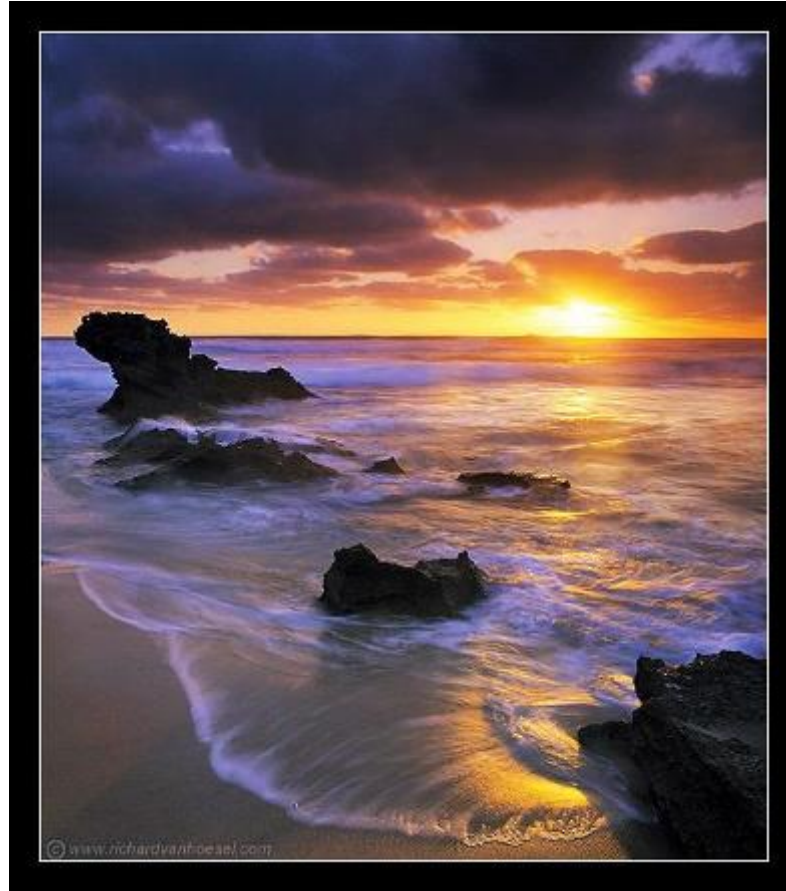


Capturing Light... in human and machine



CS180: Computer Vision and Comp. Photography
Alexei Efros & Angjoo Kanazawa, UC Berkeley, Fall 2023

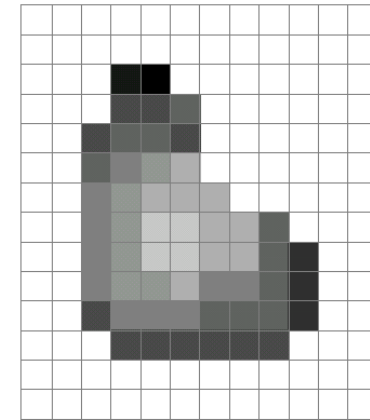
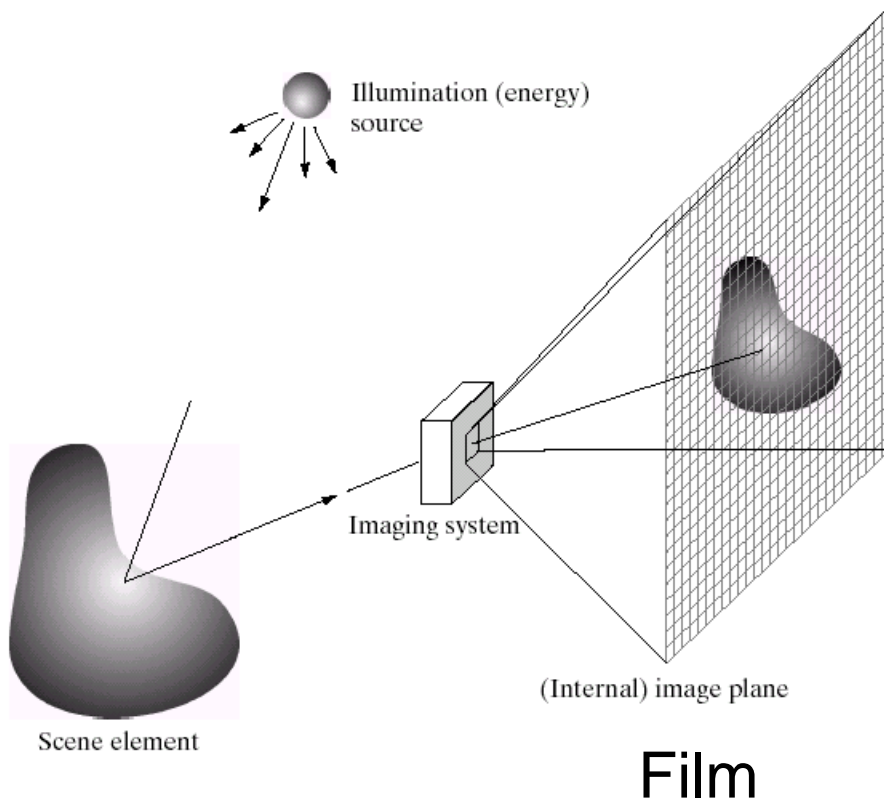
Etymology

PHOTOGRAPHY

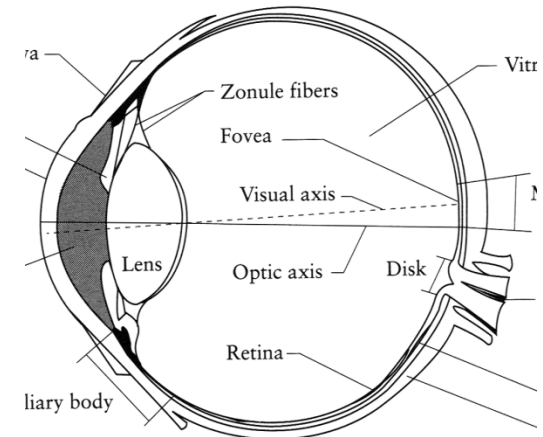
light

drawing
/ writing

Image Formation

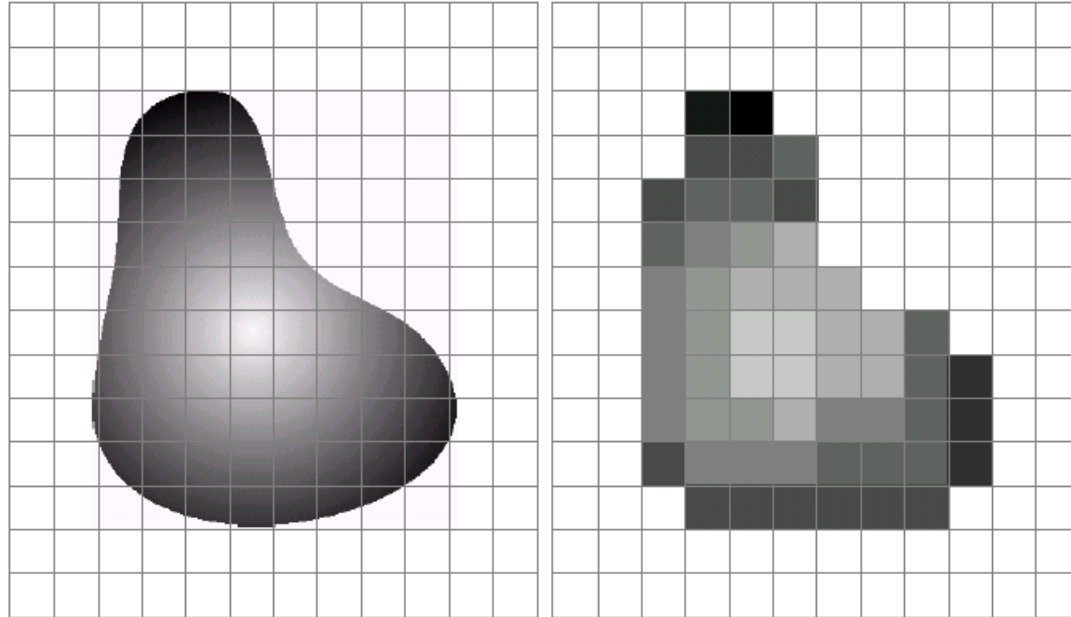


Digital Camera



The Eye

Sensor Array



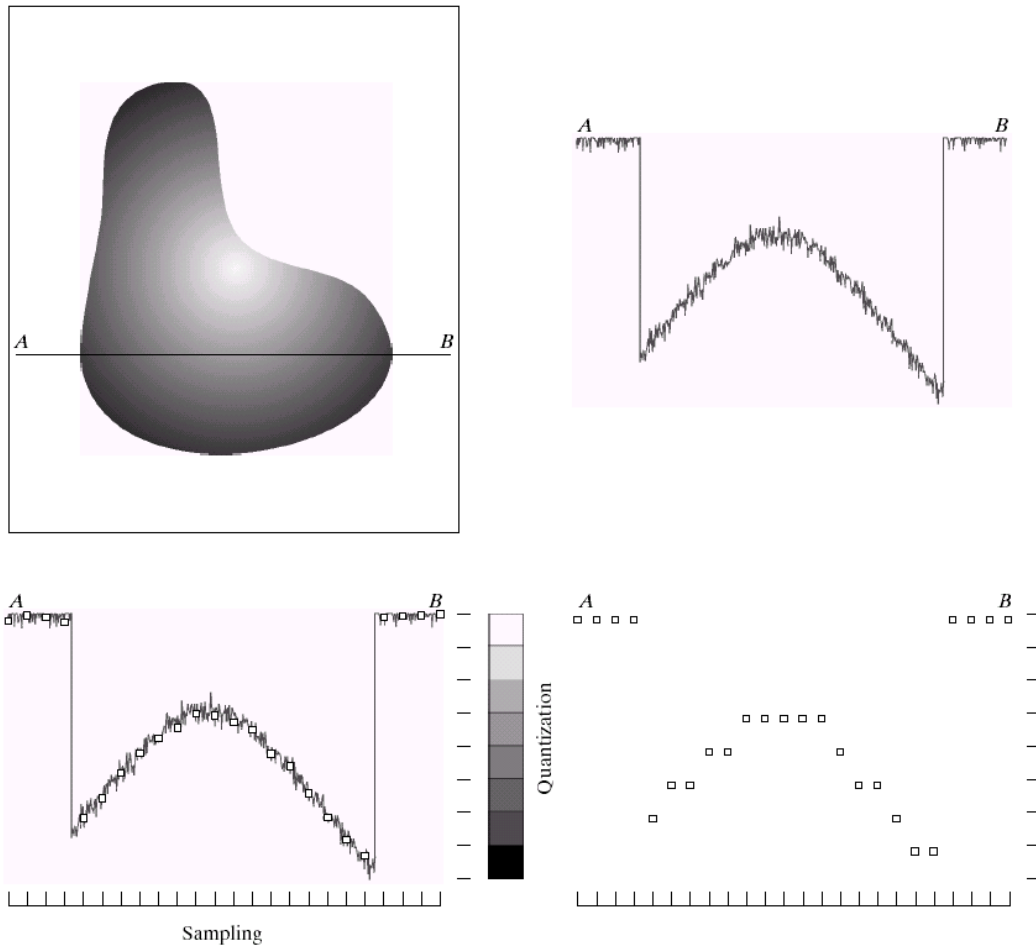
a b

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



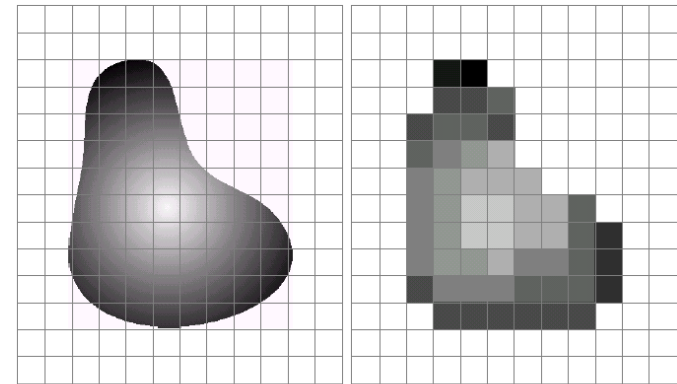
CMOS sensor

Sampling and Quantization



a b
c d

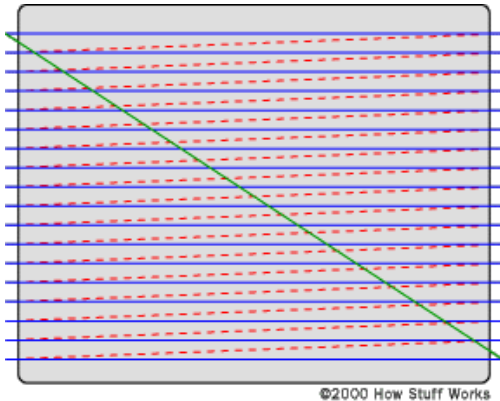
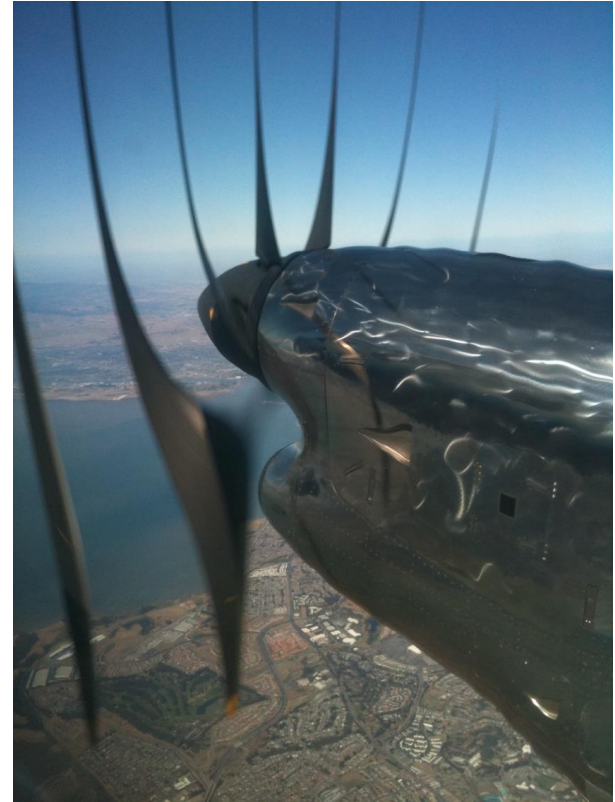
FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.



a b

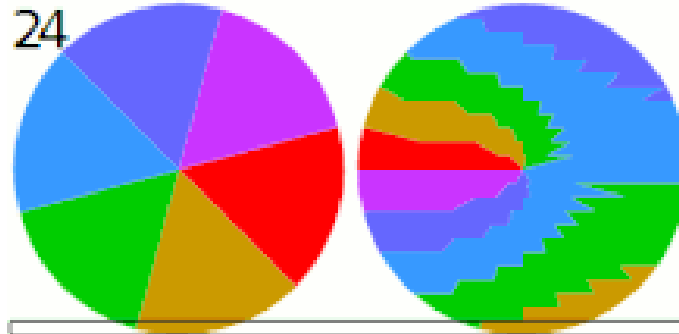
FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Global vs. Rolling Shutter



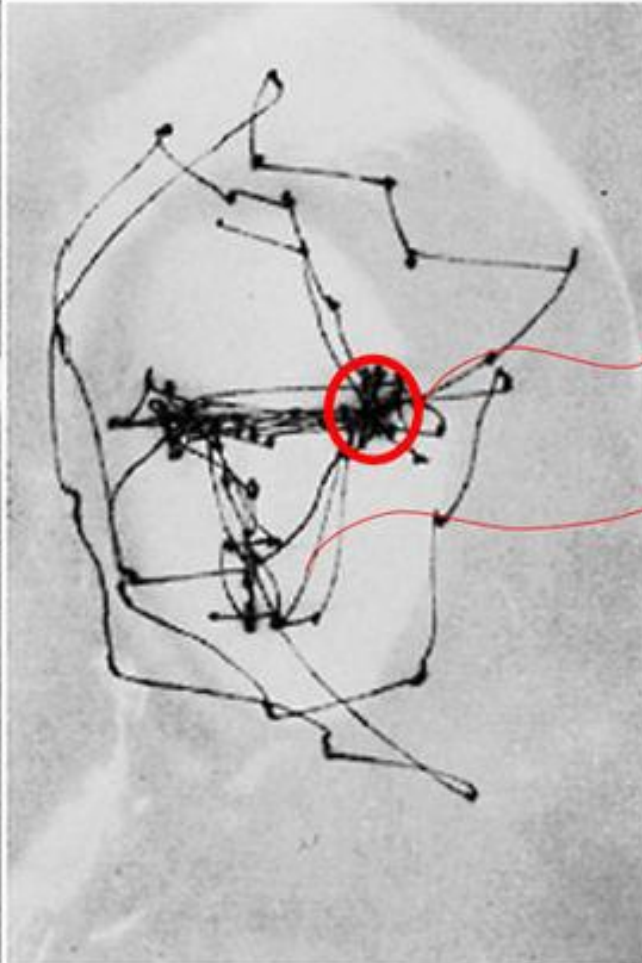
©2000 How Stuff Works

24



http://en.wikipedia.org/wiki/Rolling_shutter

Saccadic eye movement



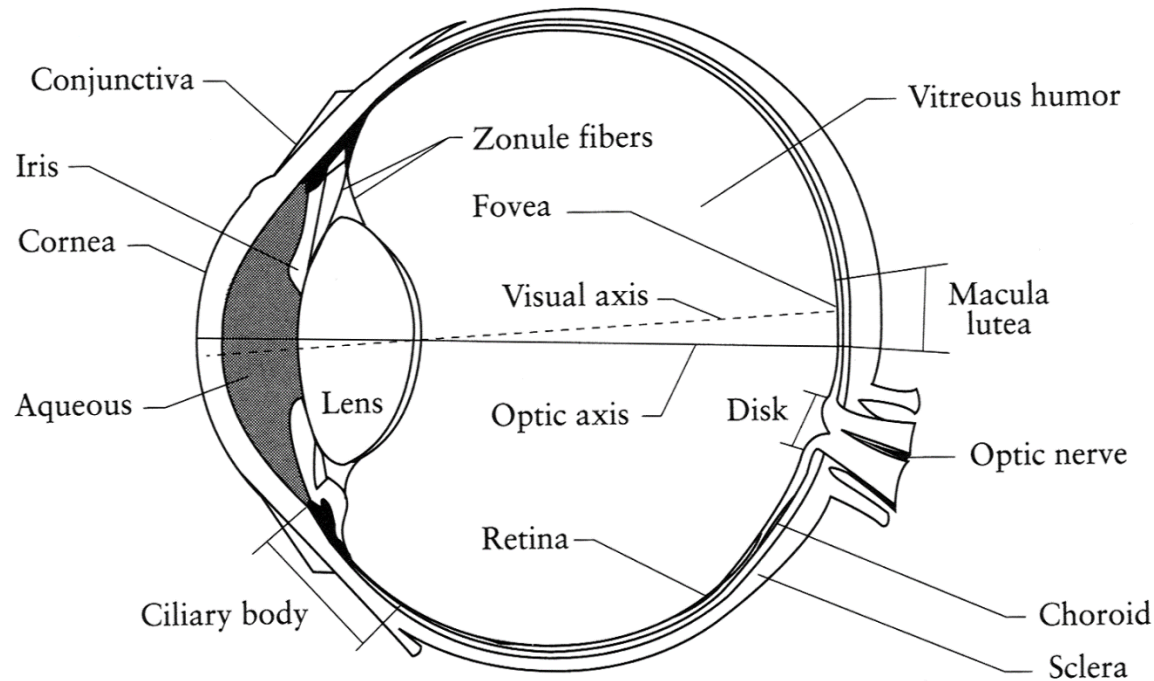
Micro-saccadic movements

Large-saccadic movements

Saccadic eye movement



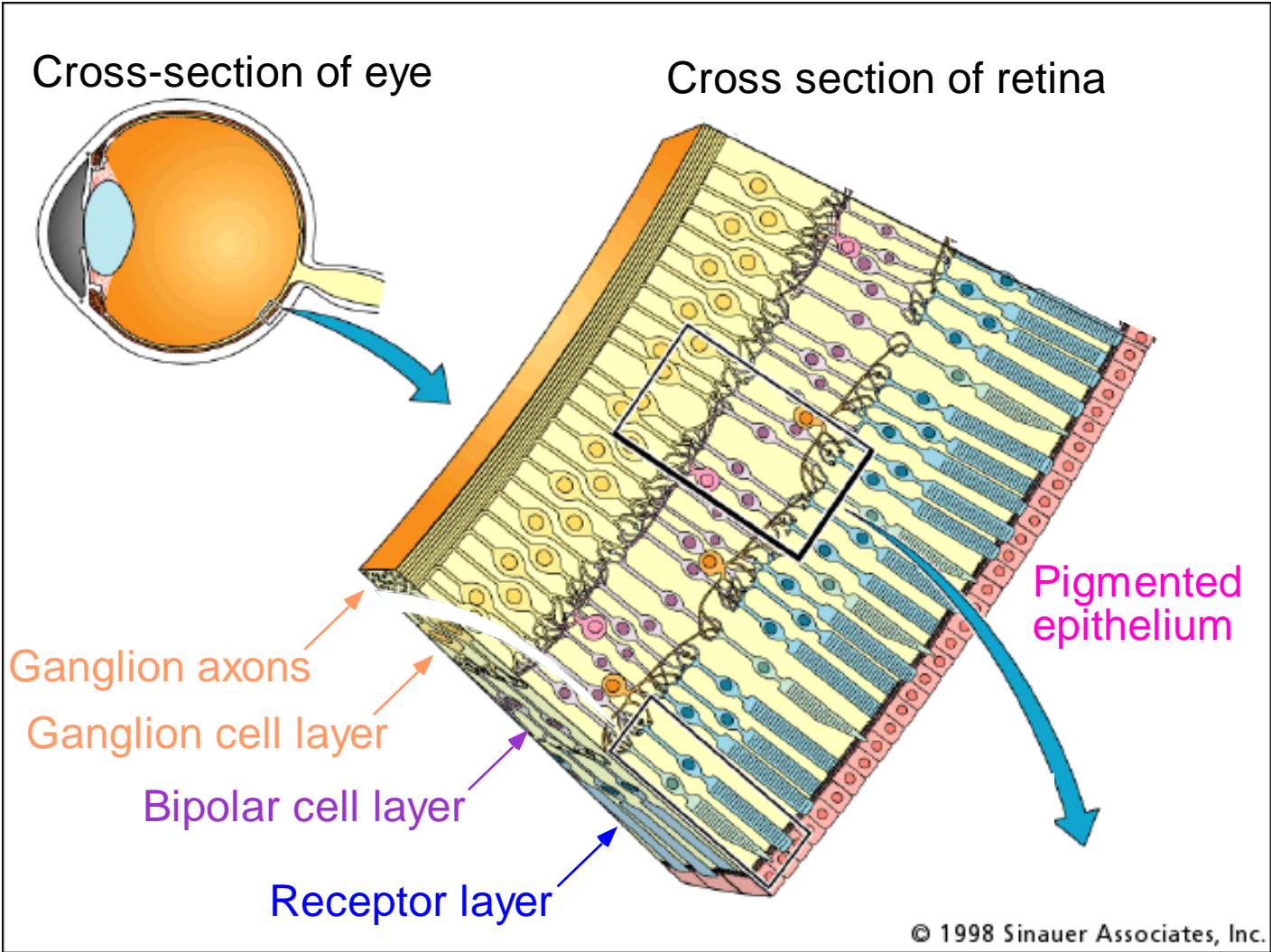
The Eye



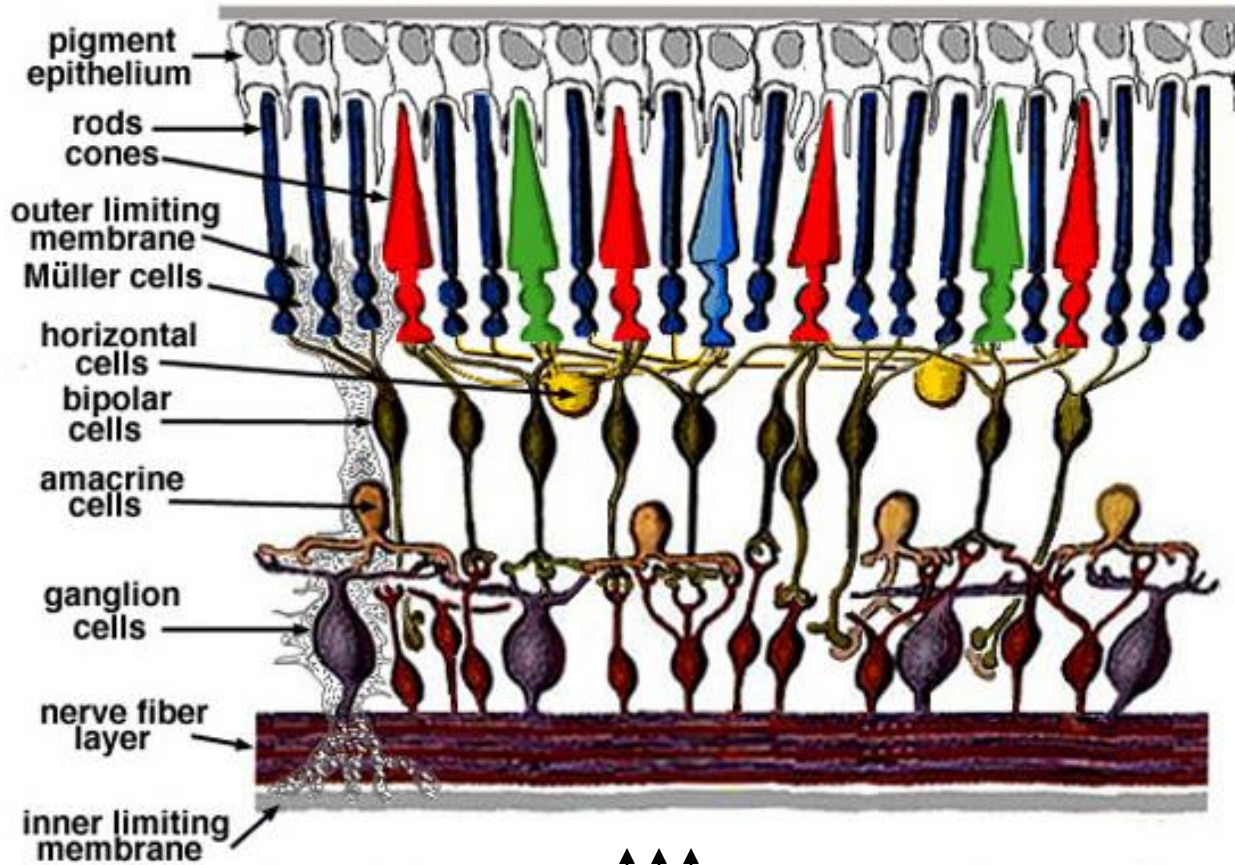
The human eye is a camera!

- **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



Retina up-close



Light

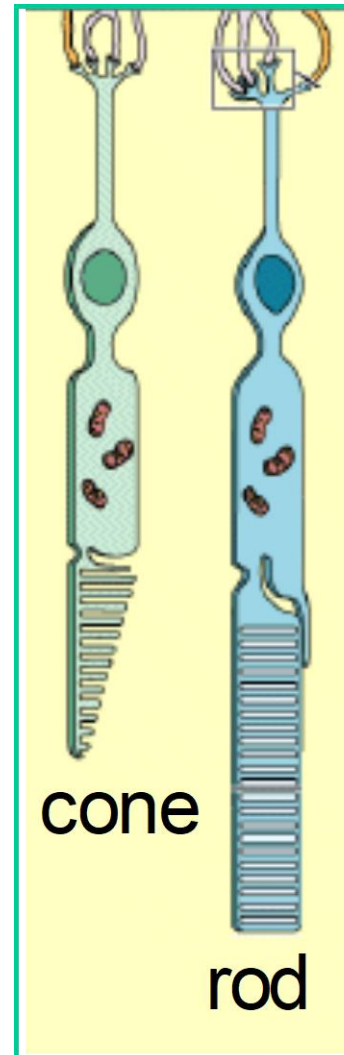
Two types of light-sensitive receptors

Cones

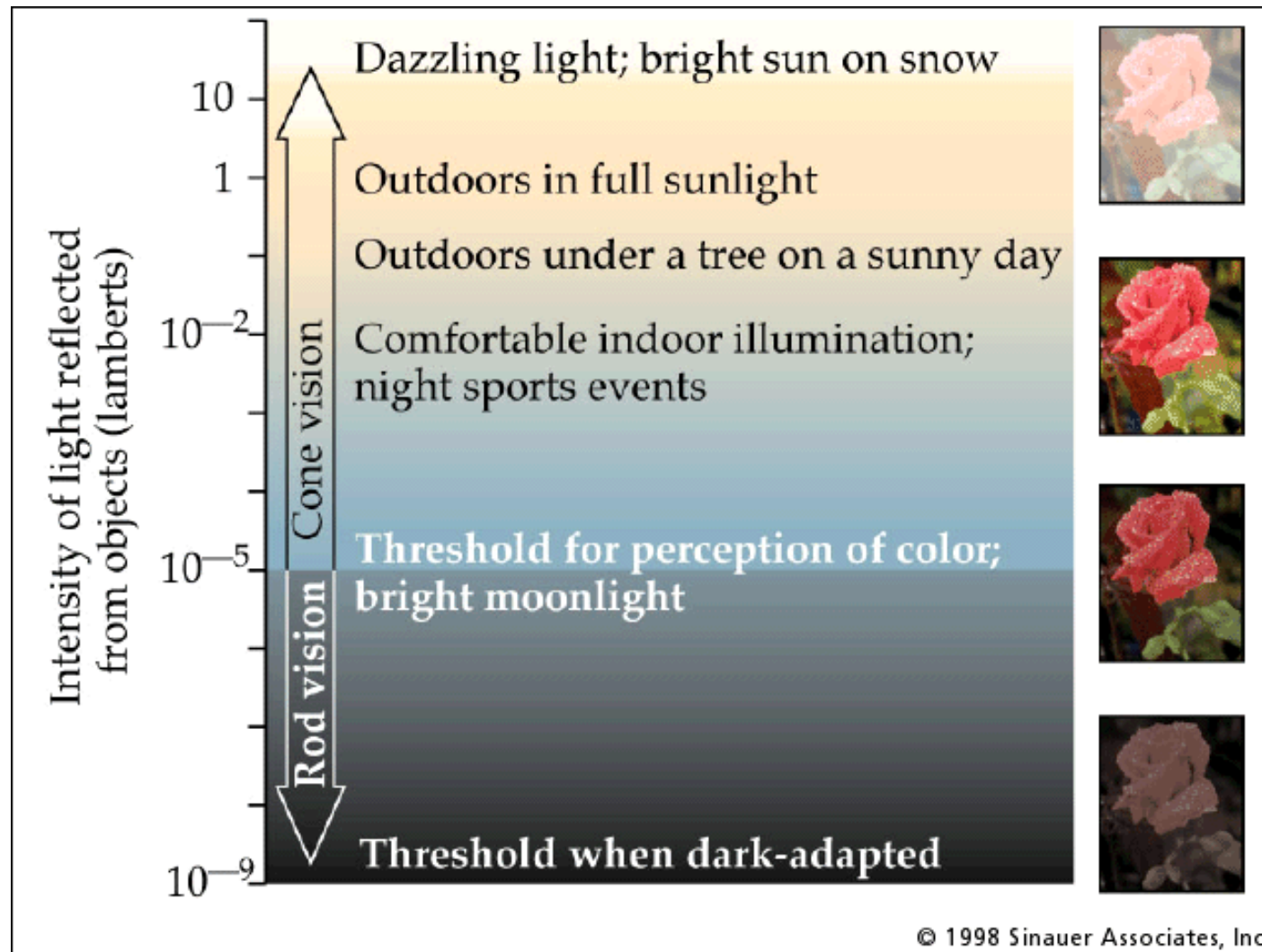
cone-shaped
less sensitive
operate in high light
color vision

Rods

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

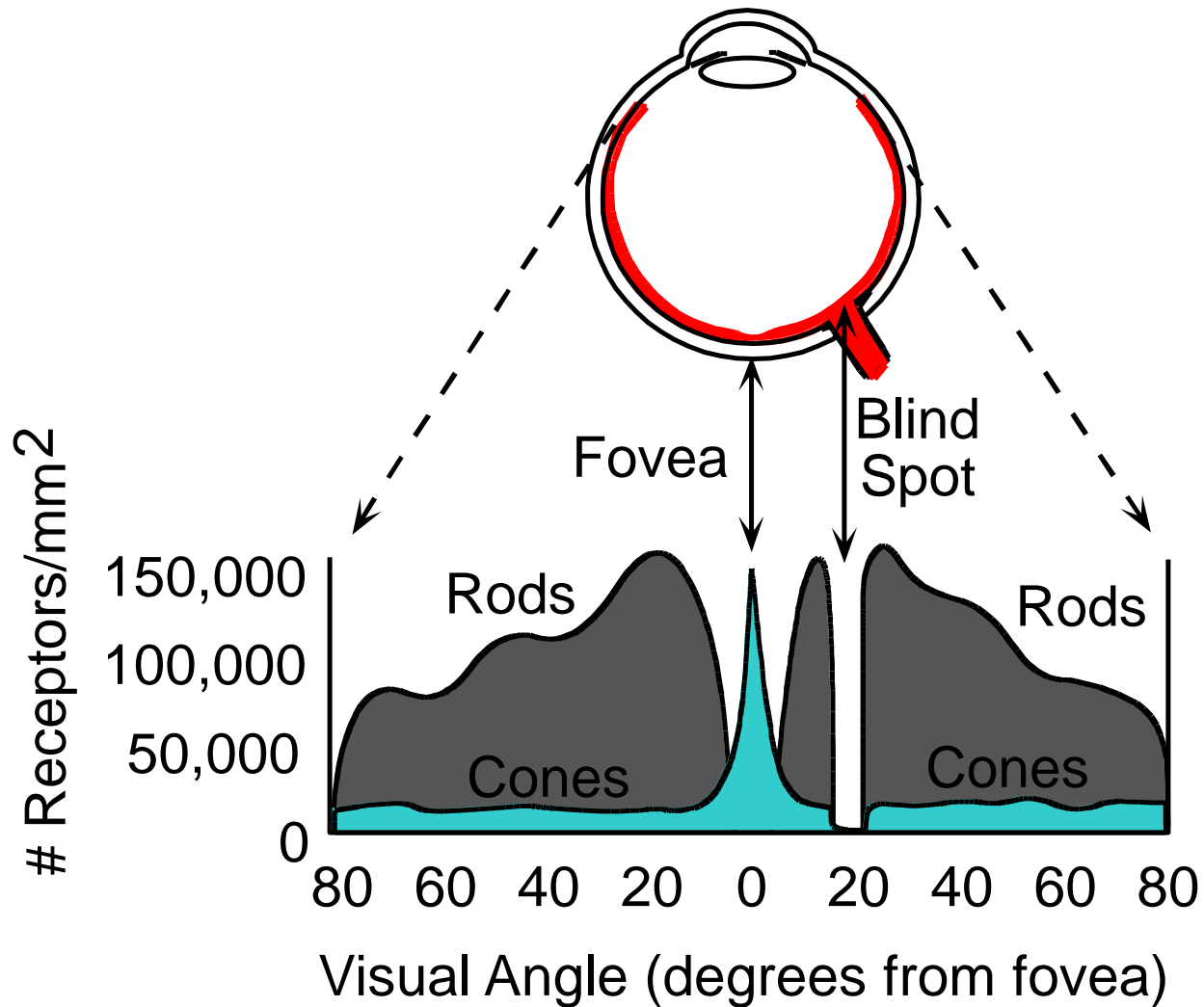


Rod / Cone sensitivity

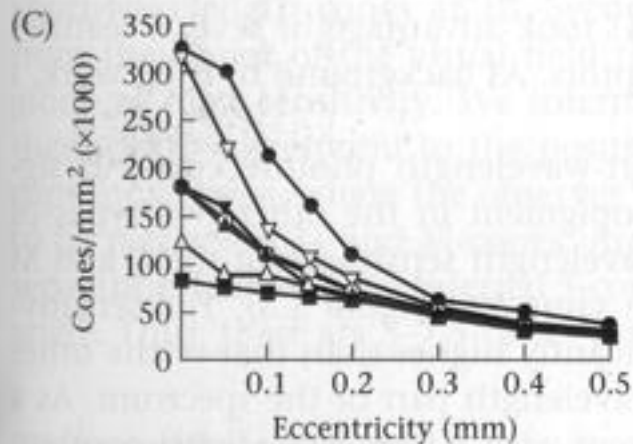
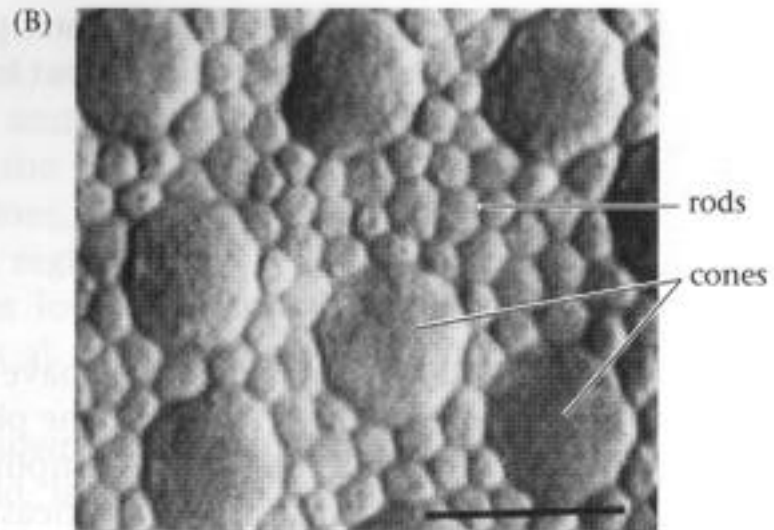
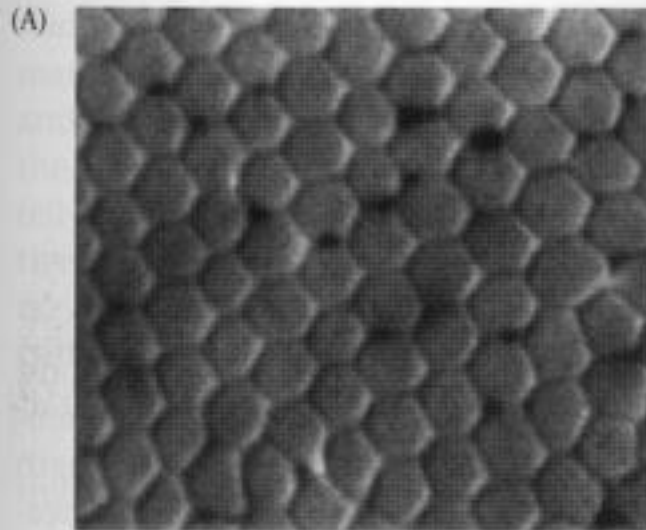


The famous sock-matching problem...

Distribution of Rods and Cones

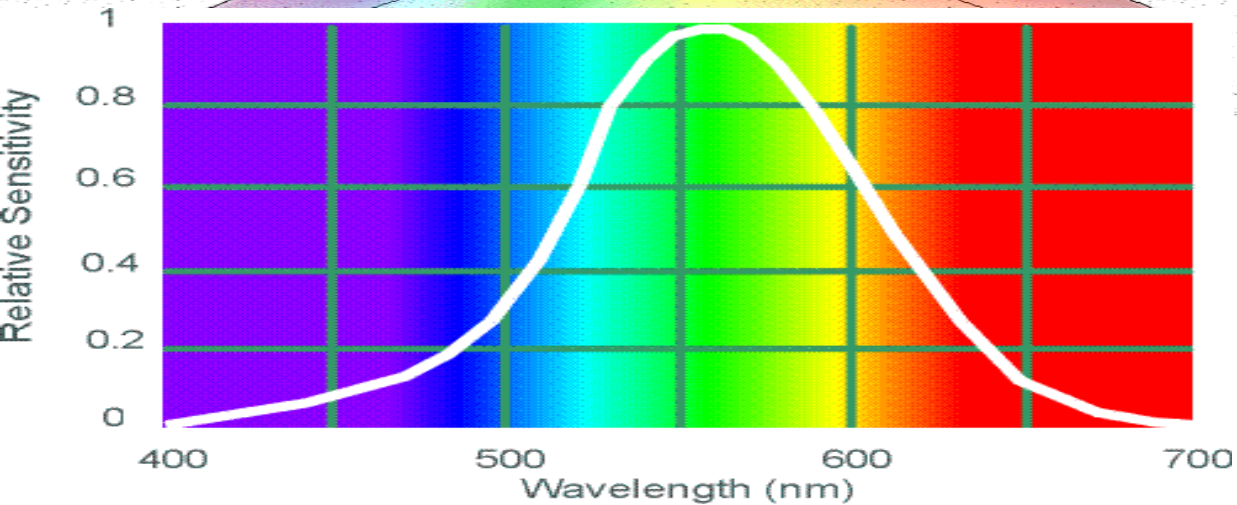
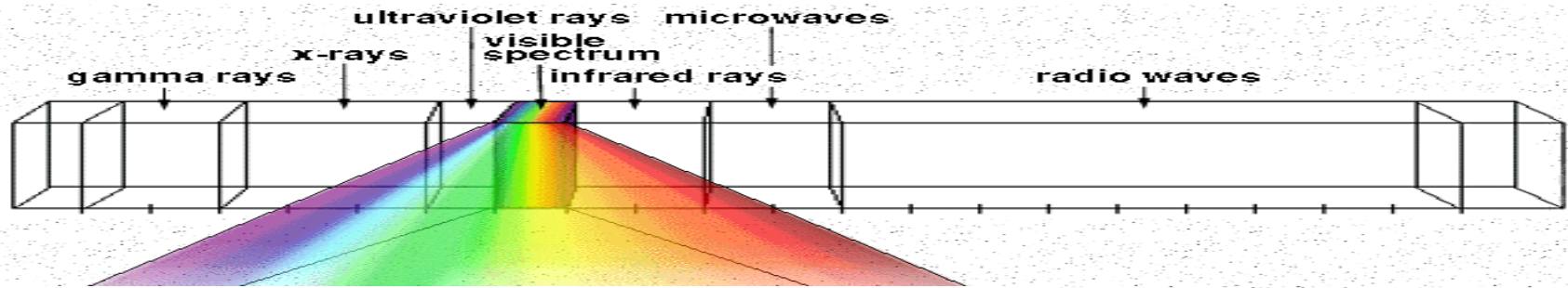


Night Sky: why are there more stars off-center?



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.

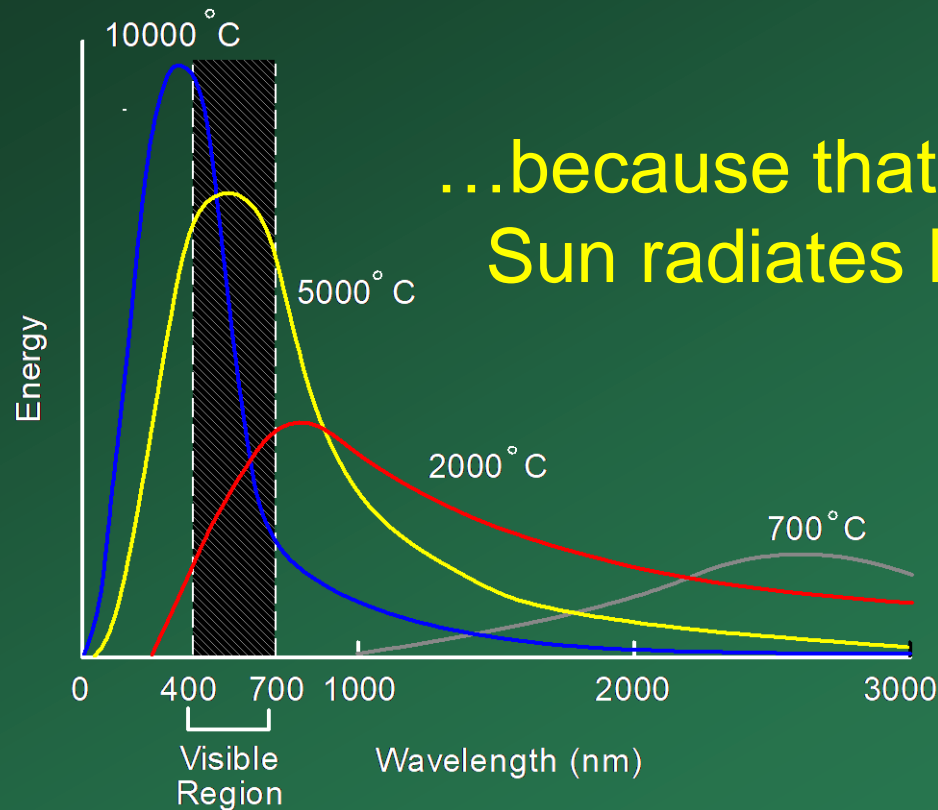
Electromagnetic Spectrum



Human Luminance Sensitivity Function

Visible Light

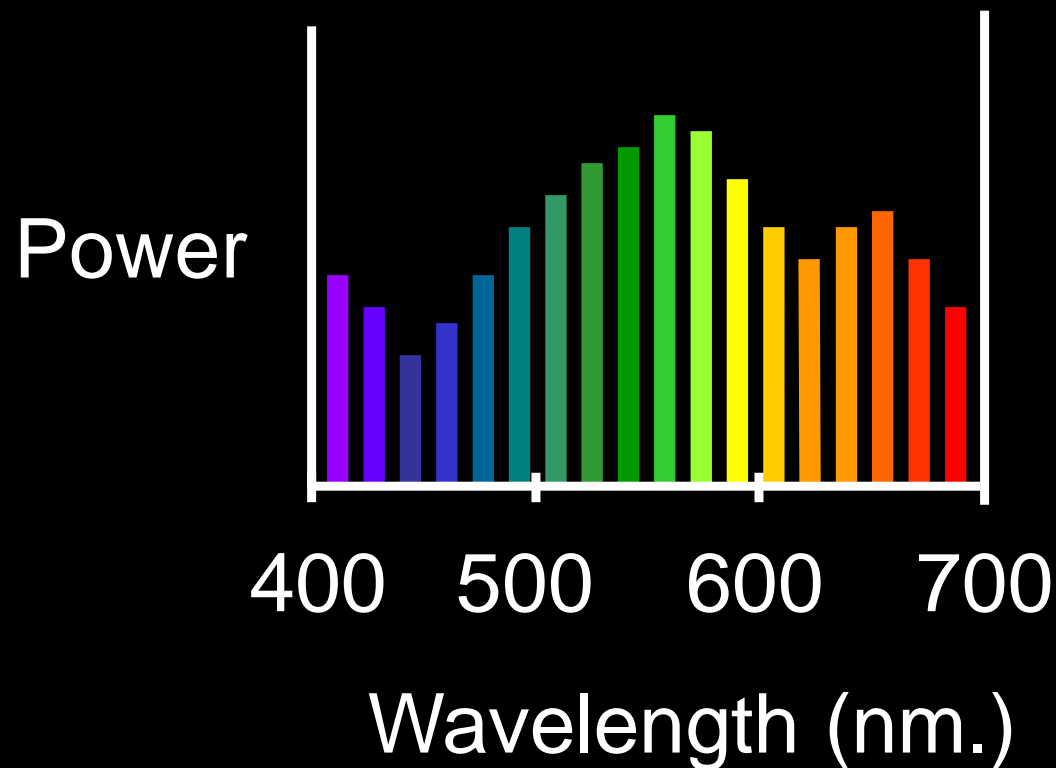
Why do we see light of these wavelengths?



...because that's where the Sun radiates EM energy

The Physics of Light

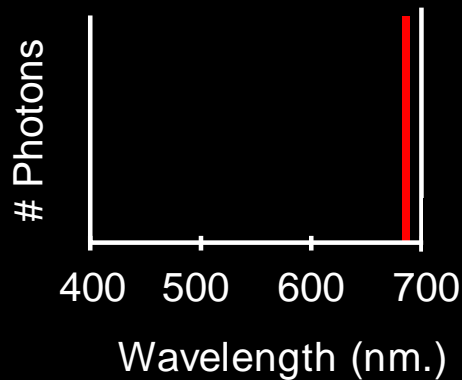
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



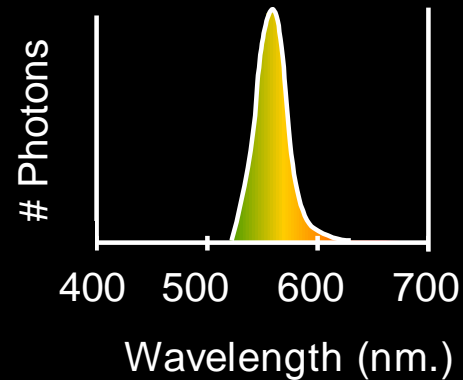
The Physics of Light

Some examples of the spectra of light sources

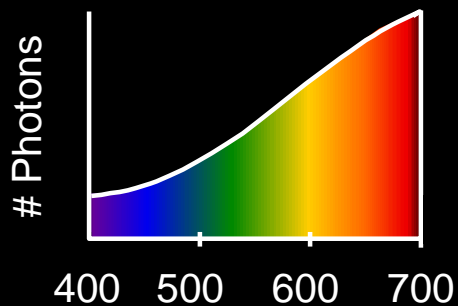
A. Ruby Laser



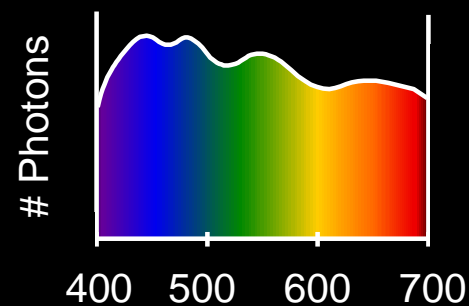
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb



D. Normal Daylight

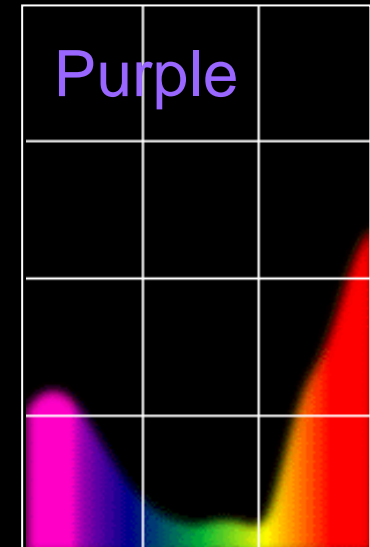
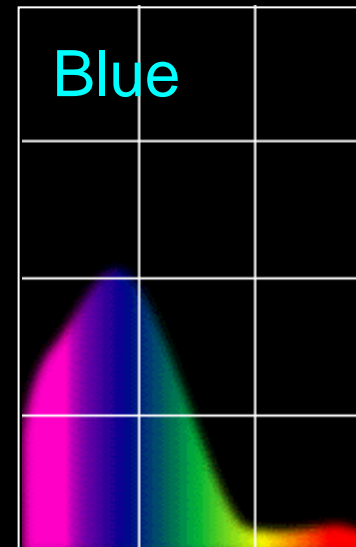
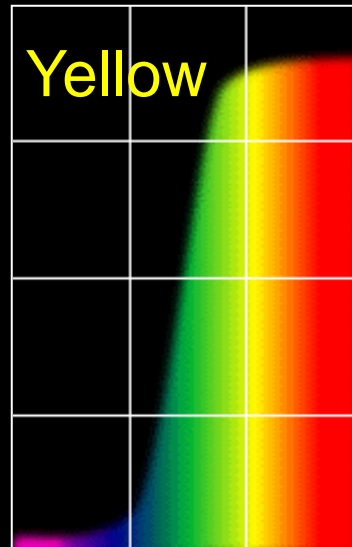
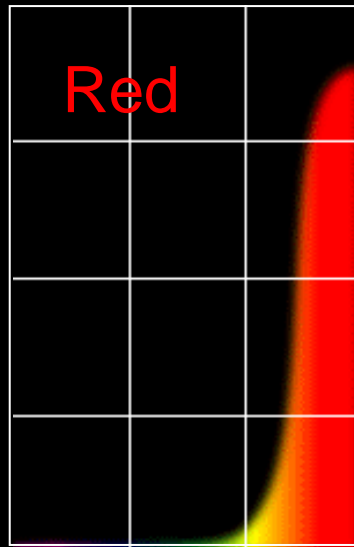


The Physics of Light

Some examples of the reflectance spectra of surfaces



% Photons Reflected



400

700

400

700

400

700

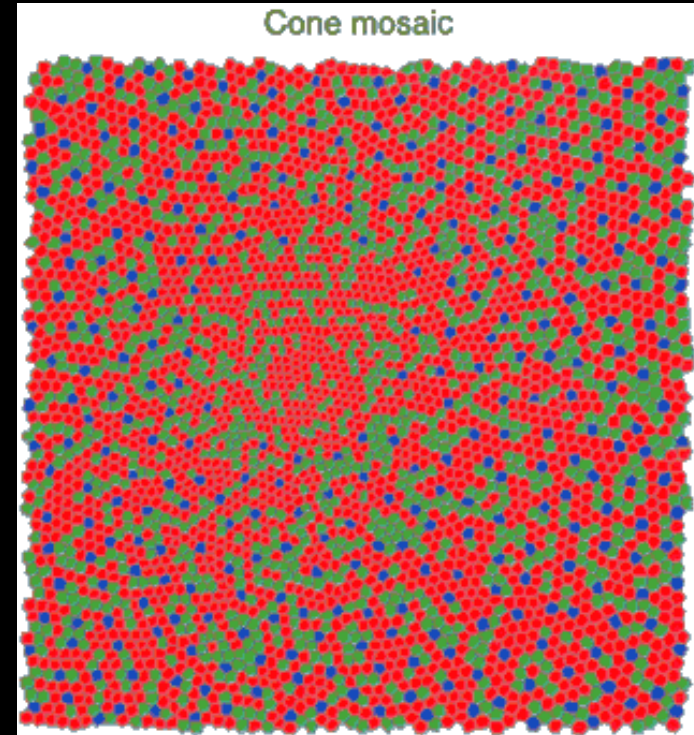
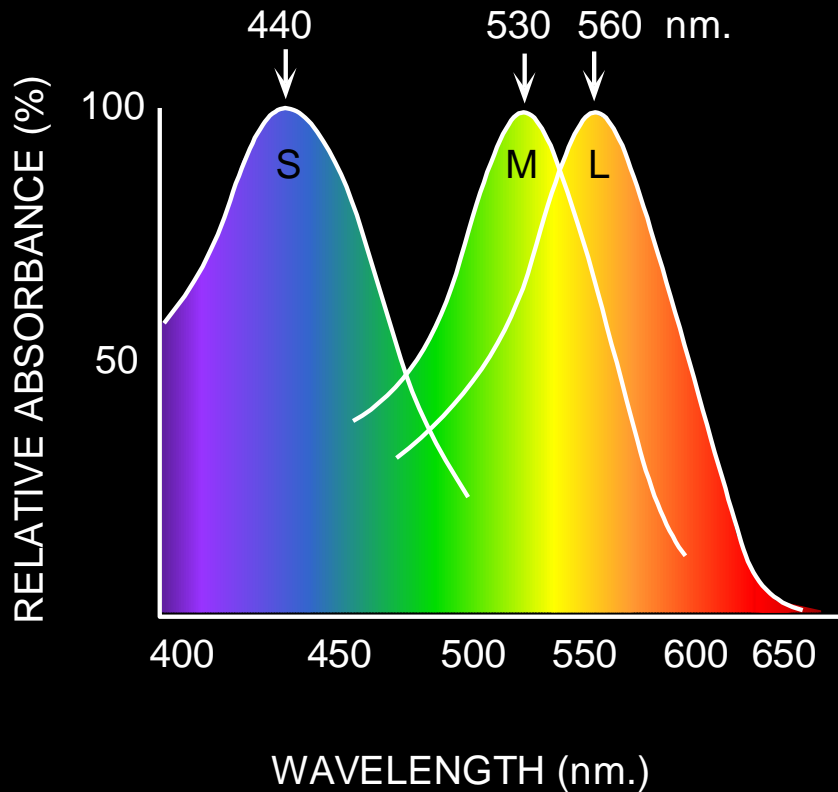
400

700

Wavelength (nm)

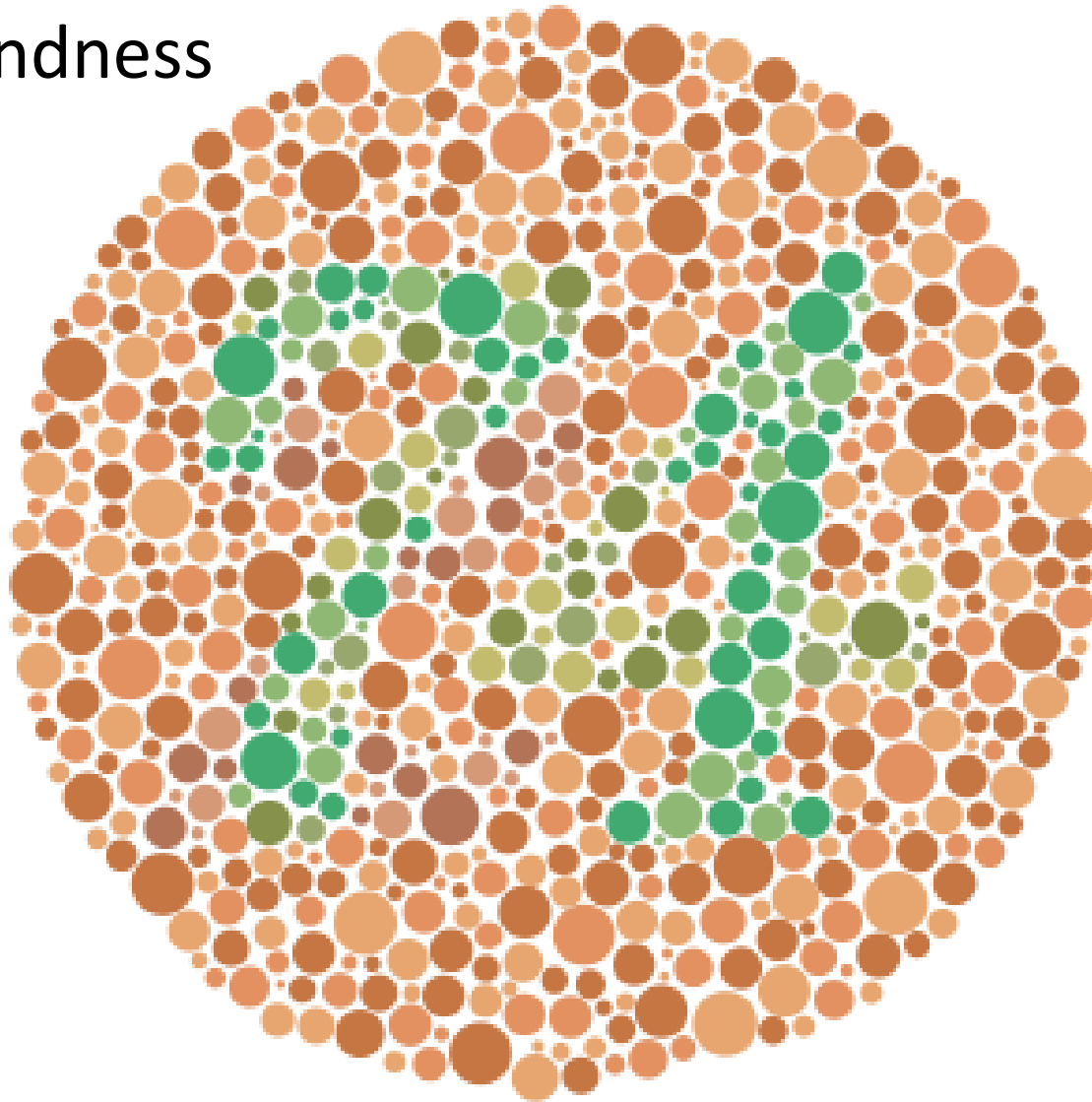
Physiology of Color Vision

Three kinds of cones:



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

Color Blindness



Ishihara color test plate. The number "74" should be clearly visible to viewers with normal color vision. Viewers with red-green color blindness will read it as "21", and viewers with monochromacy may see nothing.

Not everyone is trichromat

- Types of Dichromacy:
 - Deuteranopia: missing M cones
 - Protanopia: missing L cones
 - Tritanopia: missing S cones
- “M” and “L” on the X-chromosome
 - Why men are more likely to be color blind
 - “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)
 - 12 (mantis shrimp)
- See Ren Ng’s class for whole semester on this!



NORMAL VISION



DEUTERANOMALIA



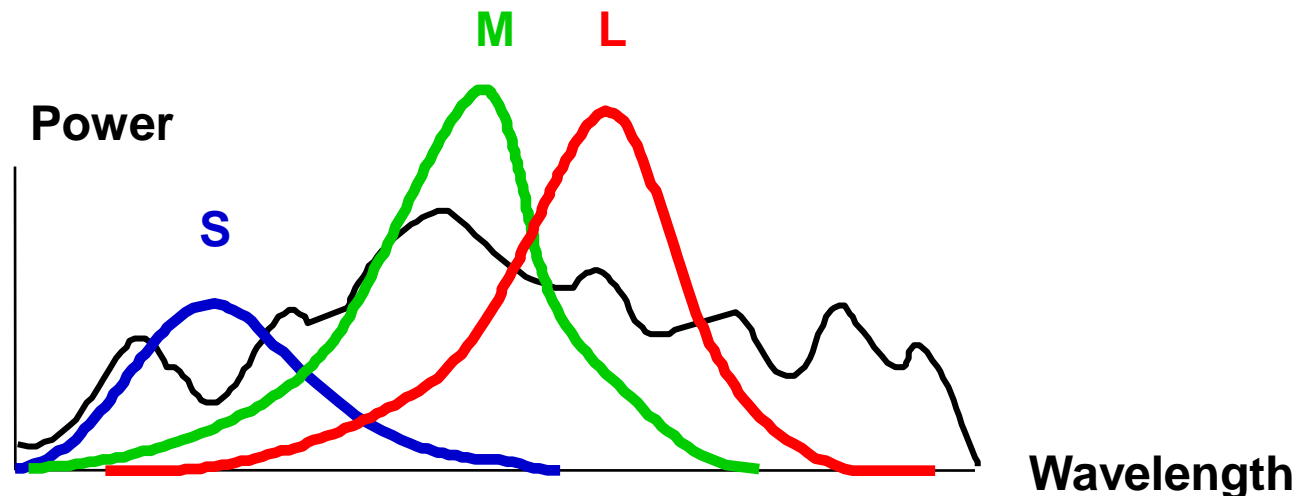
PROTANOPIA



TRITANOPIA

© www.color-blindness.com/

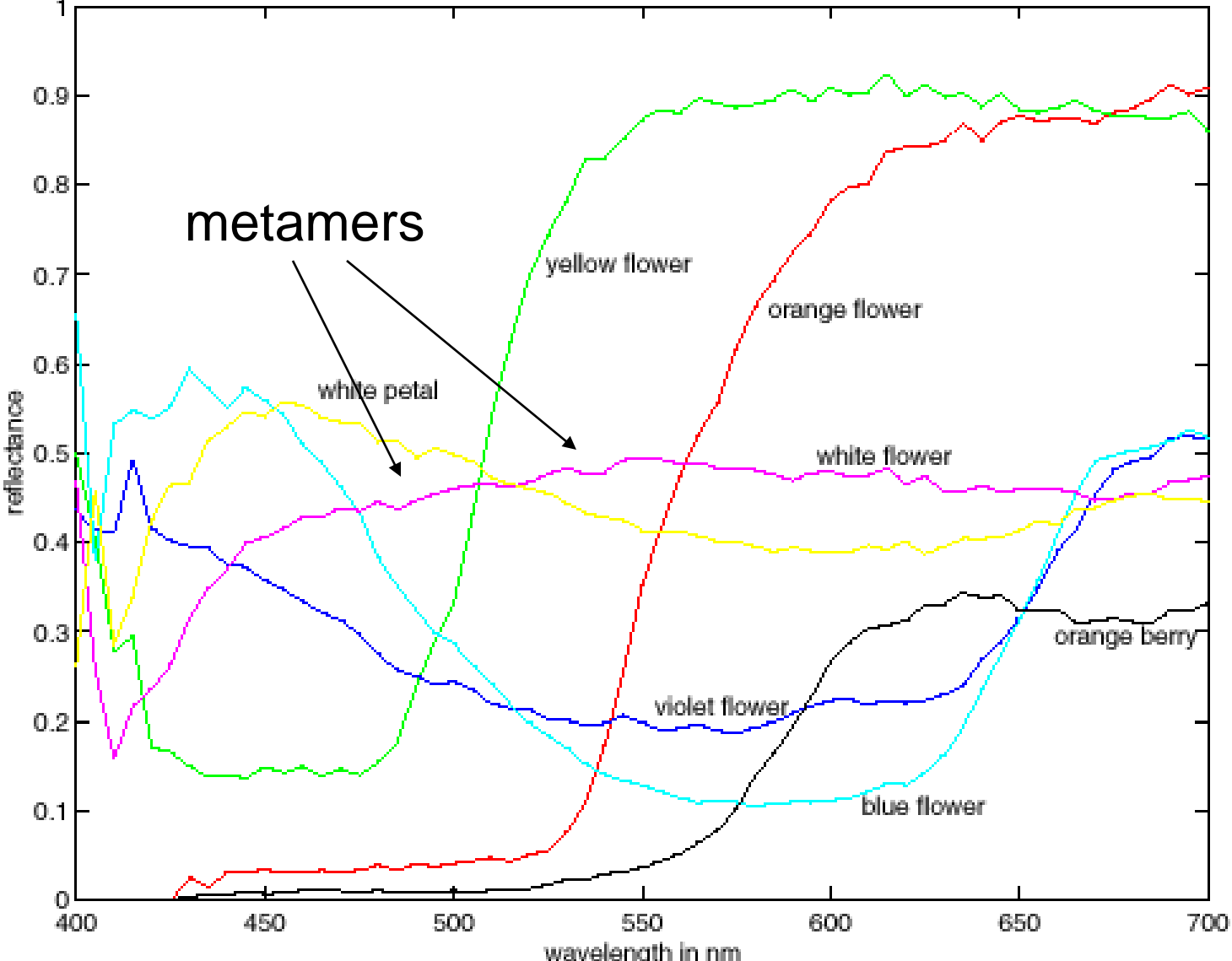
Trichromacy



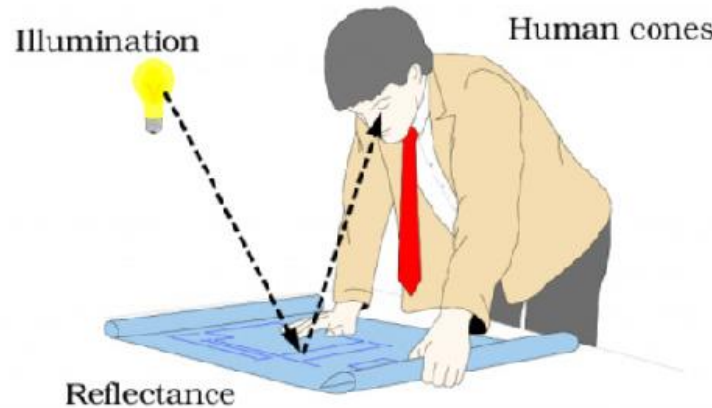
Rods and cones act as *filters* on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
 - Each cone yields one number
- How can we represent an entire spectrum with 3 numbers?
- We can't! A lot of the information is lost
 - As a result, two different spectra may appear indistinguishable
 - » such spectra are known as **metamers**

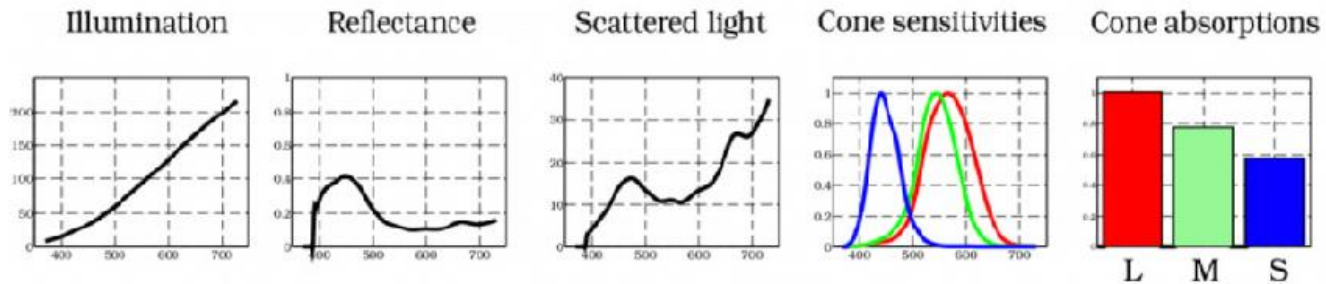
We are all color-blind!



Spectral Radiometry: Color Image Formation



Wandell 1995



incoming illumination \times reflectance = outgoing scene radiance

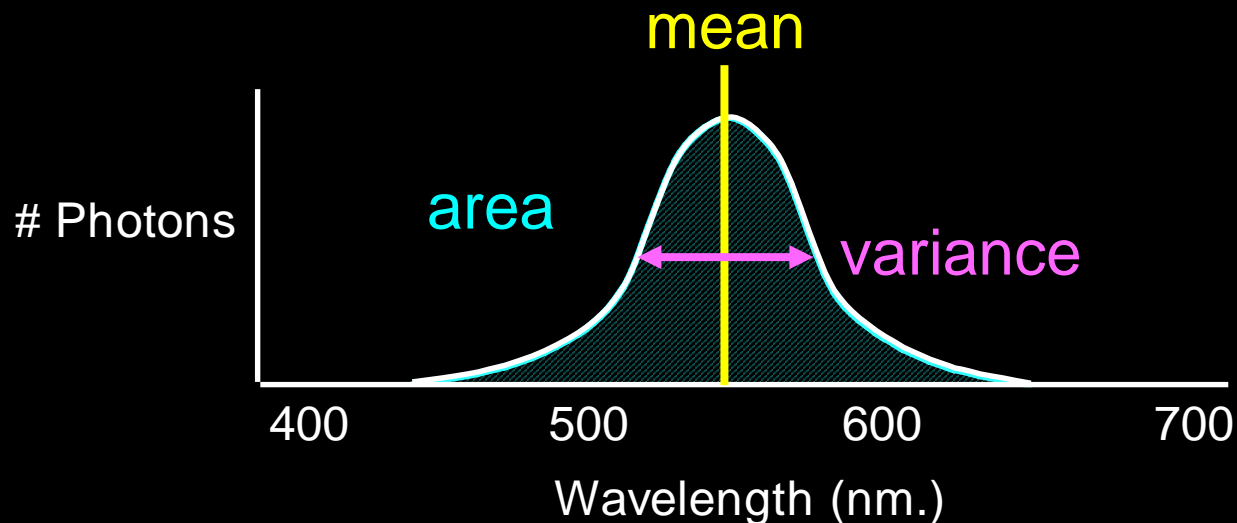
$$\int_{\lambda} \text{scene radiance} \times \text{cone sensitivities} d\lambda = \text{cone absorptions}$$

The Psychophysics of “Color”

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

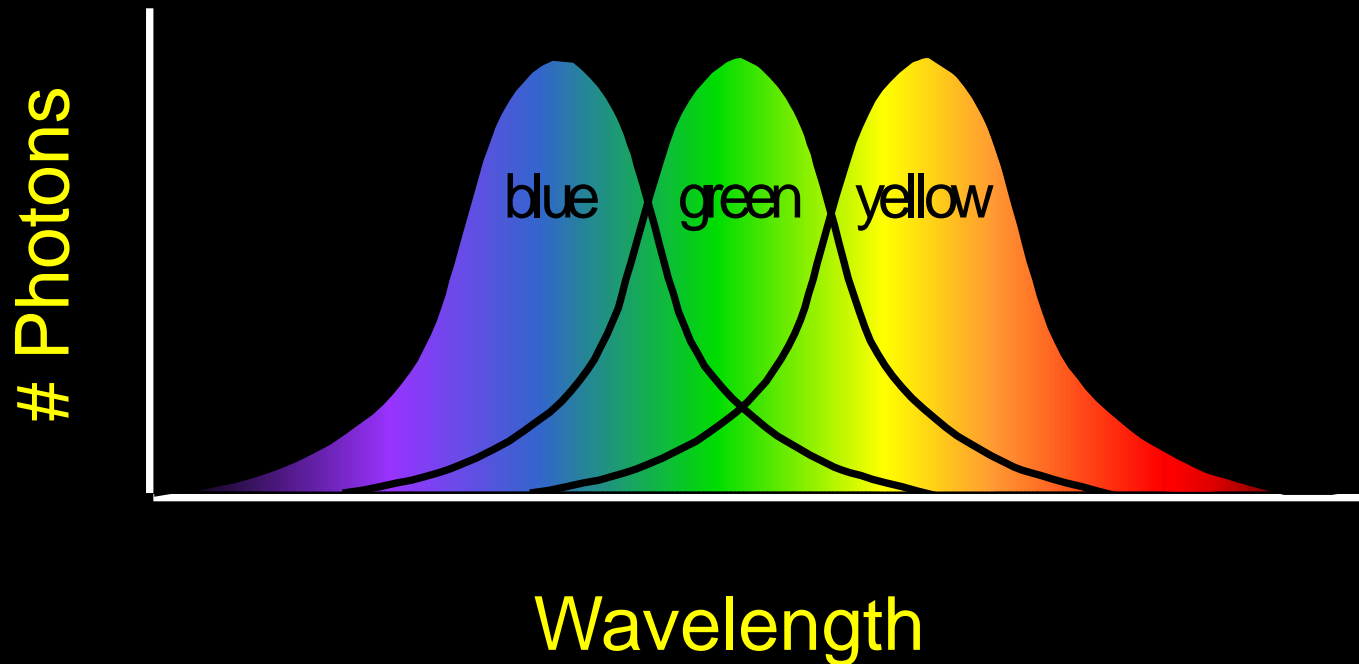
A helpful constraint:

Consider only physical spectra with normal distributions



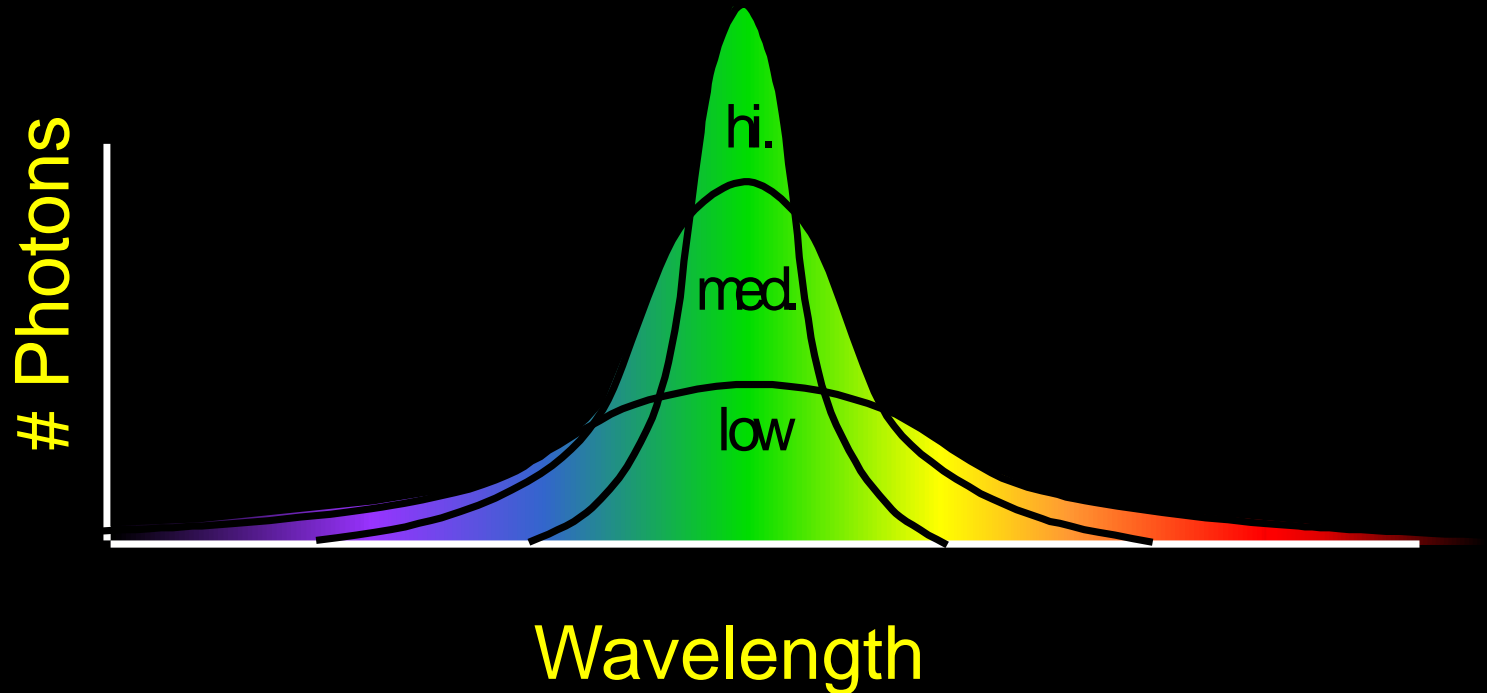
The Psychophysical Correspondence

Mean ↔ Hue



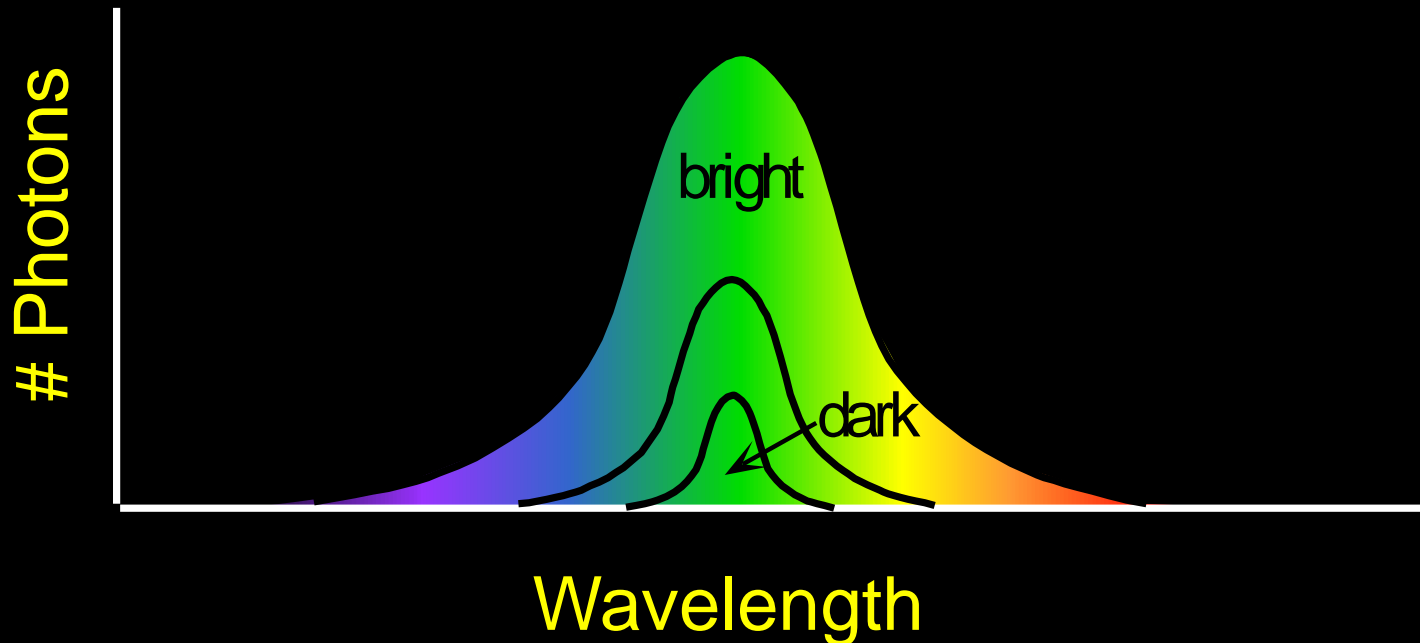
The Psychophysical Correspondence

Variance \longleftrightarrow Saturation



The Psychophysical Correspondence

Area \longleftrightarrow Brightness



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).

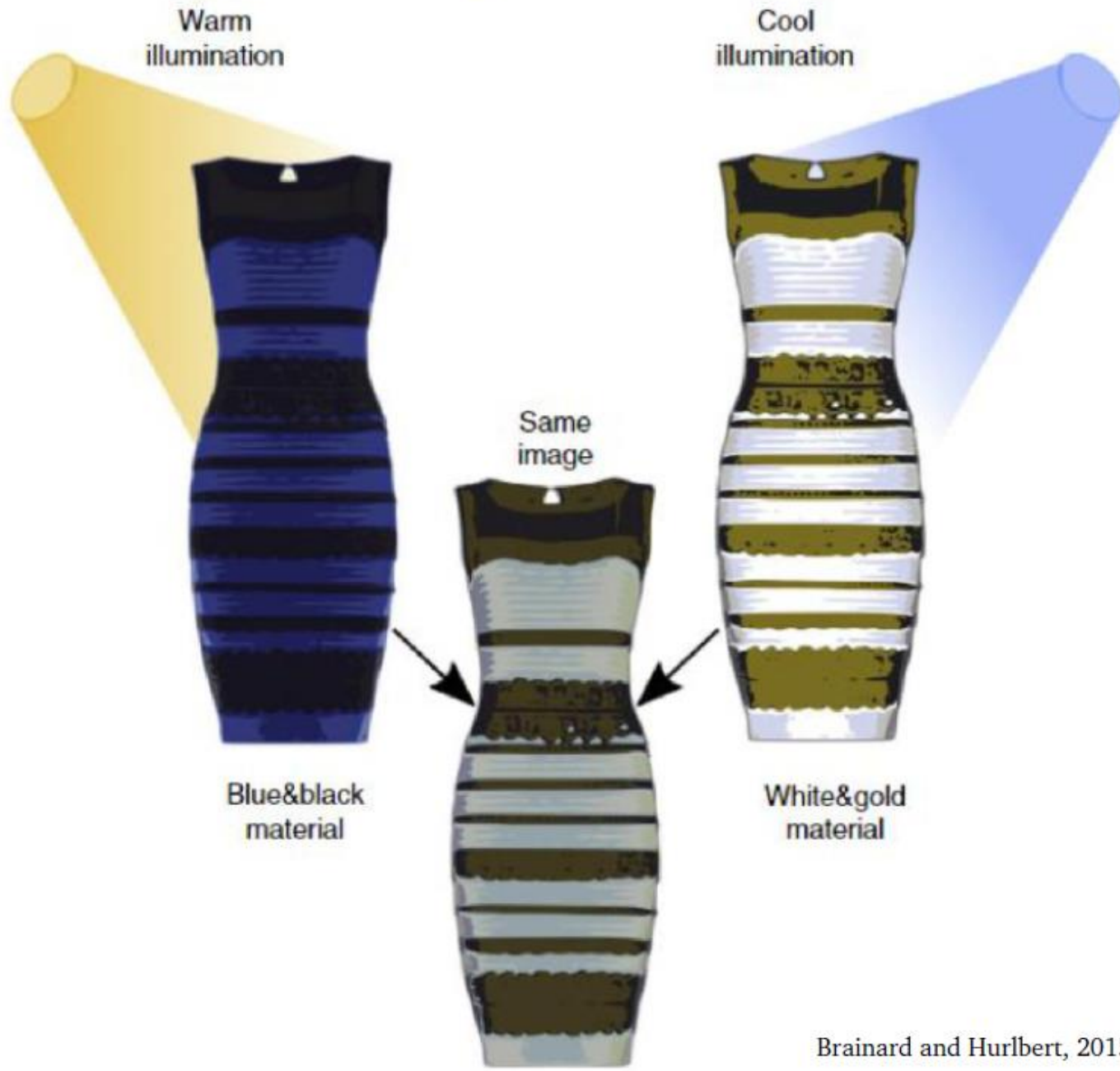


What color is the “The Dress”?



https://en.wikipedia.org/wiki/The_dress

Two Scene Interpretations of #thedress



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

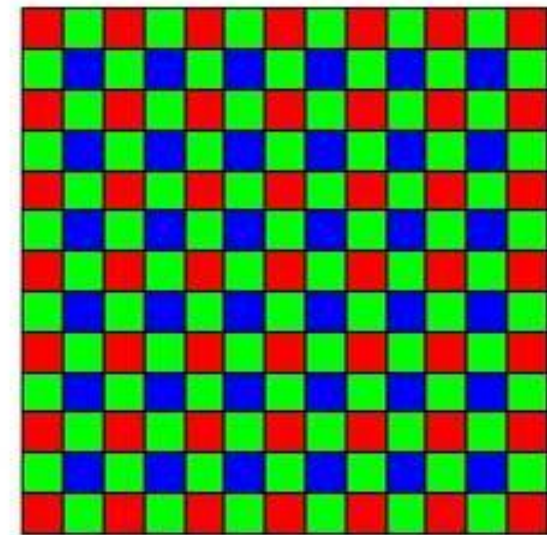
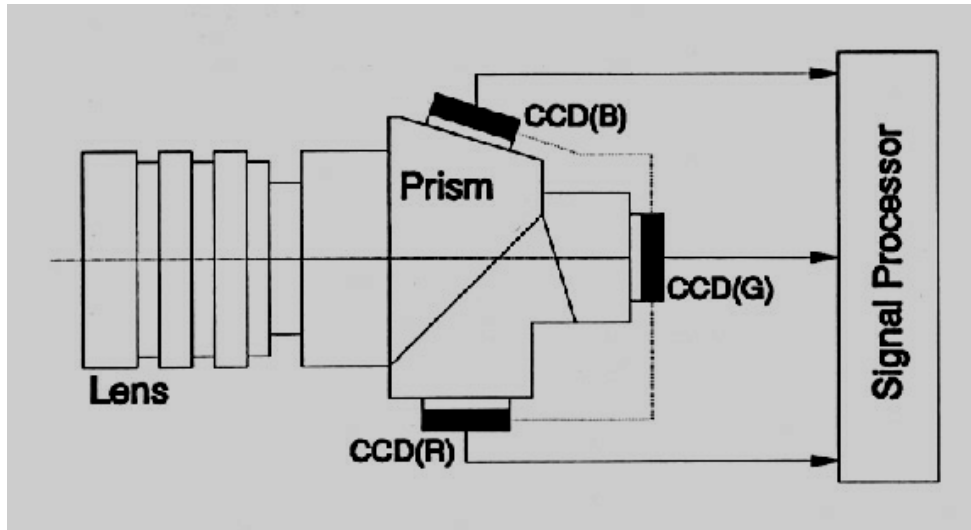
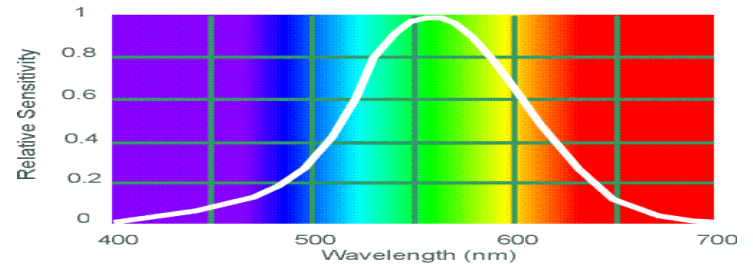


- Manual
 - Choose color-neutral object in the photos and normalize
- Automatic (AWB)
 - Grey World: force average color of scene to grey
 - White World: force brightest object to white

Color Sensing in Camera (RGB)

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

Why more green?



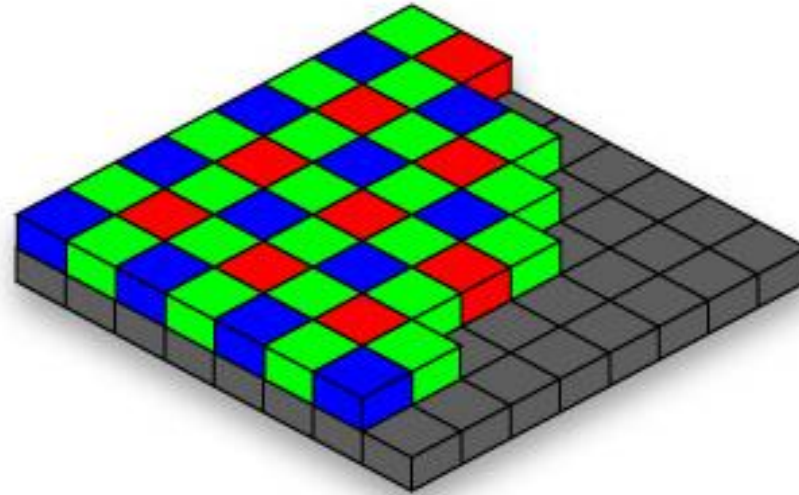
Bayer filter

Ruff Works

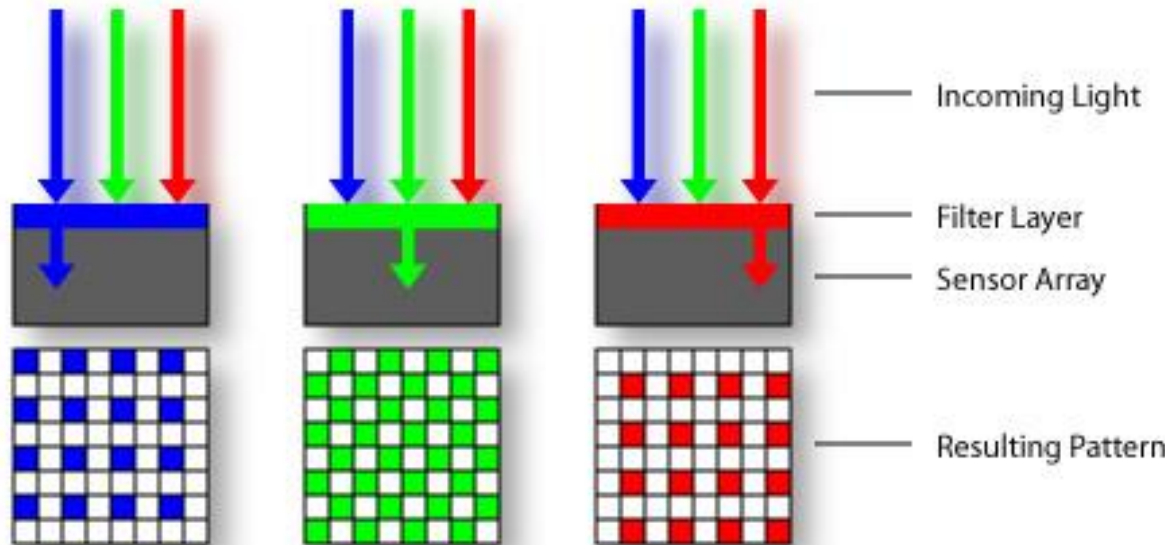
Why 3 colors?

<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](http://www.cooldictionary.com/words/Bayer-filter.wikipedia)

Color Image

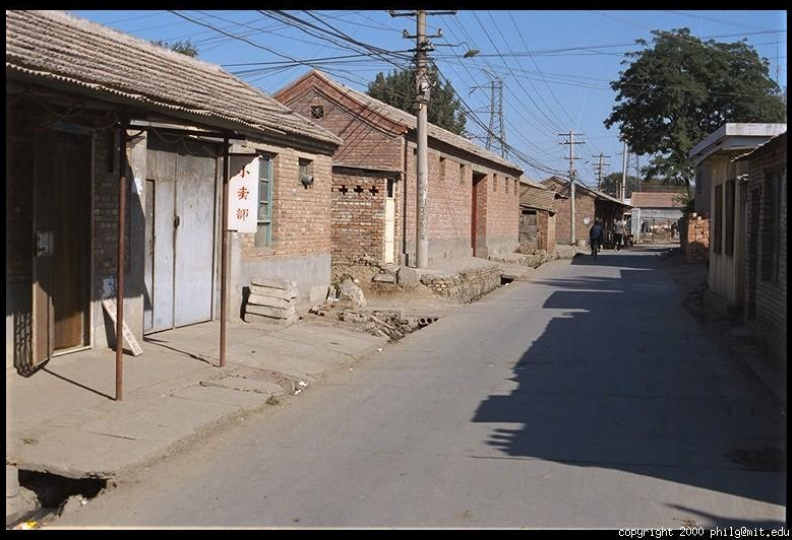
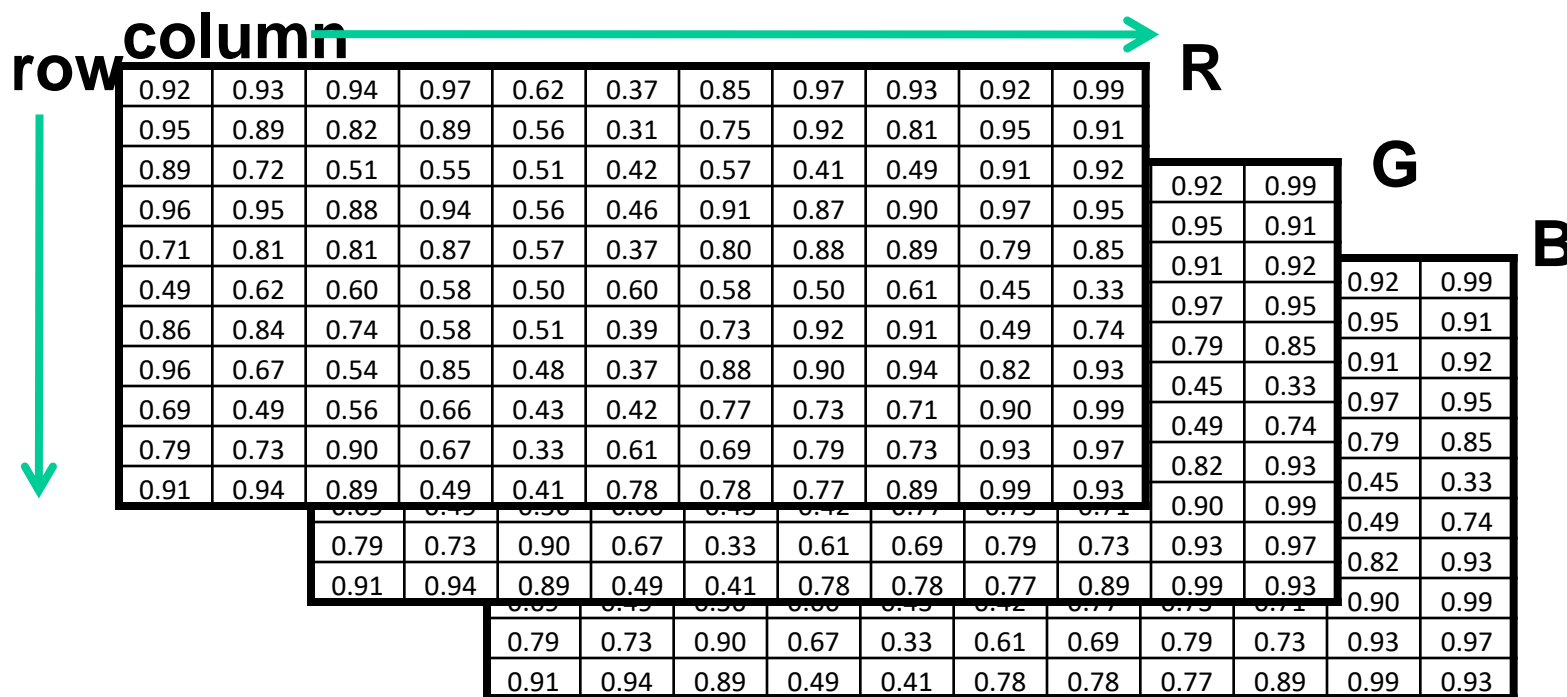


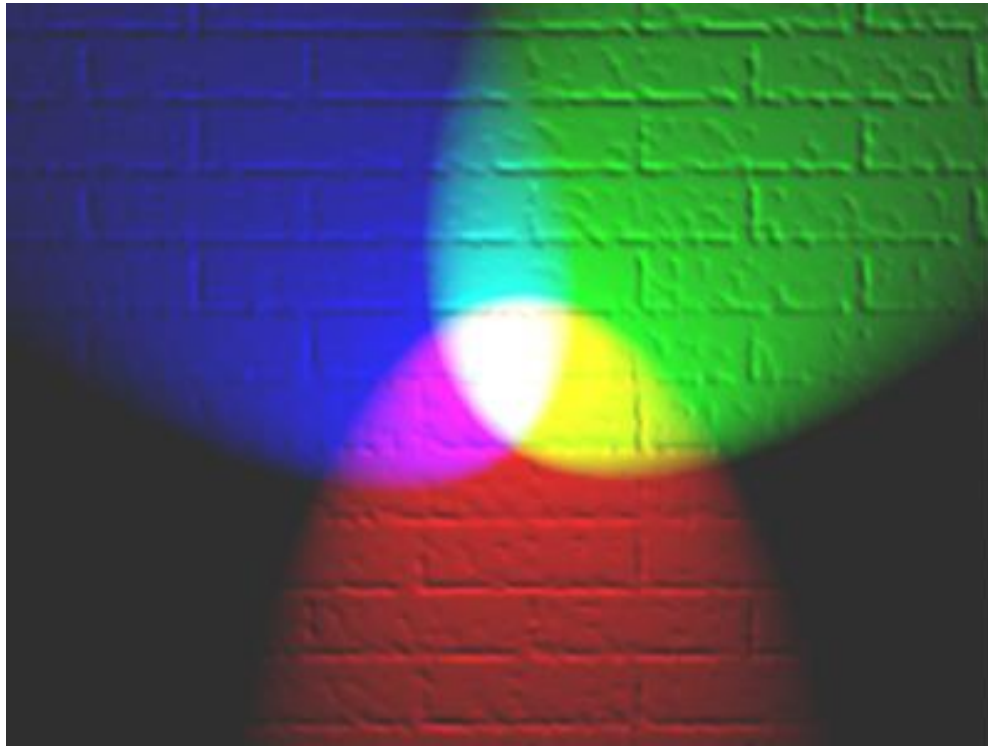
Image representation

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
 - $im(1,1,1)$ = top-left pixel value in R-channel
 - $im(y, x, b)$ = y pixels down, x pixels to right in the bth channel
 - $im(N, M, 3)$ = bottom-right pixel in B-channel
- `imread(filename)` returns a uint8 image (values 0 to 255)
 - Convert to double format (values 0 to 1) with `im2double`



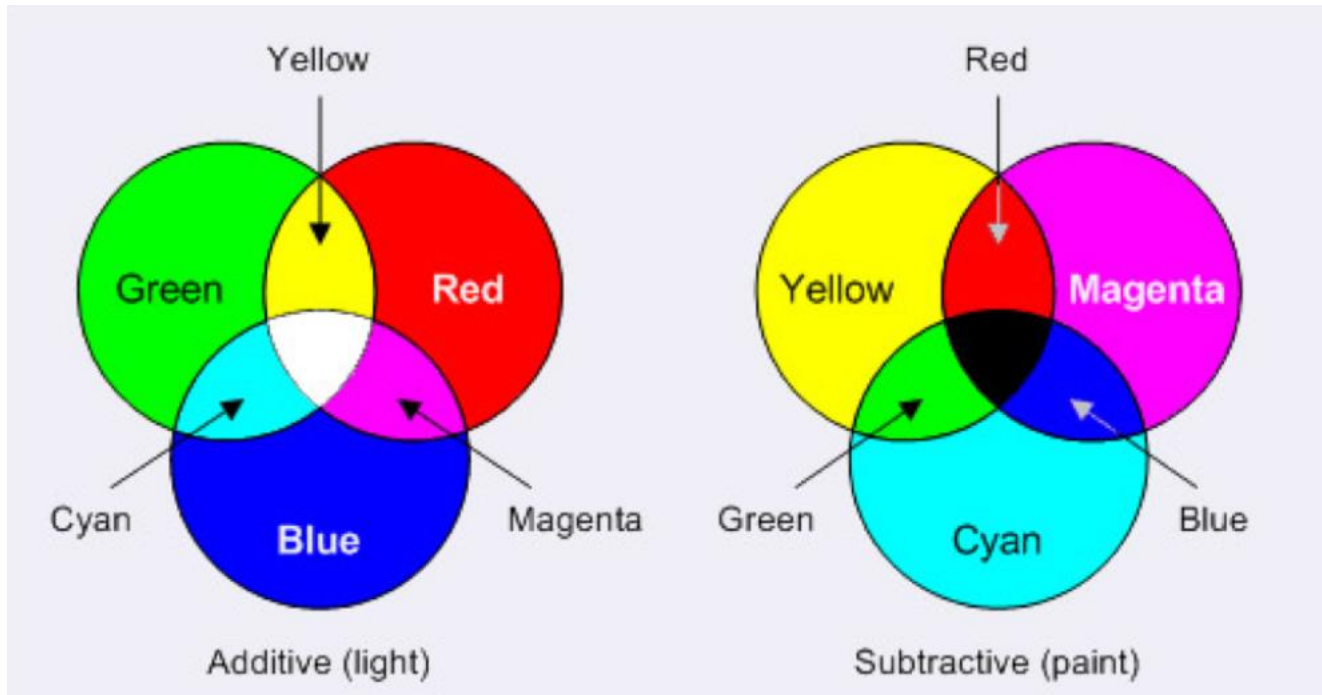
Color spaces

How can we represent color?



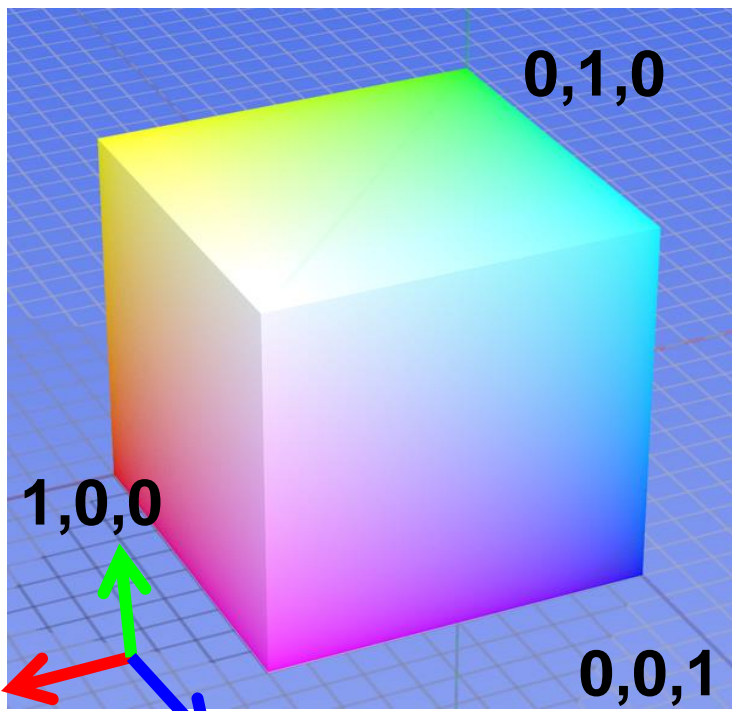
Color spaces: RGB vs. CMY(K)

Light projection vs paint



Color spaces: RGB

Default color space



RGB cube

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



R
(G=0,B=0)

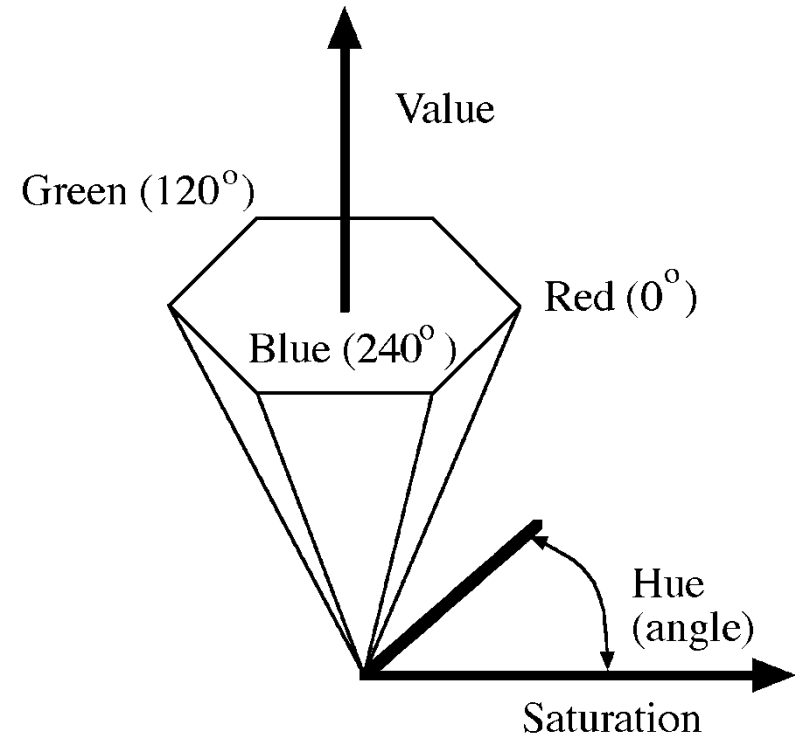
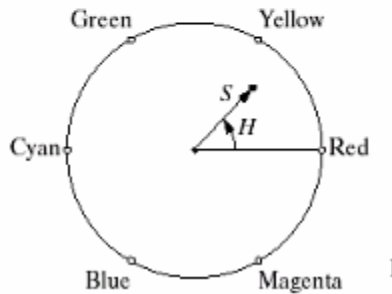
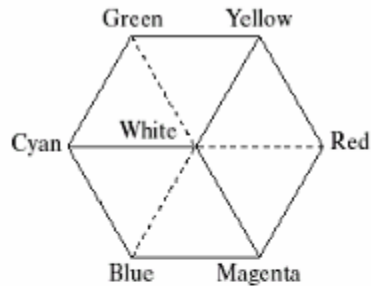


G
(R=0,B=0)



B
(R=0,G=0)

HSV



Hue, Saturation, Value (Intensity)

- RGB cube on its vertex

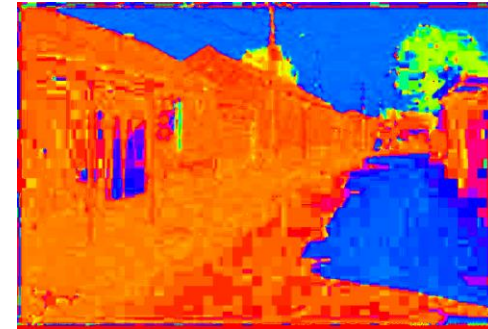
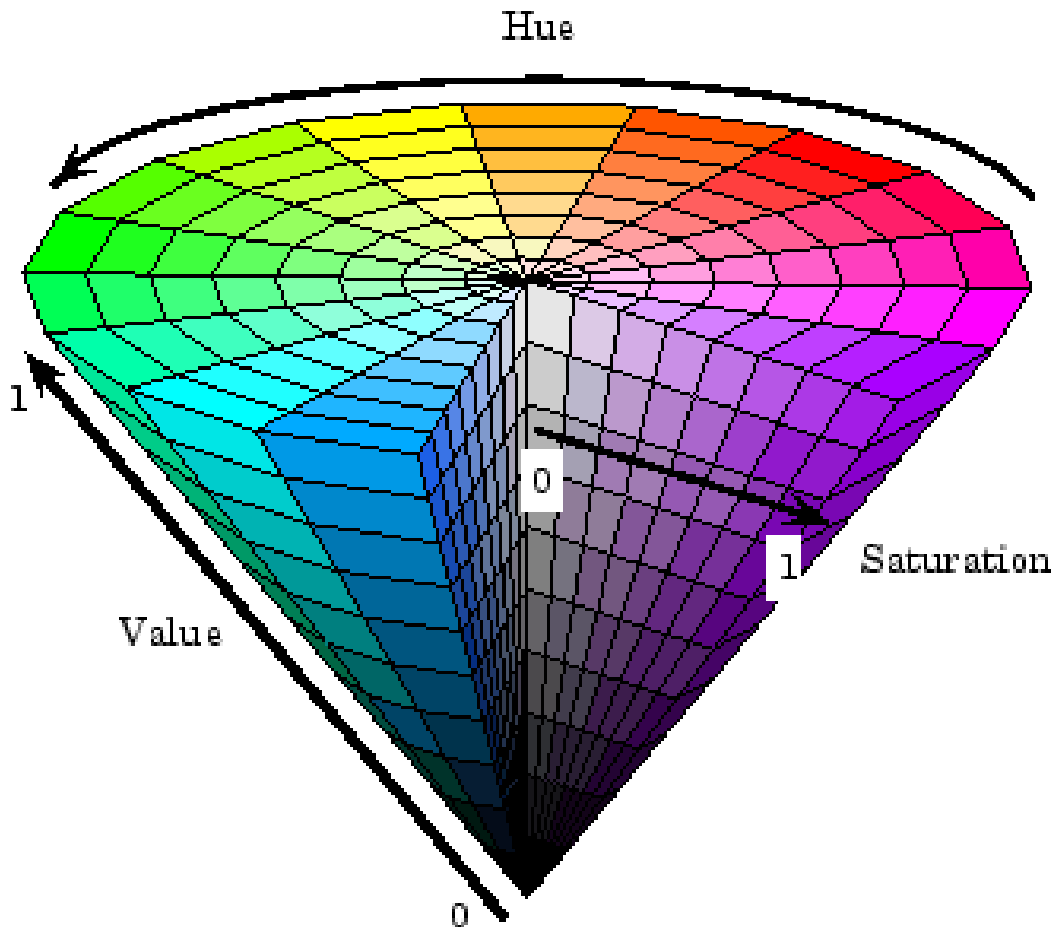
Decouples the three components (a bit)

Use `rgb2hsv()` and `hsv2rgb()` in Matlab

Color spaces: HSV



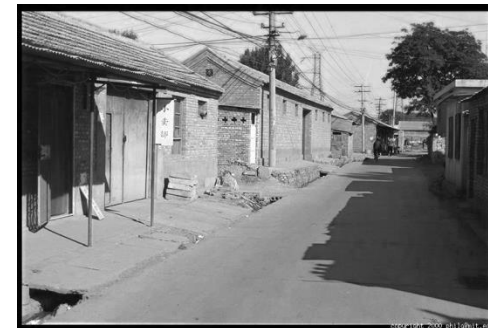
Intuitive color space



H
(S=1,V=1)



S
(H=1,V=1)

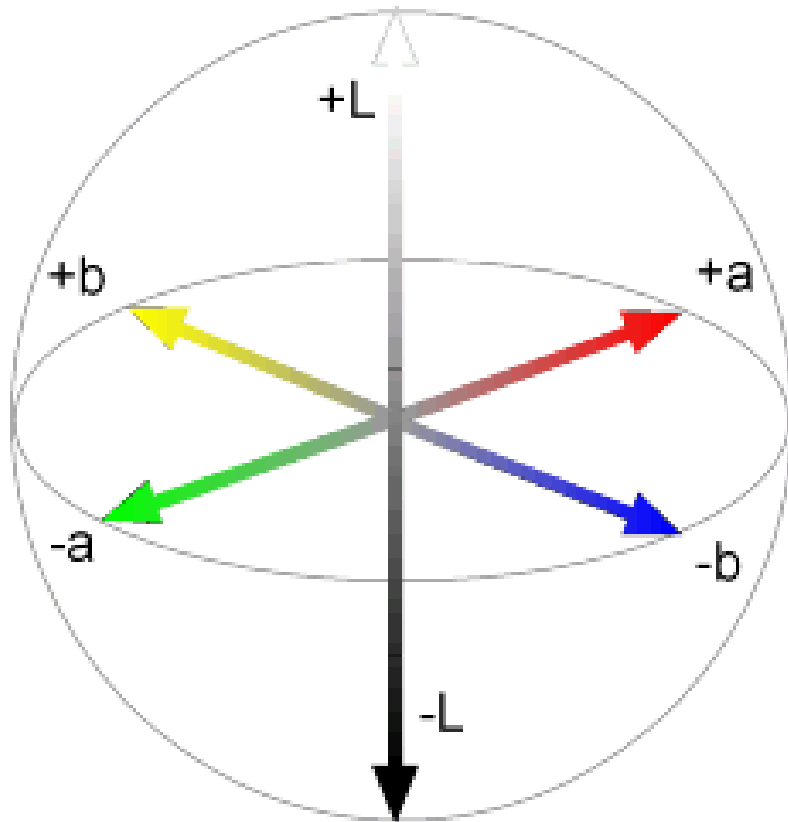


V
(H=1,S=0)

Color spaces: L*a*b*



“Perceptually uniform”* color space



L
(a=0,b=0)



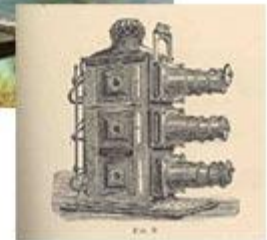
a
(L=65,b=0)



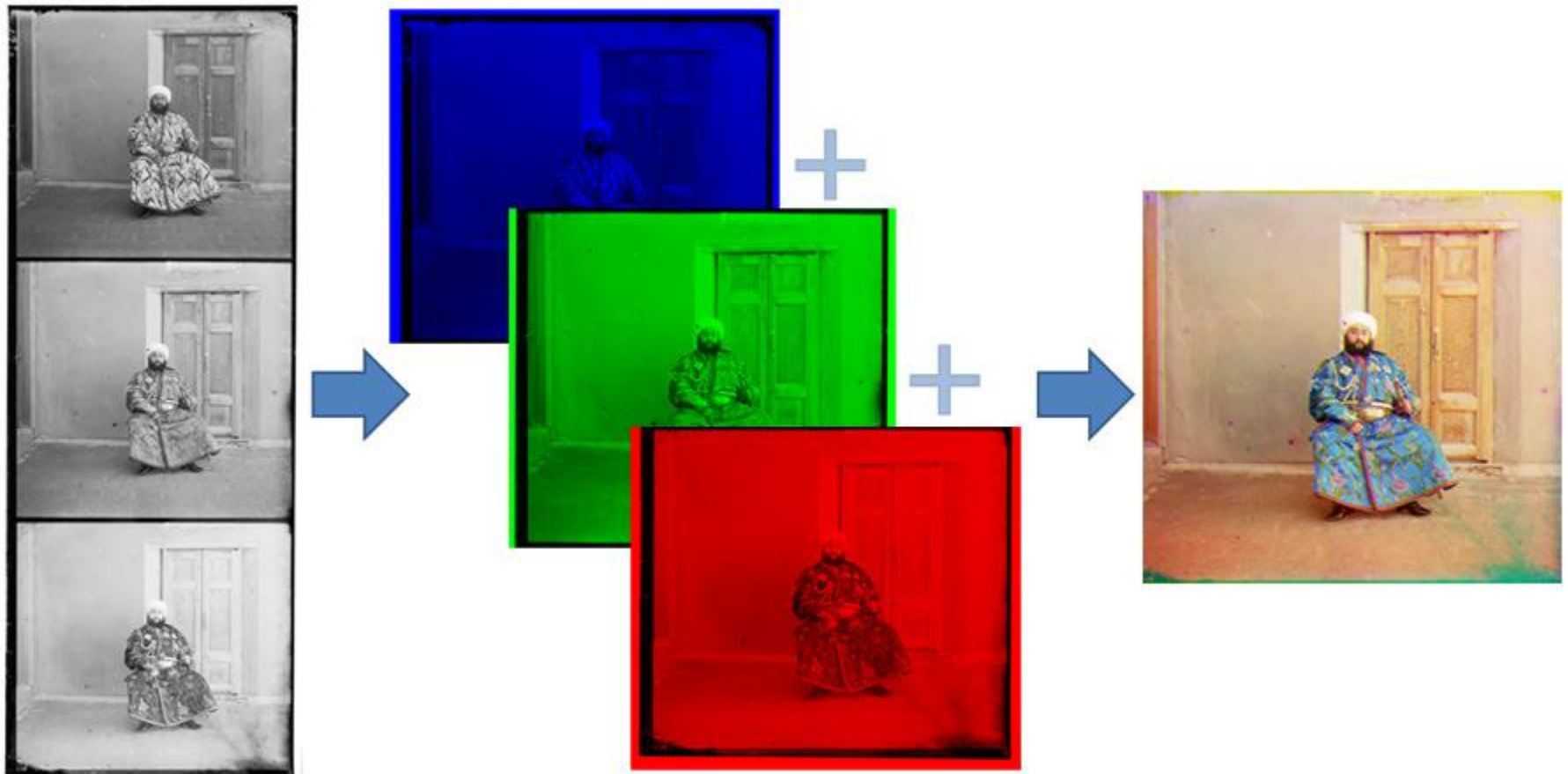
b
(L=65,a=0)

Programming Project #1

Prokudin-Gorskii's Color Photography (1907)



Programming Project #1



Programming Project #1

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

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

- Normalized Correlation (NCC):

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

