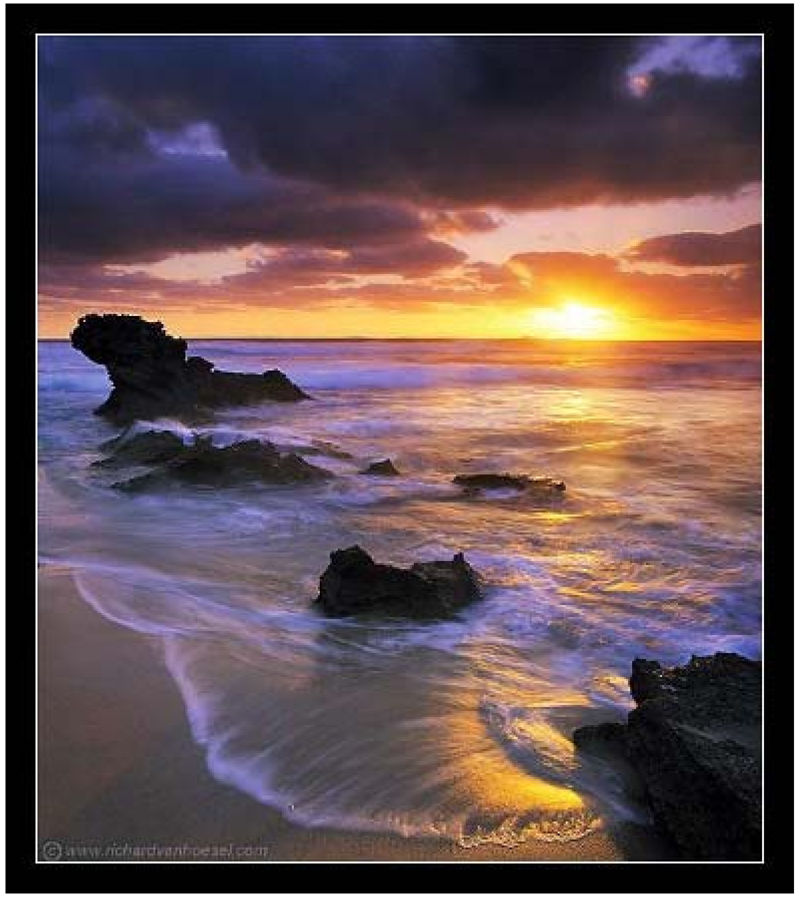
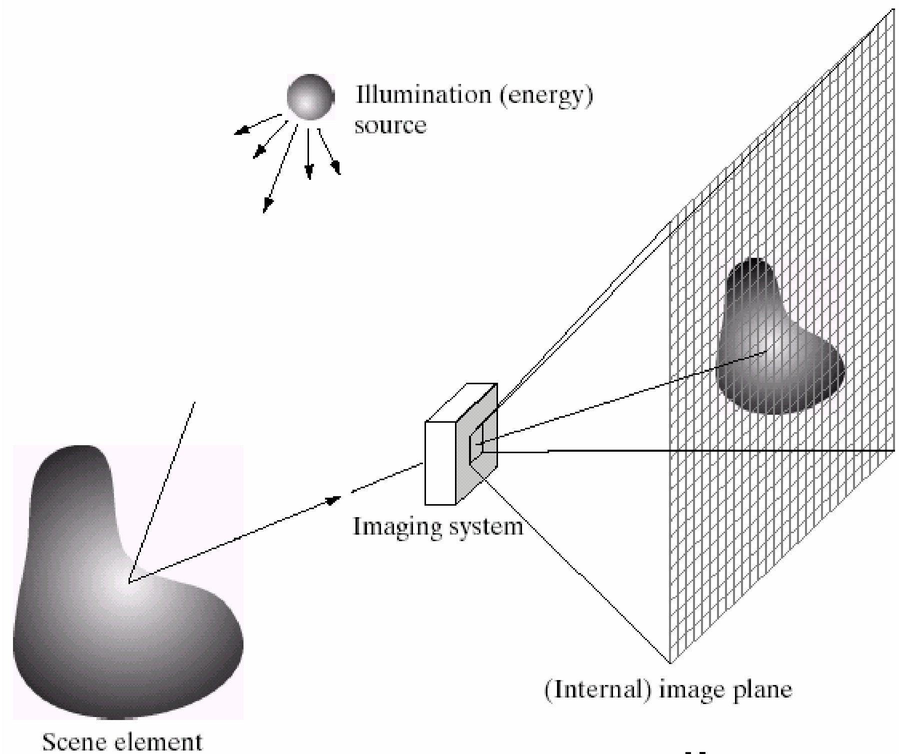
Capturing Light… in man and machine



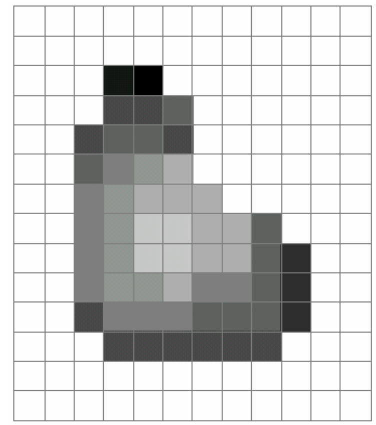
15-463: Computational Photography
Alexei Efros, CMU, Fall 2006

Some figures from Steve Seitz, Steve Palmer, Paul Debevec, and Gonzalez et al.

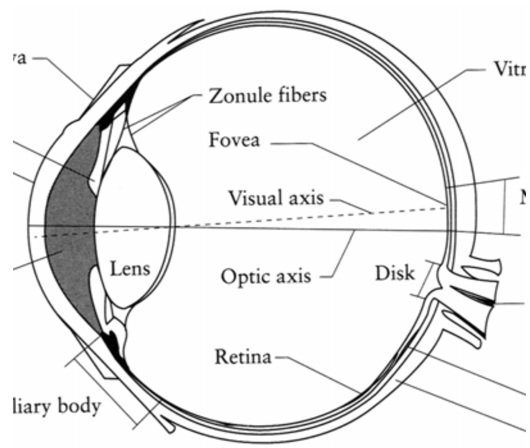
Image Formation



Film



Digital Camera



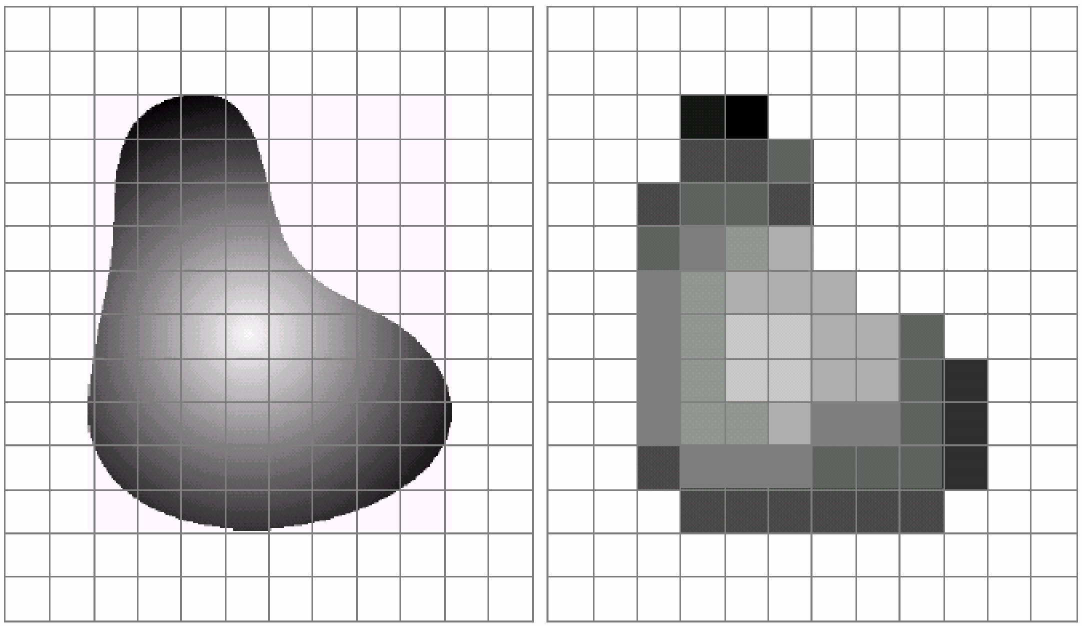
The Eye

Digital camera

A digital camera replaces film with a sensor array

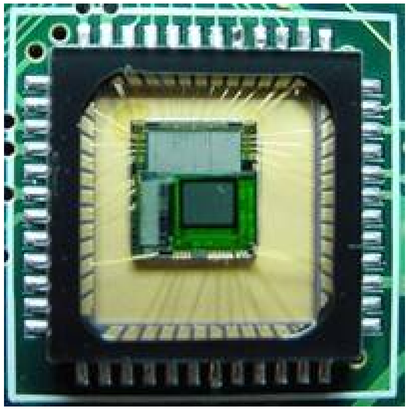
- Each cell in the array is light-sensitive diode that converts photons to electrons
- Two common types
  - Charge Coupled Device (CCD)
  - CMOS
- http://electronics.howstuffworks.com/digital-camera.htm

Sensor Array



a b

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



CMOS sensor

Sampling and Quantization

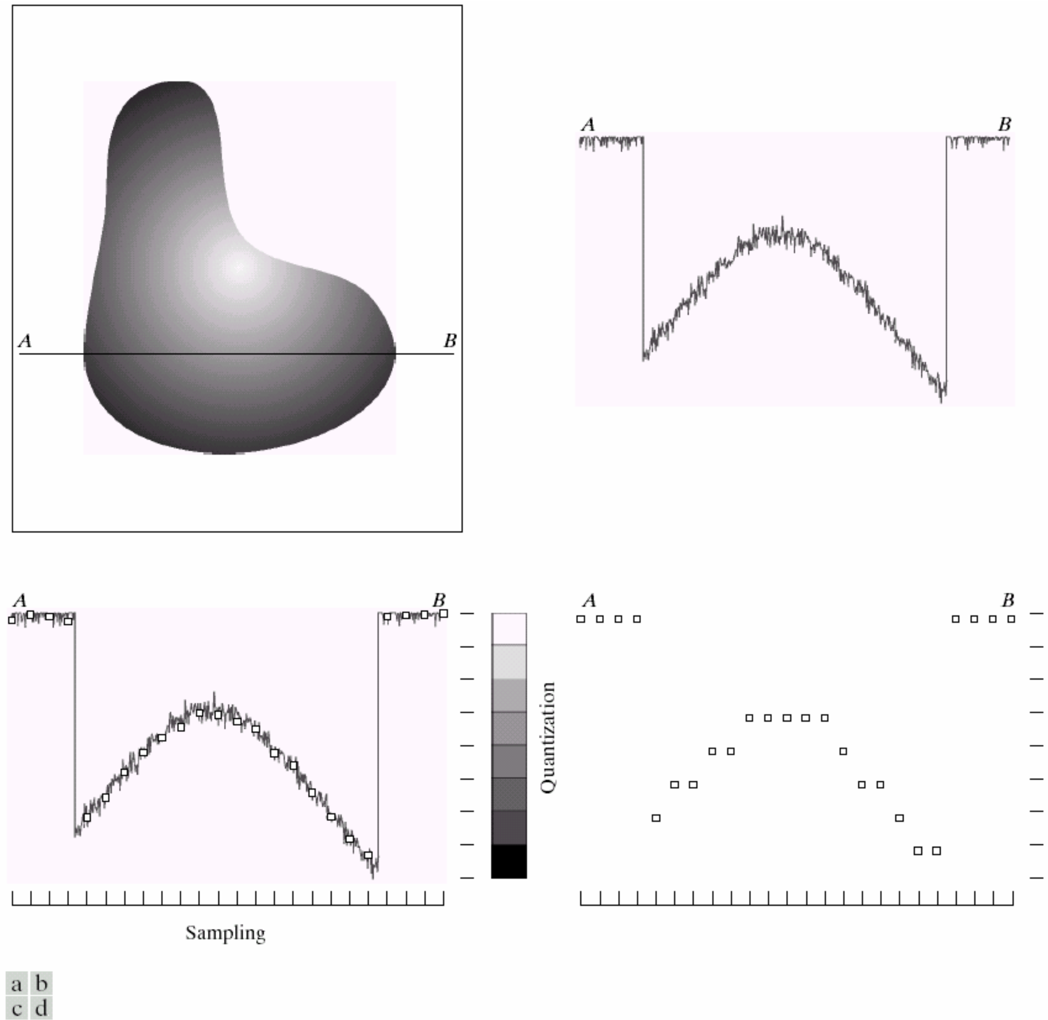
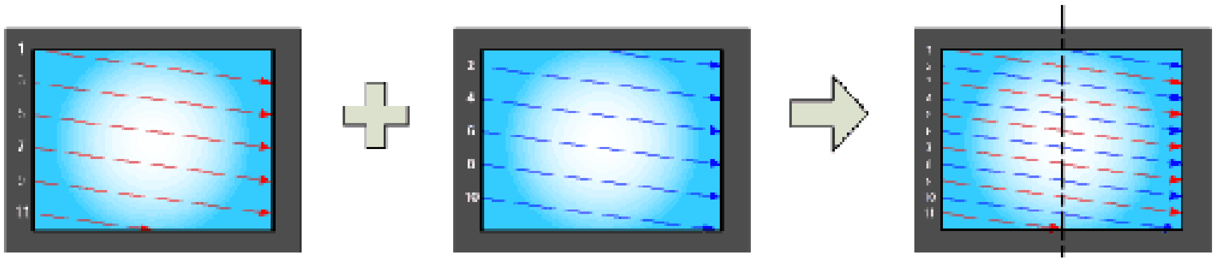
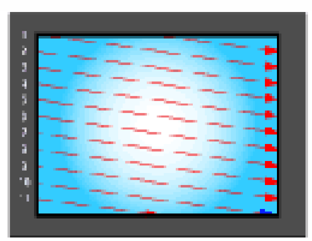


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

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

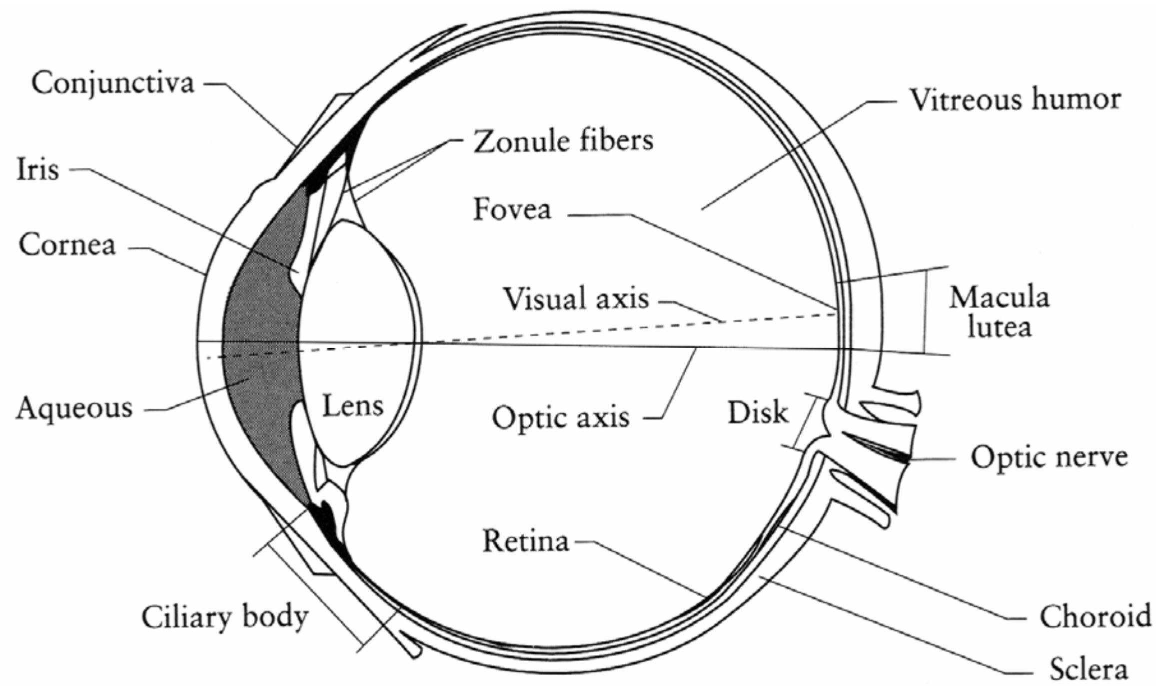
Progressive scan

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

Interlace

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

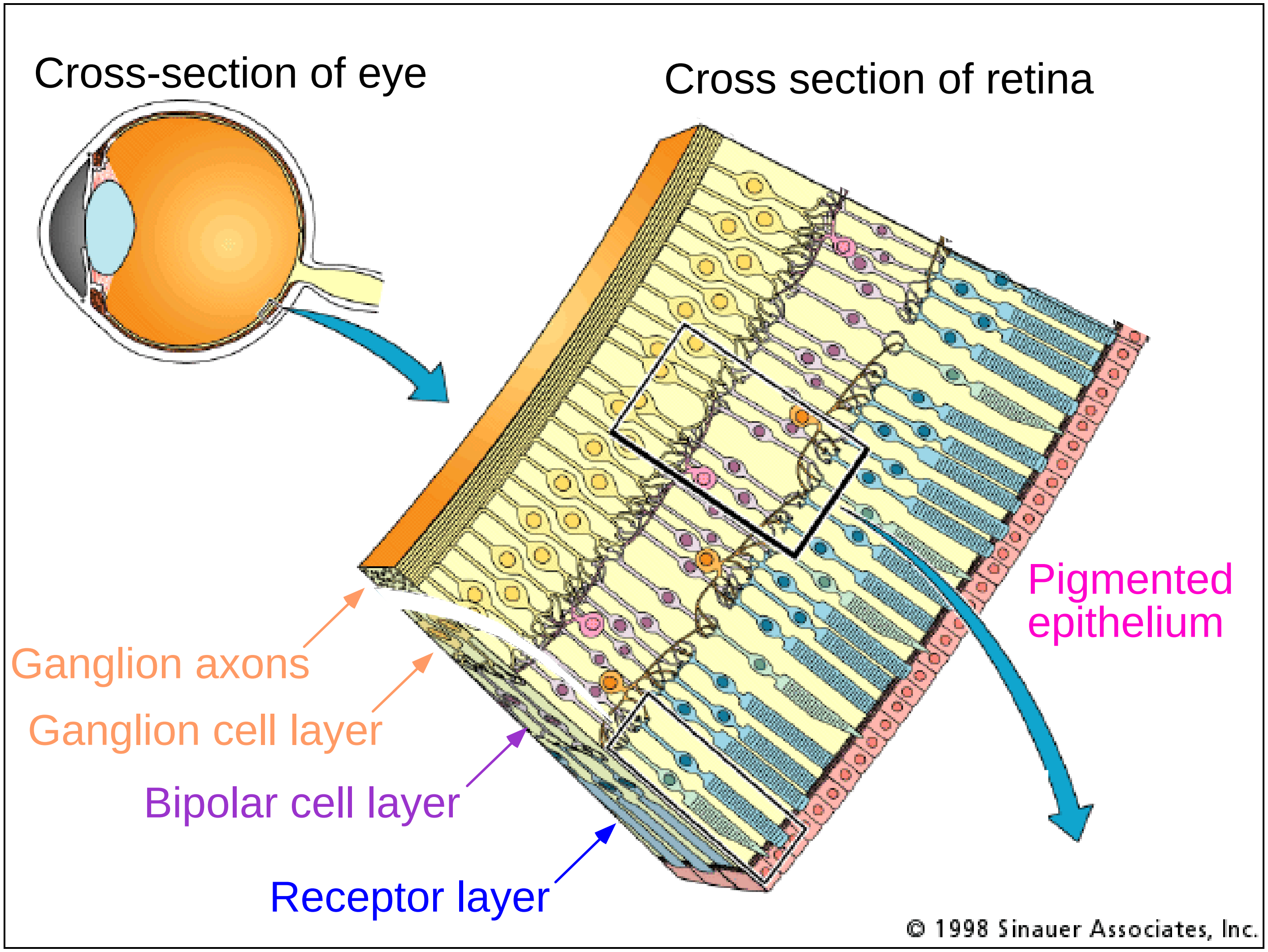
The Eye



The human eye is a camera!

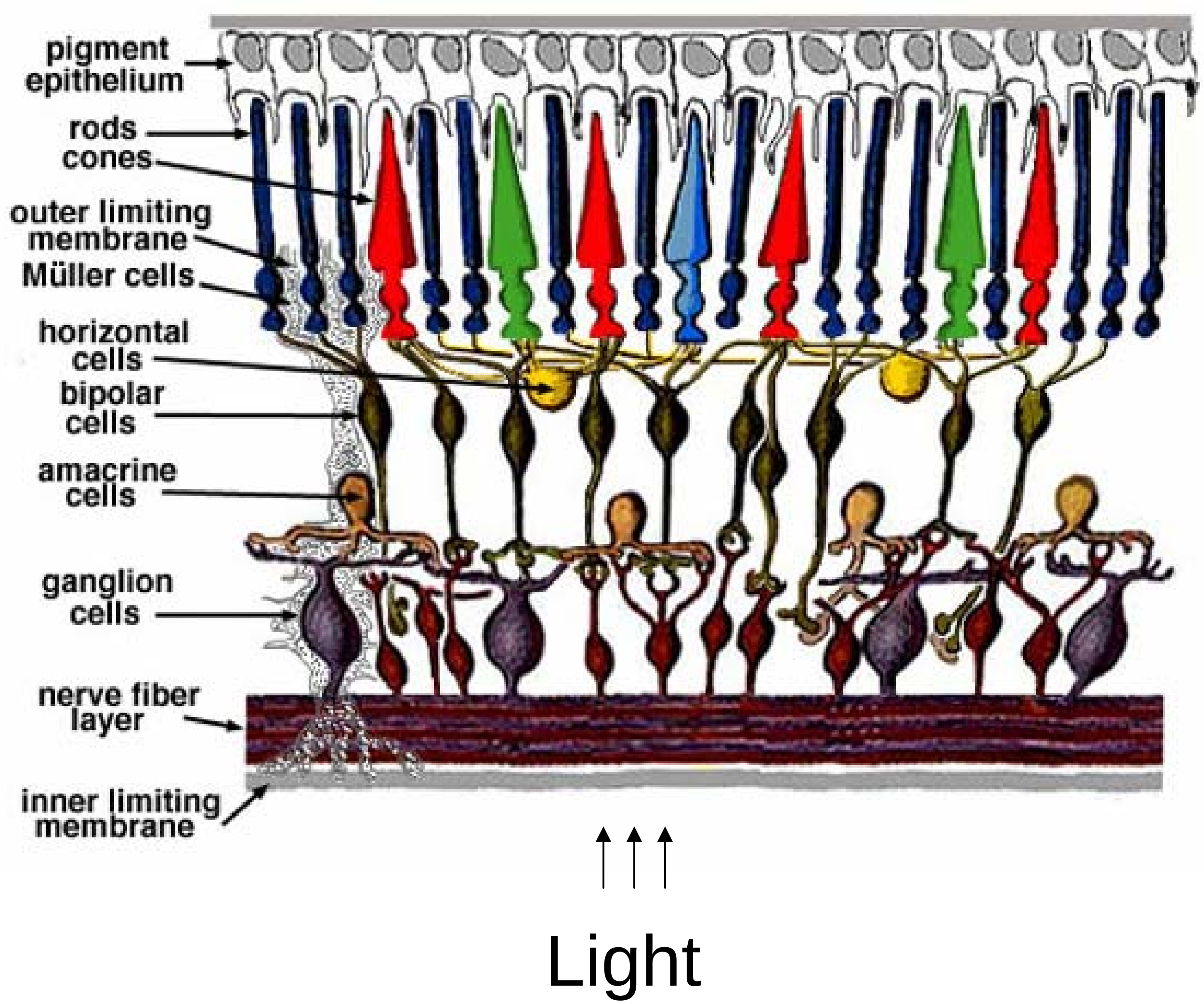
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  – photoreceptor cells (rods and cones) in the **retina**

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



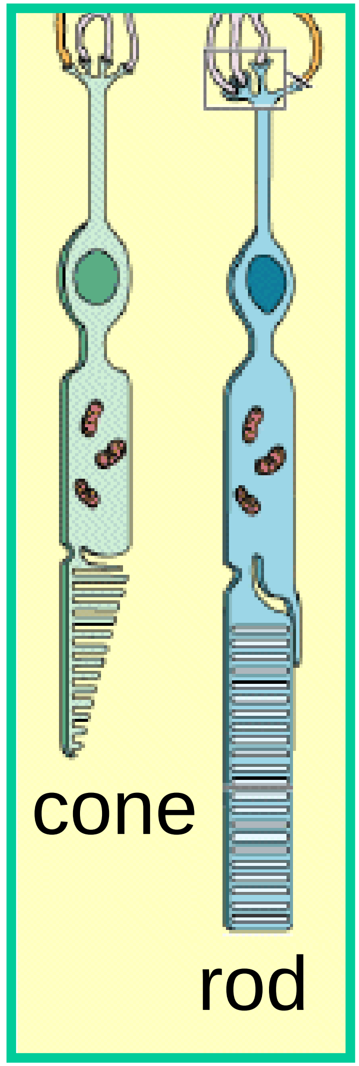
Two types of light-sensitive receptors

Cones

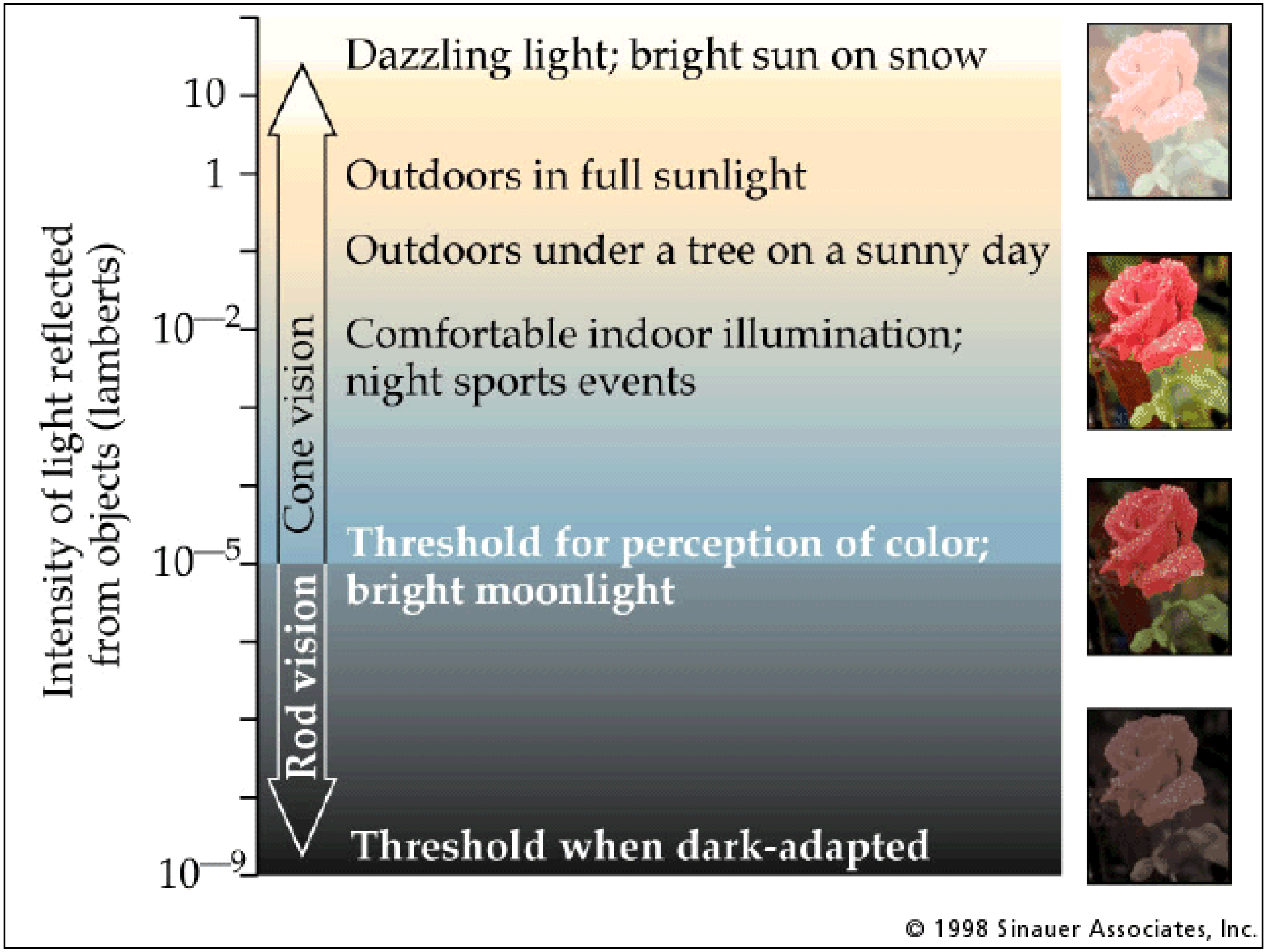
cone-shaped
less sensitive
operate in high light
color vision

Rods

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

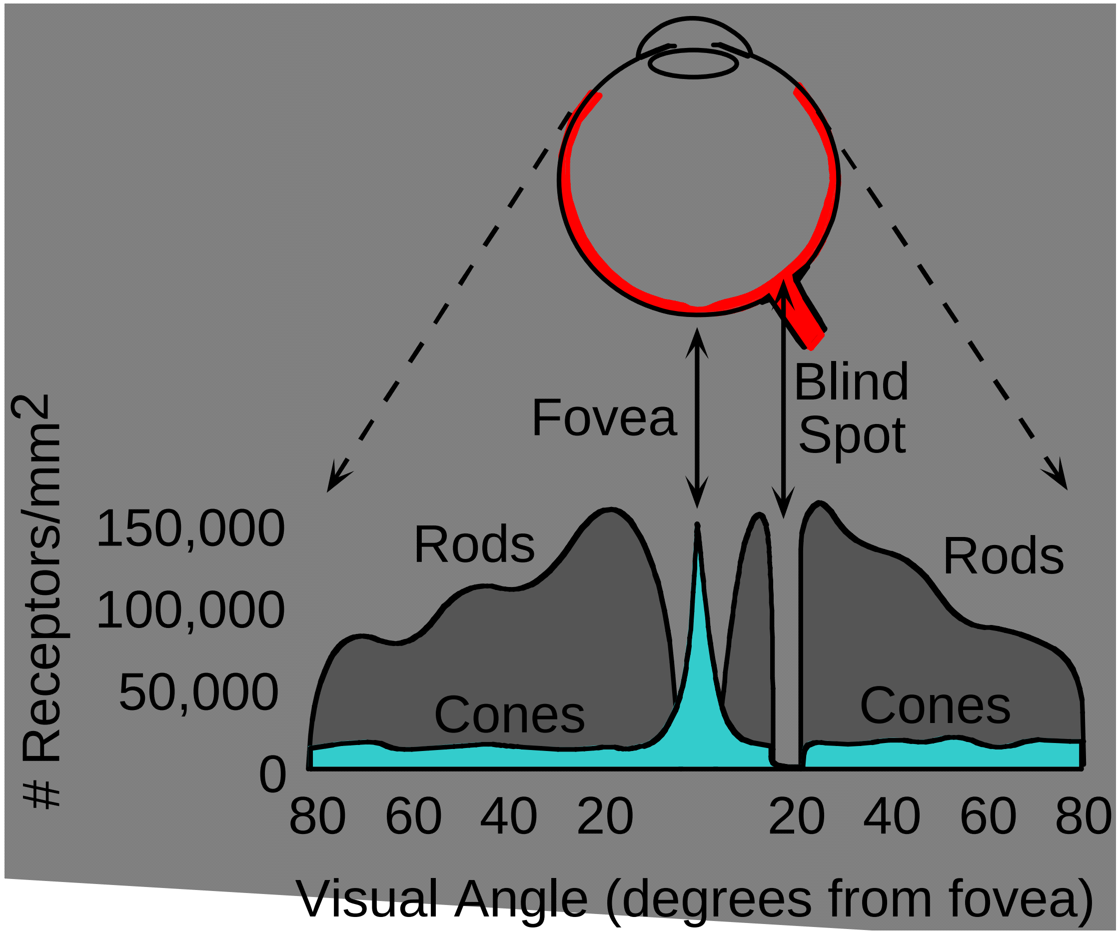


Rod / Cone sensitivity



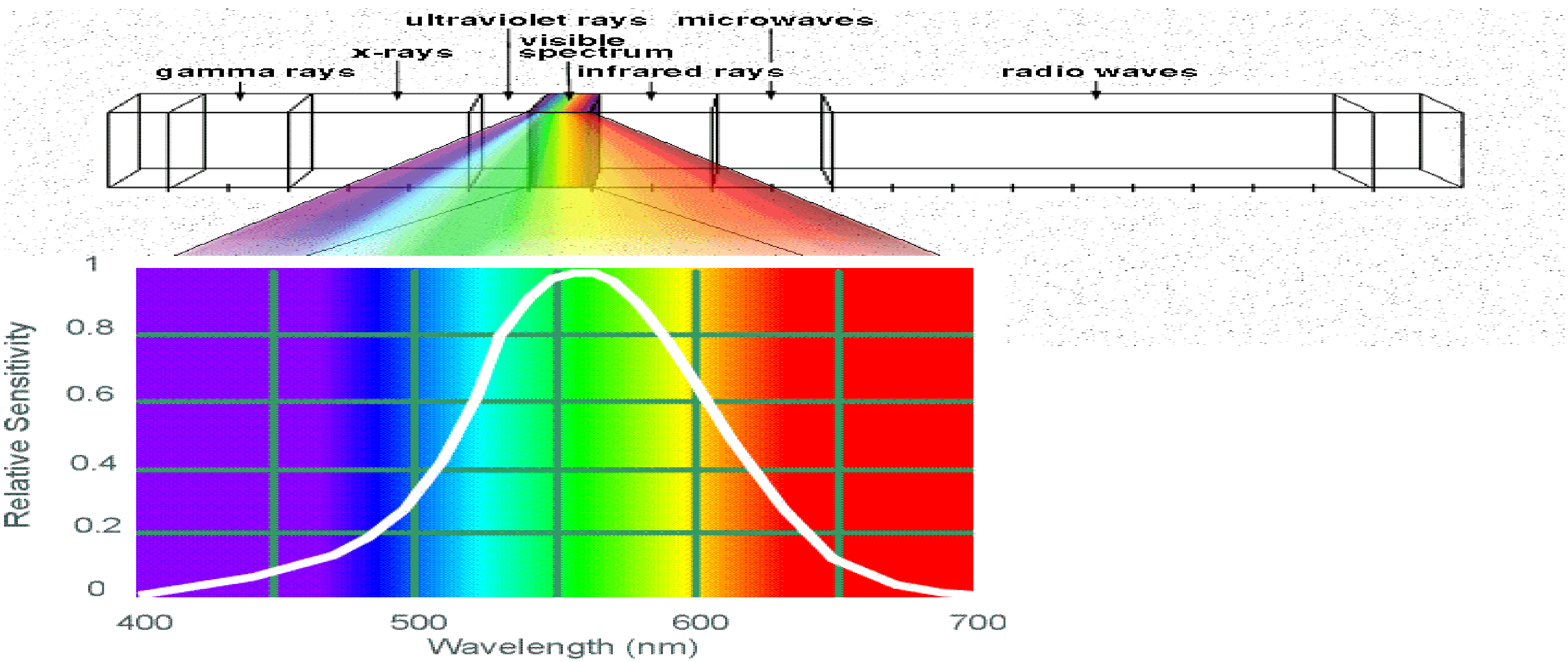
The famous sock-matching problem…

Distribution of Rods and Cones



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

Electromagnetic Spectrum

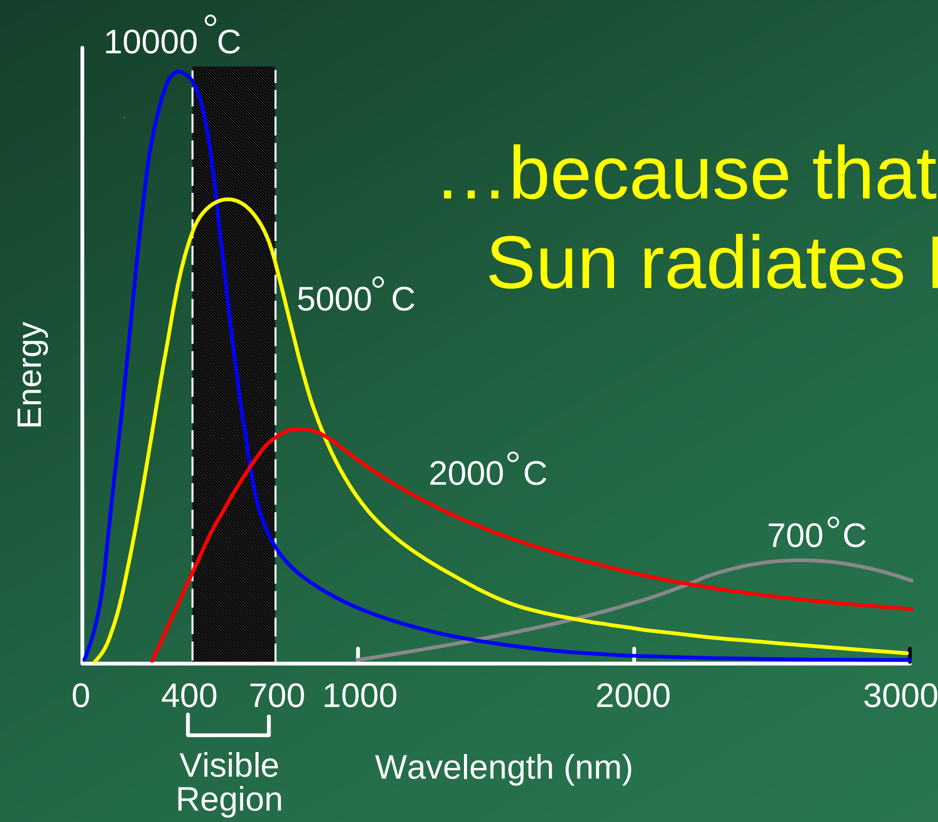


Human Luminance Sensitivity Function

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

Visible Light

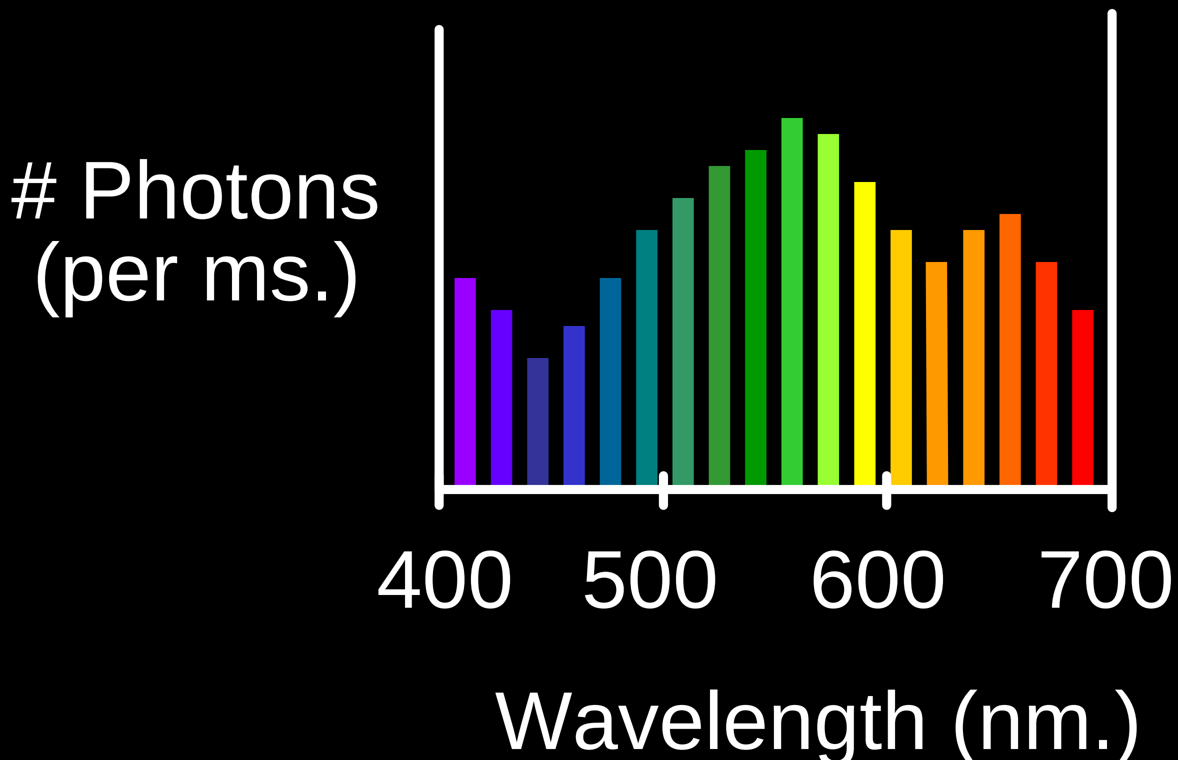
Why do we see light of these wavelengths?



…because that's where the Sun radiates EM energy

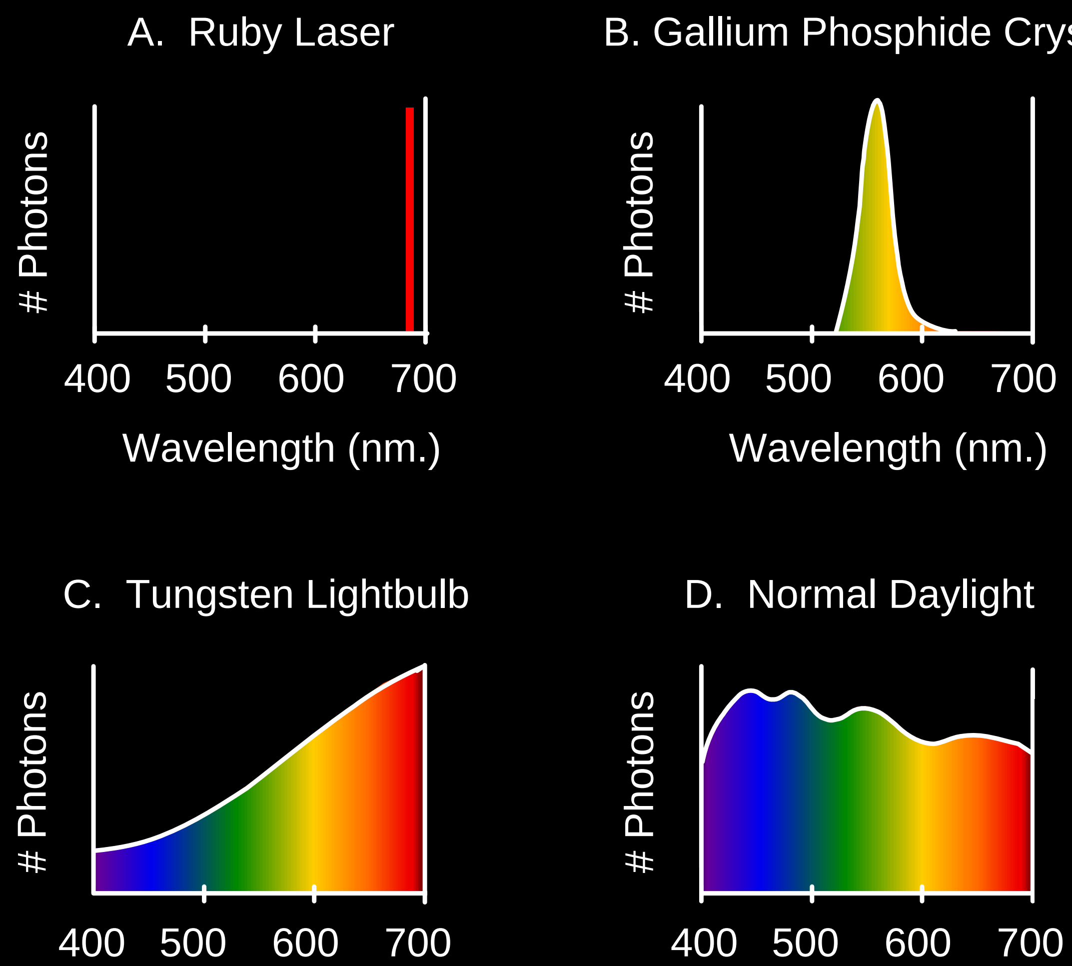
The Physics of Light

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.



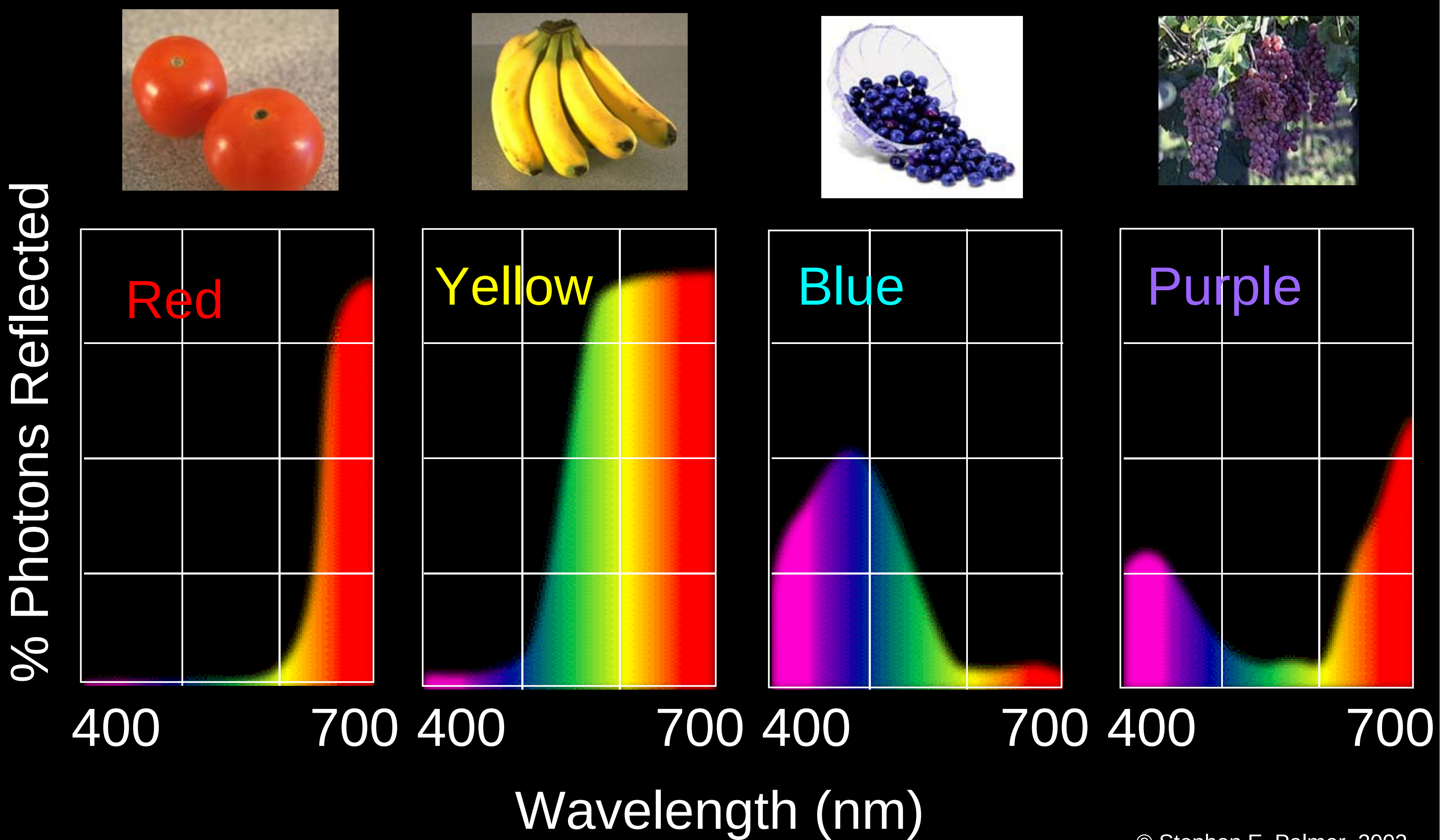
The Physics of Light

Some examples of the spectra of light sources



The Physics of Light

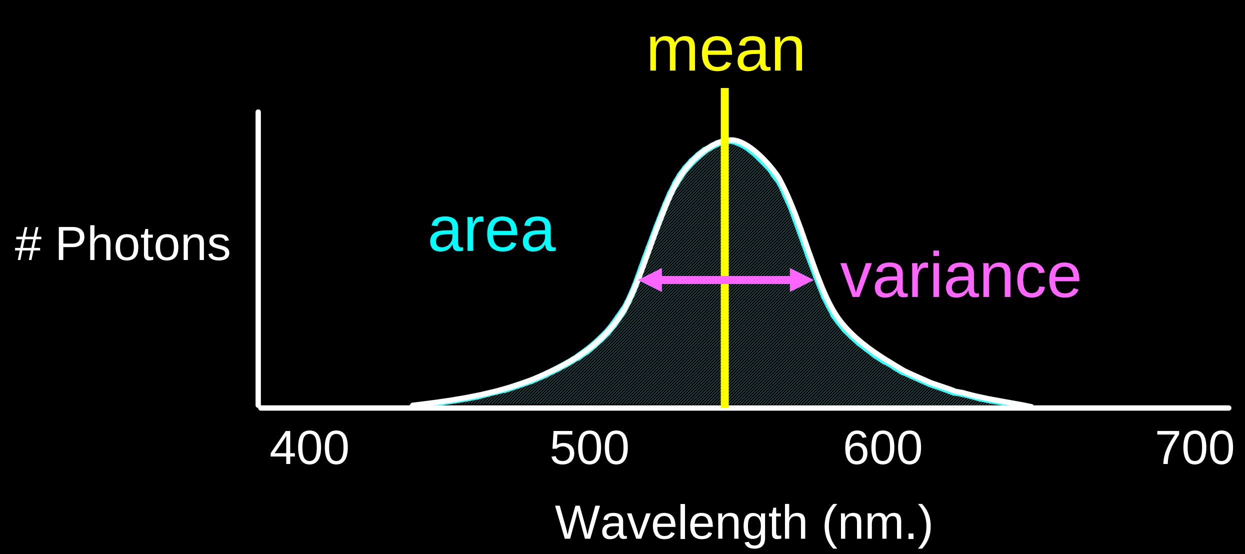
Some examples of the reflectance spectra of surfaces



The Psychophysical Correspondence

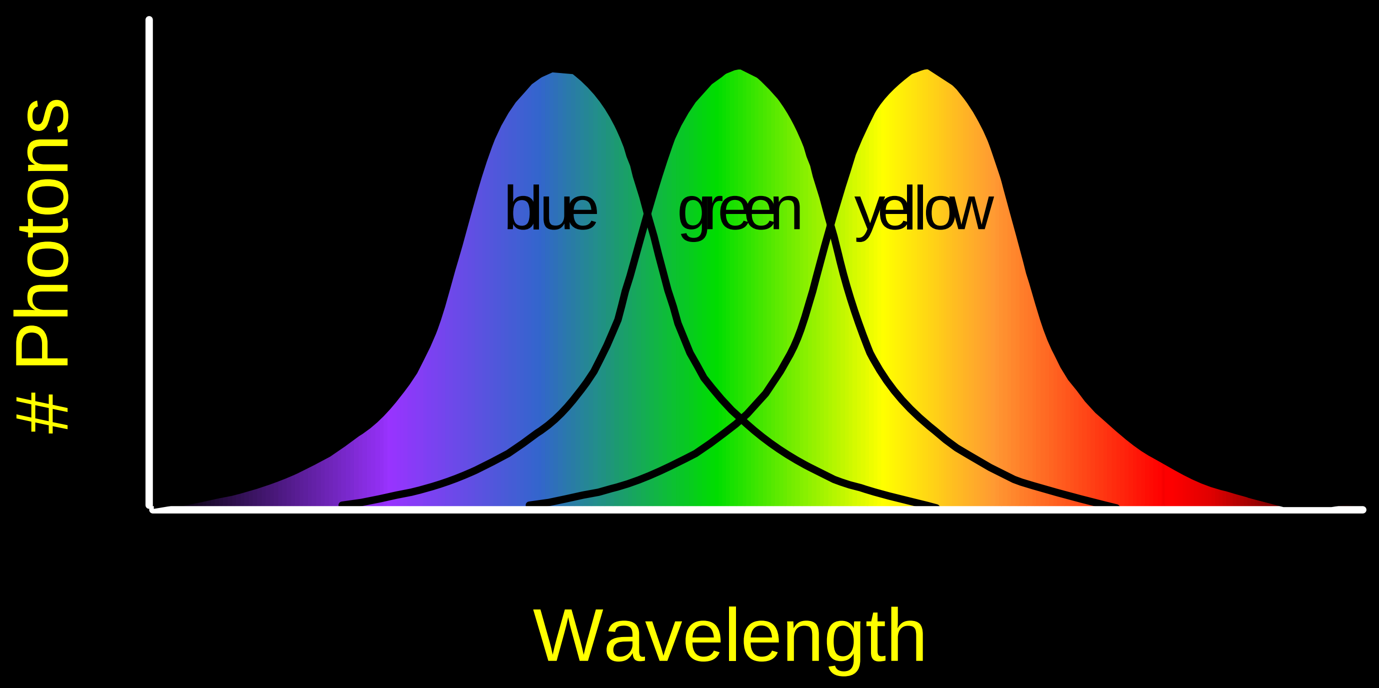
There is no simple functional description for the perceived color of all lights under all viewing conditions, but ……

A helpful constraint:
Consider only physical spectra with normal distributions



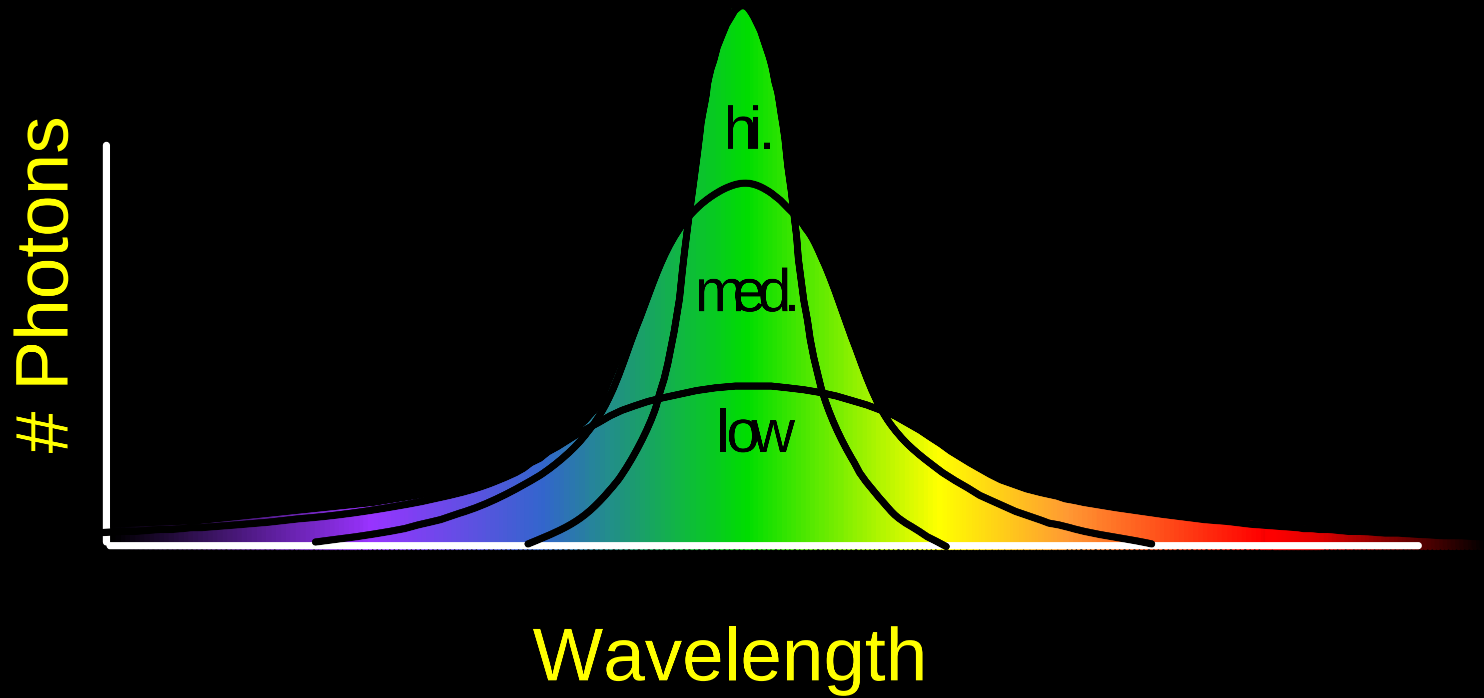
The Psychophysical Correspondence

Mean ⟷ Hue



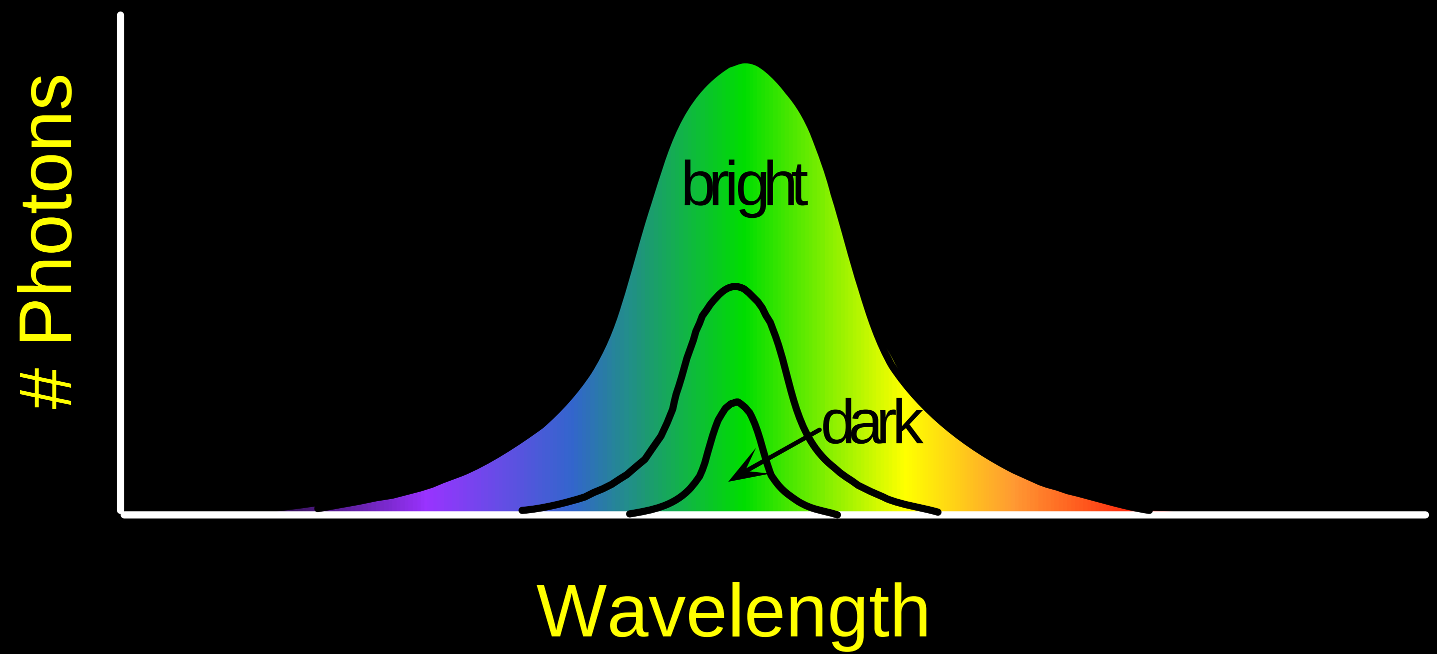
The Psychophysical Correspondence

Variance ⟷ Saturation



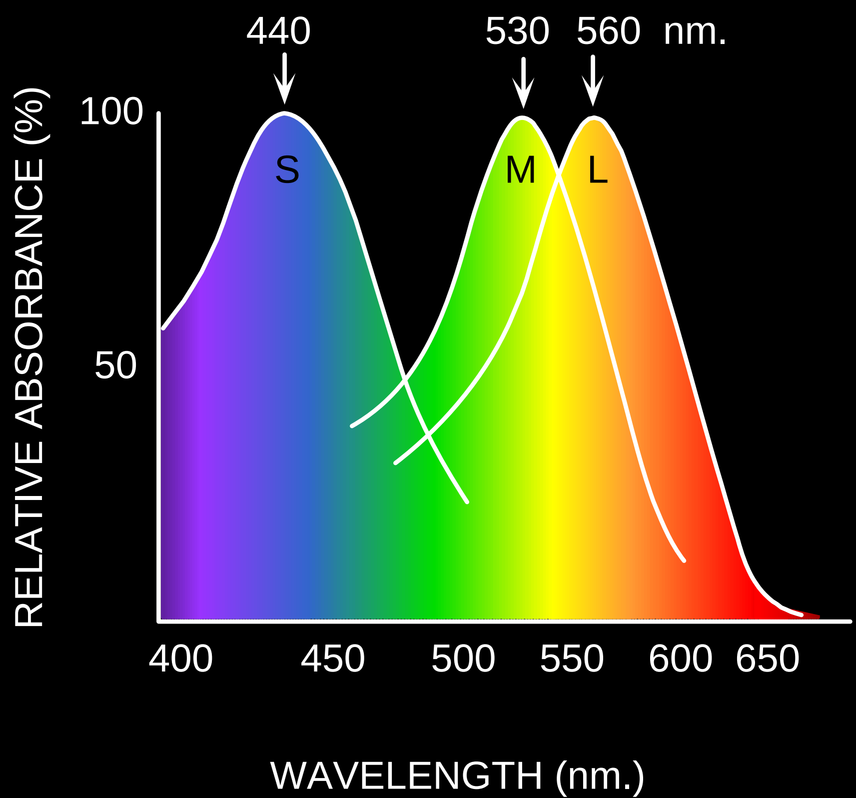
The Psychophysical Correspondence

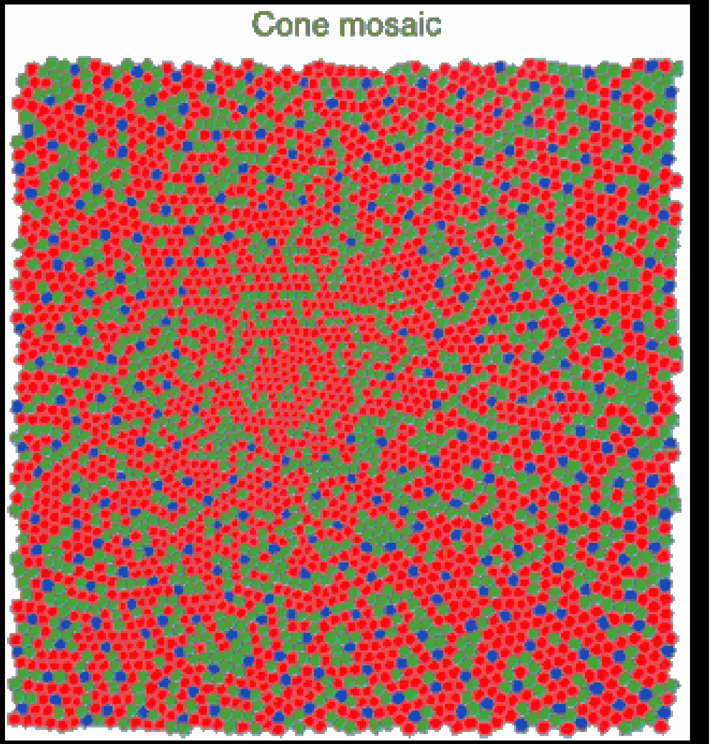
Area ⟷ Brightness



Physiology of Color Vision

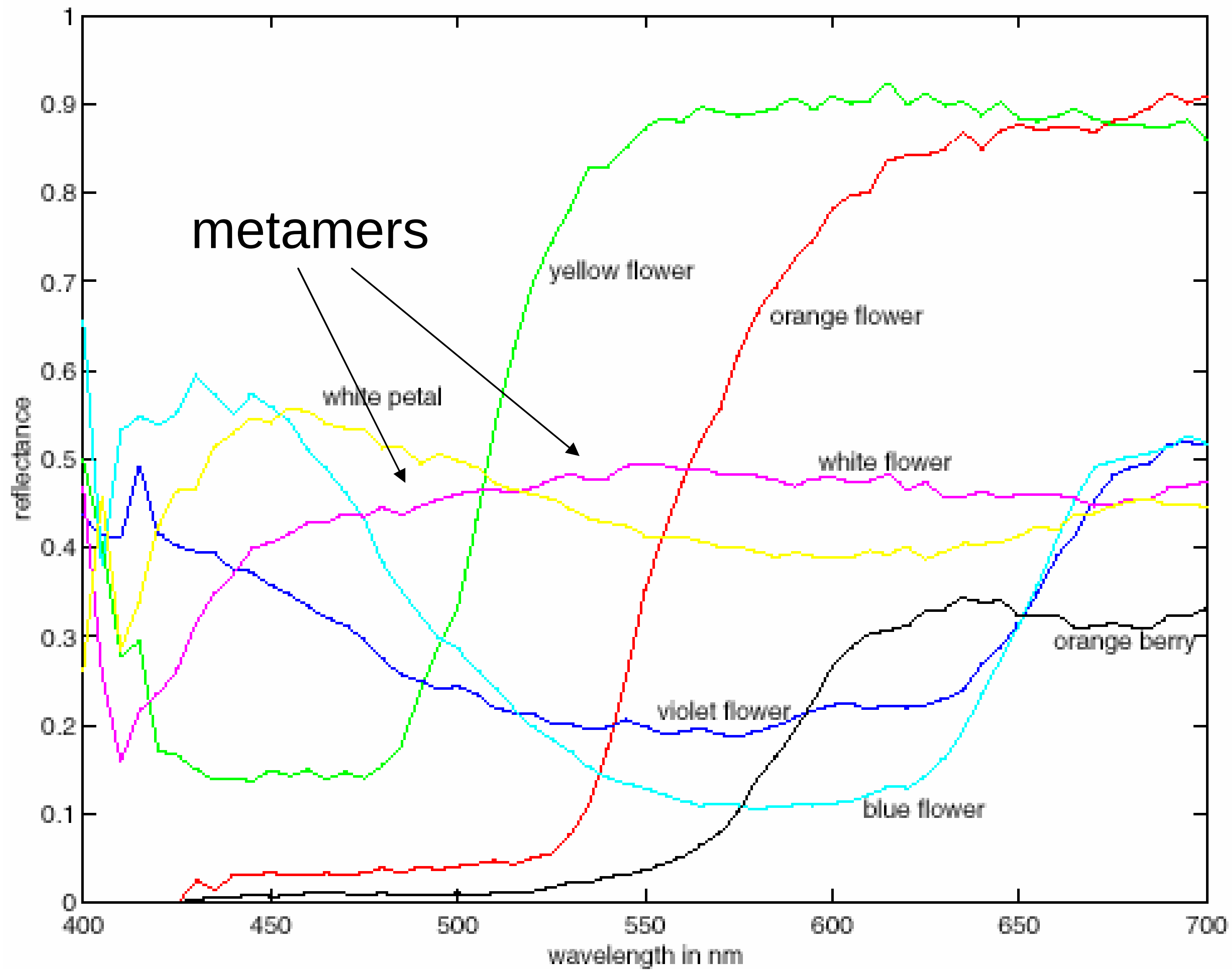
Three kinds of cones:





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

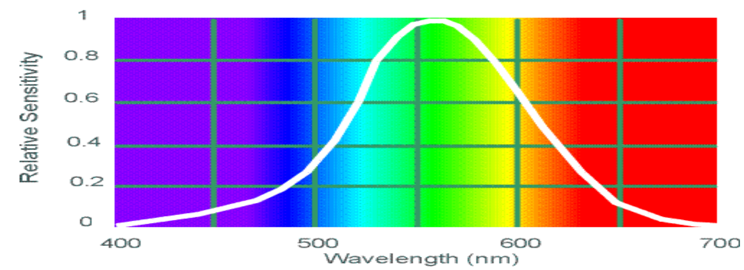
More Spectra

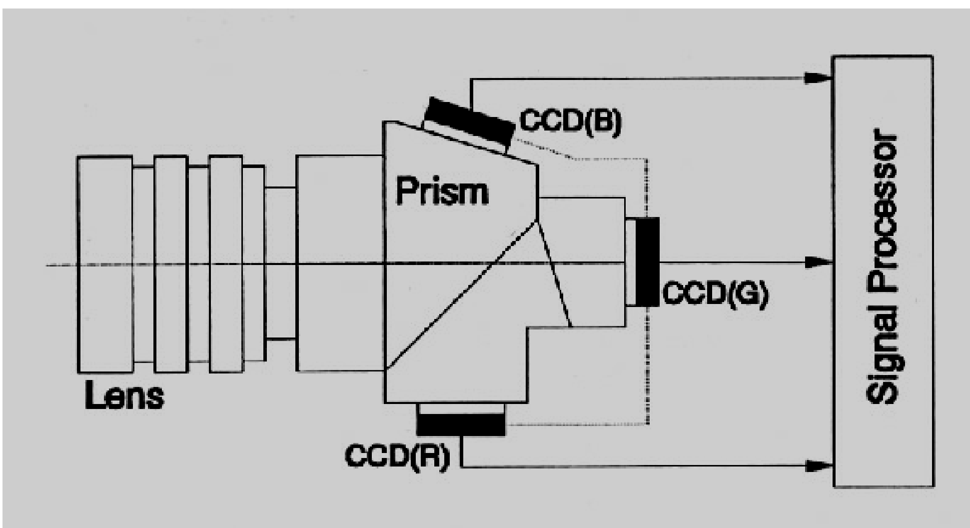


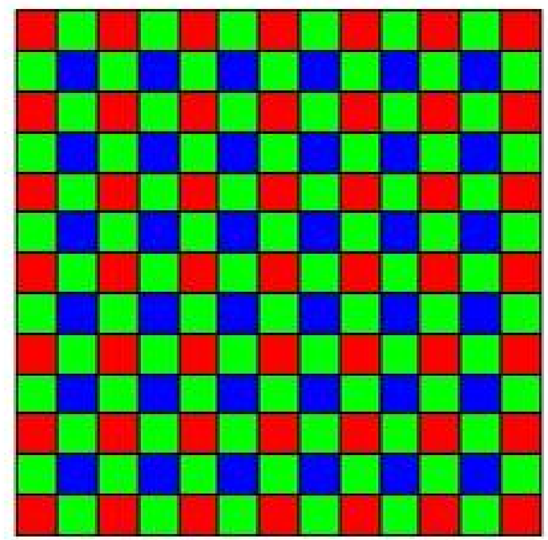
Color Sensing in Camera (RGB)

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

Why more green?







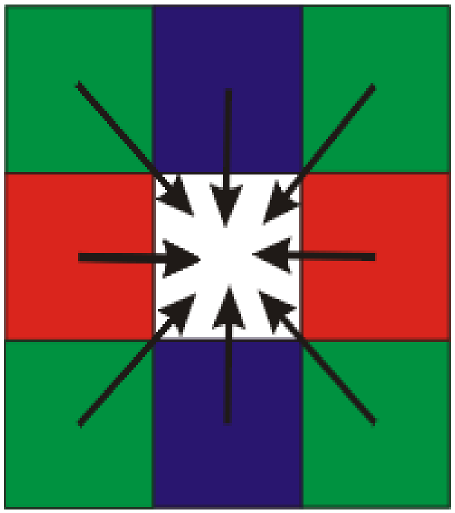
Bayer filter

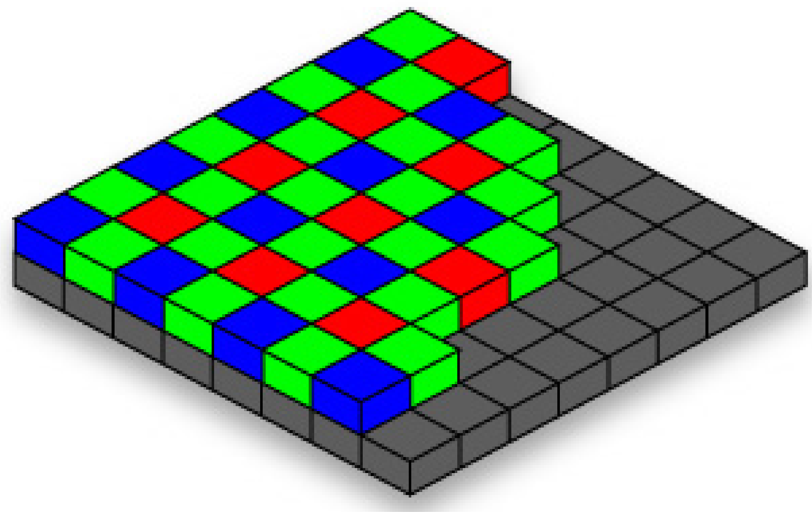
Stuff Works

Why 3 colors?

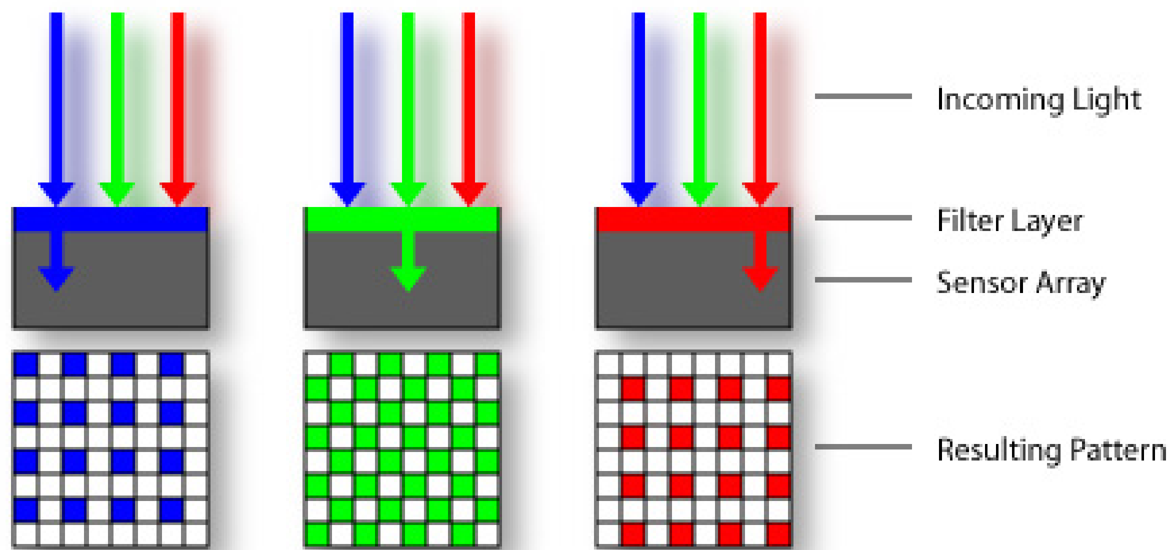
http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Practical Color Sensing: Bayer Grid





Estimate RGB
at ‘G’ cels from neighboring values



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

RGB color space

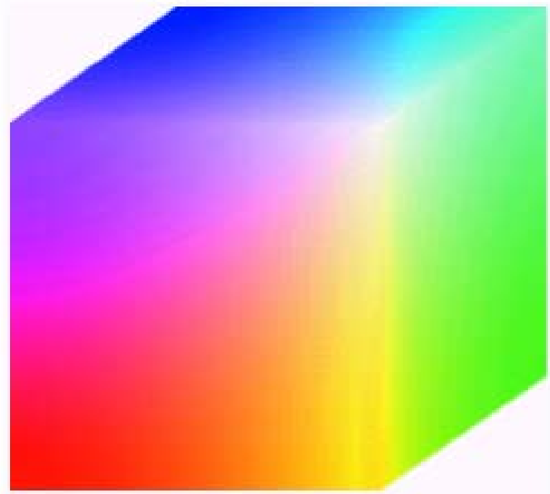
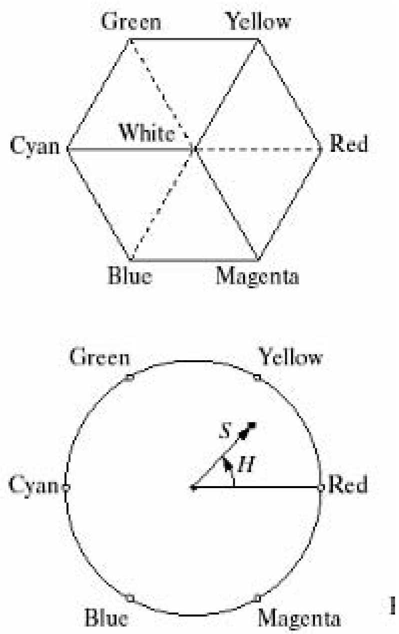


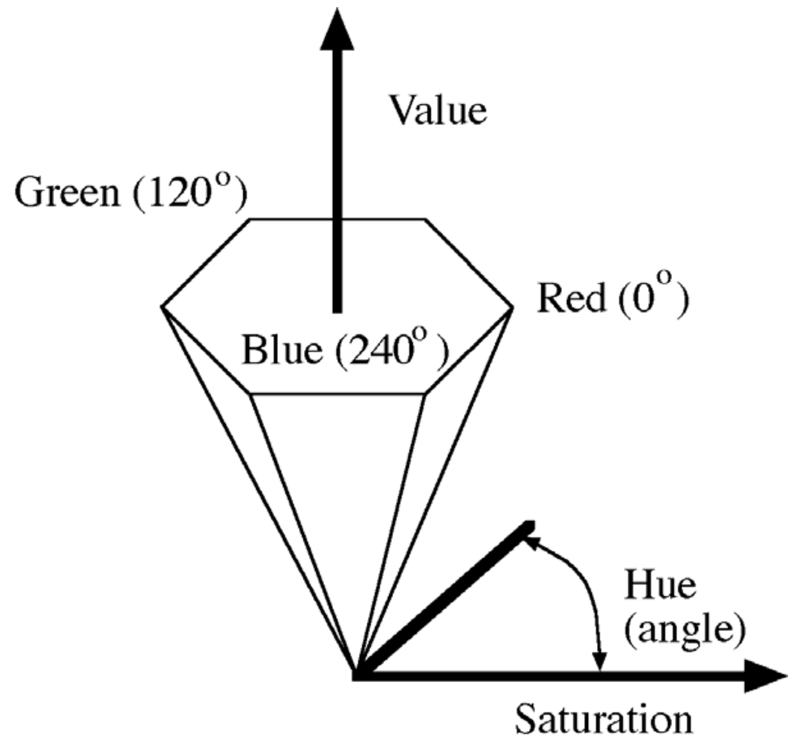
FIGURE 6.8 RGB 24-bit color cube.

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

Programming Assignment #1

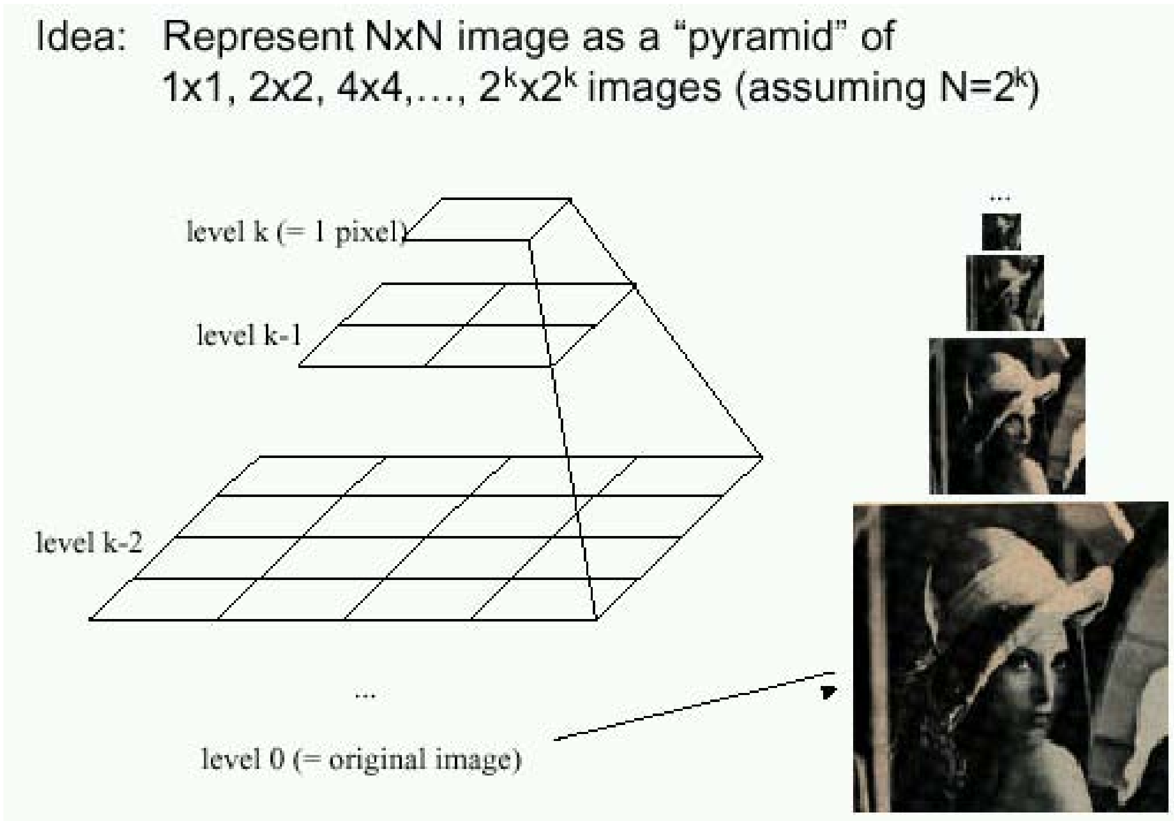
- How to compare R,G,B channels?
- No right answer
  - Sum of Squared Differences (SSD):

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

  - Normalized Correlation (NCC):

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

Image Pyramids (preview)



Known as a **Gaussian Pyramid** [Burt and Adelson, 1983]

- In computer graphics, a *mip map* [Williams, 1983]
- A precursor to *wavelet transform*

White Balance

White World / Gray World assumptions

Image Formation

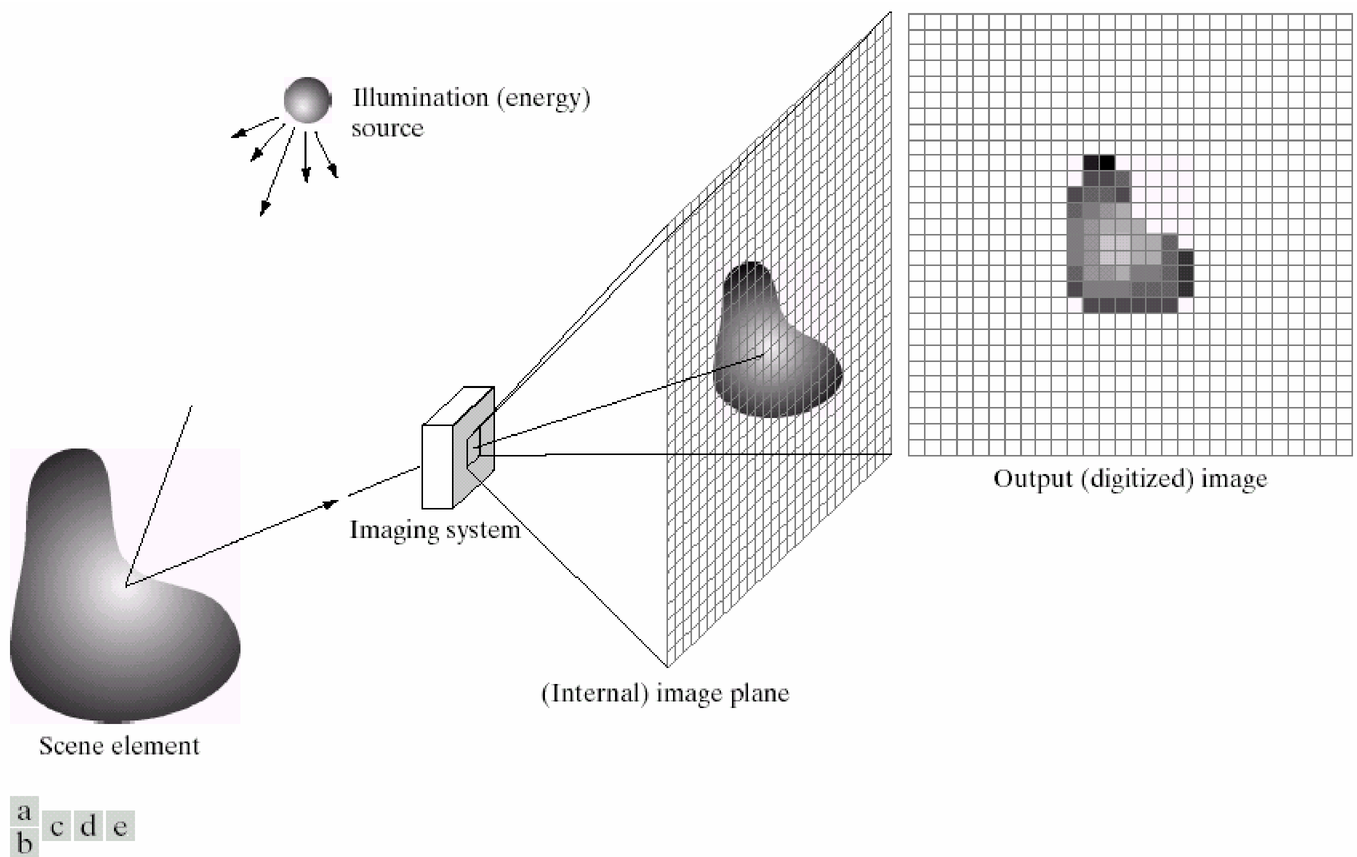


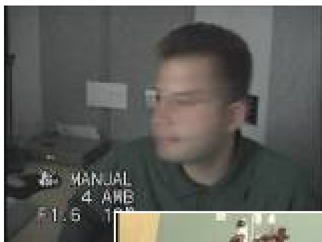
FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

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

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

Problem: Dynamic Range

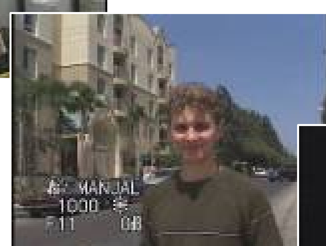
The real world is
High dynamic range



1

1500

25,000

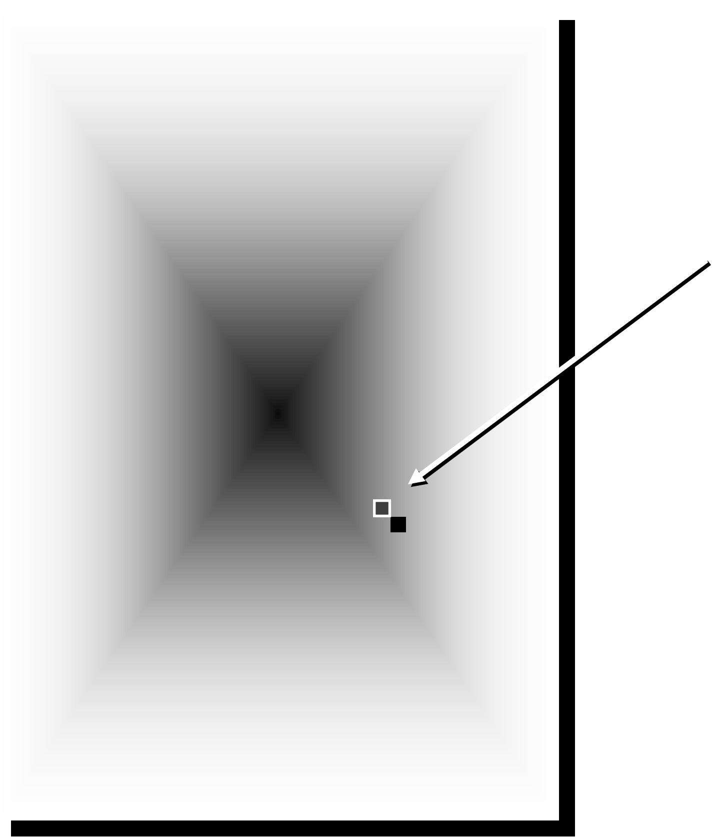


400,000

2,000,000,000

Is Camera a photometer?

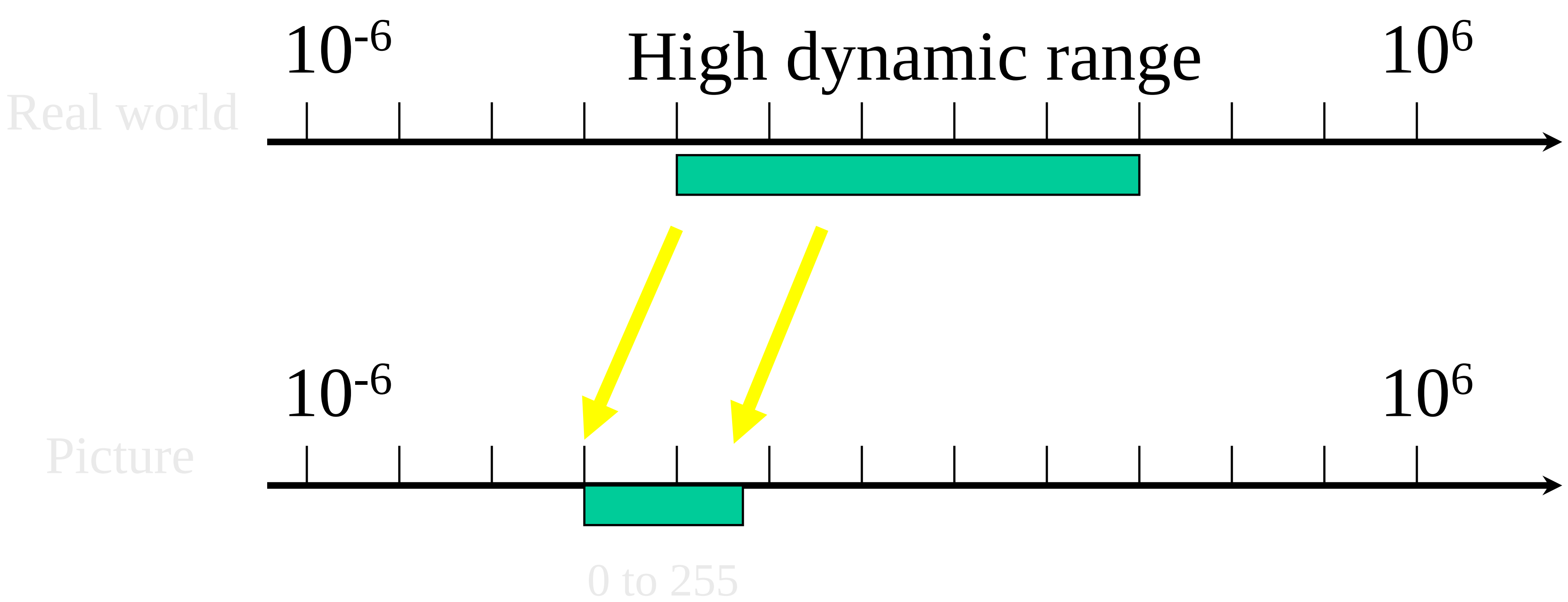
Image



pixel (312, 284) = 42

42 photos?

Long Exposure



Short Exposure

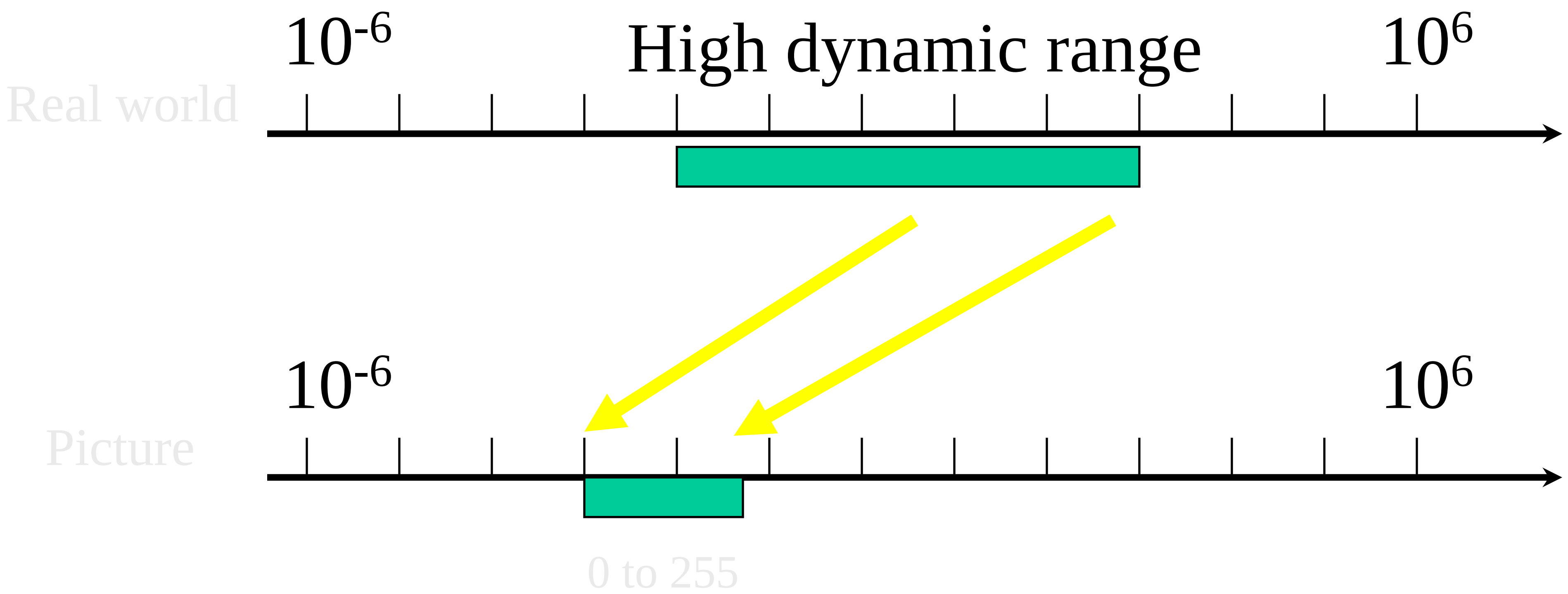
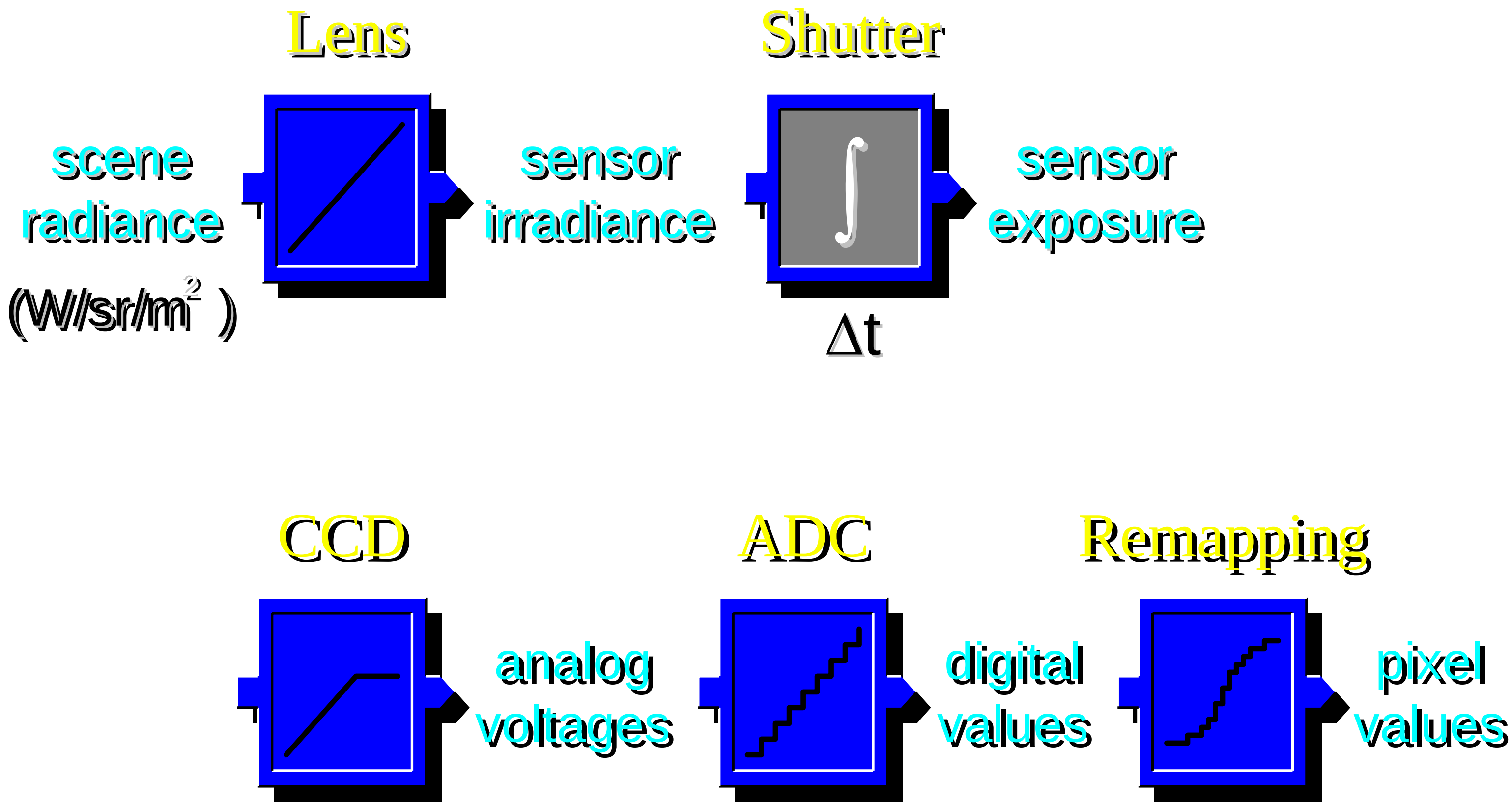


Image Acquisition Pipeline



Camera is NOT a photometer!

Varying Exposure

What does the eye sees?

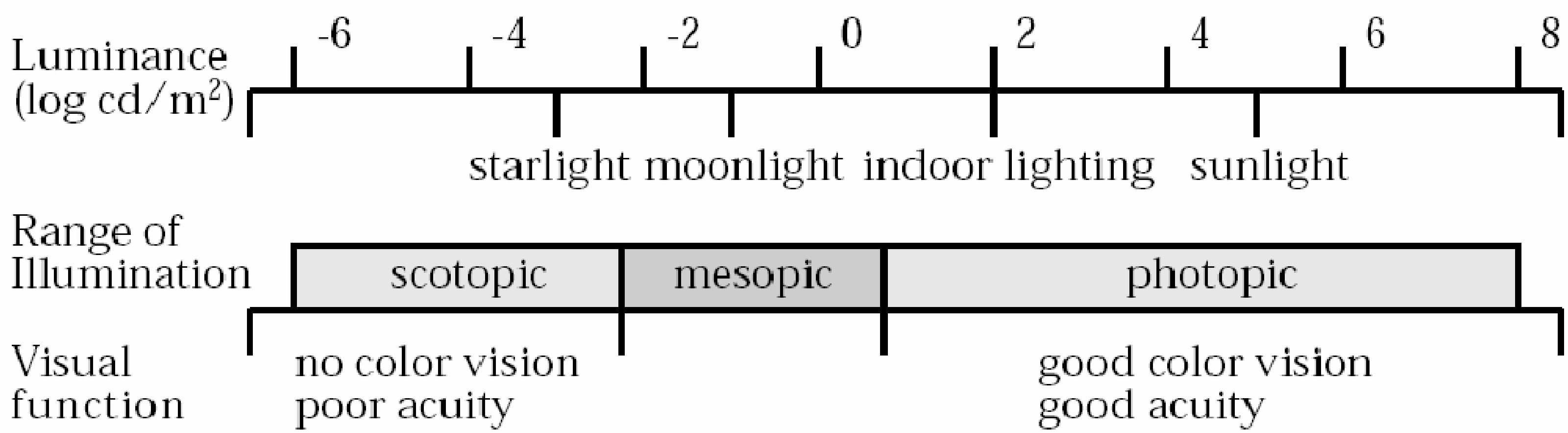
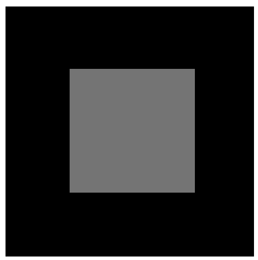


Figure 1: The range of luminances in the natural environment and associated visual parameters. After Hood (1986).

The eye has a huge dynamic range
Do we see a true radiance map?

Eye is not a photometer!

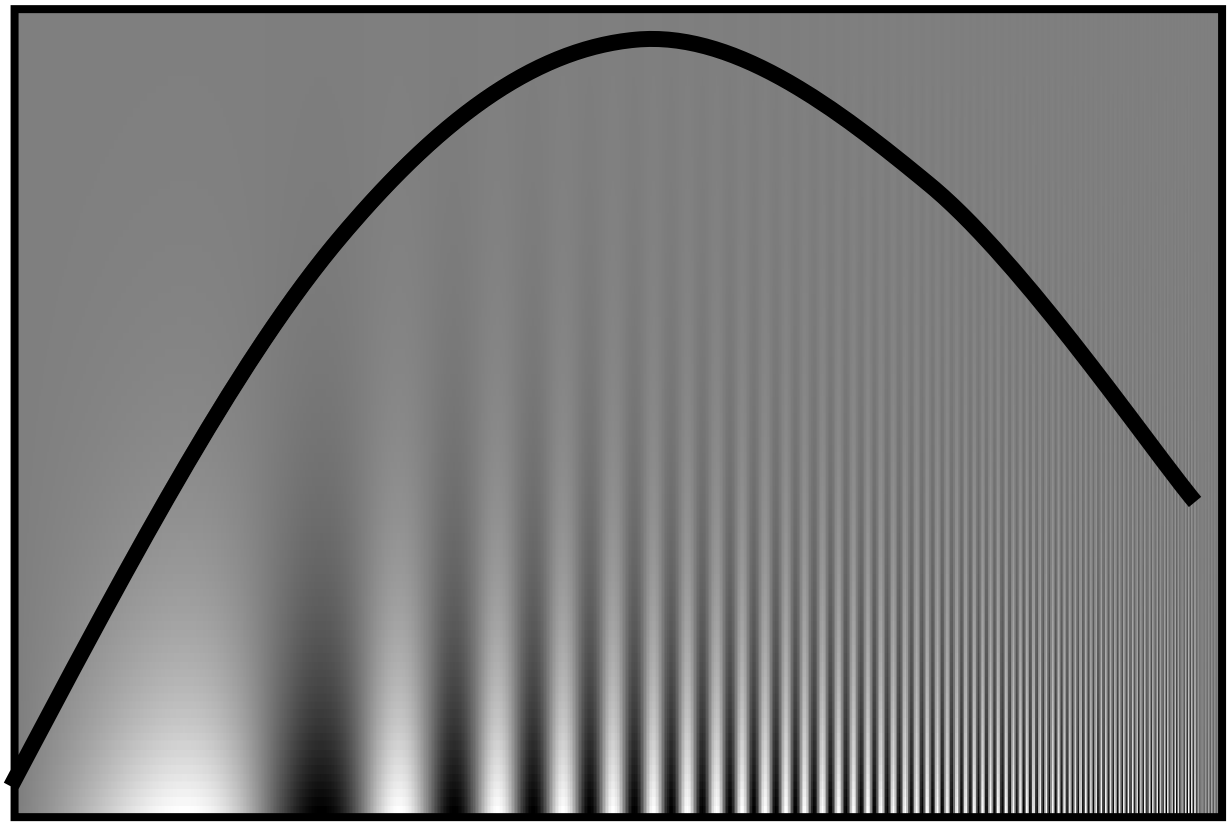


"Every light is a shade, compared to the higher lights, till you come to the sun; and every shade is a light, compared to the deeper shades, till you come to the night."

— John Ruskin, 1879

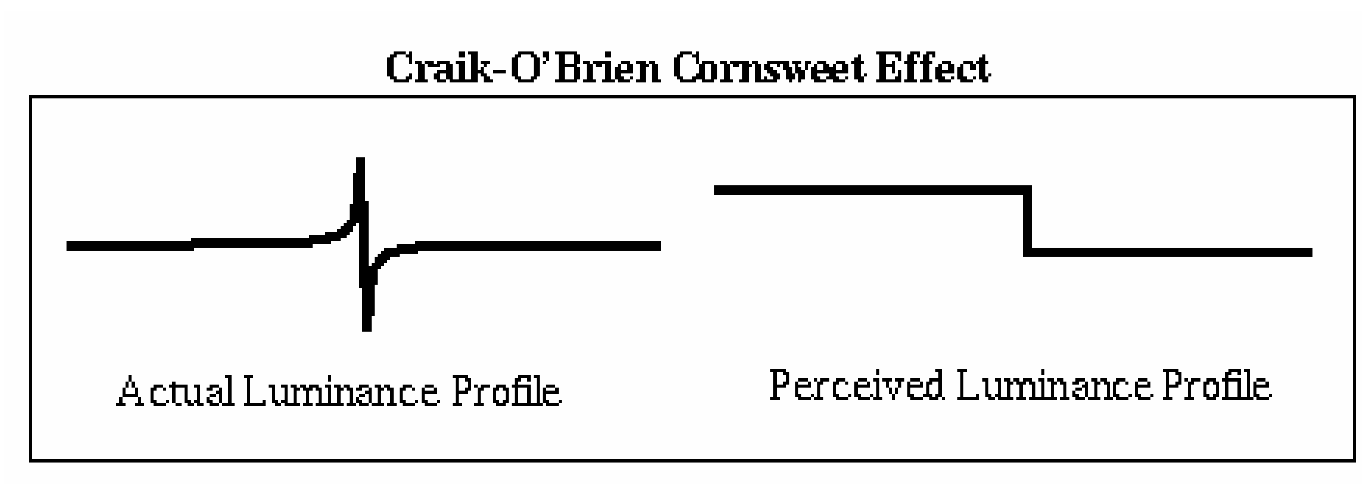
Cornsweet Illusion

Sine wave



Campbell-Robson contrast sensitivity curve

Metamers



Eye is sensitive to changes
(more on this later…)