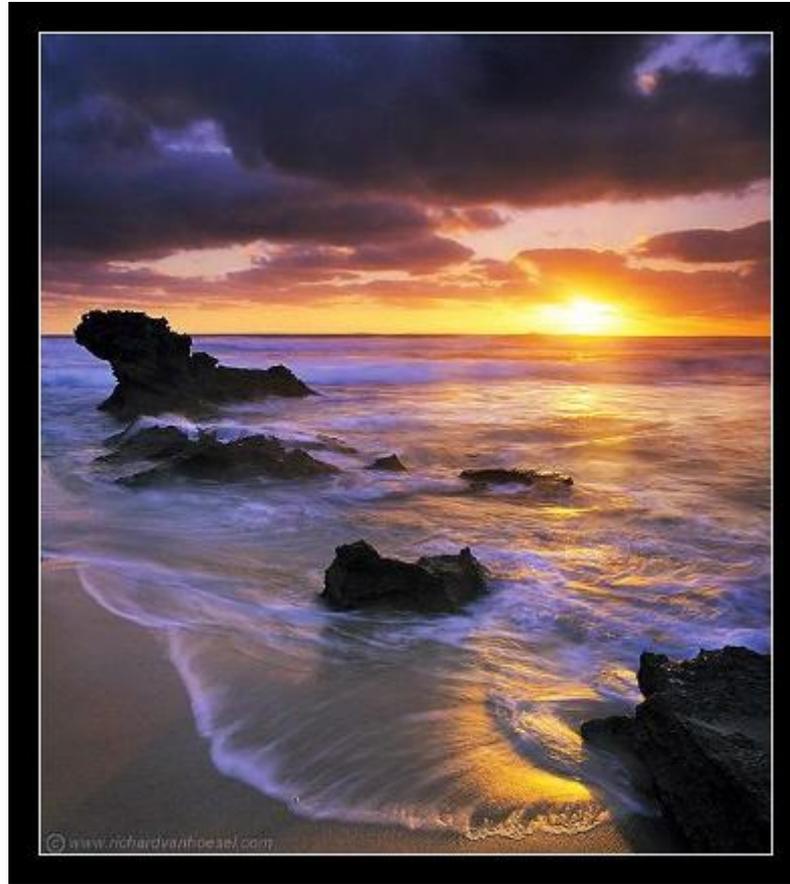# Capturing Light… in man and machine



15-463: Computational Photography
Alexei Efros, CMU, Fall 2010
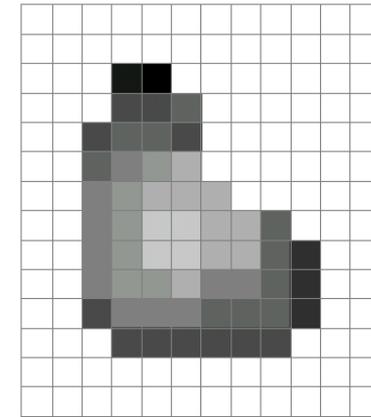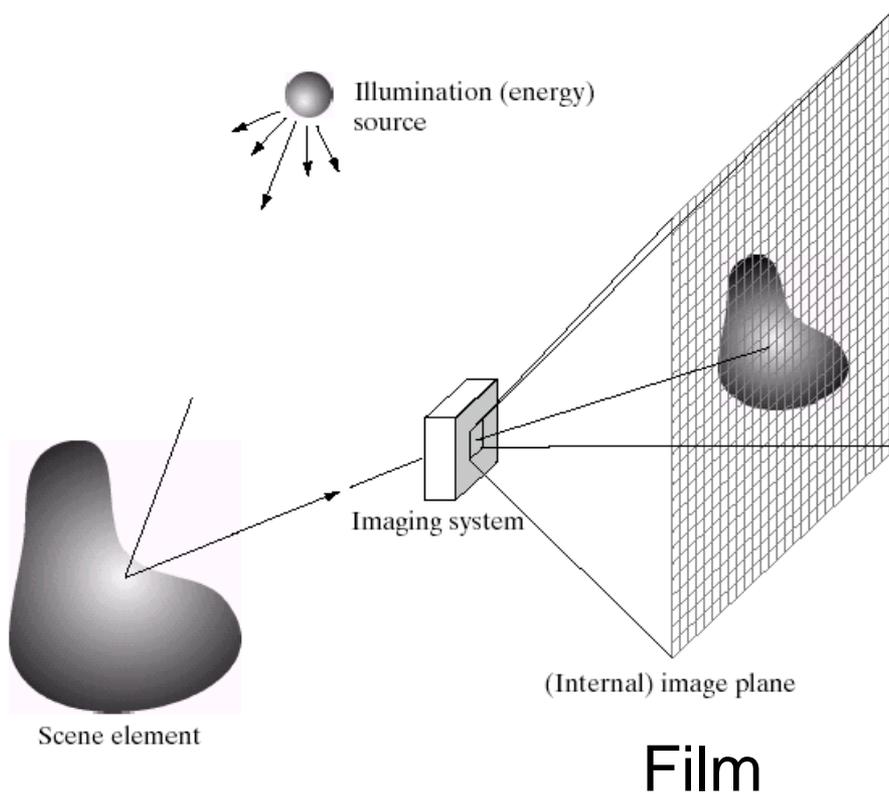
# Etymology

PHOTOGRAPHY

light

drawing / writing
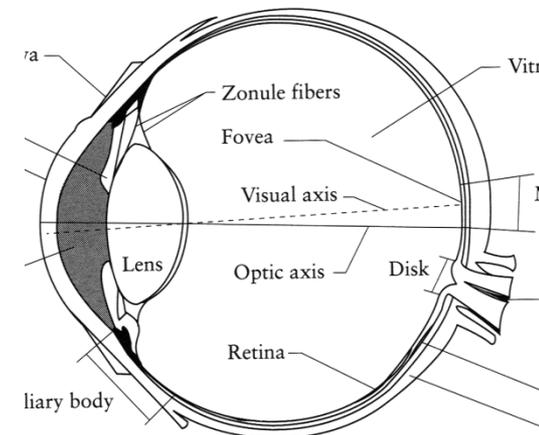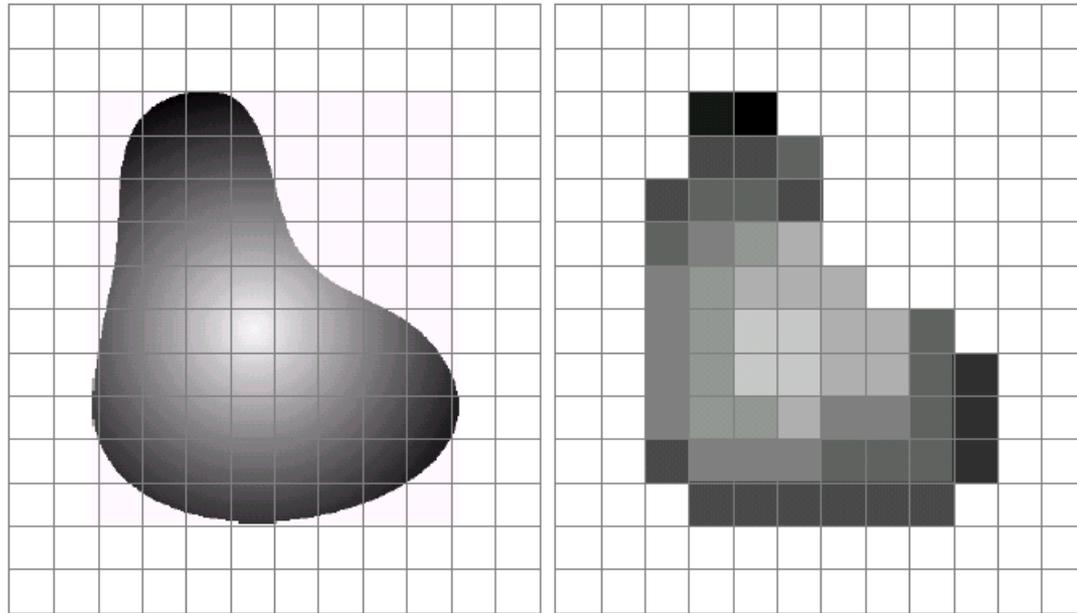
# Image Formation

Illumination (energy) source

Imaging system

(Internal) image plane

Scene element

**Film**

**Digital Camera**

Zonule fibers

Fovea

Visual axis

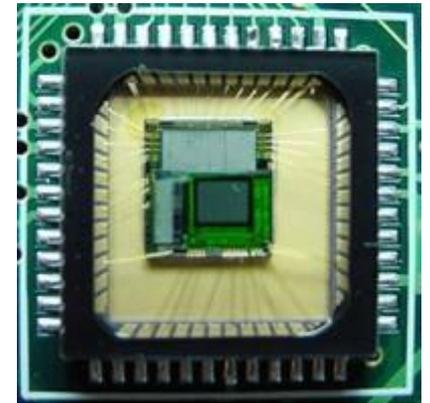Optic axis

Disk

Lens

Retina

liary body

**The Eye**

# Sensor Array



CMOS sensor

a b

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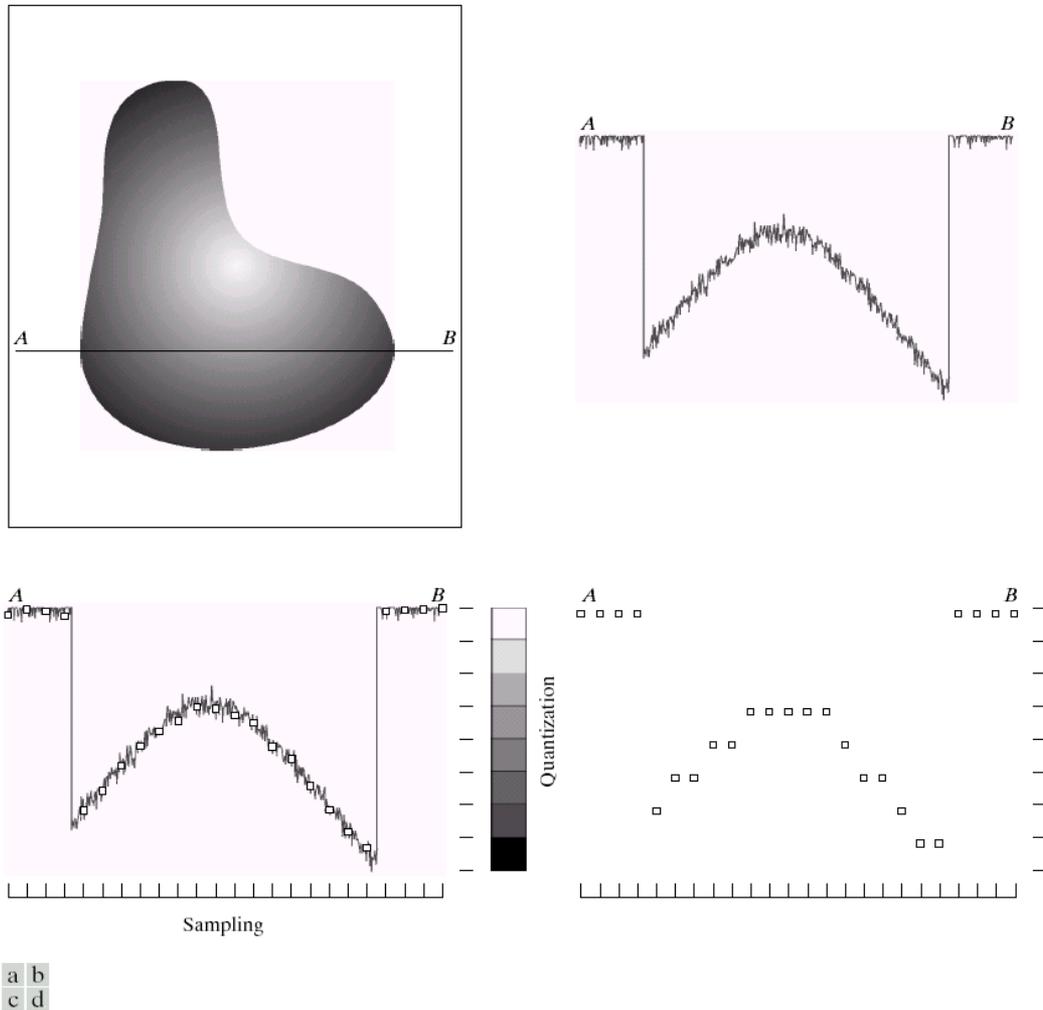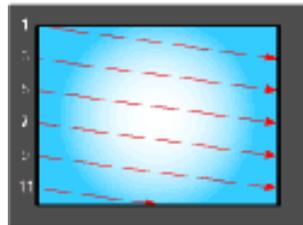
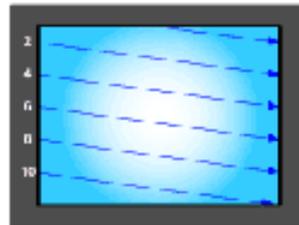# Sampling and Quantization



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.
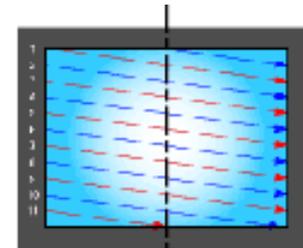
# Interlace vs. progressive scan
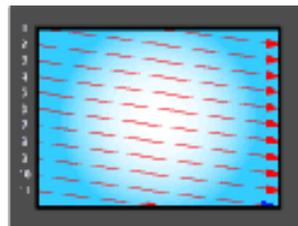


1st field: Odd field

2nd field: Even field

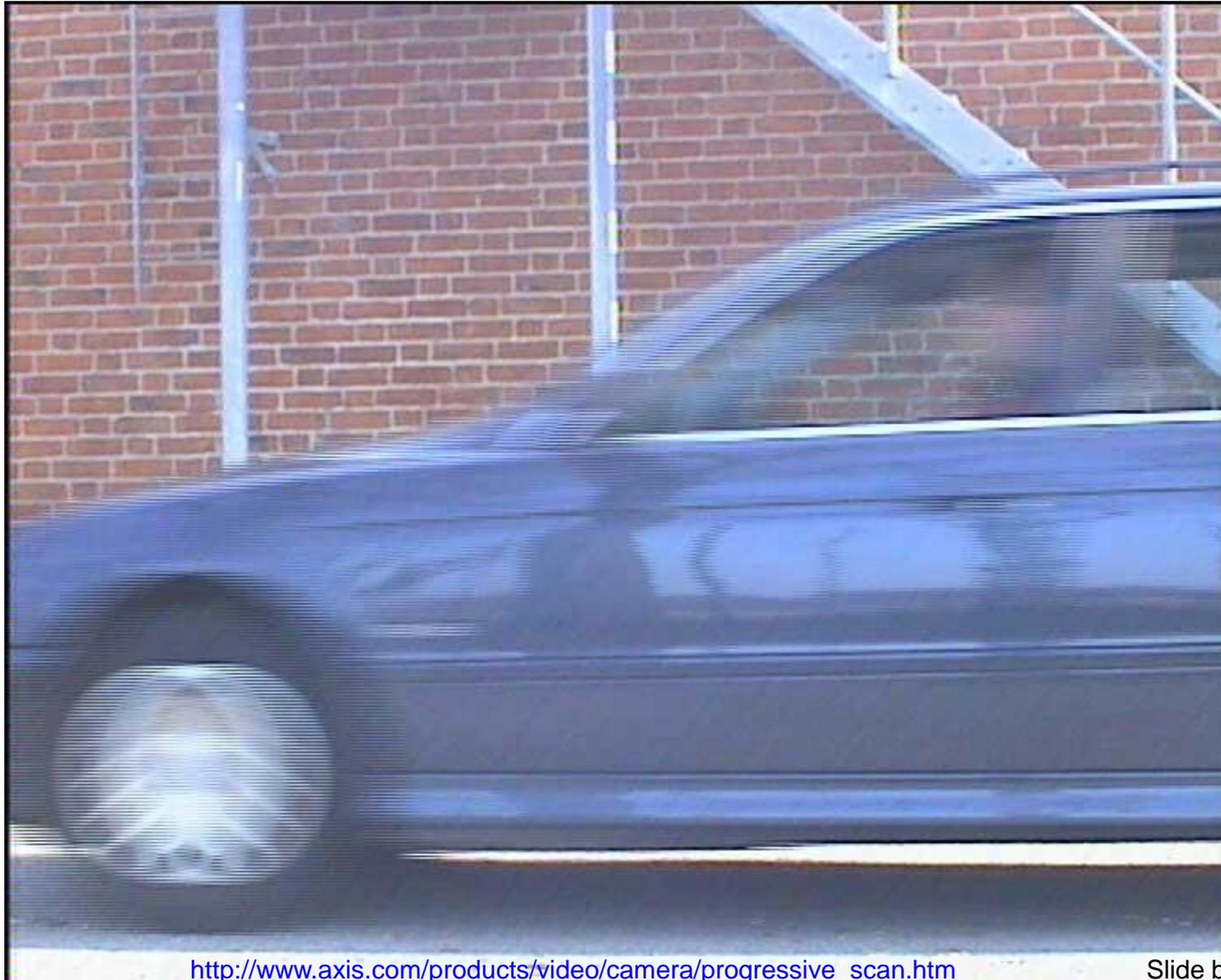One complete frame
using interlaced scanning

One complete frame
using progressive scanning

Slide by Steve Seitz

# Progressive scan

Slide by Steve Seitz

# Interlace

Slide by Steve Seitz
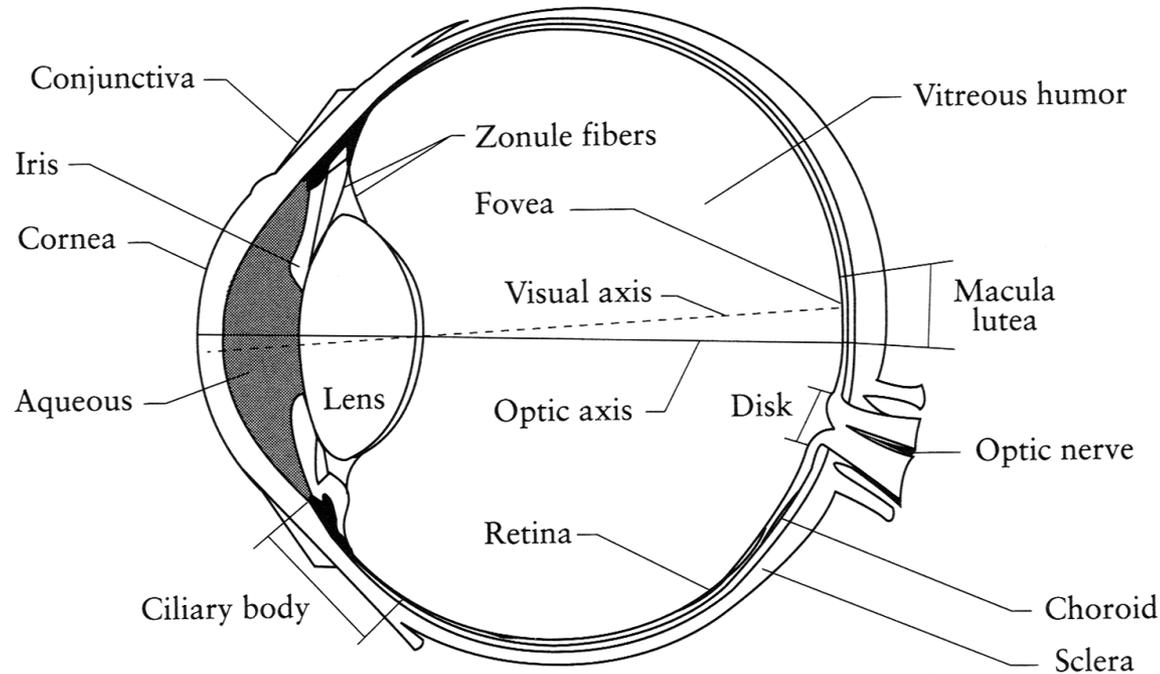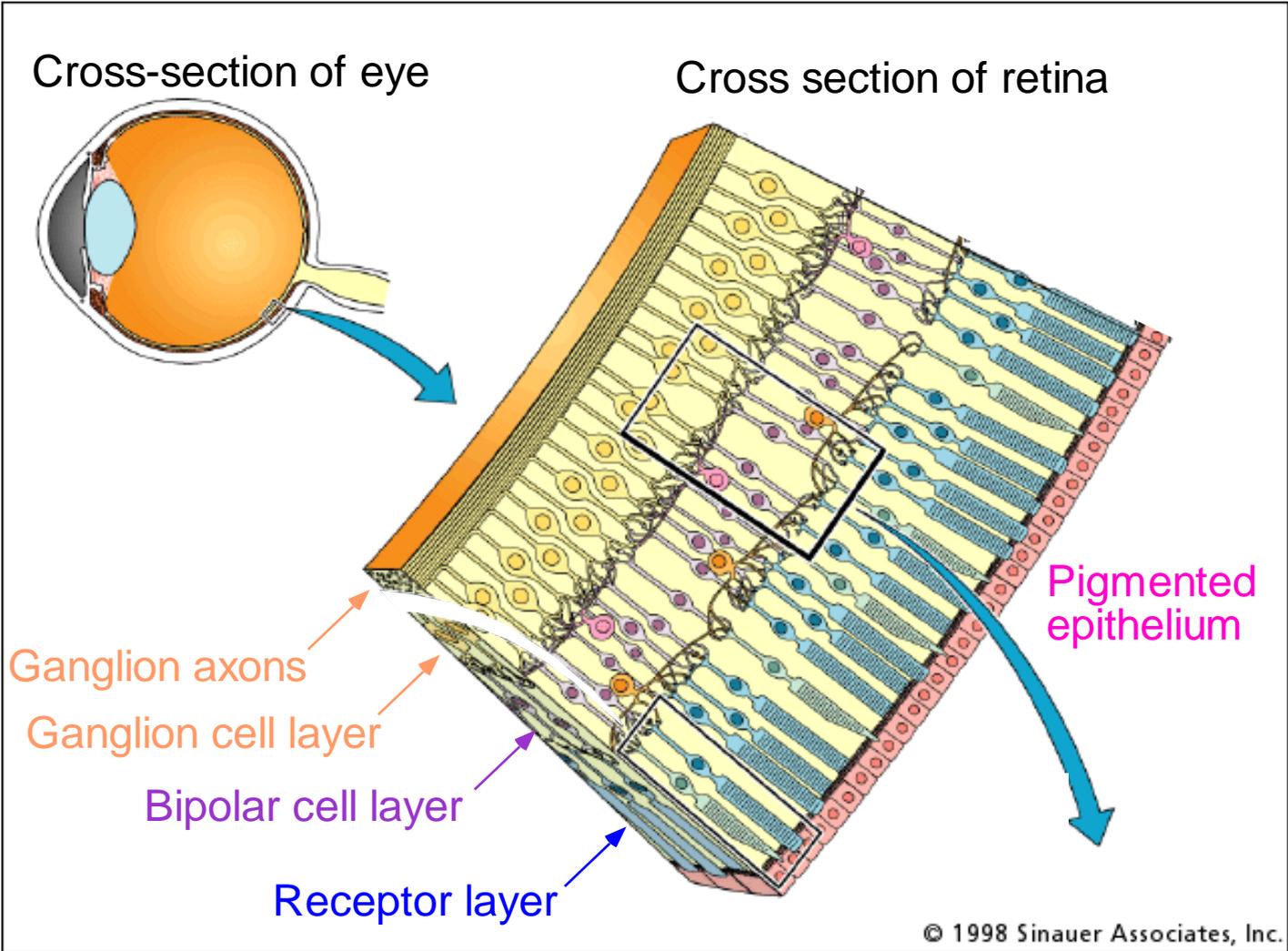
# The Eye



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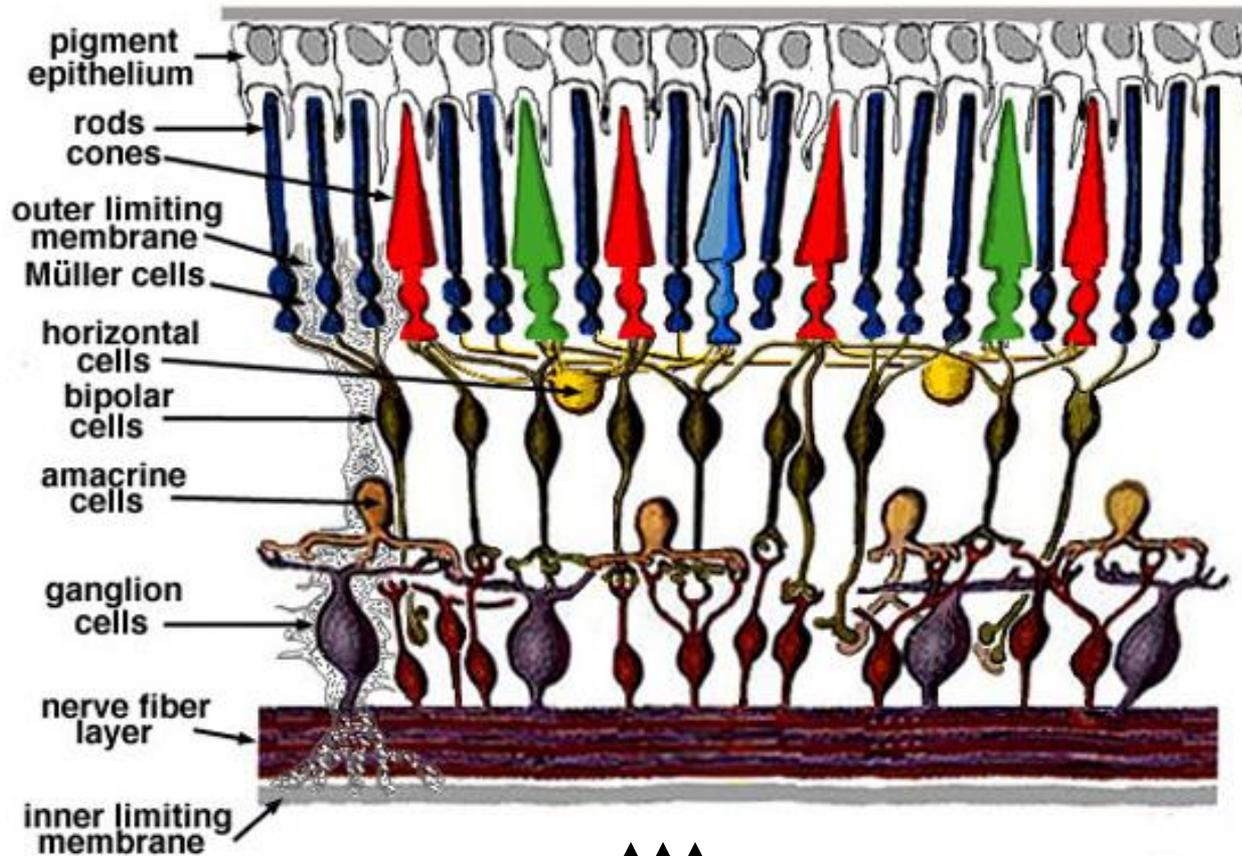
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

# The Retina



Cross-section of eye

Cross section of retina

Pigmented epithelium

Ganglion axons

Ganglion cell layer

Bipolar cell layer

Receptor layer

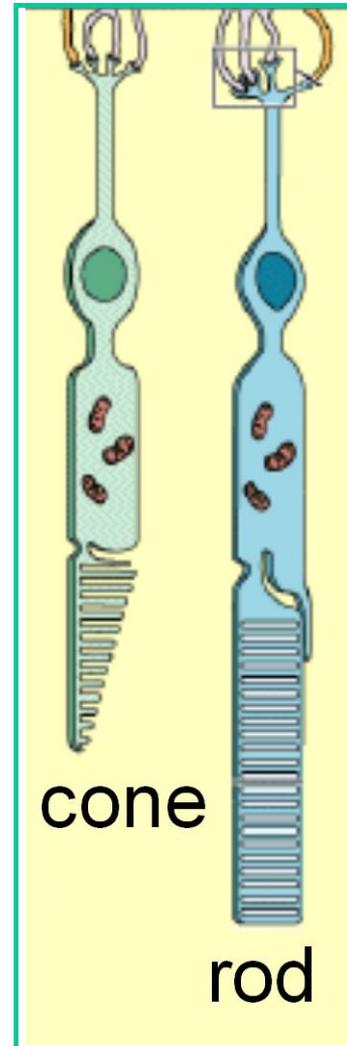© 1998 Sinauer Associates, Inc.

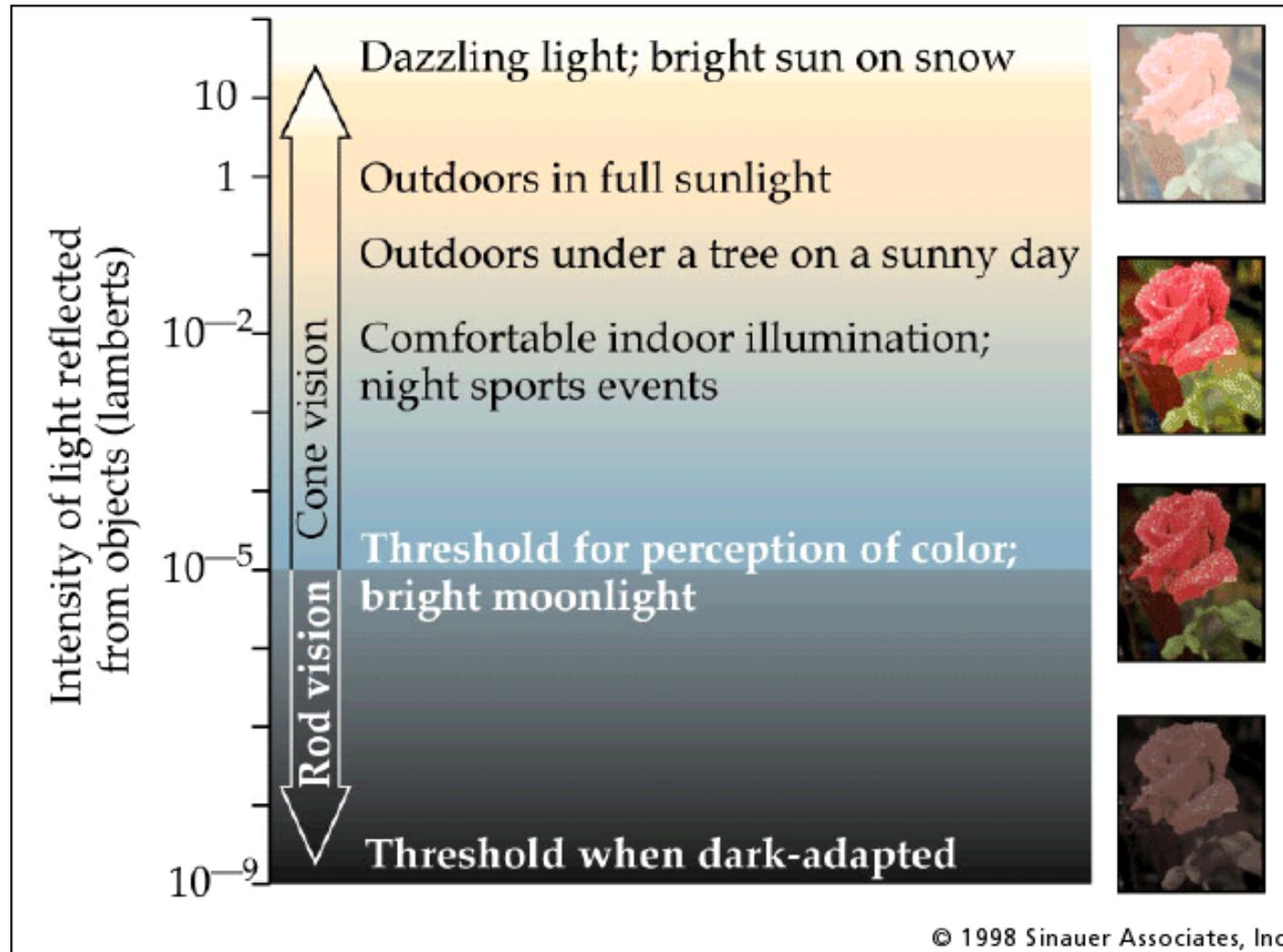# Retina up-close

# Two types of light-sensitive receptors

**Cones**
cone-shaped
less sensitive
operate in high light
color vision

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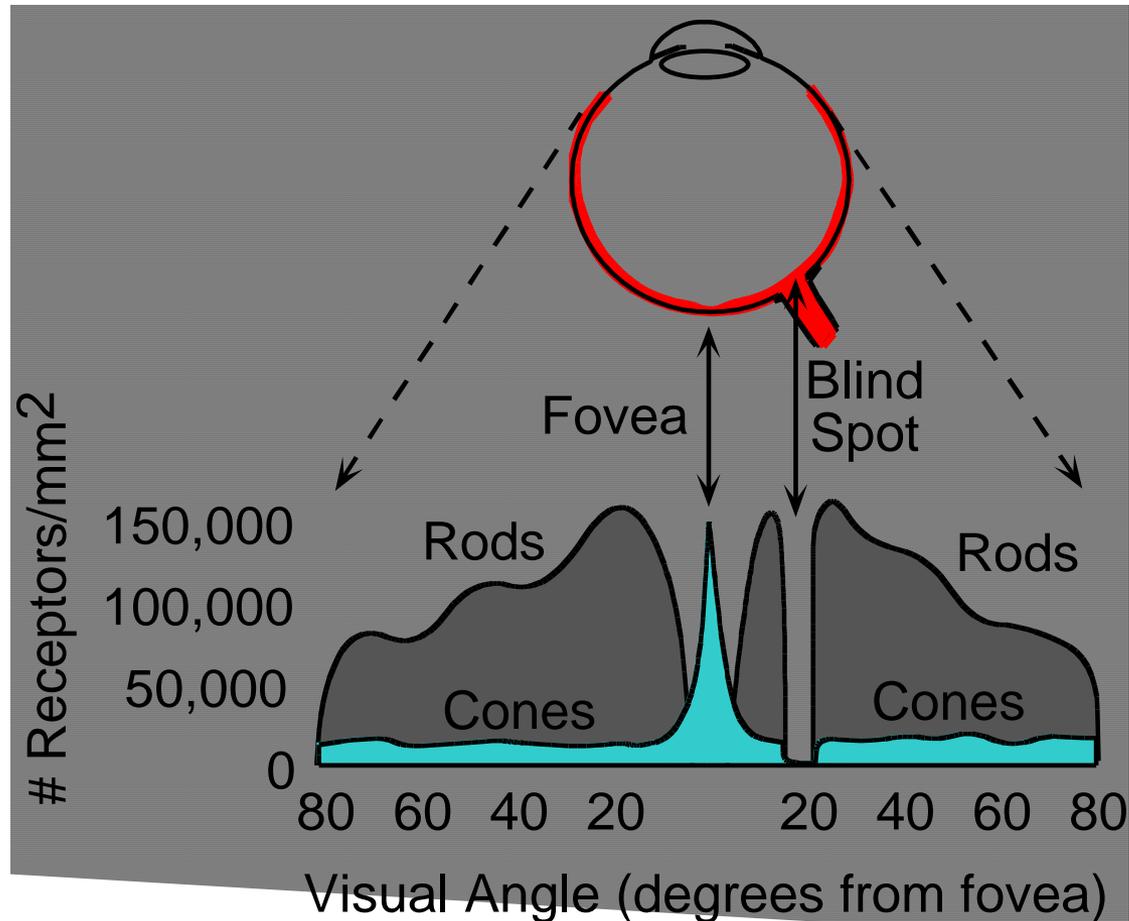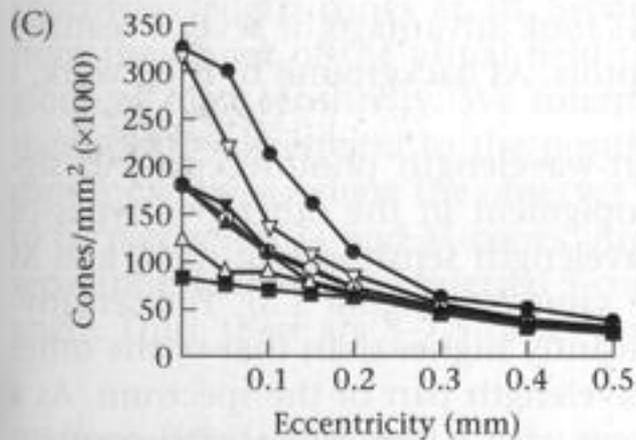operate at night
gray-scale vision

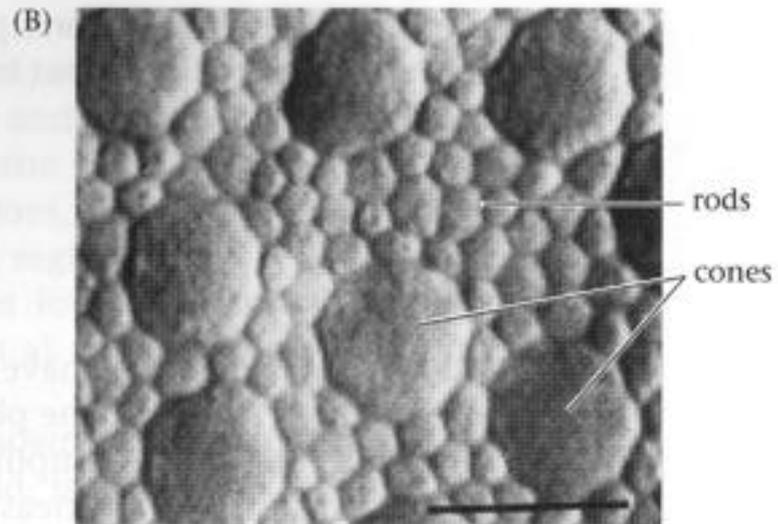cone

rod

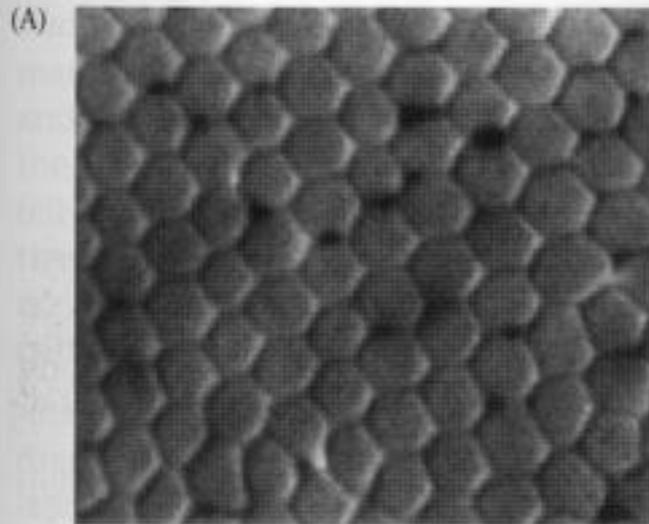# Rod / Cone sensitivity



The famous sock-matching problem…

# Distribution of Rods and Cones



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

(A)

(B)

rods

cones

(C)

Cones/mm² (×1000)

350
300
250
200
150
100
50
0

0.1   0.2   0.3   0.4   0.5

Eccentricity (mm)

**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 $\mu$m), 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.
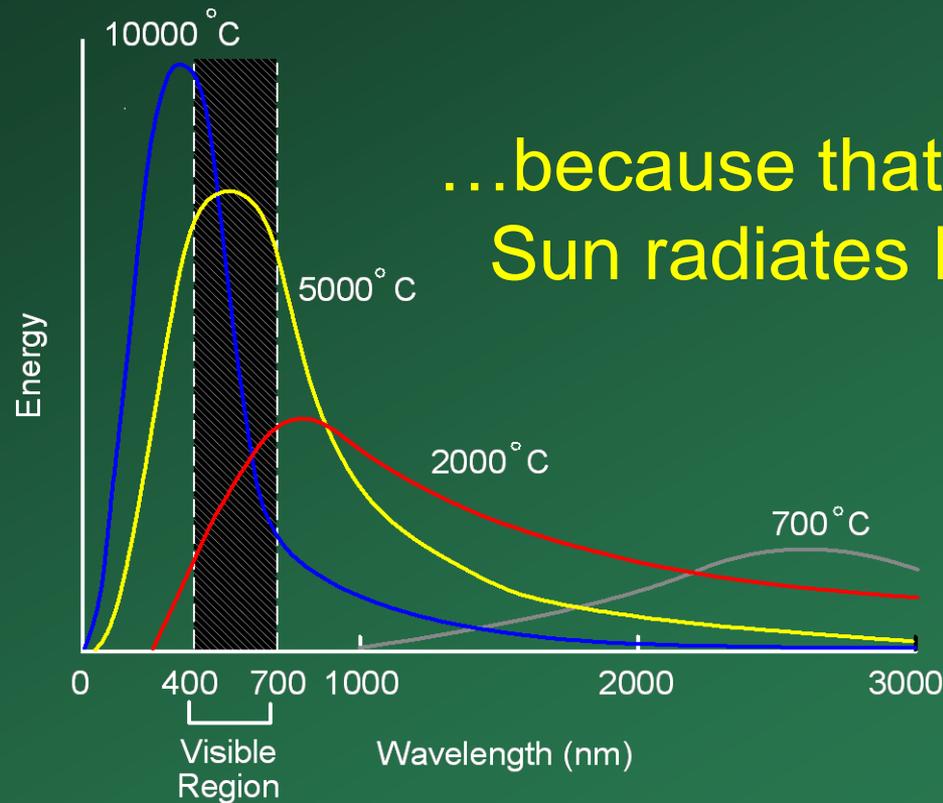
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

# Electromagnetic Spectrum
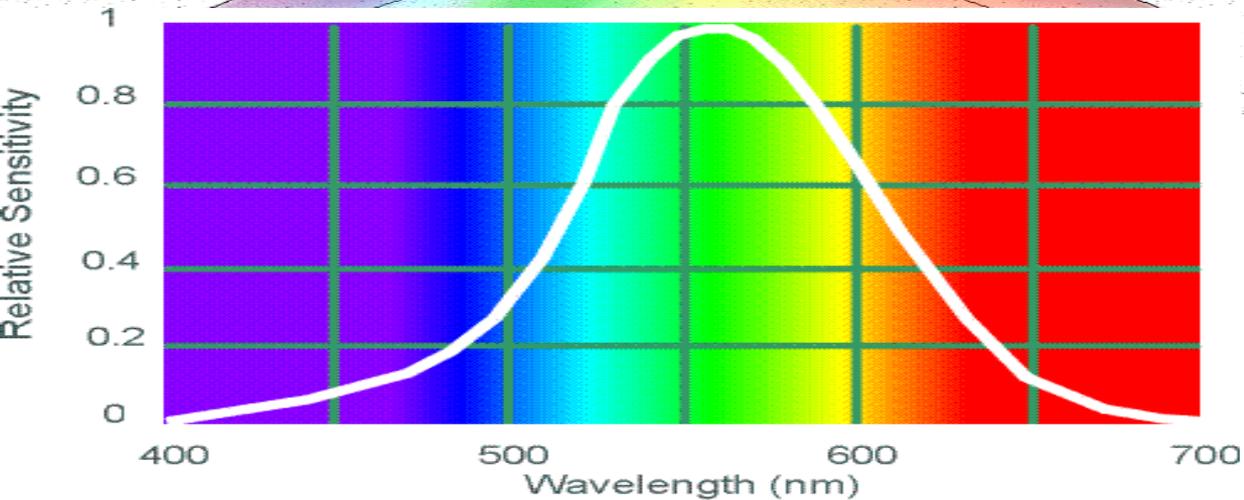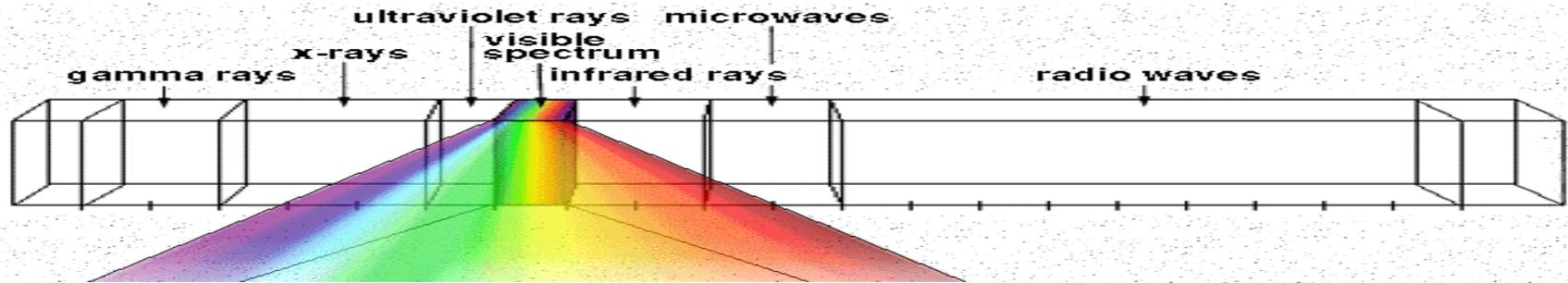


Human Luminance Sensitivity Function

# Visible Light



Why do we see light of these wavelengths?

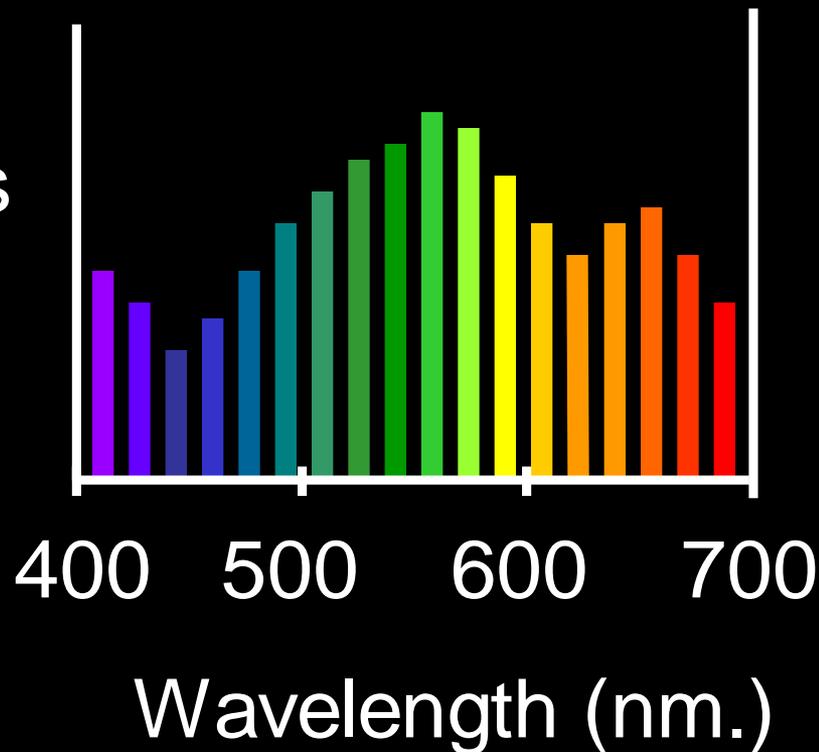…because that's where the Sun radiates EM energy

10000 °C

5000 °C

2000 °C

700 °C

Energy

0   400  700  1000        2000        3000

Wavelength (nm)

Visible Region

© Stephen E. Palmer, 2002

# 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.
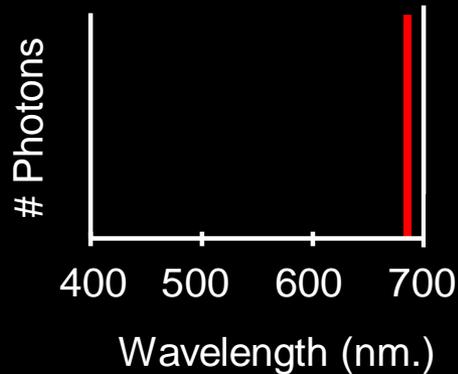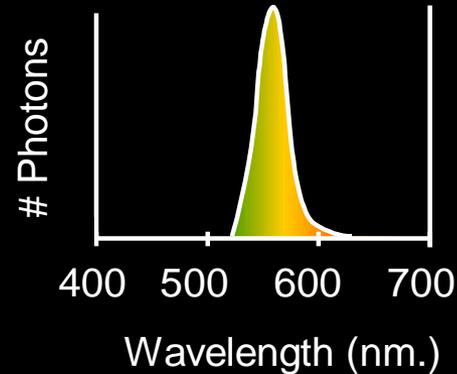
# Photons
(per ms.)

Wavelength (nm.)

400    500    600    700

# The Physics of Light
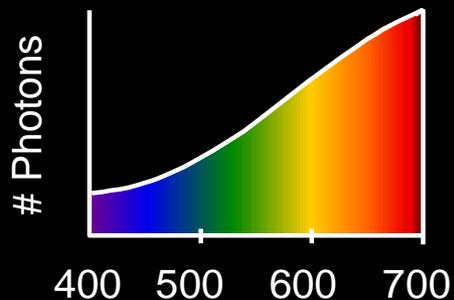
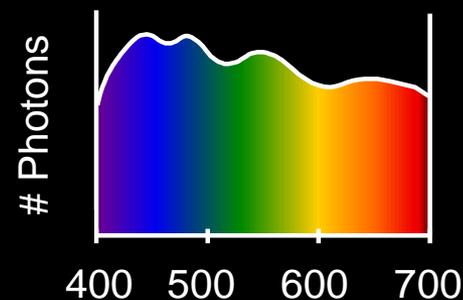## Some examples of the spectra of light sources

A.  Ruby Laser

B. Gallium Phosphide Crystal

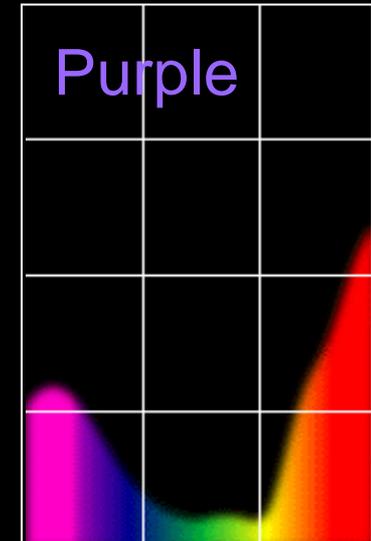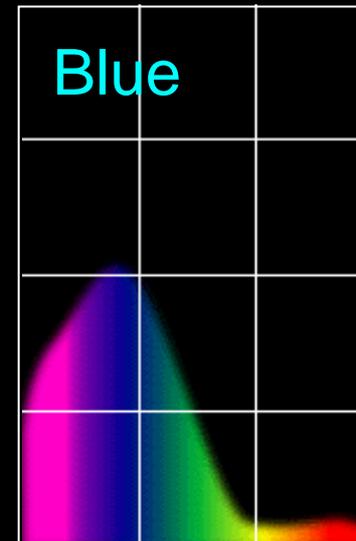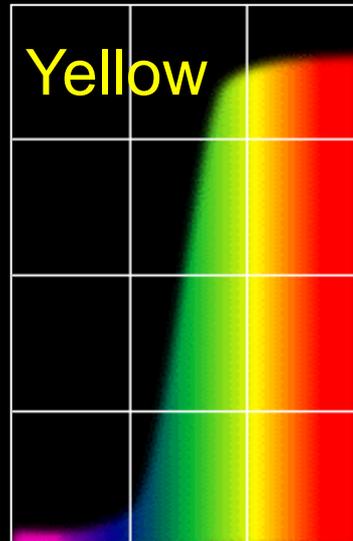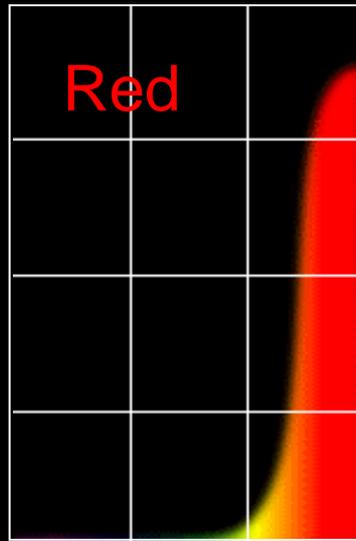C.  Tungsten Lightbulb

D.  Normal Daylight

# The Physics of Light

Some examples of the reflectance spectra of surfaces

Red    Yellow    Blue    Purple

% Photons Reflected

400    700  400    700  400    700  400    700

Wavelength (nm)

© Stephen E. Palmer, 2002
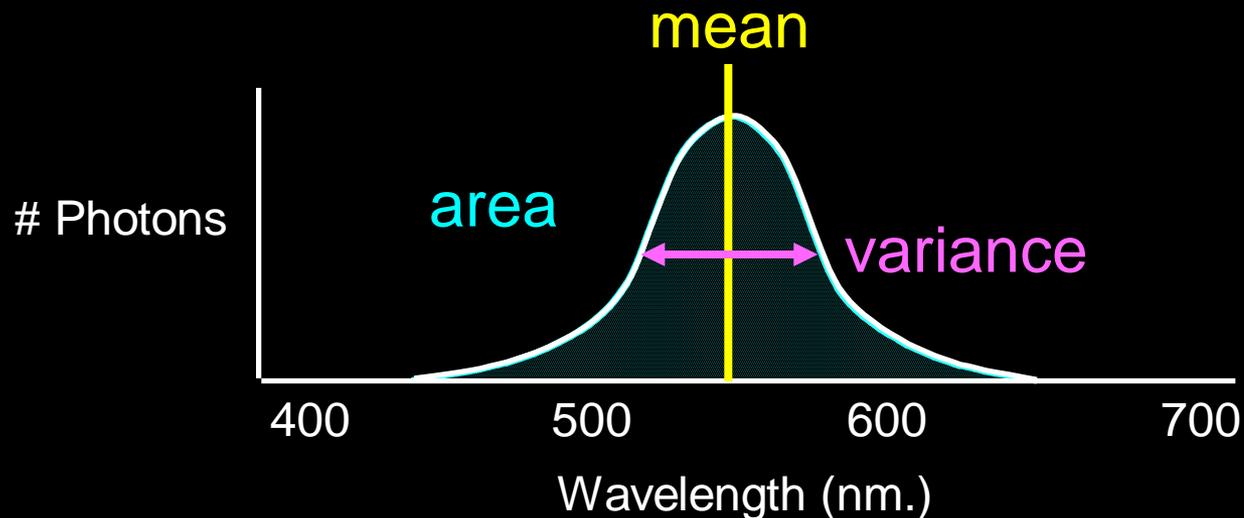
# The Psychophysical Correspondence

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

mean

# Photons

area

variance

400        500        600        700

Wavelength (nm.)

© Stephen E. Palmer, 2002
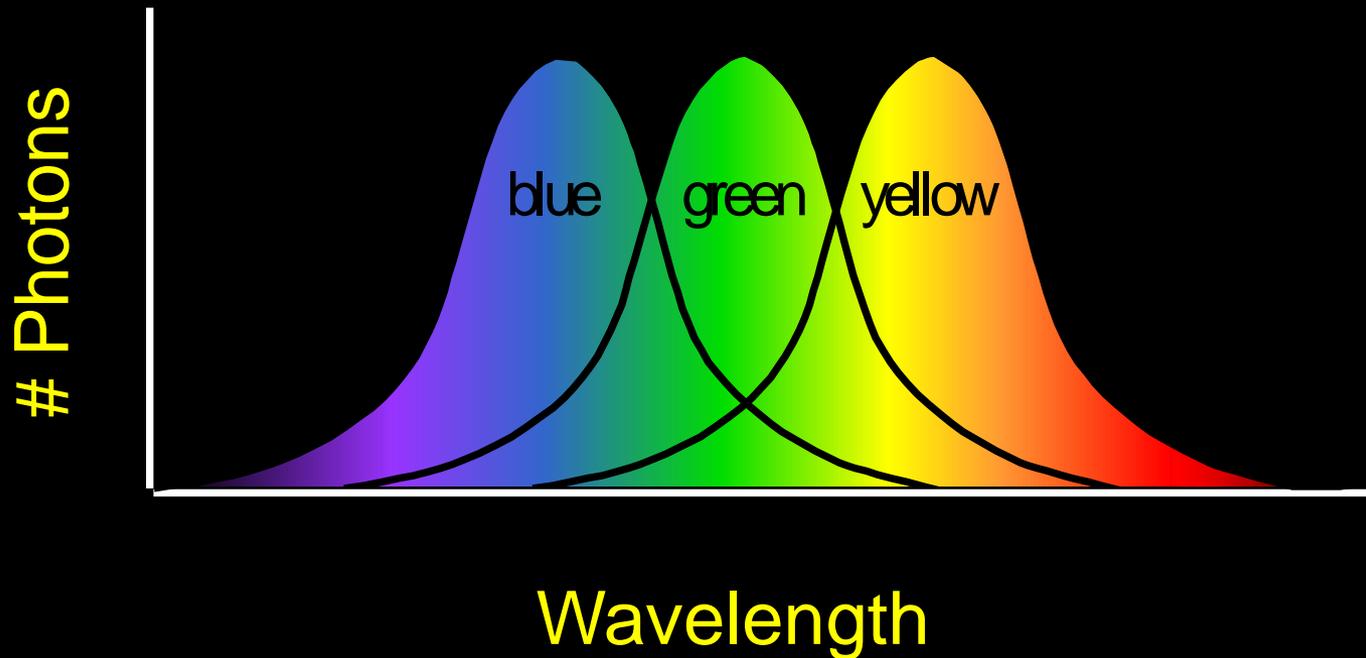
# The Psychophysical Correspondence

**Variance** ⟷ **Saturation**
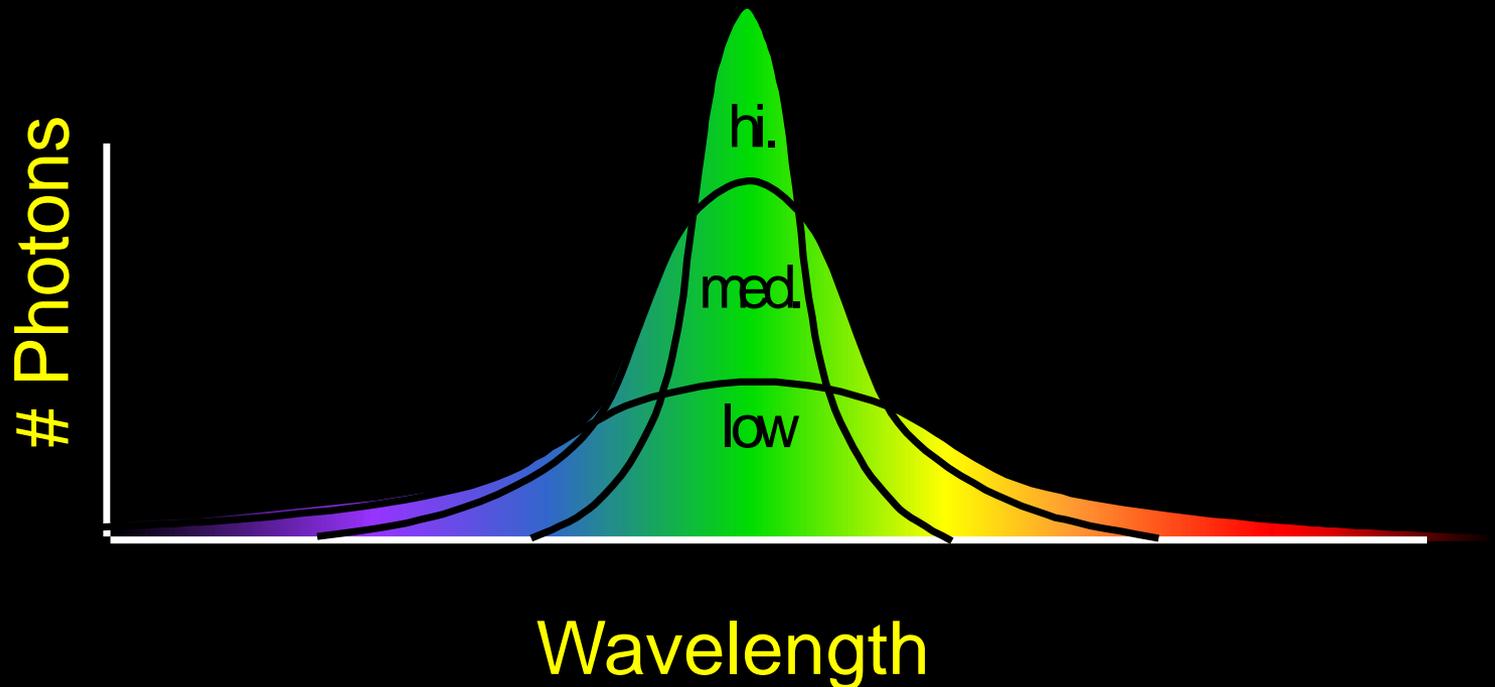
# The Psychophysical Correspondence

**Area** ⟷ **Brightness**

# Photons

bright

dark

Wavelength
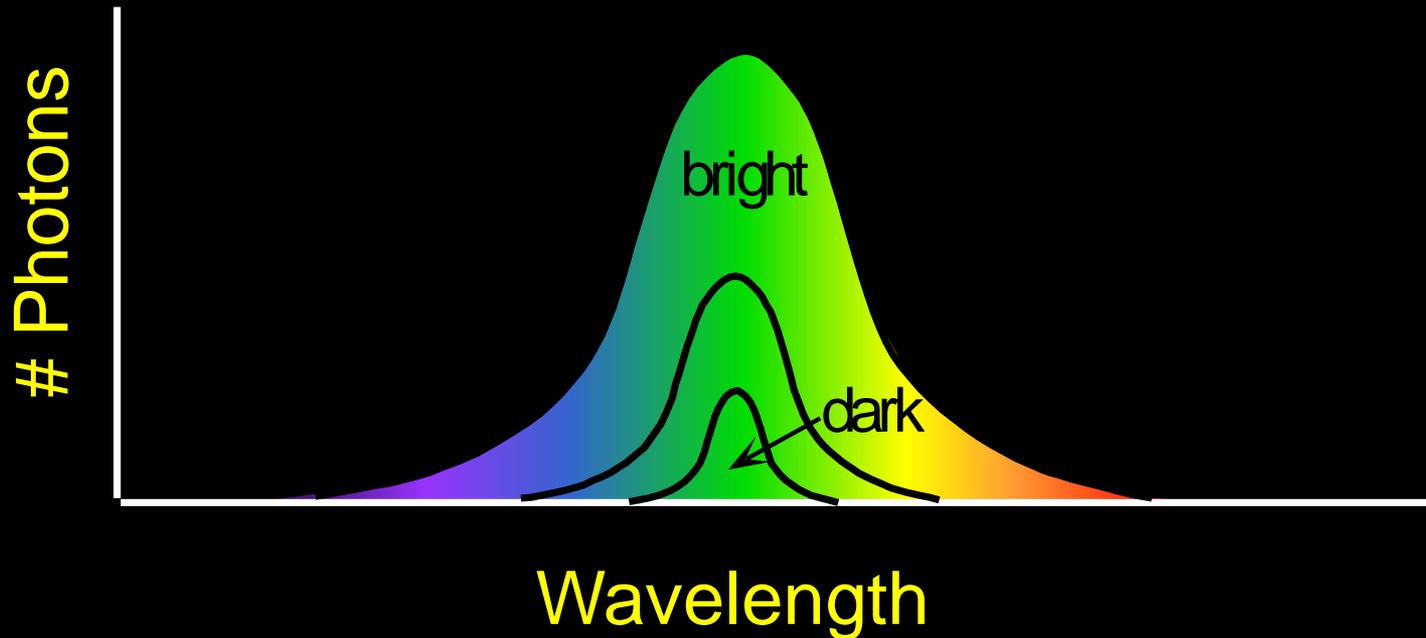
# Physiology of Color Vision

Three kinds of cones:



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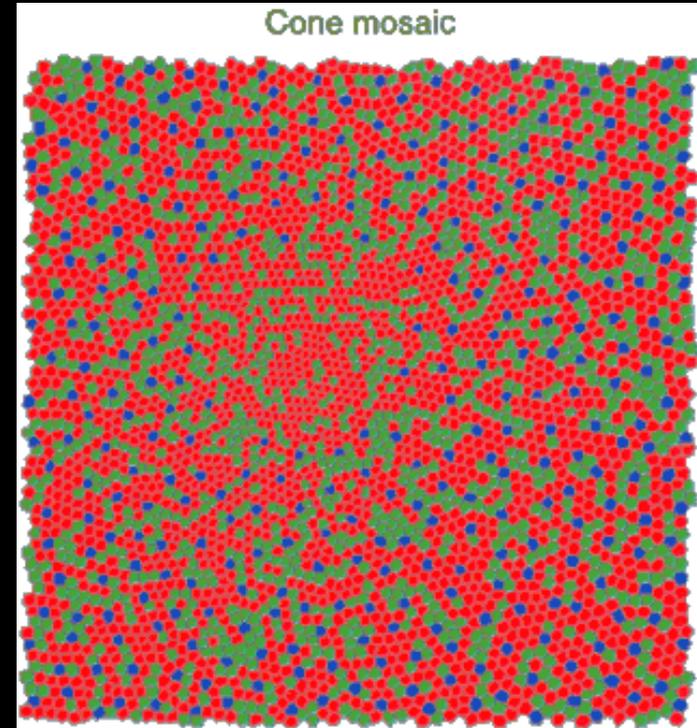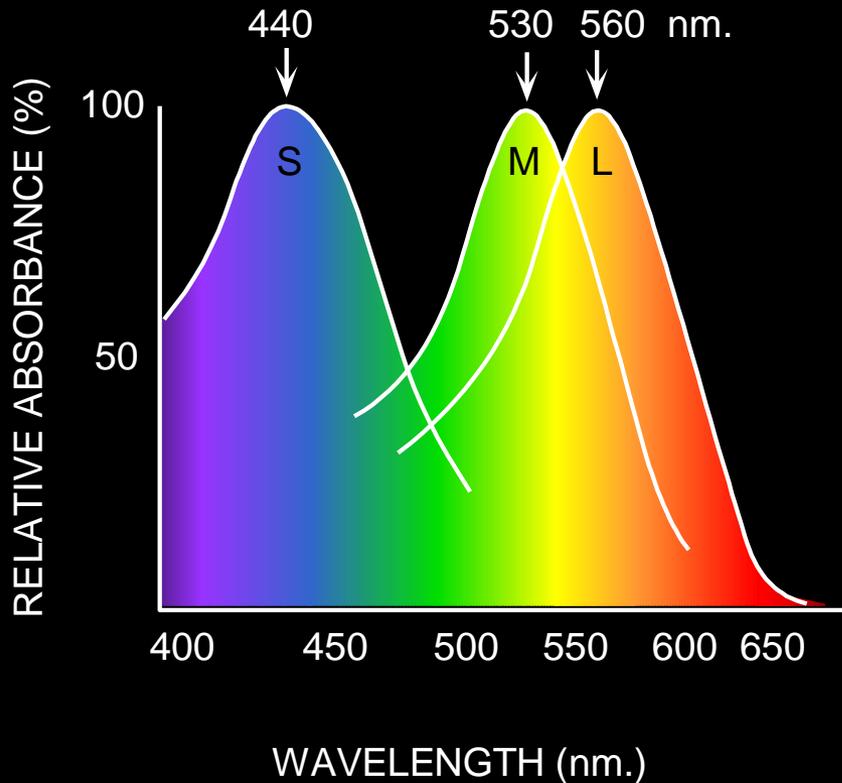
- Why are M and L cones so close?
- Why are there 3?

# More Spectra
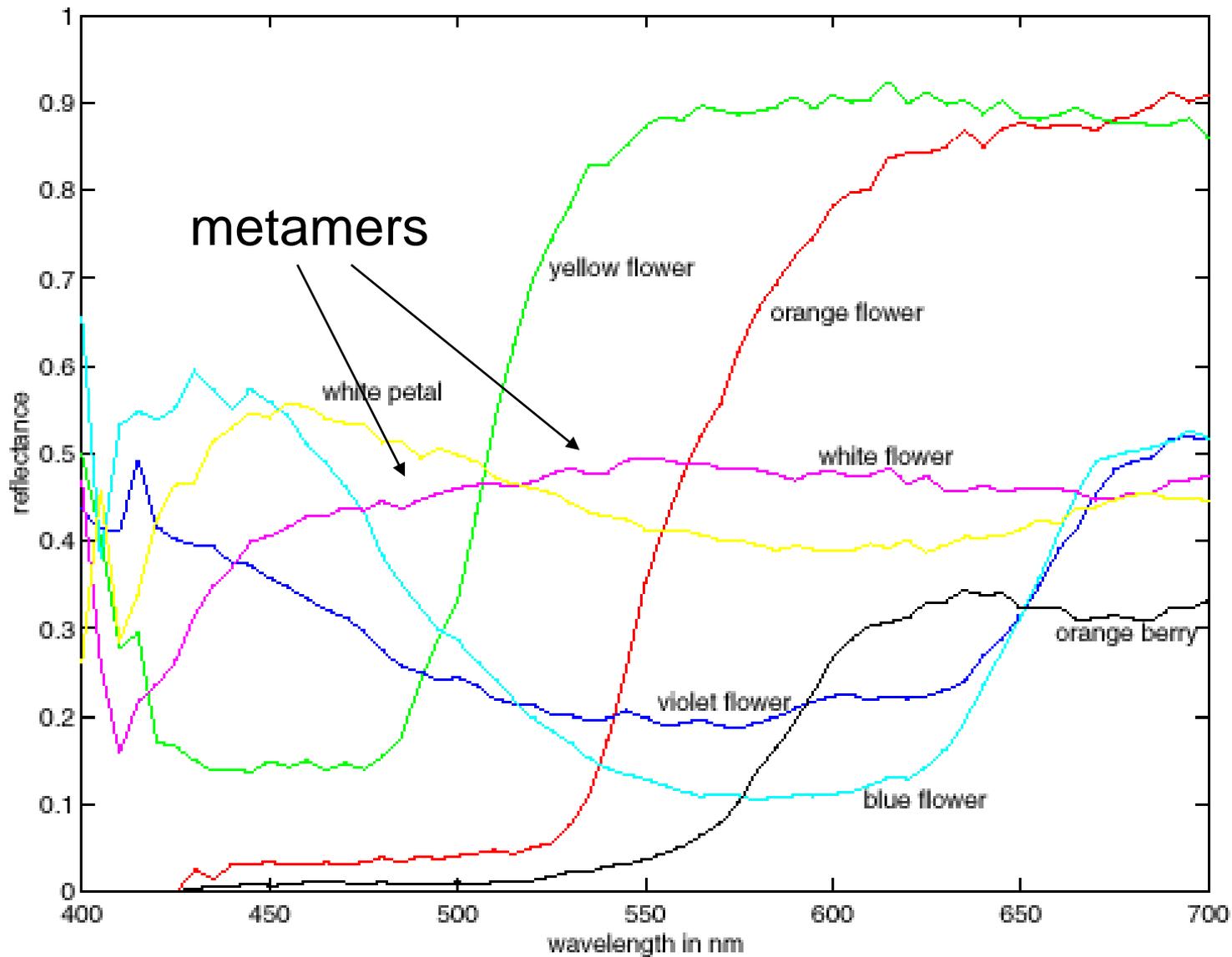
# Color Constancy

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

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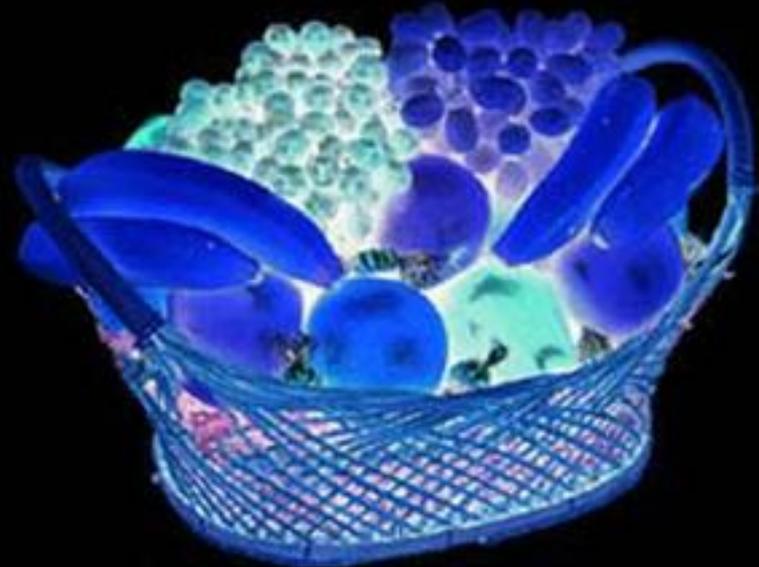
# Color Constancy

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
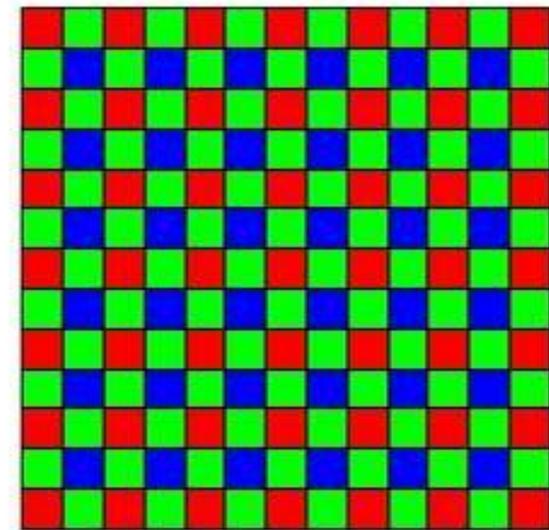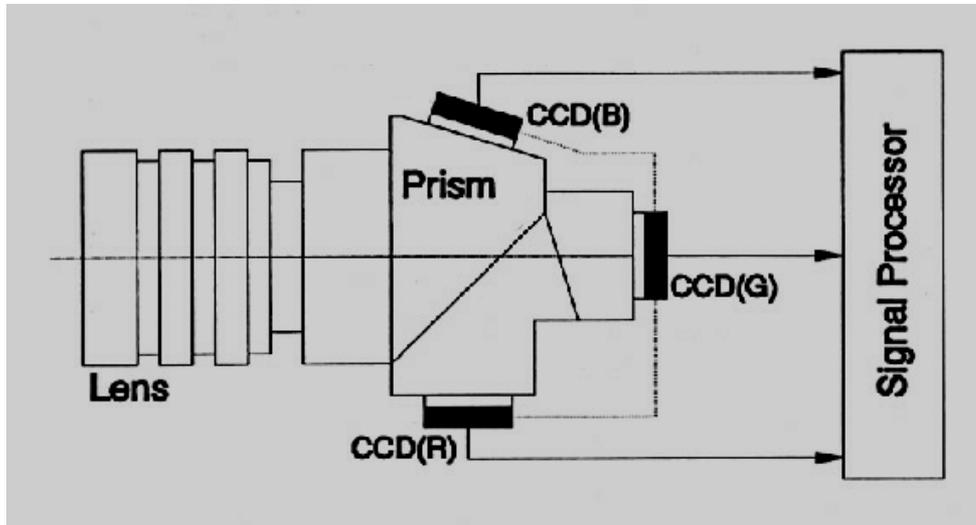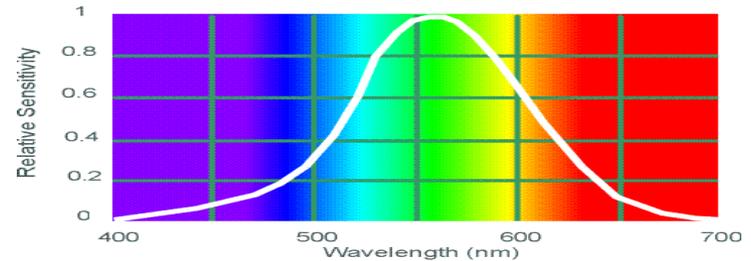
# Camera White Balancing




- ## 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)

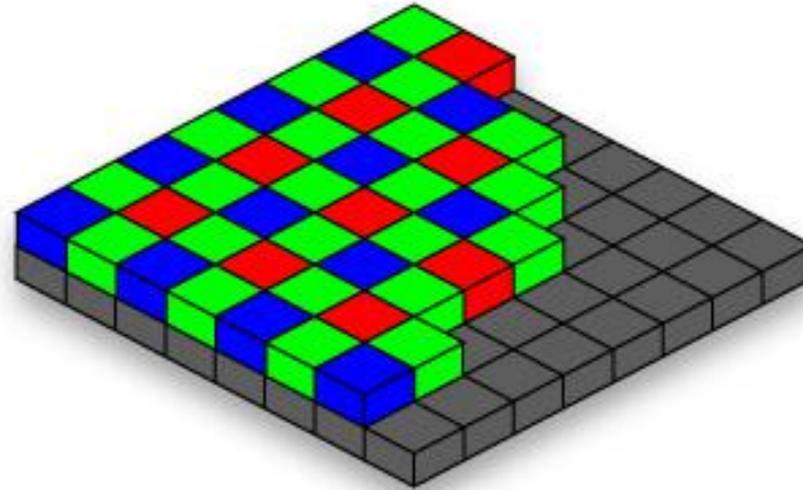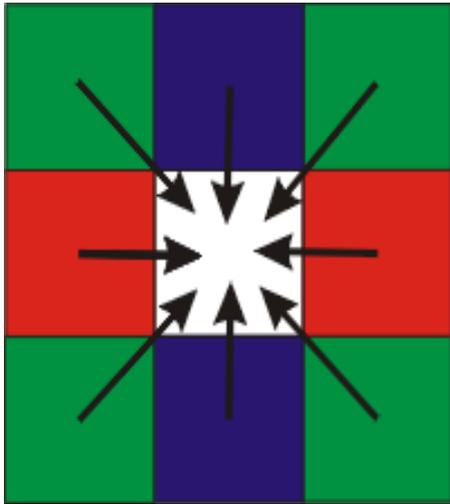3-chip vs. 1-chip: quality vs. cost

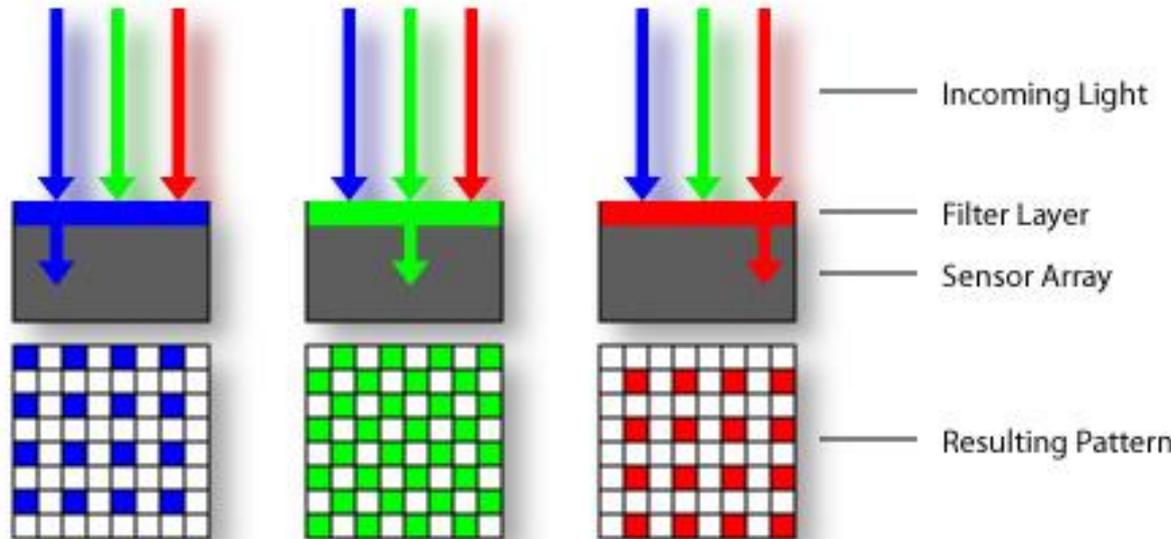Why more green?





Why 3 colors?

**Bayer filter**

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

Incoming Light

Filter Layer

Sensor Array

Resulting Pattern

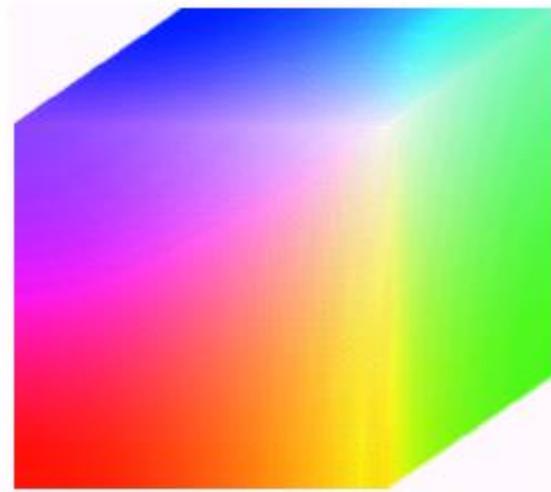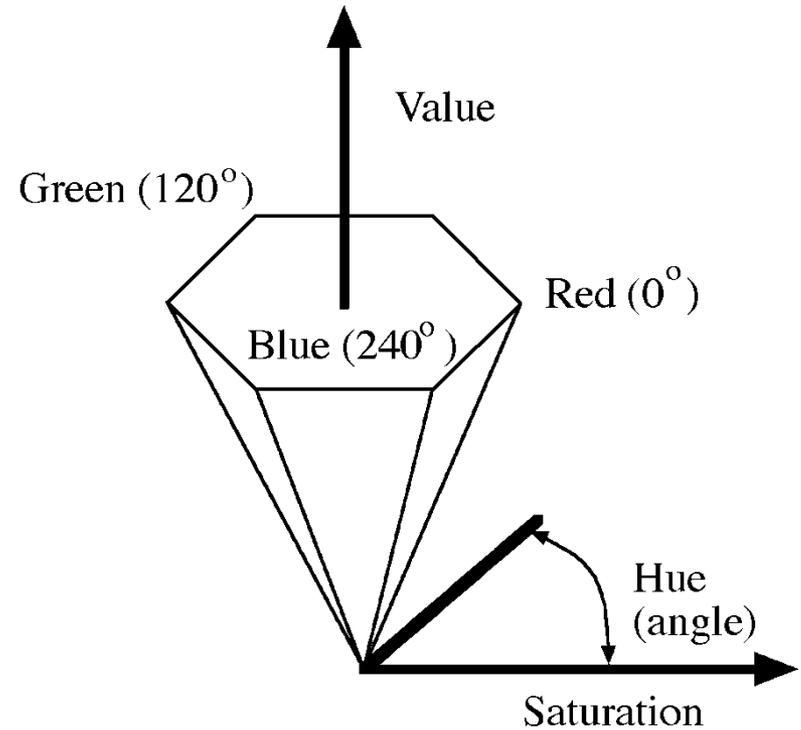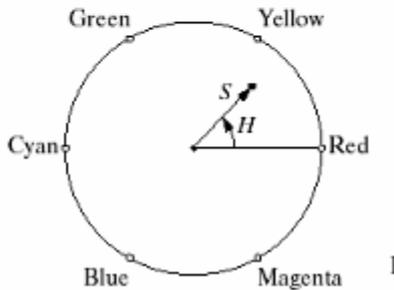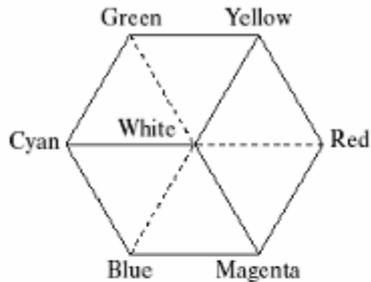Slide by Steve Seitz

# 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 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):

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

# Image Pyramids (preview)



Idea: Represent NxN image as a "pyramid" of
1x1, 2x2, 4x4,…, $2^k$x$2^k$ images (assuming N=$2^k$)

level k (= 1 pixel)

level k-1

level k-2

...

level 0 (= original image)
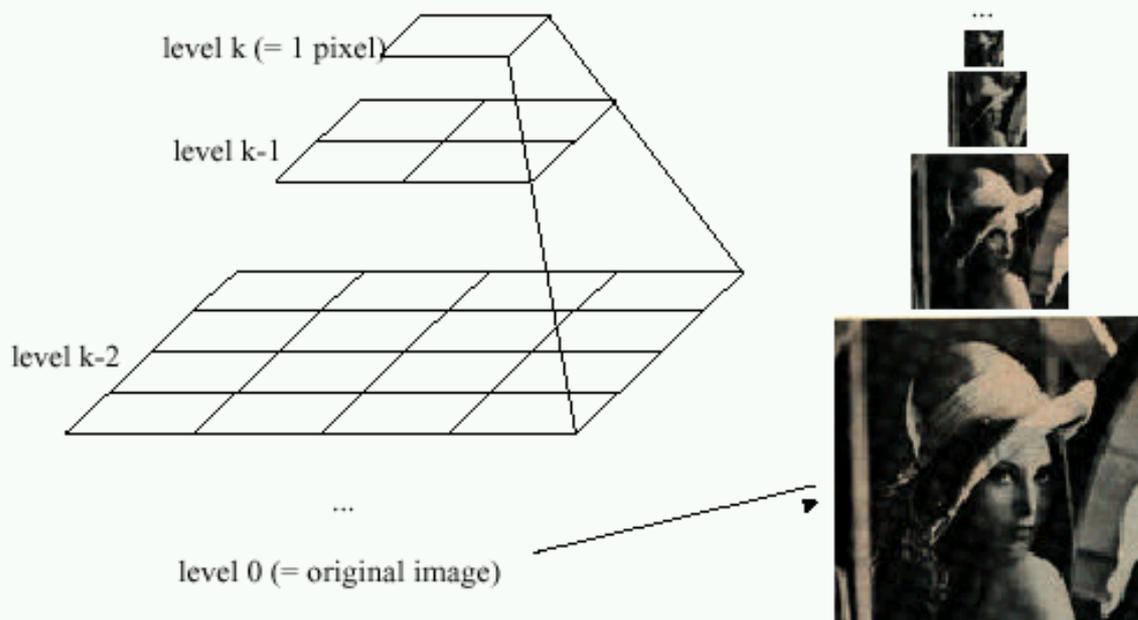
Known as a **Gaussian Pyramid** [Burt and Adelson, 1983]
- In computer graphics, a *mip map* [Williams, 1983]
- A precursor to *wavelet transform*
- *Can use* `imresize` *in Matlab*