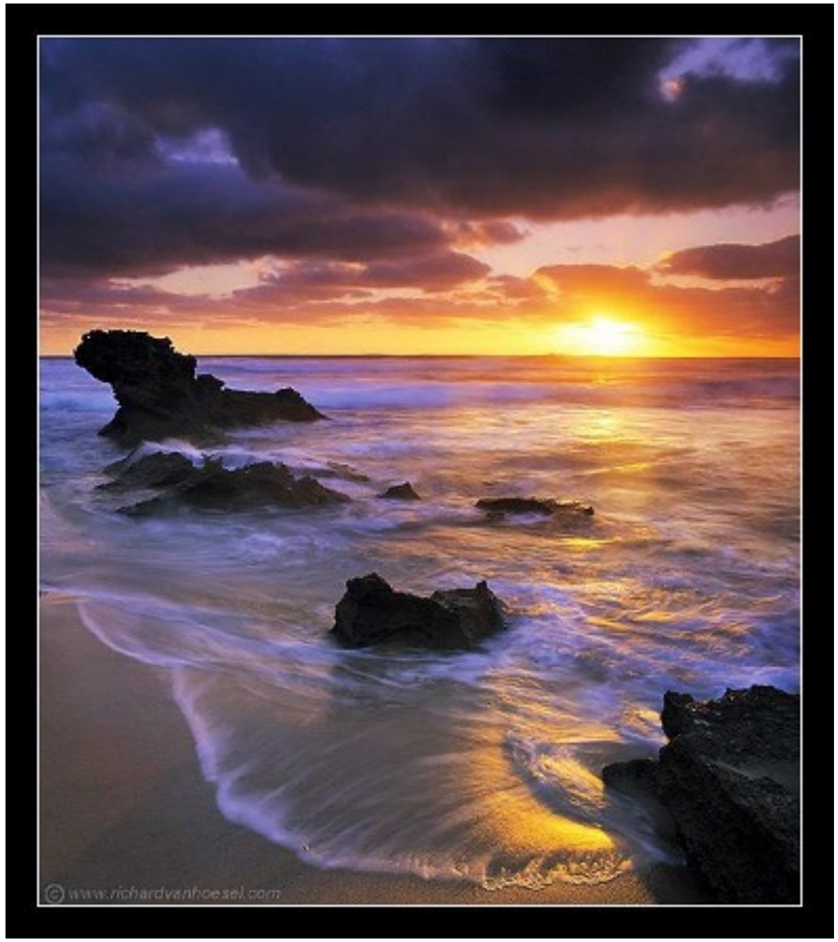
Capturing Light… in human and machine

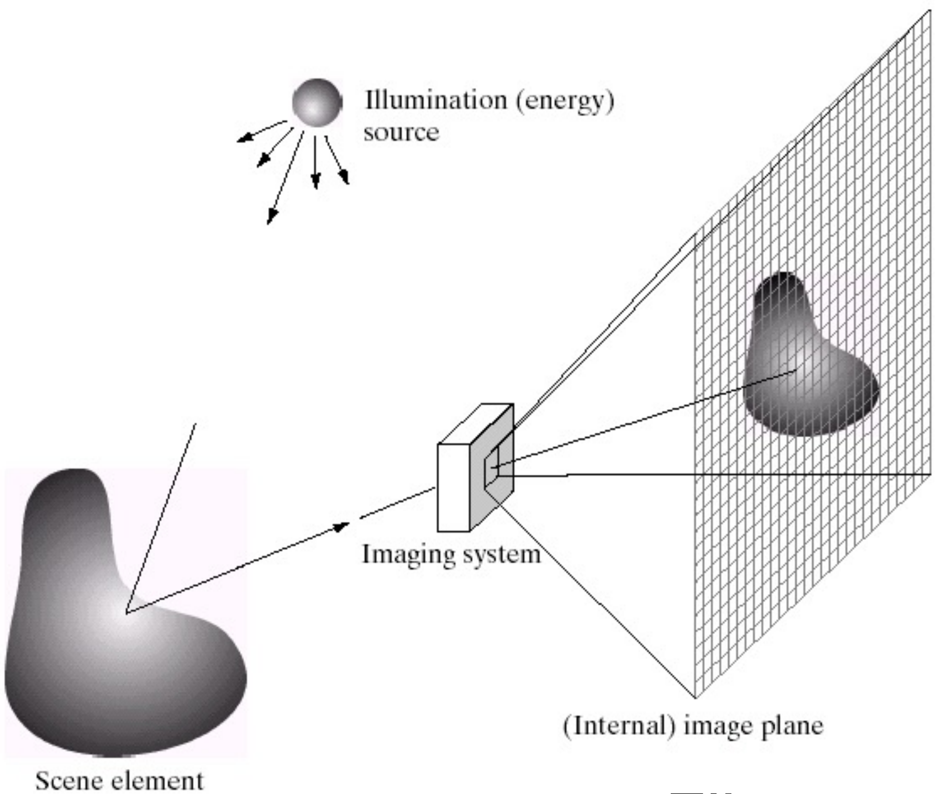


CS194-26: Computer Vision and Comp. Photography
Alexei Efros & Angjoo Kanazawa, UC Berkeley, Fall 2022

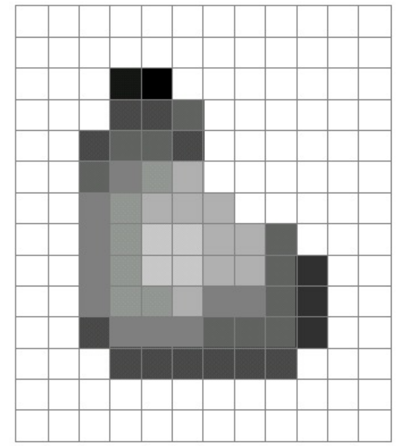
Etymology

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

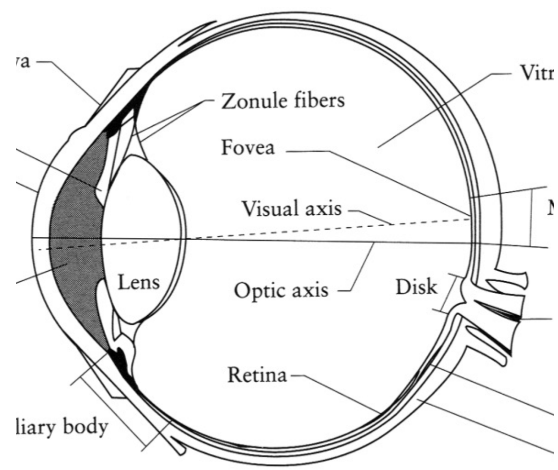
Image Formation



Film



Digital Camera



The Eye

Sensor Array

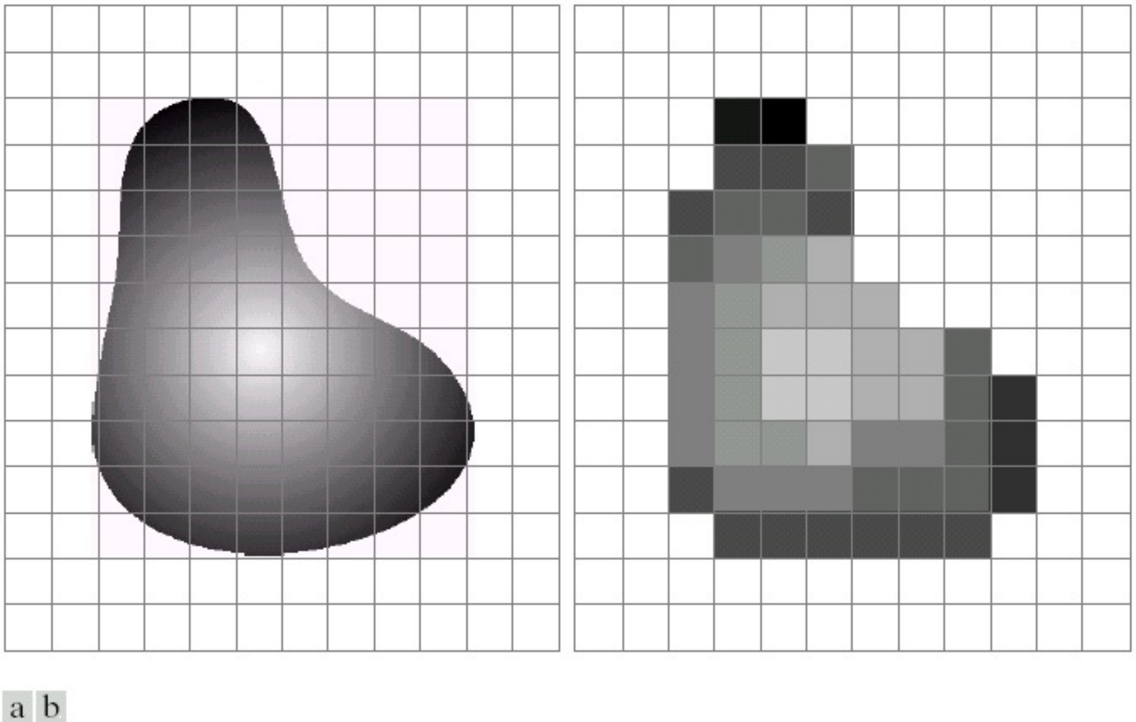


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

CMOS sensor

Sampling and Quantization

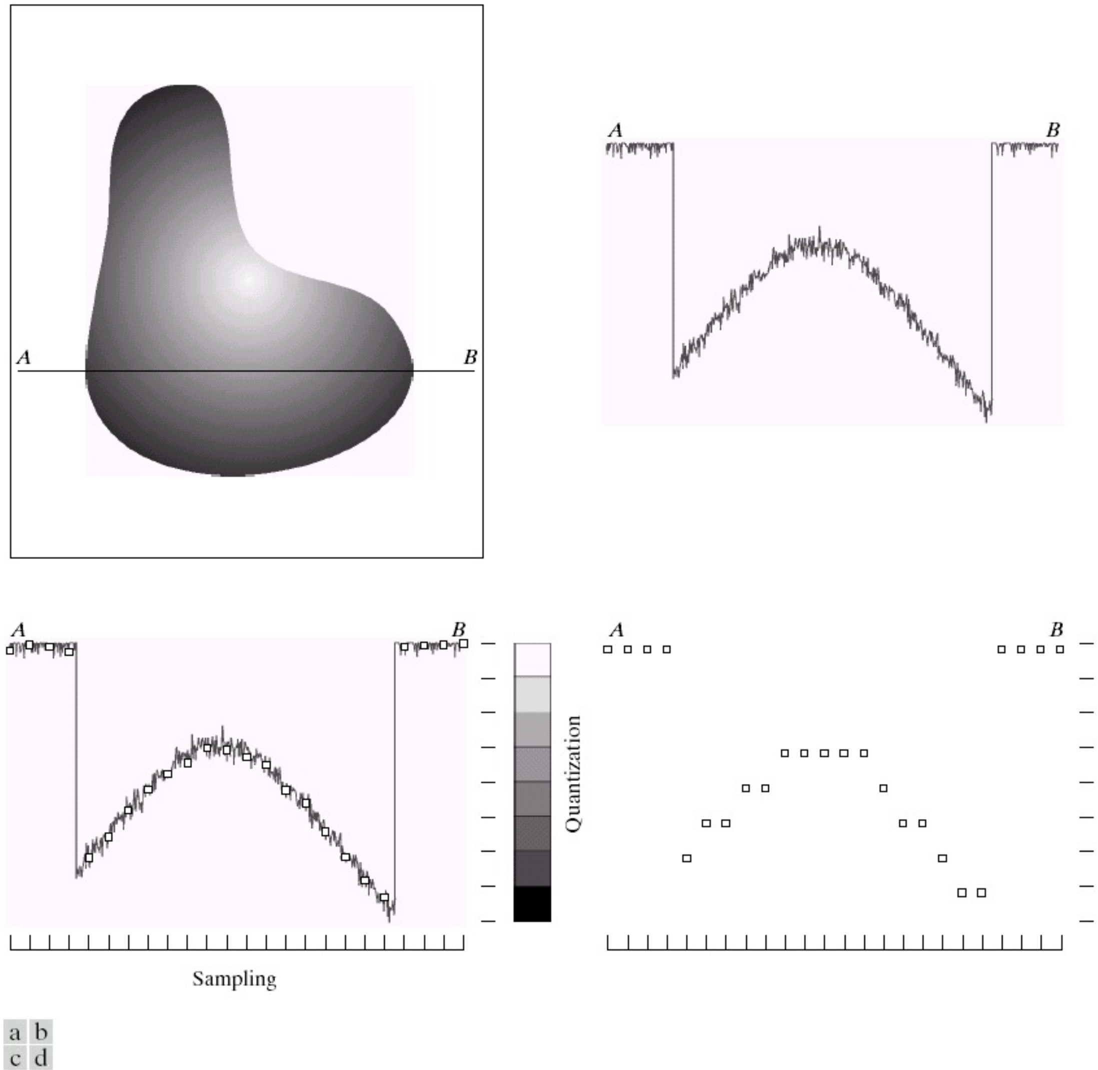


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

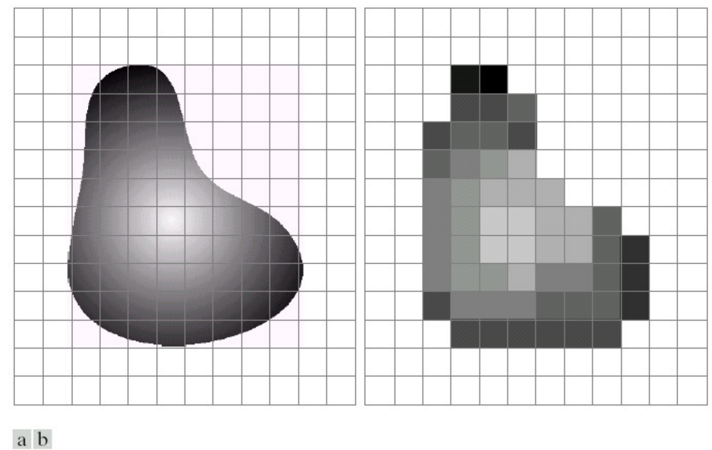
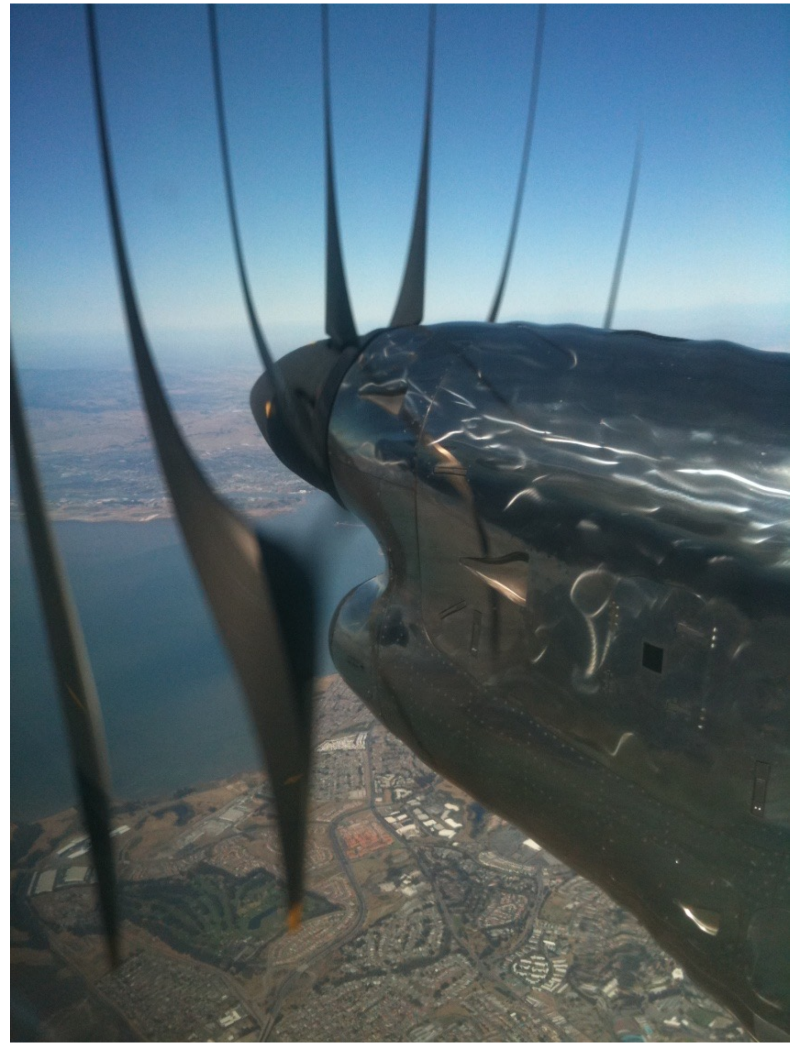
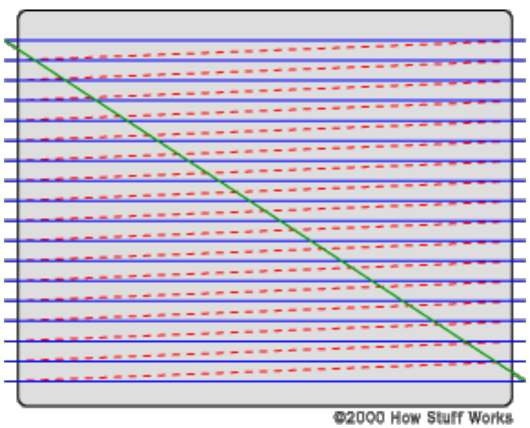


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

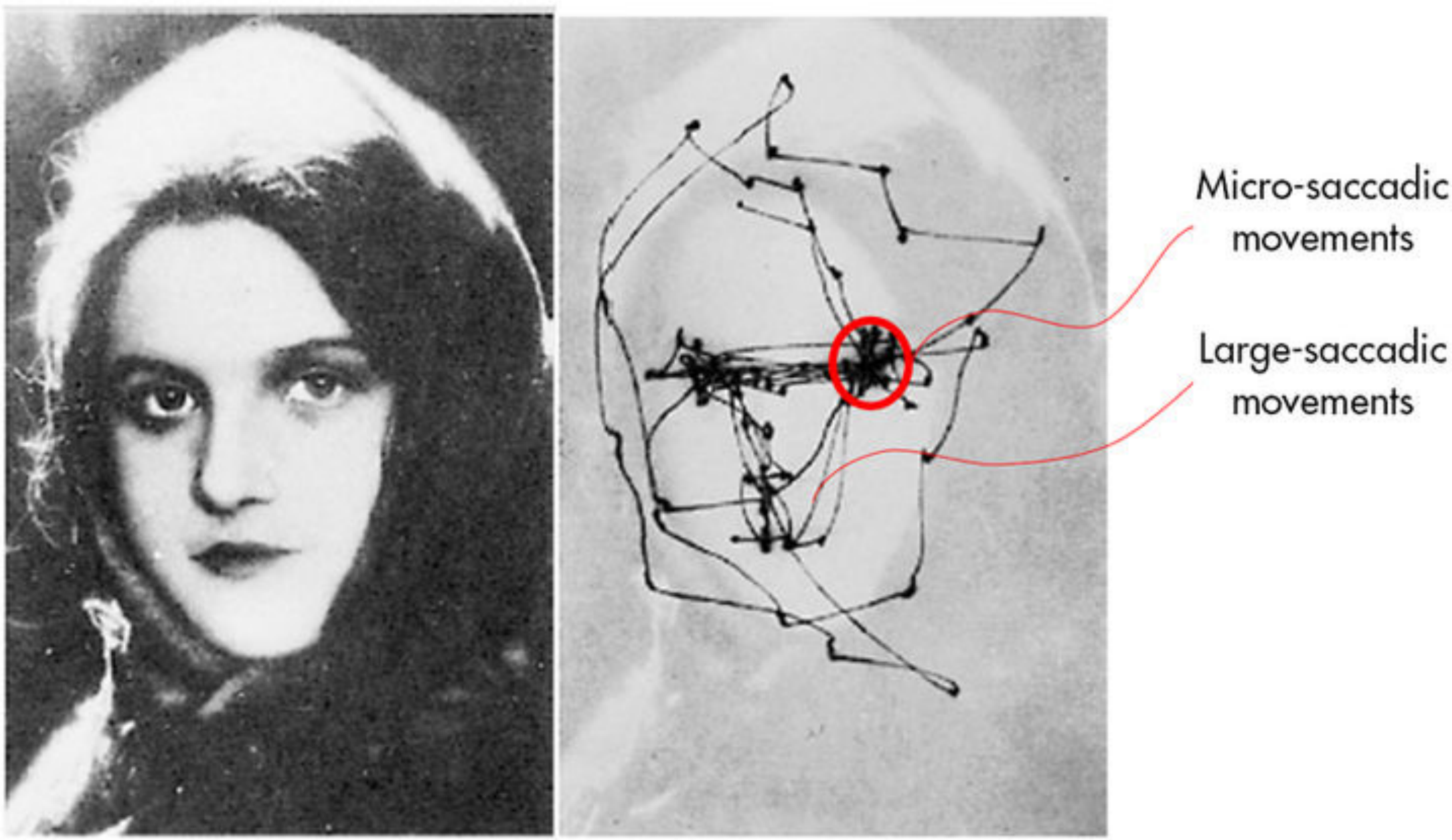
Rolling Shutter





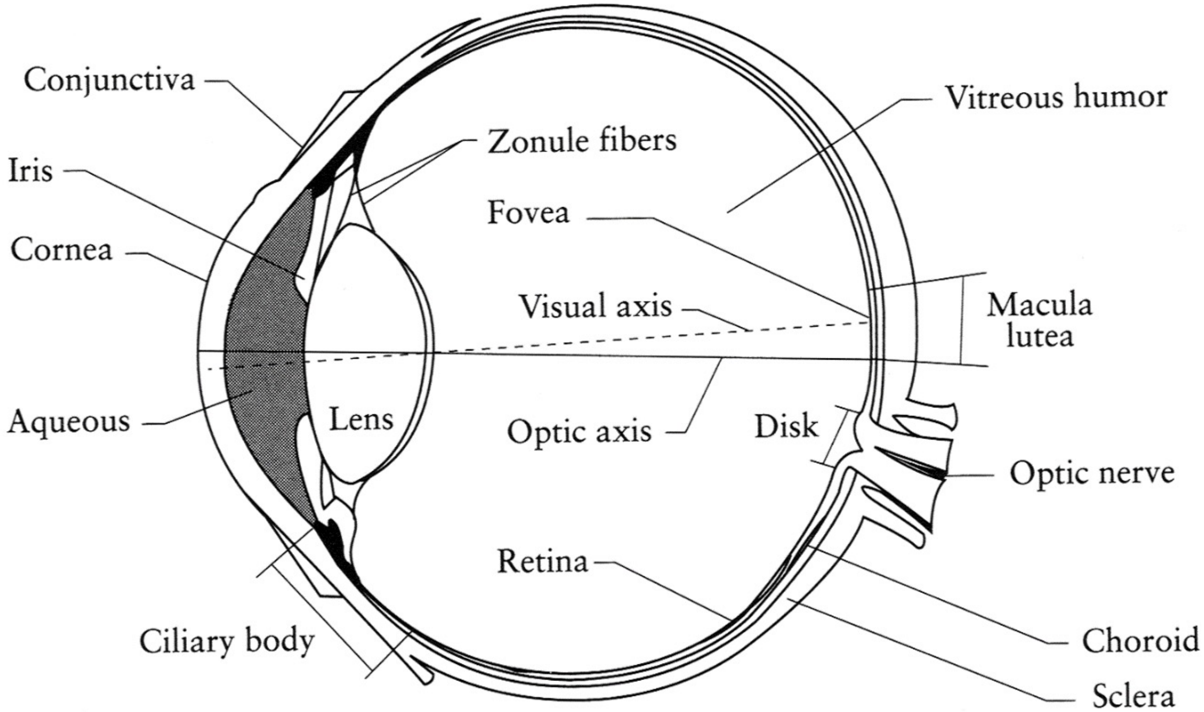
http://en.wikipedia.org/wiki/Rolling_shutter

Saccadic eye movement



Saccadic eye movement

The Eye

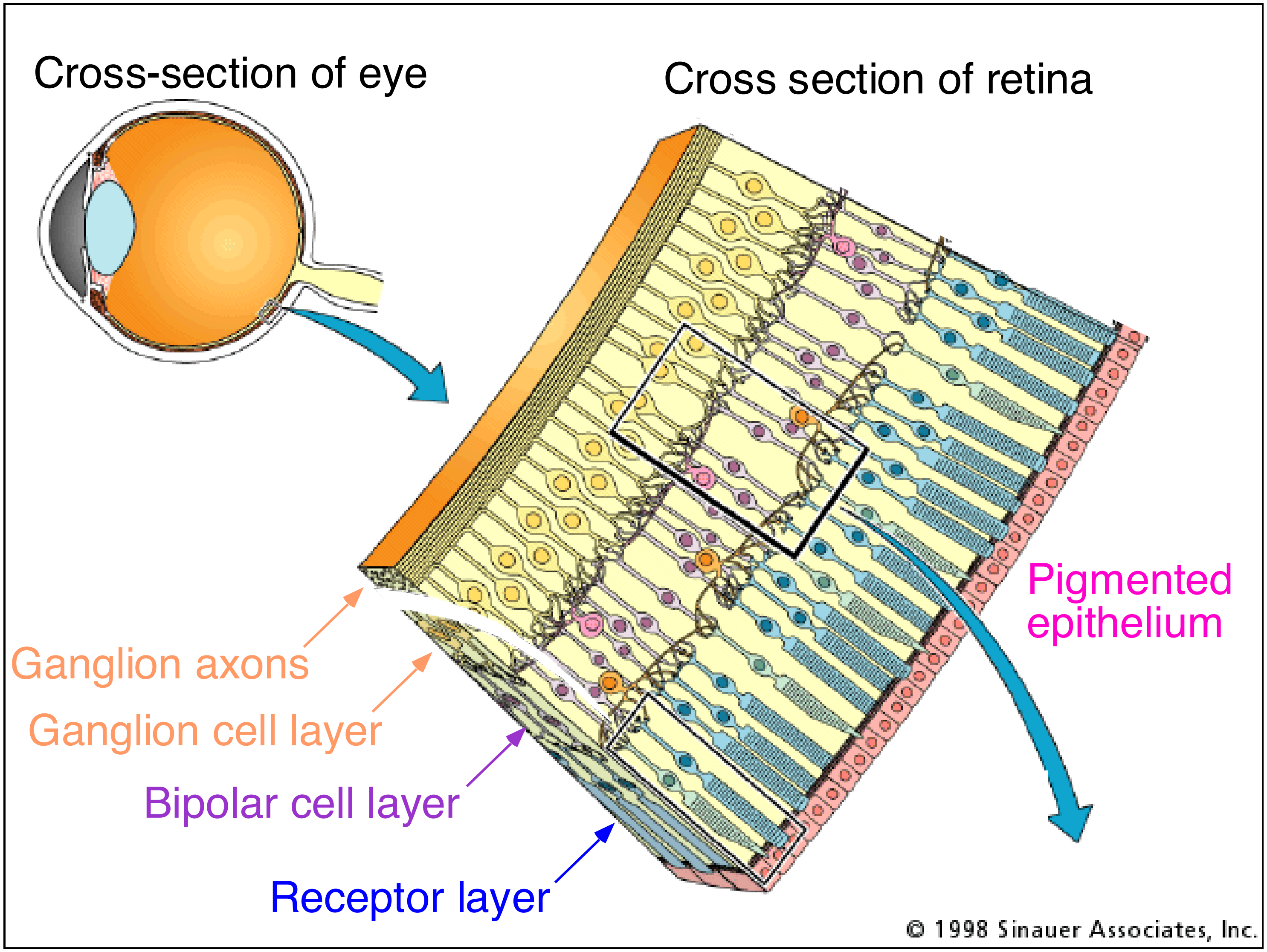


The human eye is a camera!

- **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**

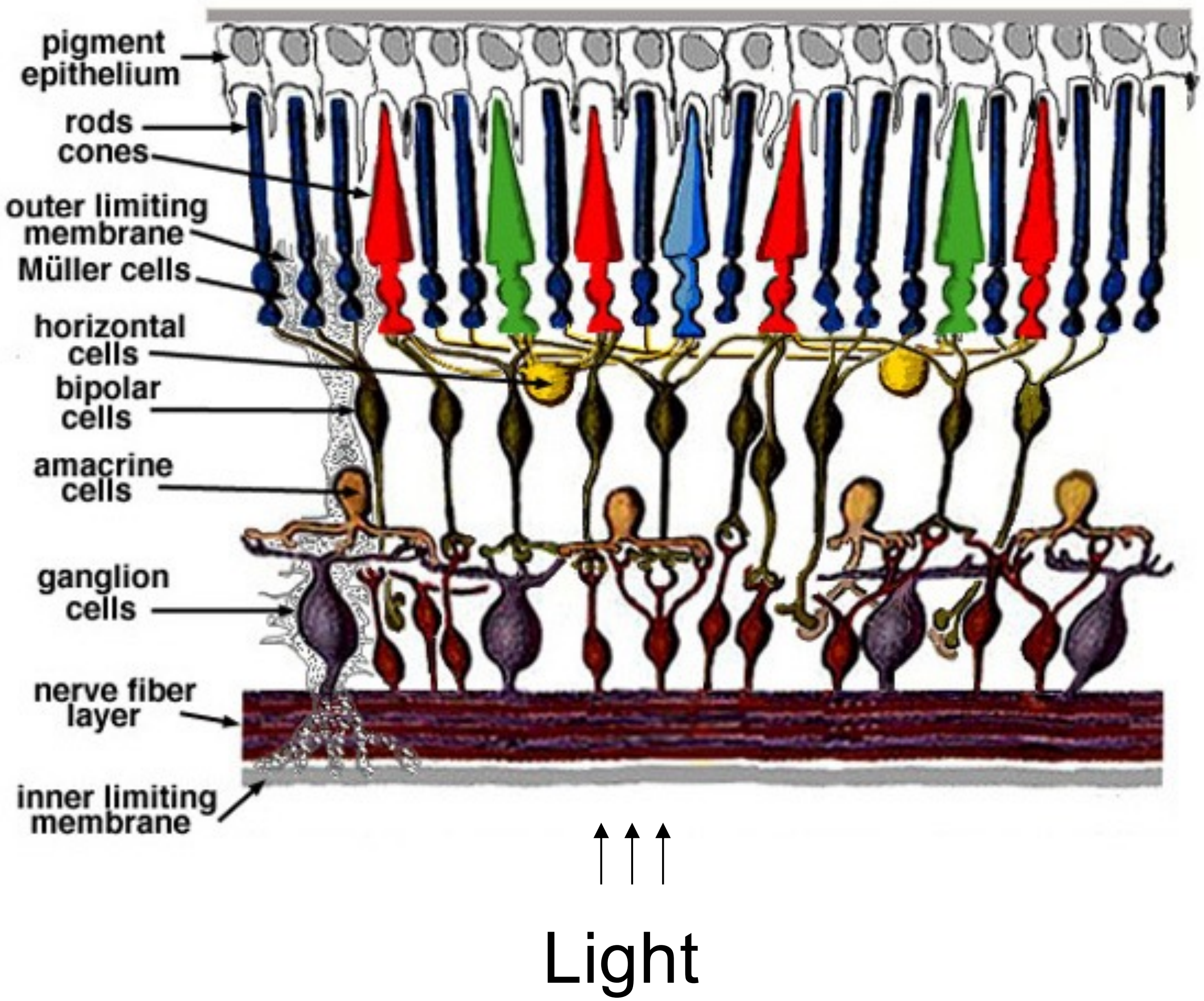
Slide by Steve Seitz

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



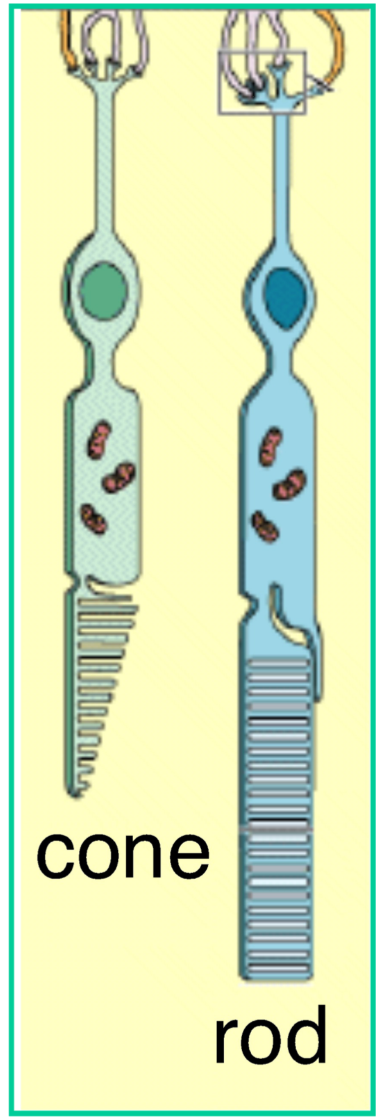
Two types of light-sensitive receptors

Cones

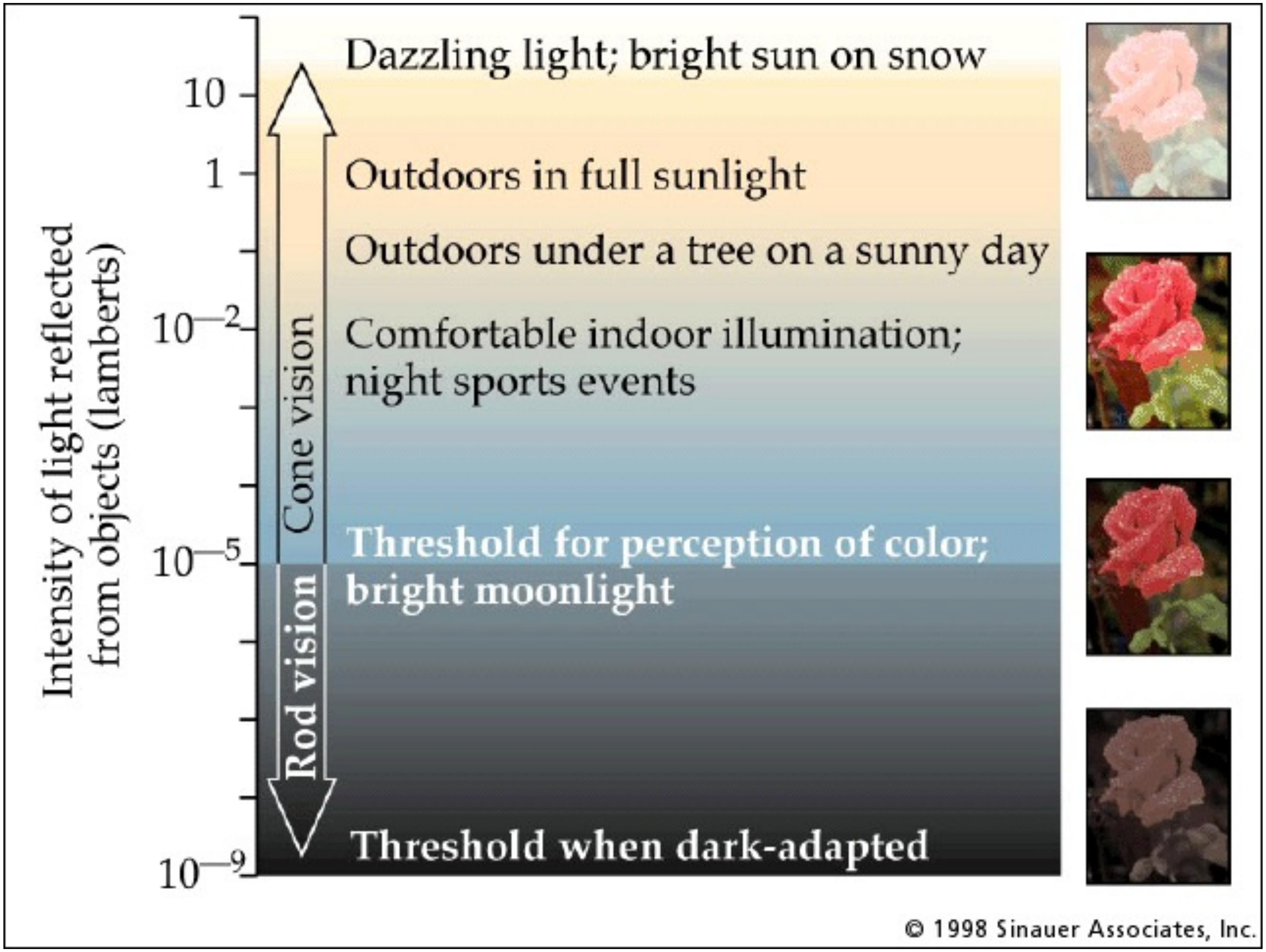
cone-shaped
less sensitive
operate in high light
color vision

Rods

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

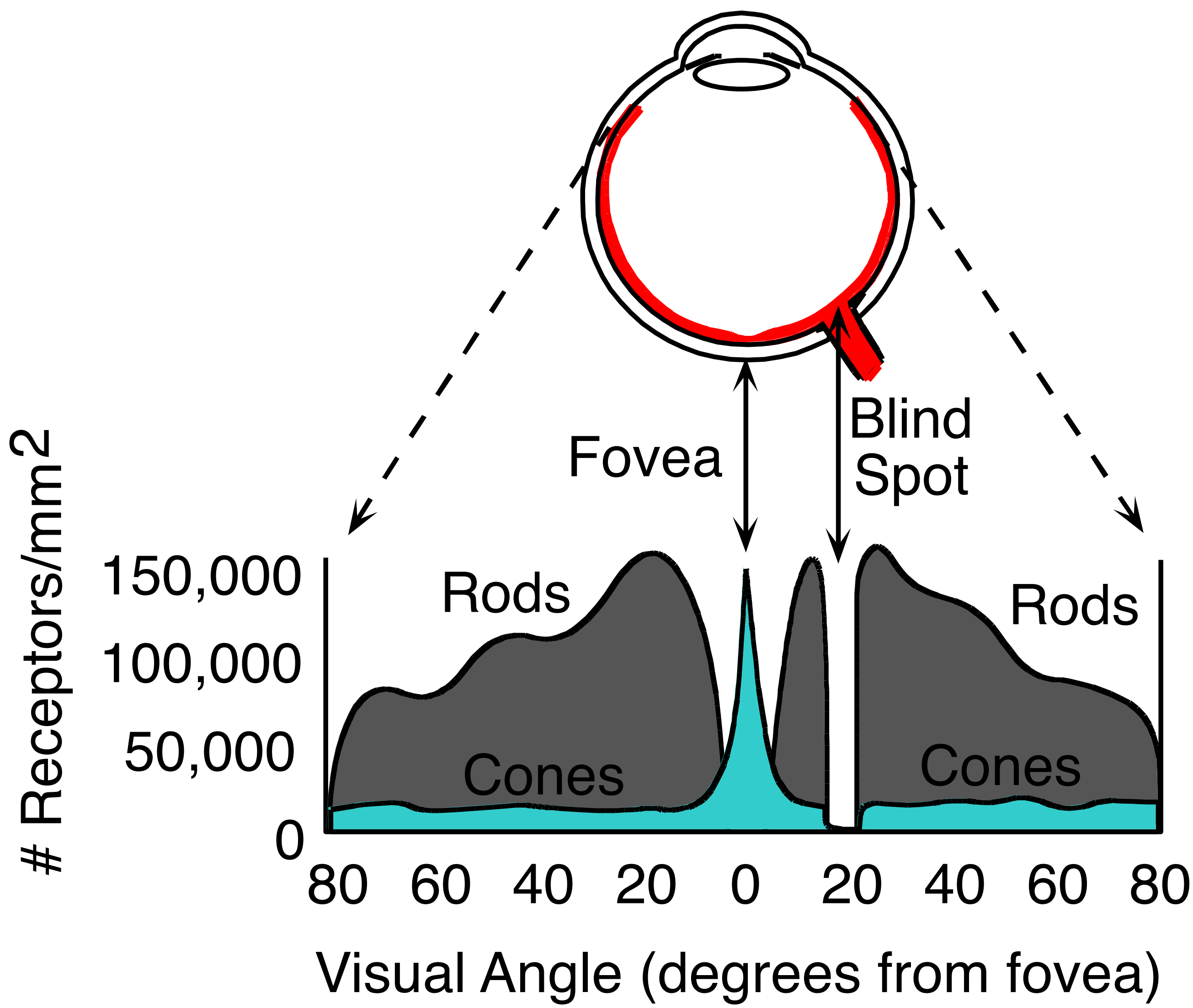


Rod / Cone sensitivity

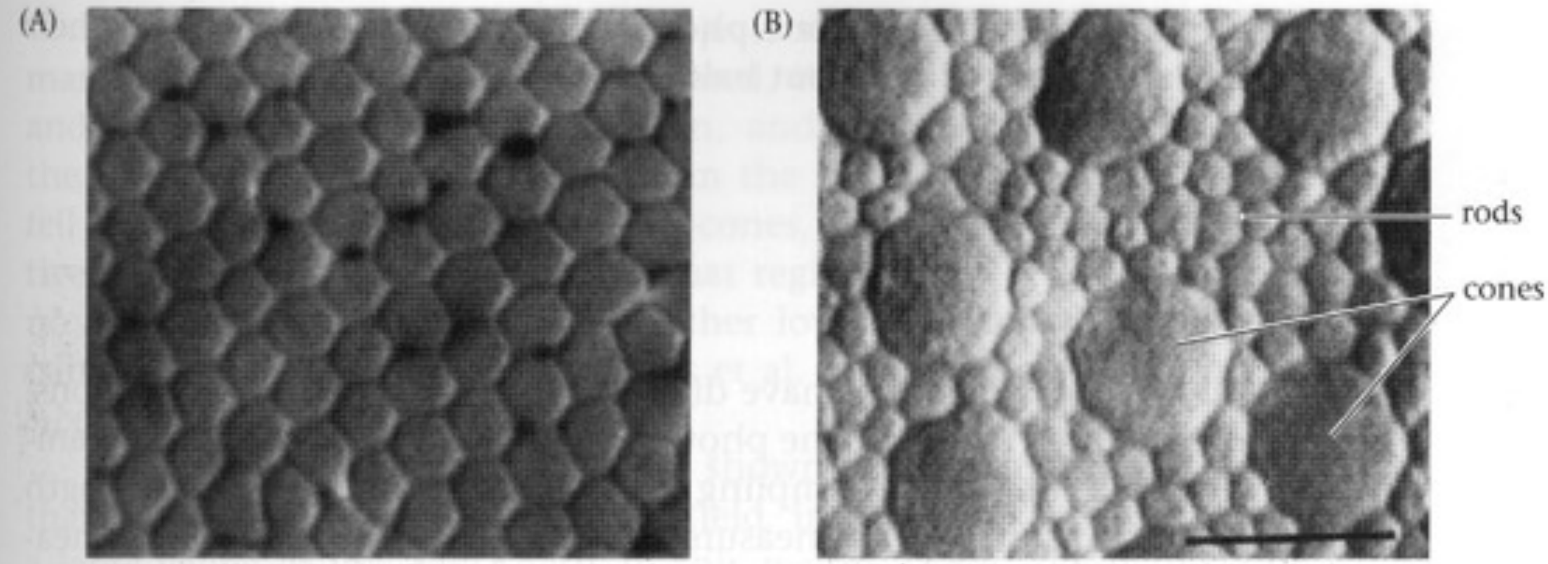


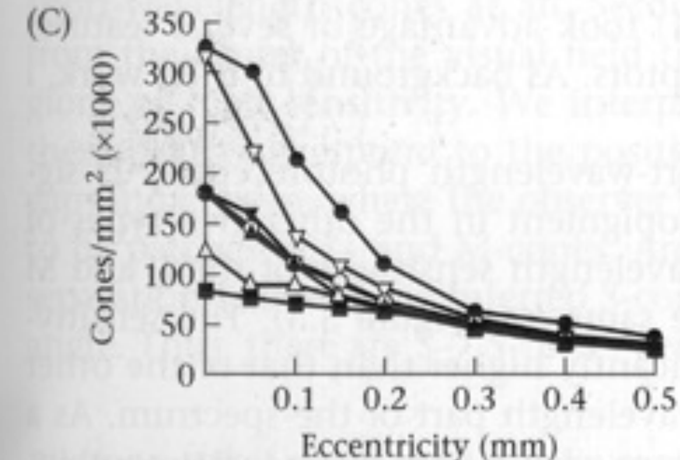
The famous sock-matching problem…

Distribution of Rods and Cones



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

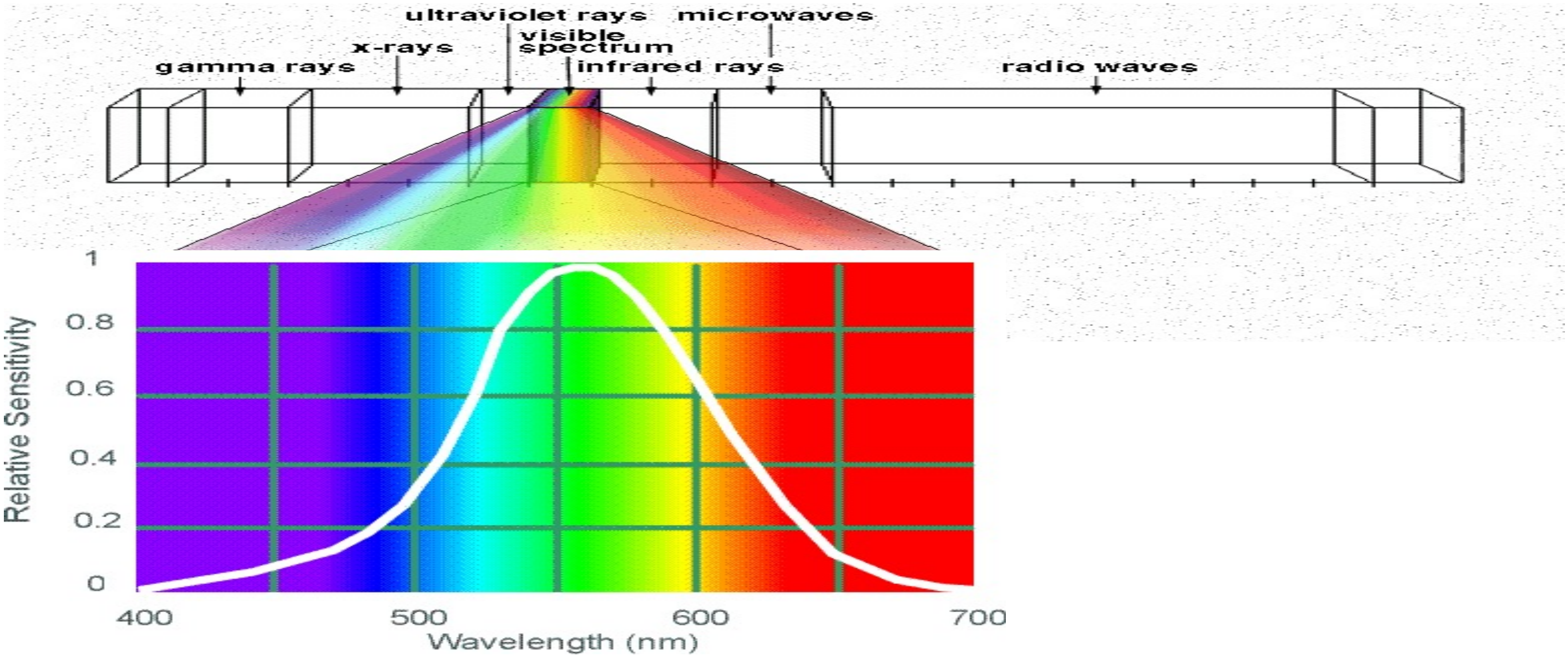




3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the 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

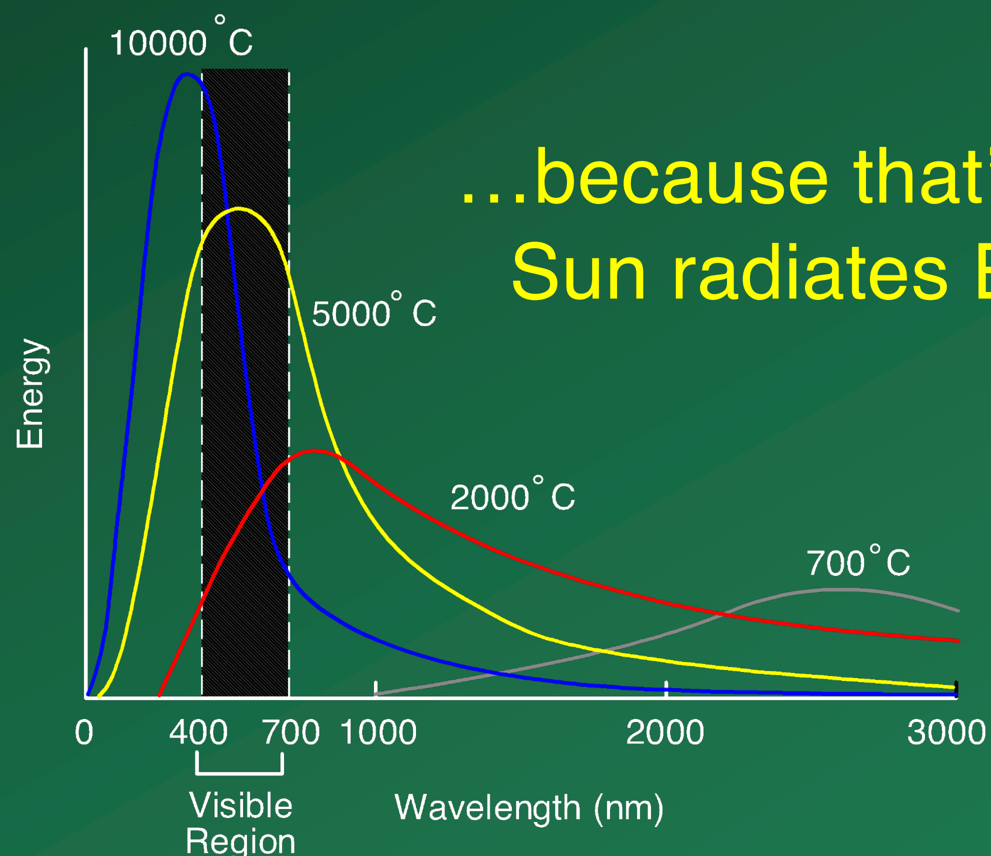


Human Luminance Sensitivity Function

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

Visible Light

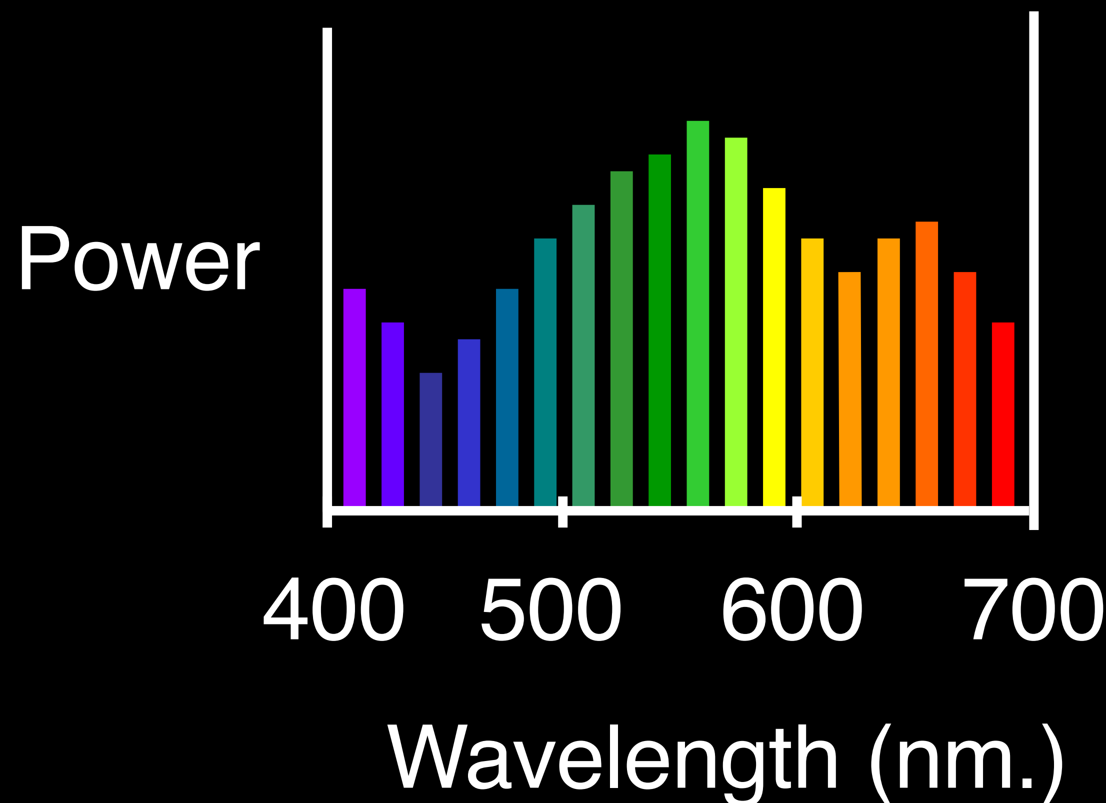
Why do we see light of these wavelengths?



…because that's where the Sun radiates EM energy

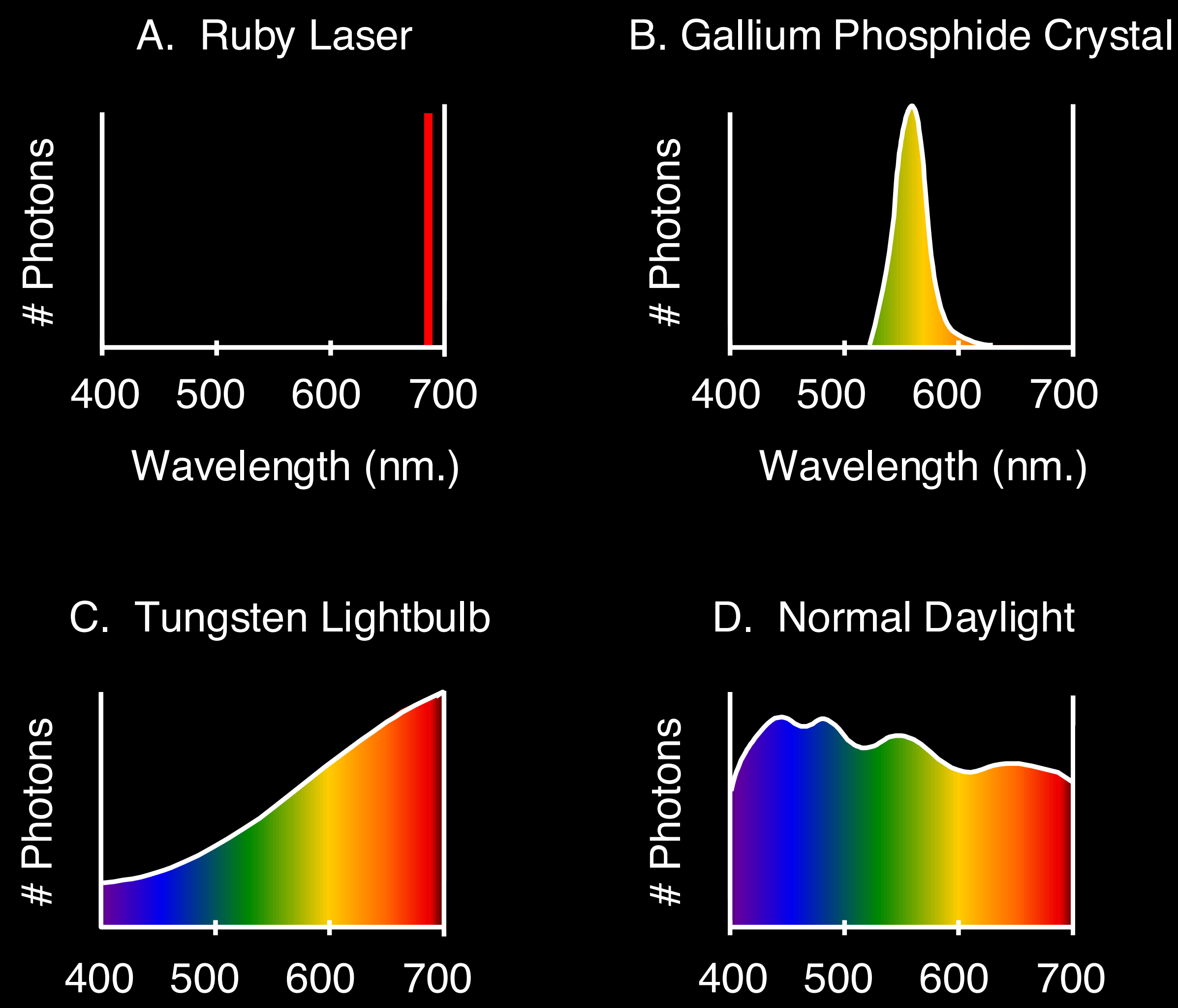
The Physics of Light

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.



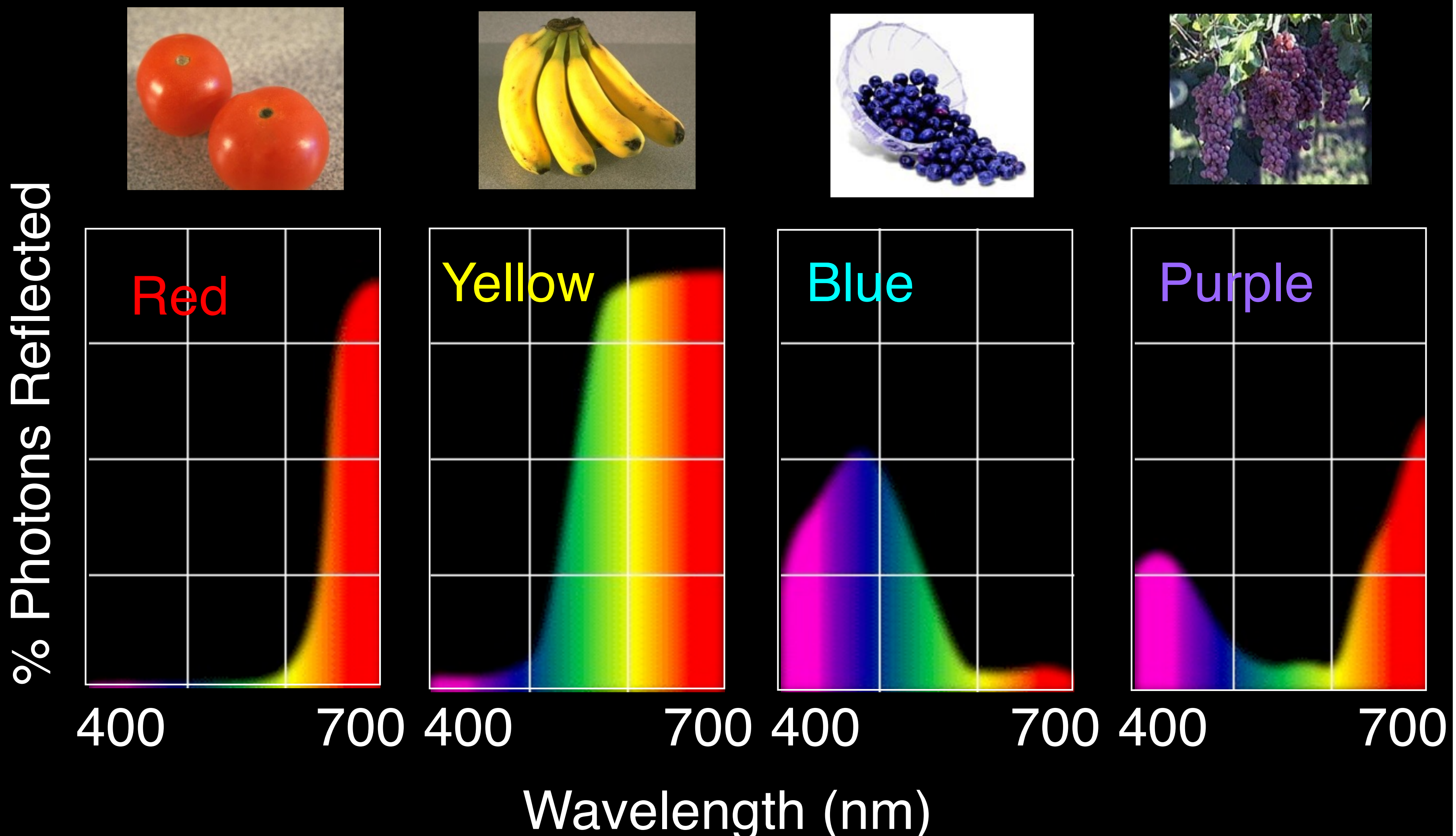
The Physics of Light

Some examples of the spectra of light sources



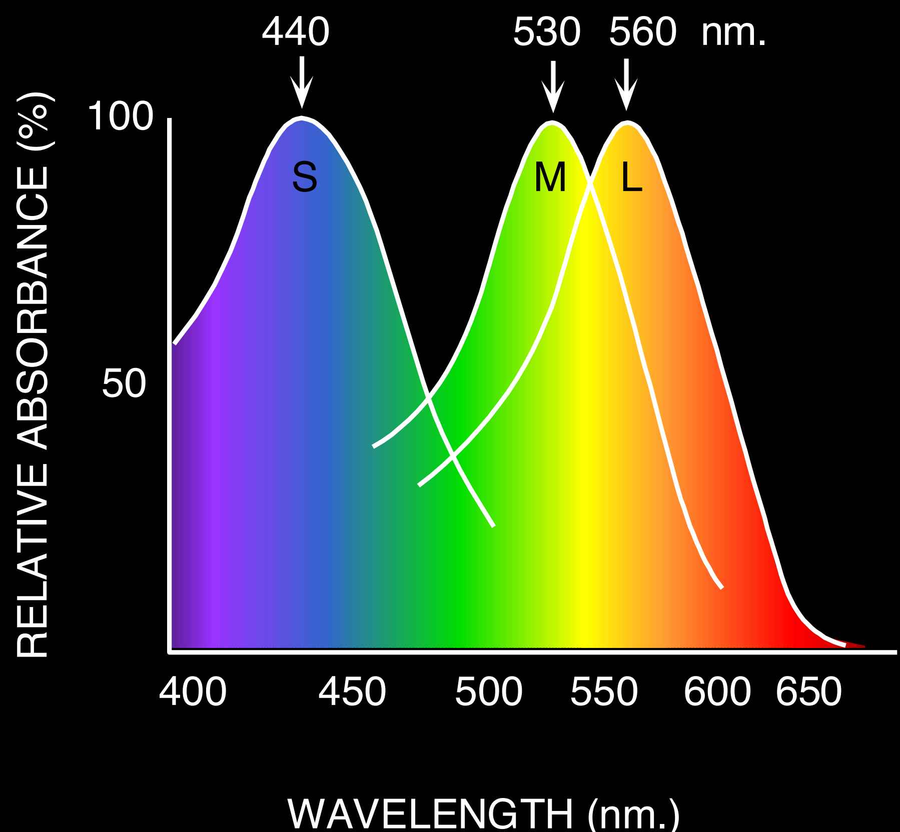
The Physics of Light

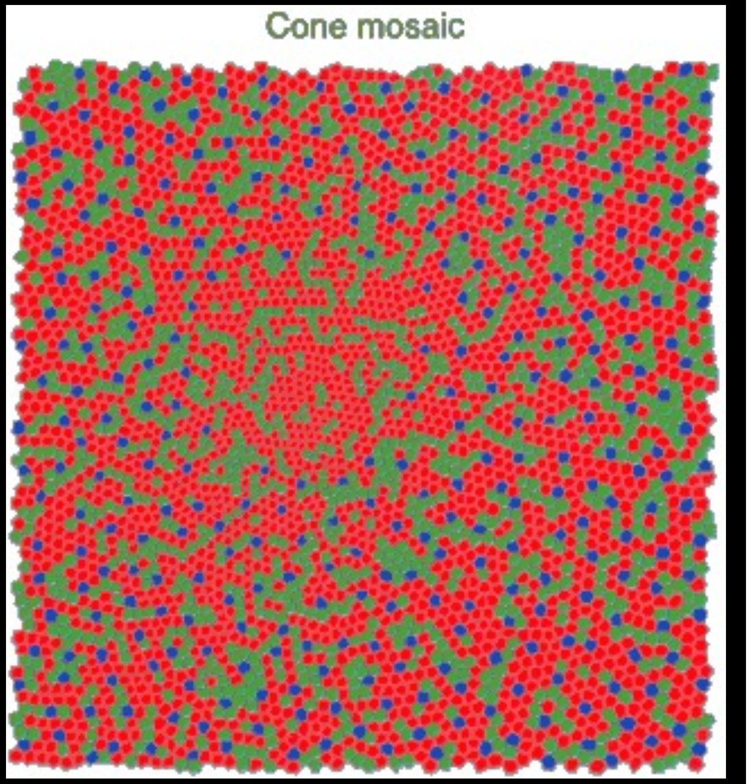
Some examples of the reflectance spectra of surfaces



Physiology of Color Vision

Three kinds of cones:





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

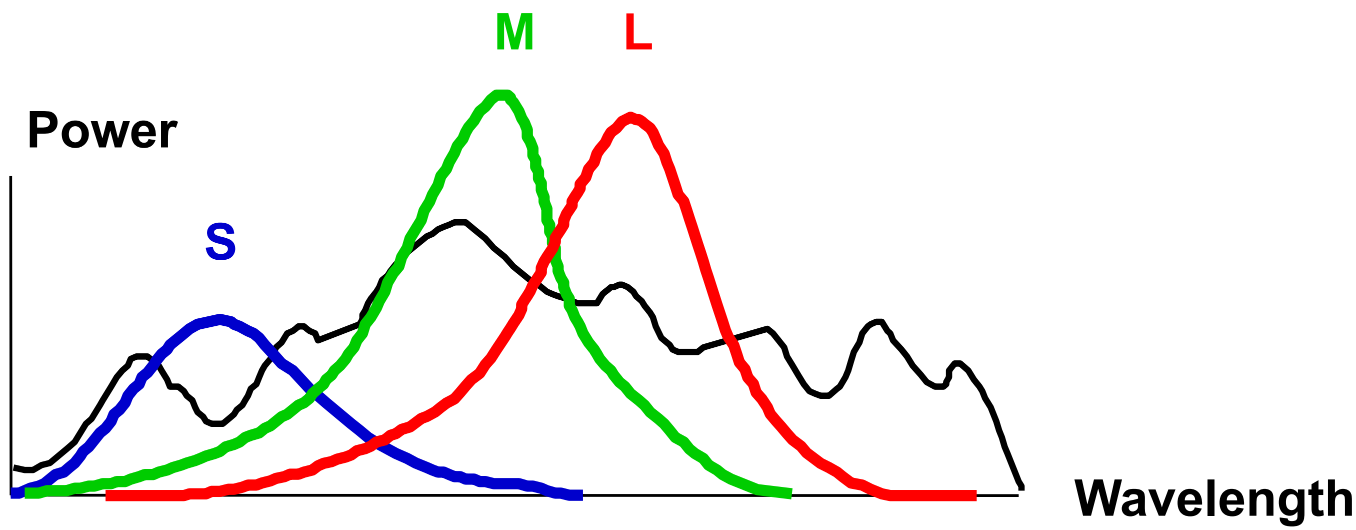
Not everyone is trichromat

- Types of color blindness:
  - 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)

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

Trichromacy



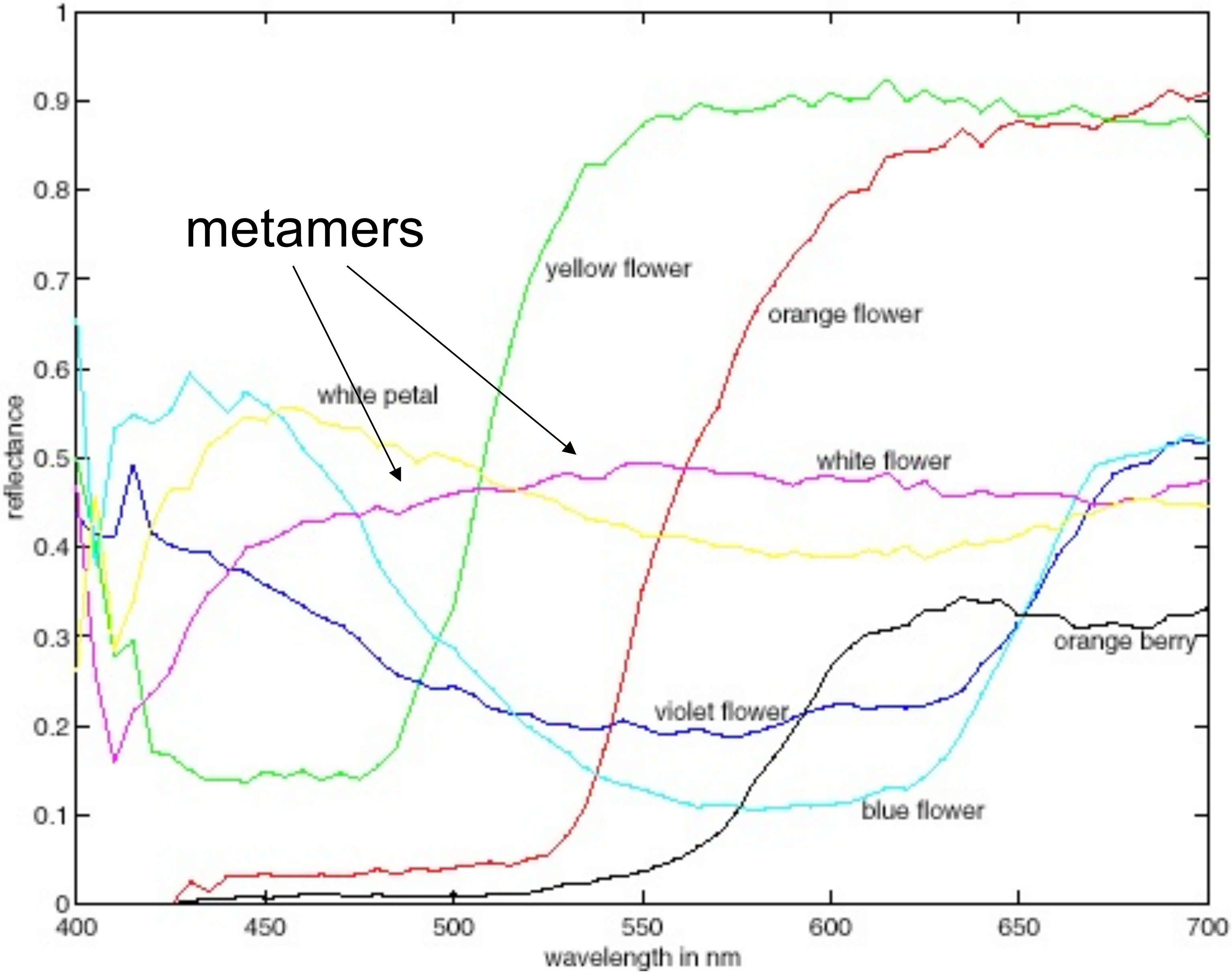
Rods and cones act as *filters* on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

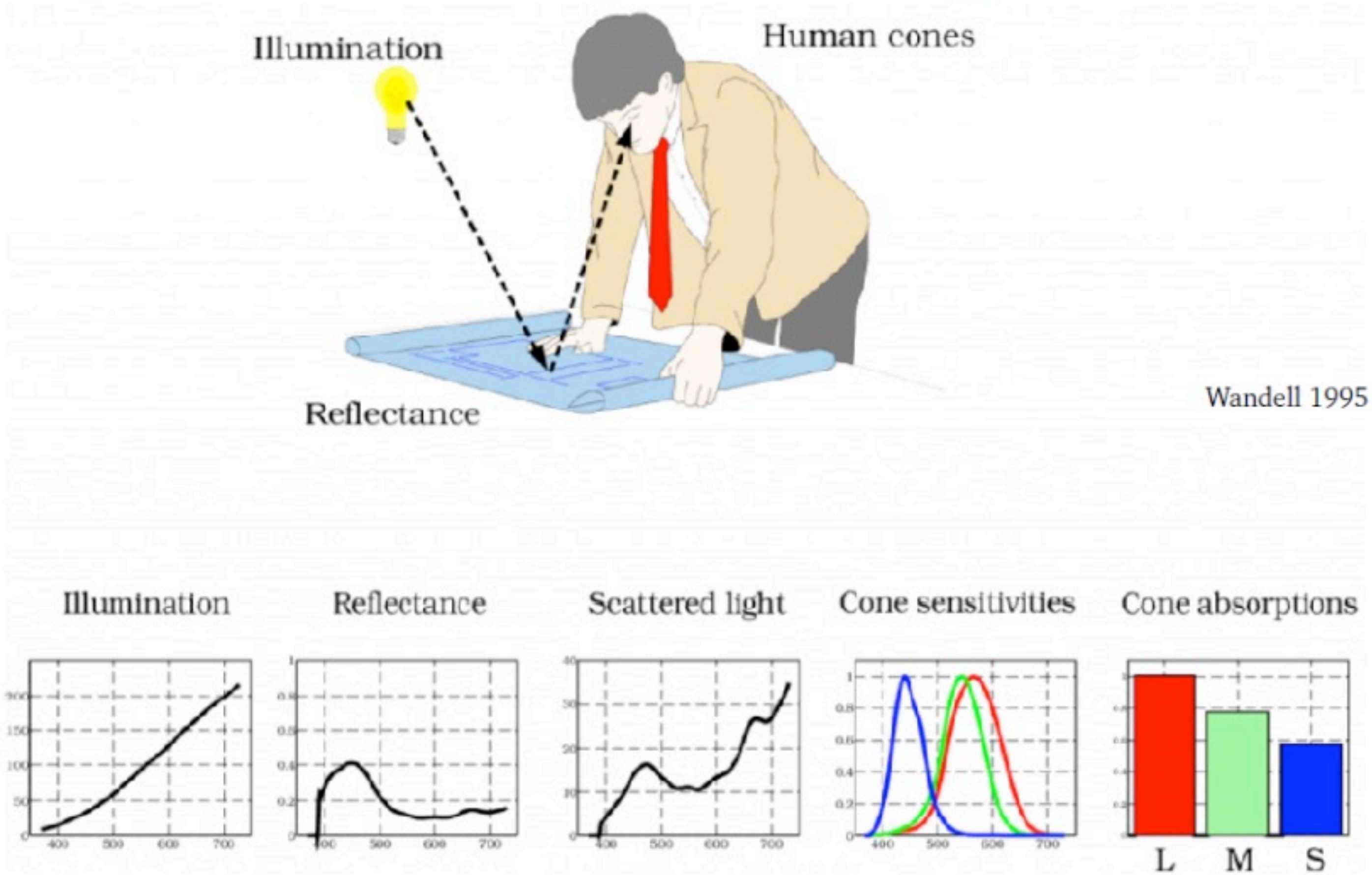
- How can we represent an entire spectrum with 3 numbers?
- We can't! Most of the information is lost
  - As a result, two different spectra may appear indistinguishable
    - » such spectra are known as **metamers**

Slide by Steve Seitz

We are all color-blind!



Spectral Radiometry: Color Image Formation



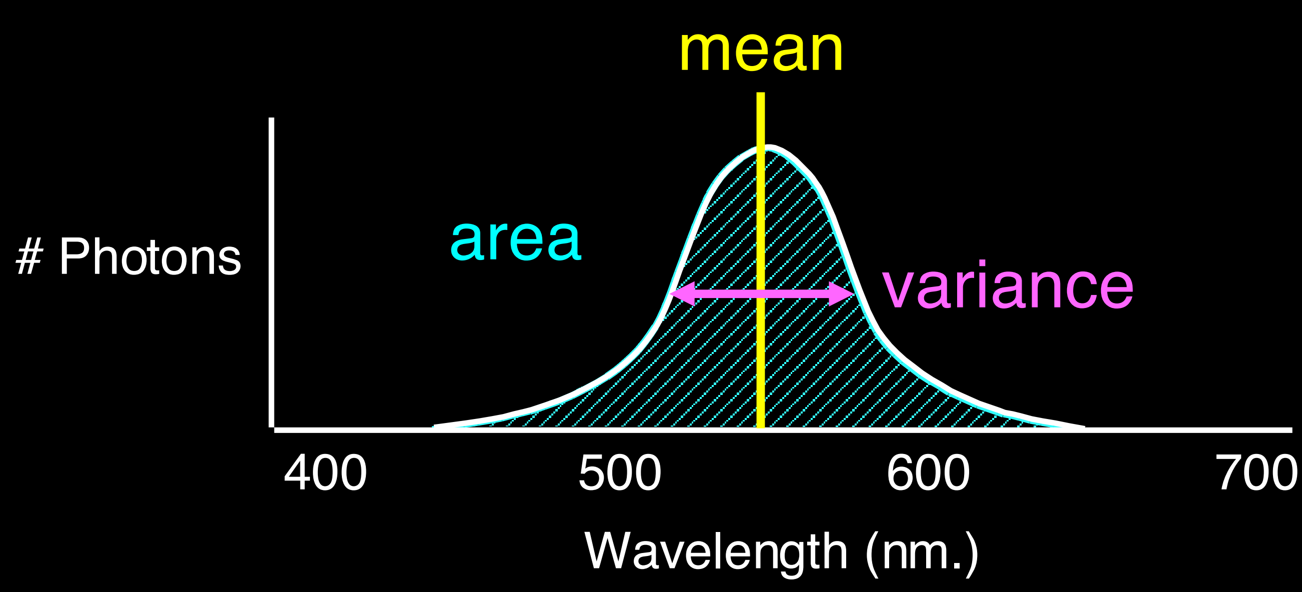
incoming illumination × reflectance = outgoing scene radiance

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

The Psychophysics of "Color"

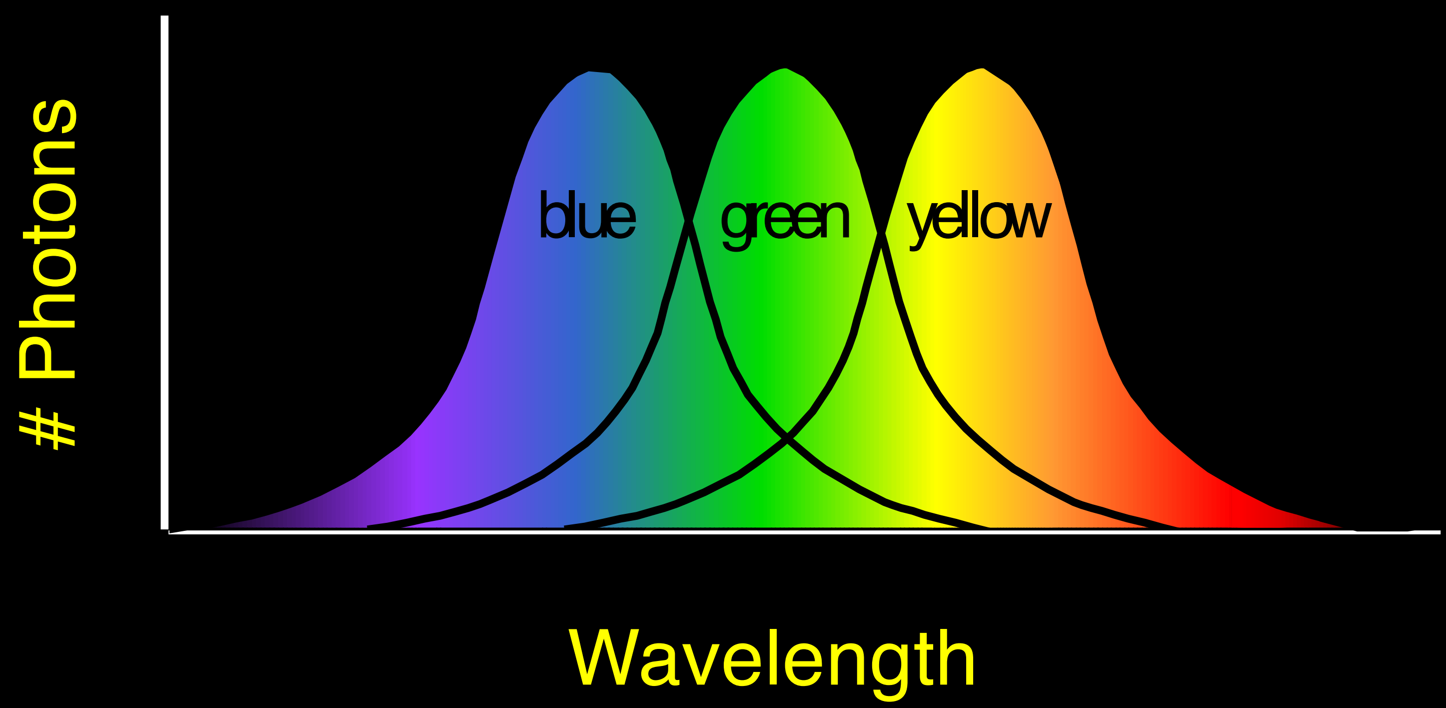
There is no simple functional description for the perceived color of all lights under all viewing conditions, but ......

A helpful constraint:
  Consider only physical spectra with normal distributions



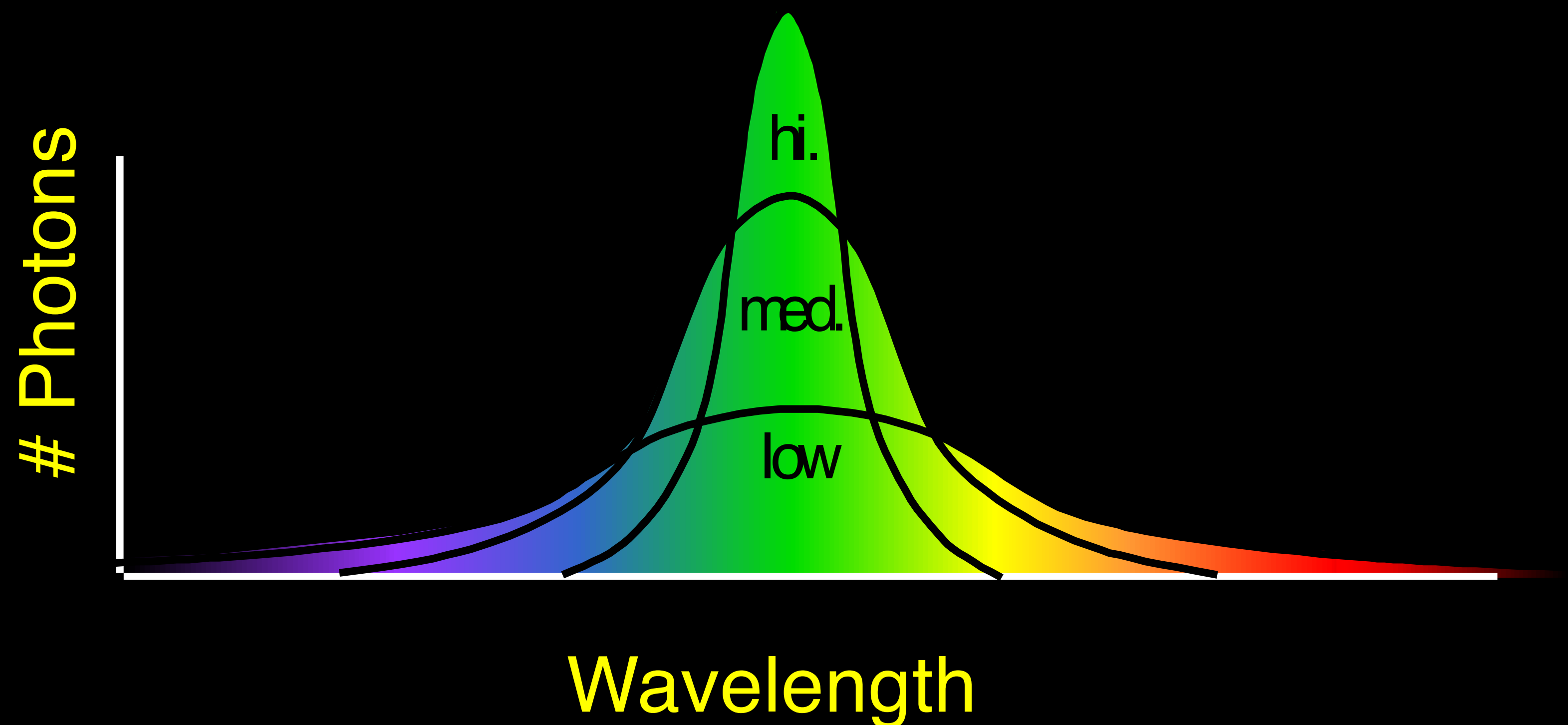
The Psychophysical Correspondence

Mean ⟷ Hue



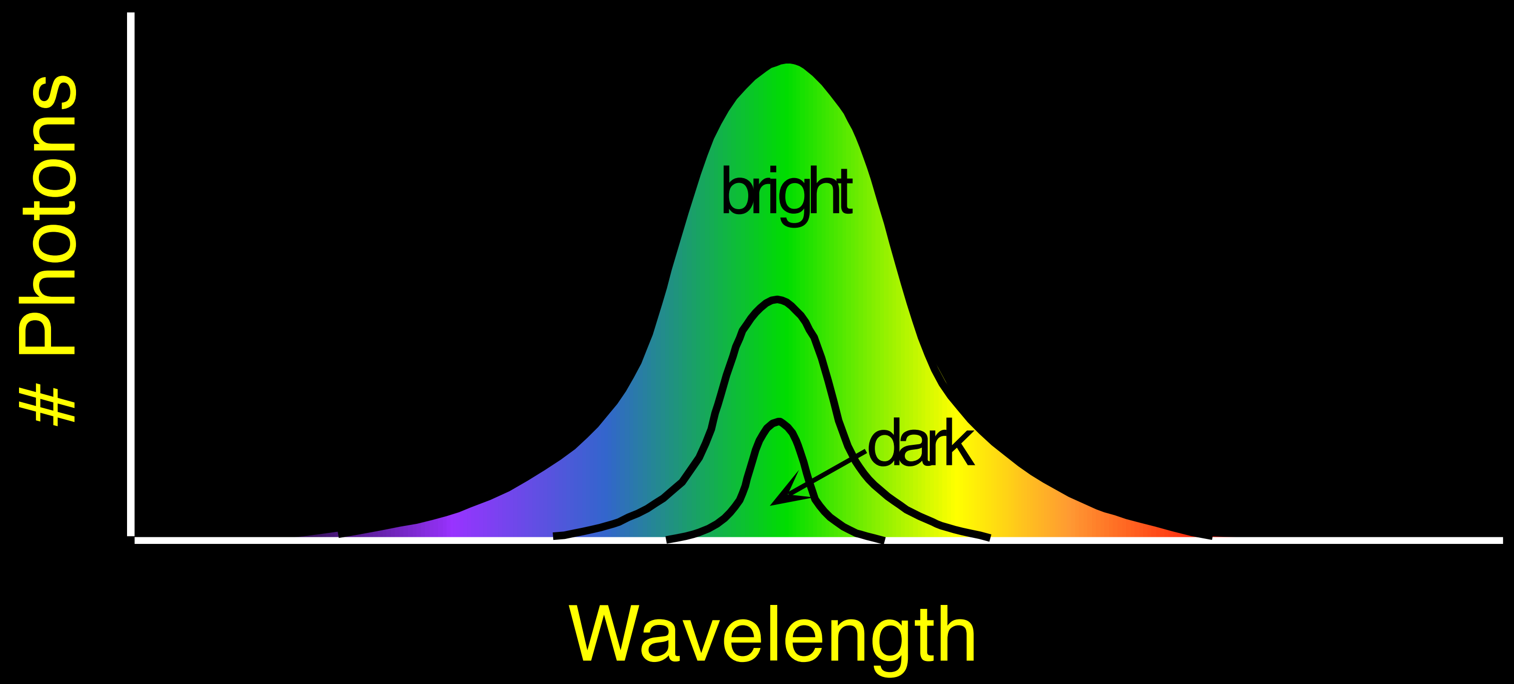
The Psychophysical Correspondence

Variance ⟷ Saturation



The Psychophysical Correspondence

Area ⟷ 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).

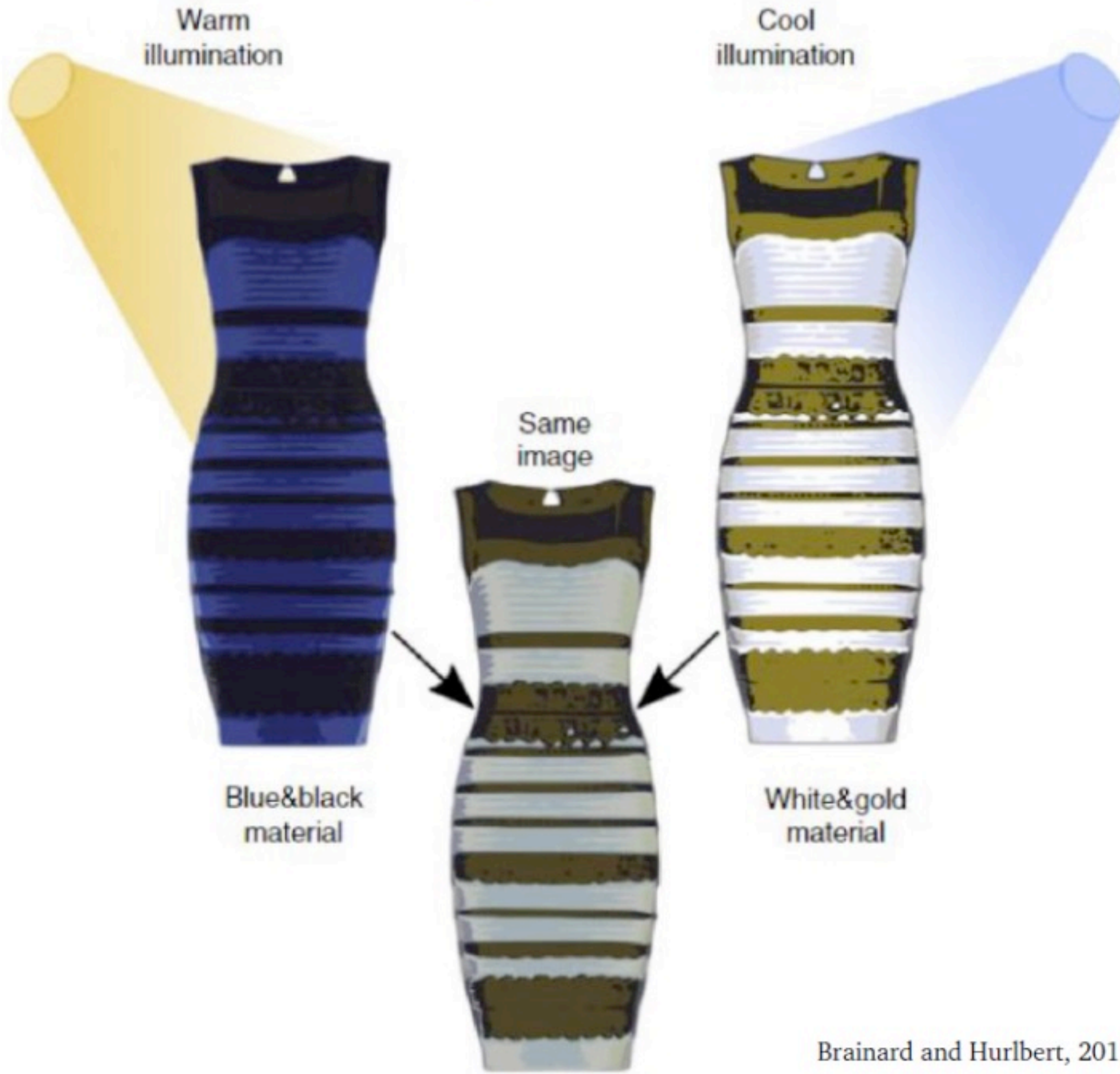
Color Constancy

~~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



Brainard and Hurlbert, 2015

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

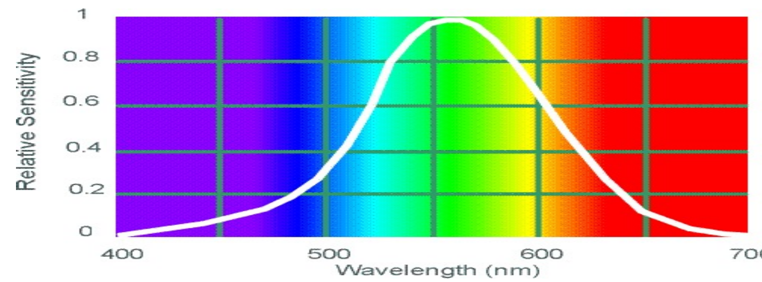
Camera White Balancing

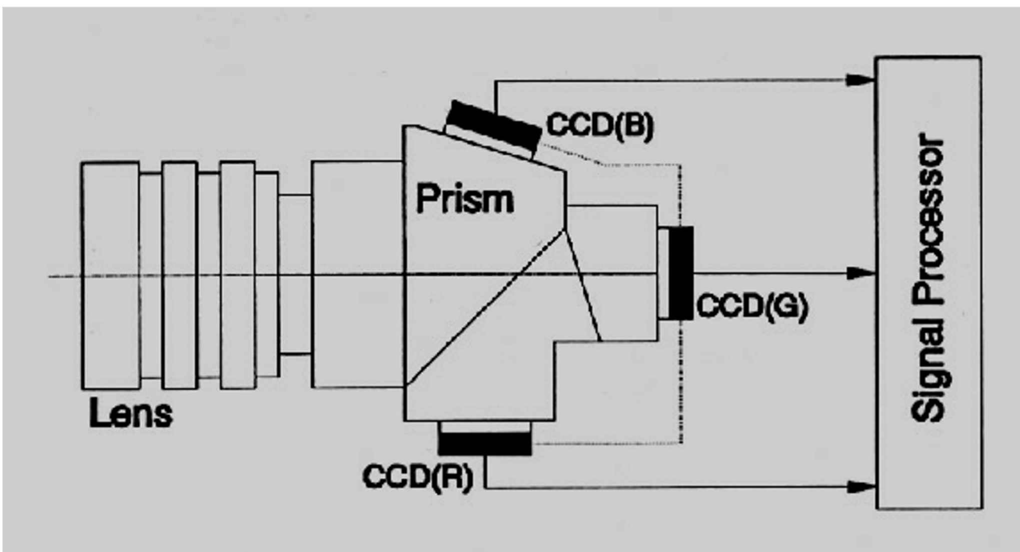
- Manual
  - Choose color-neutral object in the photos and normalize
- Automatic (AWB)
  - Grey World: force average color of scene to grey
  - White World: force brightest object to white

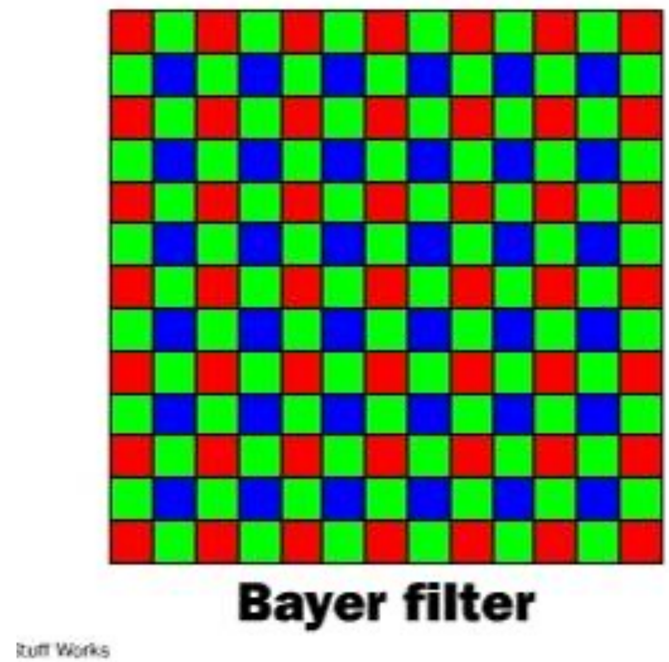
Color Sensing in Camera (RGB)

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

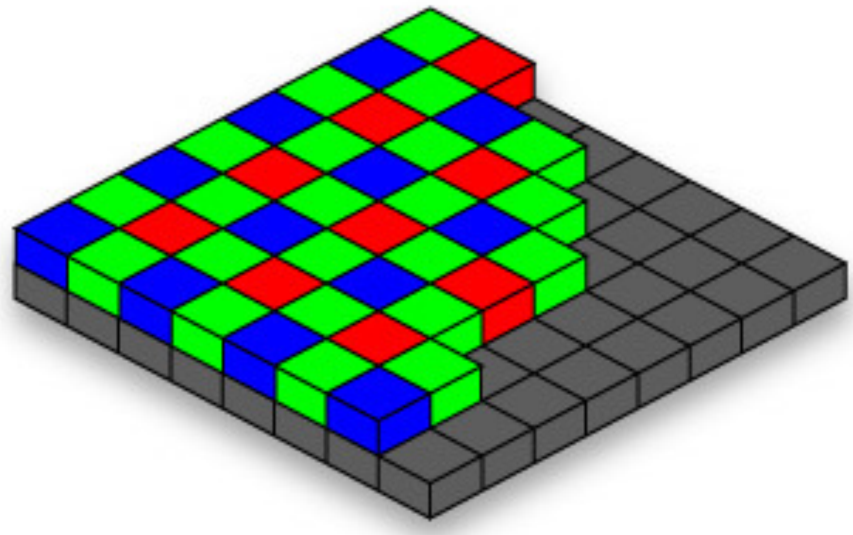
Green is in!

R

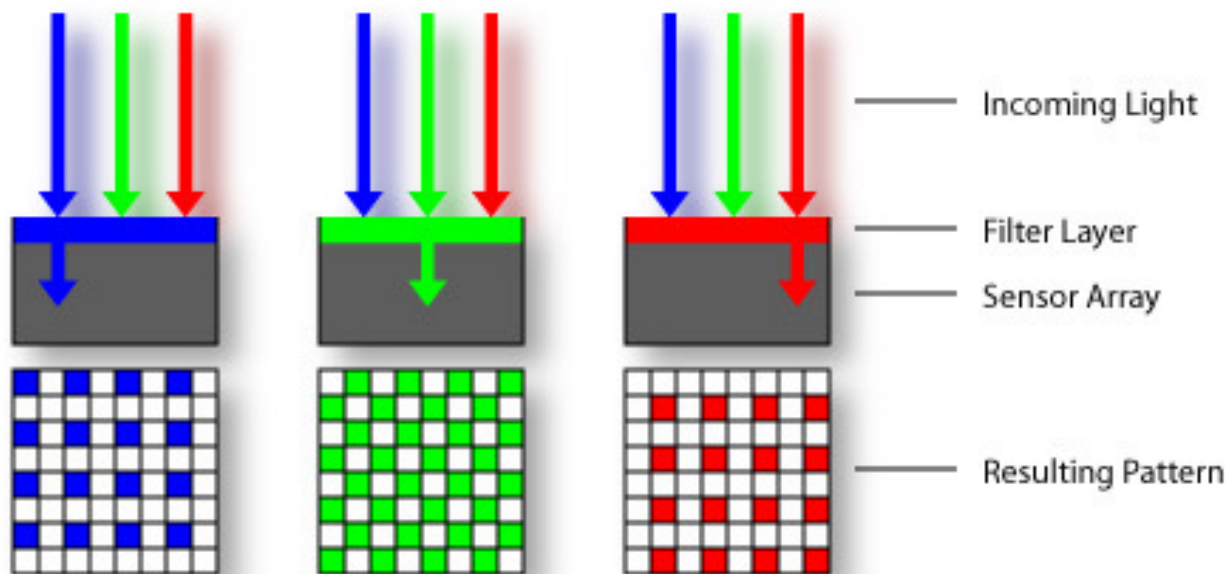
G

B

Practical Color Sensing: Bayer Grid



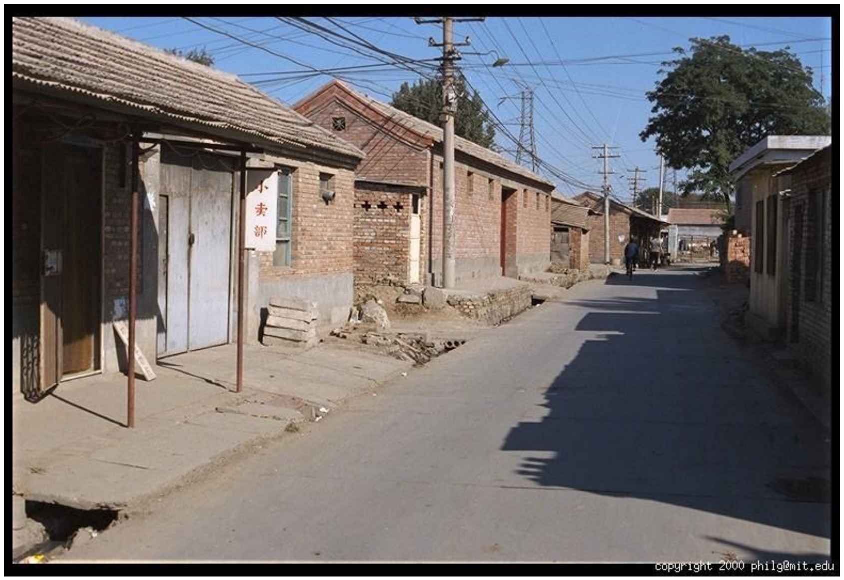
Estimate RGB
at 'G' cels from
neighboring
values



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

Slide by Steve Seitz

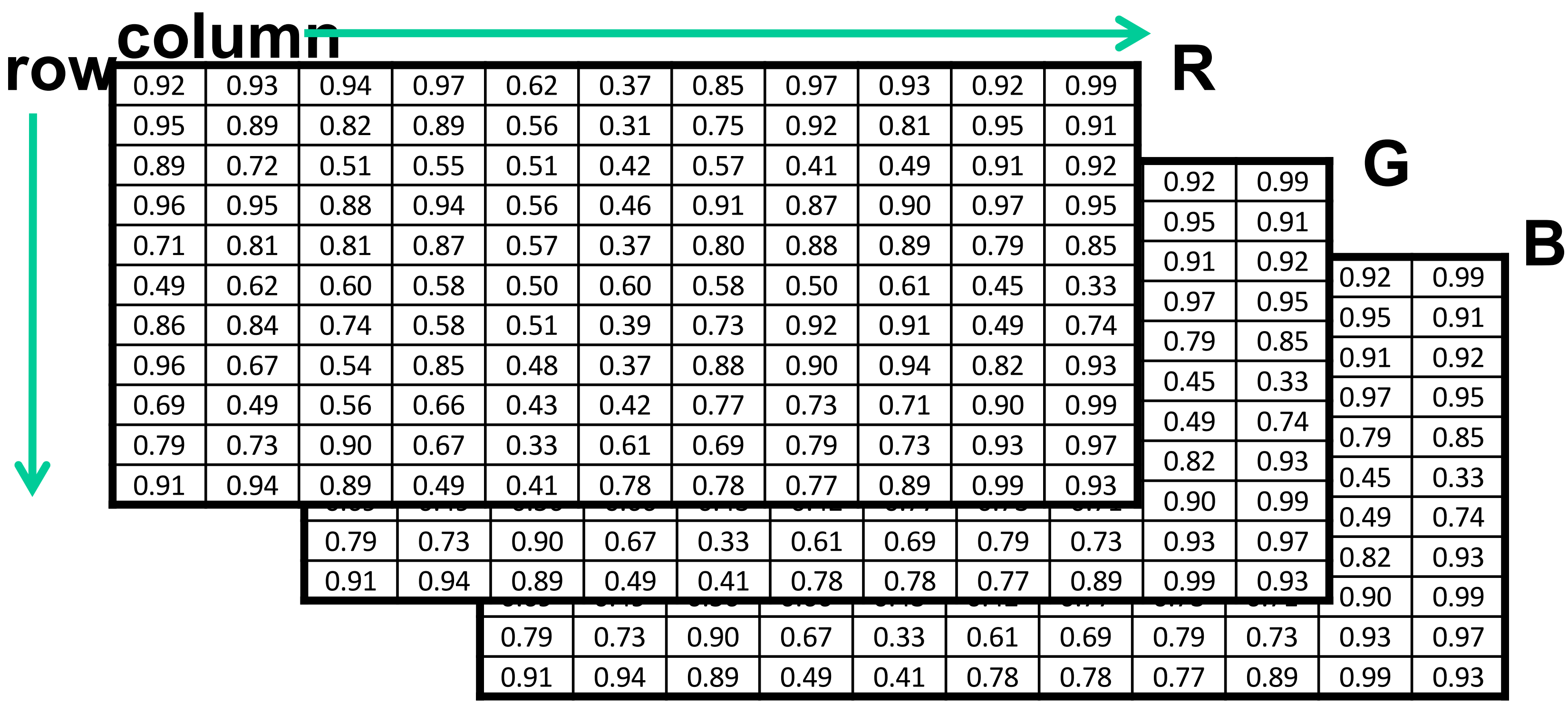
Color Image


copyright 2000 philg@mit.edu


R
G
B
copyright 2000 philg@mit.edu

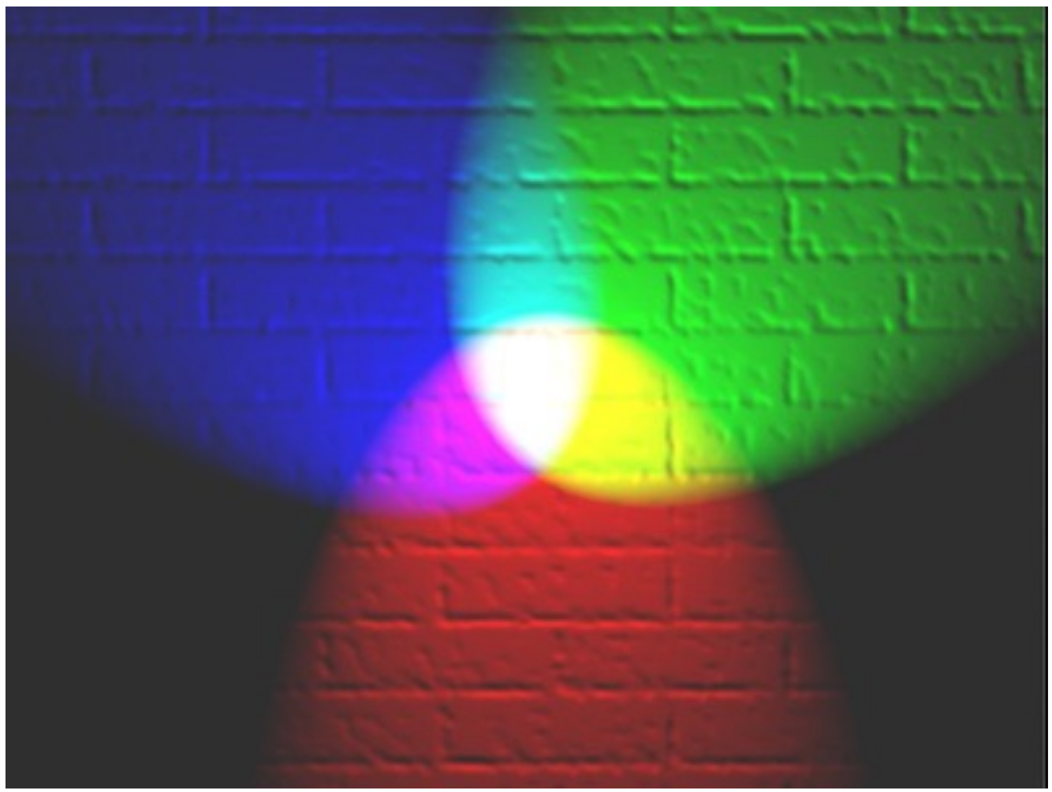
Image representation

- 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 b^{th} 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

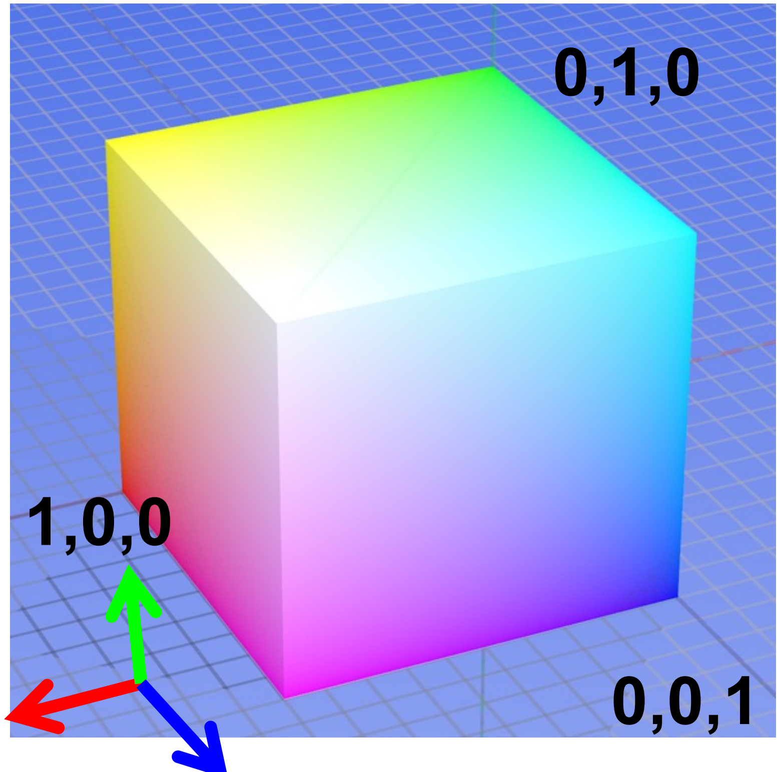
How can we represent color?



http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

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)

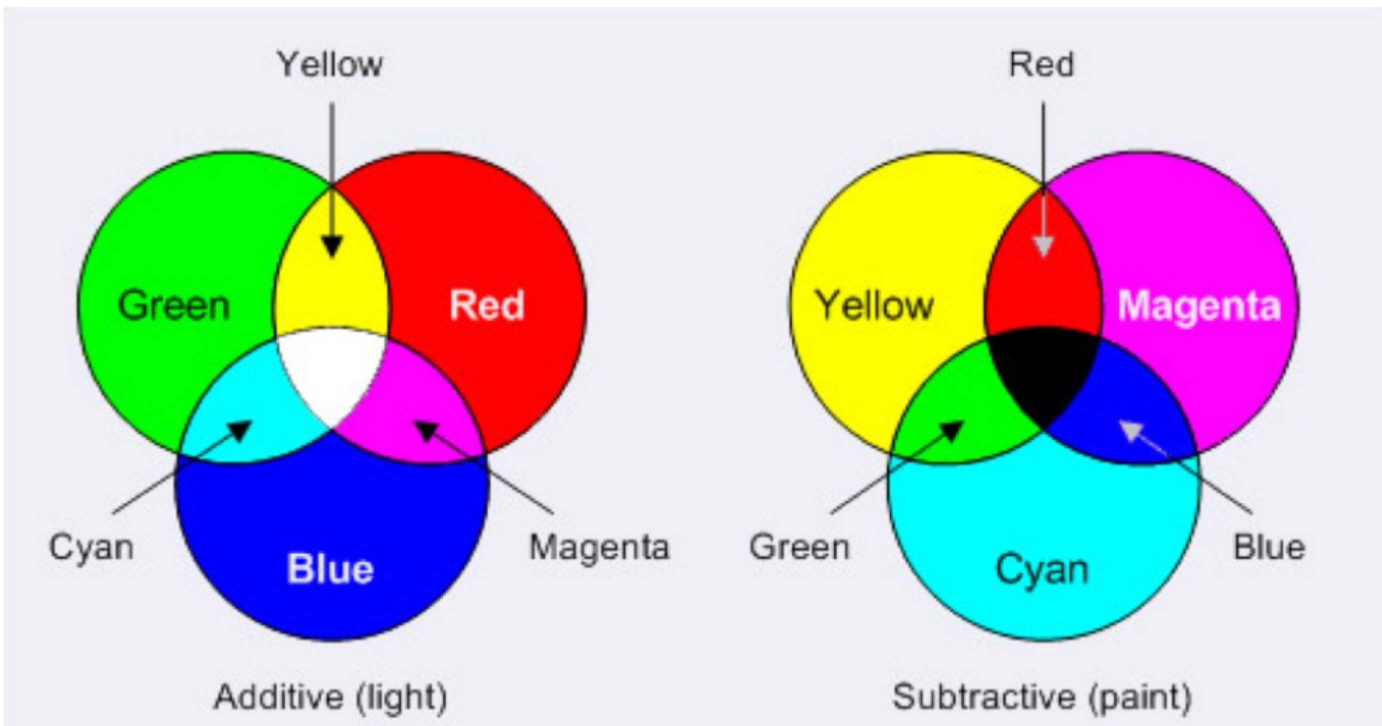
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

Color spaces: CMYK

How paint works

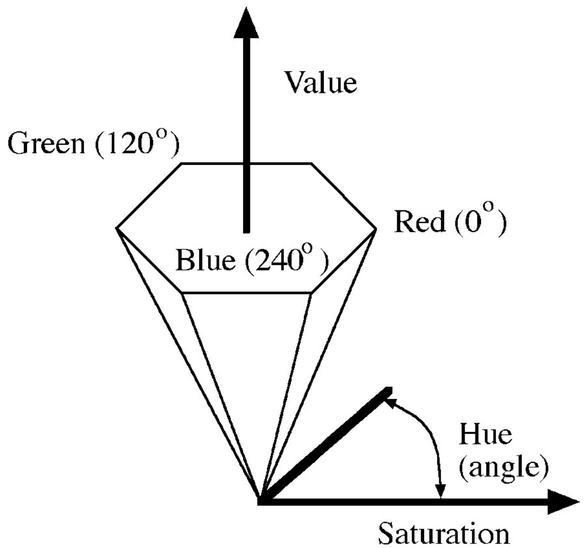
White is the background color (all colors!)

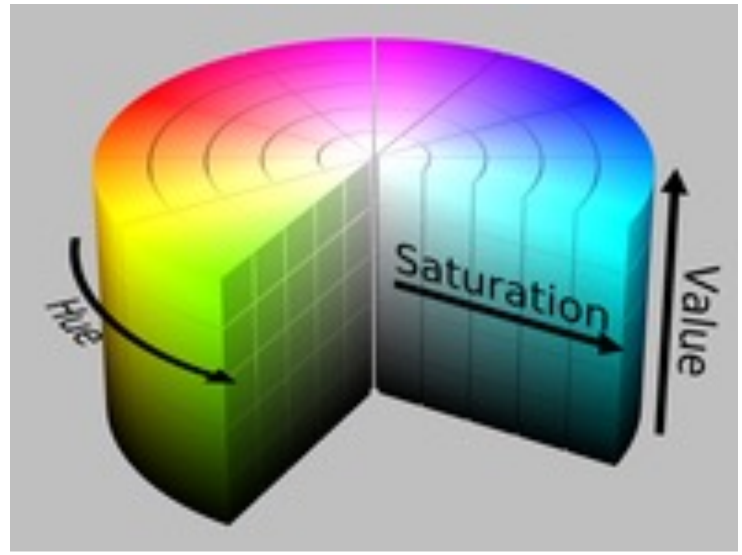
Opposite of RGB (stage light)



Source: https://intranet.mcad.edu/kb/cmyk-vs-rgb-what-color-space-should-i-work

HSV





Perceptual dimensions of color:

Hue: the “kind” of color, regardless of its attributes

Saturation: Purity, “colorfulness”

Value (or lightness): total amount of light

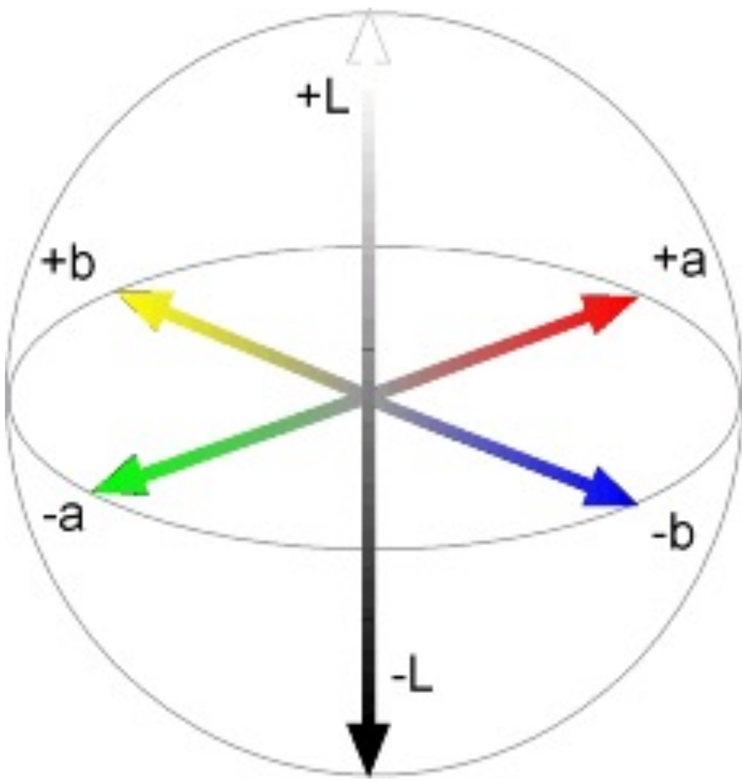
Use rgb2hsv() and hsv2rgb() in Matlab, in Python w/skimage

Slide from Steve Seitz / Ren Ng

Color spaces: L*a*b*

"Perceptually uniform"* color space

L = Luma (Lightness)
a = Red to Green
b = Blue to yellow



L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

Example: Original Image

Slide credit: Ren Ng

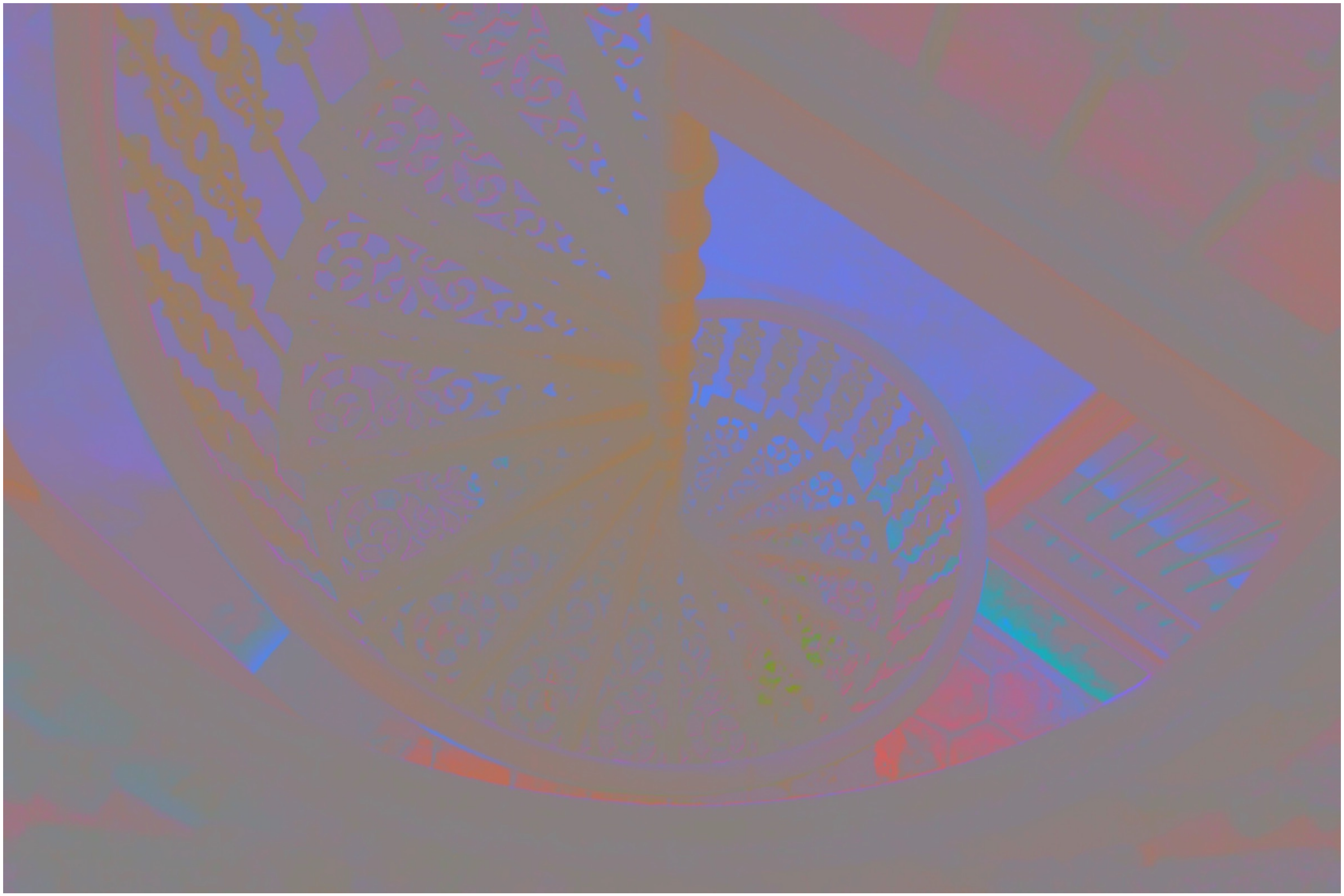
Example: Y only

Slide credit: Ren Ng

Example: Y only – Downsampled by 4x4

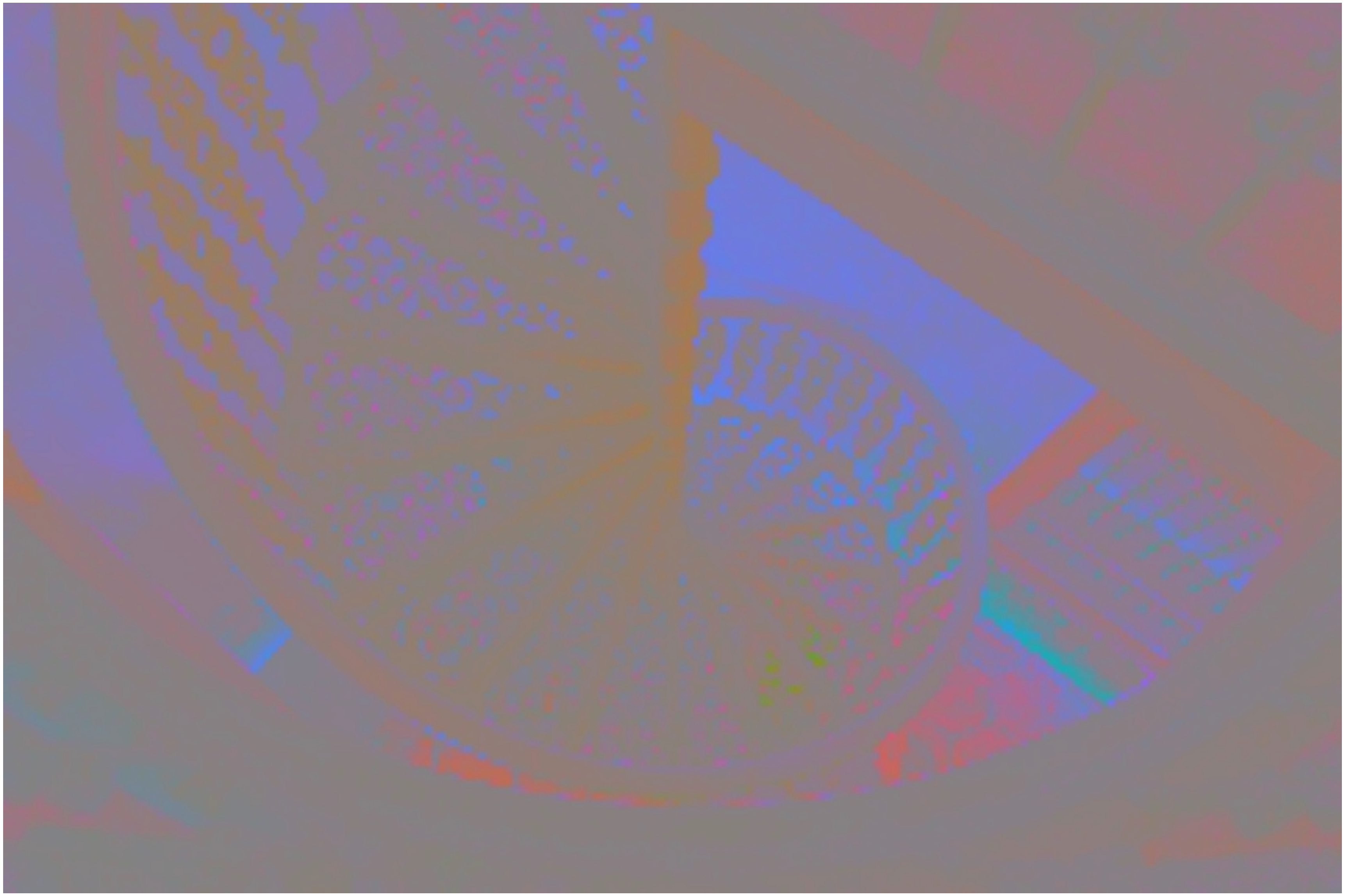
Slide credit: Ren Ng

Example: Chroma only (ab)



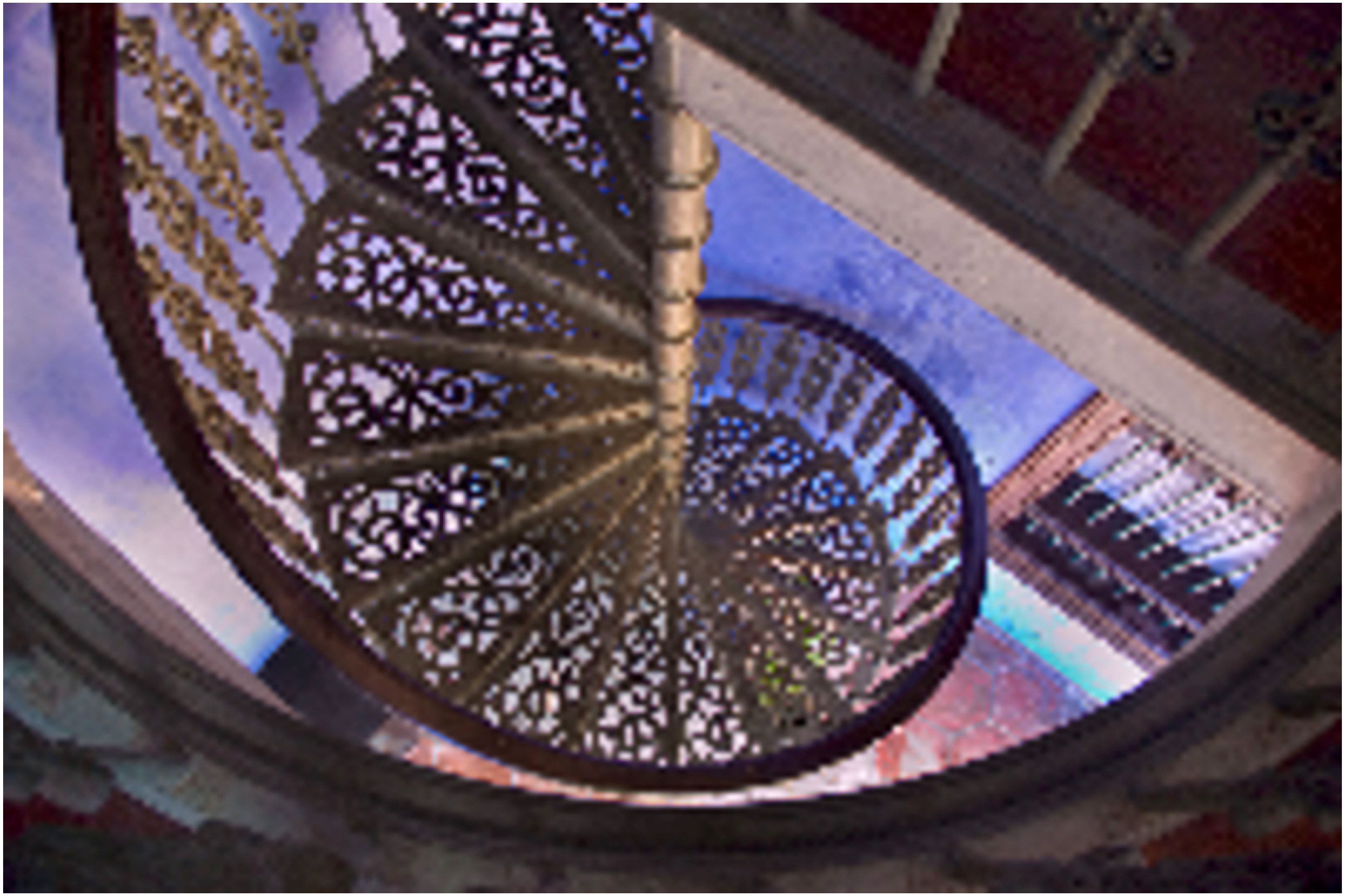
Slide credit: Ren Ng

Example: Chroma only – Downsampled 4x4



Slide credit: Ren Ng

Example: Compression in Luma



Down-sampled L, full resolution ab

Slide credit: Ren Ng

Example: Compression in Chroma channels (ab)

Full resolution L, downsampled ab

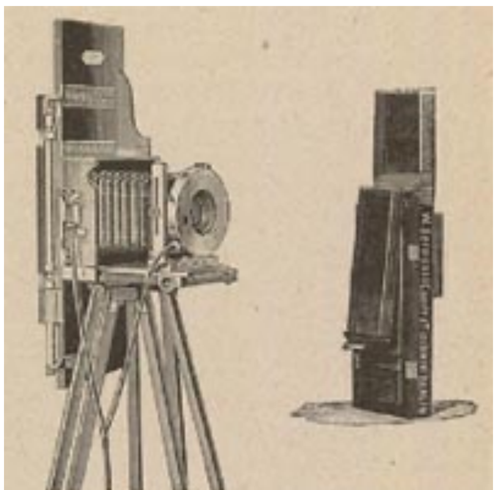
Slide credit: Ren Ng

Example: Original Image

Slide credit: Ren Ng

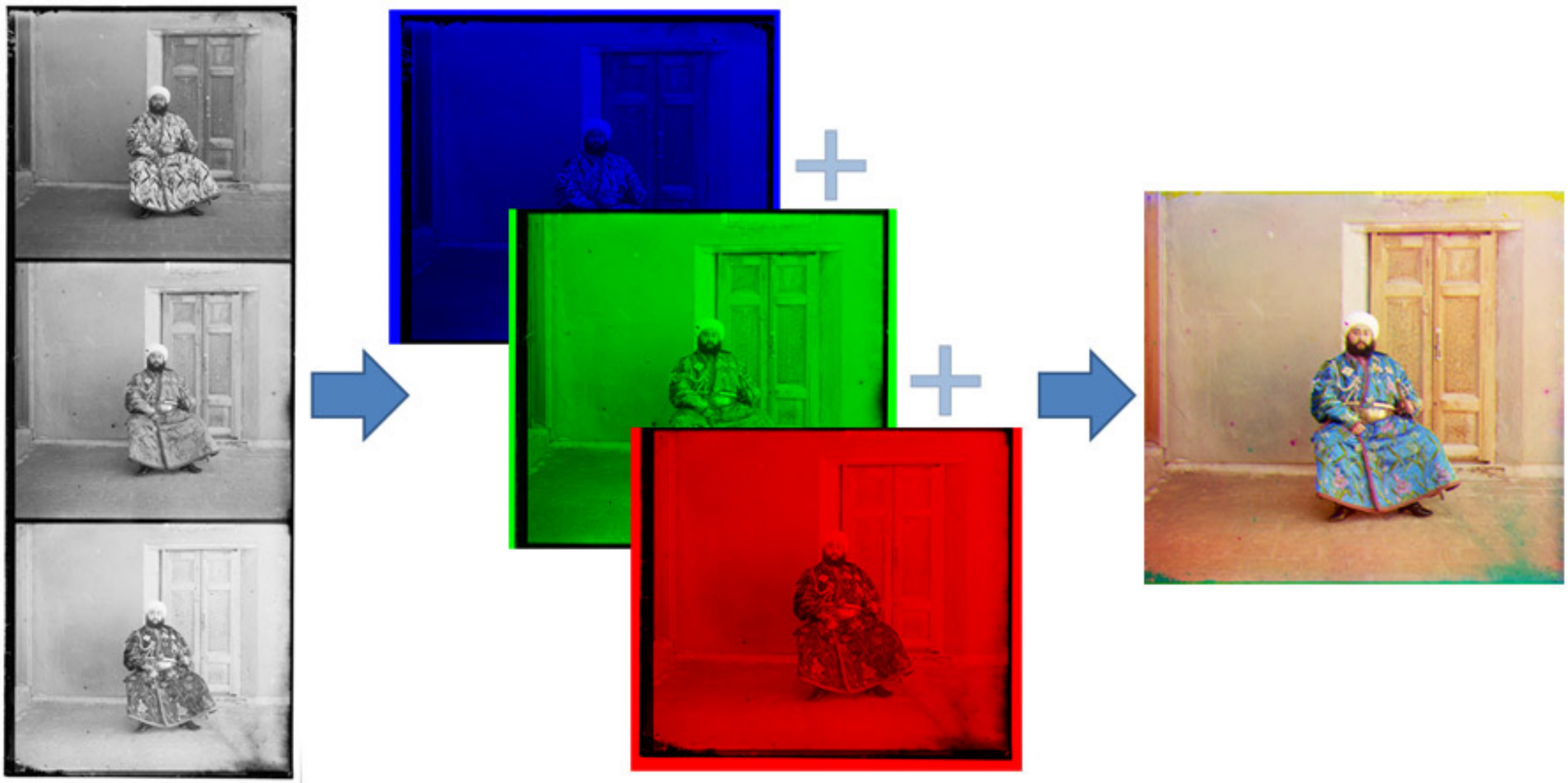
Programming Project #1

Prokudin-Gorskii's Color Photography (1907)



Общій видъ камеры и кассеты Д-ра Мите.

Programming Project #1



Programming Project #1

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

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

  - Normalized Correlation (NCC):

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

Watch these 5 min videos!

Color in 5 min: https://youtu.be/6tTNgvAl1y4

Displays in 5 min: https://youtu.be/1albYPL9Cfg