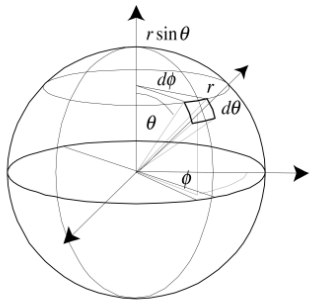
  ⇒ circle has 2π radians

- **Solid angle** $\Omega = \frac{A}{R^2}$

  ⇒ sphere has 4π steradians

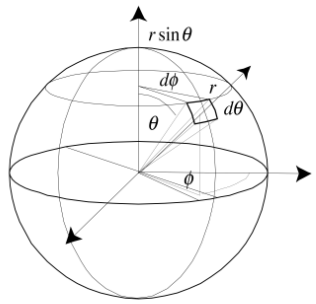


Differential Solid Angles



$$dA = (r\,d\theta)(r\sin\theta\,d\phi)$$
$$= r^2 \sin\theta\,d\theta\,d\phi$$

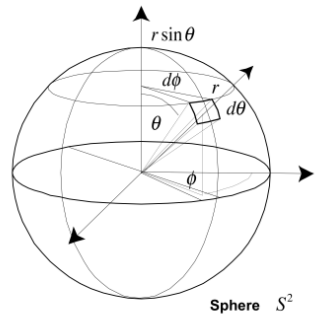
Differential Solid Angles



$$dA = (r\,d\theta)(r\sin\theta\,d\phi)$$
$$= r^2 \sin\theta\,d\theta\,d\phi$$

$$d\omega = \frac{dA}{r^2} = \sin\theta\,d\theta\,d\phi$$

Differential Solid Angles



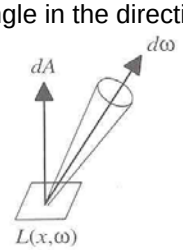
$$d\omega = \sin\theta\,d\theta\,d\phi$$

$$\Omega = \int_{S^2} d\omega$$
$$= \int_0^{\pi}\int_0^{2\pi} \sin\theta\,d\theta\,d\phi$$
$$= \int_{-1}^{1}\int_0^{2\pi} d\cos\theta\;d\phi$$
$$= 4\pi$$

Sphere S^2

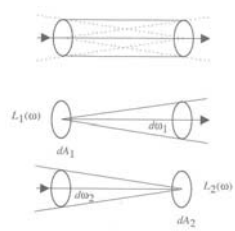
Radiance

- Power per unit projected area perpendicular to the ray per unit solid angle in the direction of the ray
- Symbol: $L(x,\omega)$ (W/m^2 sr)
- Flux given by $d\Phi = L(x,\omega) \cos\theta\, d\omega\, dA$



Radiance properties

- Radiance constant as propagates along ray
  - Derived from conservation of flux
  - Fundamental in Light Transport.



$$d\Phi_1 = L_1 d\omega_1 dA_1 = L_2 d\omega_2 dA_2 = d\Phi_2$$

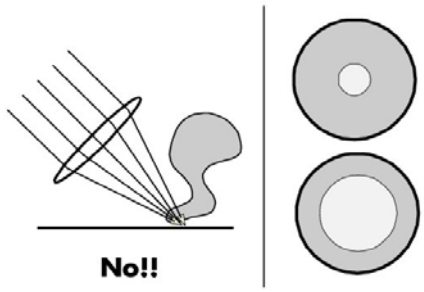
$$d\omega_1 = dA_2/r^2 \qquad d\omega_2 = dA_1/r^2$$

$$d\omega_1 dA_1 = \frac{dA_1 dA_2}{r^2} = d\omega_2 dA_2$$

$$\therefore L_1 = L_2$$

Quiz

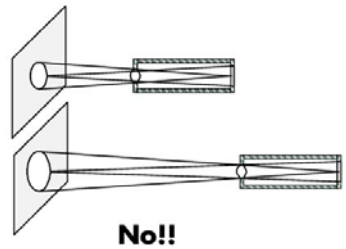
Does radiance increase under a magnifying glass?



No!!

Quiz

Does the brightness that a wall appears to the eye depend on the distance of the viewer to the wall?



No!!

Radiance properties

- Sensor response proportional to radiance (constant of proportionality is throughput)
  - Far away surface: See more, but subtends smaller angle
  - Wall equally bright across viewing distances

Consequences

- Radiance associated with rays in a ray tracer
- Other radiometric quants derived from radiance

Irradiance, Radiosity

- Irradiance E is radiant power per unit area
- Integrate incoming radiance over hemisphere
  - Projected solid angle (cos θ dω)
  - Uniform illumination: Irradiance = π [CW 24,25]
  - Units: W/m^2
- Radiant Exitance (radiosity)
  - Power per unit area leaving surface (like irradiance)

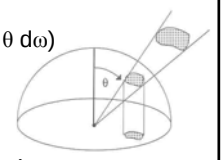
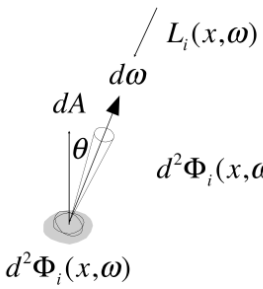


Figure 2.8: Projection of differential area.

Directional Power Arriving at a Surface



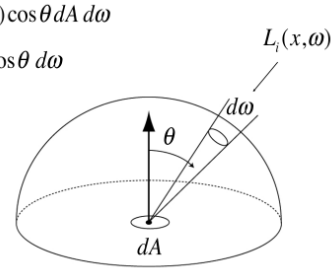
$$d^2\Phi_i(x,\omega) = L_i(x,\omega)\cos\theta\, dA d\omega$$

Irradiance from the Environment

$$d^2\Phi_i(x,\omega) = L_i(x,\omega)\cos\theta\, dA\, d\omega$$

$$dE(x,\omega) = L_i(x,\omega)\cos\theta\, d\omega$$

Light meter



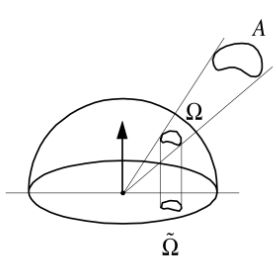
$$E(x) = \int_{H^2} L_i(x,\omega)\cos\theta\, d\omega$$

Uniform Area Source

$$E(x) = \int_{H^2} L\cos\theta\, d\omega$$

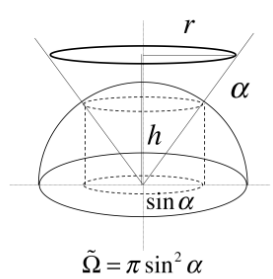
$$= L\int_{\Omega} \cos\theta\, d\omega$$

$$= L\tilde{\Omega}$$



Uniform Disk Source

Geometric Derivation



$$\tilde{\Omega} = \pi \sin^2\alpha$$

Algebraic Derivation

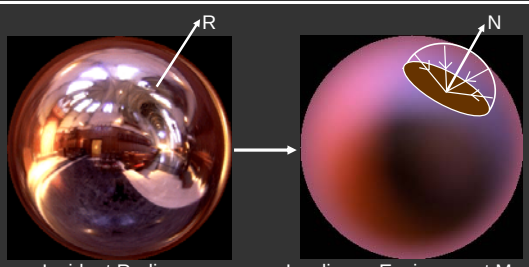
$$\tilde{\Omega} = \int_1^{\cos\alpha}\int_0^{2\pi} \cos\theta\, d\phi\, d\cos\theta$$

$$= 2\pi \left.\frac{\cos^2\theta}{2}\right|_1^{\cos\alpha}$$

$$= \pi \sin^2\alpha$$

$$= \pi \frac{r^2}{r^2+h^2}$$

Irradiance Environment Maps



Incident Radiance
(Illumination Environment Map)

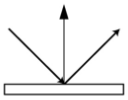
Irradiance Environment Map

Radiometry

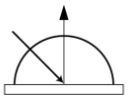
- Physical measurement of electromagnetic energy
- *Measure spatial (and angular) properties of light*
  - Radiance, Irradiance
  - *Reflection functions: Bi-Directional Reflectance Distribution Function or BRDF*
  - *Reflection Equation*
  - Simple BRDF models
- Environment Maps

Types of Reflection Functions

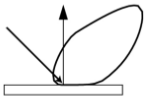
Ideal Specular
- **Reflection Law**
- **Mirror**



Ideal Diffuse
- **Lambert's Law**
- **Matte**



Specular
- **Glossy**
- **Directional diffuse**



Materials

Plastic **Metal** **Matte**

From Apodaca and Gritz, *Advanced RenderMan*

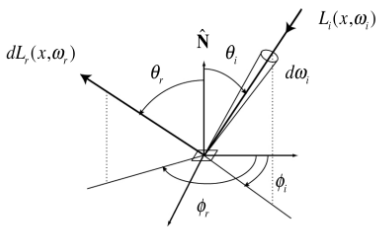
Spheres [Matusik et al.]

Building up the BRDF

- Bi-Directional Reflectance Distribution Function [Nicodemus 77]
- Function based on incident, view direction
- Relates incoming light energy to outgoing
- Unifying framework for many materials

The BRDF

Bidirectional Reflectance-Distribution Function



$$f_r(\omega_i \to \omega_r) \equiv \frac{dL_r(\omega_i \to \omega_r)}{dE_i} \quad \left[\frac{1}{sr}\right]$$

BRDF

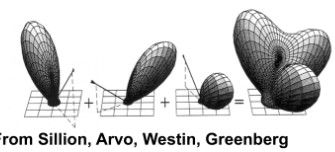
- Reflected Radiance proportional Irradiance
- Constant proportionality: BRDF
- Ratio of outgoing light (radiance) to incoming light (irradiance)
  - Bidirectional Reflection Distribution Function
  - (4 Vars) units 1/sr

$$f(\omega_i, \omega_r) = \frac{L_r(\omega_r)}{L_i(\omega_i)\cos\theta_i d\omega_i}$$

$$L_r(\omega_r) = L_i(\omega_i) f(\omega_i, \omega_r)\cos\theta_i d\omega_i$$

Properties of BRDF's

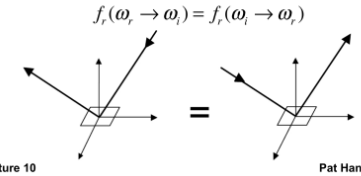
1. Linearity



From Sillion, Arvo, Westin, Greenberg

2. Reciprocity principle

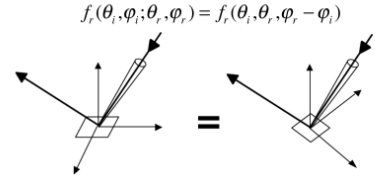
$$f_r(\omega_r \to \omega_i) = f_r(\omega_i \to \omega_r)$$



Properties of BRDF's

3. Isotropic vs. anisotropic

$$f_r(\theta_i, \varphi_i; \theta_r, \varphi_r) = f_r(\theta_i, \theta_r, \varphi_r - \varphi_i)$$



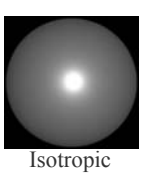
Reciprocity *and* isotropy

$$f_r(\theta_i, \theta_r, \varphi_r - \varphi_i) = f_r(\theta_r, \theta_i, \varphi_i - \varphi_r) = f_r(\theta_i, \theta_r, |\varphi_r - \varphi_i|)$$

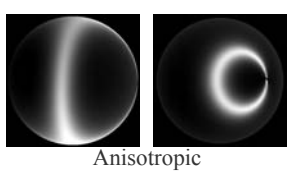
4. Energy conservation

Isotropic vs Anisotropic

- Isotropic: Most materials (you can rotate about normal without changing reflections)
- Anisotropic: brushed metal etc. preferred tangential direction



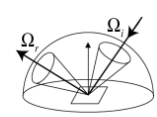
Isotropic



Anisotropic

Energy Conservation

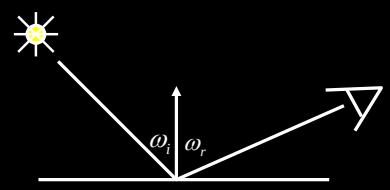
$$\frac{d\Phi_r}{d\Phi_i} = \frac{\int_{\Omega_r} L_r(\omega_r)\cos\theta_r \, d\omega_r}{\int_{\Omega_i} L_i(\omega_i)\cos\theta_i \, d\omega_i}$$



$$= \frac{\int_{\Omega_r}\int_{\Omega_i} f_r(\omega_i \to \omega_r) L_i(\omega_i)\cos\theta_i \, d\omega_i \cos\theta_r \, d\omega_r}{\int_{\Omega_i} L_i(\omega_i)\cos\theta_i \, d\omega_i}$$

$$\leq 1$$

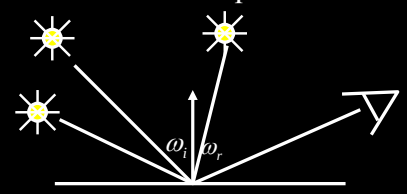
Reflection Equation



$$L_r(\omega_r) = L_i(\omega_i)\, f(\omega_i, \omega_r)(\omega_i \bullet n)$$

Reflected Radiance (Output Image) | Incident radiance (from light source) | BRDF | Cosine of Incident angle

Reflection Equation

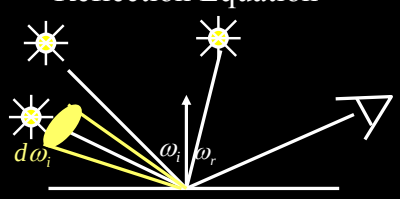


Sum over all light sources

$$L_r(\omega_r) = \sum_i L_i(\omega_i)\, f(\omega_i, \omega_r)(\omega_i \bullet n)$$

Reflected Radiance (Output Image) | Incident radiance (from light source) | BRDF | Cosine of Incident angle

Reflection Equation



Replace sum with integral

$$L_r(\omega_r) = \int_\Omega L_i(\omega_i)\, f(\omega_i, \omega_r)(\omega_i \bullet n)\, d\omega_i$$

Reflected Radiance (Output Image) | Incident radiance (from light source) | BRDF | Cosine of Incident angle

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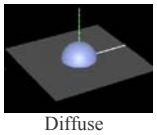
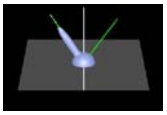
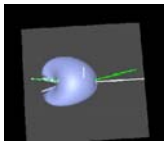
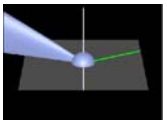
Brdf Viewer plots


Diffuse


Torrance-Sparrow


Anisotropic



by written by Szymon Rusinkiewicz

Ideal Diffuse Reflection

Assume light is equally likely to be reflected in any output direction (independent of input direction).

$$L_{r,d}(\omega_r) = \int f_{r,d} L_i(\omega_i) \cos\theta_i \, d\omega_i$$
$$= f_{r,d} \int L_i(\omega_i) \cos\theta_i \, d\omega_i$$
$$= f_{r,d} E$$

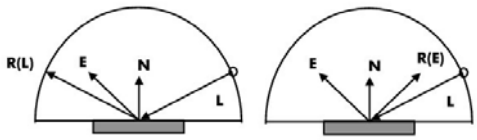
$$M = \int L_r(\omega_r) \cos\theta_r \, d\omega_r = L_r \int \cos\theta_r \, d\omega_r = \pi L_r$$

$$\rho_d = \frac{M}{E} = \frac{\pi L_r}{E} = \frac{\pi f_{r,d} E}{E} = \pi f_{r,d} \quad \Rightarrow \quad f_{r,d} = \frac{\rho_d}{\pi}$$

Lambert's Cosine Law $M = \rho_d E = \rho_d E_s \cos\theta_s$

CS348B Lecture 10 | Pat Hanrahan, Spring 2002

Phong Model



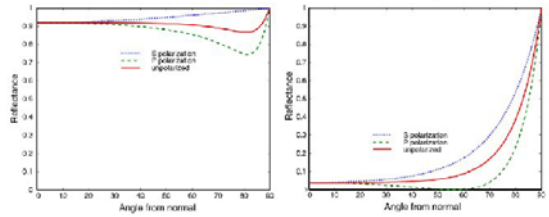
$$\left(\hat{\mathbf{E}} \bullet \mathbf{R}(\hat{\mathbf{L}})\right)^s \qquad \left(\hat{\mathbf{L}} \bullet \mathbf{R}(\hat{\mathbf{E}})\right)^s$$

Reciprocity: $\left(\hat{\mathbf{E}} \bullet \mathbf{R}(\hat{\mathbf{L}})\right)^s = \left(\hat{\mathbf{L}} \bullet \mathbf{R}(\hat{\mathbf{E}})\right)^s$

Distributed light source!

Fresnel Reflectance

Metal (Aluminum) **Dielectric (N=1.5)**



Gold F(0)=0.82
Silver F(0)=0.95

Glass n=1.5 F(0)=0.04
Diamond n=2.4 F(0)=0.15

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

Experiment

Reflections from a shiny floor

From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97

Analytical BRDF: TS example

- One famous analytically derived BRDF is the Torrance-Sparrow model.
- T-S is used to model specular surface, like the Phong model.
  - more accurate than Phong
  - has more parameters that can be set to match different materials
  - derived based on assumptions of underlying geometry. (instead of 'because it works well')

Torrance-Sparrow

- Assume the surface is made up grooves at the microscopic level.

- Assume the faces of these grooves (called microfacets) are perfect reflectors.
- Take into account 3 phenomena

Shadowing Masking Interreflection

Torrance-Sparrow Result

Fresnel term: allows for wavelength dependency

Geometric Attenuation: reduces the output based on the amount of shadowing or masking that occurs.

$$f = \frac{F(\theta_i)G(\omega_i, \omega_r)D(\theta_h)}{4\cos(\theta_i)\cos(\theta_r)}$$

How much of the macroscopic surface is visible to the light source

How much of the macroscopic surface is visible to the viewer

Distribution: distribution function determines what percentage of microfacets are oriented to reflect in the viewer direction.

Other BRDF models

- Empirical: Measure and build a 4D table
- Anisotropic models for hair, brushed steel
- Cartoon shaders, funky BRDFs
- Capturing spatial variation
- Very active area of research

Radiometry

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- Measure spatial (and angular) properties of light
  - Radiance, Irradiance
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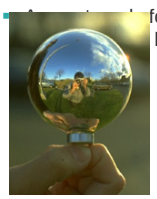
- *Environment Maps*

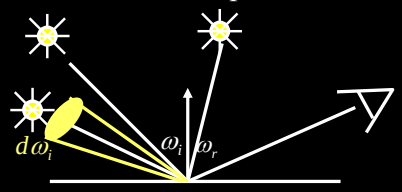
Environment Maps

- Light as a function of direction, from entire environment
- Captured by photographing a chrome steel or mirror sphere
- for or
  locat



Blinn and Newell 1976, Miller and Hoffman, 1984
Later, Greene 86, Cabral et al. 87

Reflection Equation



Replace sum with integral

$$L_r(\omega_r) = \int_\Omega L_i(\omega_i)\, f(\omega_i, \omega_r)(\omega_i \bullet n)\, d\omega_i$$

Reflected Radiance (Output Image) — ***Environment Map (continuous)*** — BRDF — Cosine of Incident angle

Environment Maps

- Environment maps widely used as lighting representation
- Many modern methods deal with offline and real-time rendering with environment maps
- Image-based complex lighting + complex BRDFs

Demo