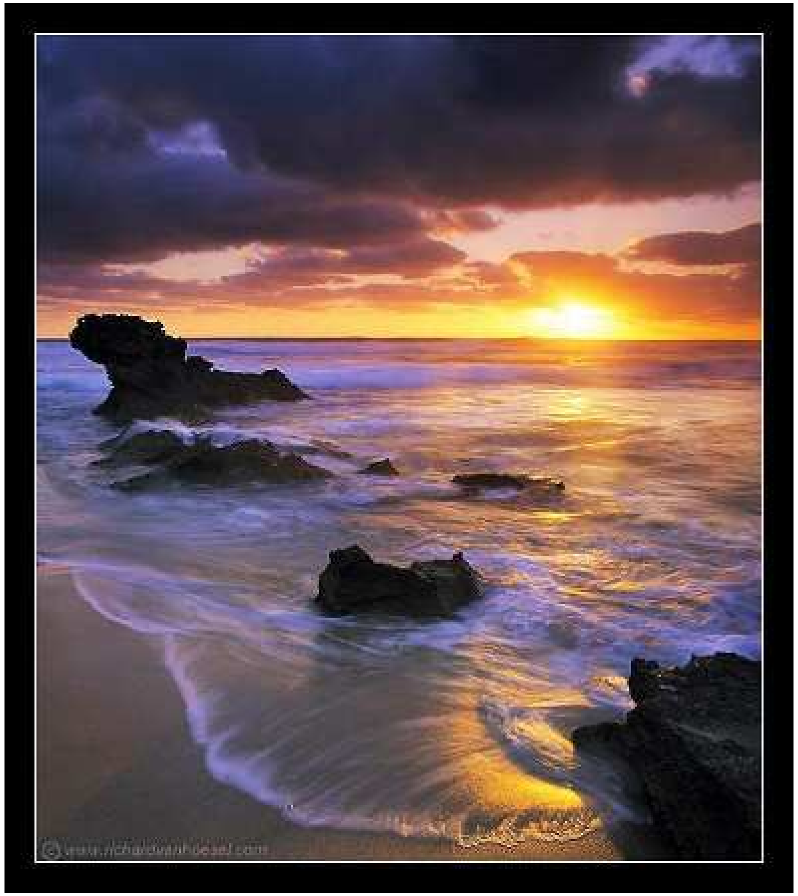
Capturing Light… in man and machine

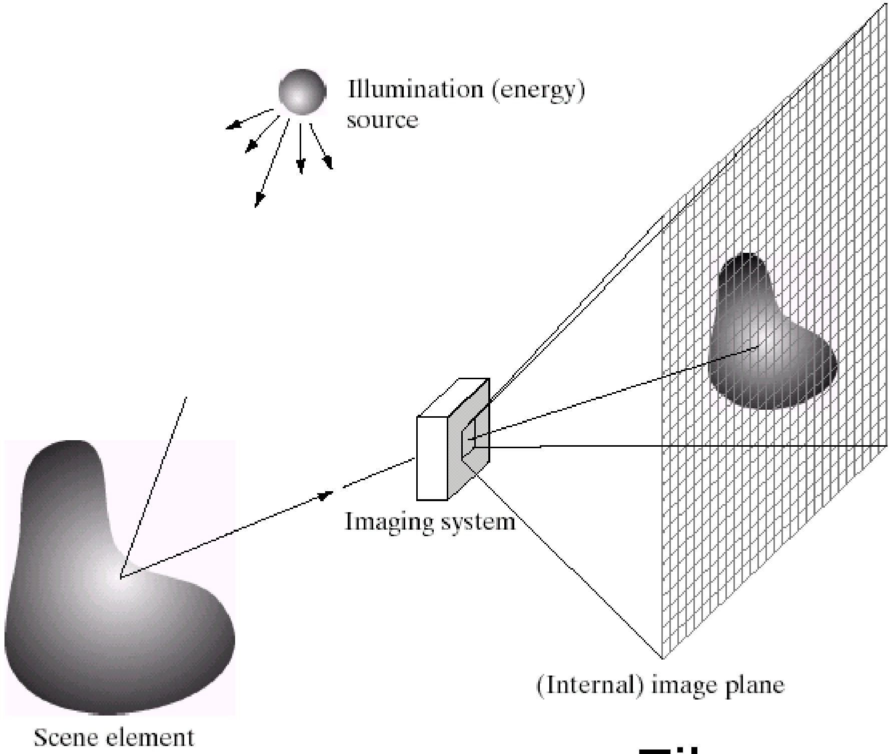


15-463: Computational Photography
Alexei Efros, CMU, Fall 2011

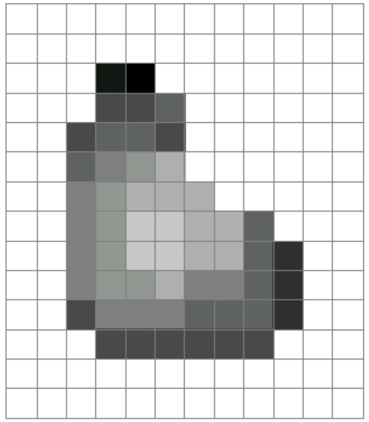
Etymology

$$\underbrace{\text{PHOTO}}_{\text{light}}\underbrace{\text{GRAPHY}}_{\text{drawing / writing}}$$

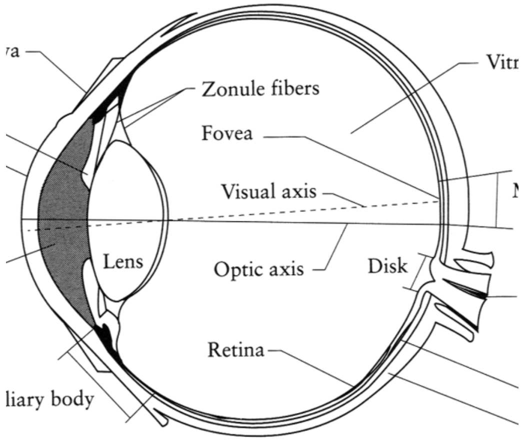
Image Formation



Film



Digital Camera



The Eye

Sensor Array

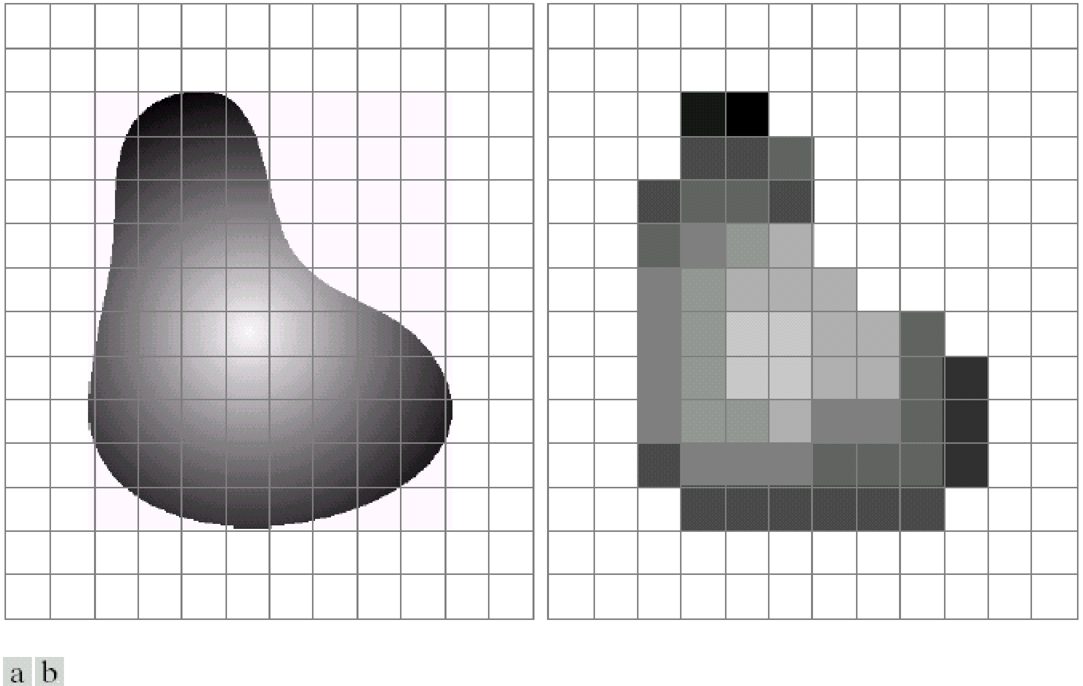
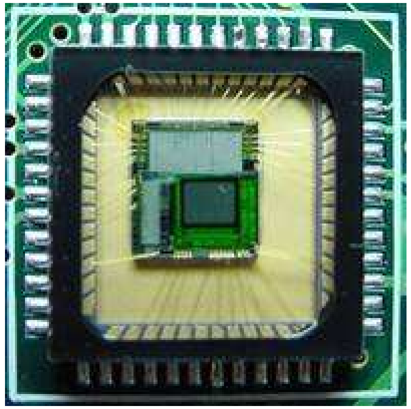
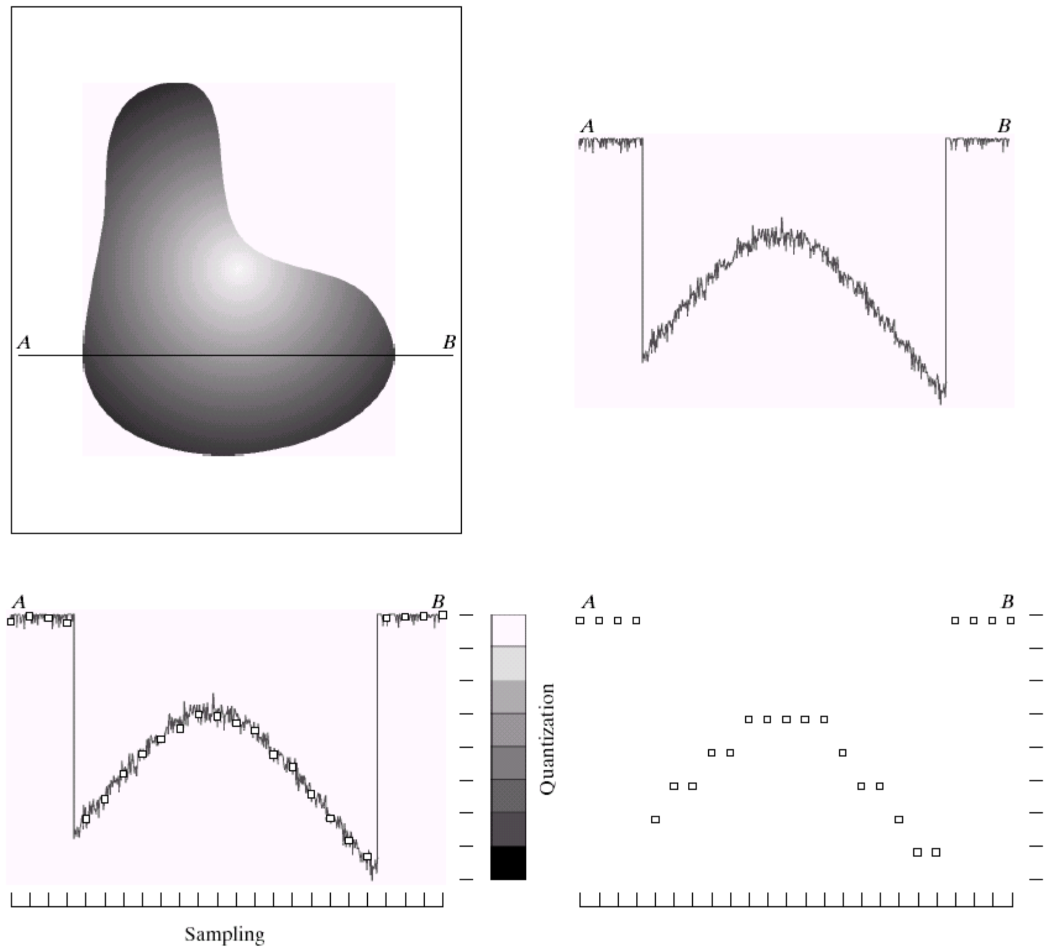


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

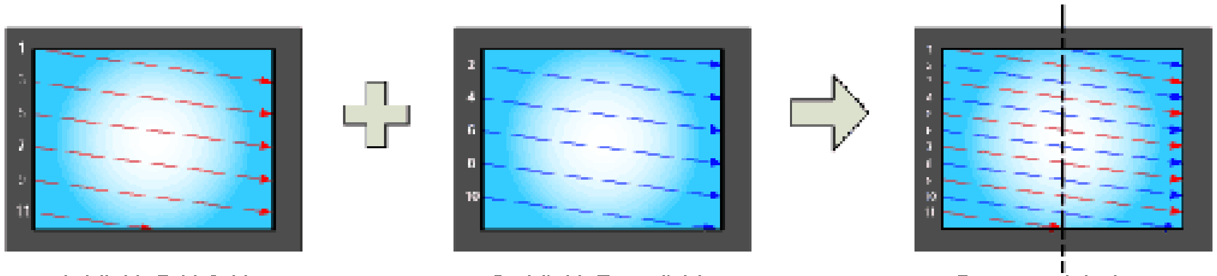
Sampling and Quantization



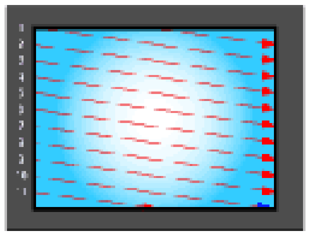
a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Interlace vs. progressive scan



1st field: Odd field
2nd field: Even field
One complete frame
using interlaced scanning



One complete frame
using progressive scanning

http://www.axis.com/products/video/camera/progressive_scan.htm

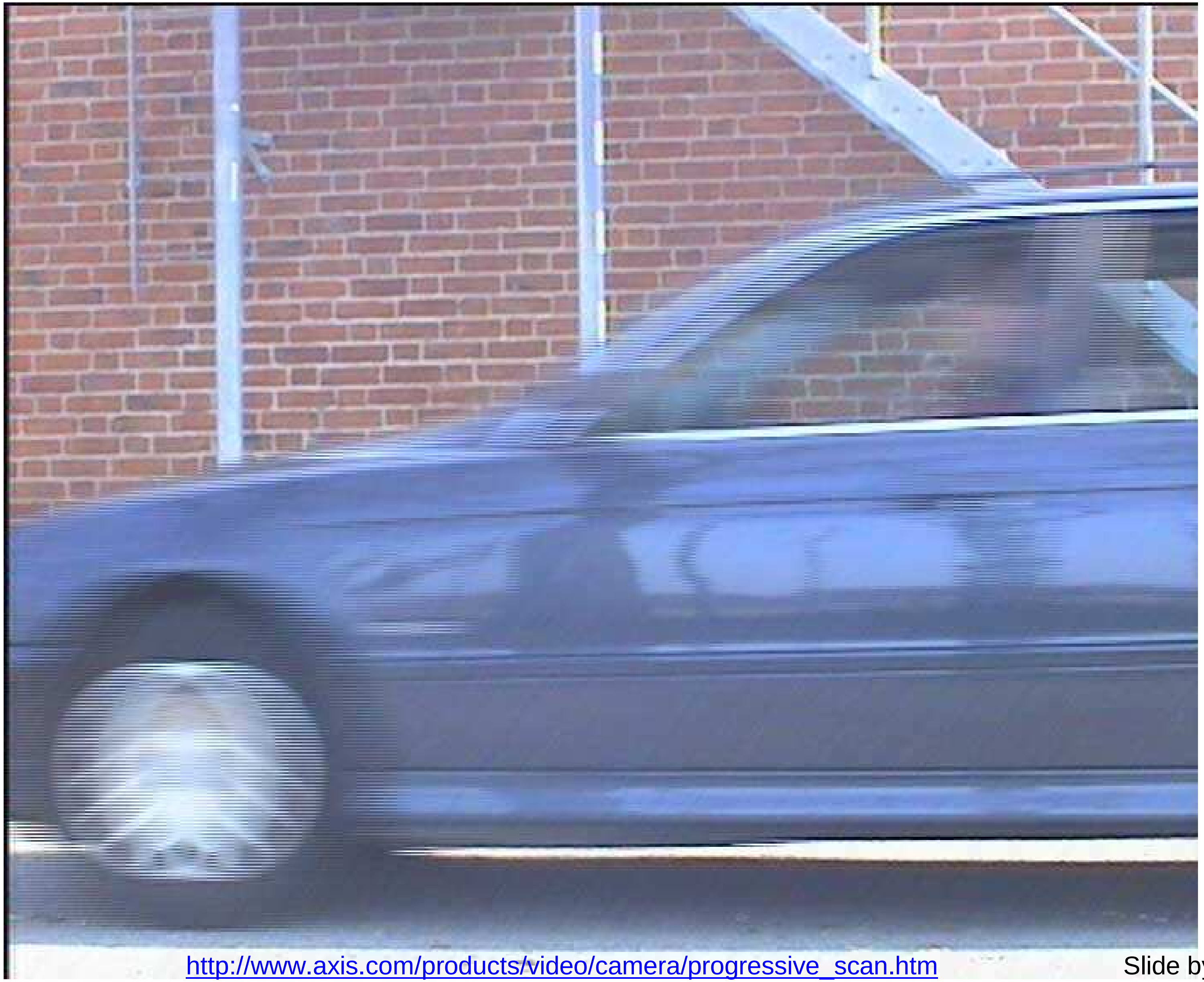
Slide by Steve Seitz

Progressive scan

http://www.axis.com/products/video/camera/progressive_scan.htm

Slide by Steve Seitz

Interlace



http://www.axis.com/products/video/camera/progressive_scan.htm

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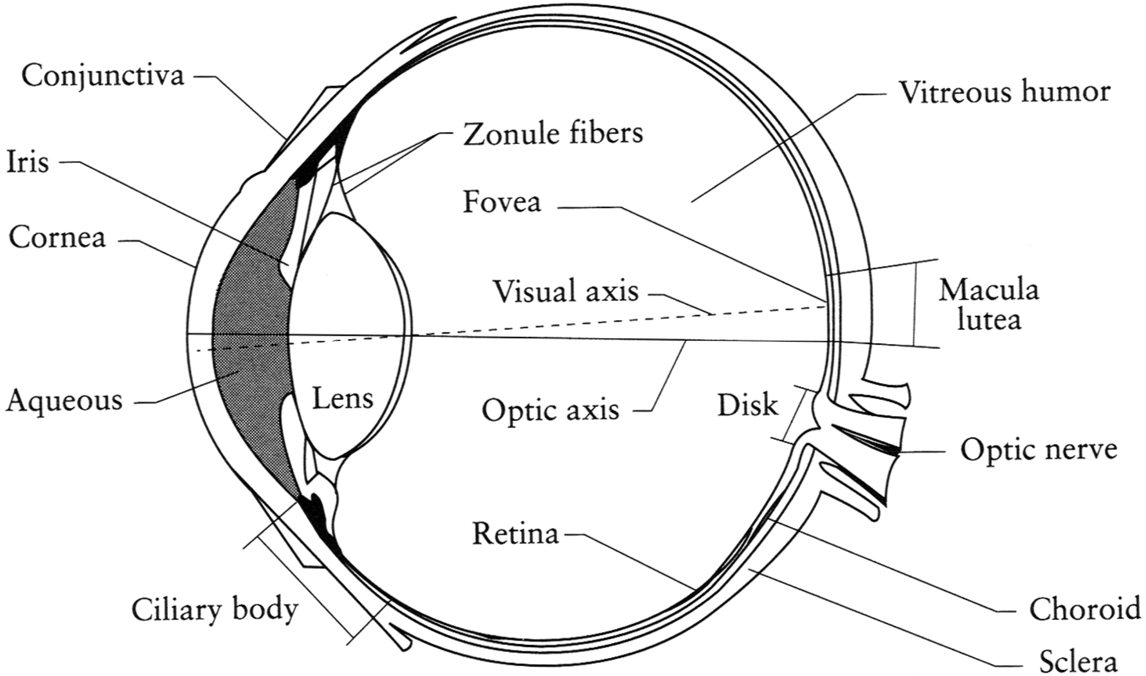
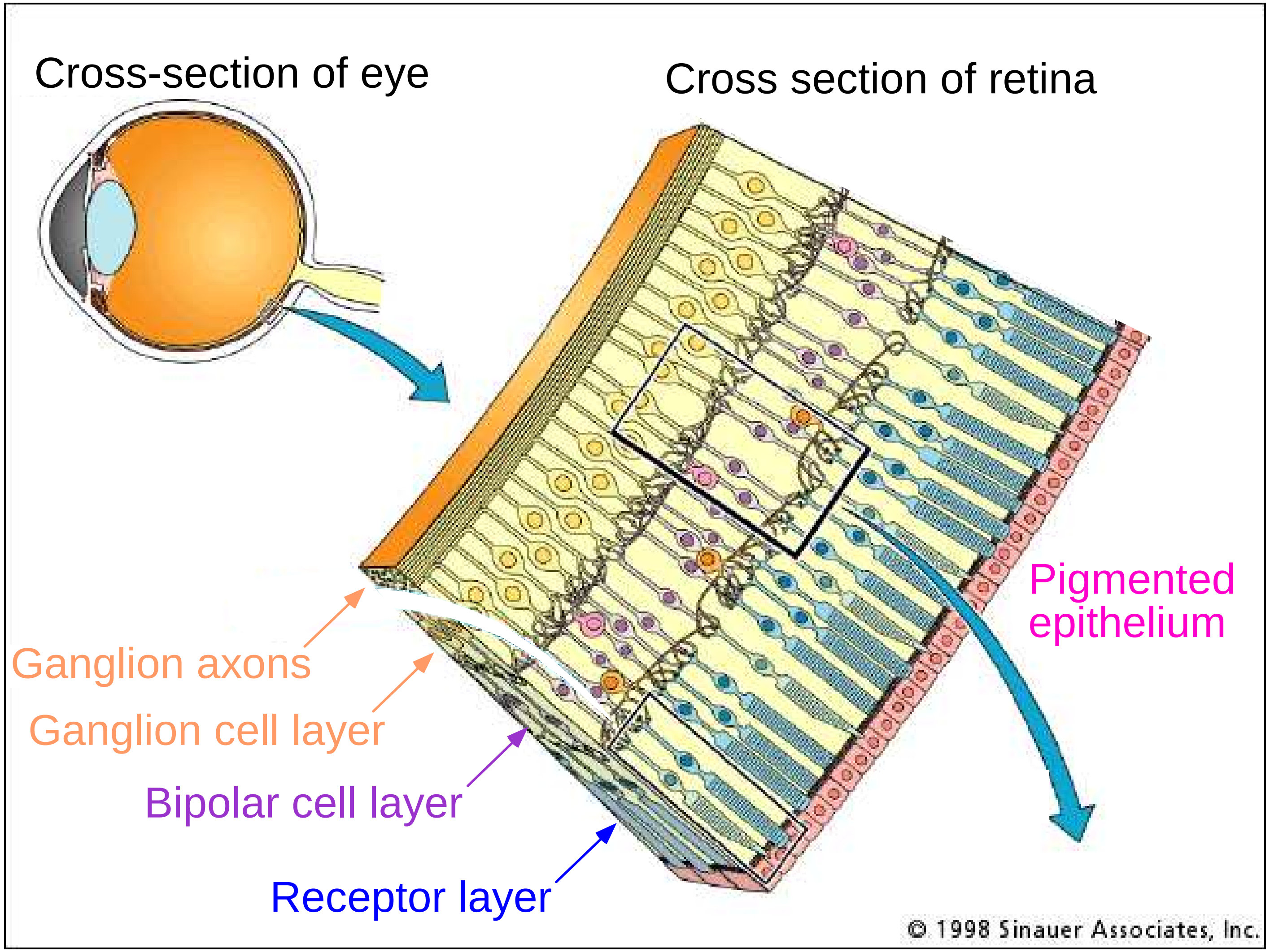
The Eye



The human eye is a camera!

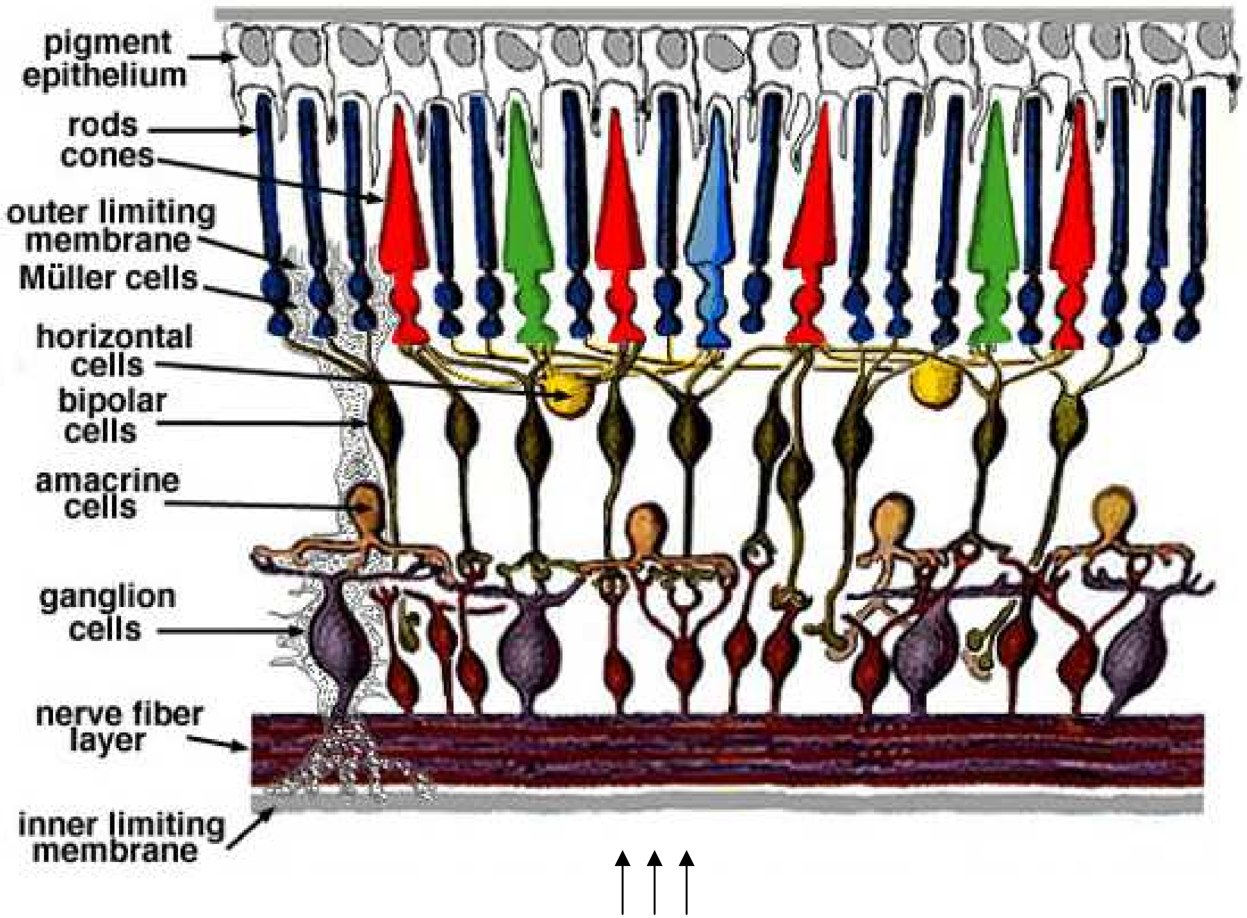
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What’s the “film”?
  - photoreceptor cells (rods and cones) in the **retina**

The Retina



Cross-section of eye
Cross section of retina
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
Pigmented epithelium
© 1998 Sinauer Associates, Inc.

Retina up-close



Light

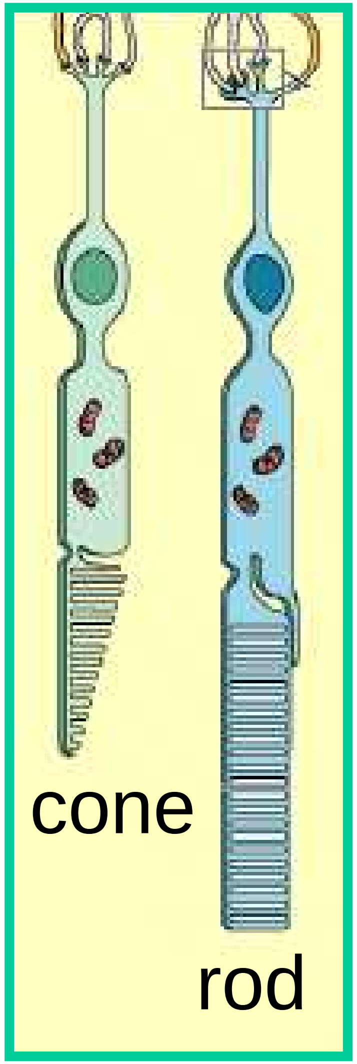
Two types of light-sensitive receptors

Cones

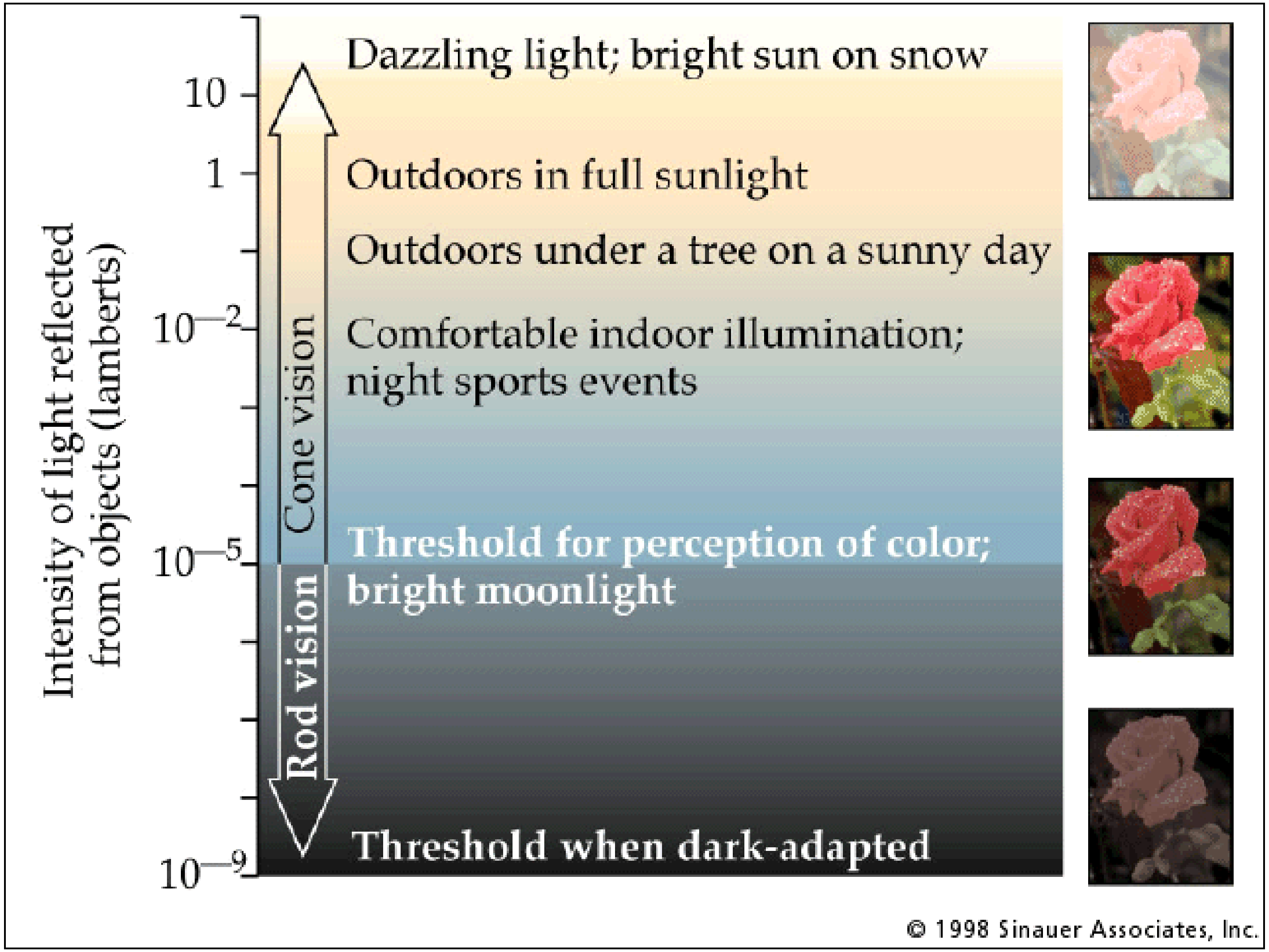
cone-shaped
less sensitive
operate in high light
color vision

Rods

rod-shaped
highly sensitive
operate at night
gray-scale vision

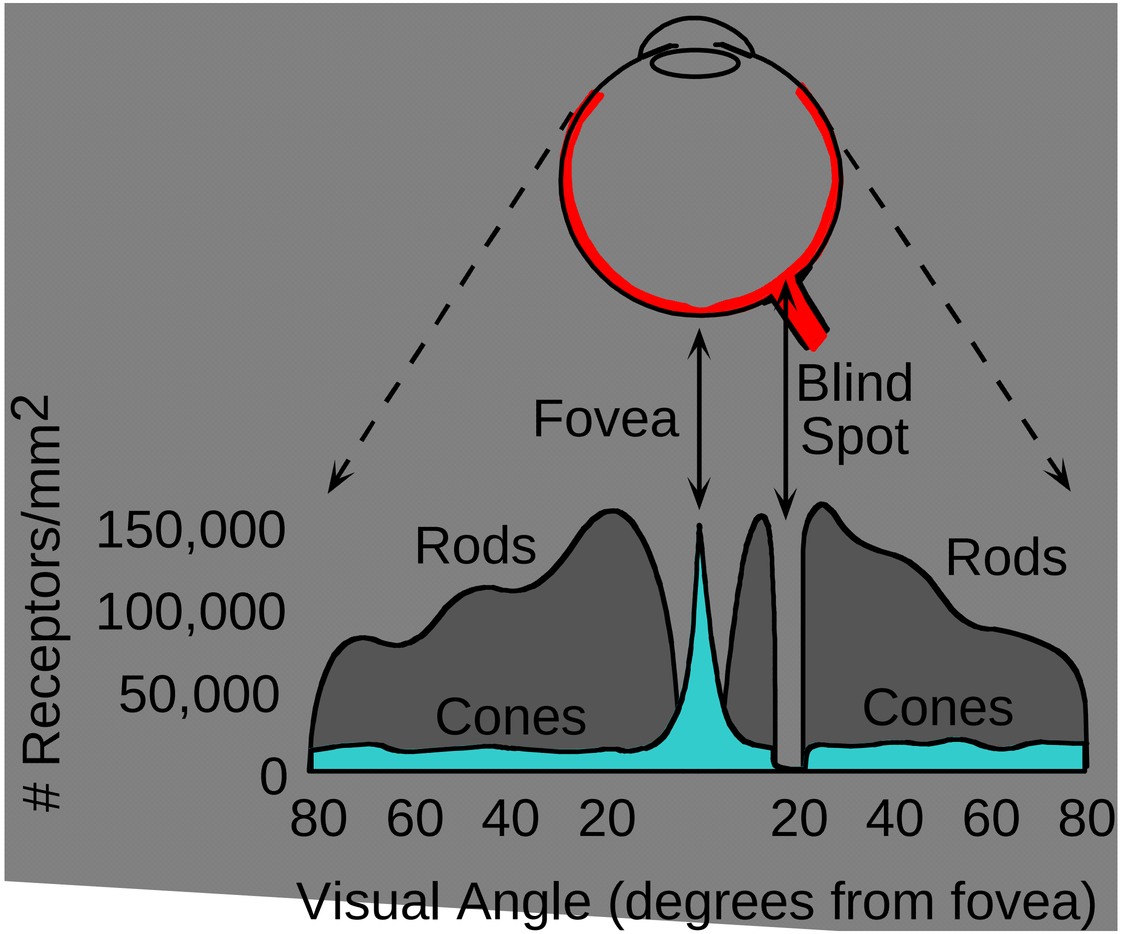


Rod / Cone sensitivity

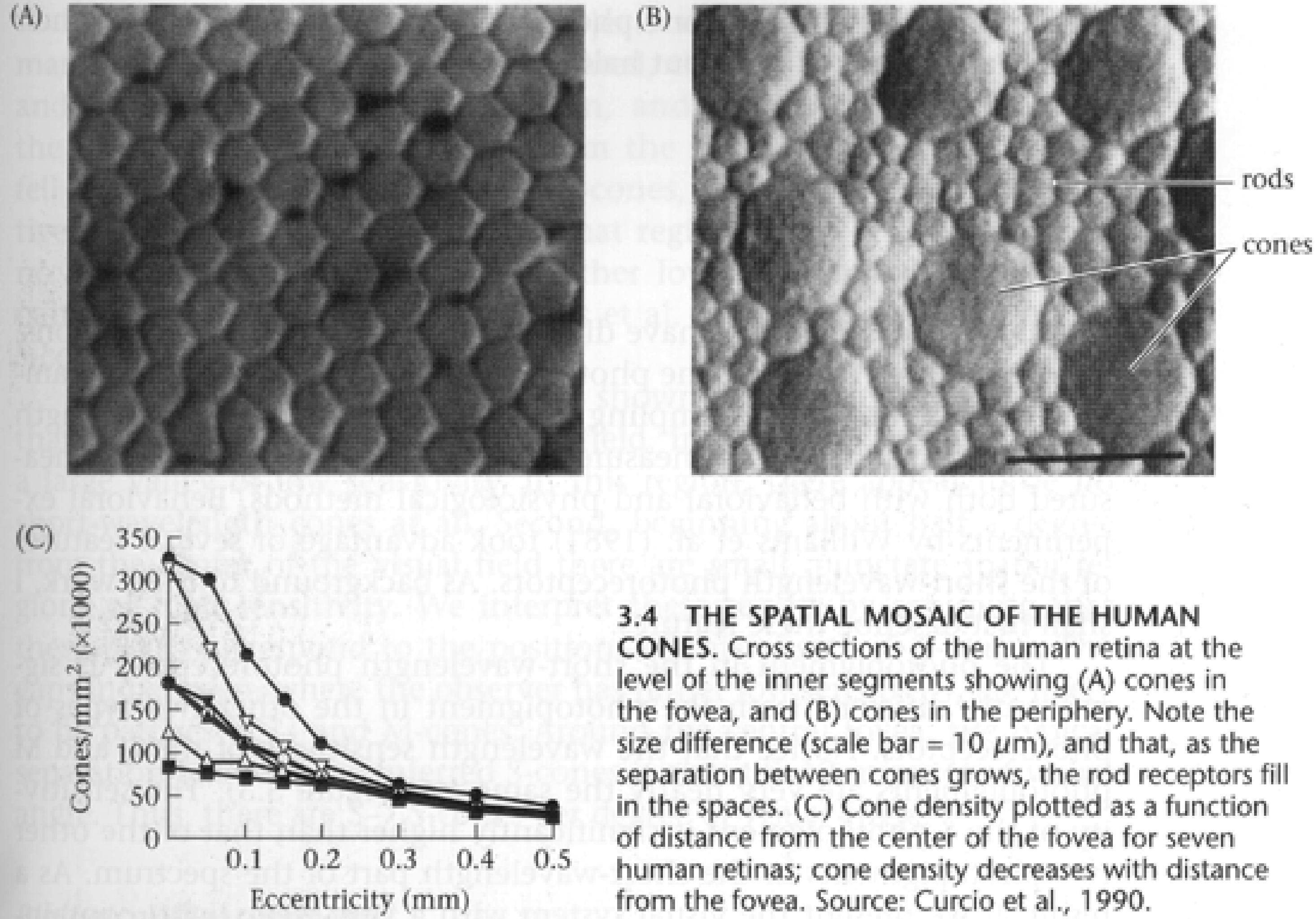


The famous sock-matching problem…

Distribution of Rods and Cones



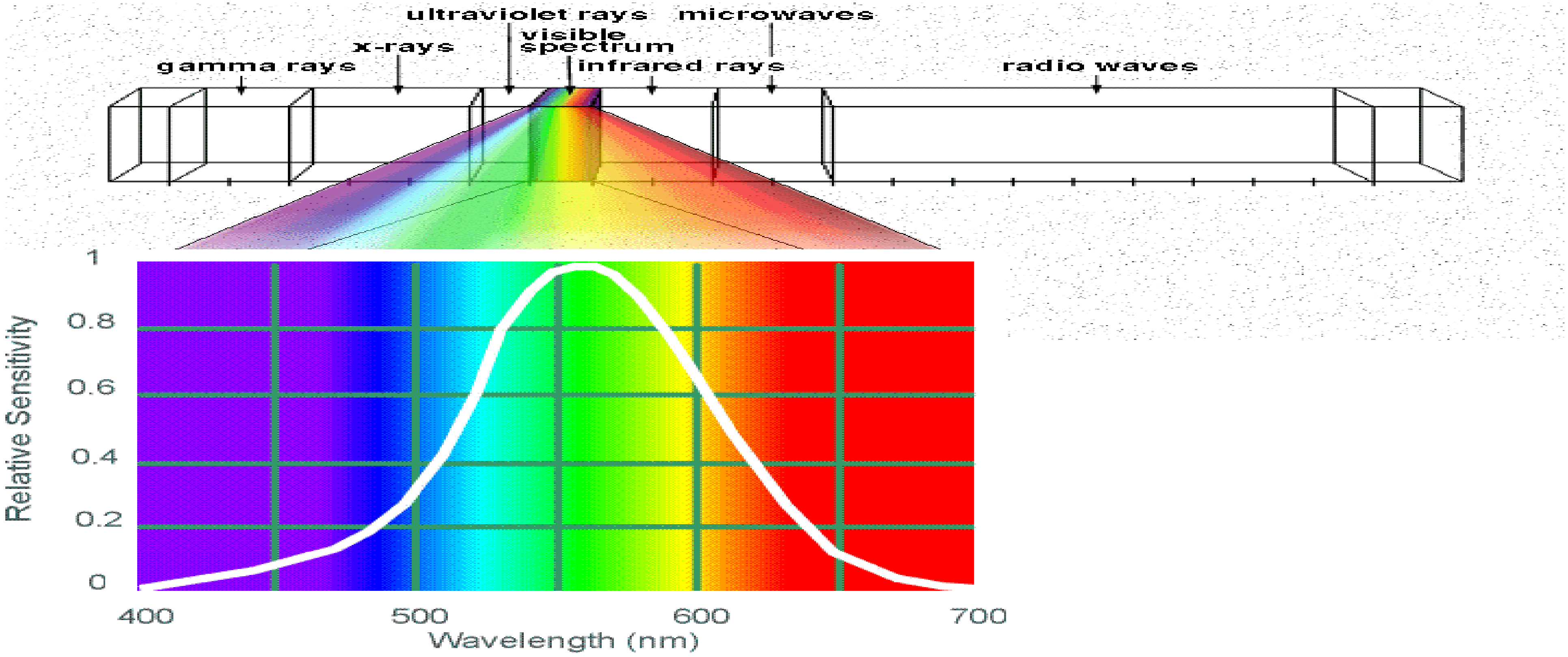
Night Sky: why are there more stars off-center?



3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

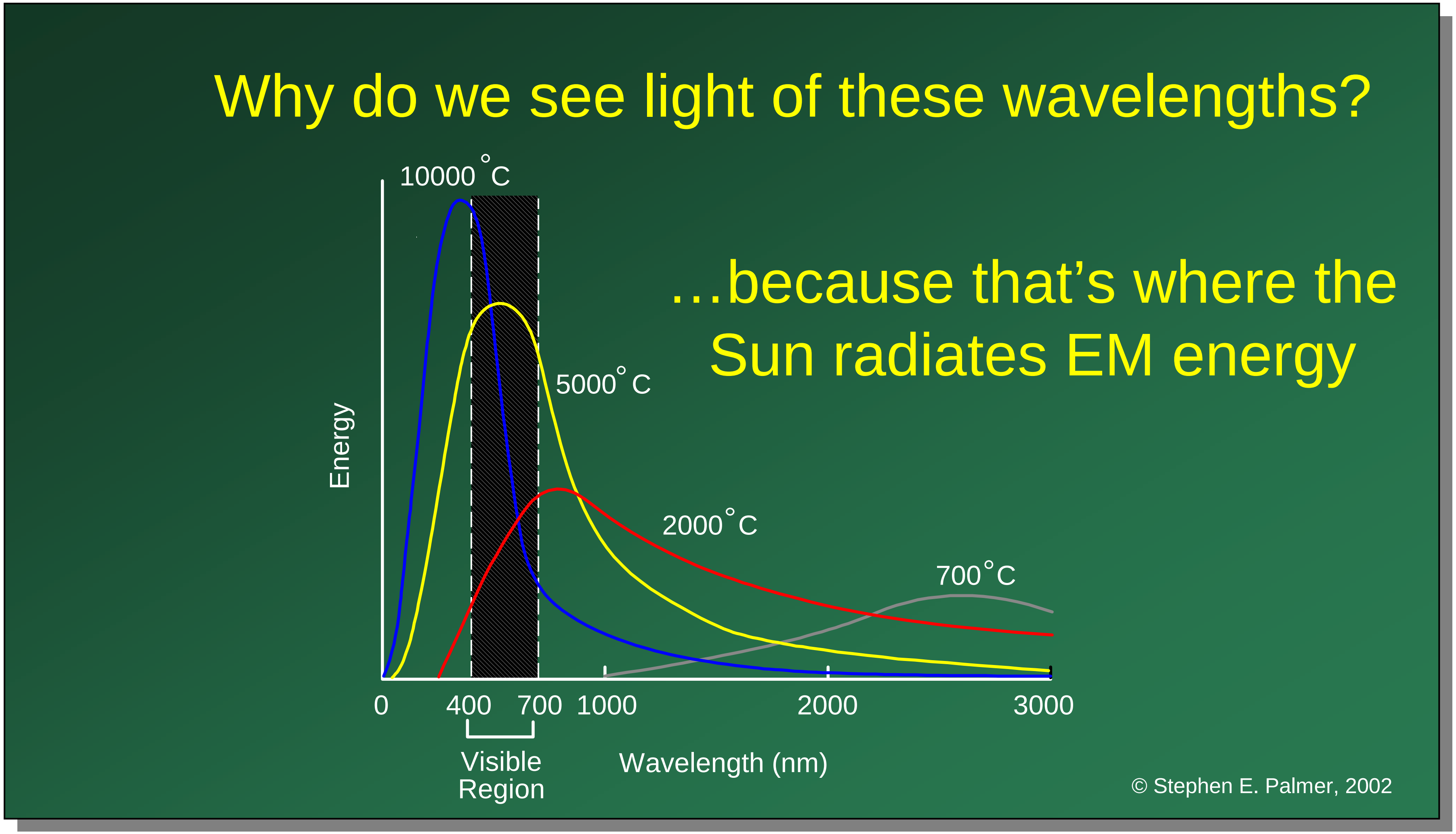
Electromagnetic Spectrum



Human Luminance Sensitivity Function

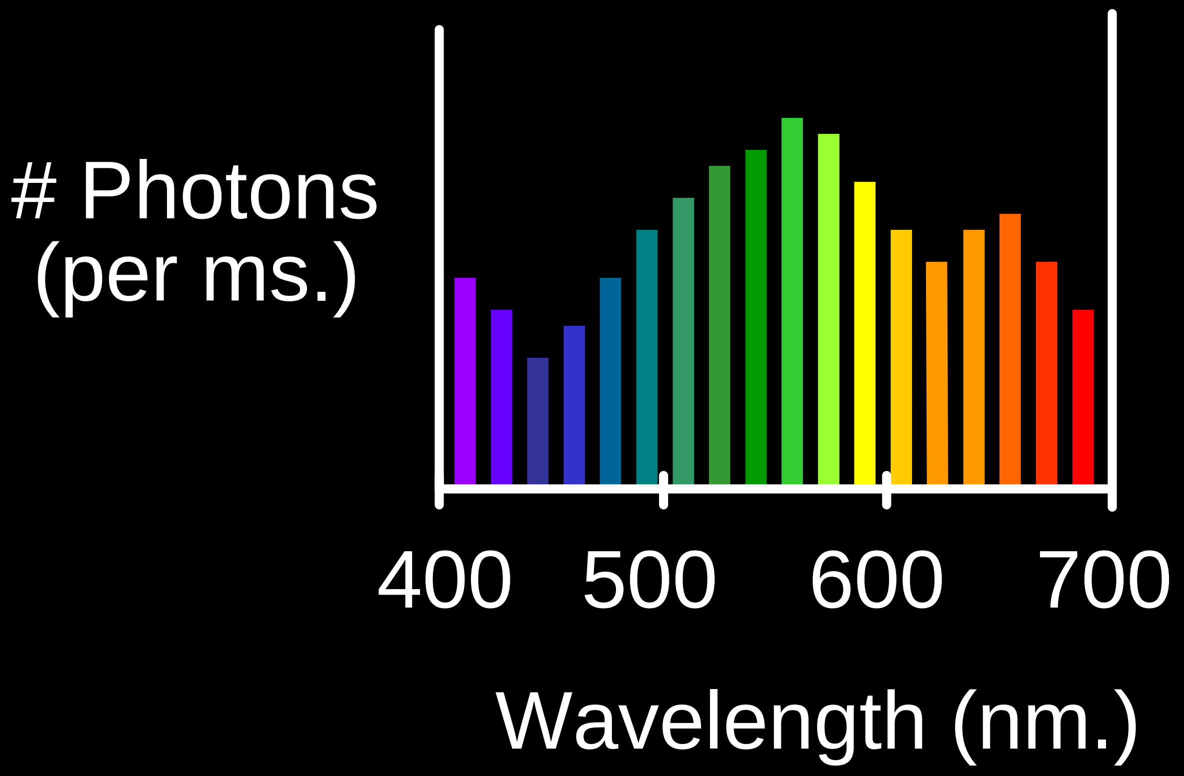
http://www.yorku.ca/eye/photopik.htm

Visible Light



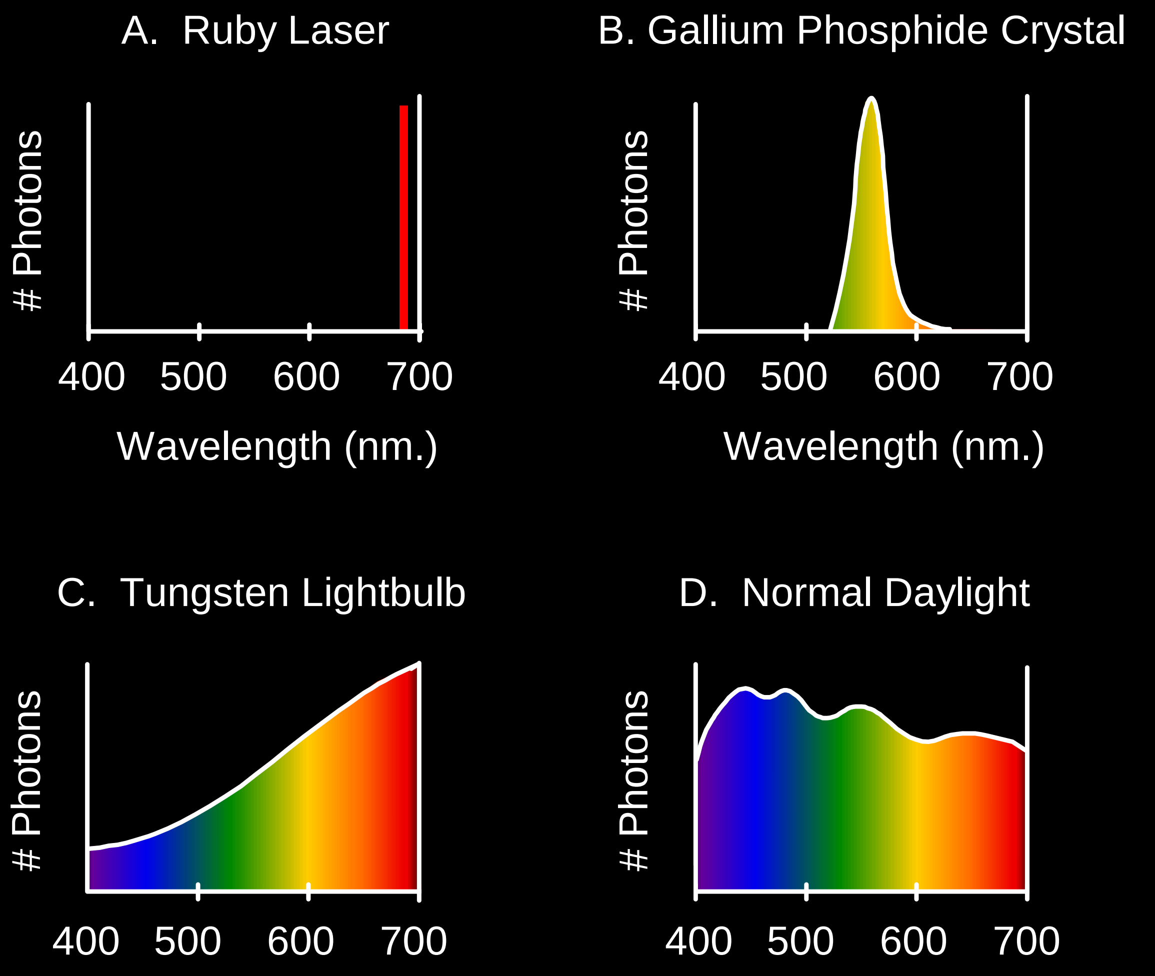
The Physics of Light

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.



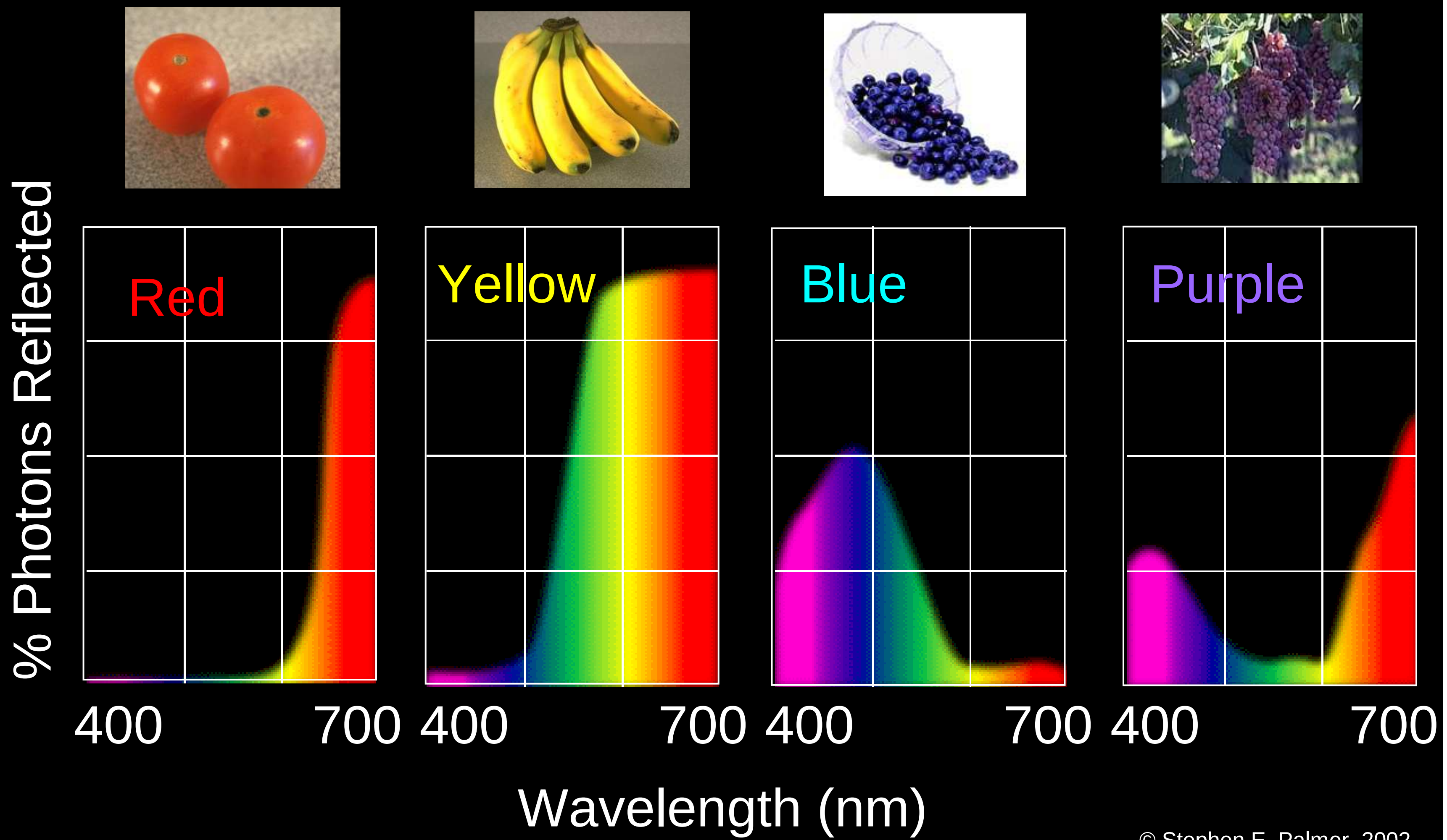
The Physics of Light

Some examples of the spectra of light sources



The Physics of Light

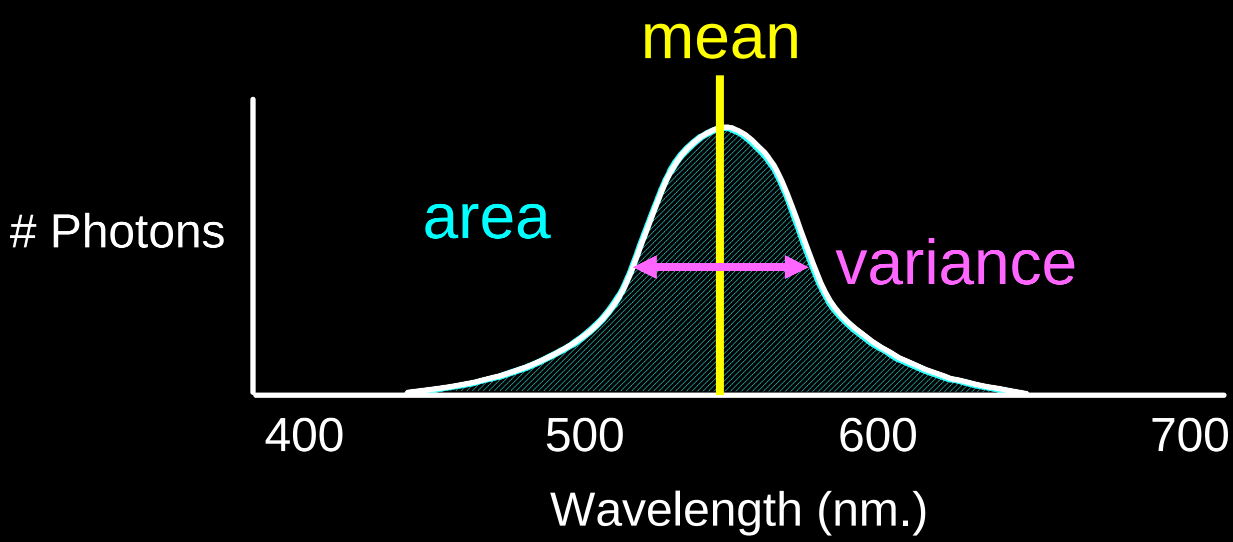
Some examples of the reflectance spectra of surfaces



The Psychophysical Correspondence

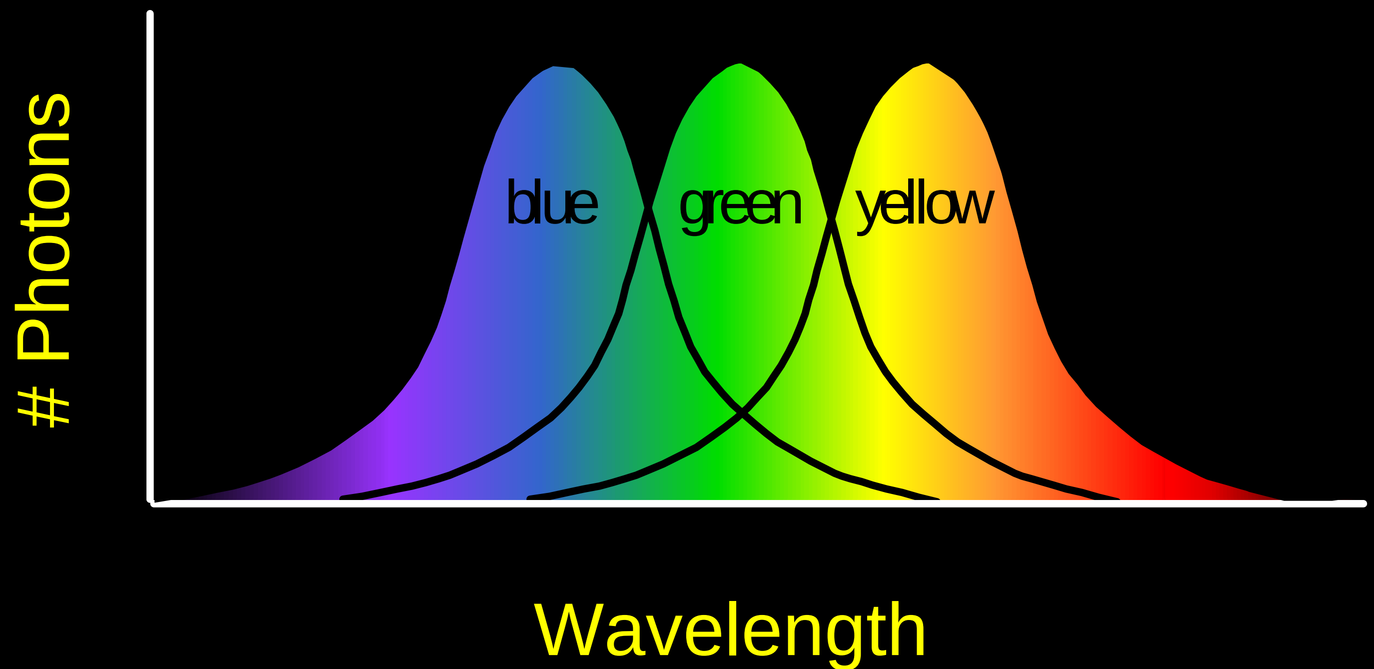
There is no simple functional description for the perceived color of all lights under all viewing conditions, but …...

A helpful constraint:
  Consider only physical spectra with normal distributions



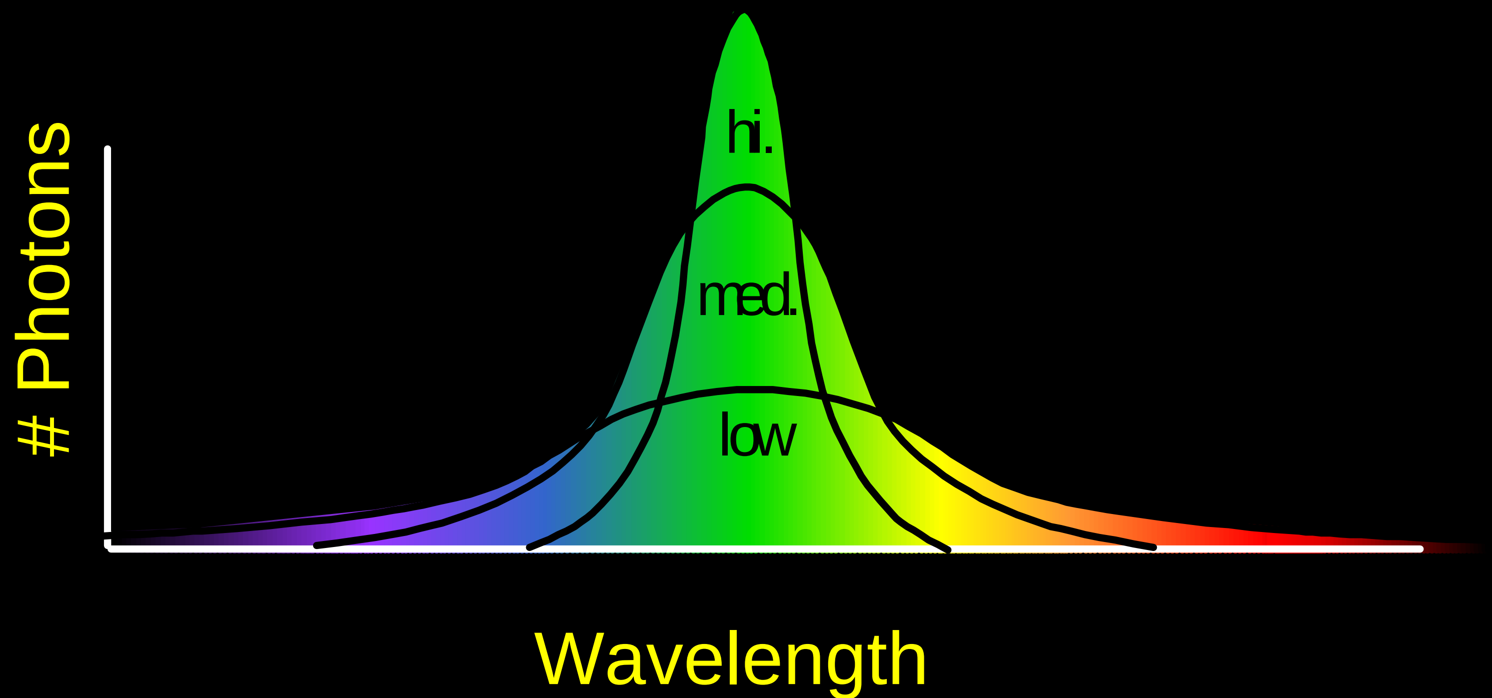
The Psychophysical Correspondence

Mean ⟷ Hue



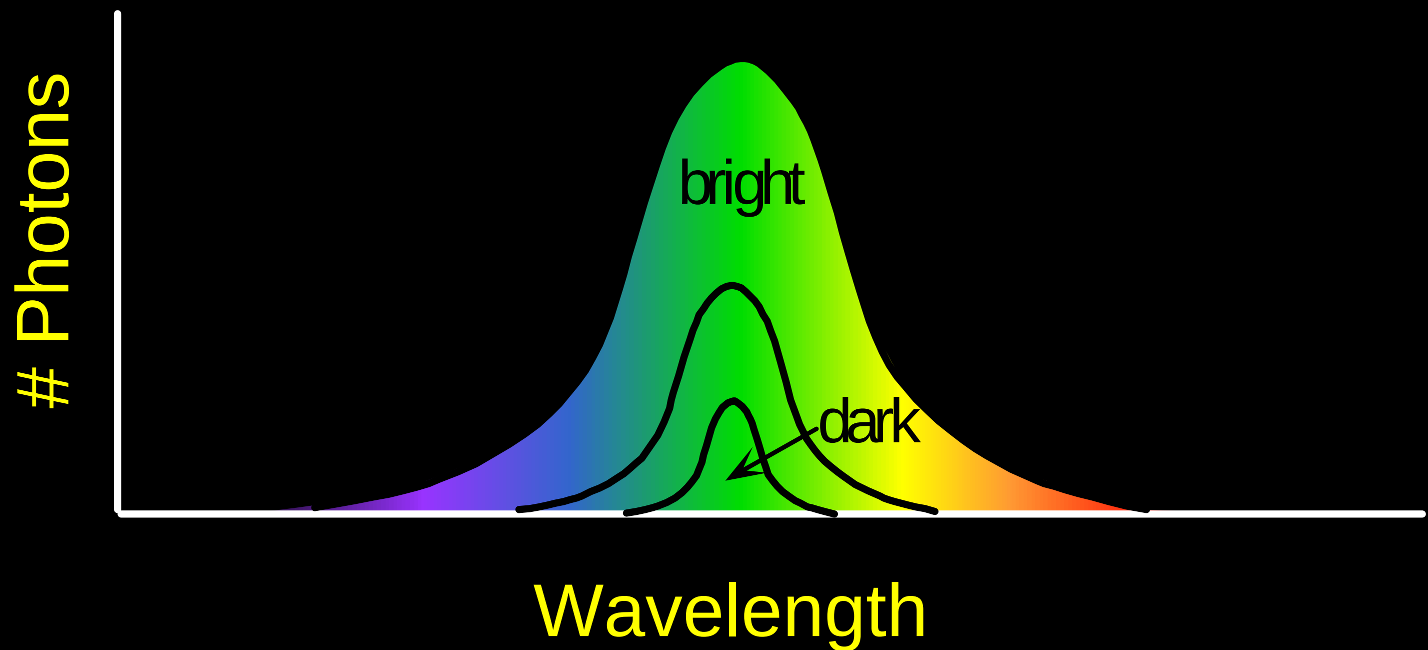
The Psychophysical Correspondence

Variance ⟷ Saturation



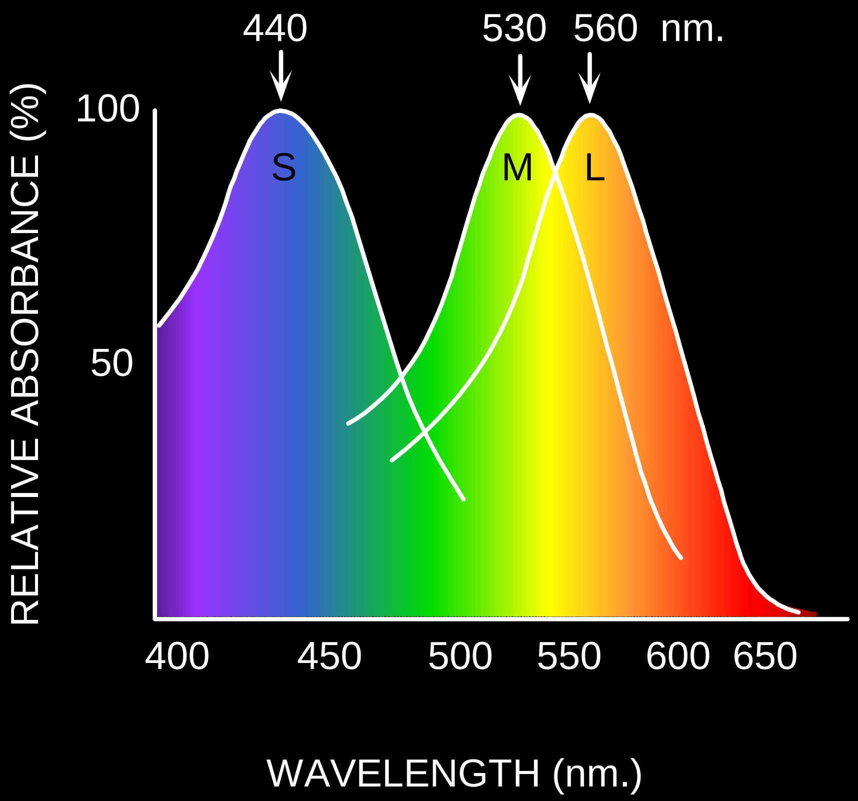
The Psychophysical Correspondence

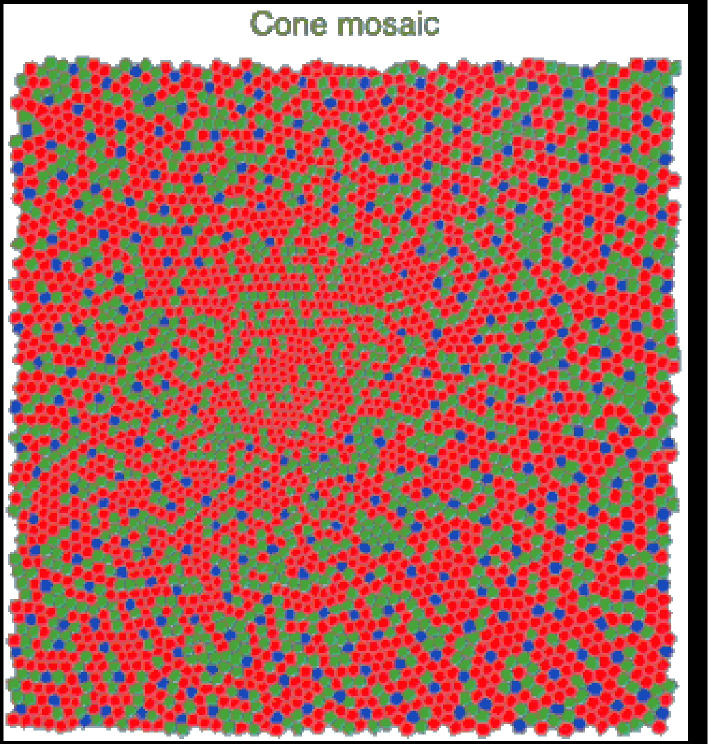
Area ⟷ Brightness



Physiology of Color Vision

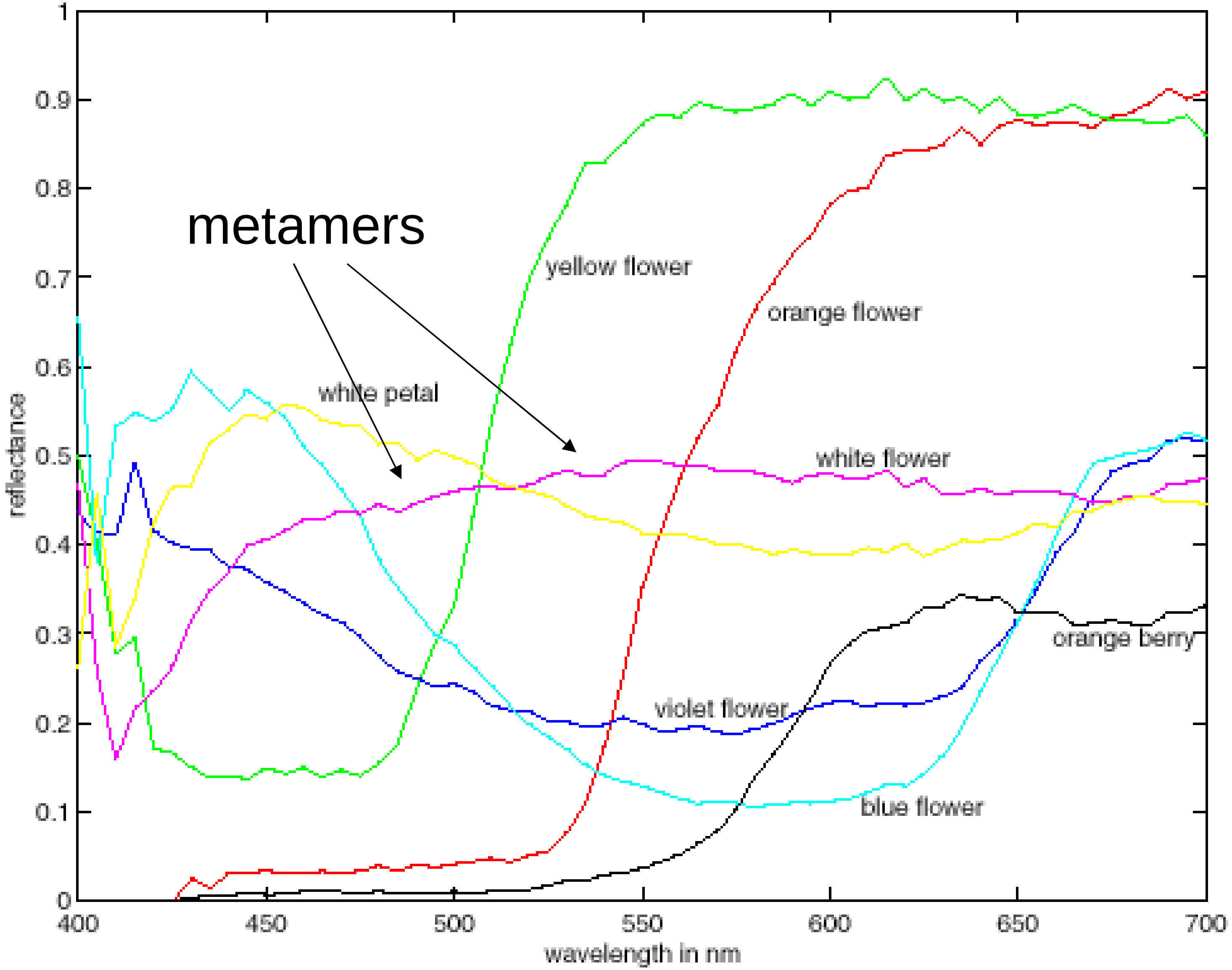
Three kinds of cones:





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

More Spectra



Color Constancy

The "photometer metaphor" of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).

Color Constancy

The "photometer metaphor" of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).

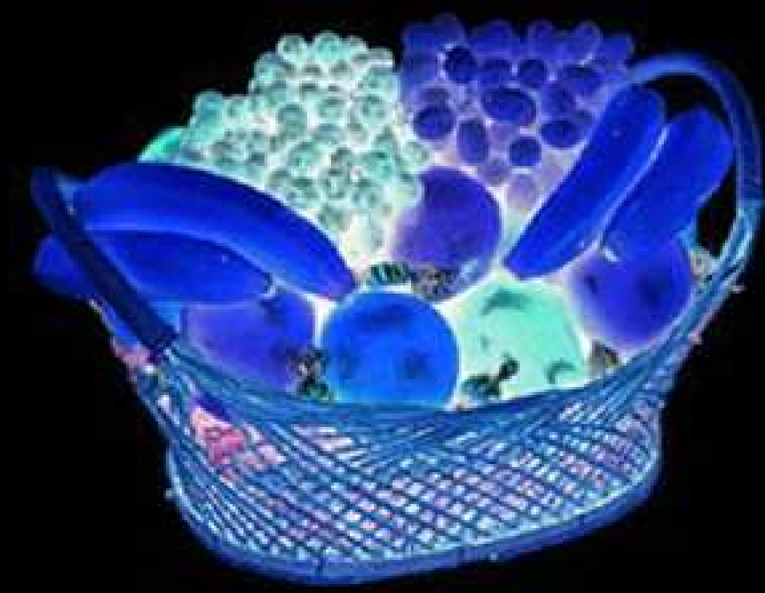
Color Constancy

~~The "photometer metaphor" of color perception:~~
~~Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).~~

Color Constancy

~~Do we have constancy over~~
~~all global color transformations?~~

60% blue filter



Complete inversion

Color Constancy

Color Constancy: the ability to perceive the invariant color of a surface despite ecological Variations in the conditions of observation.

Another of these hard inverse problems:

Physics of light emission and surface reflection underdetermine perception of surface color

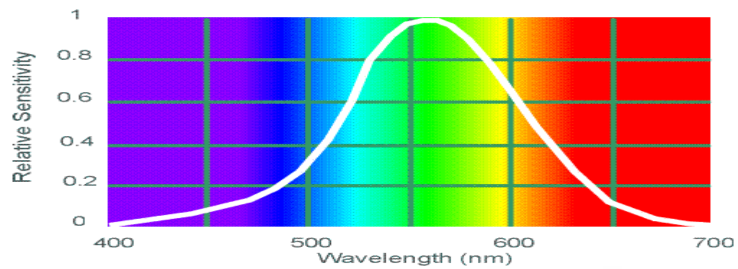
Camera White Balancing

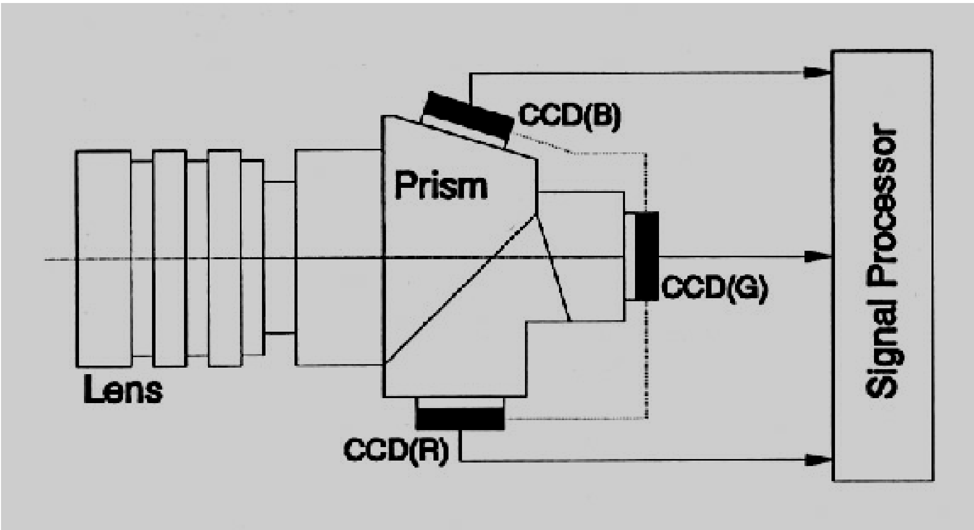
- Manual
  - Choose color-neutral object in the photos and normalize
- Automatic (AWB)
  - Grey World: force average color of scene to grey
  - White World: force brightest object to white

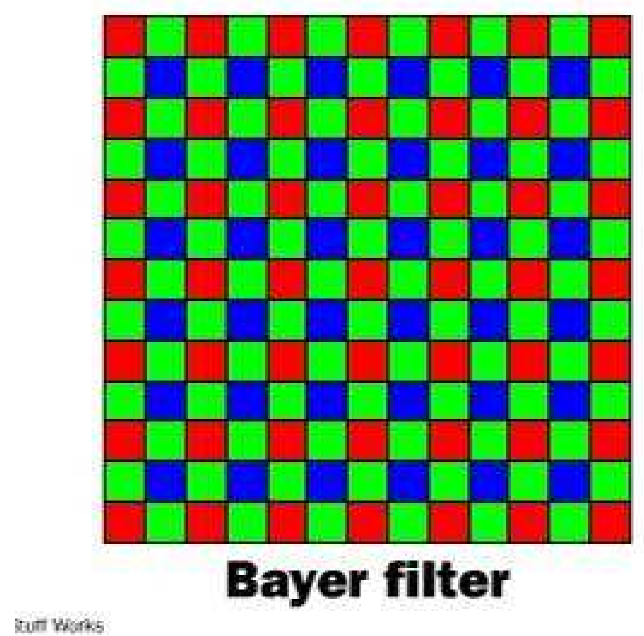
Color Sensing in Camera (RGB)

3-chip vs. 1-chip: quality vs. cost

Why more green?





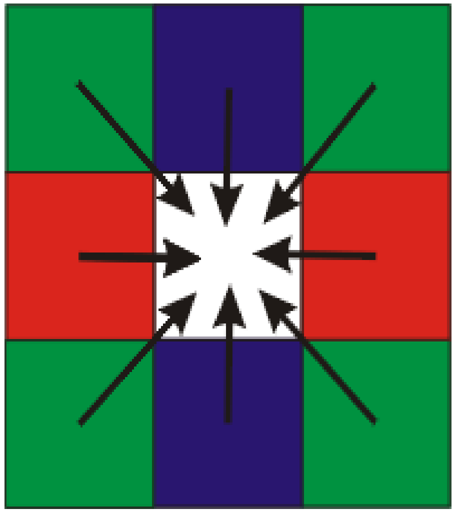


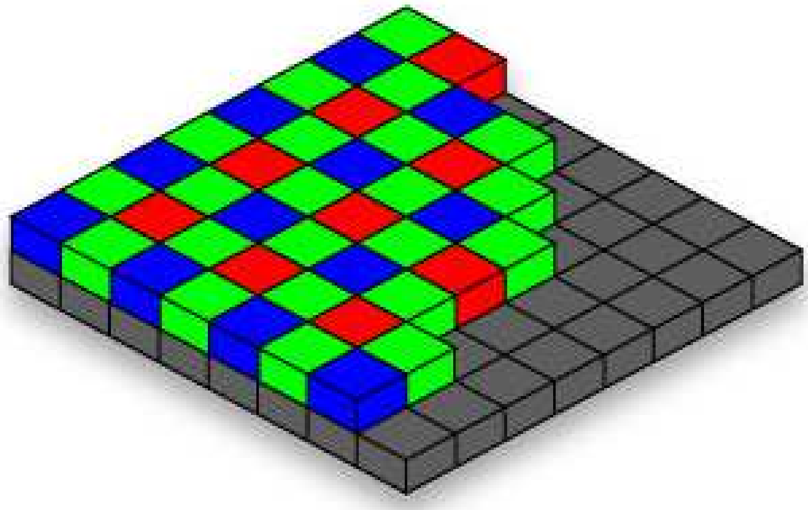
Why 3 colors?

http://www.cooldictionary.com/words/Bayer-filter.wikipedia

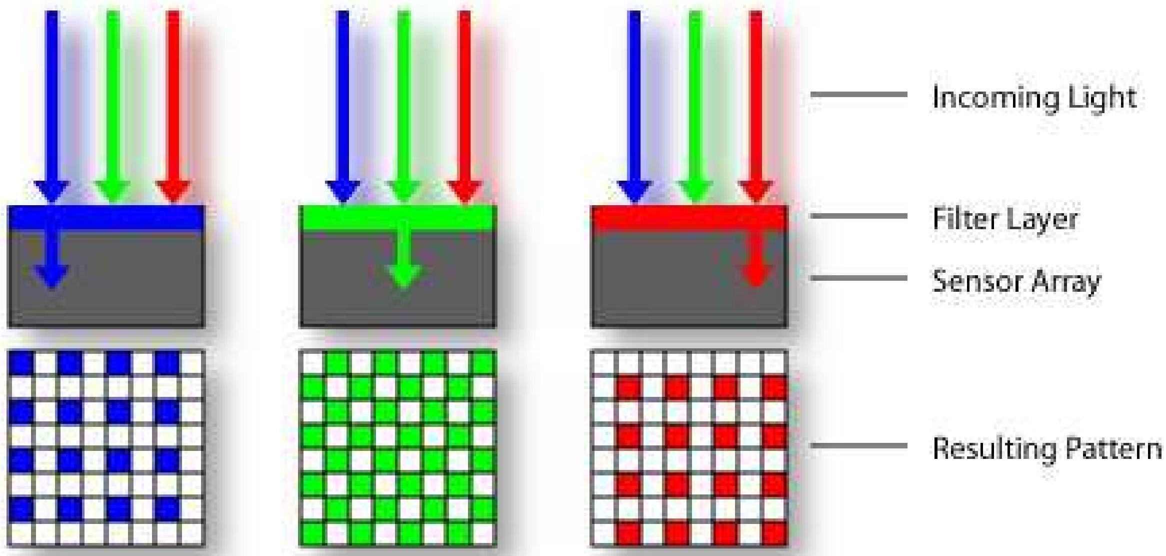
Slide by Steve Seitz

Practical Color Sensing: Bayer Grid





Estimate RGB
at ‘G’ cels from
neighboring
values



http://www.cooldictionary.com/words/Bayer-filter.wikipedia

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RGB color space

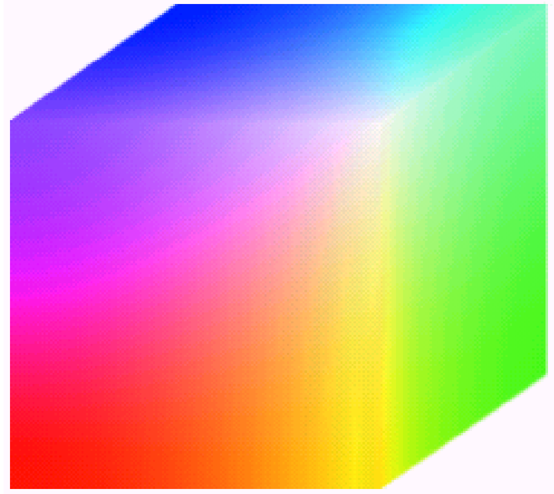
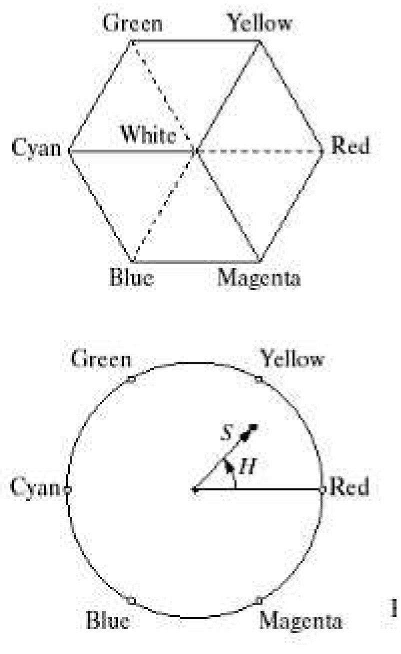


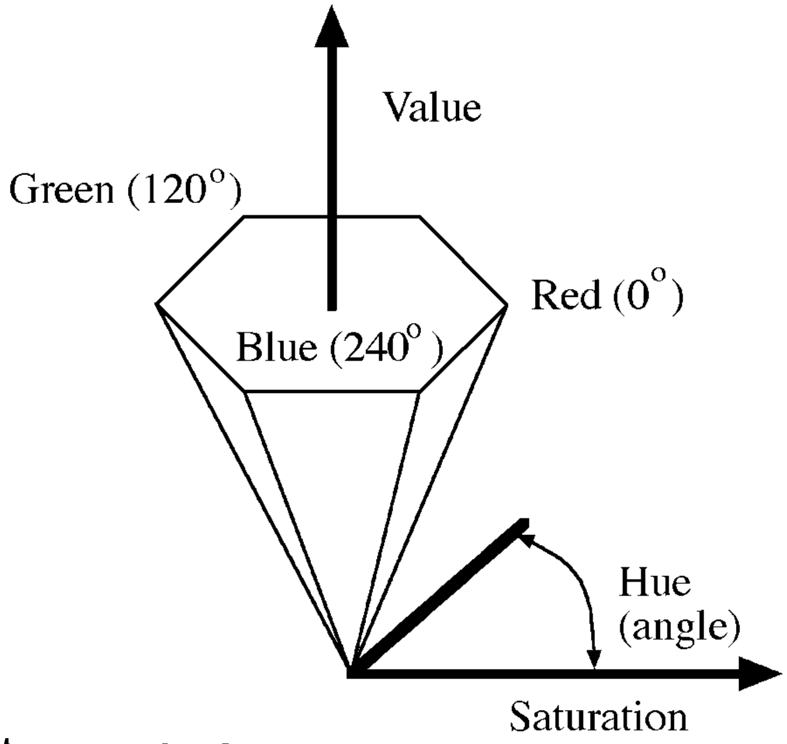
FIGURE 6.8 RGB 24-bit color cube.

RGB cube

- Easy for devices
- But not perceptual
- Where do the grays live?
- Where is hue and saturation?

HSV





Hue, Saturation, Value (Intensity)

- RGB cube on its vertex

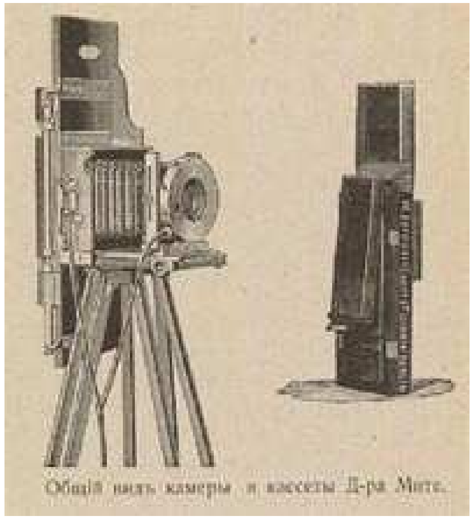
Decouples the three components (a bit)

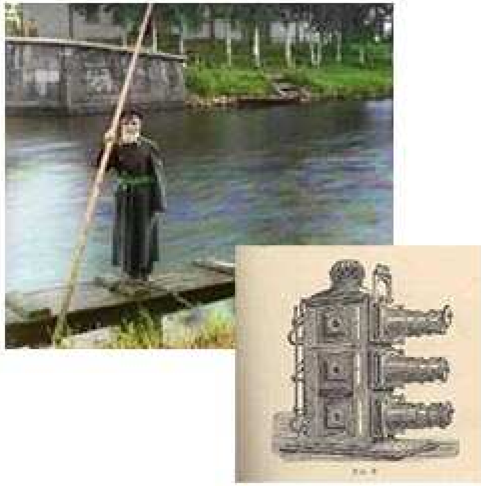
Use rgb2hsv() and hsv2rgb() in Matlab

Slide by Steve Seitz

Programming Project #1

Prokudin-Gorskii’s Color Photography (1907)





Programming Project #1

- How to compare R,G,B channels?
- No right answer
  - Sum of Squared Differences (SSD):

$$ssd(u,v) = \sum_{(x,y)\in N} \left[I(u+x, v+y) - P(x,y)\right]^2$$

  - Normalized Correlation (NCC):

$$ncc(u,v) = \frac{\sum_{(x,y)\in N} \left[I(u+x, v+y) - \bar{I}\right]\left[P(x,y) - \bar{P}\right]}{\sqrt{\sum_{(x,y)\in N} \left[I(u+x, v+y) - \bar{I}\right]^2 \sum_{(x,y)\in N} \left[P(x,y) - \bar{P}\right]^2}}$$