

# Light and Color



"Empire of Light", Magritte

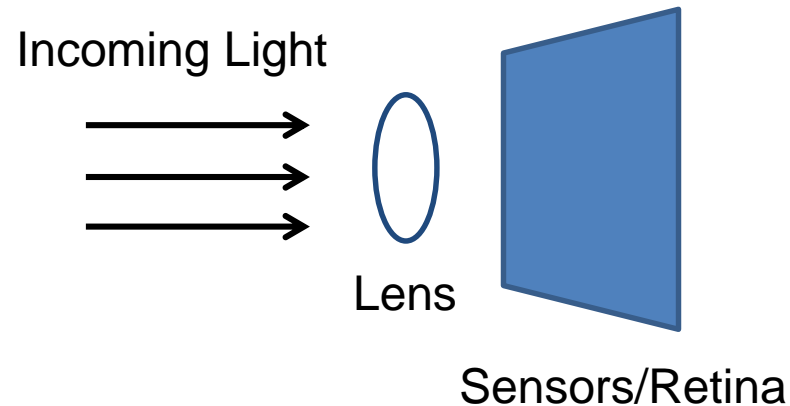
Computational Photography  
Derek Hoiem, University of Illinois

# Announcements

- Project 1 due next Mon (9/14), 11:59pm
  - Choosing cutoff:  $\sigma > 1$
  - Remember to convert images to double or single
  - Don't use built-in code for pyramids, contrast equalization etc., ask if not sure

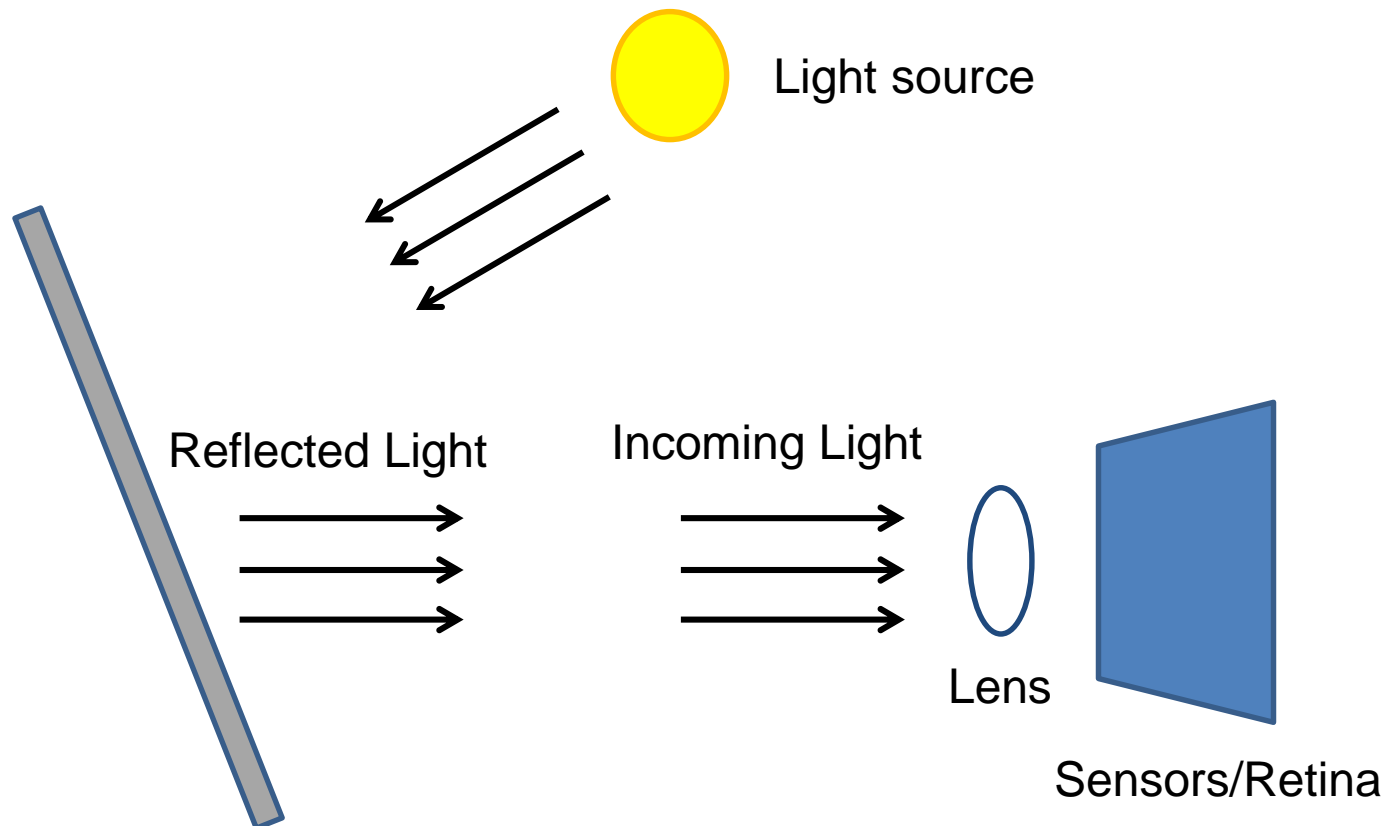
# Today's class

- How is incoming light measured by the eye or camera?



# Today's class

- How is incoming light measured by the eye or camera?
- How is light reflected from a surface?



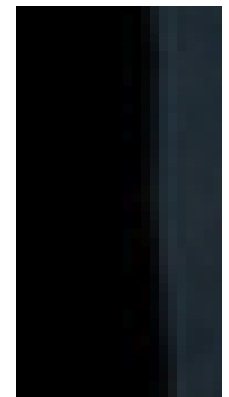
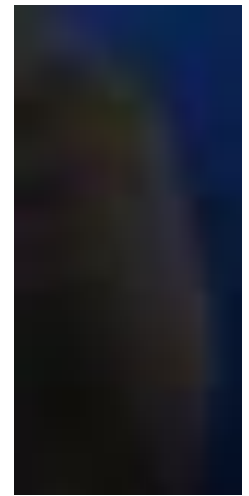
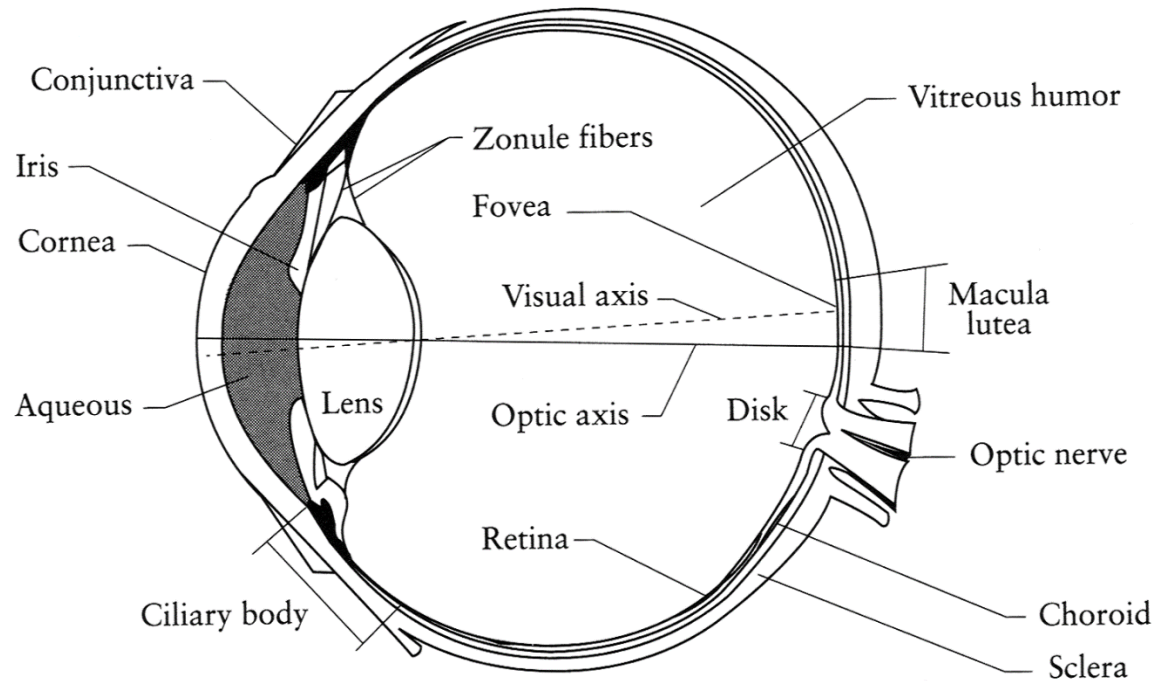


Photo by [nickwheeleroz](#), Flickr

# The Eye

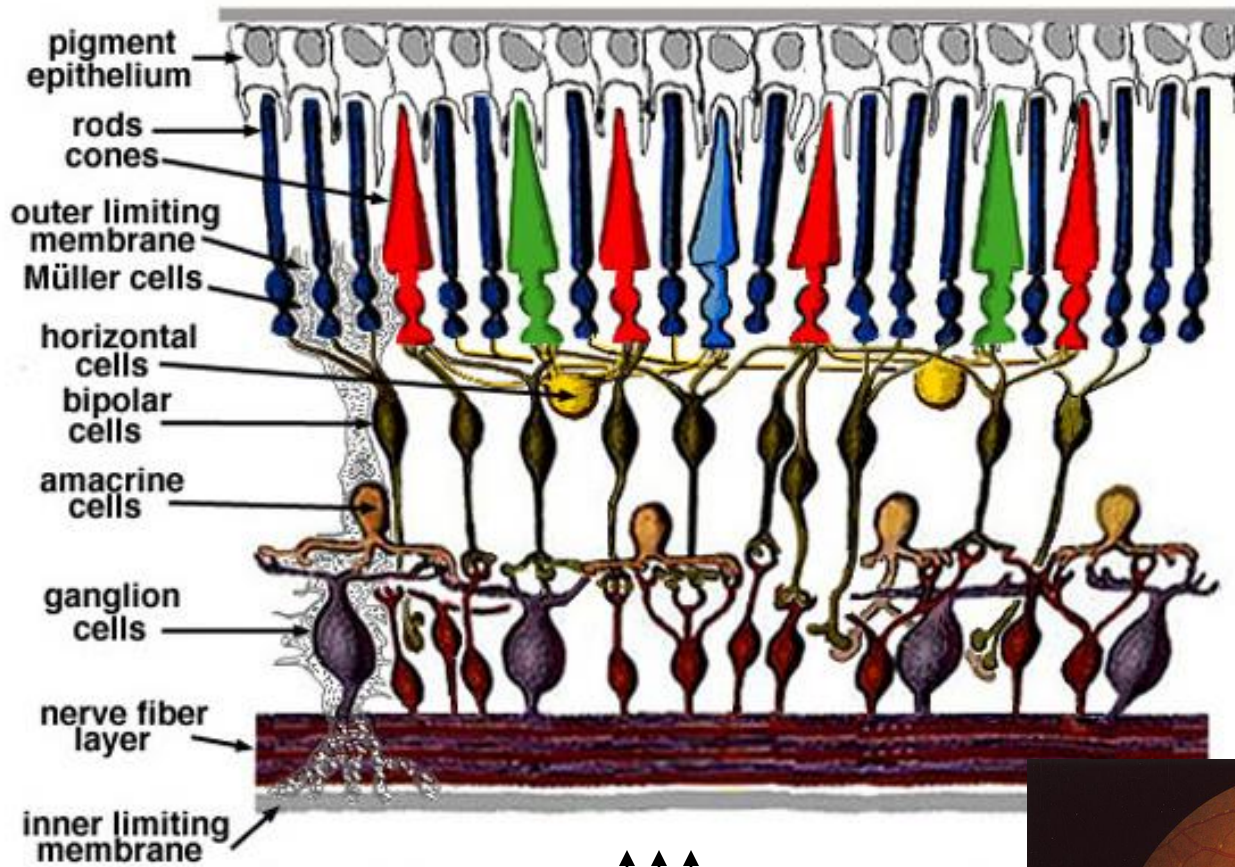
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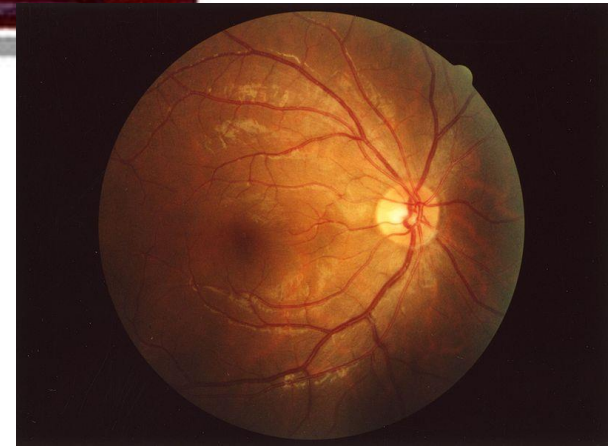
## The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the “film”?
  - photoreceptor cells (rods and cones) in the **retina**

# Retina up-close



↑↑↑  
Light



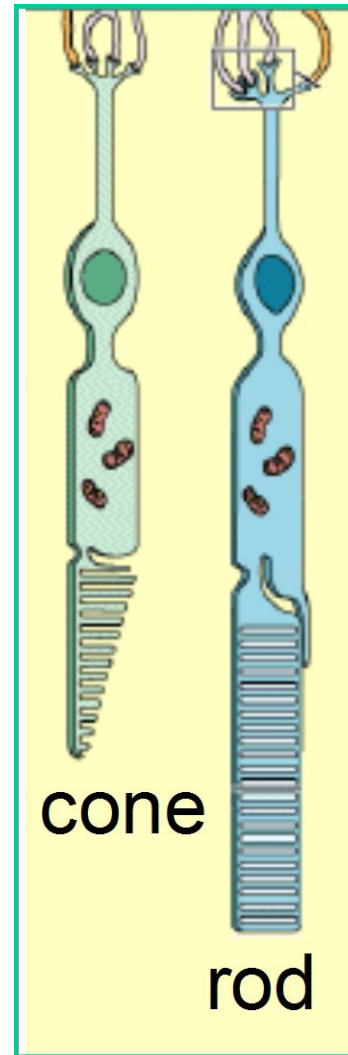
# Two types of light-sensitive receptors

## **Cones**

cone-shaped  
less sensitive  
operate in high light  
color vision

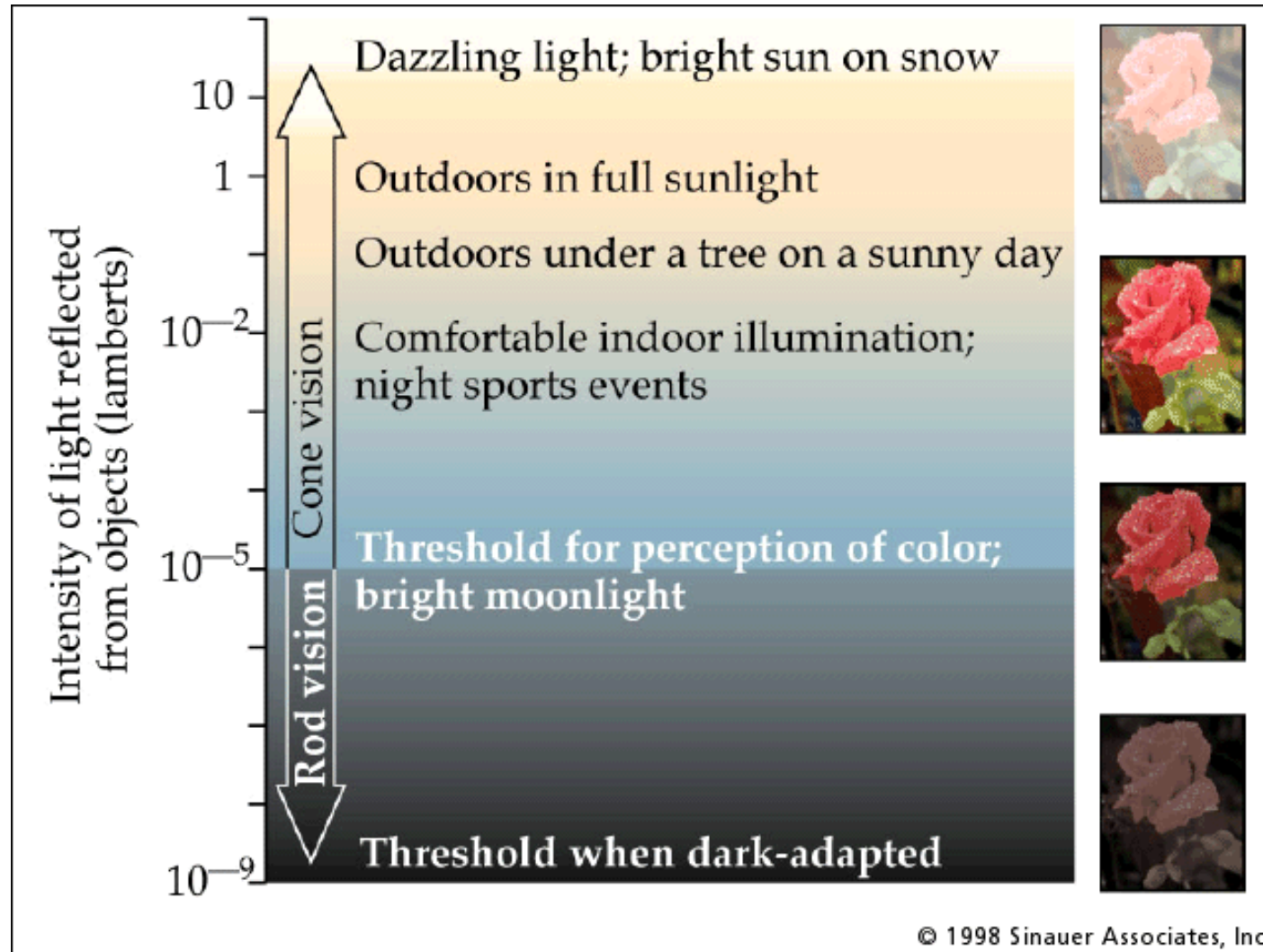
## **Rods**

rod-shaped  
highly sensitive  
operate at night  
gray-scale vision  
slower to respond

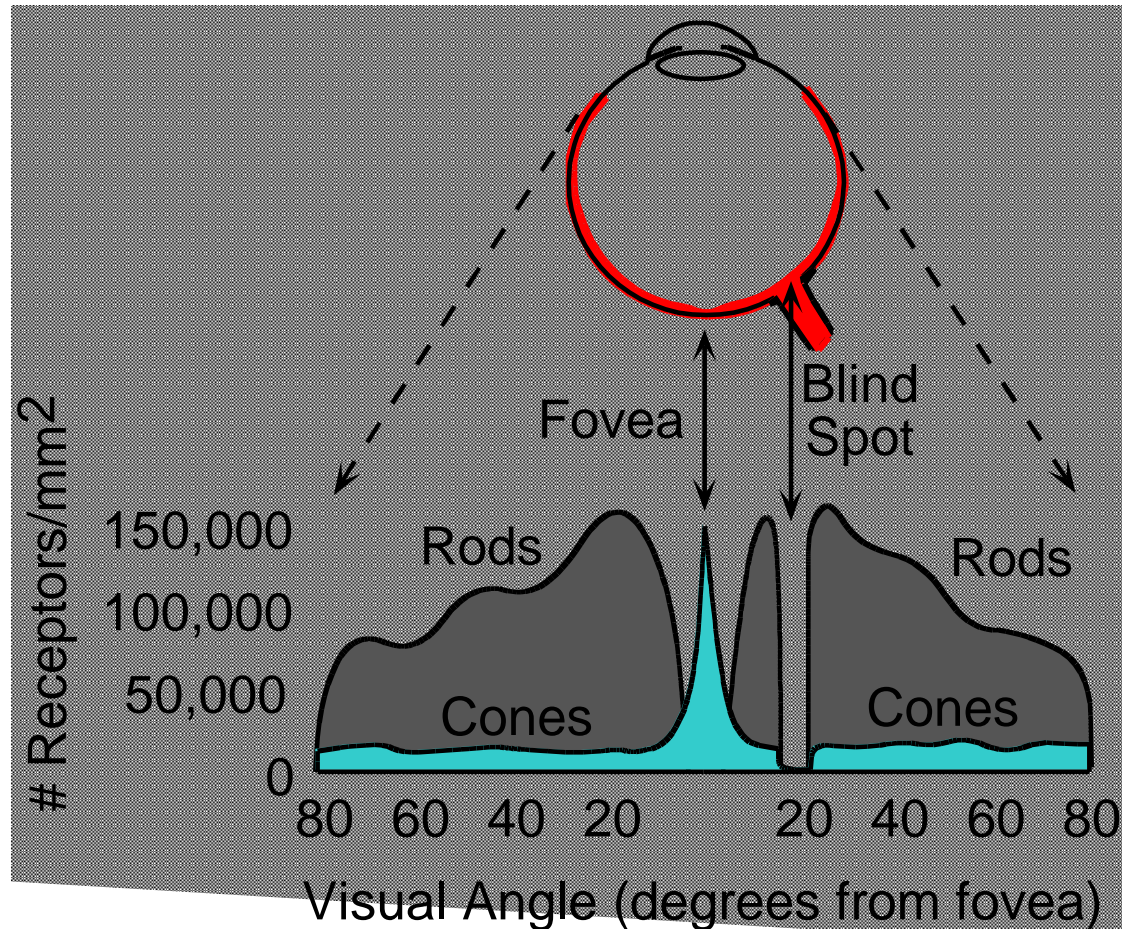




# Rod / Cone sensitivity

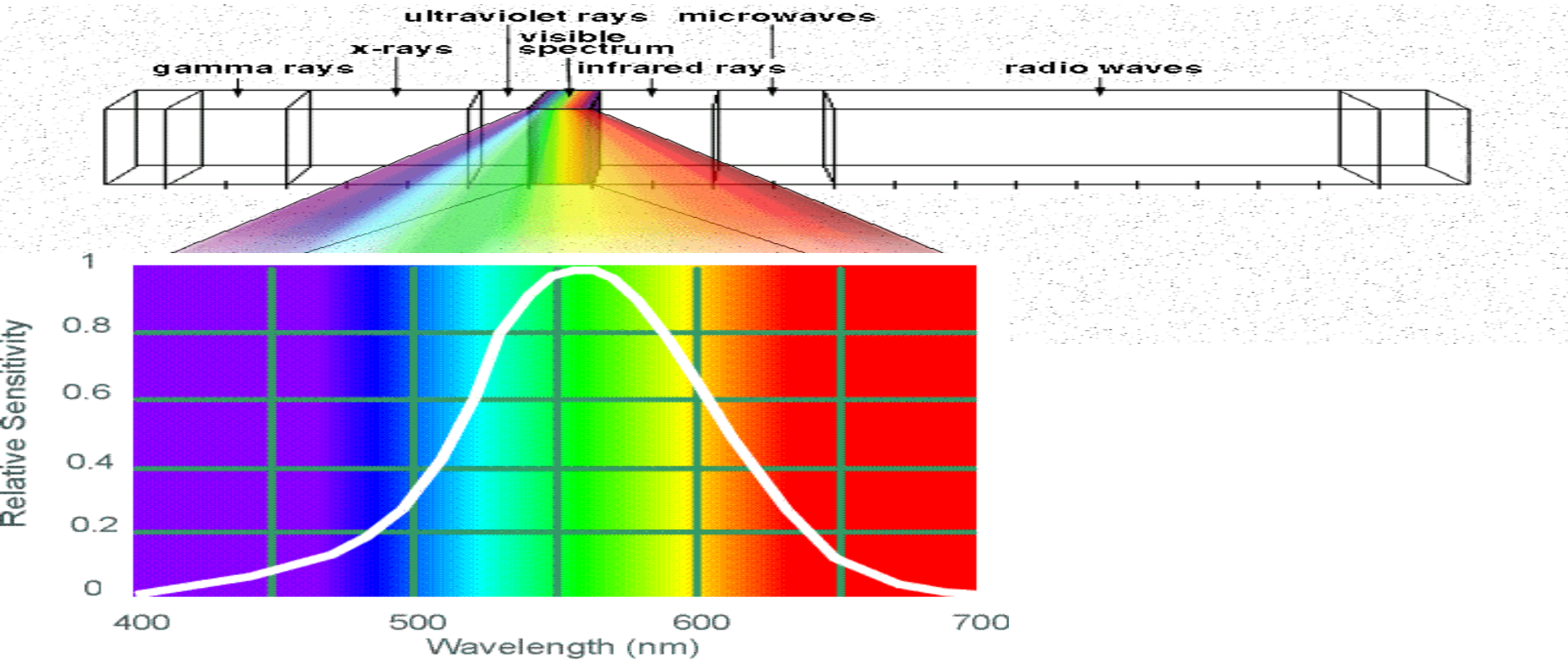


# Distribution of Rods and Cones



Night Sky: why are there more stars off-center?

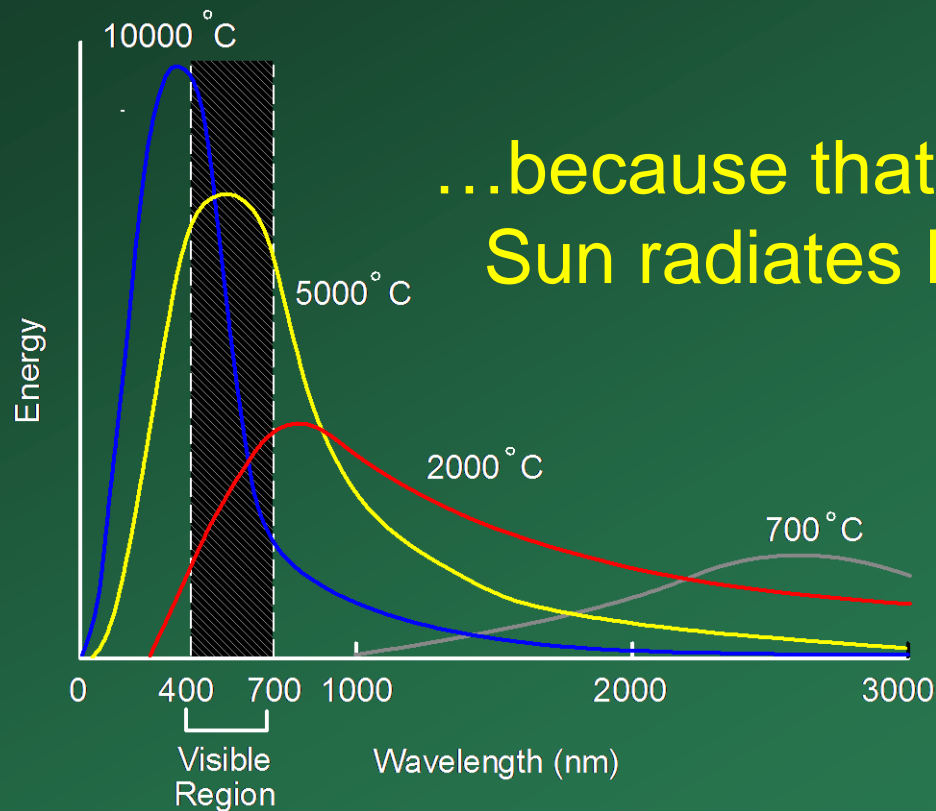
# Electromagnetic Spectrum



Human Luminance Sensitivity Function

# Visible Light

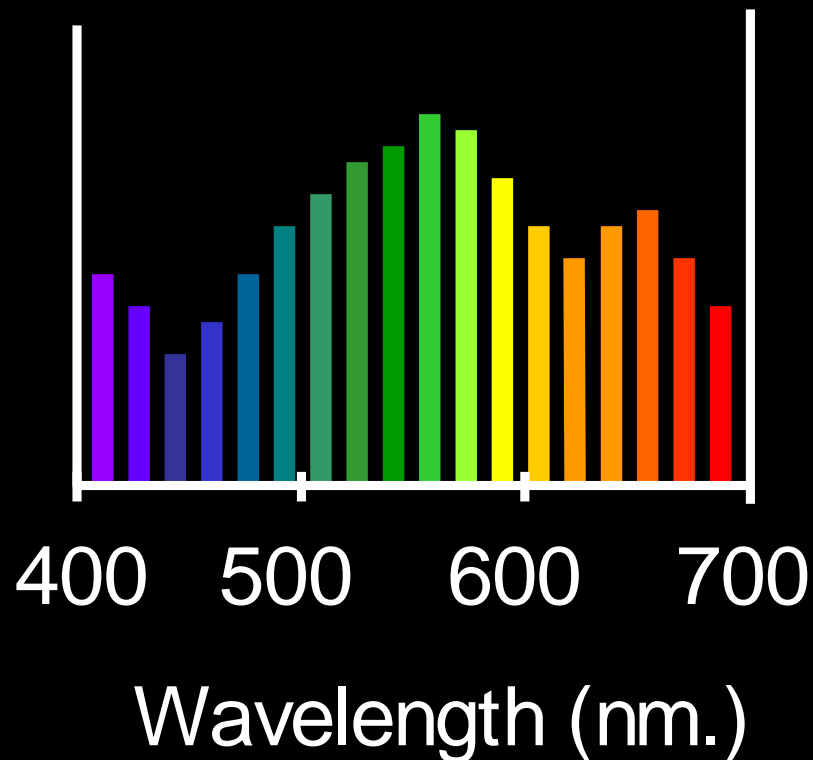
Why do we see light of these wavelengths?



# 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.

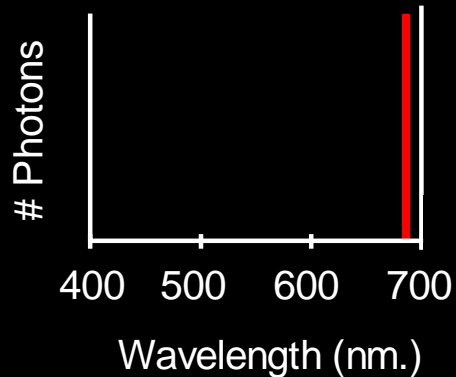
# Photons  
(per ms.)



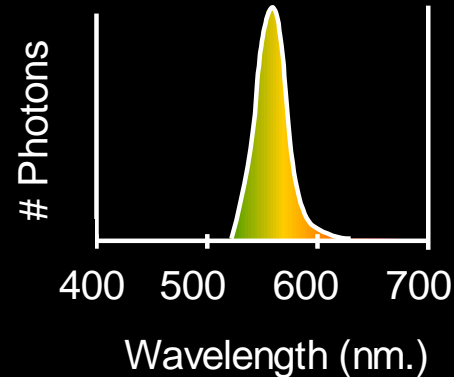
# The Physics of Light

## Some examples of the spectra of light sources

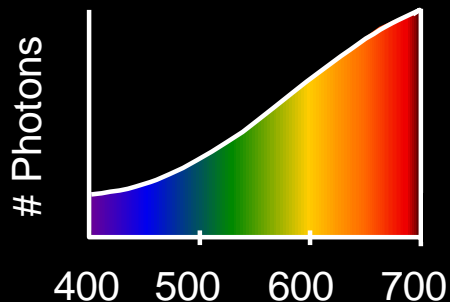
A. Ruby Laser



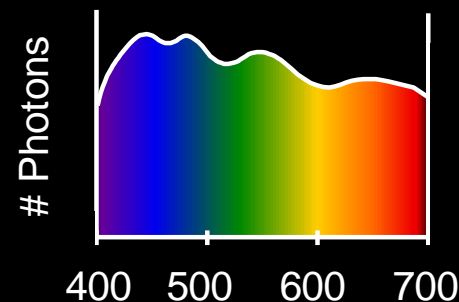
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb

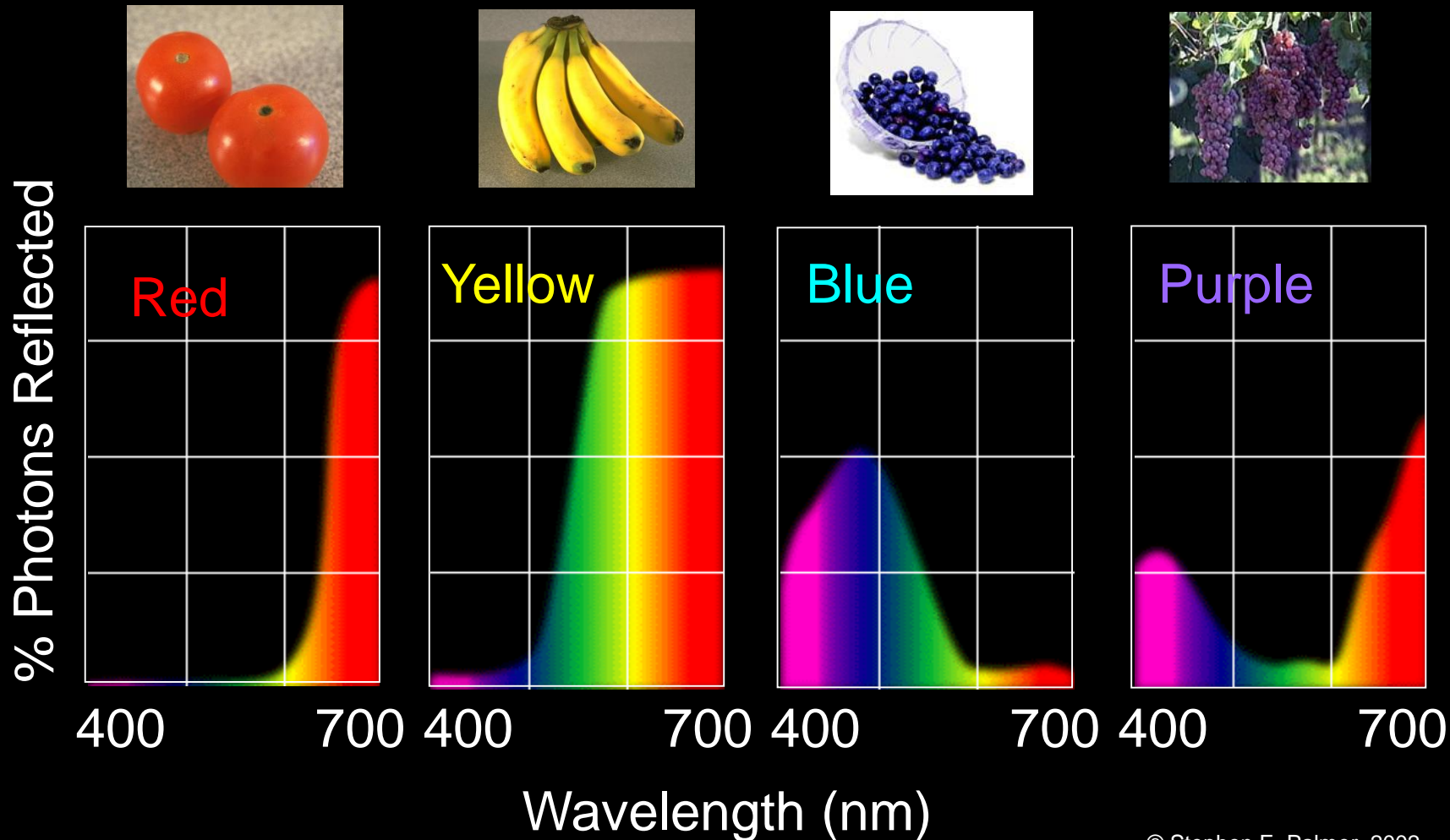


D. Normal Daylight

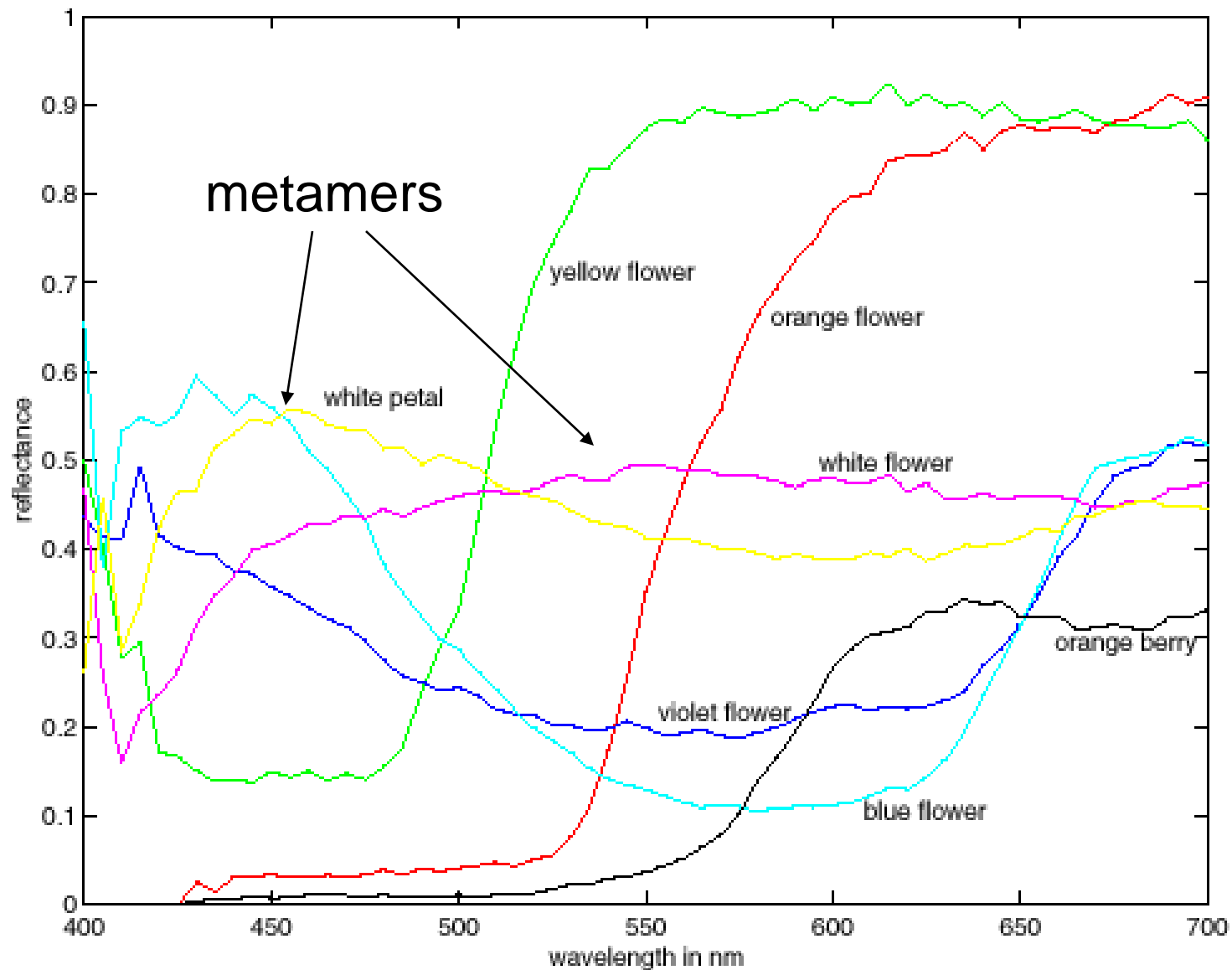


# The Physics of Light

Some examples of the reflectance spectra of surfaces



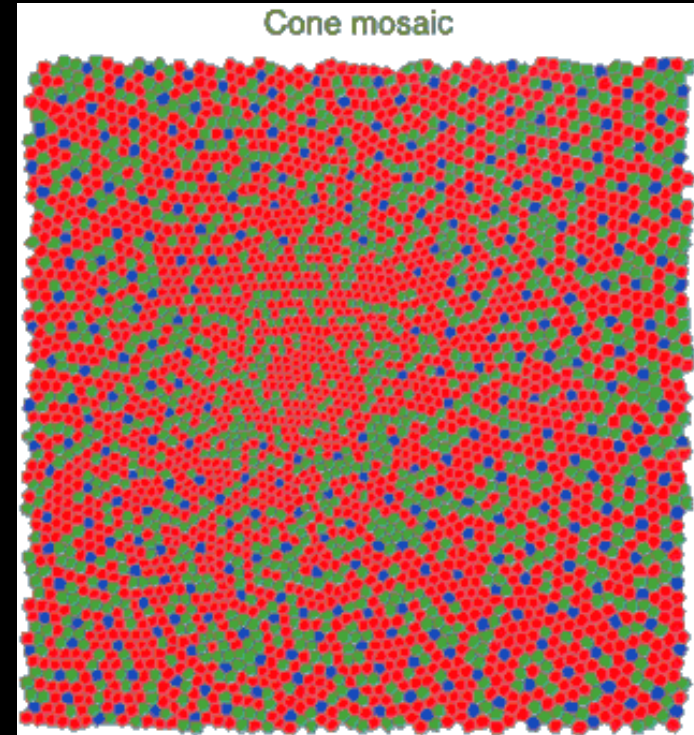
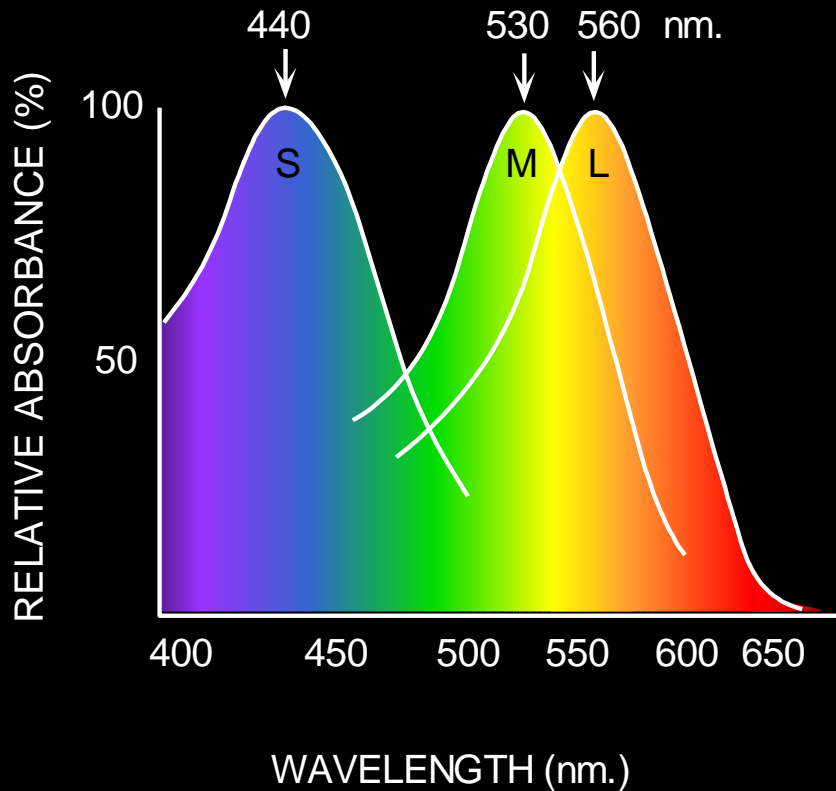
# More Spectra





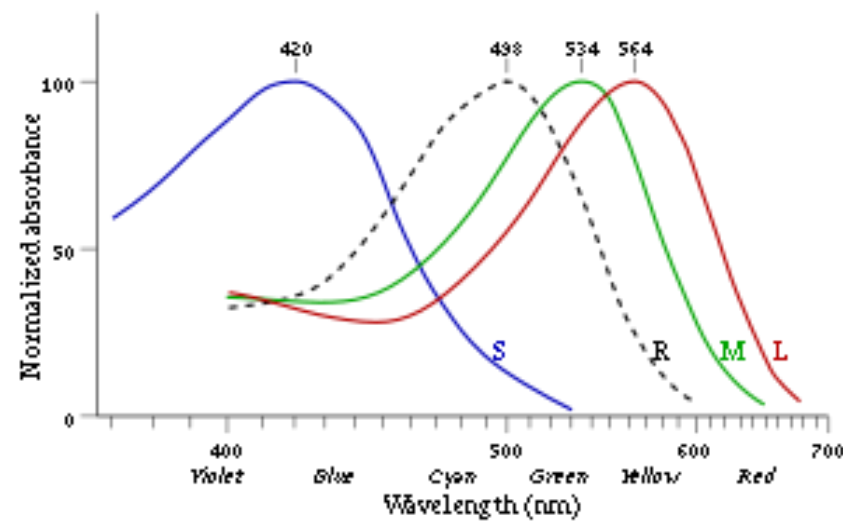
# Physiology of Color Vision

## Three kinds of cones:



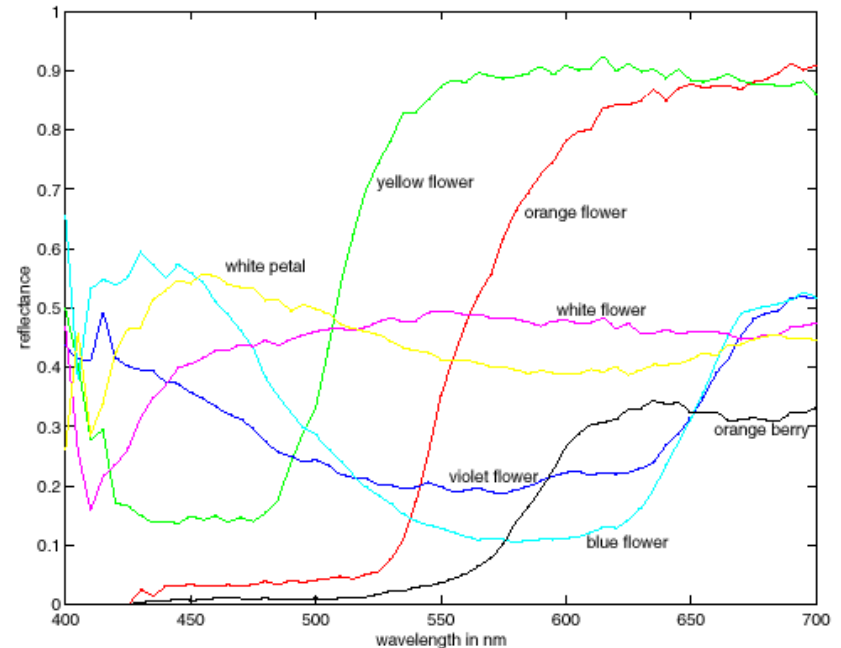
- Why are M and L cones so close?
- Why are there 3?

# 3 is better than 2...



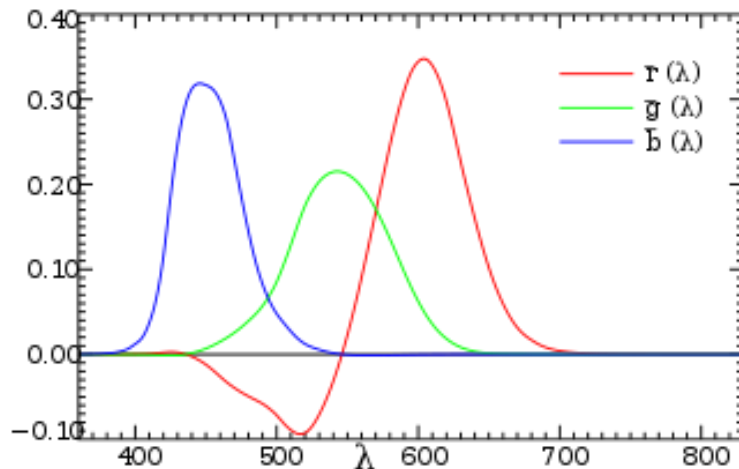
- “M” and “L” on the X-chromosome
  - Why men are more likely to be color blind (see what it’s like: <http://www.vischeck.com/vischeck/vischeckURL.php>)
- “L” has high variation, so some women are tetrachromatic
- Some animals have 1 (night animals), 2 (e.g., dogs), 4 (fish, birds), 5 (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp)

# We don't perceive a spectrum (or even RGB)

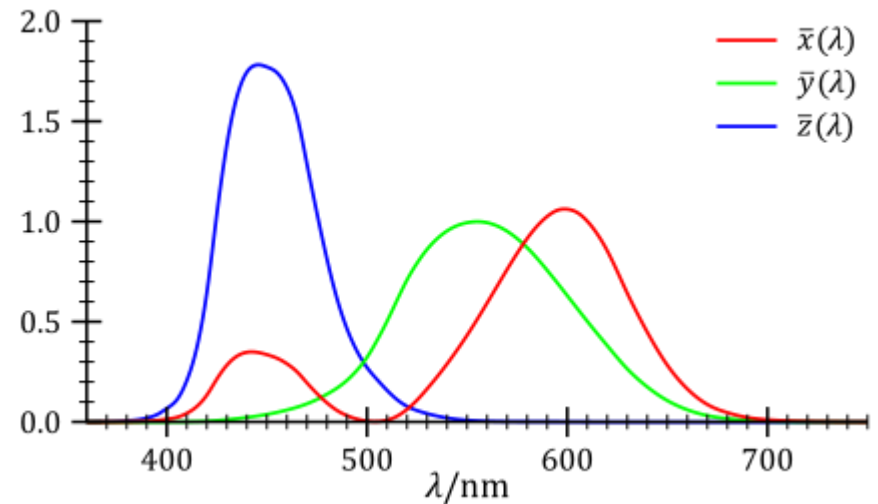


- We perceive
  - Hue: mean wavelength, color
  - Saturation: variance, vividness
  - Intensity: total amount of light
- Same perceived color can be recreated with combinations of three primary colors (“trichromacy”)

# Trichromacy and CIE-XYZ



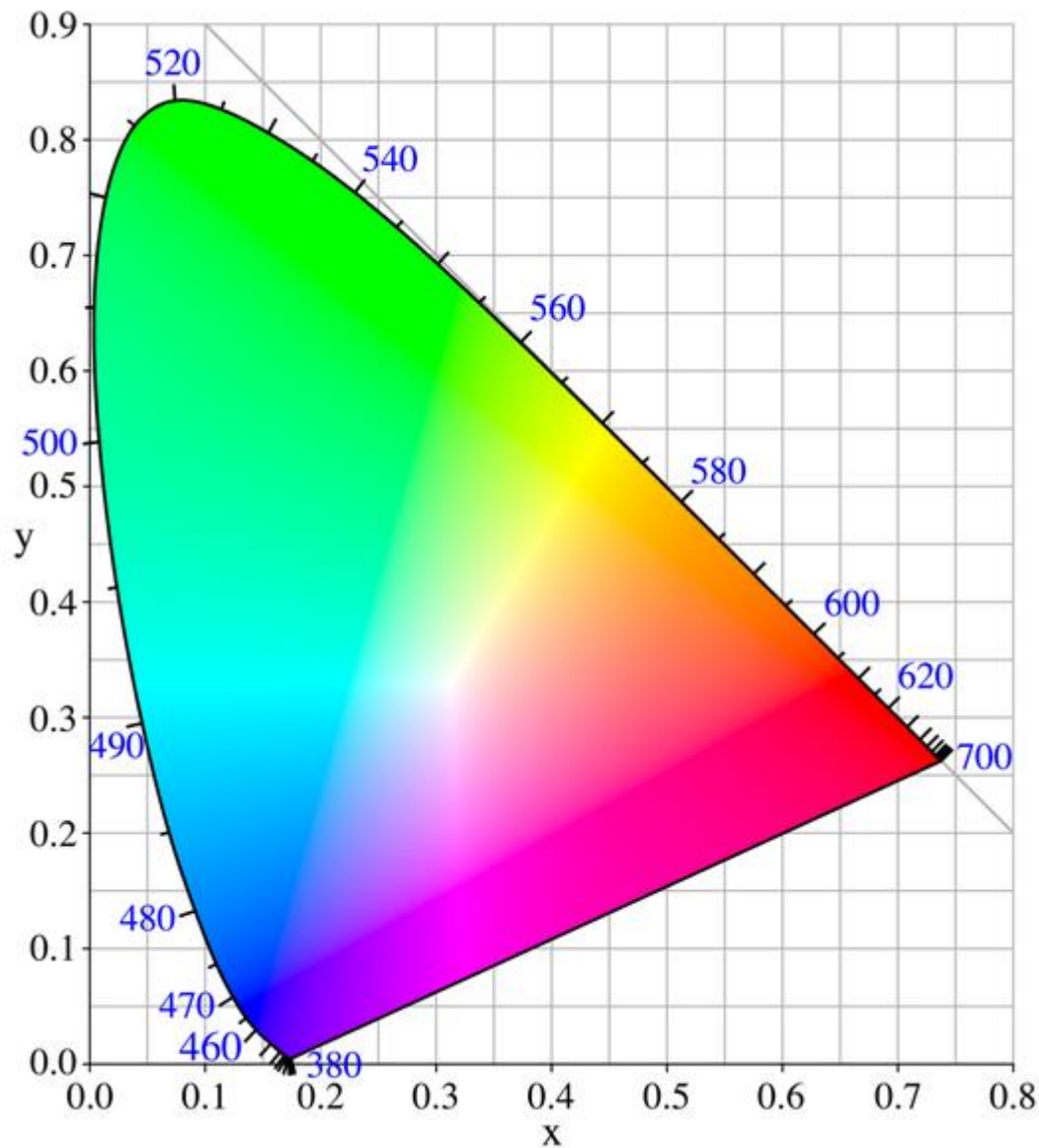
Perceptual equivalents with RGB



Perceptual equivalents with CIE-XYZ

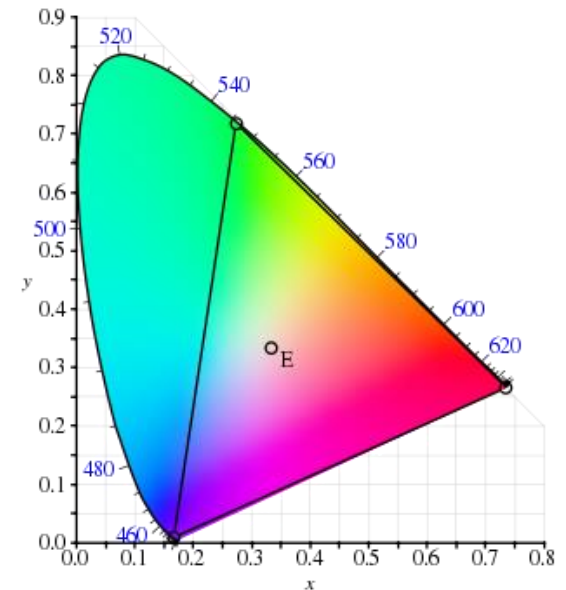
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

# CIE-XYZ



$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$



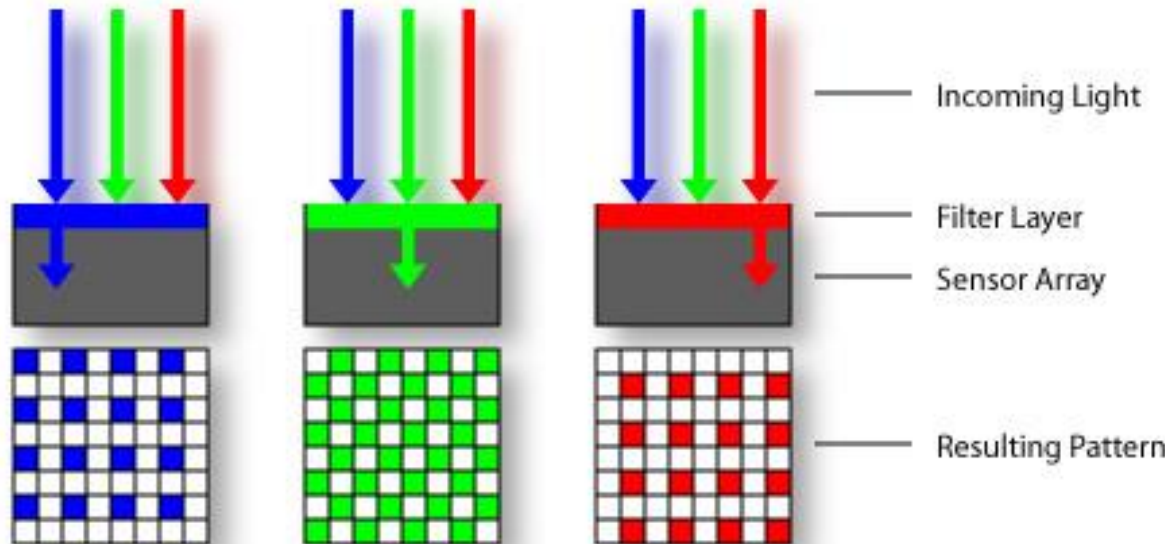
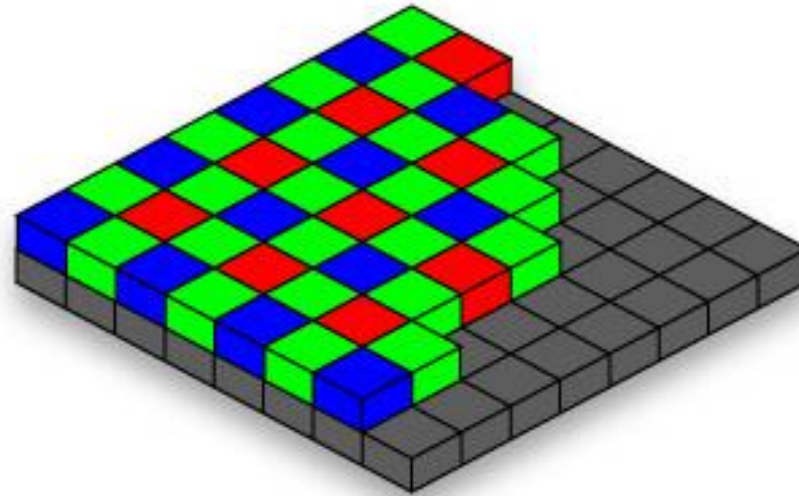
RGB portion is in triangle

# Color Sensing: Bayer Grid

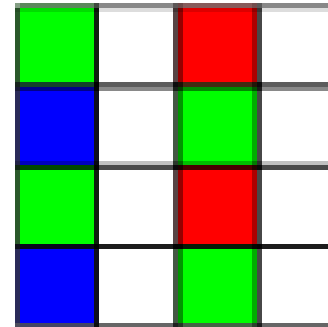
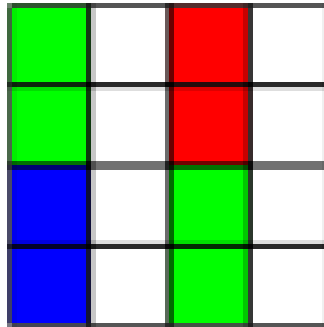
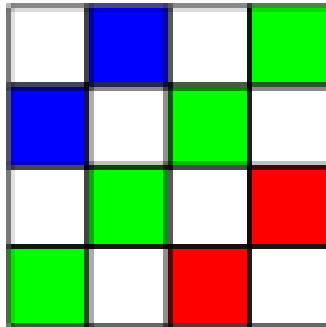
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Estimate RGB at each cell  
from neighboring values



# Alternative to Bayer: RGB+W

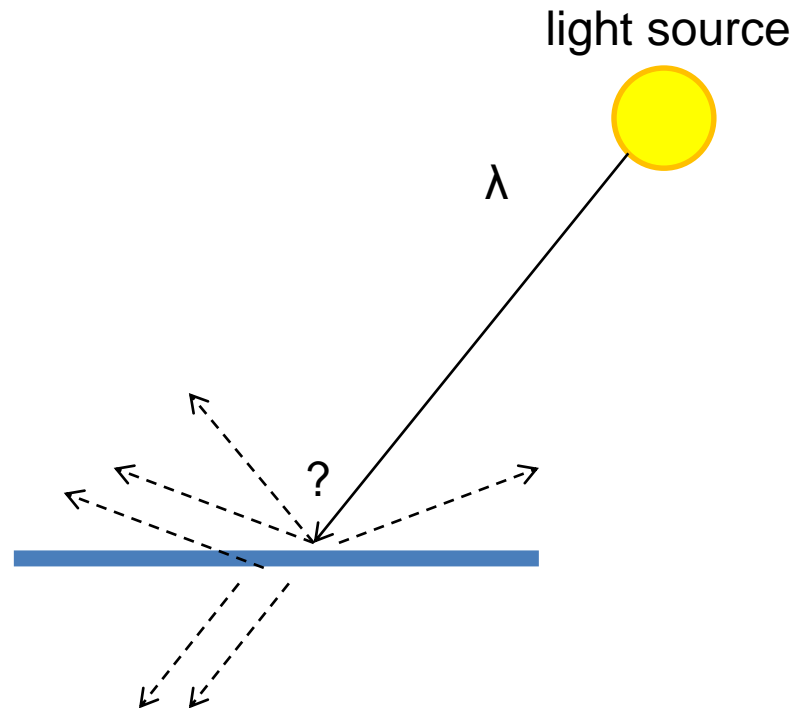


Kodak 2007

# How is light reflected from a surface?

Depends on

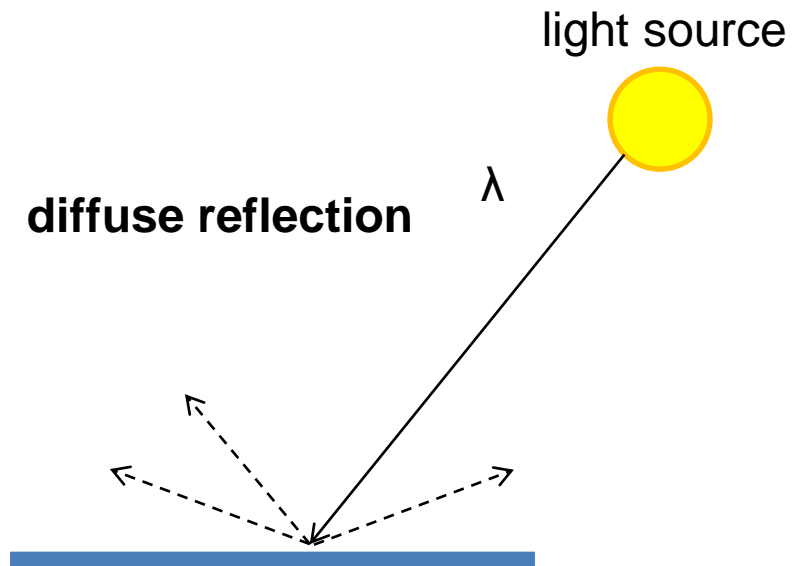
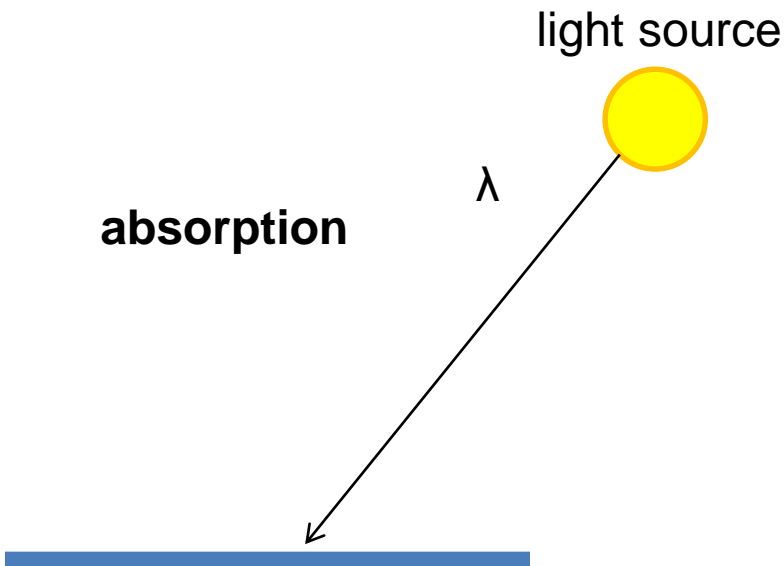
- Illumination properties: wavelength, orientation, intensity
- Surface properties: material, surface orientation, roughness, etc.





# Lambertian surface

- Some light is absorbed (function of albedo)
- Remaining light is reflected in all directions (diffuse reflection)
- Examples: soft cloth, concrete, matte paints



# Diffuse reflection

Intensity *does* depend on illumination angle because less light comes in at oblique angles.

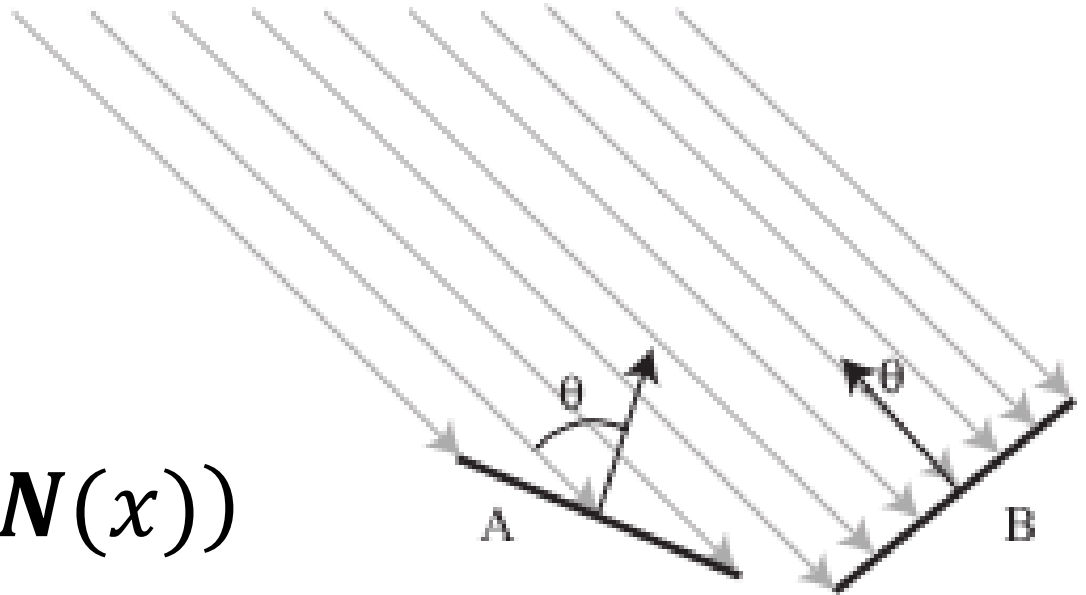
$\rho$  = albedo

$\mathbf{S}$  = directional source

$\mathbf{N}$  = surface normal

$I$  = image intensity

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

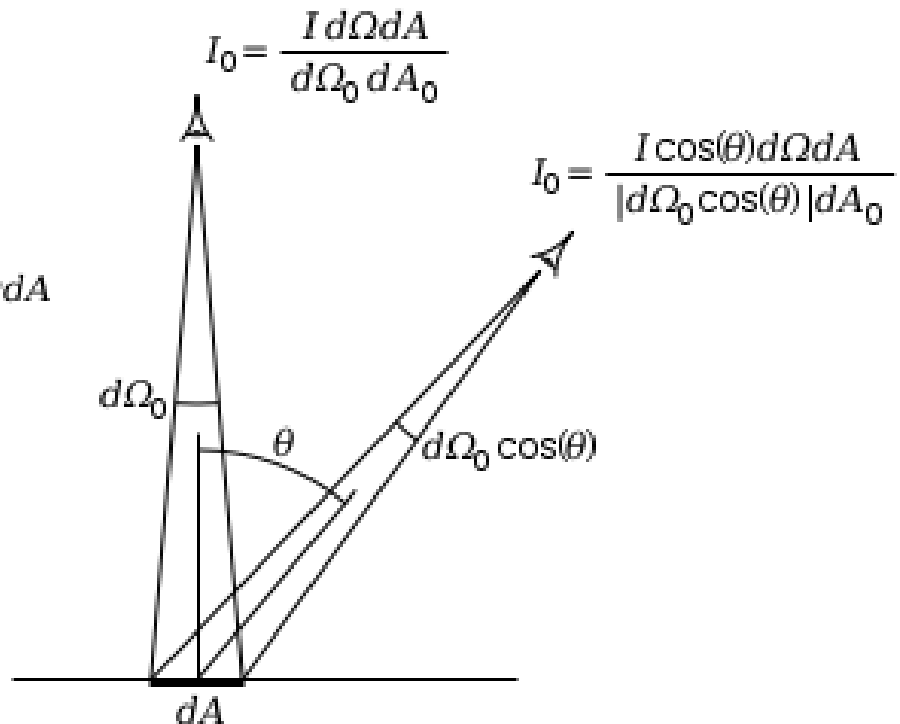
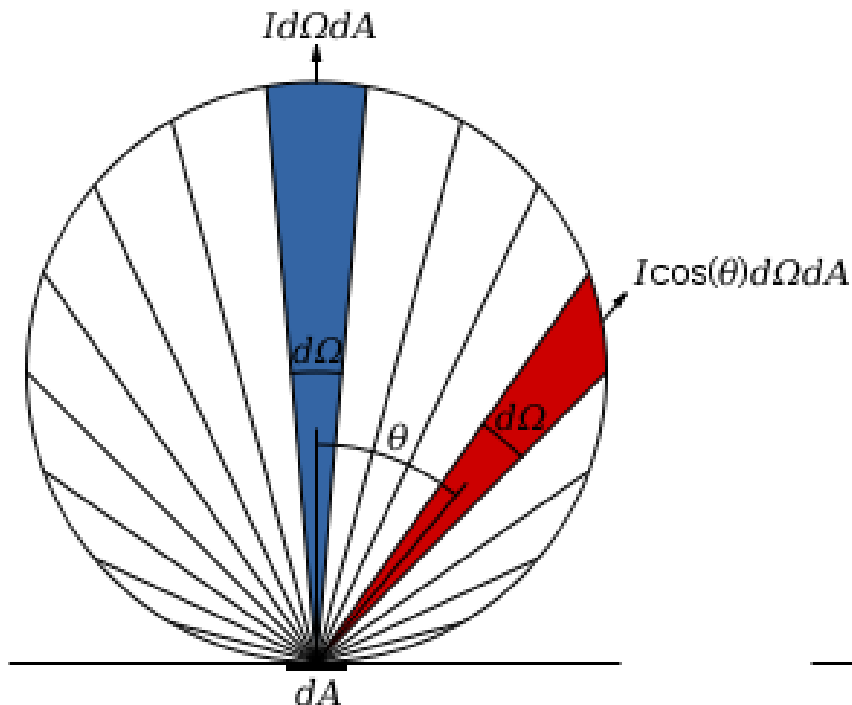




# Diffuse reflection

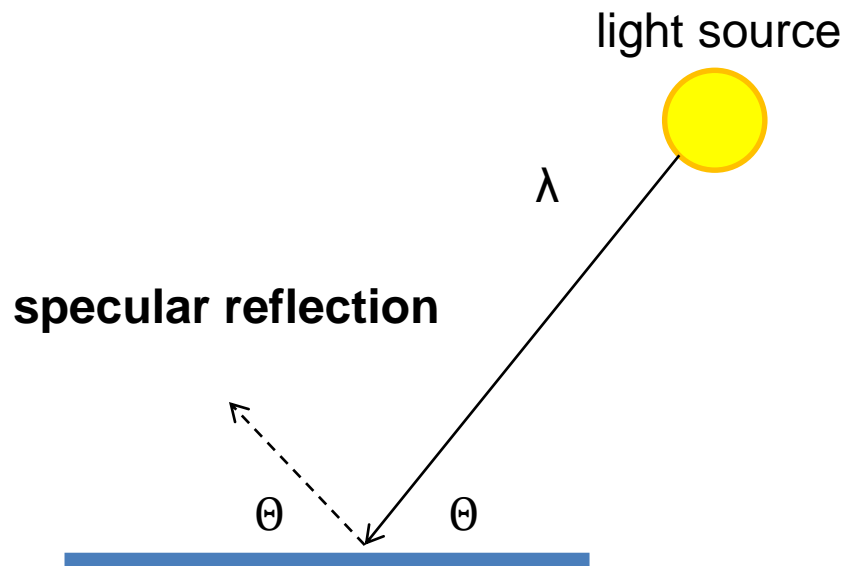
Perceived intensity does *not* depend on viewer angle.

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



# Specular Reflection

- Reflected direction depends on light orientation and surface normal
- E.g., mirrors are fully specular



Flickr, by suzysputnik



Flickr, by piratejohnny

# Many surfaces have both specular and diffuse components

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



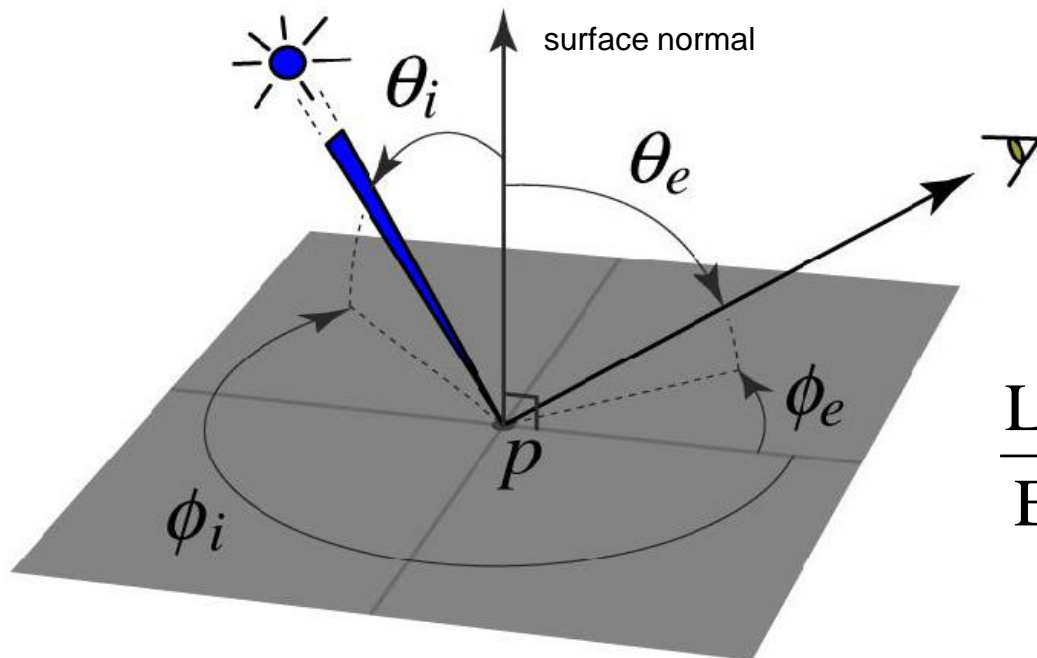
Photo: [northcountryhardwoodfloors.com](http://northcountryhardwoodfloors.com)





# 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



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

$$\frac{L_e(\theta_e, \phi_e)}{E_i(\theta_i, \phi_i)} = \frac{L_e(\theta_e, \phi_e)}{L_i(\theta_i, \phi_i) \cos \theta_i d\omega}$$

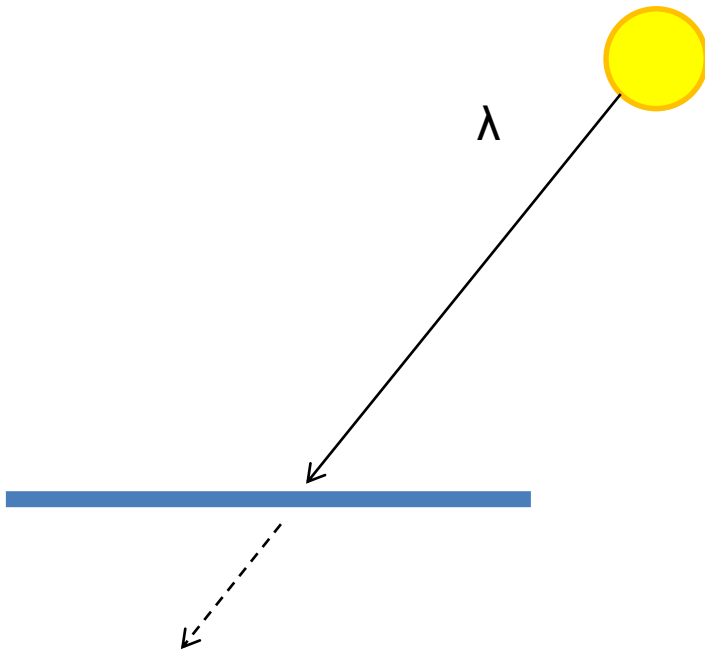
# More complicated effects



**transparency**

light source

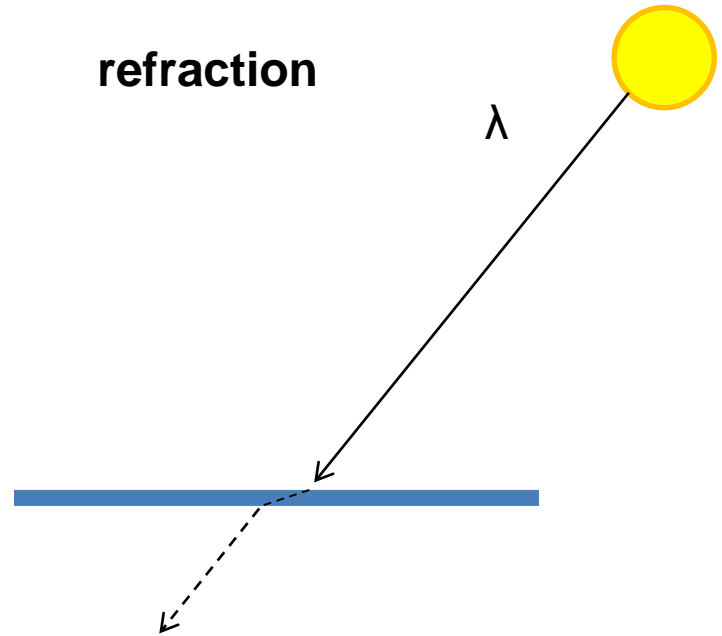
$\lambda$



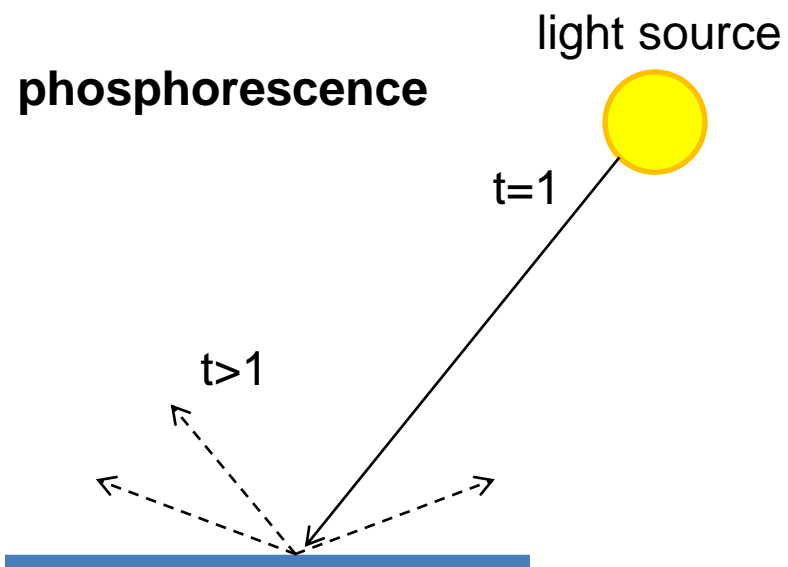
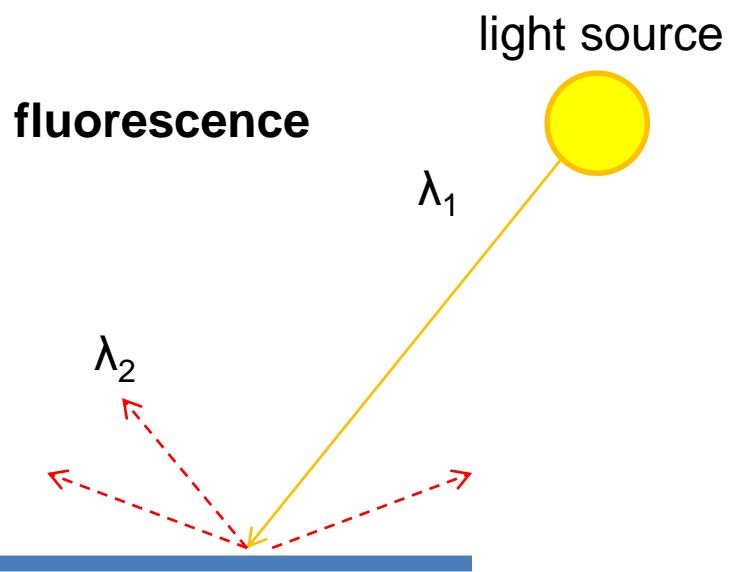
**refraction**

light source

$\lambda$



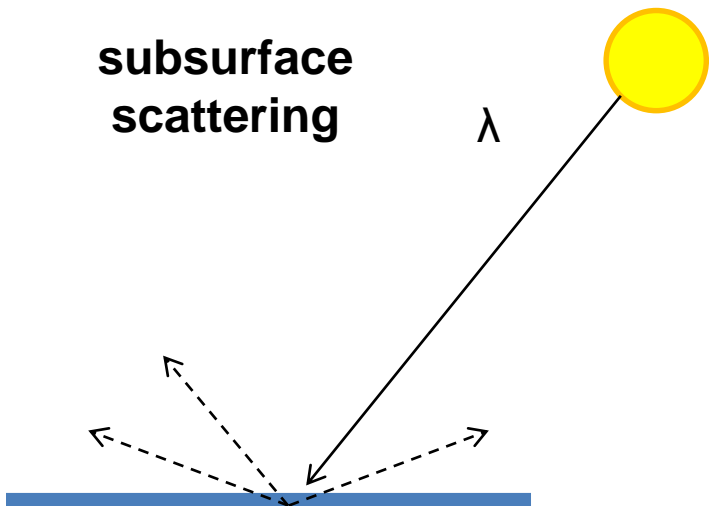




**subsurface  
scattering**

light source

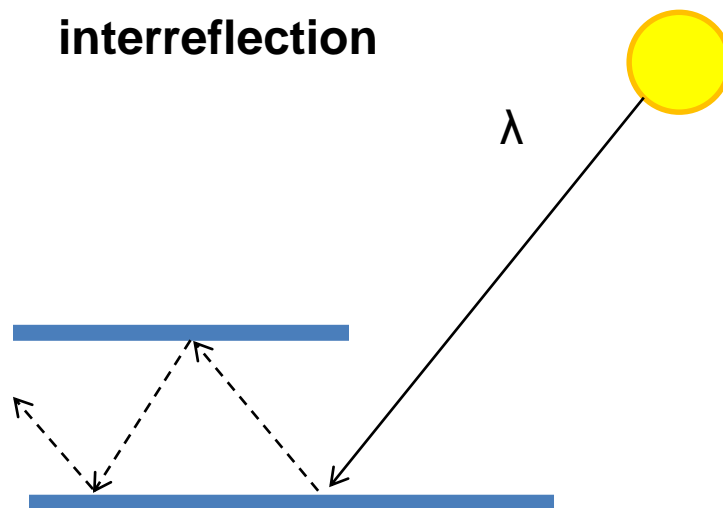
$\lambda$



**interreflection**

light source

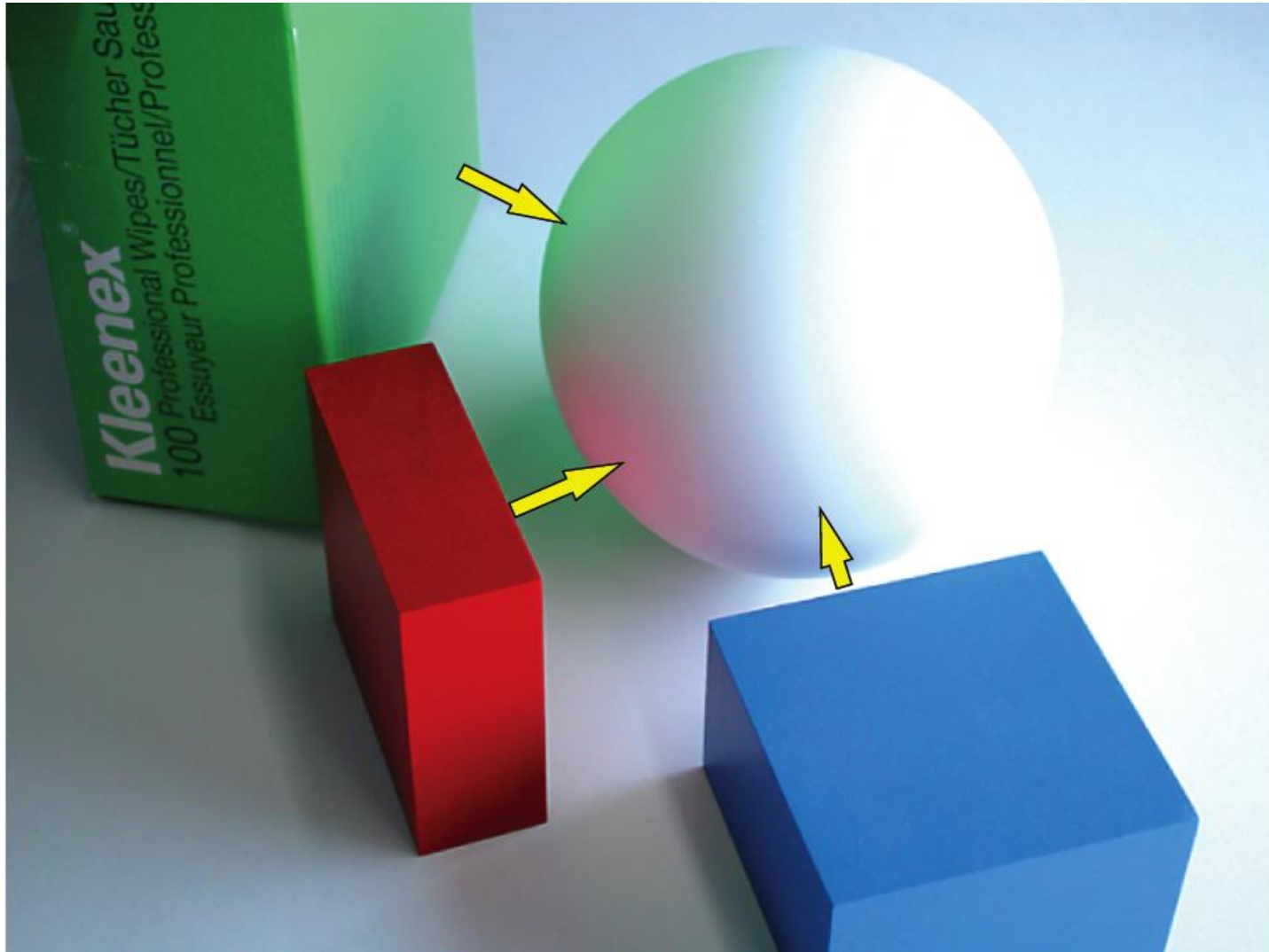
$\lambda$



Inter-reflection is a major source of light



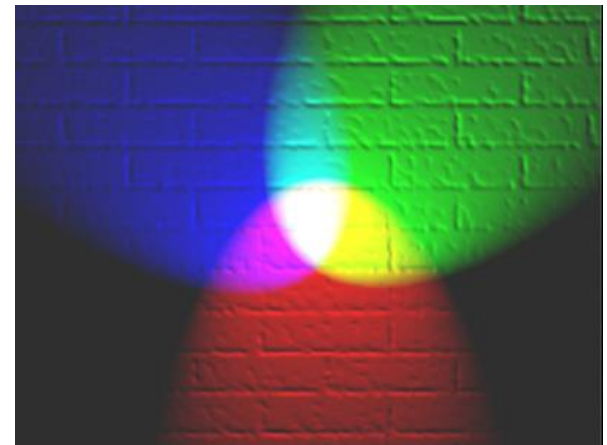
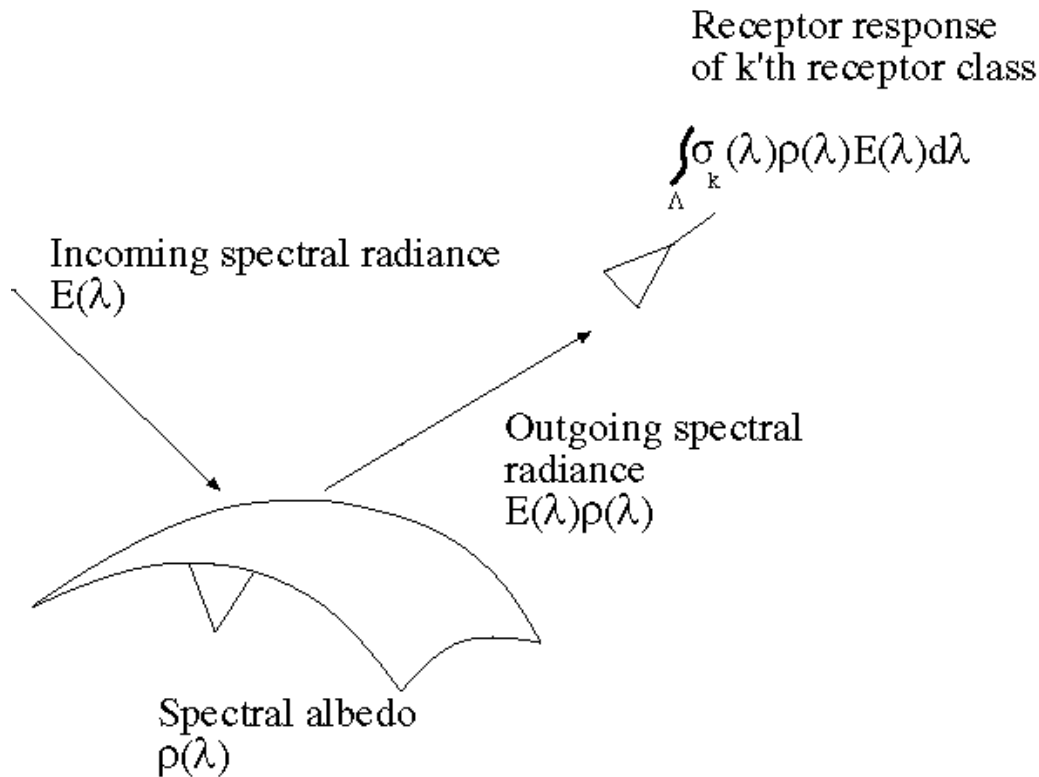
# Inter-reflection affects the apparent color of objects



From Koenderink slides on image texture and the flow of light

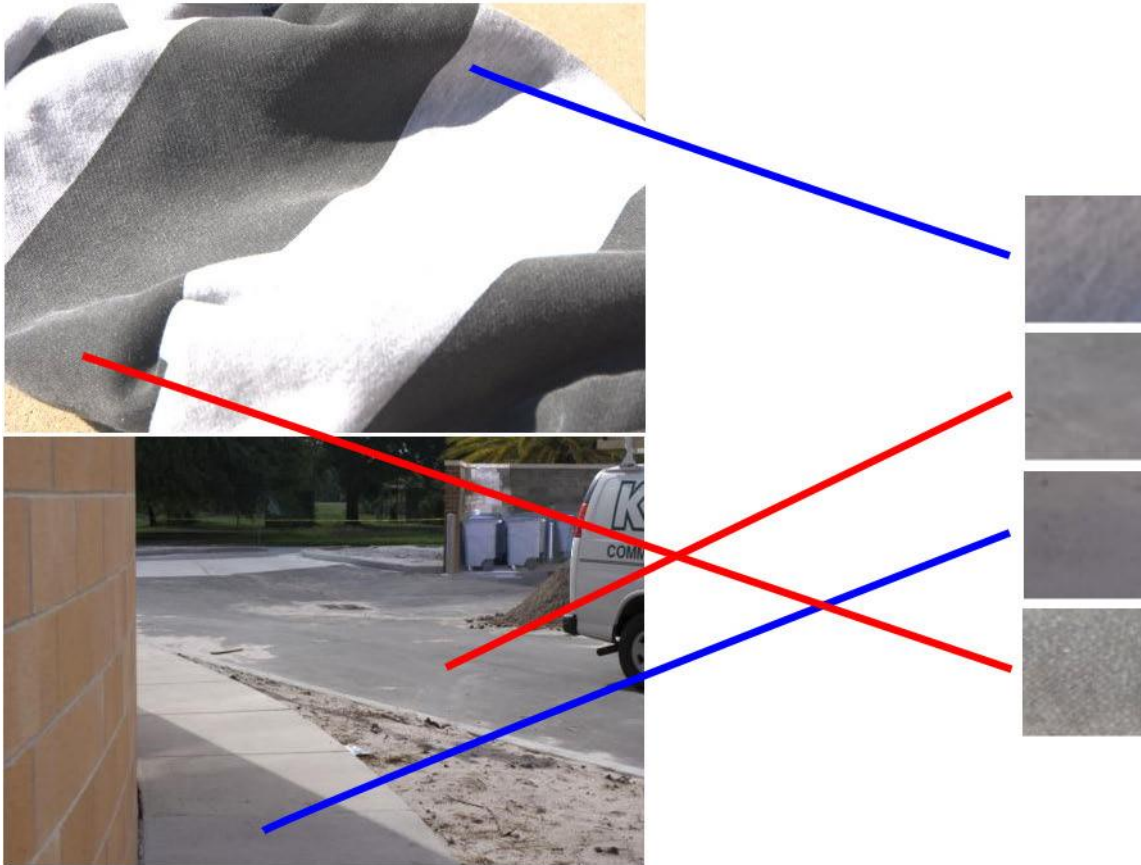
# The color of objects

- Colored light arriving at the camera involves two effects
  - The color of the light source (illumination + inter-reflections)
  - The color of the surface



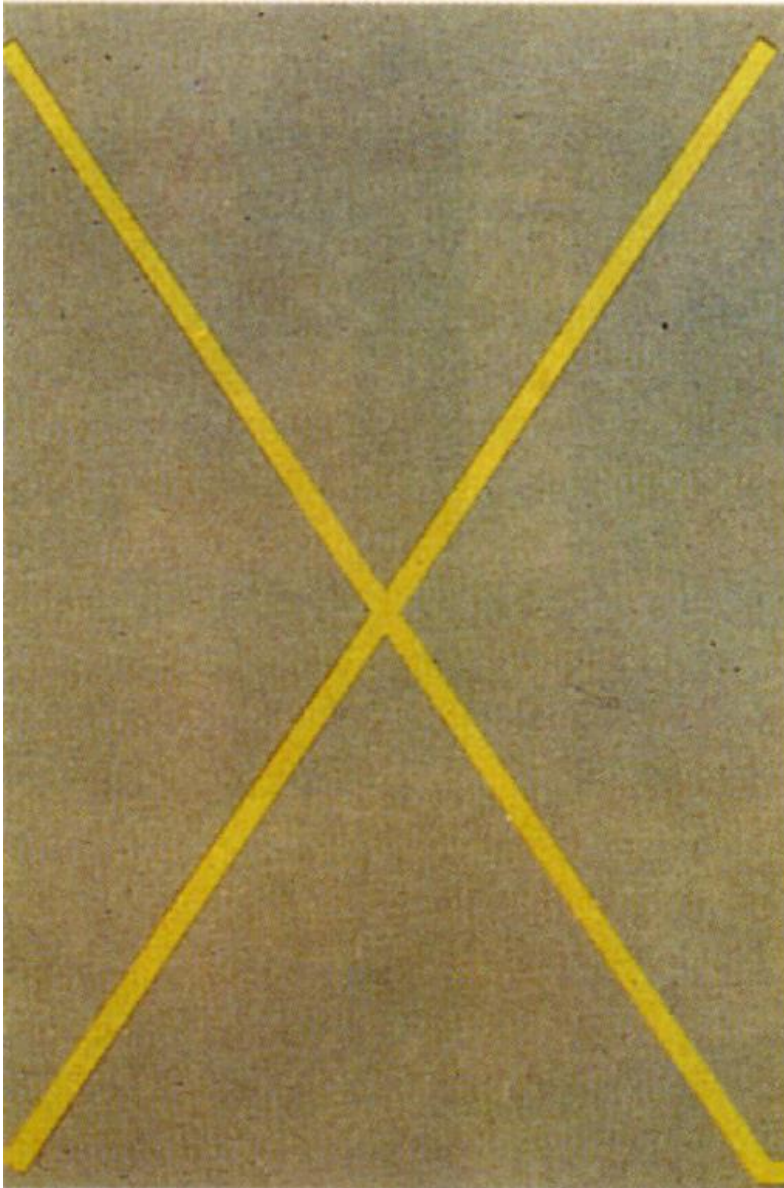
# Color constancy

- Interpret surface in terms of albedo or “true color”, rather than observed intensity
  - Humans are good at it
  - Computers are not nearly as good





# Color illusions

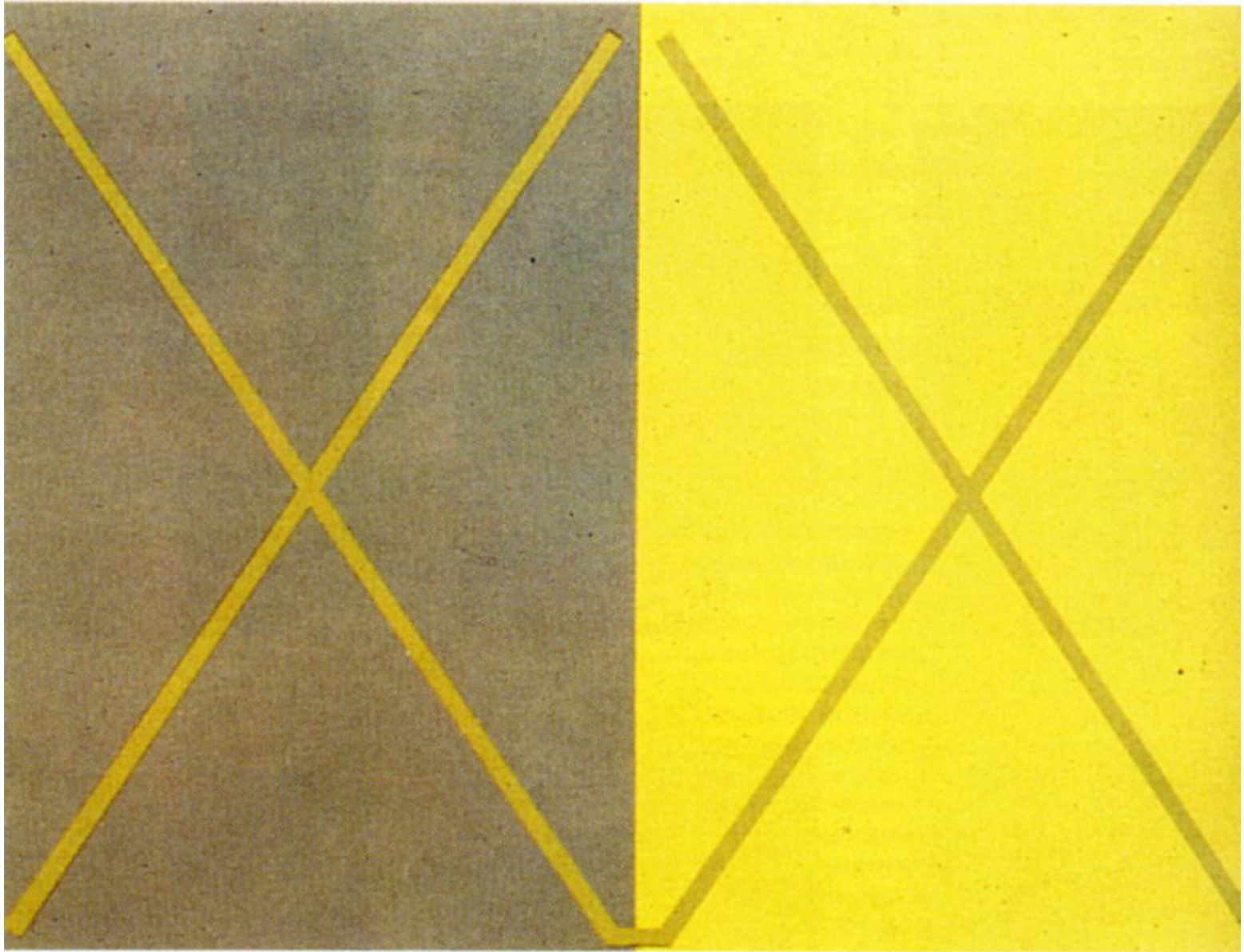


# Color illusions





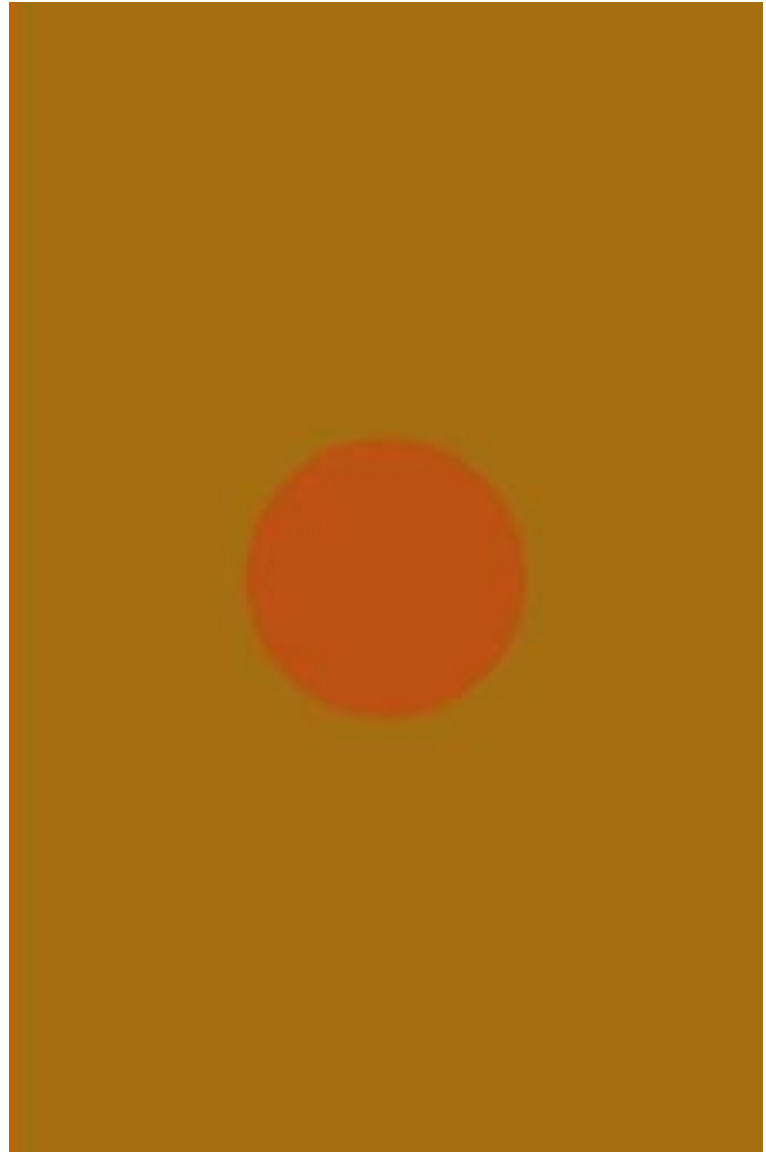
# Color illusions



# Color illusions



# Color illusions

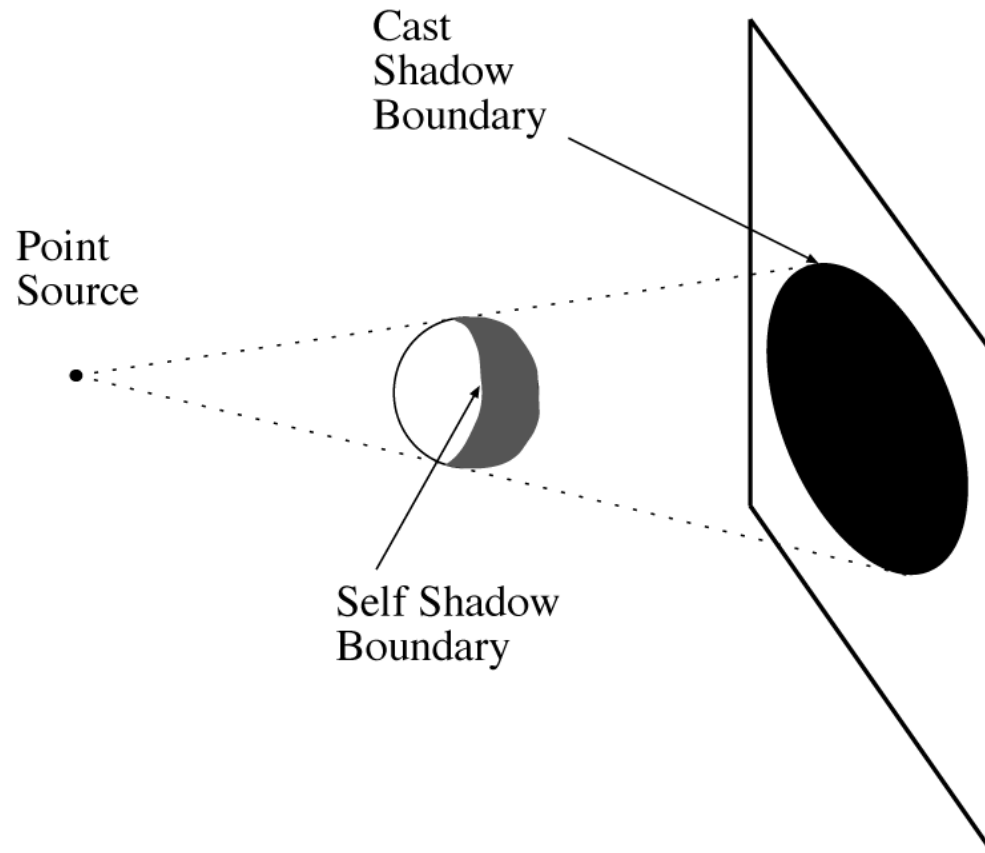


# Color illusions



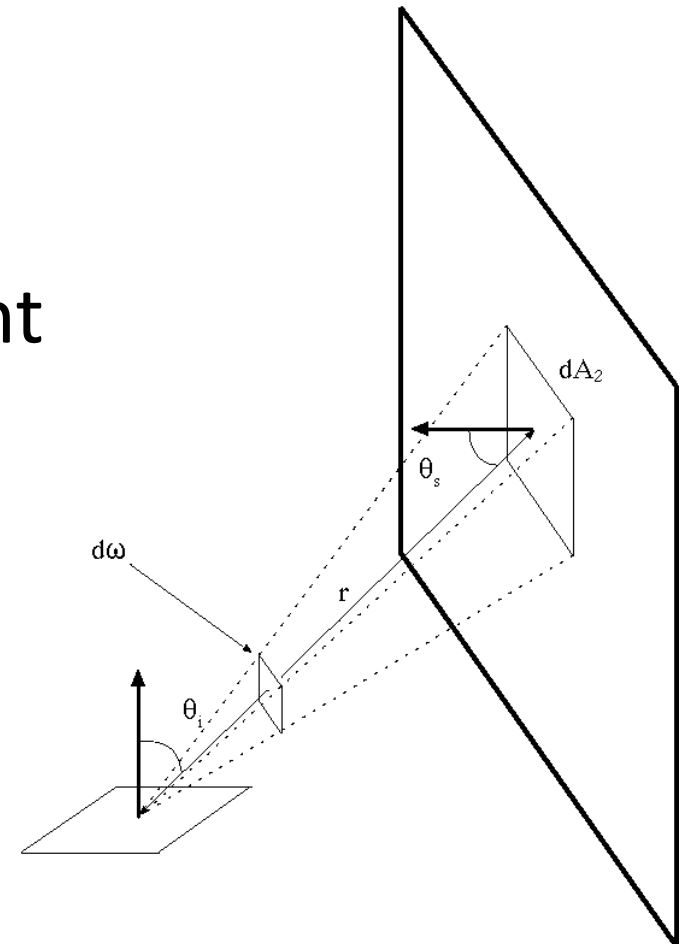
# Shadows cast by a point source

- A point that can't see the source is in shadow
- For point sources, the geometry is simple

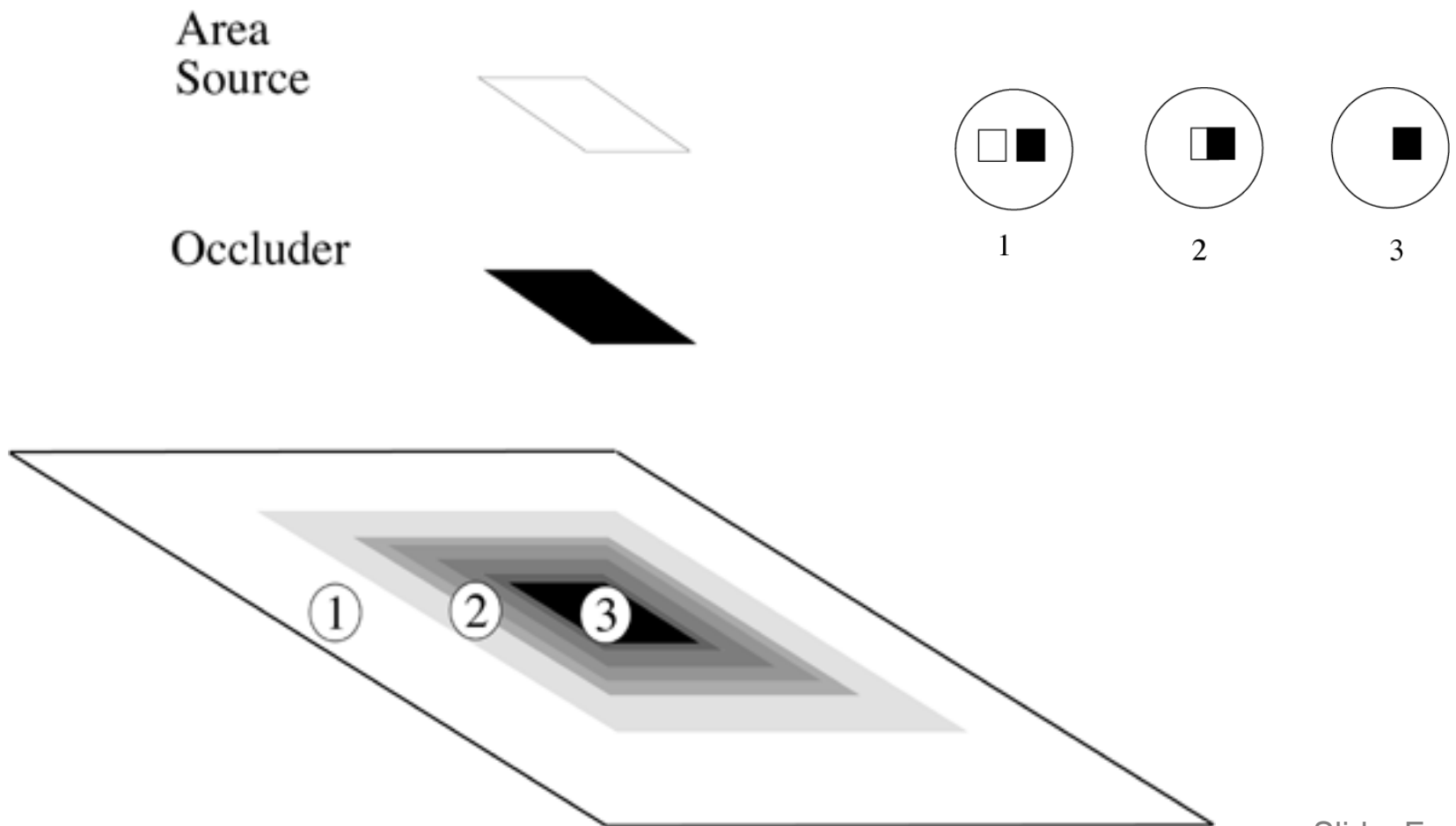


# Area sources

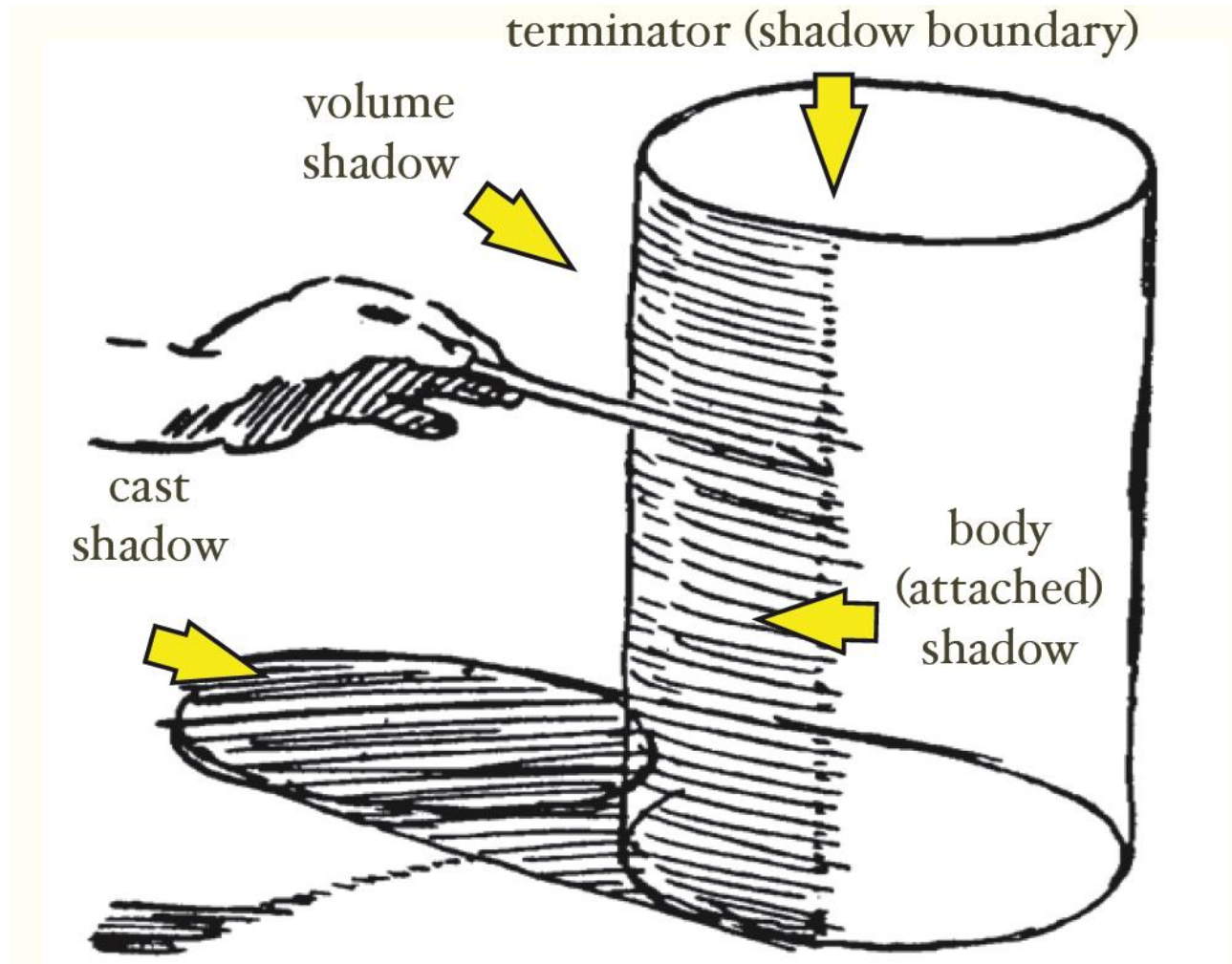
- Examples: diffuser boxes, white walls
- The energy received at a point due to an area source is obtained by adding up the contribution of small elements over the whole source



# Area Source Shadows



# Shading and shadows are major cues to shape and position



From Koenderink slides on image texture and the flow of light

Slide: Forsyth



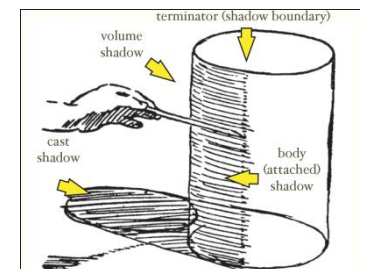
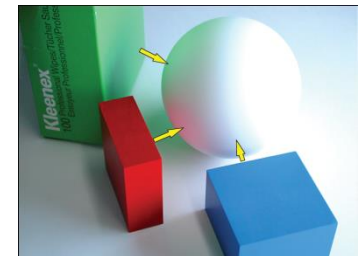
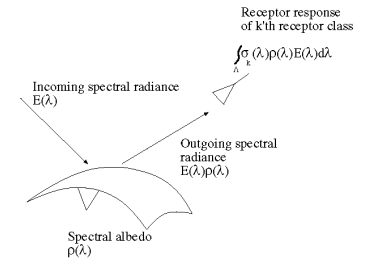
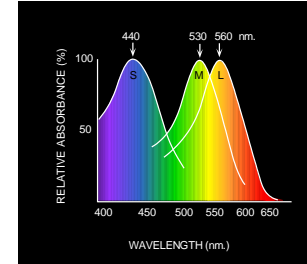
# Recap



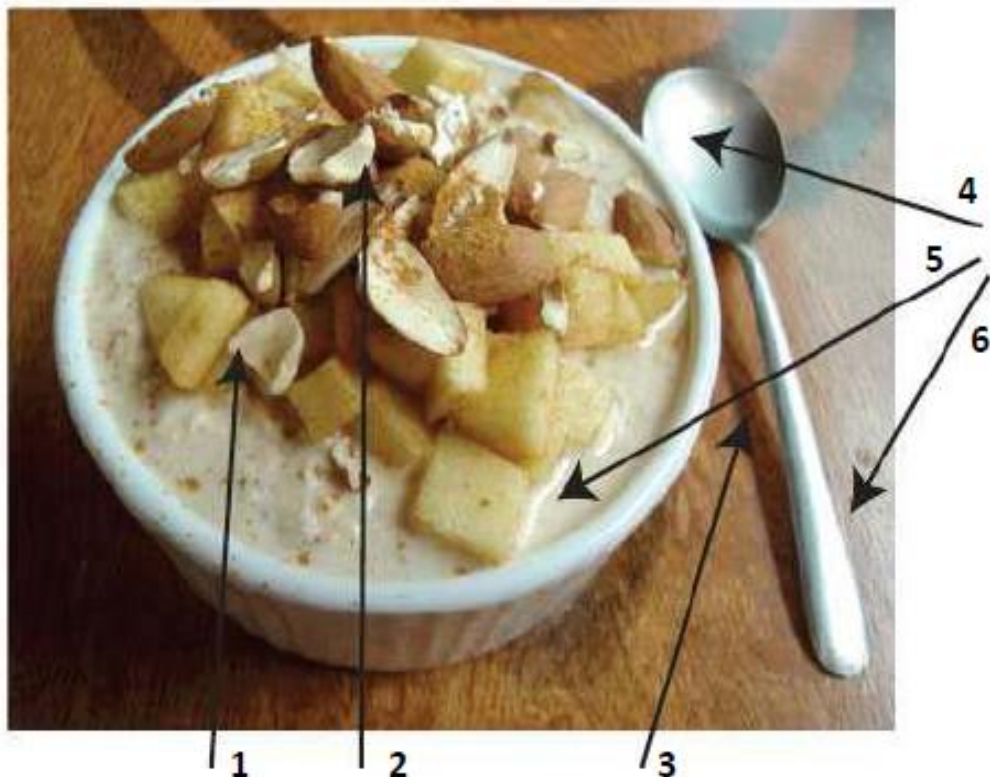
1. Why is (2) brighter than (1)? Each points to the asphalt.
2. Why is (4) darker than (3)? 4 points to the marking.
3. Why is (5) brighter than (3)? Each points to the side of the wooden block.
4. Why isn't (6) black, given that there is no direct path from it to the sun?

# Things to remember

- Light has a spectrum of wavelengths
  - Humans (and RGB cameras) have color sensors sensitive to three ranges
- Observed light depends on: illumination intensities, surface orientation, material (albedo, specular component, diffuse component), etc.
- Every object is an indirect light source for every other
- Shading and shadows are informative about shape and position



# Take-home questions



- A. For each of the arrows in the above image, name the reasons the pixel near the end of the arrow has its brightness value and explain very briefly. The arrow pointing to milk is pointing to the thin bright line at the edge of the piece of apple; the arrow pointing to the spoon handle is pointing to the bright area on the handle.

Possible factors: albedo, shadows, texture, specularities, curvature, lighting direction