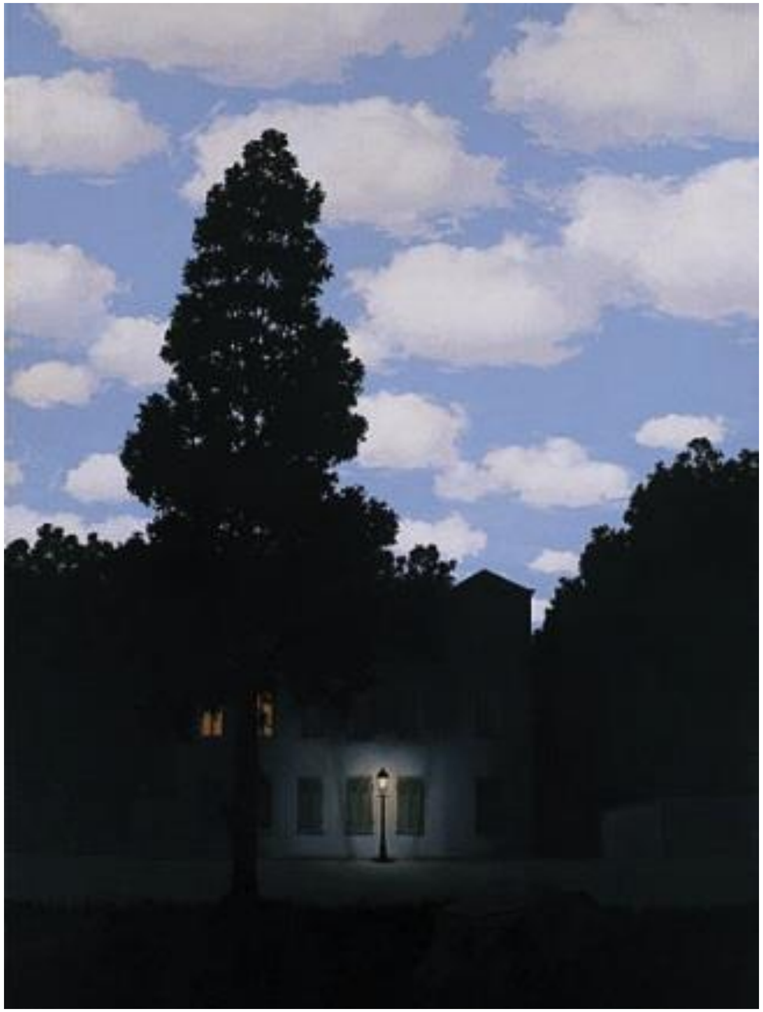
Radiometry

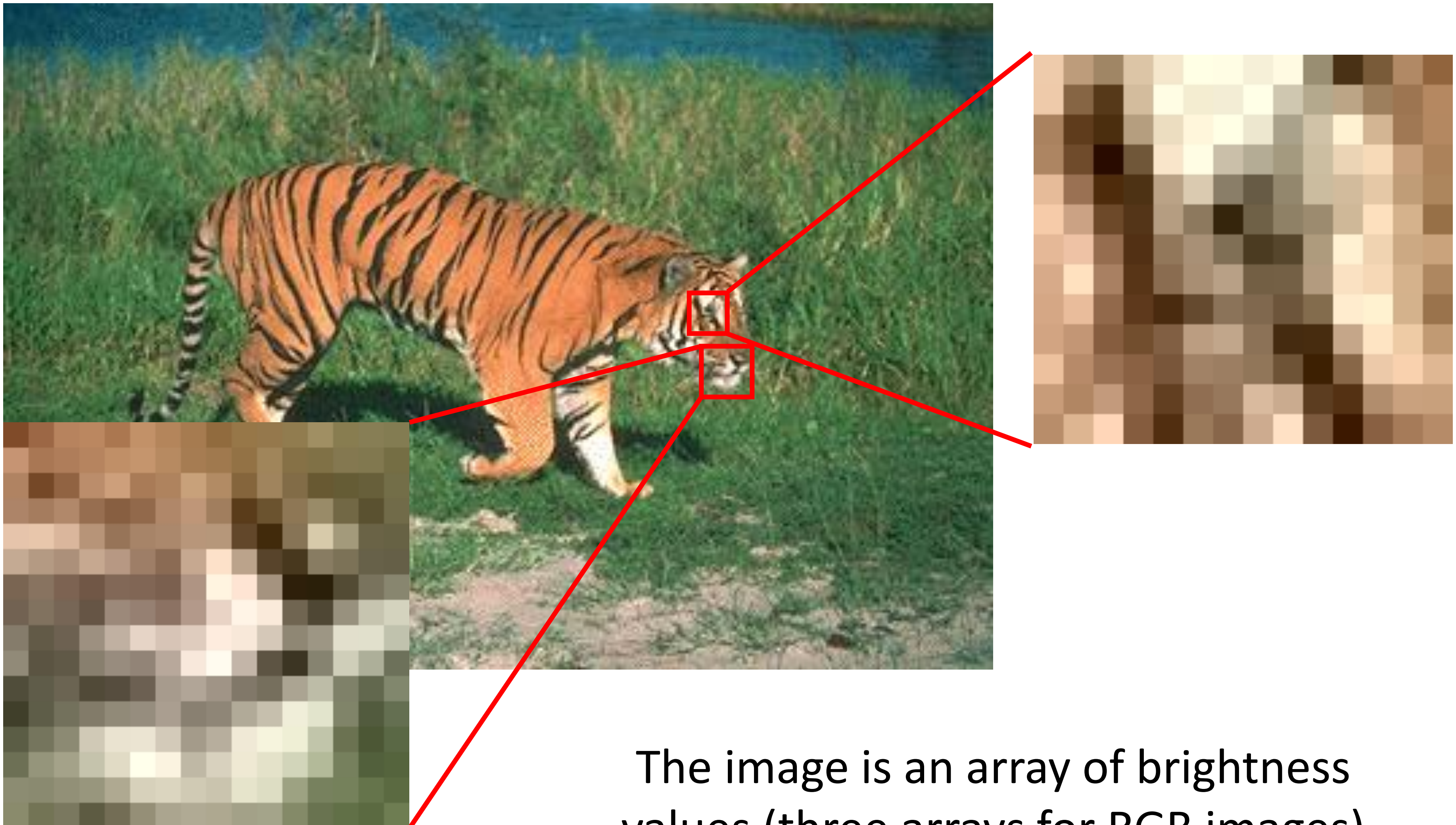


“Empire of Light”, Magritte

Alexei Efros
CS280, Spring 2024

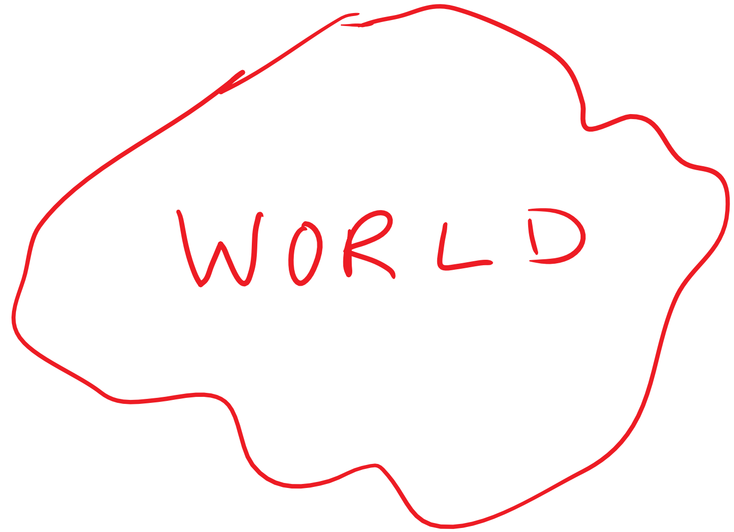
with slides from Hoiem, Malik, Freeman

What is in an image?



The image is an array of brightness values (three arrays for RGB images)

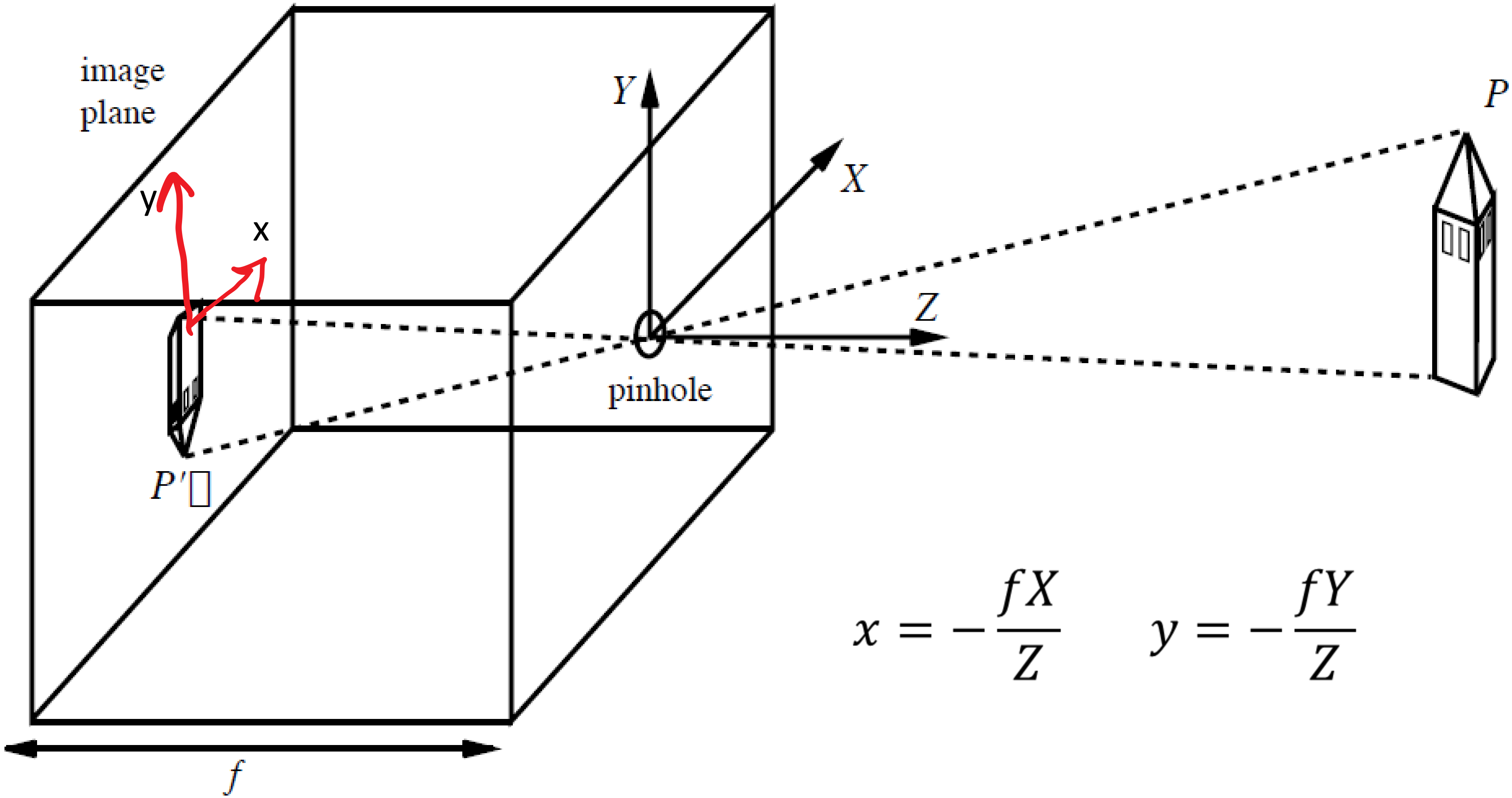
A camera creates an image …



The image I(x,y) measures how much light is captured at pixel (x,y)

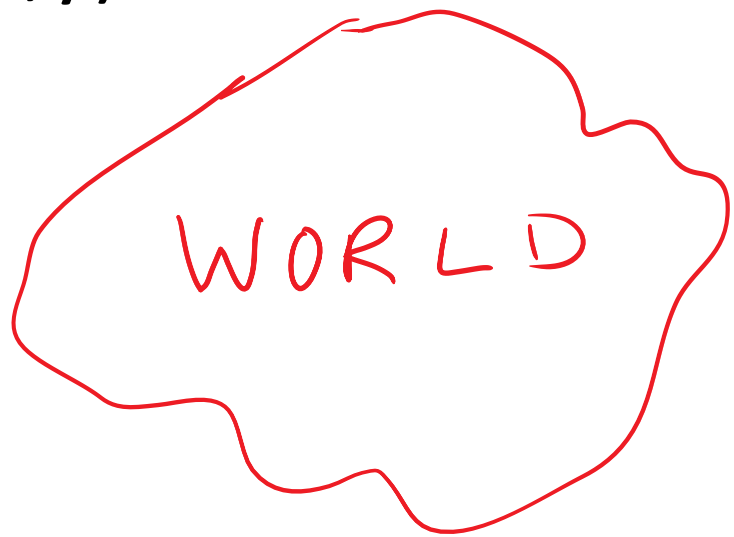
We want to know
- Where does a point (X,Y,Z) in the world get imaged?
- **What is the brightness at the resulting point (x,y)?**

The pinhole camera models where a scene point is projected



$$x = -\frac{fX}{Z} \qquad y = -\frac{fY}{Z}$$

Now let us try to understand brightness at a pixel (x,y) …

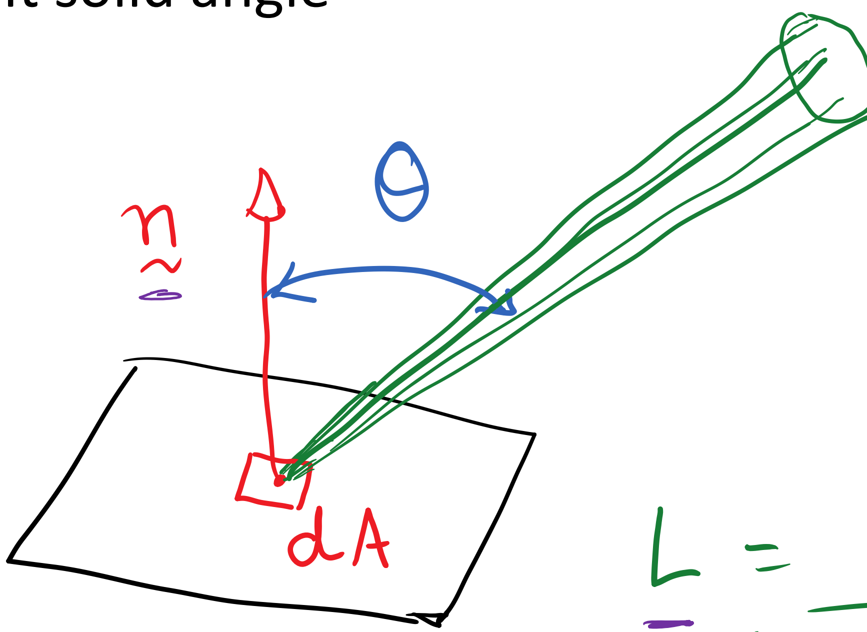


The image I(x,y) measures how much light is captured at pixel (x,y). Proportional to the number of photons captured at the sensor element (CCD/CMOS/Rod/cone/..) in a time interval.

We use the scientific term IRRADIANCE for this concept.
Irradiance is defined as the radiant power per unit area, and has units W/m^2. Usually denoted by E.

Radiance is a directional quantity

Radiant power travelling in a given direction per unit area (measured perpendicular to the direction of travel) per unit solid angle

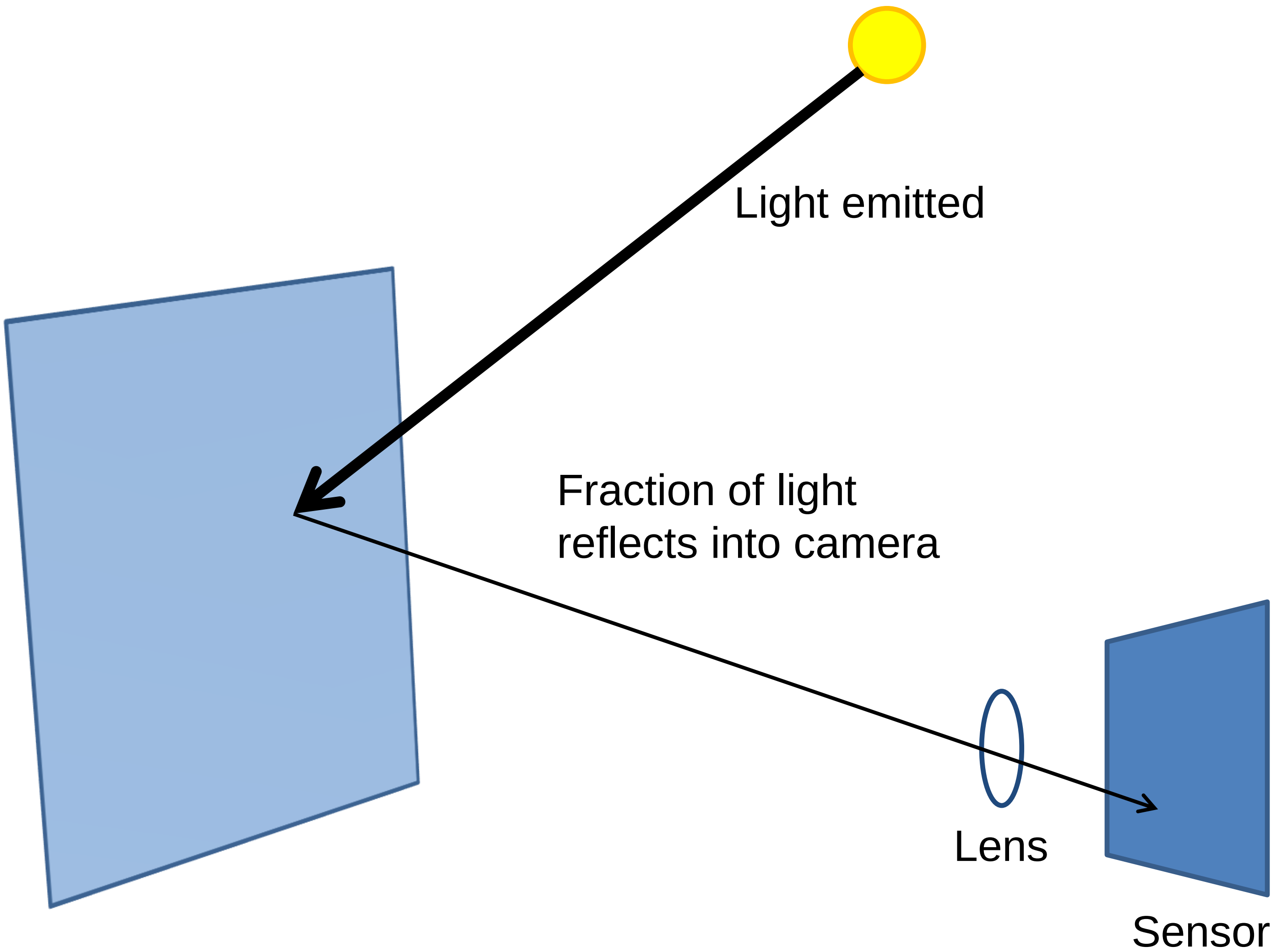


$$\underline{L} = \frac{\text{Power}}{(dA\cos\theta)(d\Omega)}$$

units are $W\, m^{-2}\, sr^{-1}$

Read more on Wikipedia

How does a pixel get its value?



How does a pixel get its value?

- Major factors
  - Illumination strength and direction
  - Surface geometry
  - Surface material
  - Nearby surfaces
  - Camera gain/exposure

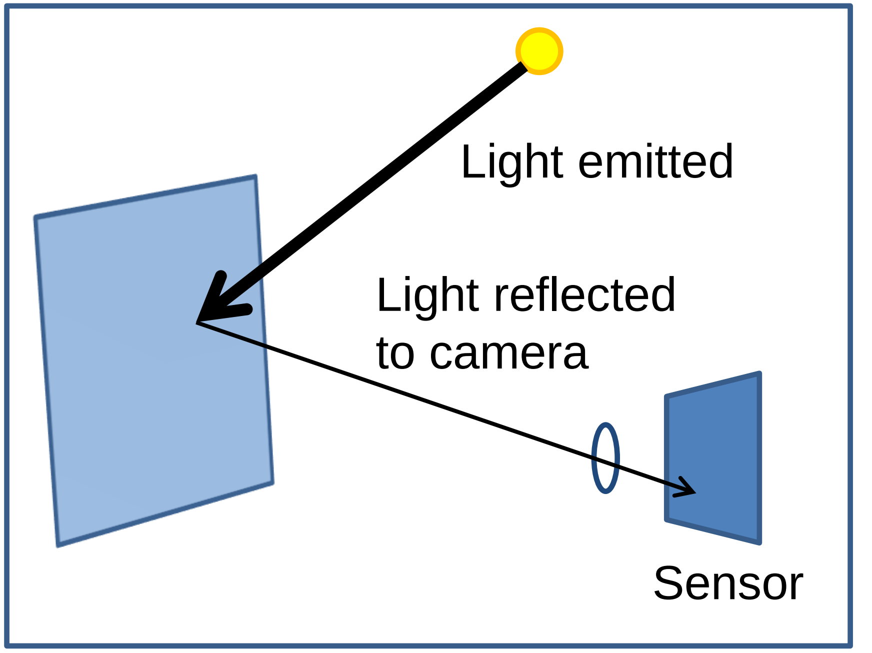


Figure 1.1: (a) Scene illuminated with a ceiling lamp. (b-c) Two images obtained by illuminating a scene with a laser pointer (the red line indicates the direction of the ray).

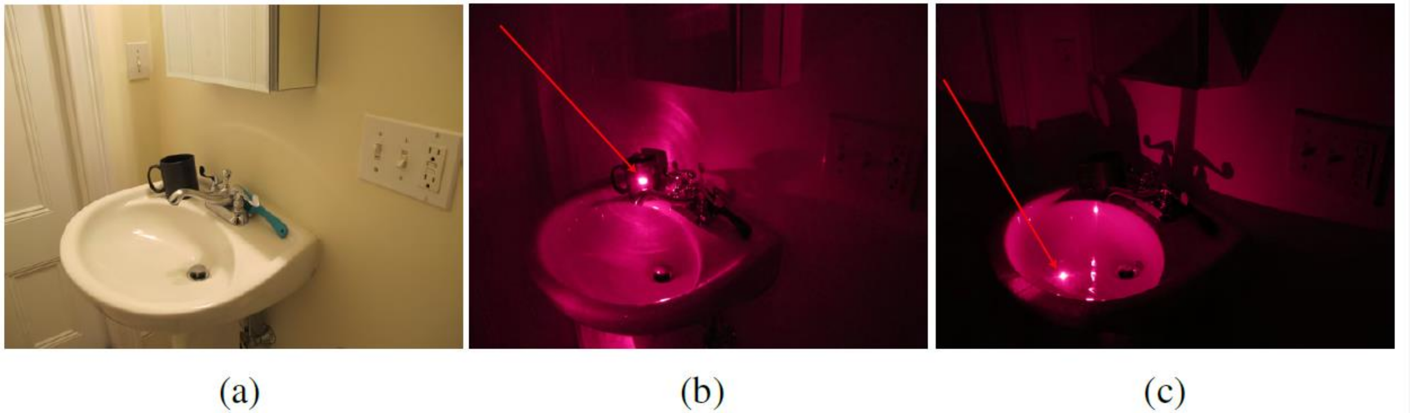
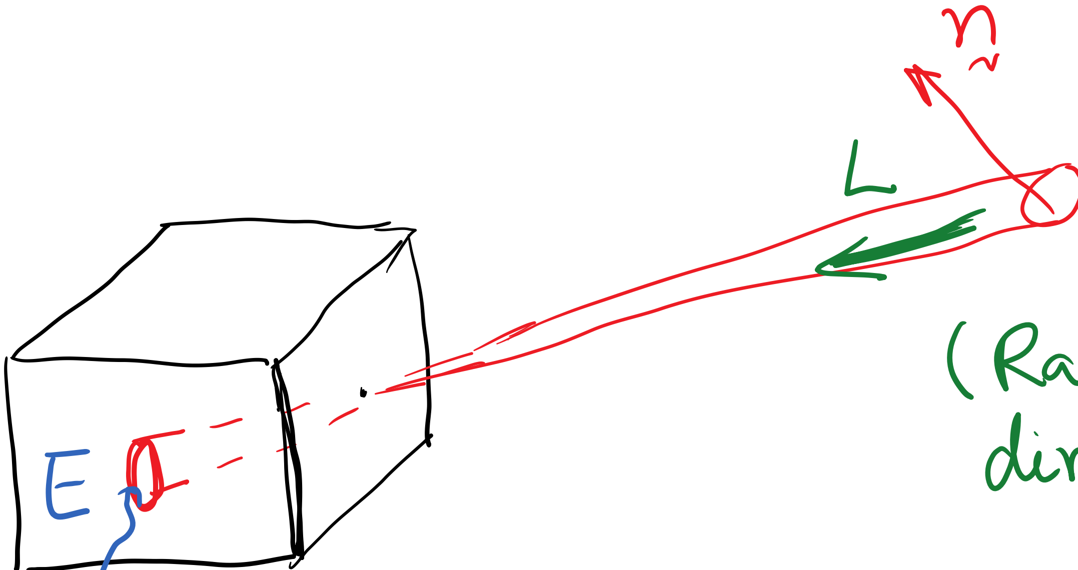


Image irradiance is proportional to scene radiance in the direction of the camera



Patch in the scene (Radiance in the direction of camera)

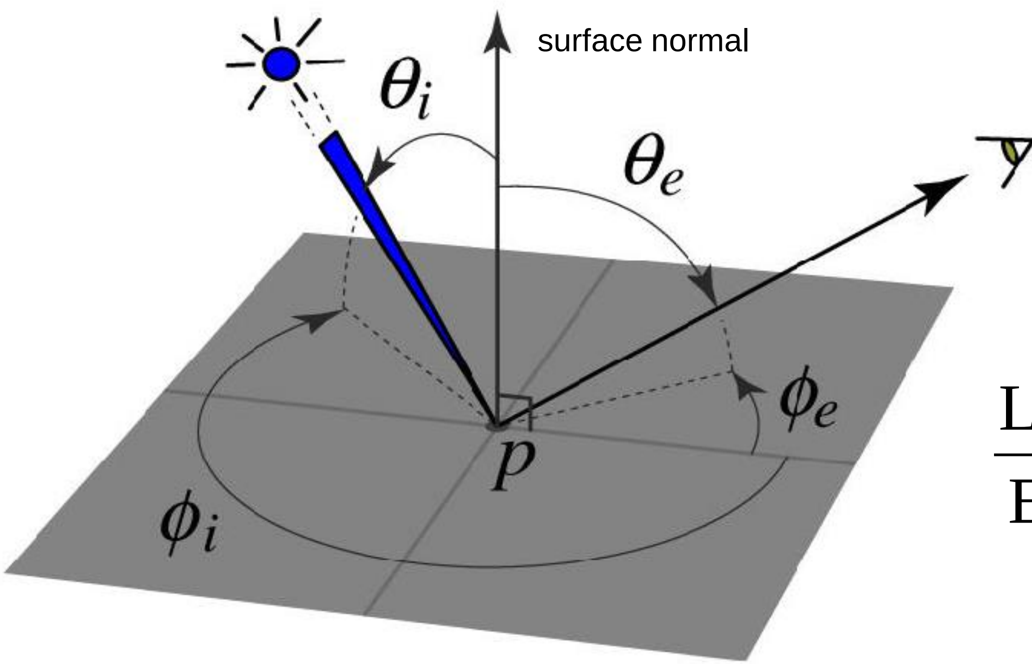
Patch on the image plane (Irradiance at the patch)

$$E \propto L$$

(True for both pinhole cameras & lens systems)

BRDF: Bidirectional Reflectance Distribution Function

- Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another

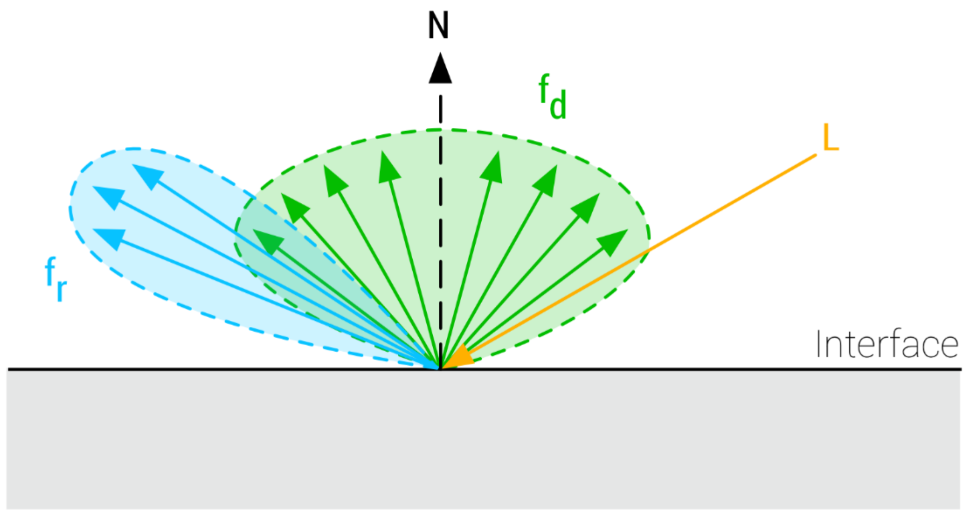


$$\rho(\theta_i, \phi_i, \theta_e, \phi_e; \lambda) =$$

$$\frac{\mathrm{L_e}(\boldsymbol{\theta}_\mathrm{e}, \boldsymbol{\phi}_\mathrm{e})}{\mathrm{E_i}(\boldsymbol{\theta}_\mathrm{i}, \boldsymbol{\phi}_\mathrm{i})} = \frac{\mathrm{L_e}(\boldsymbol{\theta}_\mathrm{e}, \boldsymbol{\phi}_\mathrm{e})}{\mathrm{L_i}(\boldsymbol{\theta}_\mathrm{i}, \boldsymbol{\phi}_\mathrm{i}) \cos \boldsymbol{\theta}_\mathrm{i} \, \mathrm{d}\boldsymbol{\omega}}$$

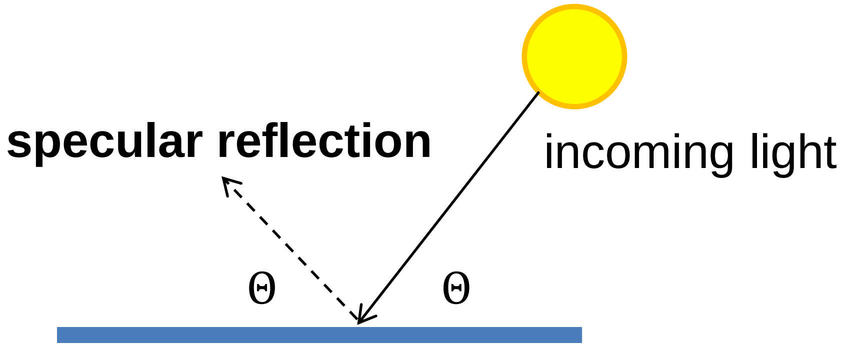
Slide credit: S. Savarese

Effect of BRDF

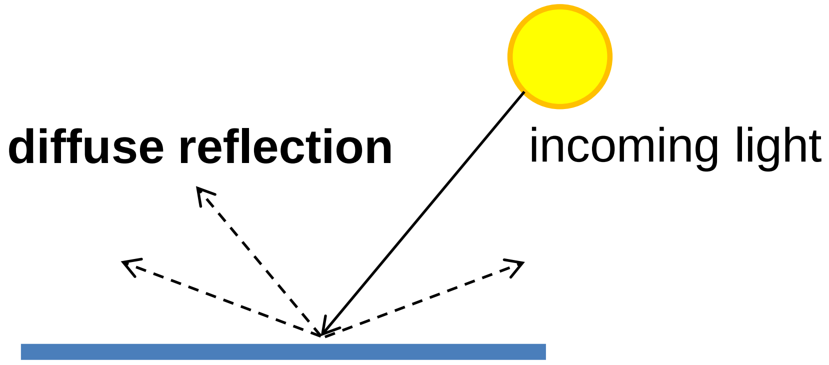


Basic models of reflection

- Specular: light bounces off at the incident angle
  - E.g., mirror

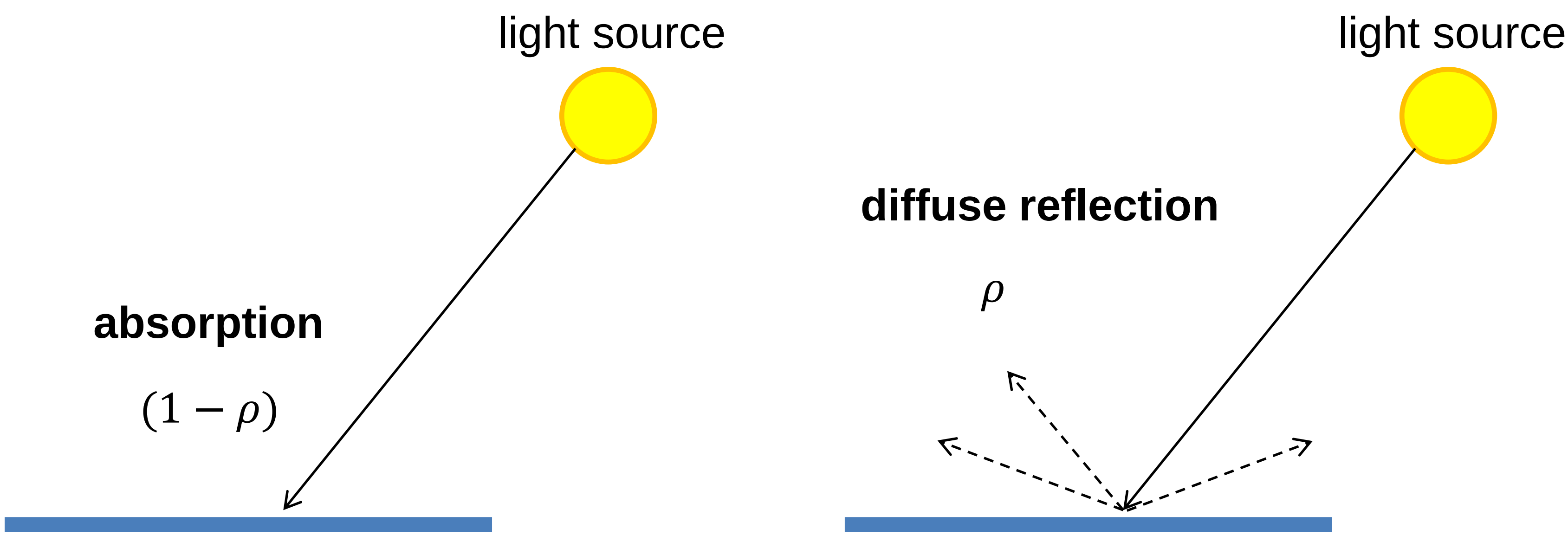


- Diffuse: light scatters in all directions
  - E.g., brick, cloth, rough wood



Lambertian reflectance model

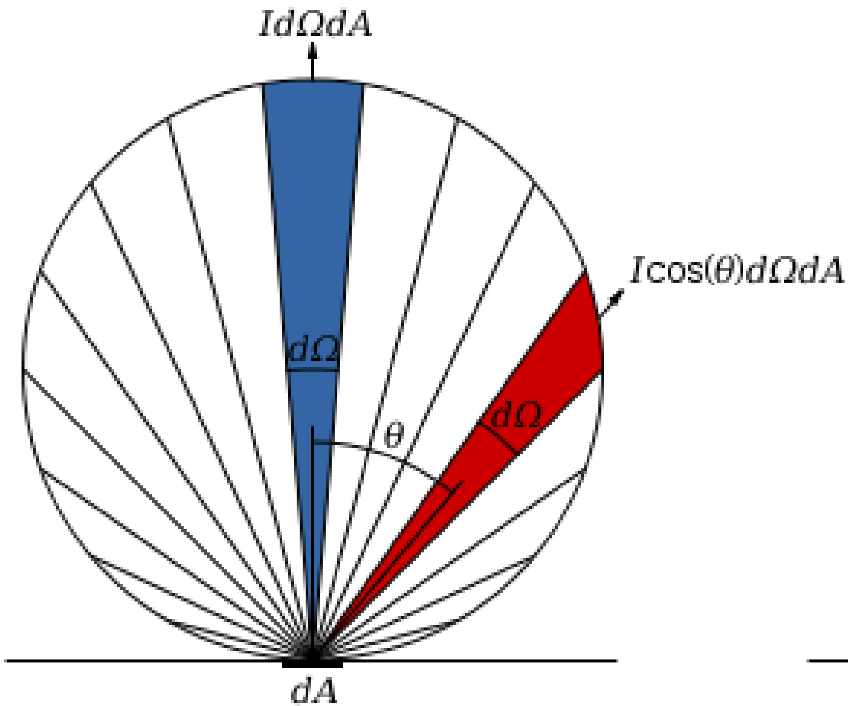
- Some light is absorbed (function of albedo ρ)
- Remaining light is scattered (diffuse reflection)
- Examples: soft cloth, concrete, matte paints

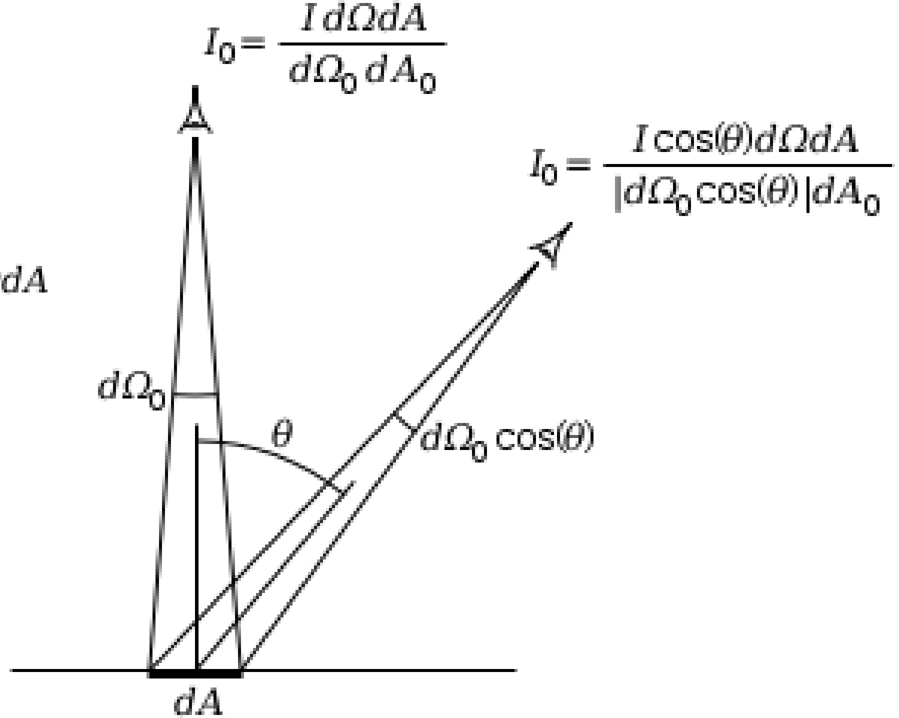


Diffuse reflection: Lambert's cosine law

Intensity does *not* depend on viewer angle.

- Amount of reflected light proportional to $\cos(\theta)$
- Visible solid angle also proportional to $\cos(\theta)$





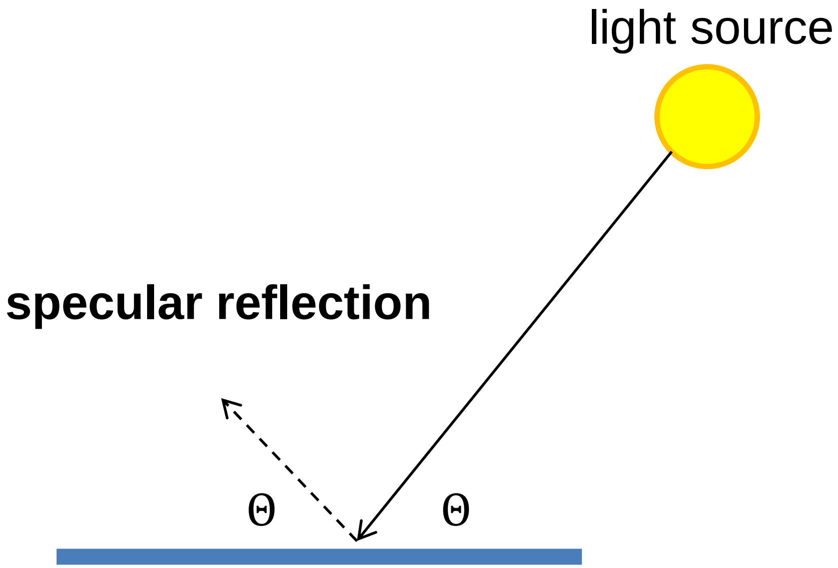
http://en.wikipedia.org/wiki/Lambert%27s_cosine_law

Specular Reflection

- Reflected direction depends on light orientation and surface normal
  - E.g., mirrors are fully specular
  - Most surfaces can be modeled with a mixture of diffuse and specular components

Flickr, by suzysputnik

Flickr, by piratejohnny



Most surfaces have both specular and diffuse components

- Specularity = spot where specular reflection dominates (typically reflects light source)

Photo: northcountryhardwoodfloors.com

Typically, specular component is small

Intensity and Surface Orientation

Intensity depends on illumination angle because less light comes in at oblique angles.

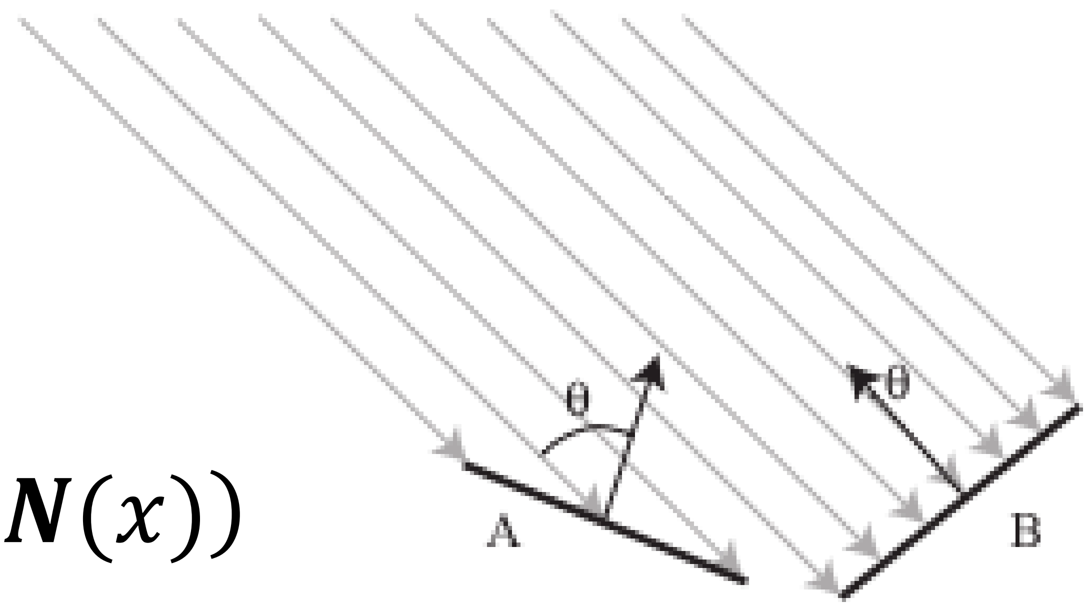
ρ = albedo

$\boldsymbol{S}$ = directional source

$\boldsymbol{N}$ = surface normal

I = reflected intensity

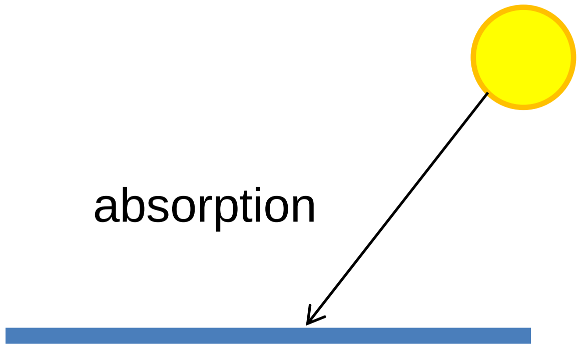
$$I(x) = \rho(x)(\boldsymbol{S} \cdot \boldsymbol{N}(x))$$



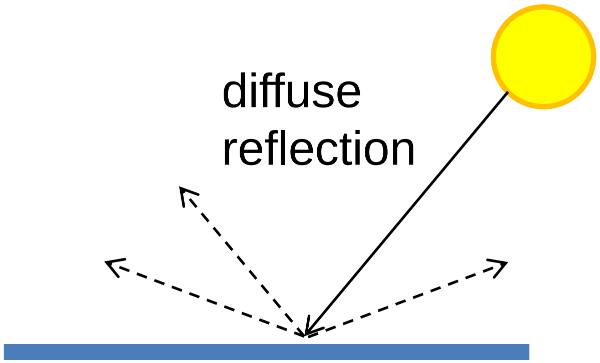

1
2

Recap

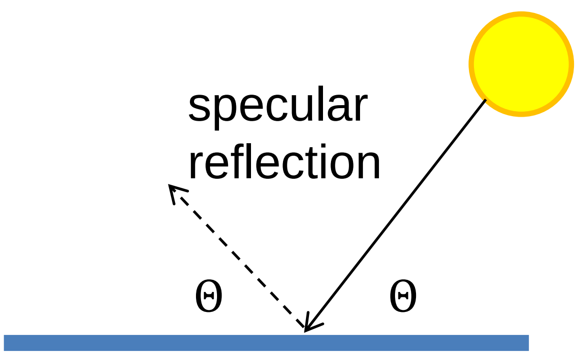
- When light hits a typical surface
  - Some light is absorbed (1-ρ)
    - More absorbed for low albedos



  - Some light is reflected diffusely
    - Independent of viewing direction

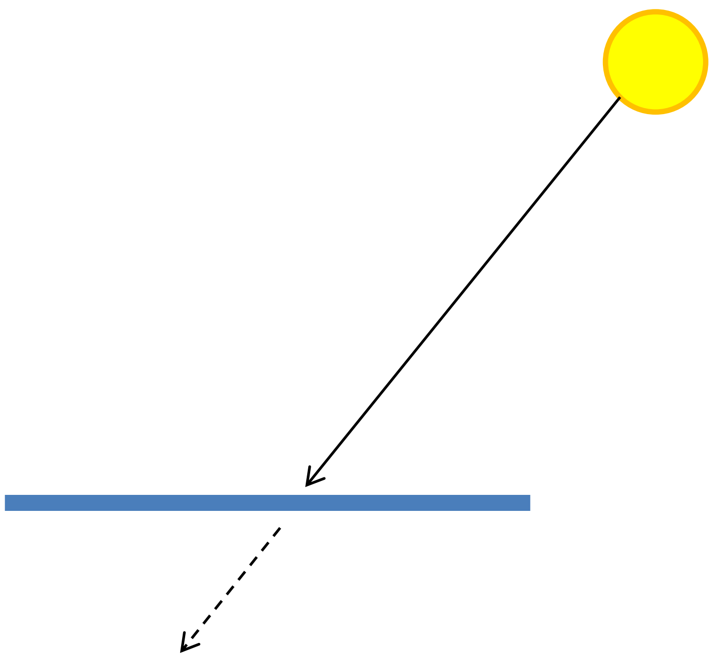


  - Some light is reflected specularly
    - Light bounces off (like a mirror), depends on viewing direction

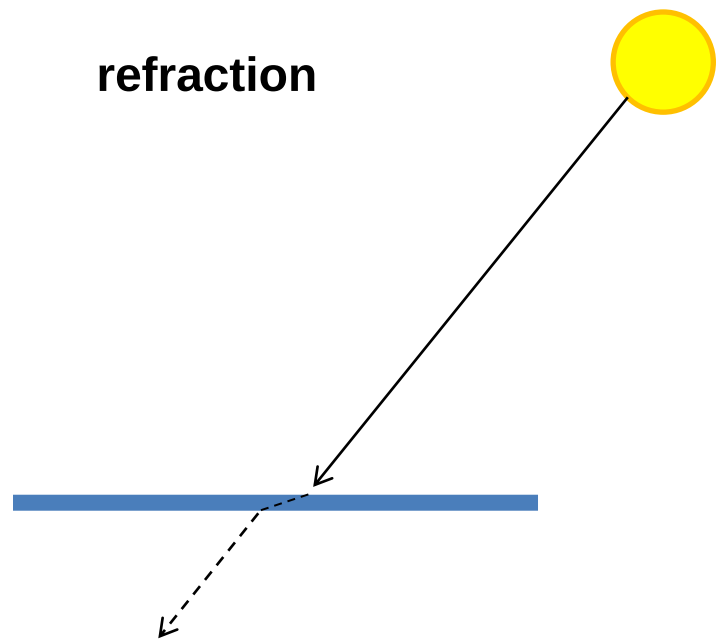


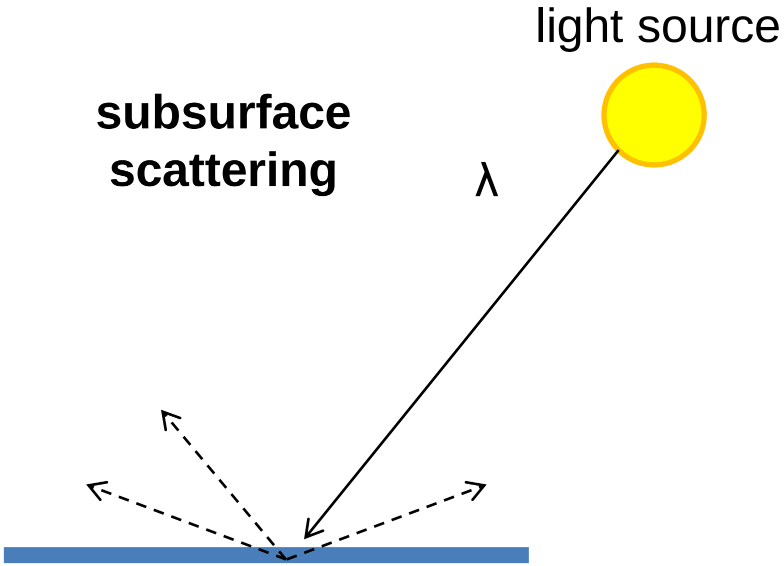
Other possible effects

transparency



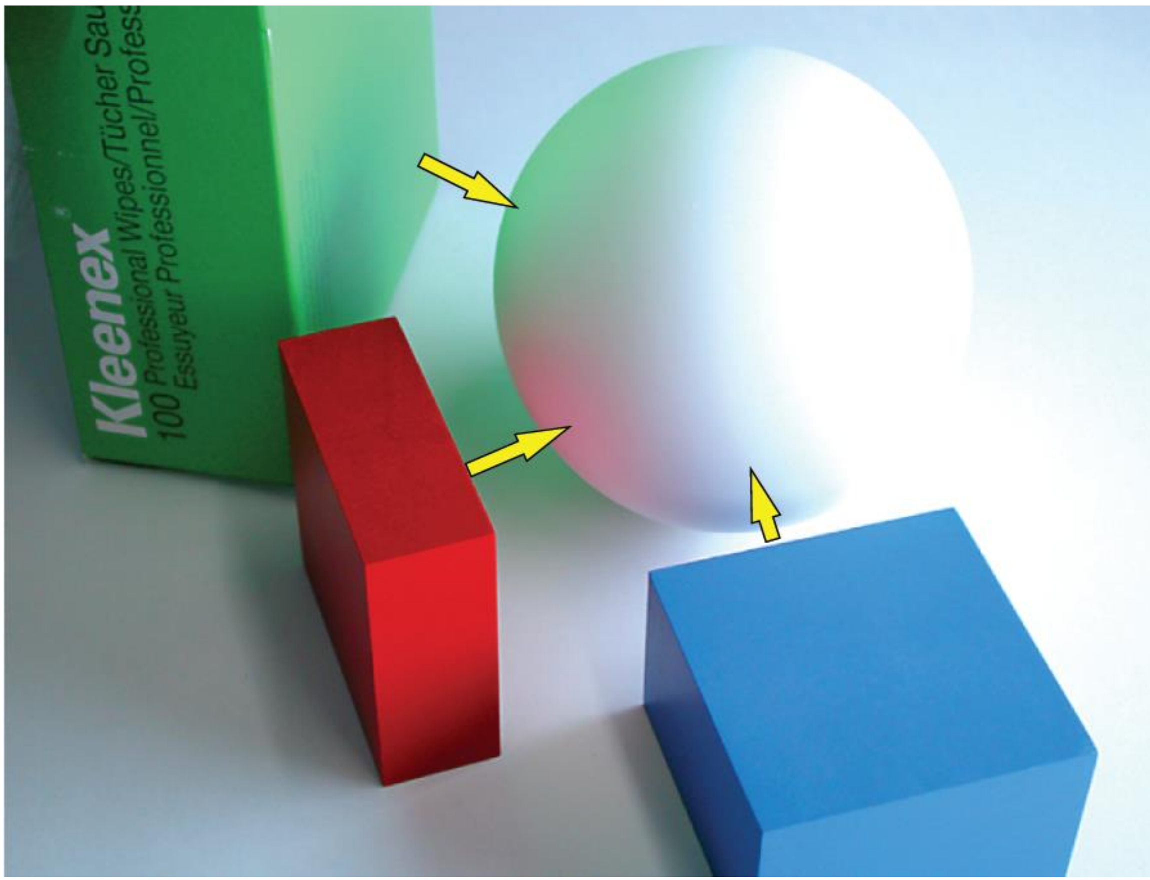
refraction




light source
subsurface
scattering
λ

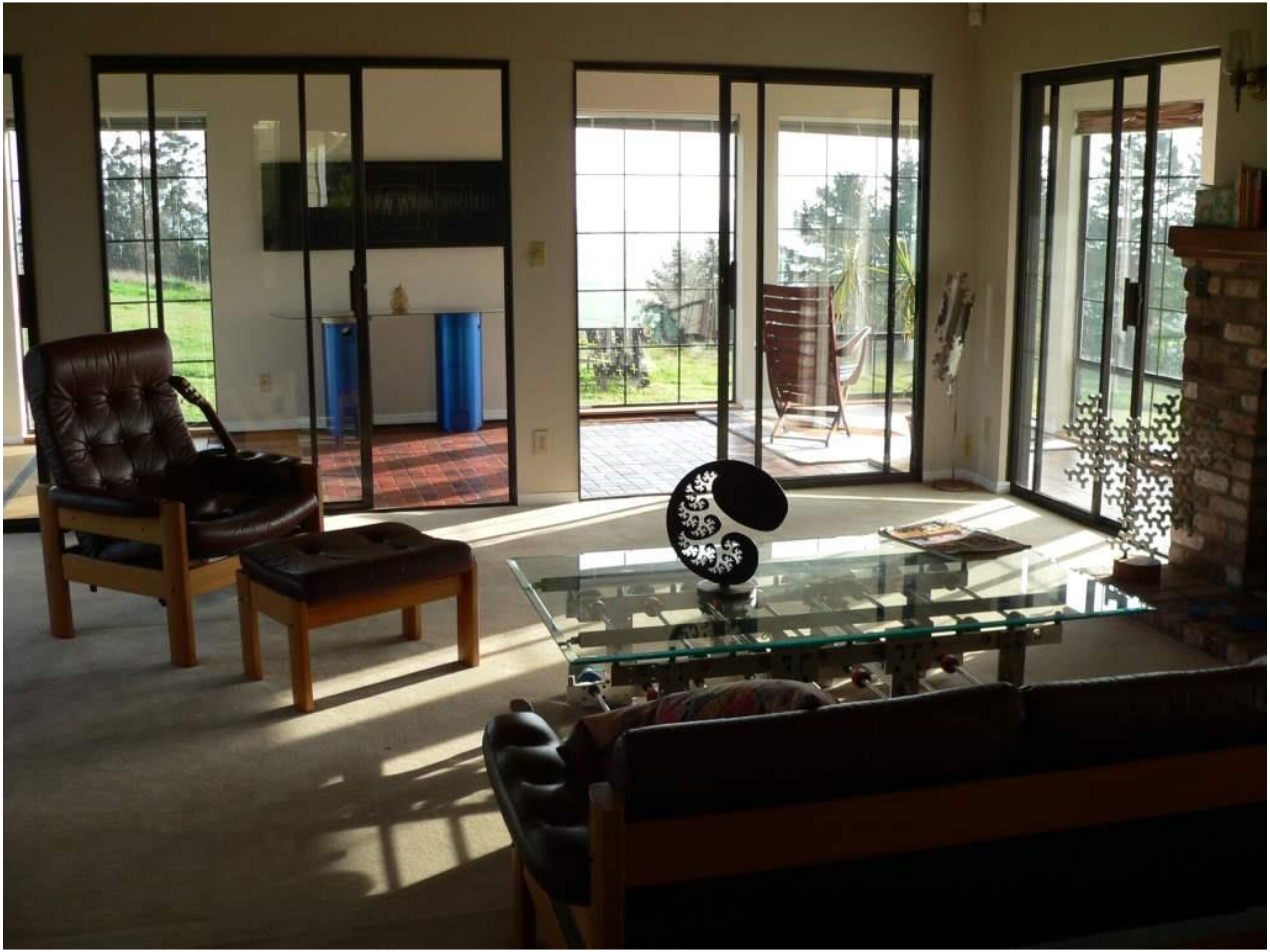
So far: light→surface→camera

- Called a local illumination model
- But much light comes from surrounding surfaces

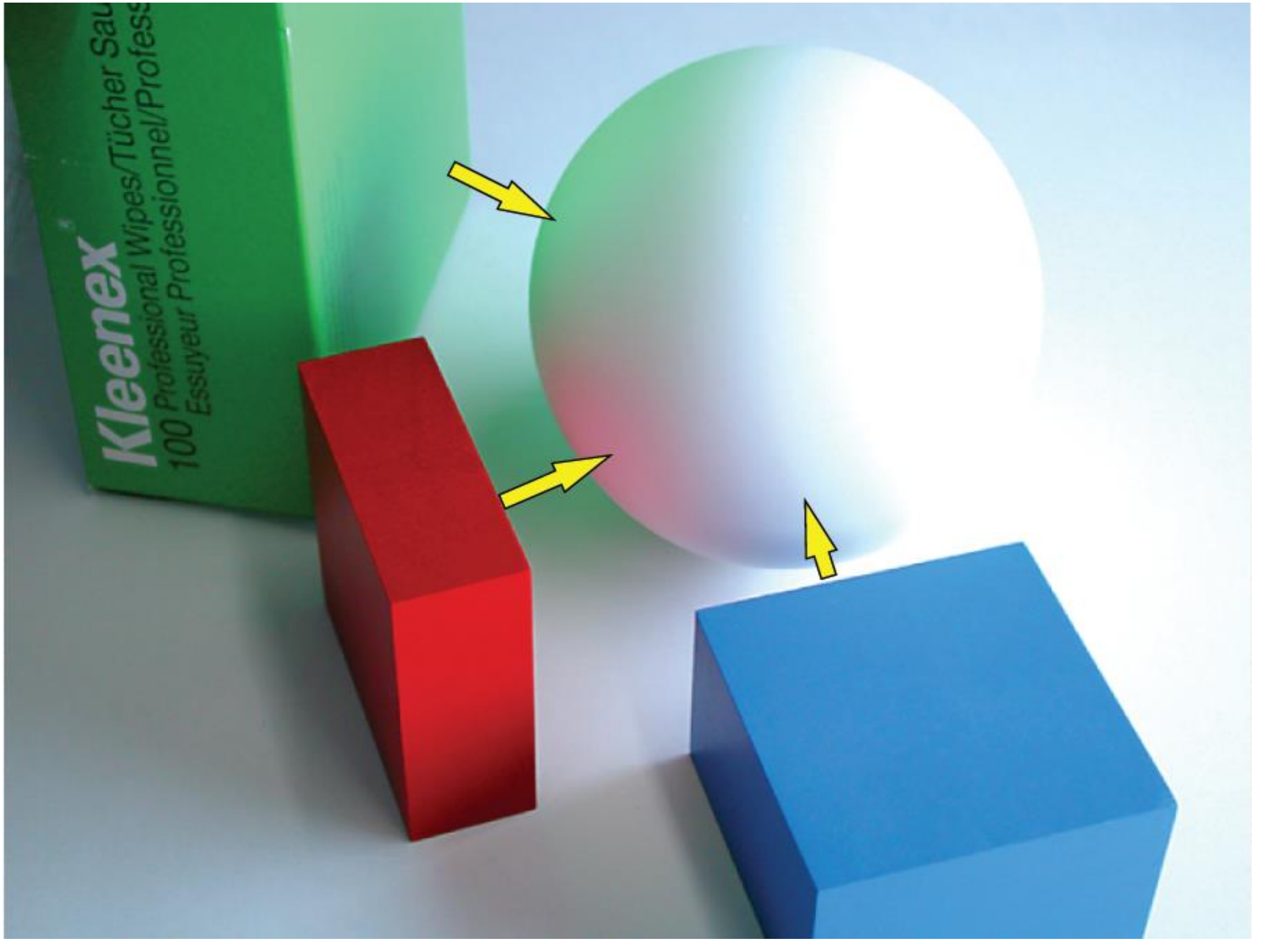


From Koenderink slides on image texture and the flow of light

Inter-reflection is a major source of light



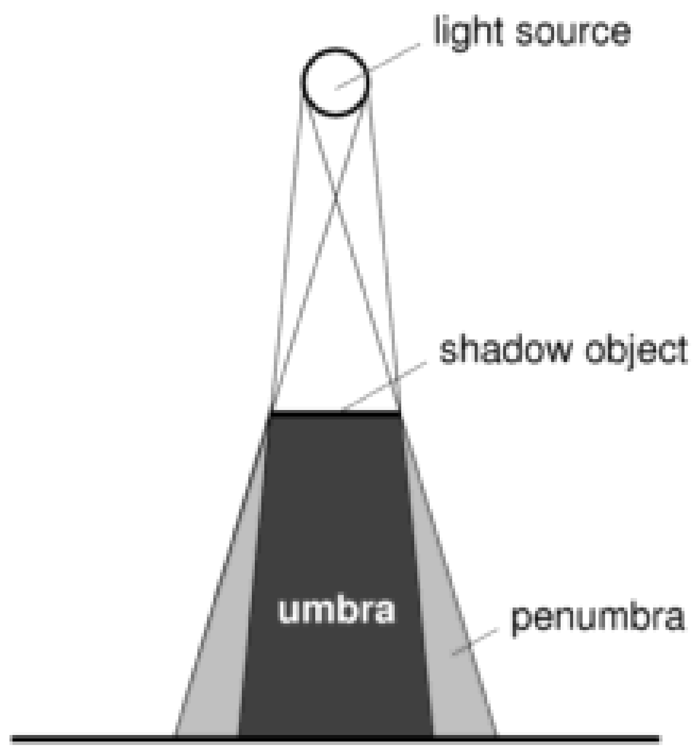
Inter-reflection affects the apparent color of objects



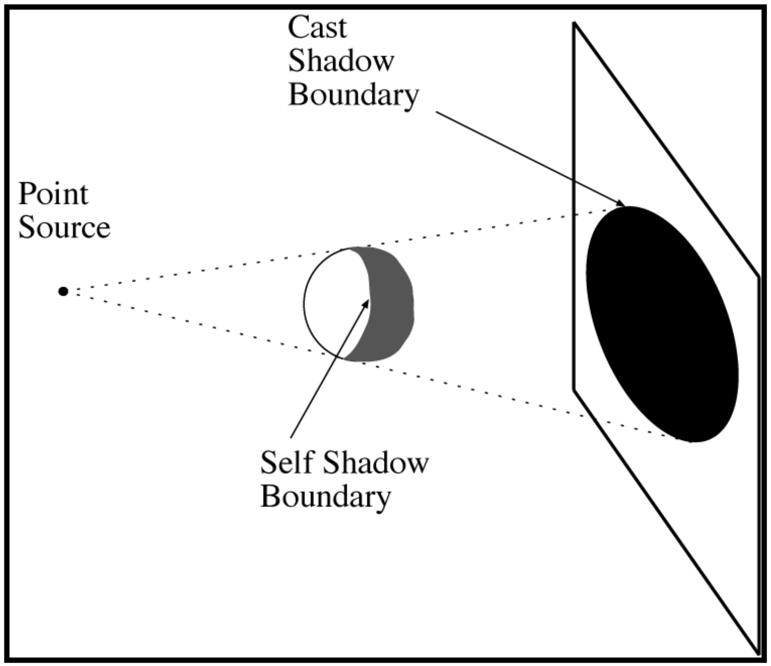
From Koenderink slides on image texture and the flow of light

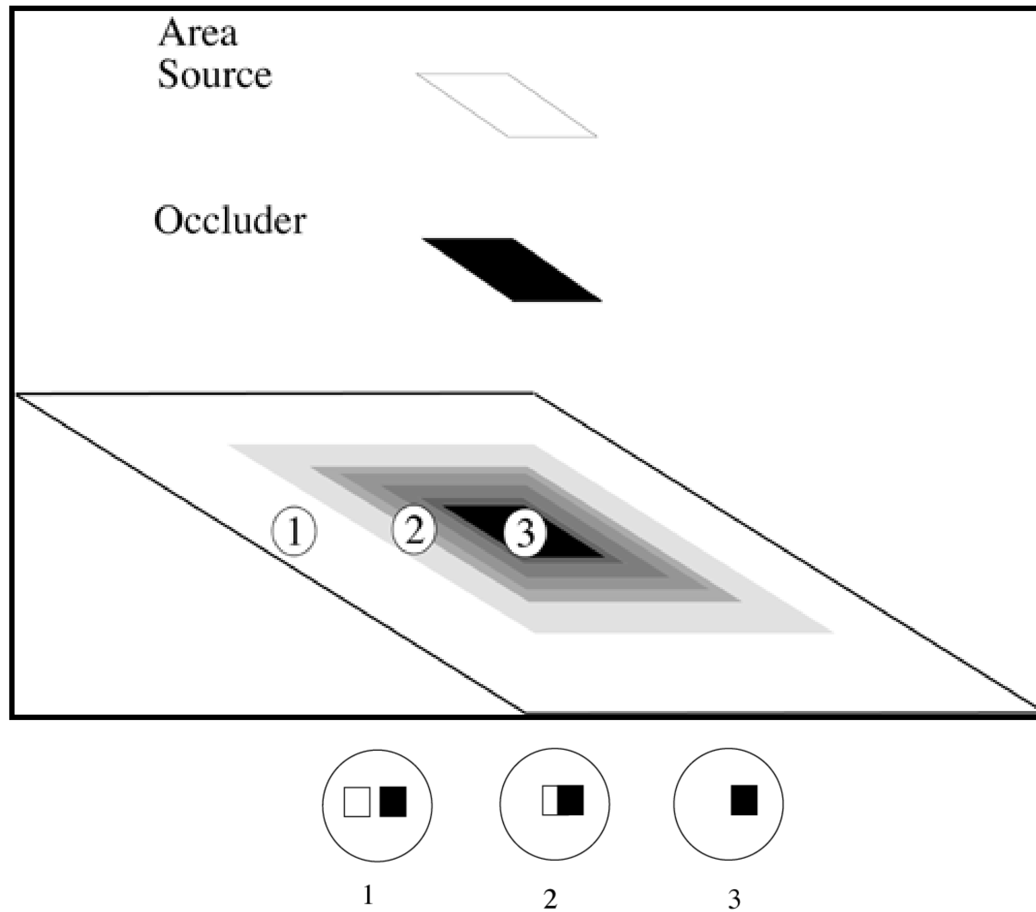
Scene surfaces also cause shadows

- Shadow: reduction in intensity due to a blocked source



Shadows


Cast
Shadow
Boundary
Point
Source
Self Shadow
Boundary


Area
Source
Occluder
1
2
3
1
2
3

Models of light sources

- Distant point source
  - One illumination direction
  - E.g., sun
- Area source
  - E.g., white walls, diffuser lamps, sky
- Ambient light
  - Substitute for dealing with interreflections
- Global illumination model
  - Account for interreflections in modeled scene

Image Formation

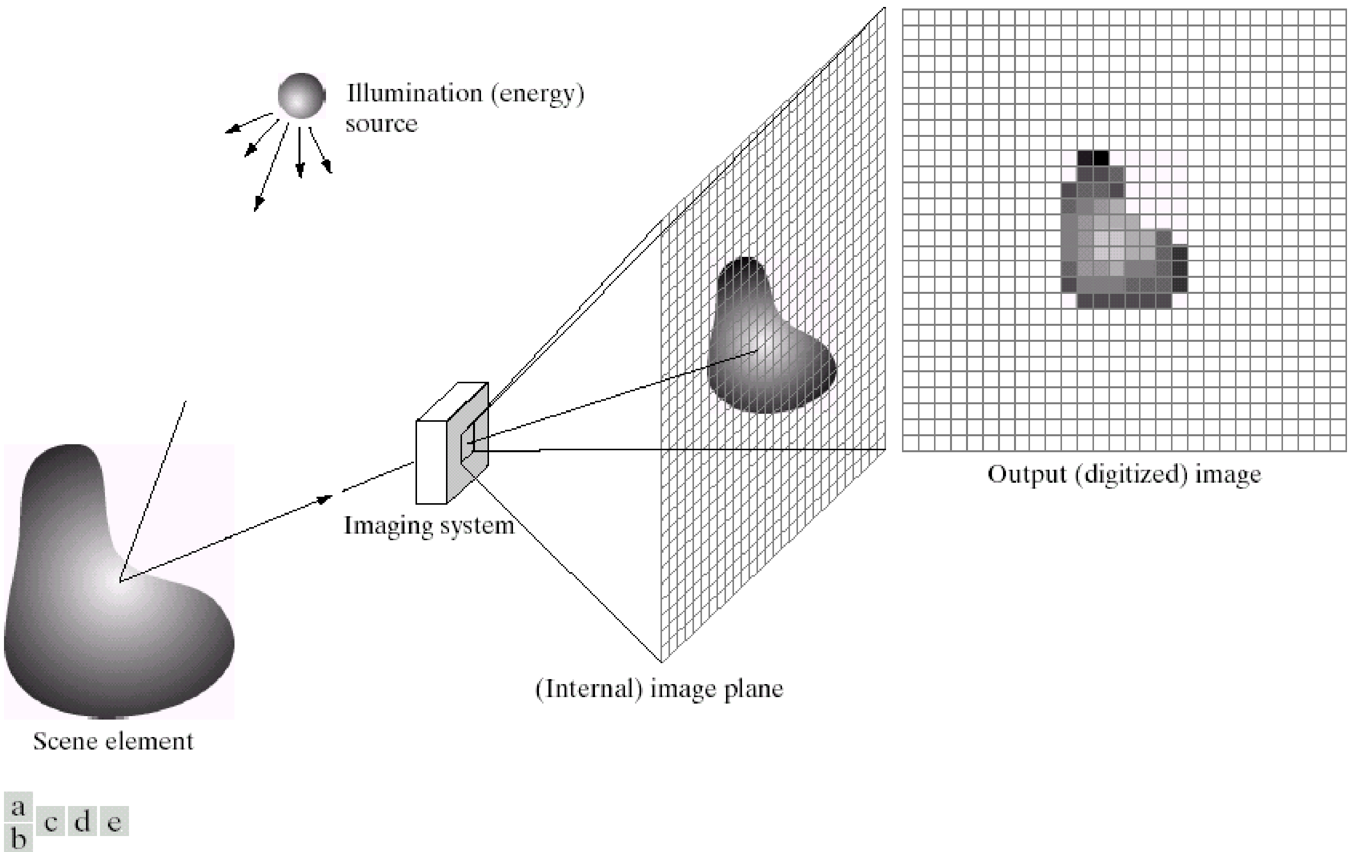


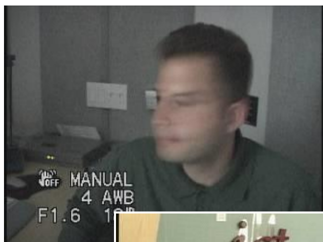
FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

*f(x,y) = reflectance(x,y) * illumination(x,y)*

Reflectance in [0,1], illumination in [0,inf]

Problem: Dynamic Range

The real world is
High dynamic range



1

1500

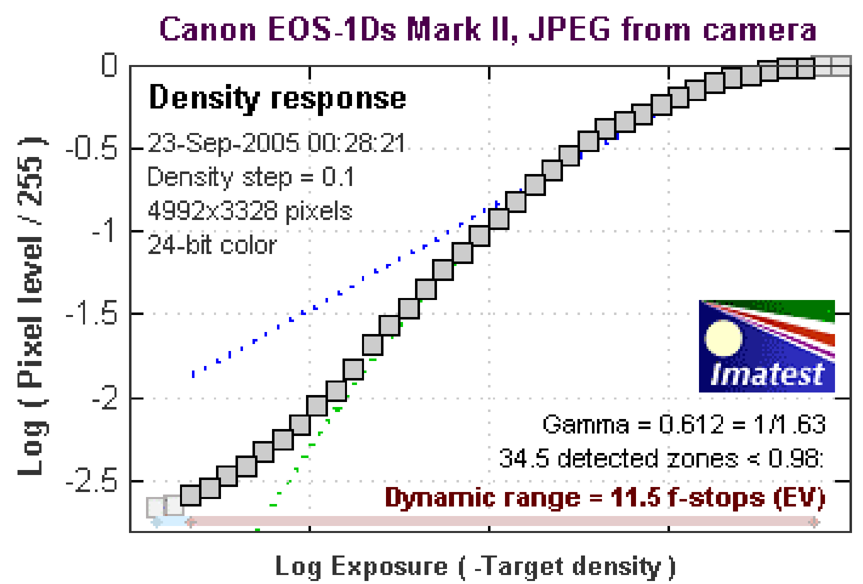
25,000

400,000

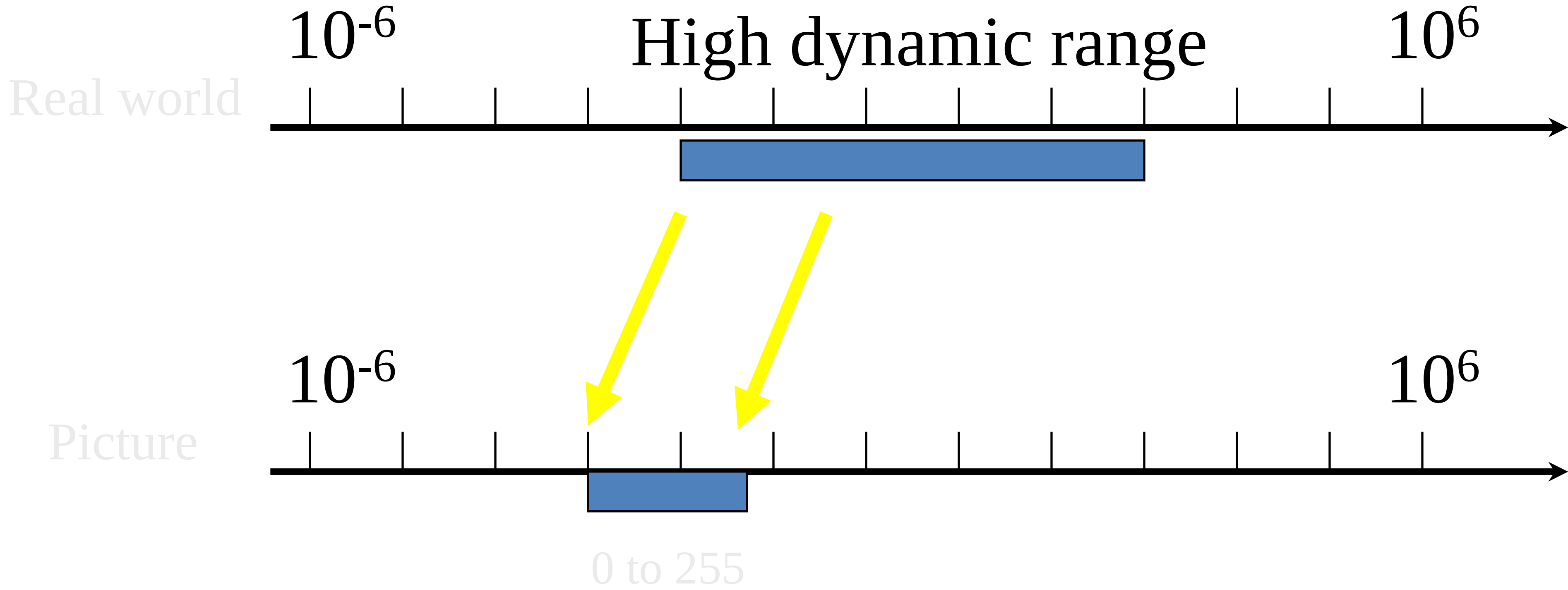
2,000,000,000

Dynamic range and camera response

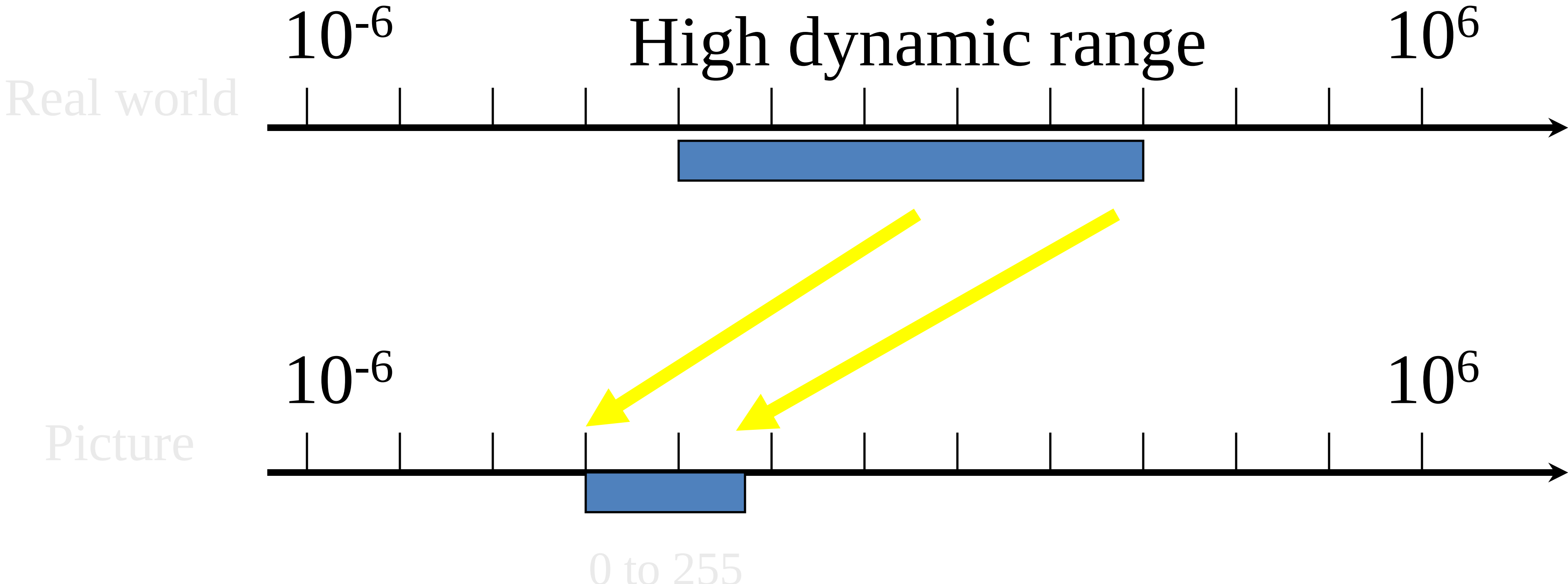
- Typical scenes have a huge dynamic range
- Camera response is roughly linear in the mid range (15 to 240) but non-linear at the extremes
  - called saturation or undersaturation



Long Exposure



Short Exposure



Radiance is a function of wavelength

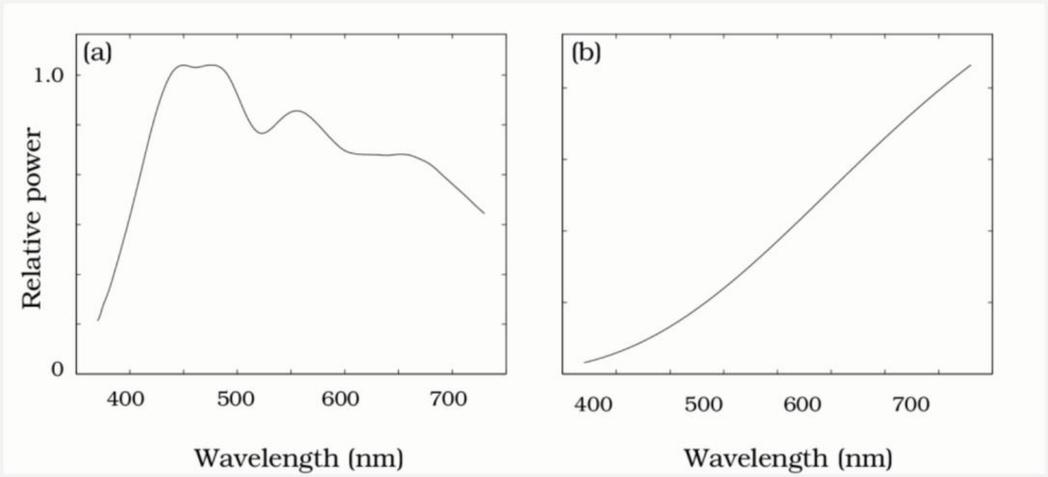
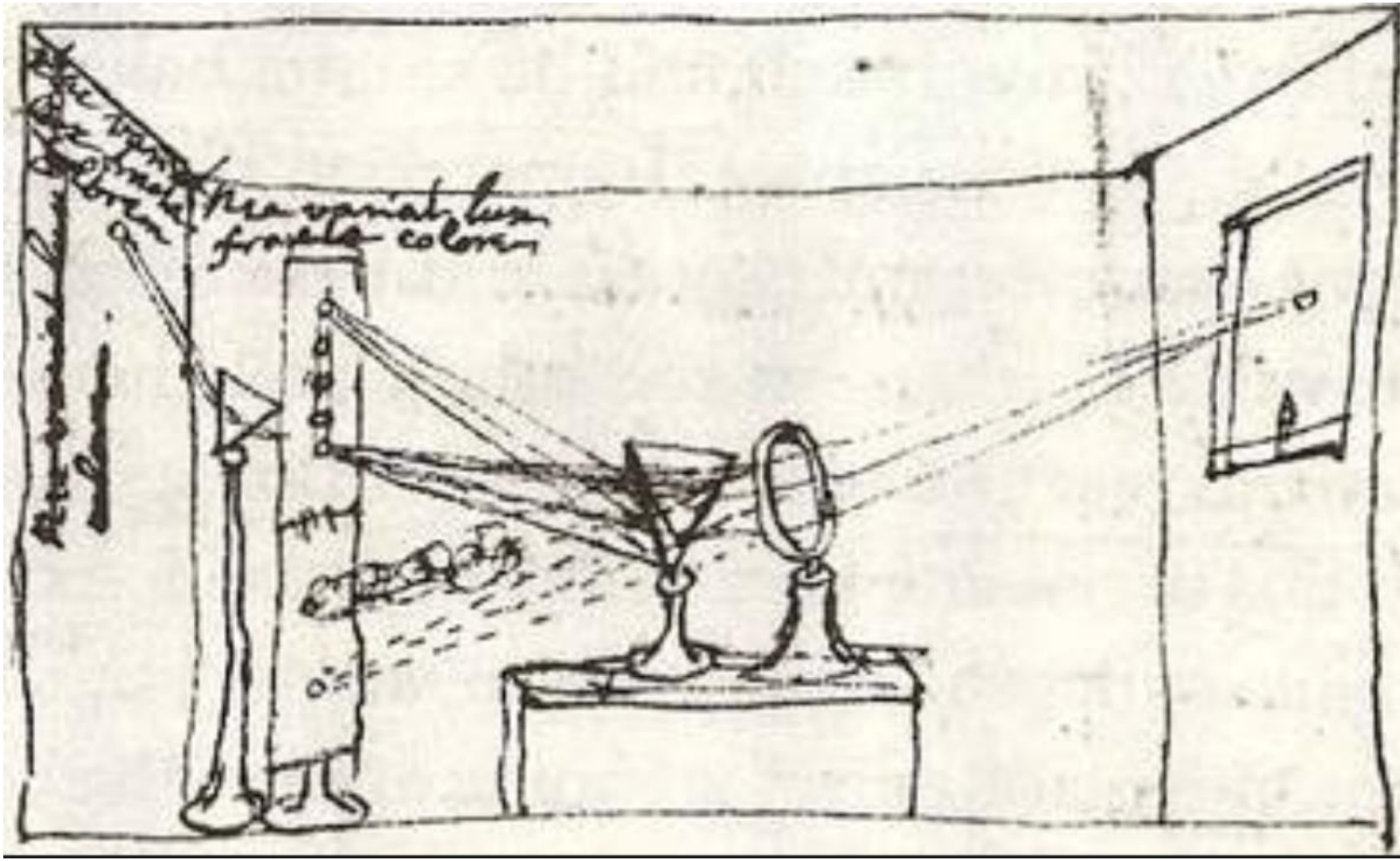
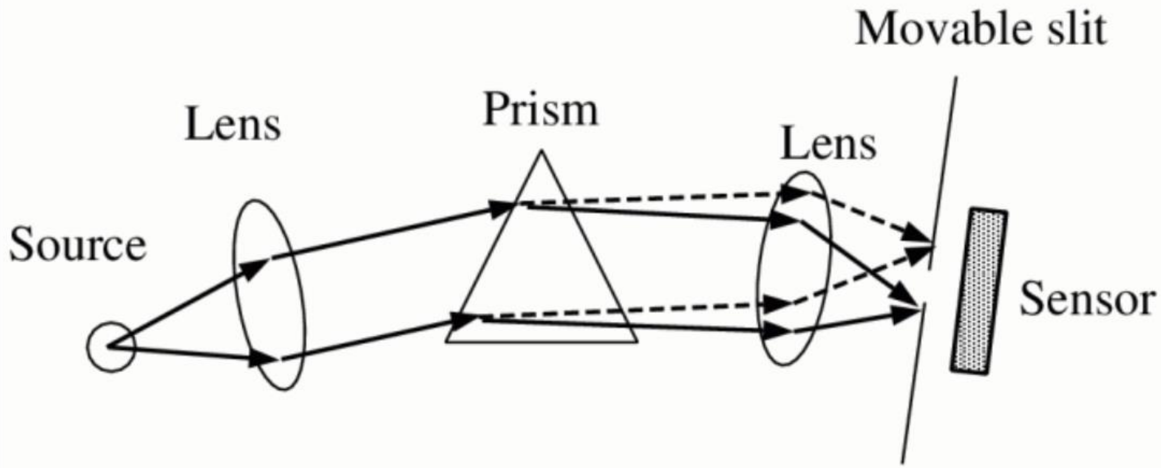


Figure 4.4. The spectral power distribution of two important light sources are shown: blue skylight (a) and the yellow disk of the sun (b).


Nec variat lux fracta colorem

Spectroradiometer

(a)



(b)

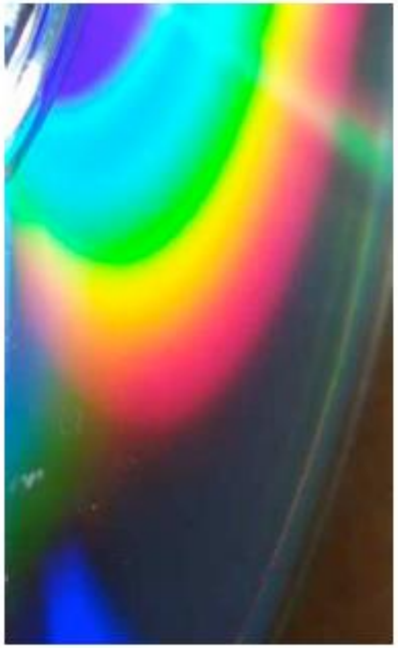
Wavelength (nm)	Color [a]
700	red
610	orange
580	yellow
540	green
480	blue
400	violet

[a] Viewed in isolation

Figure 4.2. A spectroradiometer is used to measure the spectral power distribution of light. (a) A schematic

DIY Spectroradiometer

(a)



(b)

Figure 6.3: (a) A spectrograph constructed using a compact disk (CD). Light enters through a slit at the right, diffracting from the narrowly spaced lines of the CD. (b) Photograph of diffraction pattern from sunlight, seen thorugh hole at bottom left.

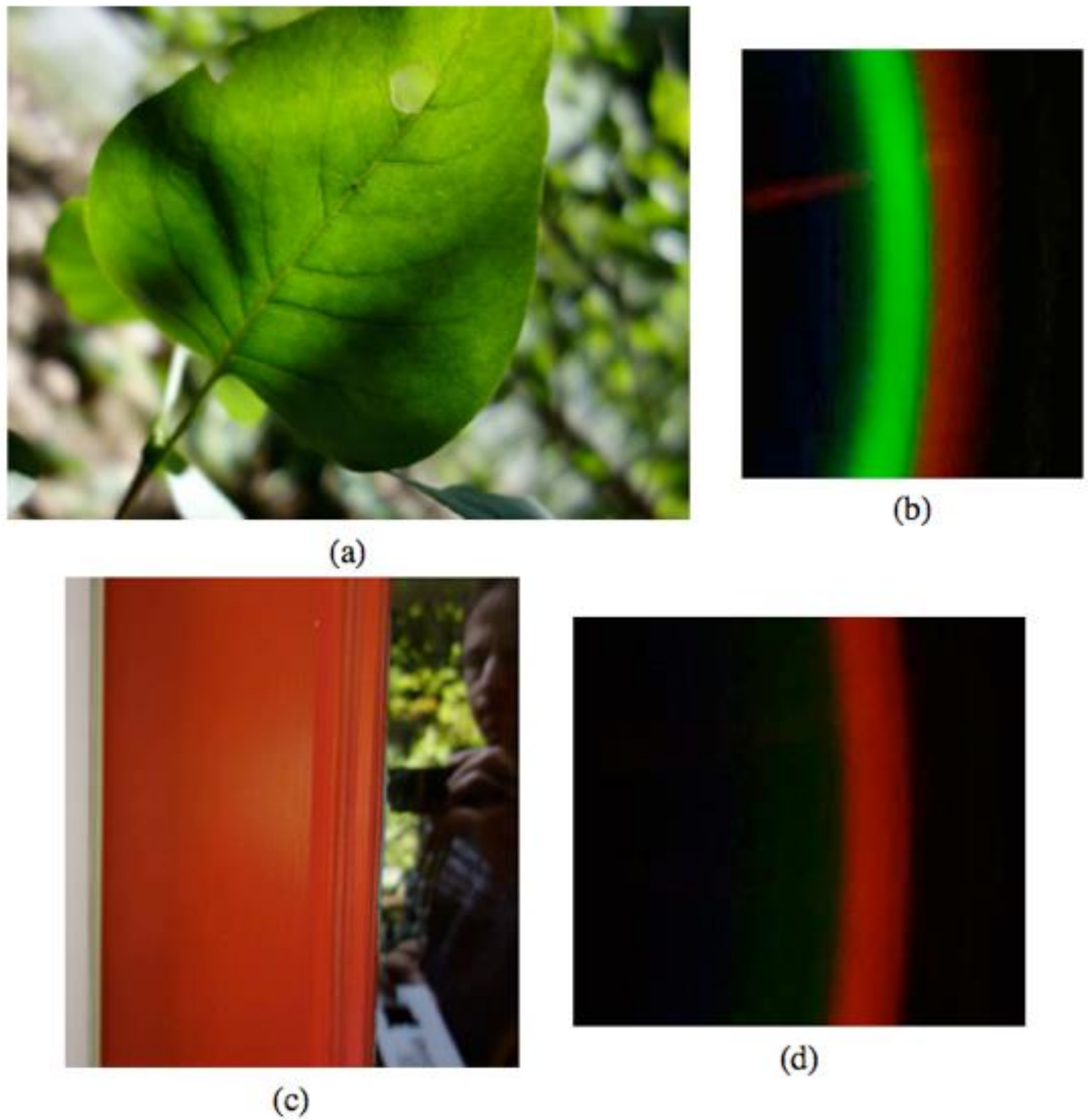


Figure 6.5: Some real-world objects and the reflected light spectra (photographed using Fig. (6.3) (a)) from outdoor viewing. (a) Leaf and (b) its reflected spectrum. (c) A red door and (d) its reflected spectrum.

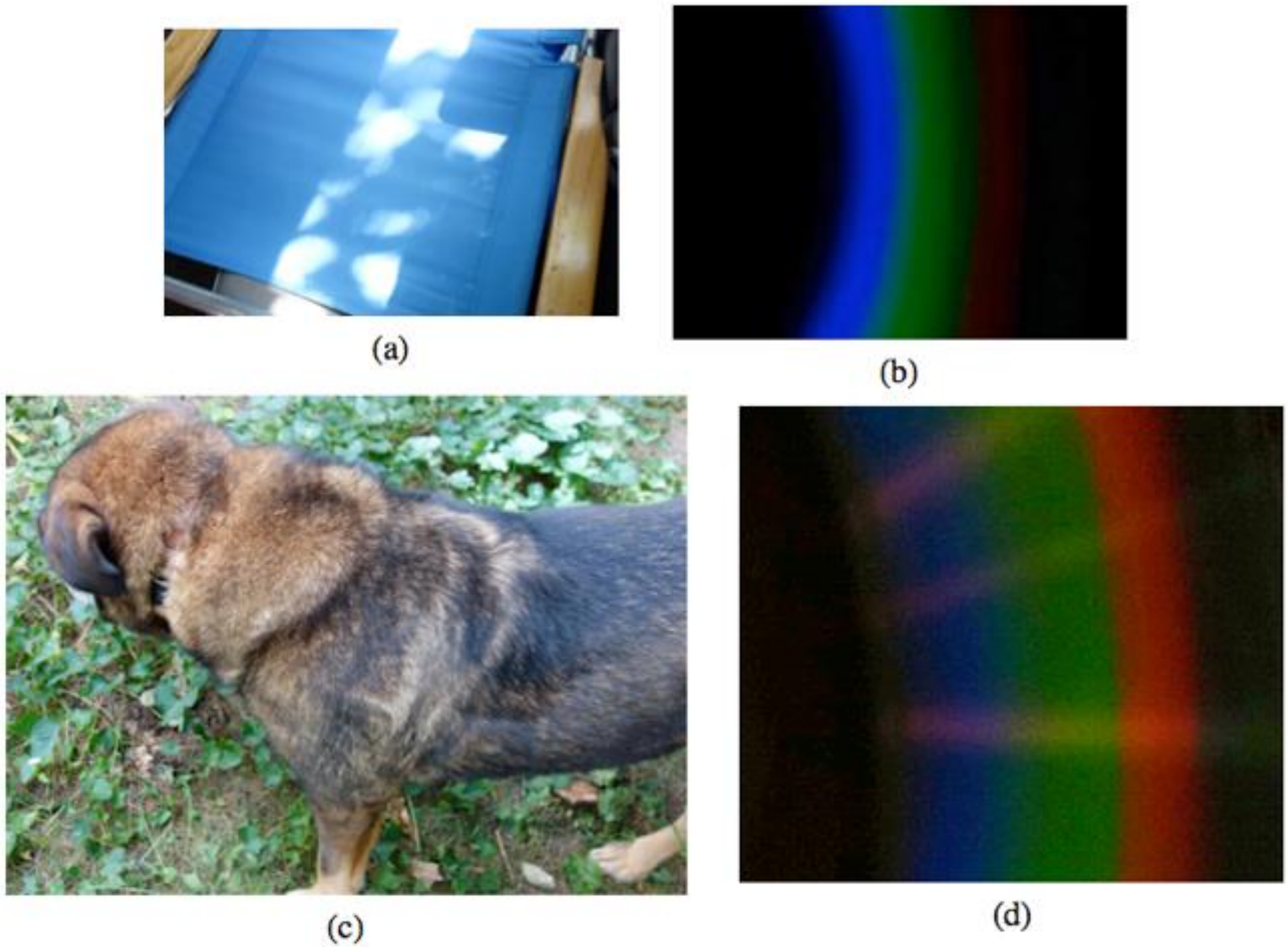
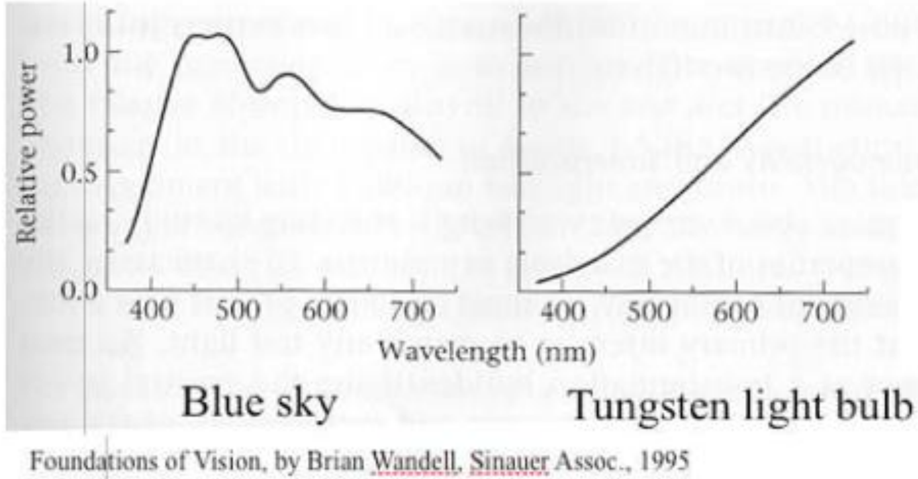


Figure 6.6: More real-world objects and the reflected light spectra. (a) Blue-green chair and (b) its reflected light. (c) Toby the dog and (d) his reflected spectrum.



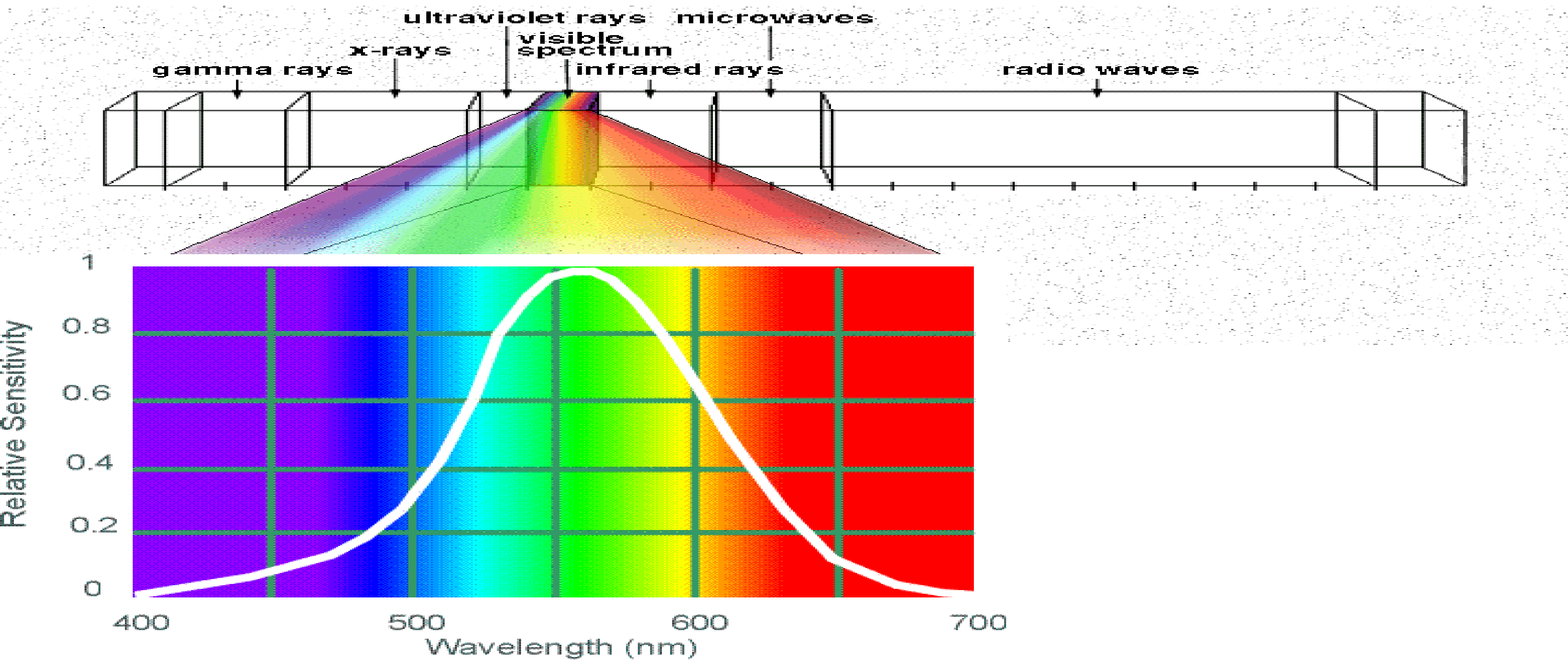
(a) (b)

(c)

(d)

Figure 6.4: (a) and (b): Plots of the power spectra of blue sky and a tungsten light bulb. Photographs show (c) a flourescent light and (d) its spectrum as viewed with the spectrograph of Fig. (6.3) (a).

Electromagnetic Spectrum

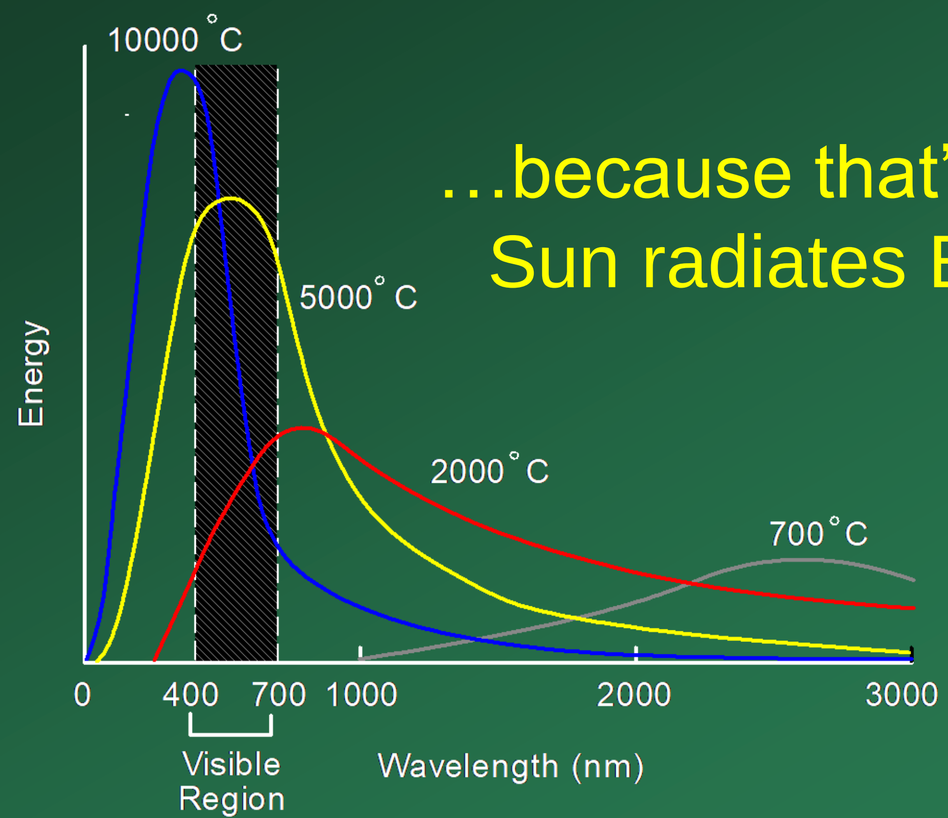


Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm

Visible Light

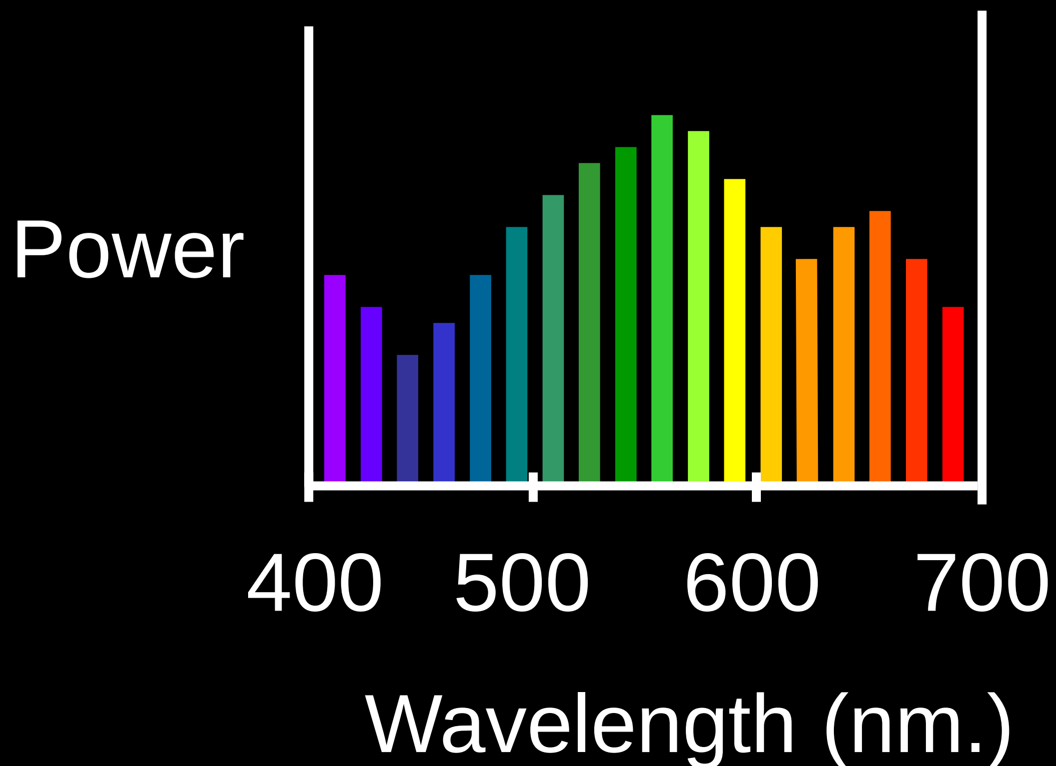
Why do we see light of these wavelengths?



…because that's where the Sun radiates EM energy

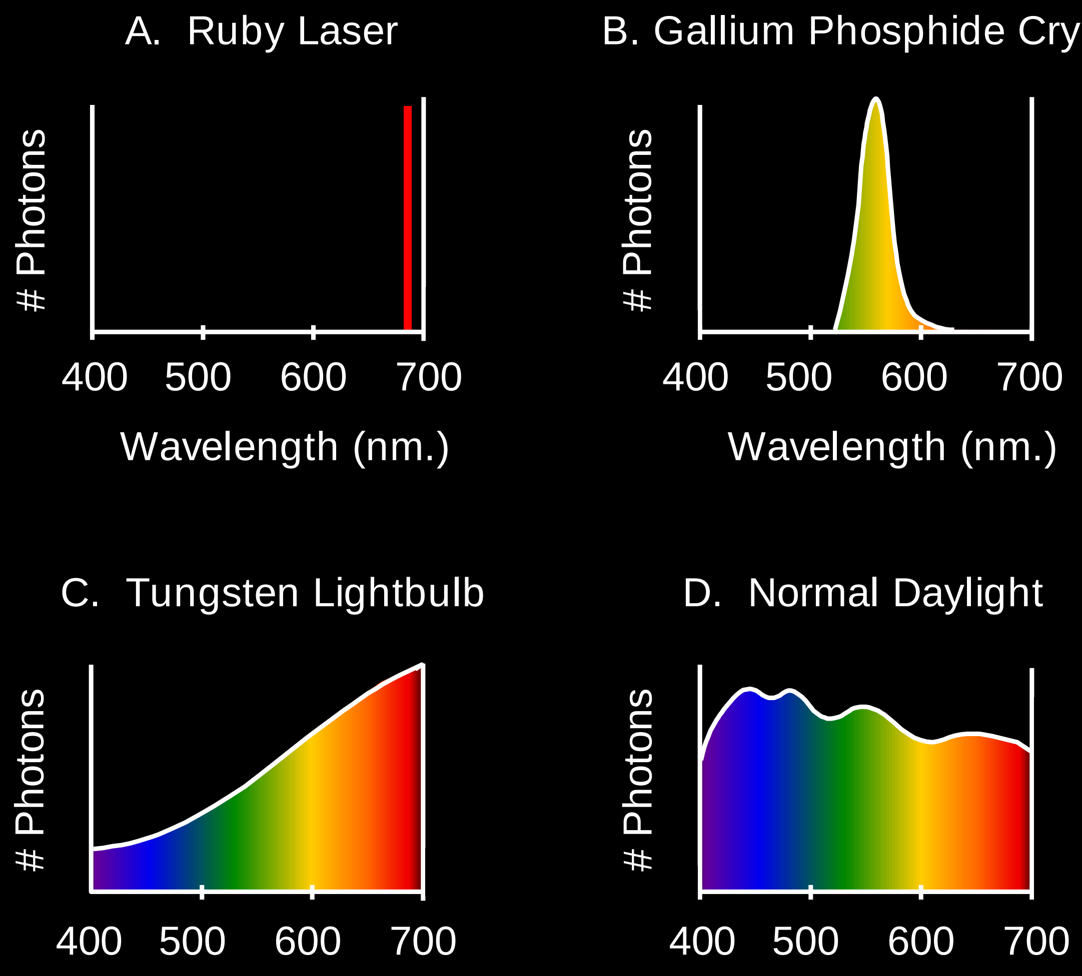
The Physics of Light

Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



The Physics of Light

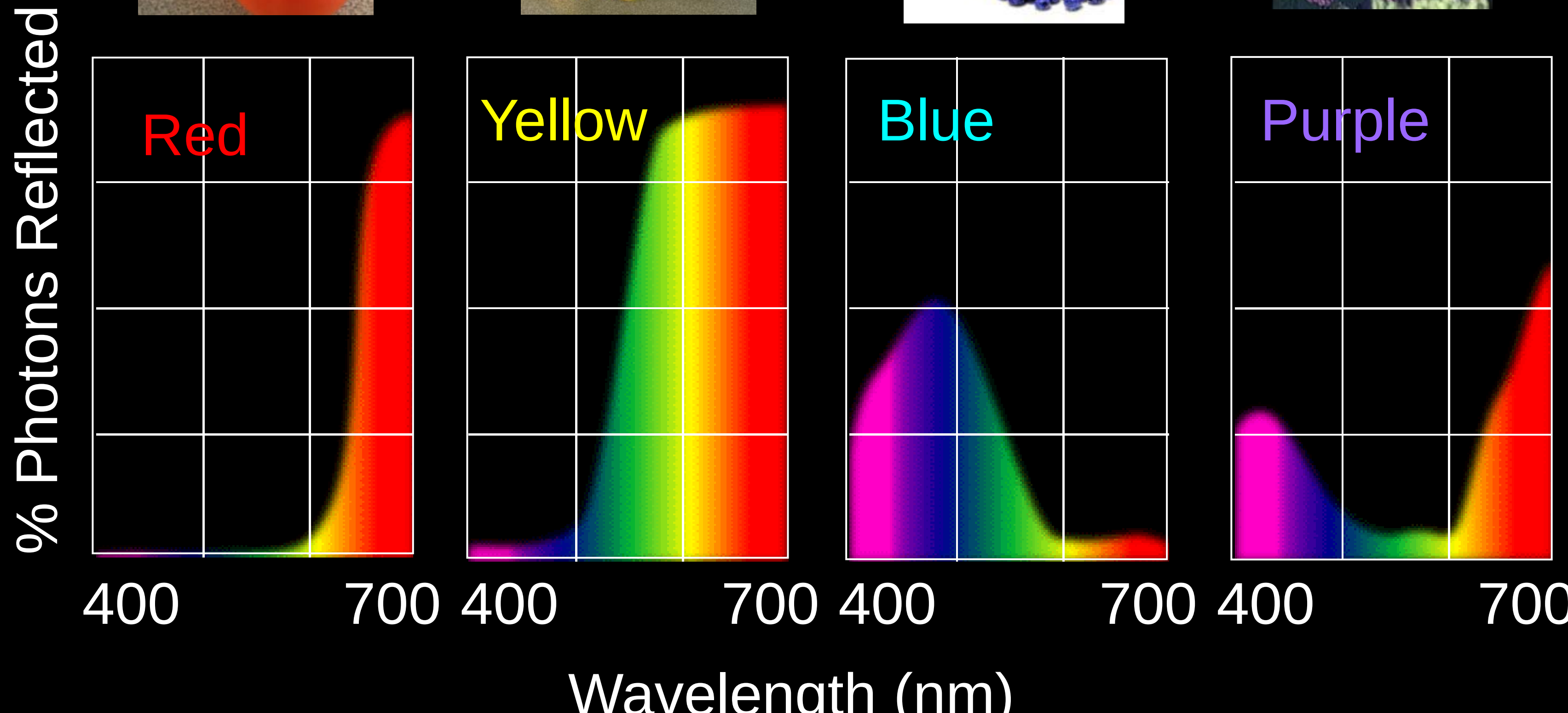
Some examples of the spectra of light sources



The Physics of Light

Some examples of the reflectance spectra of surfaces



Color names for cartoon spectra