Physics of light

Local Illumination model

interaction of light with the surface

Need to know

- how to measure light
- how to describe surface properties
- computer representation

Properties of light

- spectrum (energy per wavelength)
- polarization
- coherence

Radiometry: physical properties

Photometry: perceptual properties

Visible wavelengths: 380 nm - 770 nm

Basic Units

Force:

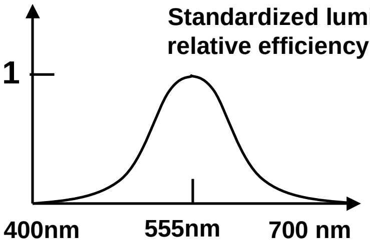
Newton = kg · m/sec^2

Energy:

joule =Newton · m

Power:

watt = joule/sec



Standardized luminous relative efficiency curve

To get “standard” eye response, integrate spectrum (energy as function of wavelength) multiplied by relative efficiency.

Luminous energy: talbot;

Luminous power: lumen = talbot/sec

Photometry and Radiometry

Radiometry units are primary. If the spectrum of light $P(\lambda)$ (measured in watts/nm) is known, then luminous power is computed as

$$684\int V(\lambda)P(\lambda)d\lambda$$

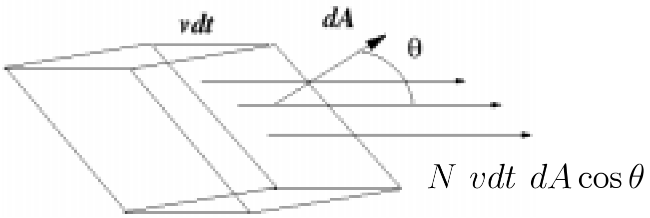
684 is an arbitrary constant measured in lumens/watt (luminosity at the wavelength 555 nm, yellow-green). If most of the energy of a light source is near 555nm, then to convert from watts to lumens multiply by 684.

Flow of light

Assumptions:

light consists out of particles (ignore wave nature)
propagates along straight rays (isotropic medium)

Flow:



N particle density

dA differential area

v particle velocity

Flux and Flux Density

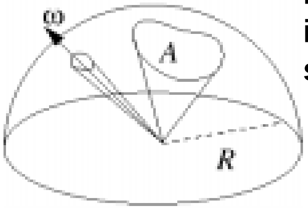
Flux = particles/unit time; differential flux through a small area:

$$d\Phi = Nv\cos\theta dA$$

Flux density = particles/(unit time unit area)

$$\frac{d\Phi}{dA} = Nv\cos\theta$$

Solid Angles



solid angle spanned by a cone is measured by the area of intersection of the cone with a sphere:

$$\Omega = \frac{A}{R^2}$$

differential solid angle can be assigned a direction. Unit: steradian (full sphere = 4π)

Measuring light

For any point in space, we can consider directional distribution of photons going through a differential area at this point.

Radiance: energy per unit time, per unit differential area perpendicular to the ray, per unit solid angle in the direction of the ray.
Measured in watts/meter^2 /steradian

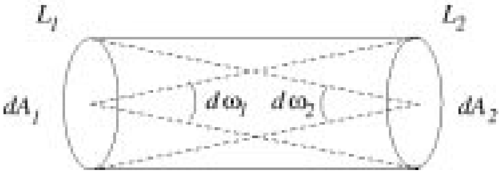
If $\phi(x,\omega) = \frac{dN}{d\Omega}$ **is directional distribution of**

photons of wavelength λ, **going through the area**

then radiance is $$L(x,\omega,\lambda) = \frac{hc}{\lambda}\phi(x,\omega)$$

energy of a photon

Constancy of Radiance



radiance is constant along a ray: consider the flow of photons in a a thin pencil; the number of photons entering onthe right with the direction inside $d\omega_1$ **exit through the other side; equating the expressions for entering and exiting diff. flows we get**

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

but $dA_1 d\omega_1 = dA_2 d\omega_2$ **so** $L_1 = L_2$

BRDF

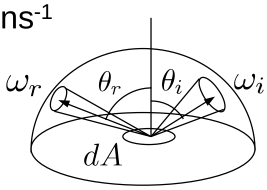
irradiance: light flow per unit area of surface

flow of radiance L spanning solid angle $d\omega_i$ creates differential irradiance $Ld\omega_i \cos\theta_i$

bidirectional reflectance distribution function:

the ratio of reflected radiance in direction r to the differtial irradiance in the direction i

units: steradians^{-1}



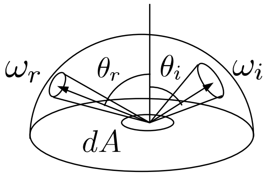
$$f(\omega_i, \omega_r) = \frac{dL_r(\omega_i, \omega_r)}{L_i \cos\theta_i d\omega_i}$$

Reflection equation

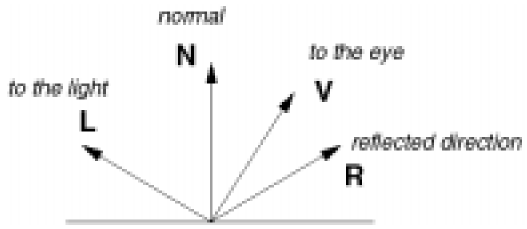
the outgoing radiance in direction r is the sum of the radiances due to radiance from all incoming directions:

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

the integral is over the upper hemisphere



Reflection geometry



$$\mathbf{V} = \omega_r,\ \mathbf{L} = \omega_i$$

$$\mathbf{R} = \mathbf{L} + 2(\mathbf{L} \cdot \mathbf{N})\mathbf{N}$$

Phong model

1. "BRDF"

$$f_r(\omega_i, \omega_r) = K_{diff} + K_{spec}(\omega_i \cdot \omega_r)^p$$

Point light source intensity: power per unit solid angle

intensity in a direction ω: $I(\omega) = \frac{d\Phi}{d\omega}$

radiance created by light source at distance r in the direction of the source: $L(\omega, r) = \frac{I(\omega)}{r^2}$

To avoid integration in the reflection equation, ignore radiance from all directions except a finite number (e.g. direction to the light sources).

Phong model

Phong model and Z-buffer rendering:

- **assume point light sources; ignore irradiance from all directions except the directions to the lights;**
- **ignore occlusions, that is, no shadows).**

Phong model and (classical) ray tracing:

- **consider reflection and transmission;**
- **take occlusions into account.**

Phong model

$$L(\mathbf{V}) = K_{amb}L_{amb} + \sum_i L_i\left(K_{diff}(\mathbf{L}_i \cdot \mathbf{N}) + K_{spec}(\mathbf{R}_i \cdot \mathbf{V})^p\right)$$

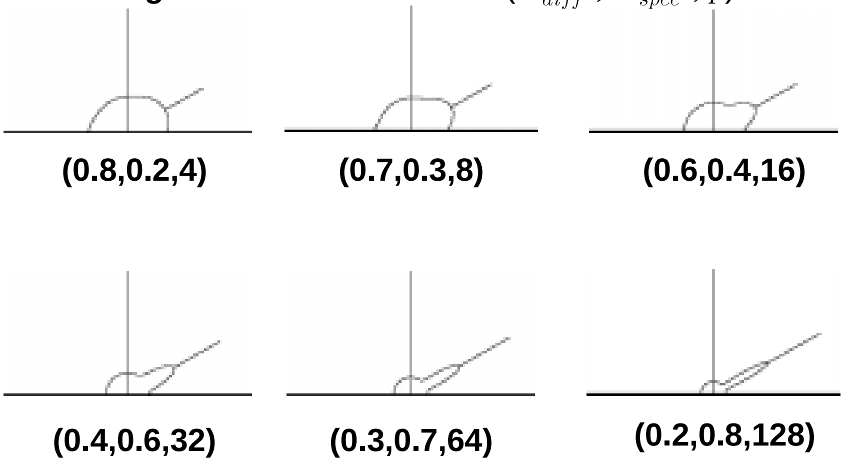
summation is over all light sources.

Ambient term: a hack. Because we ignore diffuse reflected light from objects (e.g. walls) the resulting images are often too dark.

Another hack: replace $L_i = \dfrac{I_i}{r^2}$ **with** $\dfrac{I_i}{d_c + d_l r + d_q r^2}$

Phong model

Directional plots of BRDF for a fixed incoming direction for different (K_{diff} , K_{spec} , p)



(0.8,0.2,4) (0.7,0.3,8) (0.6,0.4,16)

(0.4,0.6,32) (0.3,0.7,64) (0.2,0.8,128)

Constants and units

K_{diff} , K_{spec} **reflection coefficients, 3 color components**

p **Phong exponent, nondimensional, same for all colors**

L, L_{amb} **watts/meter^2/steradian, 3 color components**

I_i **light source intensity, 3 color components**

OpenGL model

Several additions:

ambient term per object;
emmision;
ambient, diffuse, specular light “intensities”

Setting material parameters (K_{diff},K_{spec},K_{amb},p)

```
GLfoat  mat_diffuse[3], mat_spec[3], mat_amb[3];
GLfloat shininess;

 ...
glMaterialfv(GL_FRONT,GL_DIFFUSE,mat_diffuse);
glMaterialfv(GL_FRONT,GL_SPECULAR,mat_spec);
glMaterialfv(GL_FRONT, GL_AMBIENT,mat_amb);
```

Lighting model for ray tracing

New effects: reflection, refraction; need more terms

reflection part:

$$L_1(\mathbf{V}) = \sum_{\substack{\text{visible sources}\\ \text{in front}}} L_i \left(K_{diff}(\mathbf{L}_i \cdot \mathbf{N}) + K_{spec}(\mathbf{R}_i \cdot \mathbf{V})^p\right) + k_{refl} L_{refl}$$

radiance from the reflected ray

$$L_2(\mathbf{V}) = \sum_{\substack{\text{visible sources}\\ \text{behind}}} L_i \left(K_{diff}(\mathbf{L}_i \cdot \mathbf{N}) + K_{spec}(\mathbf{T}_i \cdot \mathbf{V})^p\right) + k_{trans} L_{trans}$$

radiance from the refracted ray

$$L(\mathbf{V}) = K_{amb} L_{amb} + (1-t) L_1(\mathbf{V}) + t L_2(\mathbf{V})$$

t **is transparency**