BRIGHTNESS

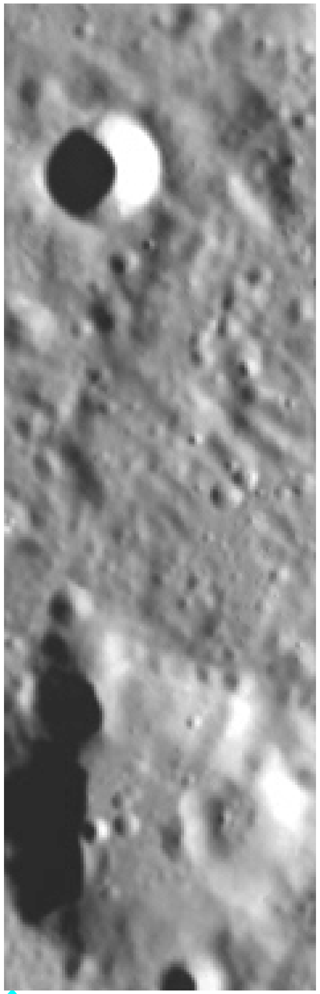
AND COLOR

Motivation

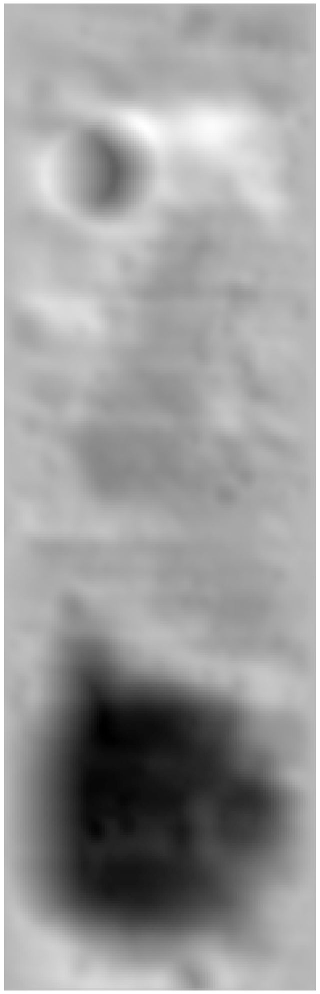
- Use images to recover information about the world
- We need to understand image formation
- We need to understand the physics of light reflection
- In some cases we can INVERT image formation process
  - We can extract invariant properties of surfaces of imaged objects
    - Geometric properties: shape reconstruction
    - Material properties: reflective properties, intrinsic color

Example

Shape from shading



Moon surface



Computed elevation map

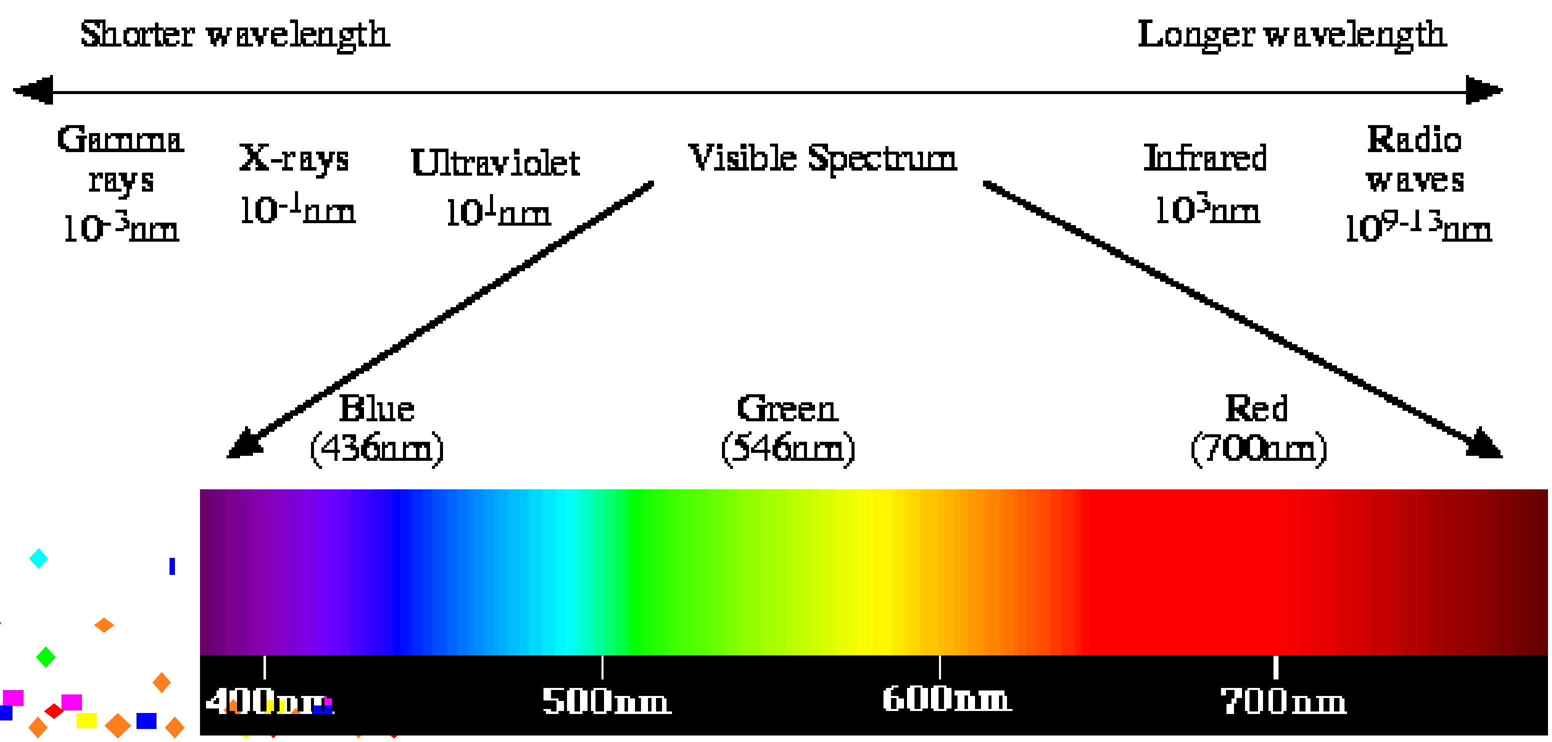
Synthetic image

Overview

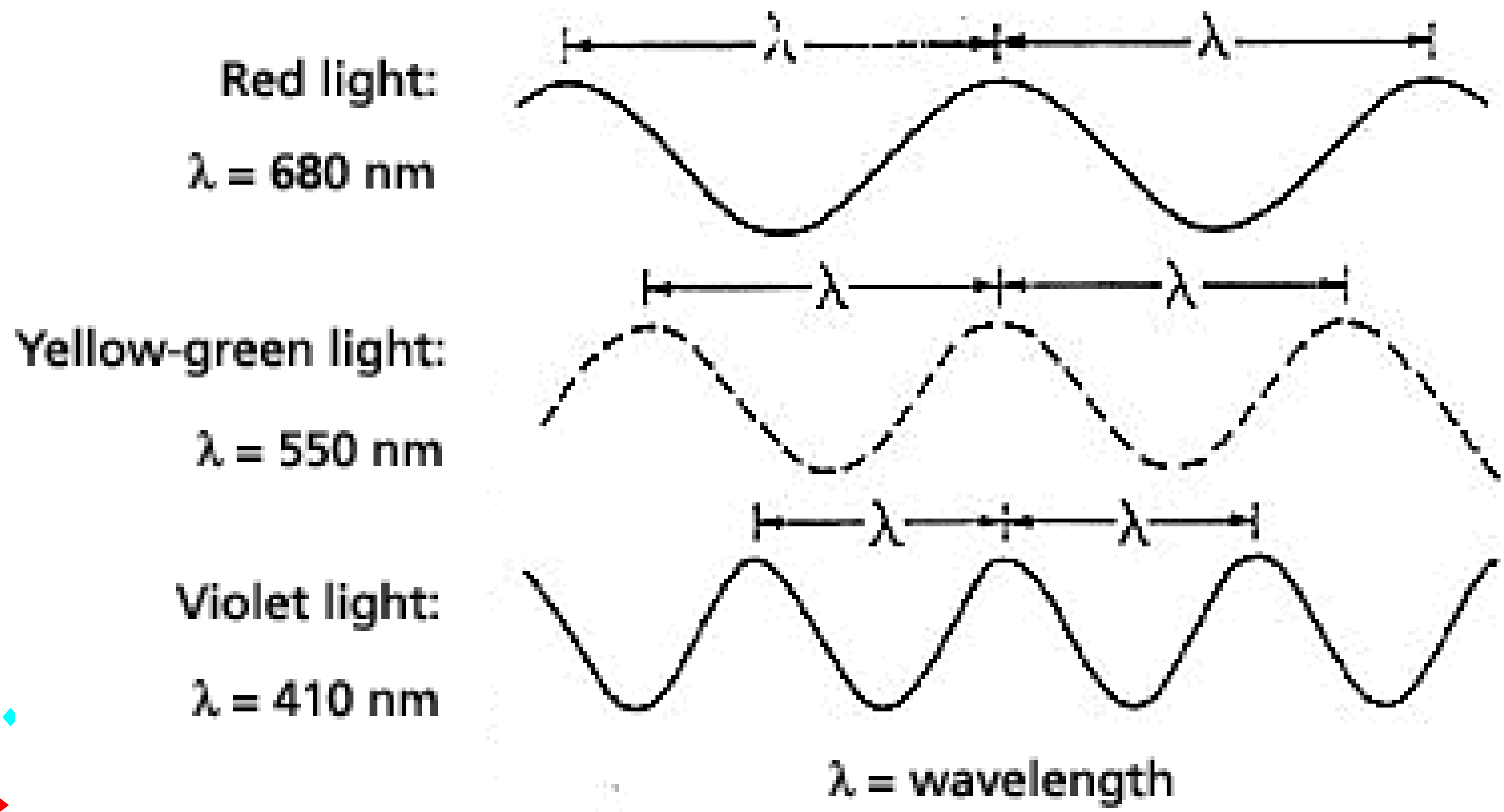
- What is Light
- Elements of Photometry
  - Related to brightness of light, not colors
  - Definitions of radiance, irradiance, radiosity, reflectance
- Color Perception
  - Effect of light spectrum
  - Color reflectance
  - Eye sensitivity
- Color Models

Electromagnetic Spectrum

- Light is just one part of electromagnetic spectrum
- X rays 0.1 nanometer
- Radio waves 1 meter or more
- Light 380 to 770 nanometers (1000 nm = 1/100 paper sheet)



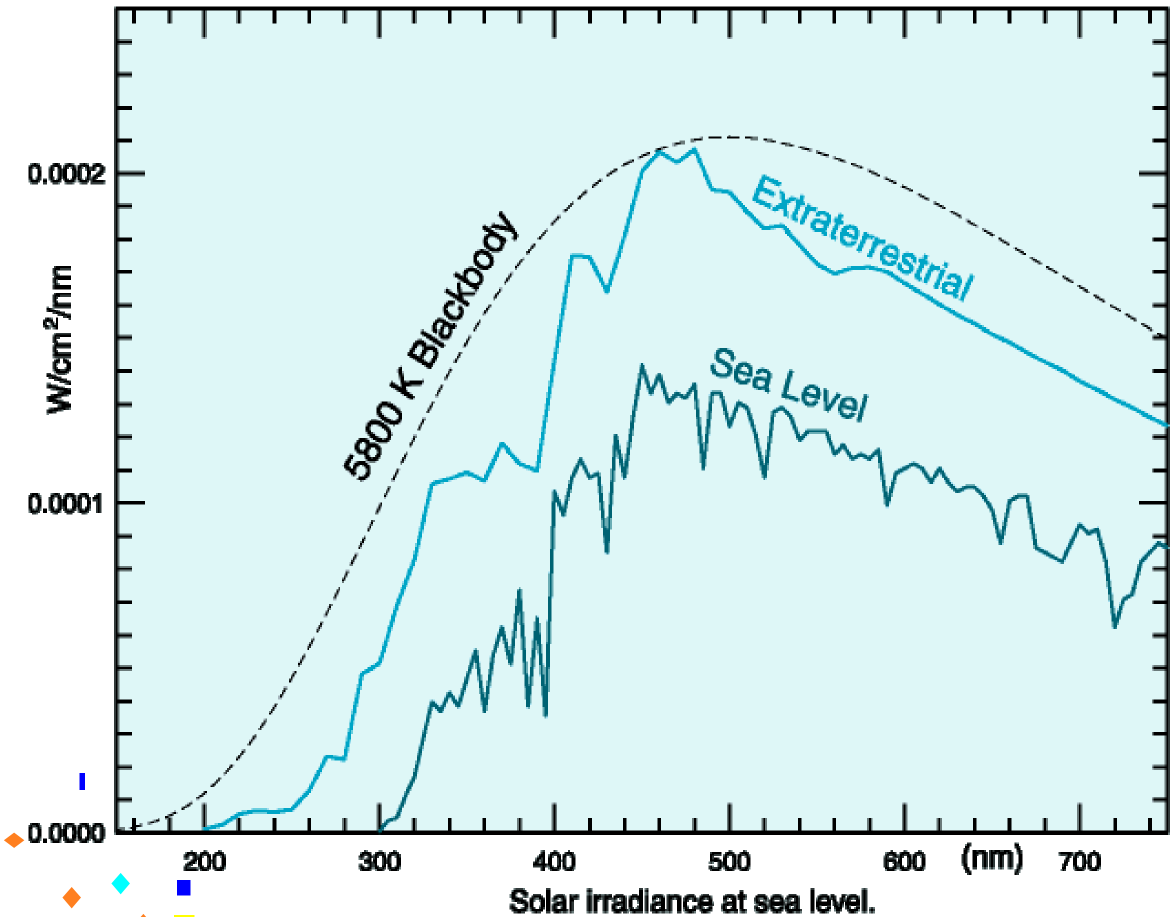
Waves



Red light:
λ = 680 nm
Yellow-green light:
λ = 550 nm
Violet light:
λ = 410 nm
λ
λ = wavelength

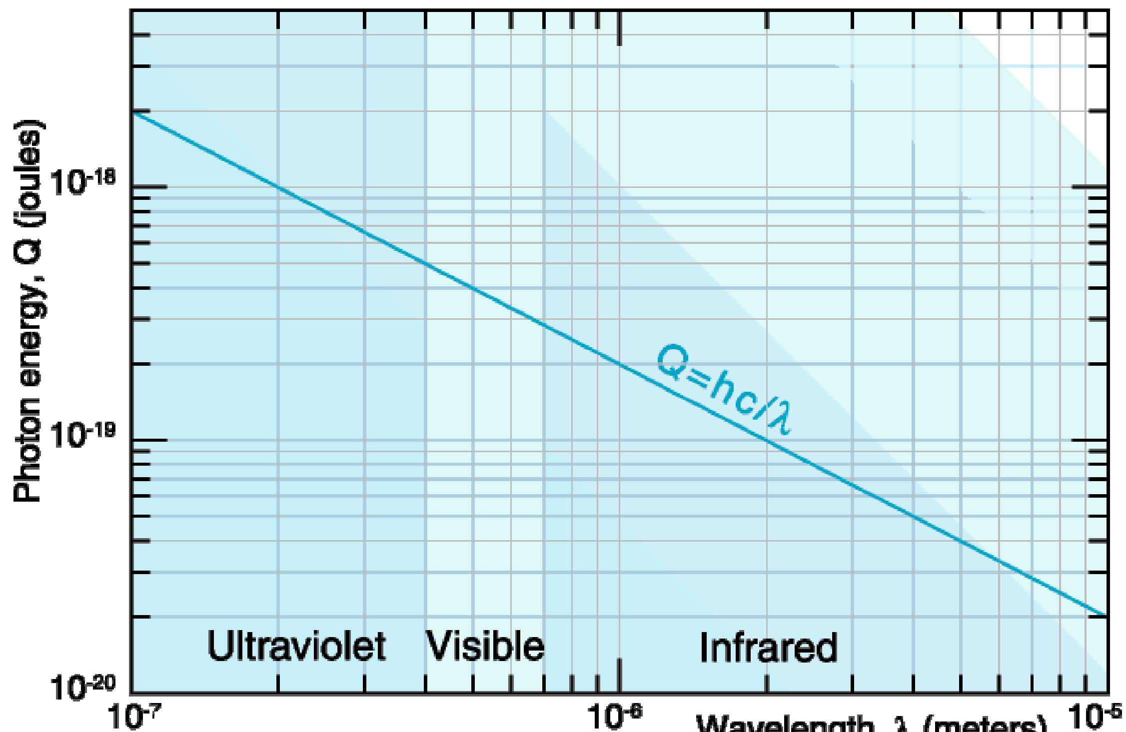
Spectral Description of Light

- A light source can be described by its spectral power distribution
  - relative power emitted at each wavelength



Photons and Waves

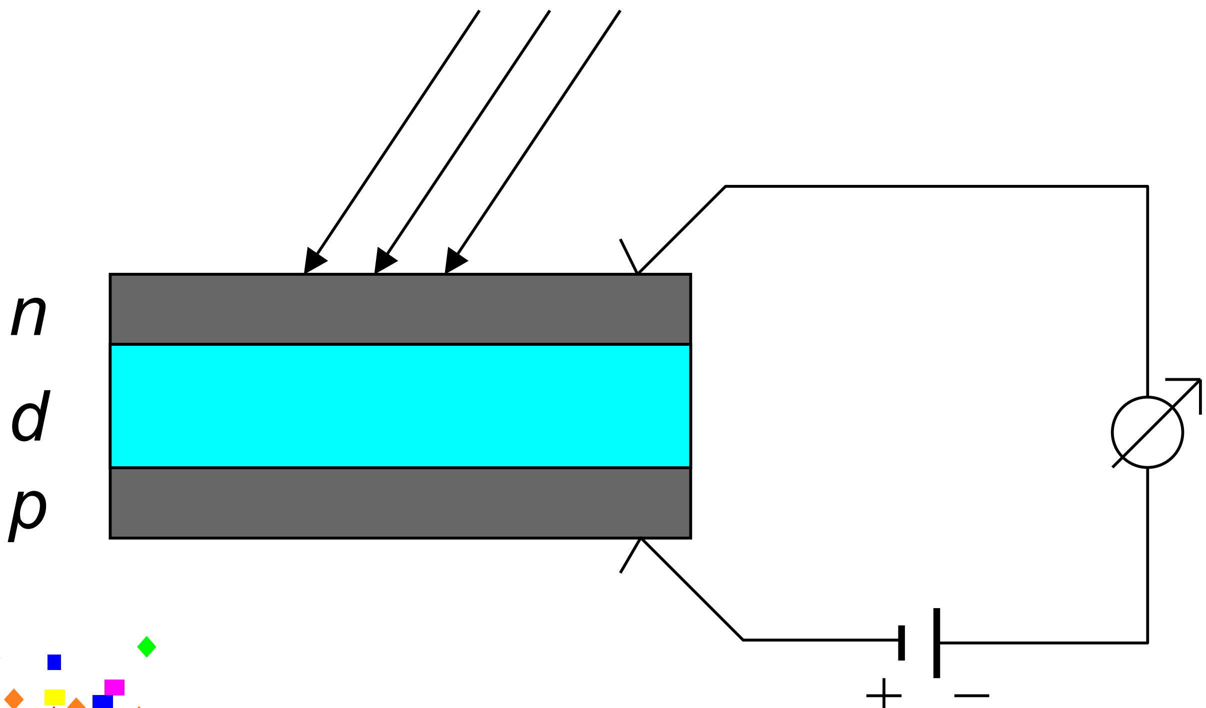
- EM radiations are both particles and waves
- At short wavelengths, particle effects
- At long wavelengths, wave behavior
- Photon energy $Q = h\,f = h\,c\,/\lambda$
- Plank's constant $h = 6.623\ 10^{-34}$ J s
- $c = 2.998\ 10^{8}$ m/s speed of light
- $f = c\,/\lambda$



Planck's equation showing photon energy vs. wavelength.

Photons

- Electron-hole pairs are separated by the built-in field and are collected in the external circuit
- Quantum efficiency $q(\lambda)$, ratio of electron flux to photon flux for each wave length
  - Weak photons go through, energetic photons are stopped too early



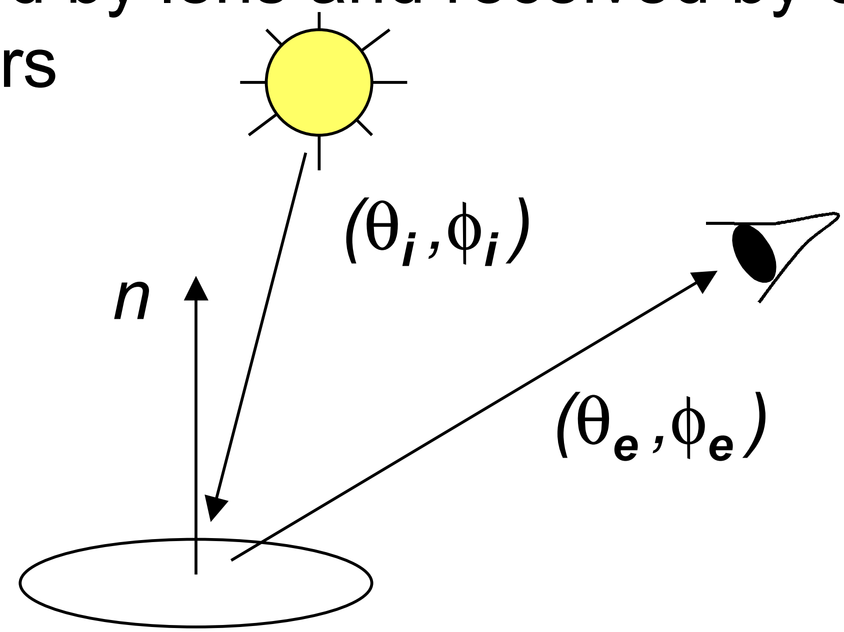
How Light Behaves

- Light interacts with materials
  - Reflection
  - Diffraction
  - Refraction
  - Transmission
- Light waves interact
  - Interference

Brightness of a Surface

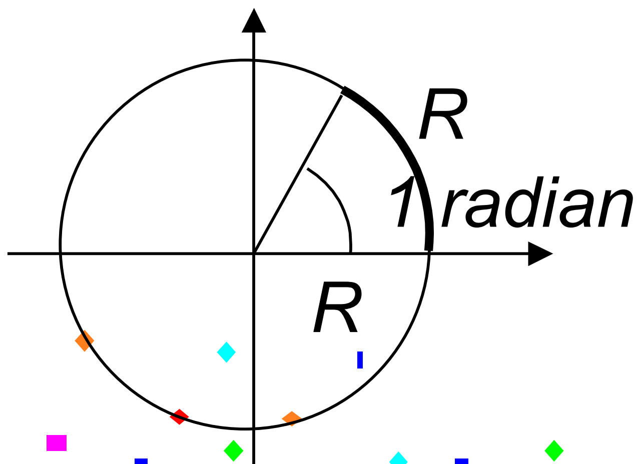
Related to

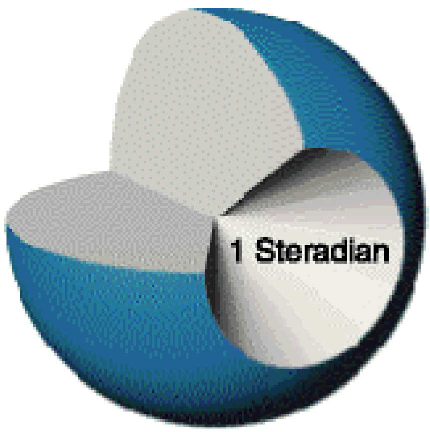
- power emitted by source (*across all wavelengths*)
- power received by surface
- power reflected by surface
- power refracted by lens and received by eye or camera sensors

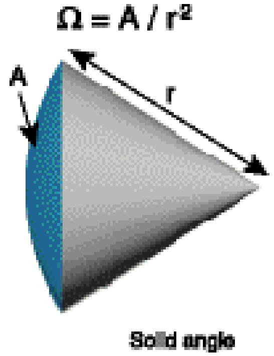


Solid angles

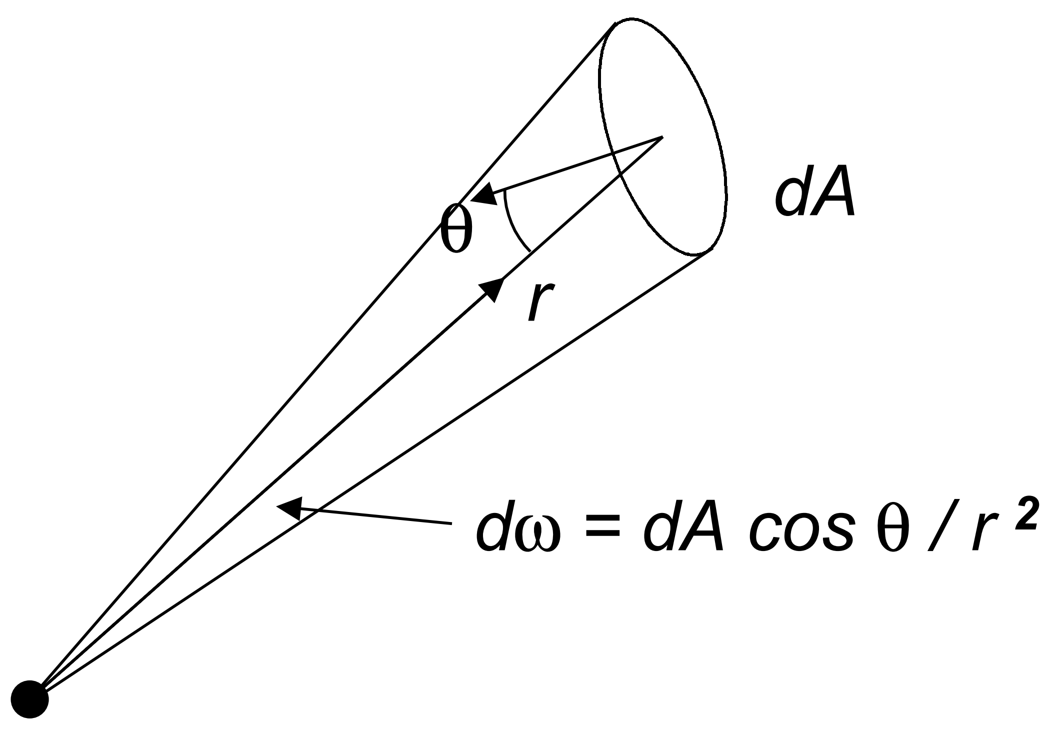
- Measure the proportion of space contained between a point to a surface.
- Unit is steradian (*sr*), angle from center of a sphere to an area on its surface equal to square of its radius
  - there are 4 π steradians in the solid angle that sees the whole space from a point (sphere area is 4 π R^2)







Infinitesimal solid angle from a point to a tilted patch

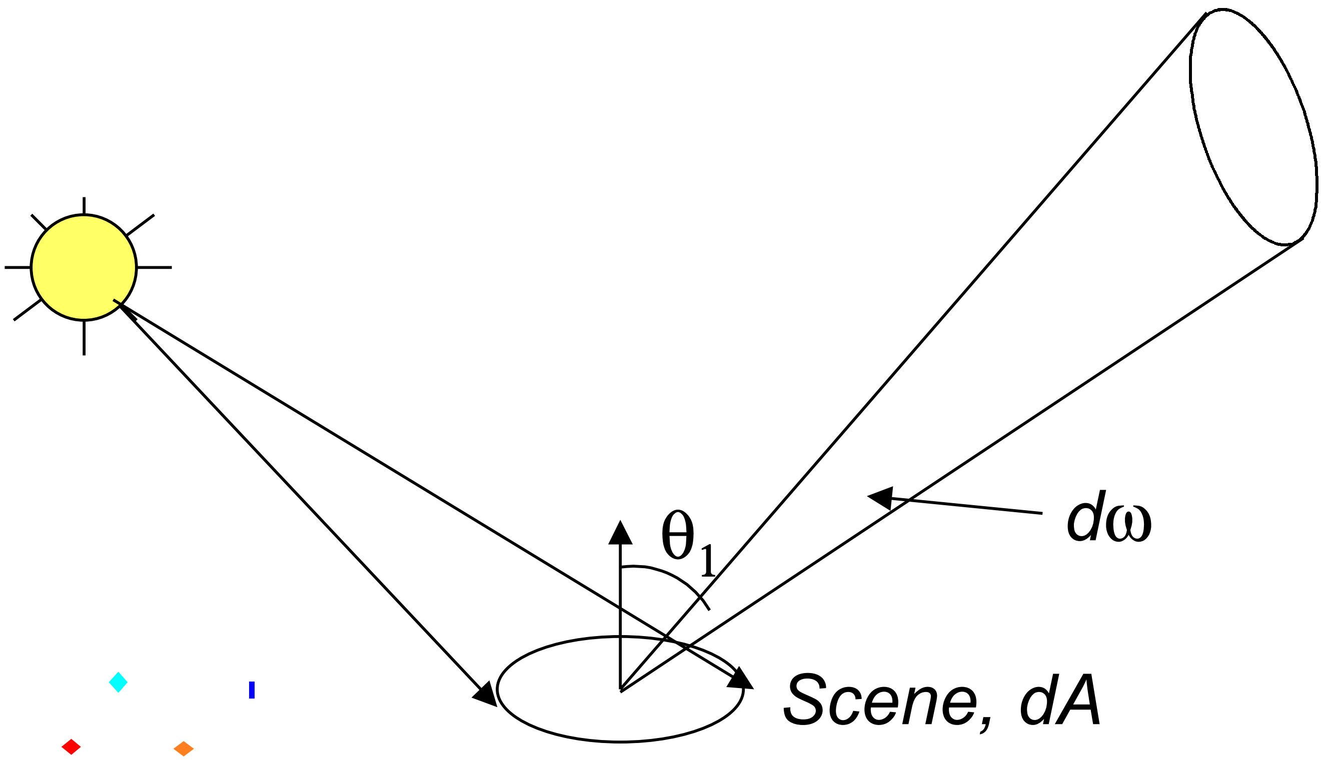


Radiance

Radiance $L(\theta_1)$ is power (energy flux) emitted per unit area into a cone having unit solid angle

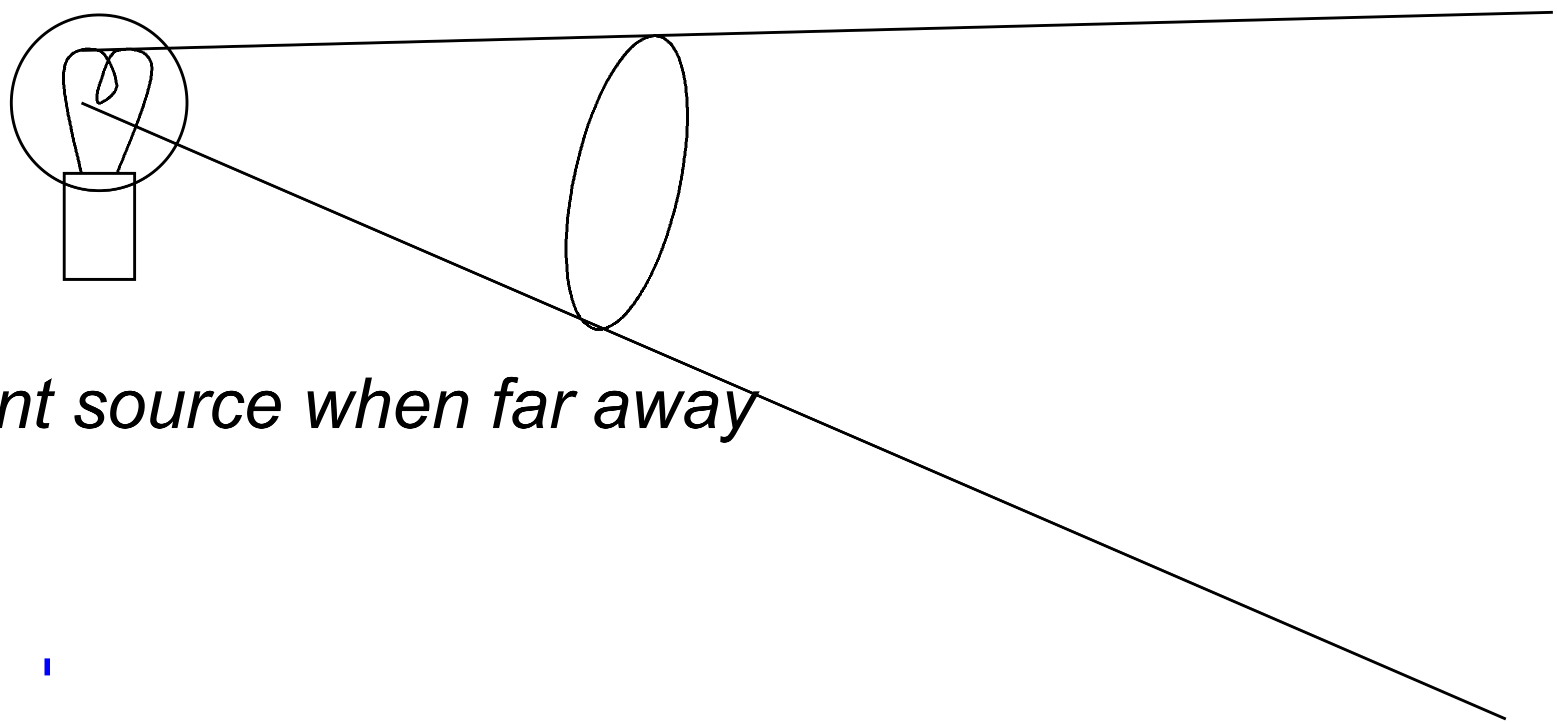
- Area used is foreshortened area in direction θ_1

$$L(\theta_1) = d^2P / (dA \cos\theta_1 \, d\omega), \text{ in } W/m^2/sr$$



Radiant Intensity

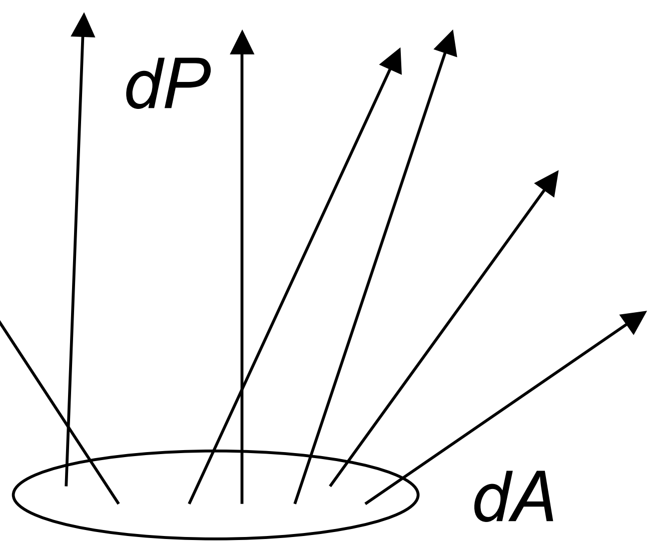
- Radiant intensity is integral of radiance with respect to *dA* over the area of radiant material
- Radiant intensity is the flux of energy (power) radiated per steradian. It is measured in W/sr
- $I = dP / d\omega$



Bulb is a point source when far away

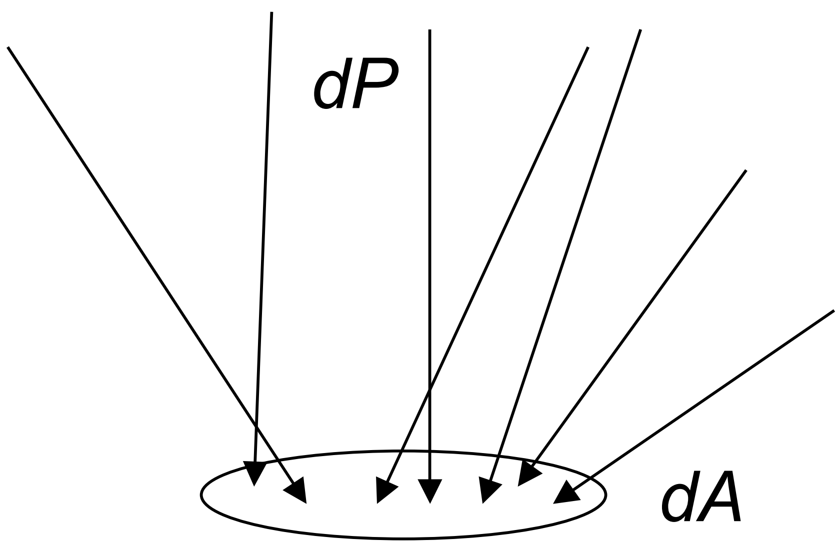
Radiosity

- Radiosity is integral of radiance with respect to $d\omega$ for a hemisphere.
- It is the power radiated per unit area
- $B = dP/dA$, in W/m^2



Irradiance

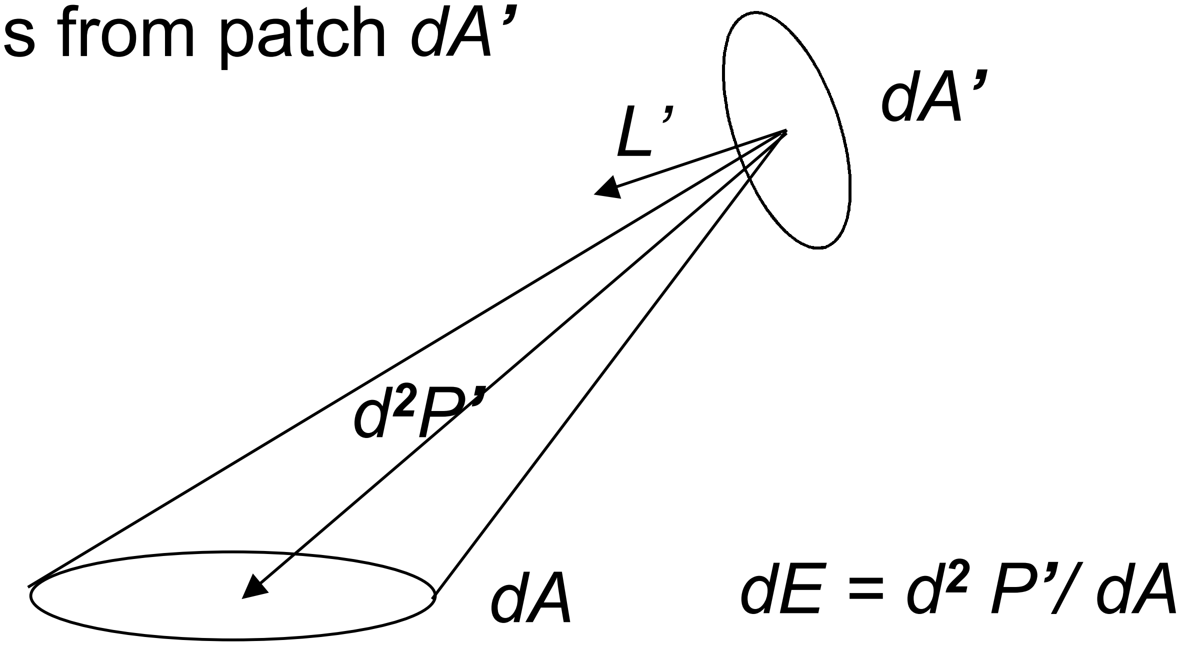
- Light power per unit area falling on a surface
- Computed by integrating radiances of sources and surfaces around



$E = dP / dA$, in W/m^2

Infinitesimal Irradiance from a Patch

- Contribution *dE* of patch *dA'* to irradiance *E* on patch *dA*
- d^2P' is a second order term: how much irradiance of patch *dA* comes from patch *dA'*

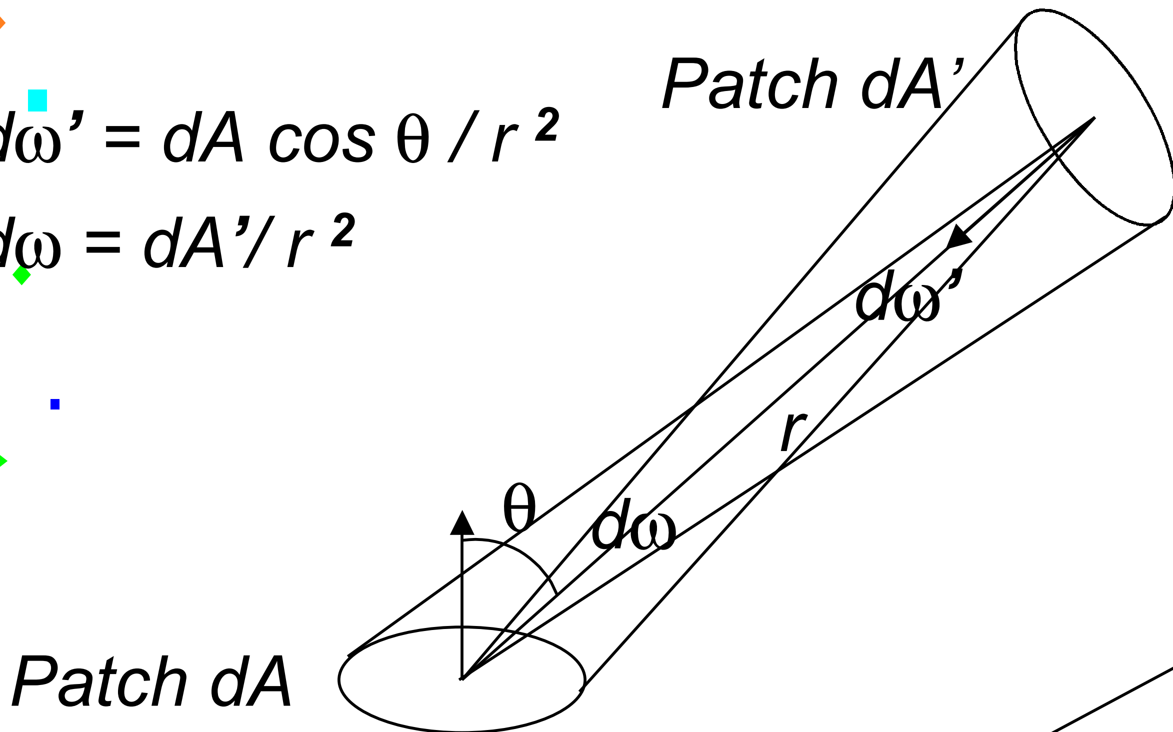


Power transfer between surface patches by radiance and irradiance

- Radiance of patch *dx* toward *dy* is related to irradiance of patch *dy* due to patch *dx*

$$d\omega' = dA \cos\theta / r^2$$

$$d\omega = dA' / r^2$$



$$d^2P = L'\, dA'\, d\omega'$$

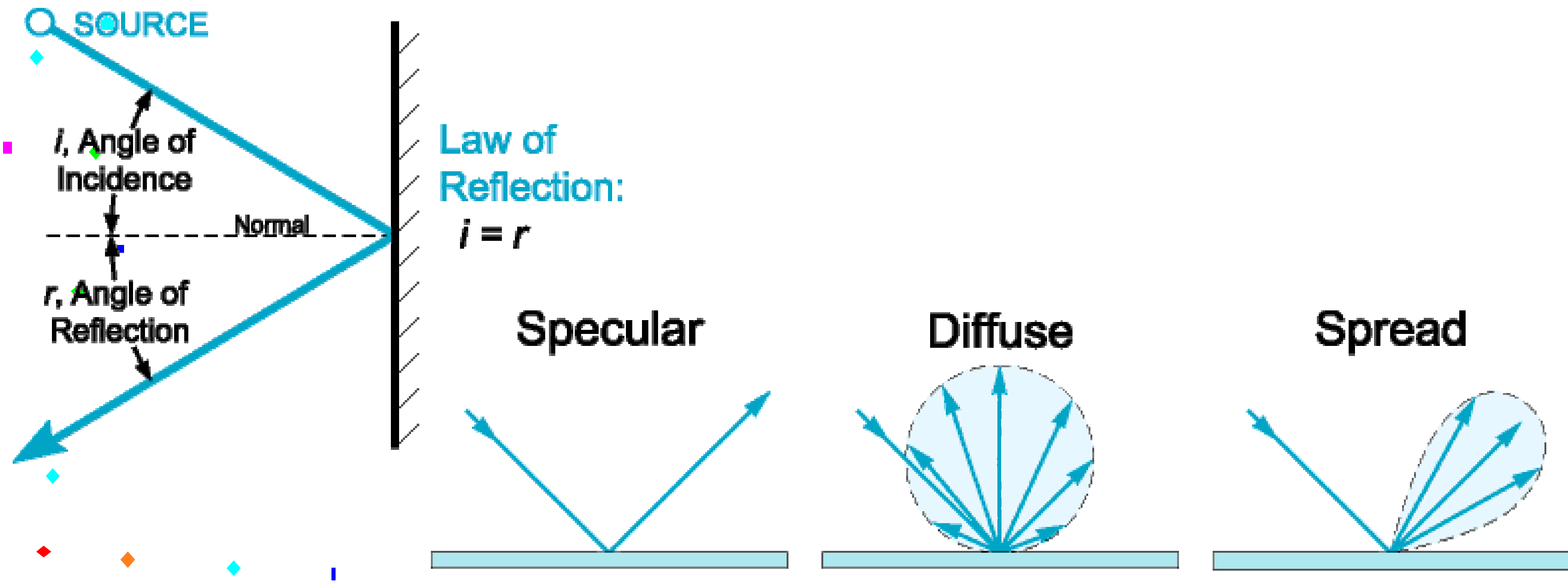
$$d^2P = L' dA'\, dA \cos\theta / r^2$$

$$dE = L' \cos\theta\, d\omega$$

$$d^2P = dE\, dA$$

Reflection

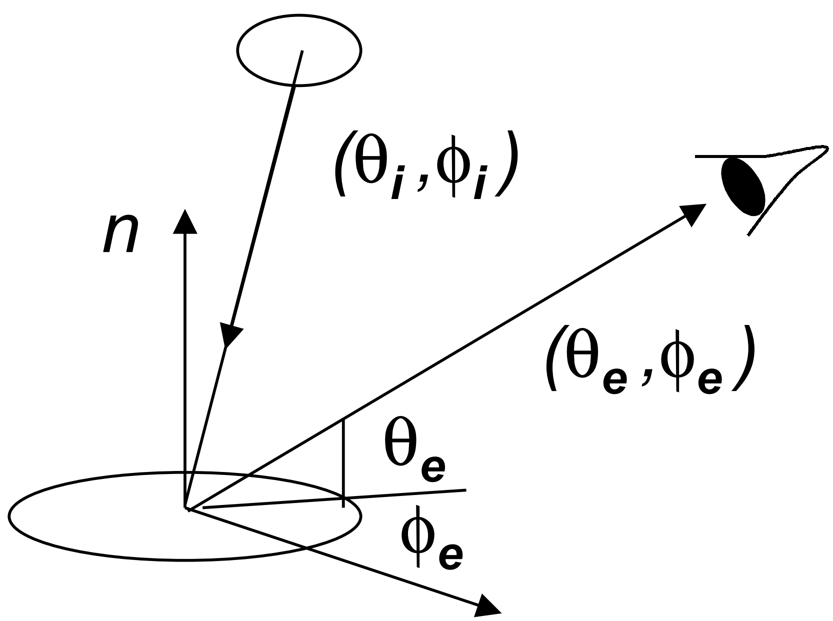
- Specular reflection
- Diffuse reflection: flour, white matte paint
- Spread reflection: combination



Specular, diffuse, and spread reflection from a surface.

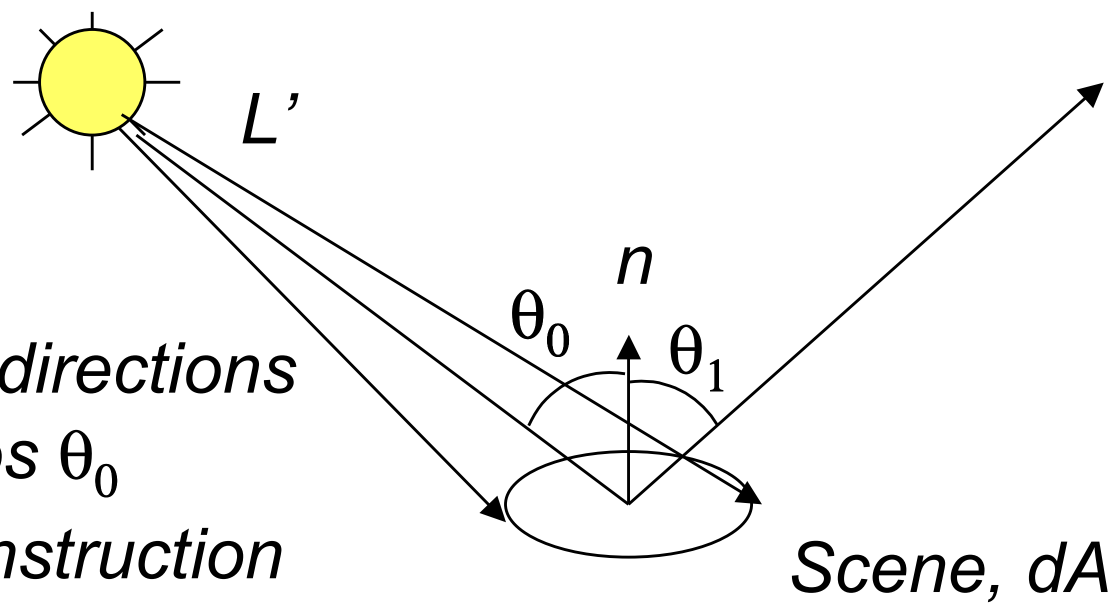
Reflectance

- Reflection is characterized by reflectance
- Reflectance is ratio radiance/irradiance
- Described by a function called
  Bidirectional Reflectance Distribution Function BRDF
- BRDF = $f(\theta_i, \phi_i, \theta_e, \phi_e) = L(\theta_e, \phi_e) / dE(\theta_i, \phi_i)$



Mirrors and Lambertian Surfaces

- Perfect mirror: the BRDF is 0 for all directions except direction of light reflection
- If BRDF is a constant *K*, surface is called a Lambertian surface
- $dE = L' \cos \theta_0 \, d\omega = k \, L' \cos \theta_0$
- $L = K \, dE = K_1 \, L' \cos \theta_0$



- *Radiance is same in all directions and is proportional to cos* θ_0
- *See moon surface reconstruction*

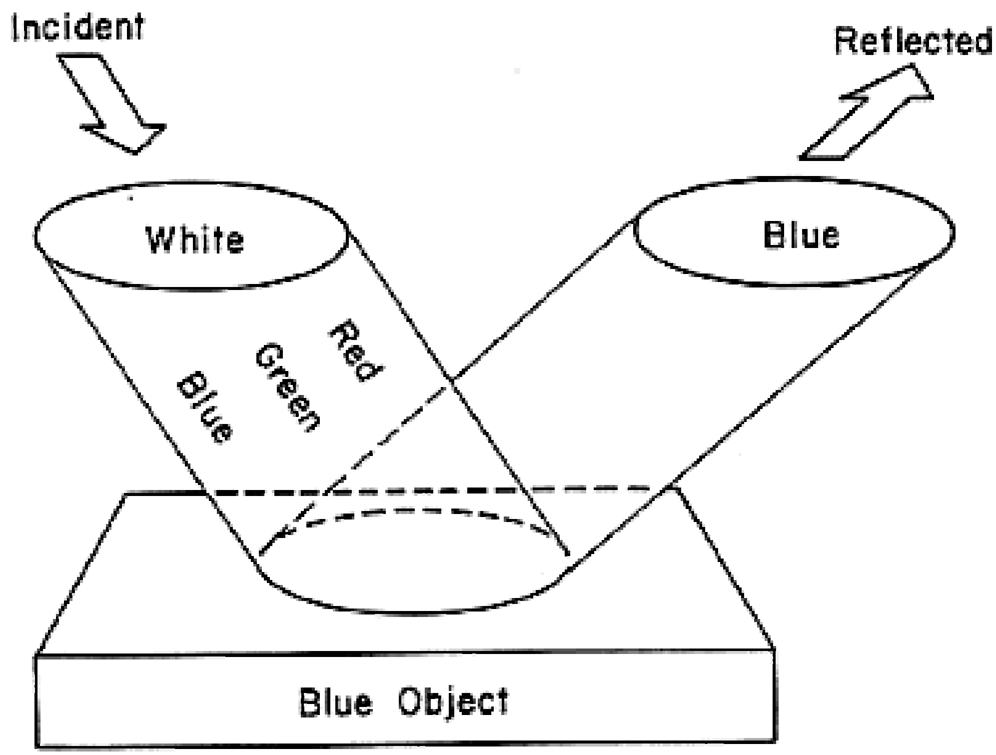
Radiance, Irradiance and Brightness

- What we can measure is image irradiance, characterized by the brightness of image pixels
- It is caused by scene radiance
- We say a scene surface is bright when its image is bright
- Brightness is informal term for both radiance and irradiance
- We will show that image irradiance is proportional to scene radiance, because of the way the optics work.

Color Perception

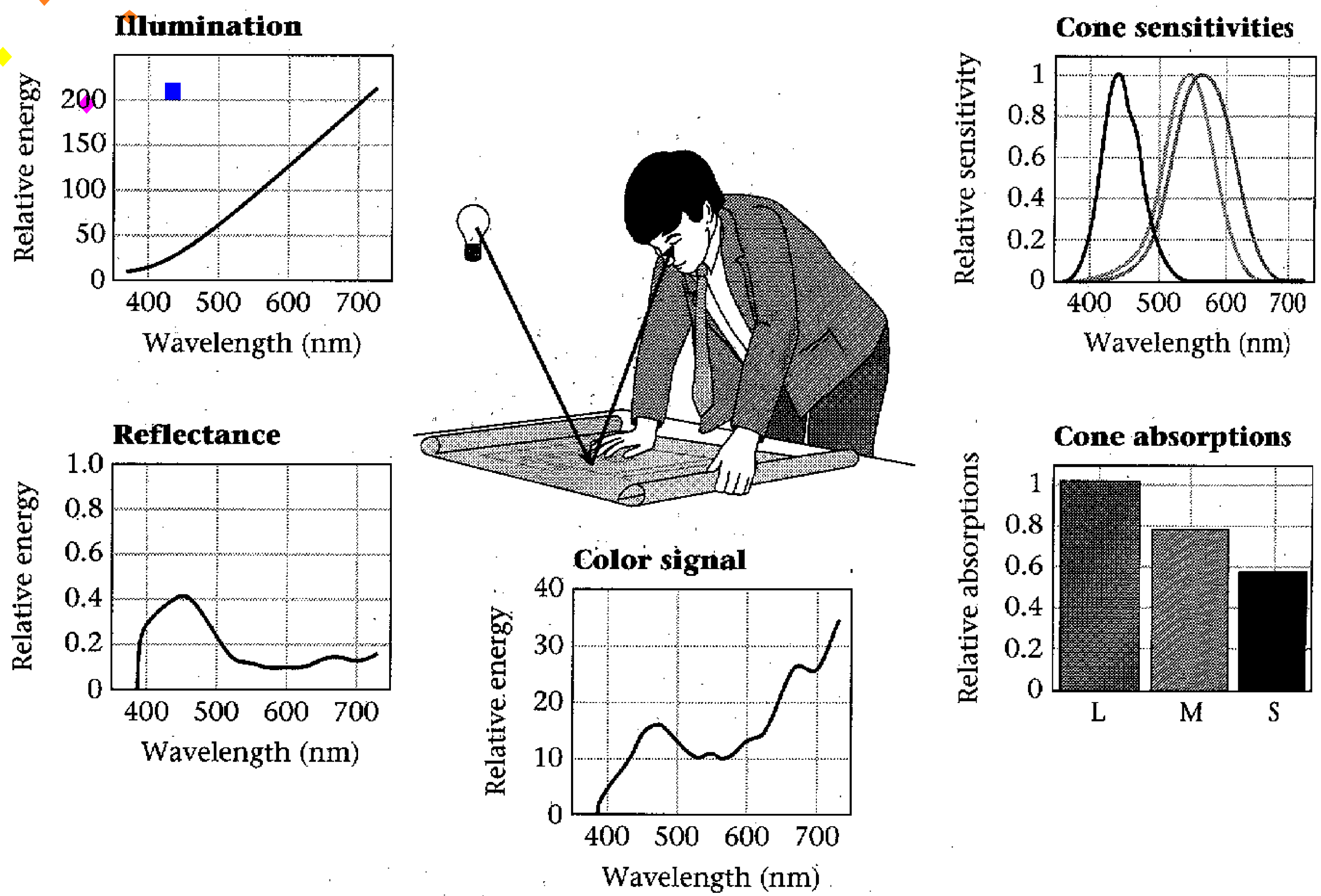
- Color is an important part of our visual experience
- We distinguish only 100 levels of grays but hundreds of thousands of colors
- Color detection is important to computer vision,
  - Object recognition is easier
  - Underutilized because more processing is required, hard to publish

Color Perception of Reflection



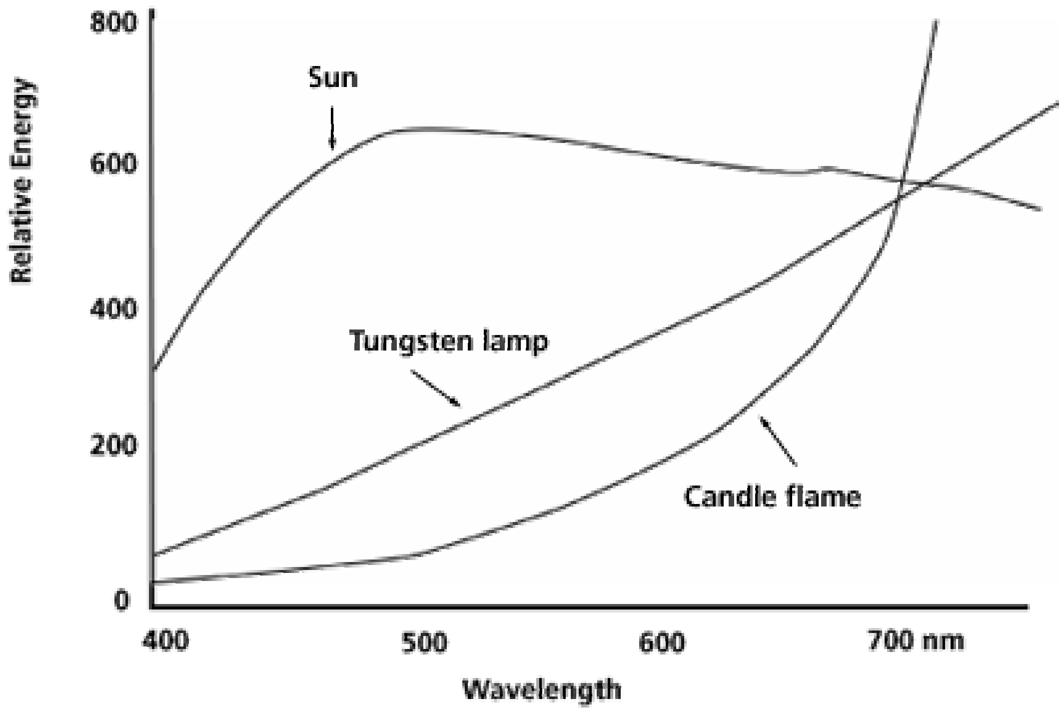
- Surface reflecting both red and green appears green when there is only green incident and red when red incident, yellow (red + green) in pure white light

Mechanism of Color Perception

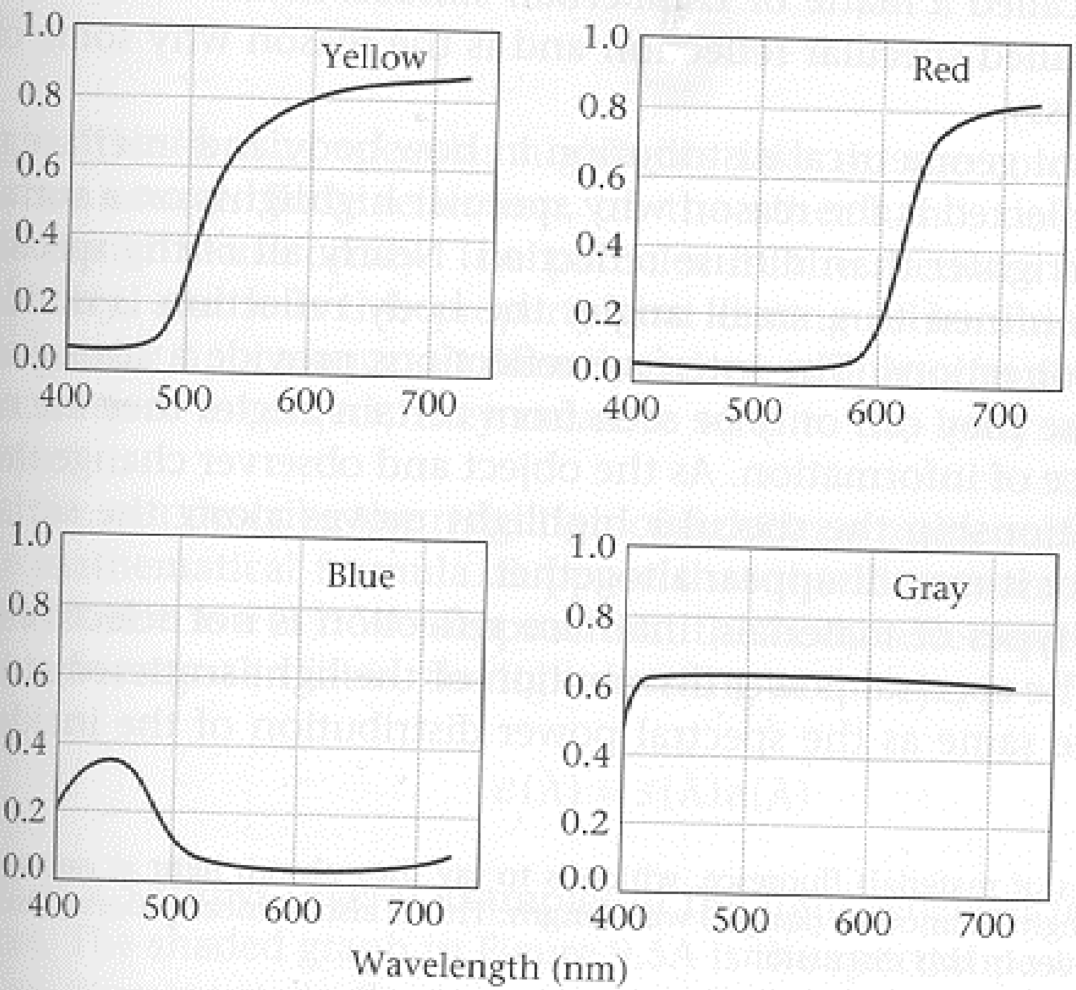


9.2 A DESCRIPTION OF SPECTRAL IMAGE FORMATION. Light from a source arrives at a surface and is reflected toward an observer. The light at the observer is absorbed by the cones and ultimately leads to a perception of color. The functions associated with the imaging process, represented by the graphs, include (counterclockwise from upper left) the spectral power distribution of the light source; the surface-reflectance function of the object; the result of multiplying these two functions to create the color signal incident at the eye; and the cone absorptions caused by the incident signal, which in turn are dependent on the cone sensitivities.

Spectral Distribution of Sources

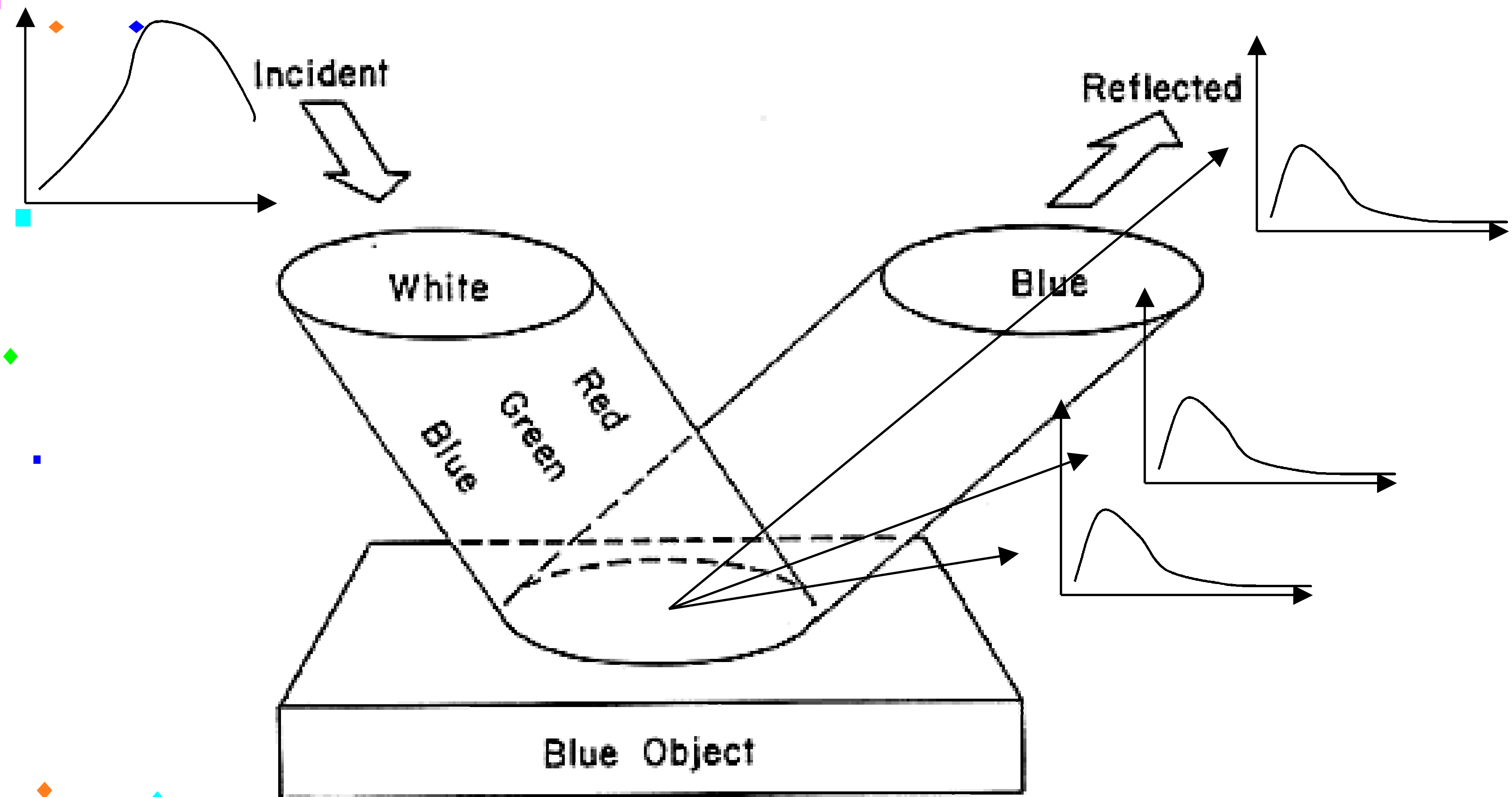


Formation of color images



9.3 THE SURFACE-REFLECTANCE FUNCTION measures the proportion of light scattered from a surface at each wavelength. The panels show the surface-reflectance functions of various colored papers along with the color name associated with the paper. Surface reflectance is correlated with the color appearance; as Newton (1704) wrote "colours in the object are nothing but a disposition to reflect this or that sort of ray more copiously than the rest."

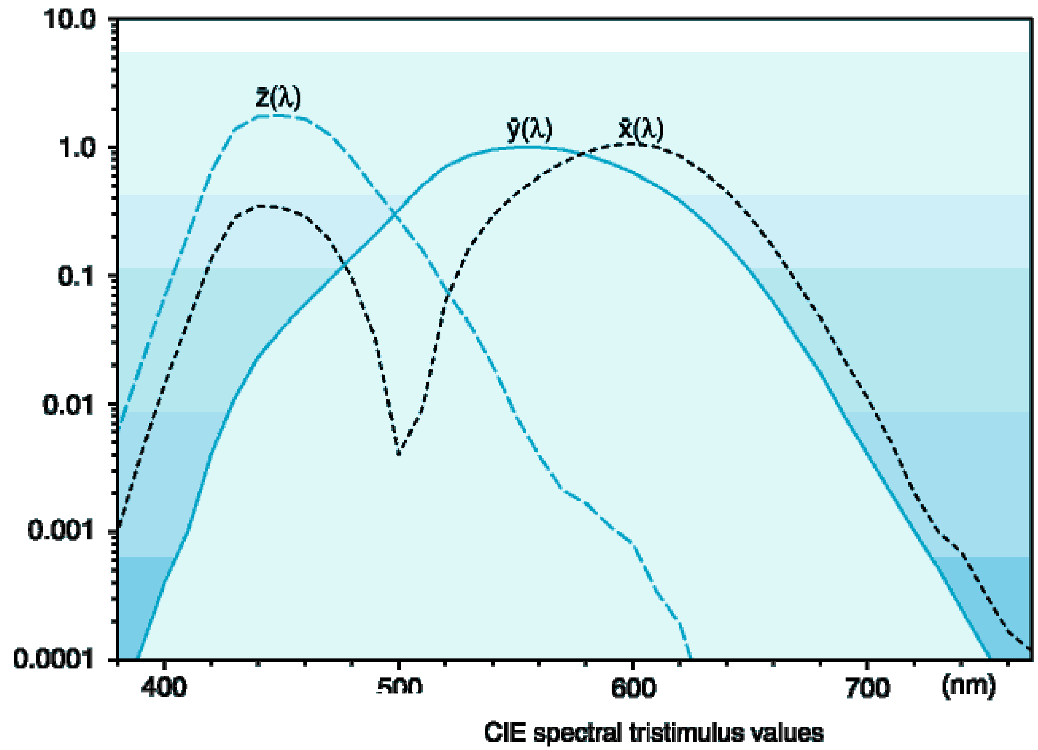
How does color reflectance relate to BRDF?



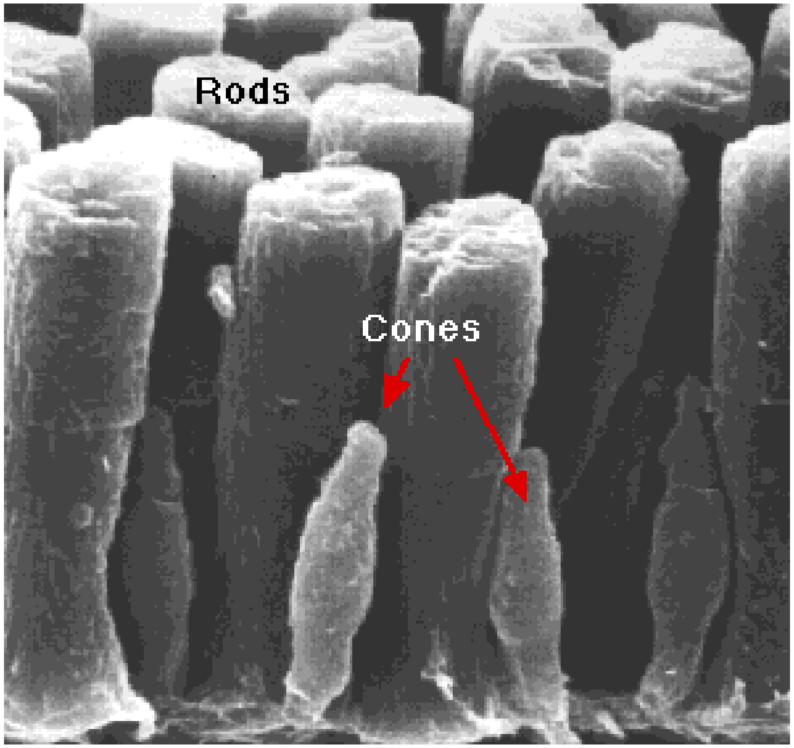
Some exceptions (butterfly wings)

Tristimulus Curves

- Color sensation arises from 3 types of neurochemical sensors in retina, the cones
  - Each with own response curve to light spectrum
  - Cones have overlap in wavelengths of sensitivity curves

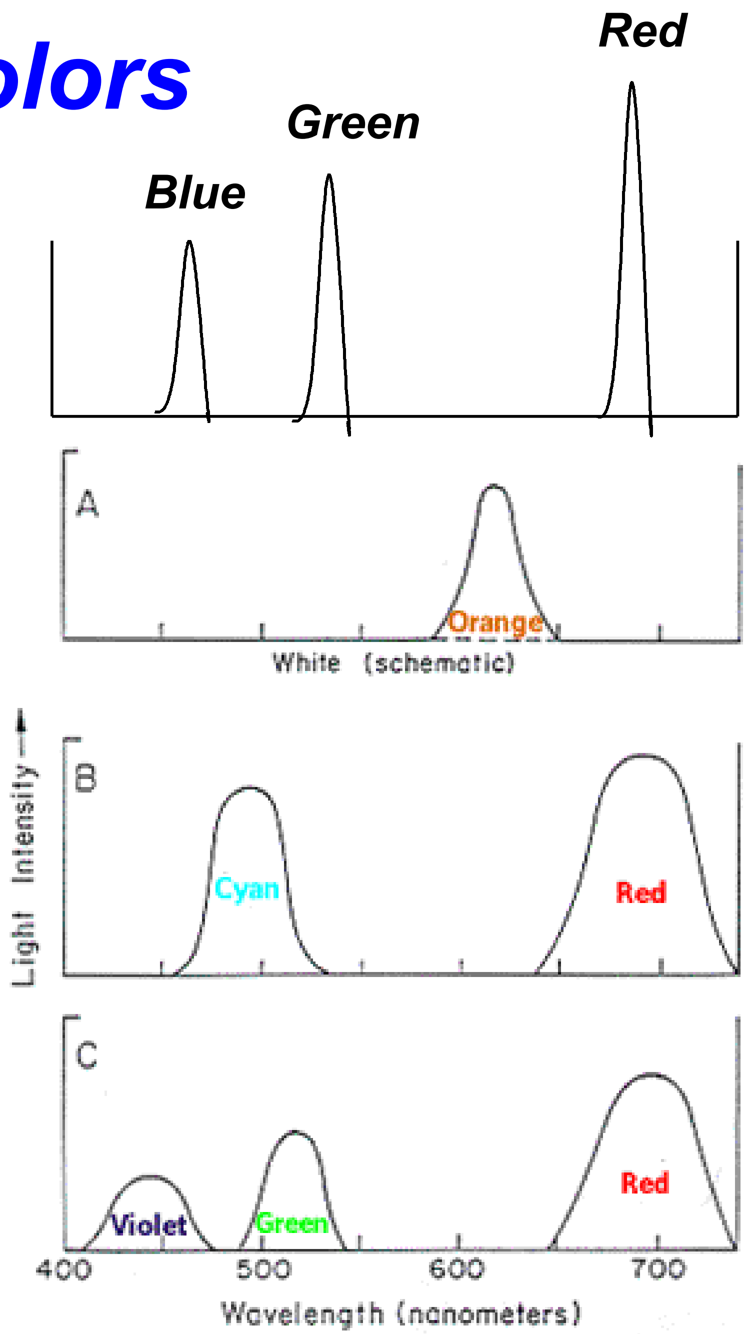


Cones and Rods



Metameric colors

- Different light spectra can produce the same color impressions if they produce the same rod and cone firings
- Surprisingly, sensation of almost all colors can be recreated by weighting 3 delta function approximations

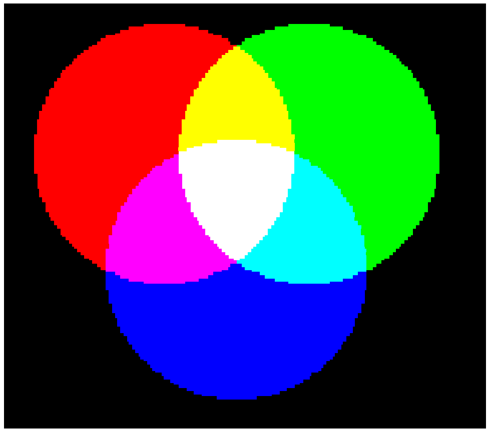


Color Models

- Color Models are useful for driving hardware that generate or capture images
  - Monitors, TVs, video cameras
  - Color printers
- Since color sensation can be reproduced by combination of pure colors, it is simpler to use phosphors and CCD elements that have sharp and narrow spectra rather than combine overlapping spectra.
- Color models describe in what proportion to combine these spectra to produce different color impressions.

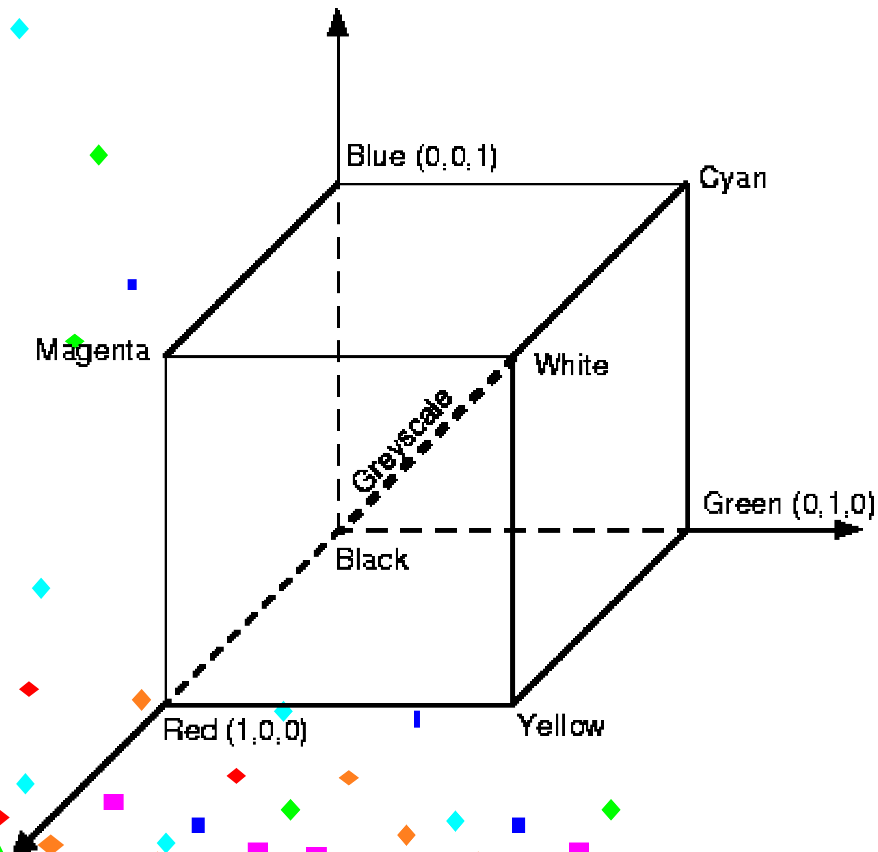
Additive Color Models

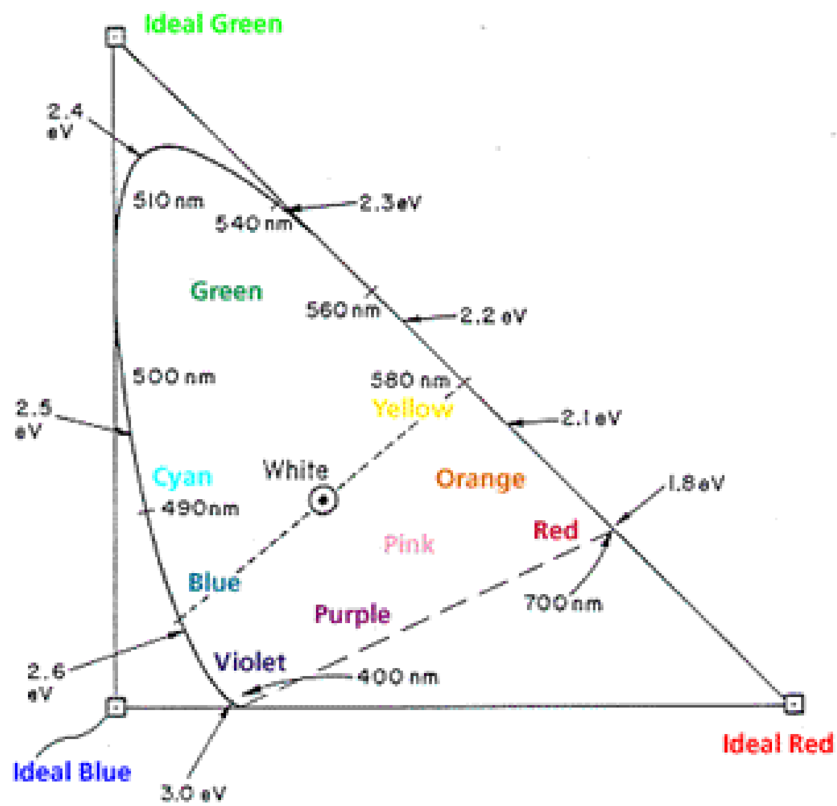
- In monitors, 3 electron beams illuminate phosphors of 3 colors that act as additive light sources
- The powers of these beams are controlled by the components of colors described by the R,G,B model



Color Models

- R, G, B cube
- 2D diagram (R/R+G+B, G/R+G+B), related to the CIE chromaticity diagram (see Pokorny)





Other Color Models

- Beyond the eyes, the brain may have its own color space. For image compression, it is important to understand which part of color information is important to people and which is not. It is intuitive to describe a color impression by saying
  - what the dominant color is: *hue* is mode of spectrum
  - How washed out by white light the color is: *saturation* is related to variance (red vs. pink)
  - how bright or dim the light is: *intensity* is area of the light spectral distribution

Intensity-Saturation-Hue Color Models

- Find a new coordinate system that reflects these three quantities
  - YIQ, linear tranformation

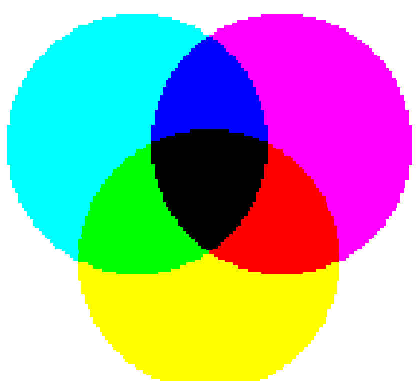
$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

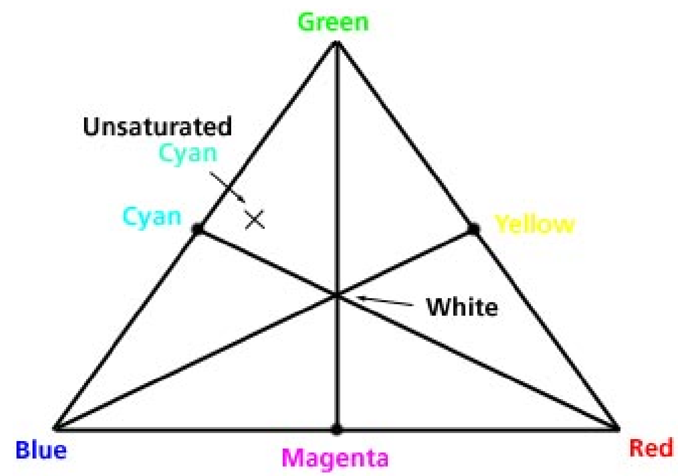
  - IHS space:
    - Diagonal (1,1,1) of RGB space is intensity axis
    - Saturation (*chroma*) is distance from that axis
    - Hue is angle about that axis

There are many more models

Subtractive Color Models

- In printers, colors are obtained by mixing inks
- In CMY model, components describe the proportions in which 3 types of ink can be mixed to obtain colors
  - Cyan color removes red light when reflecting white light
  - To create RGB color (0.3 0.8 0.9), remove 0.7 R, 0.2 G, 0.1 B, so use 0.7 C, 0.2 M, 0.1 Y.
  - (C M Y) = (1 1 1) – (R G B)





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