

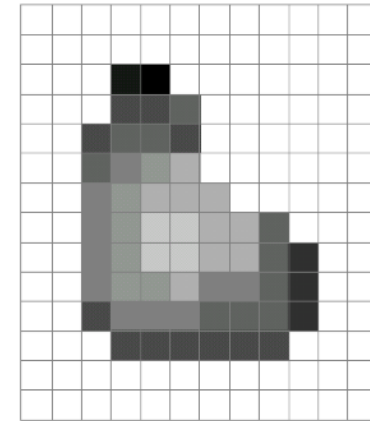
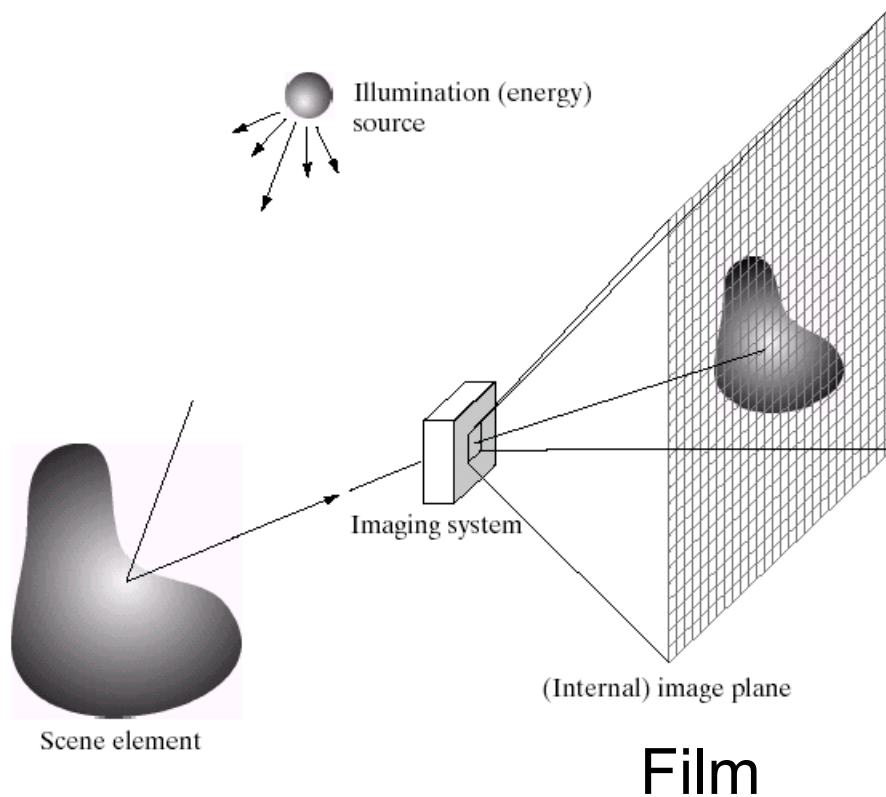
Sensing Light: Eye and Machine



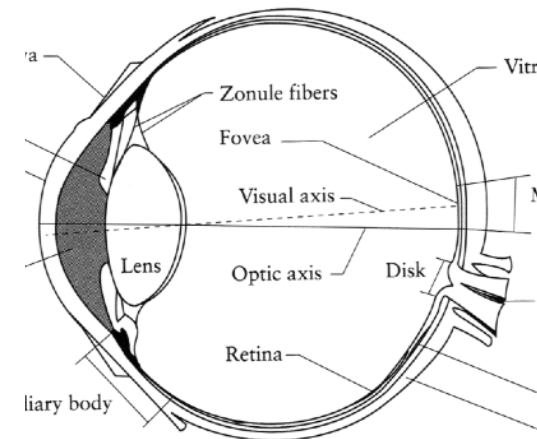
Henri Cartier-Bresson #1, by Dmitri Kessel

CS180: Computer Vision and Comp. Photography
Efros & Ng, UC Berkeley, Fall 2026

Image Formation

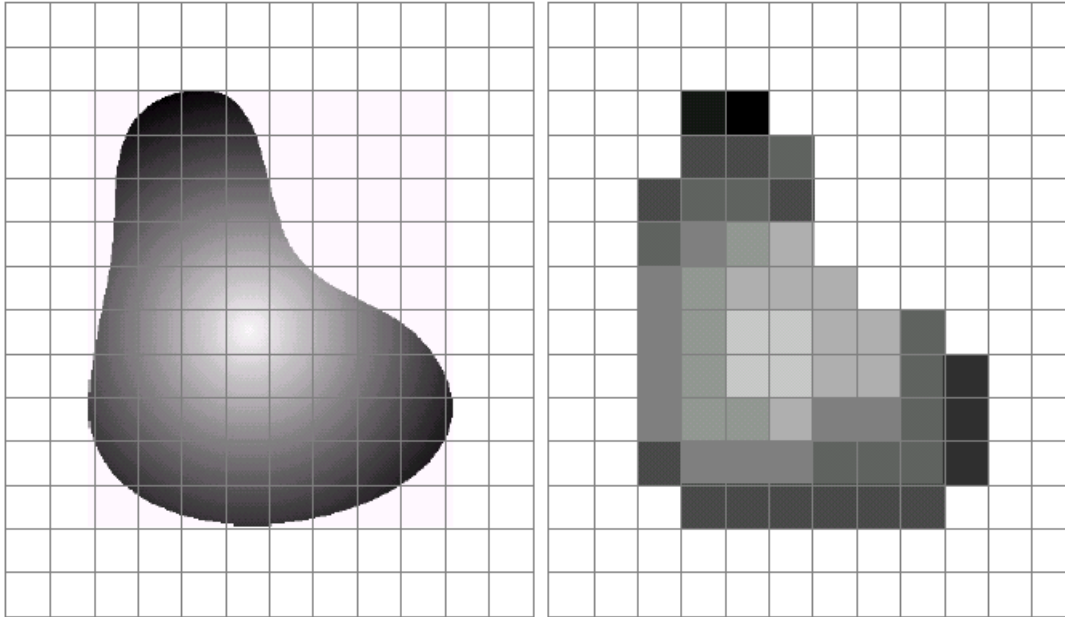


Digital Camera



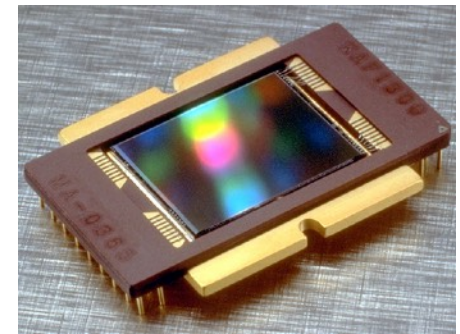
The Eye

Camera: Pixel (Picture Element) Array



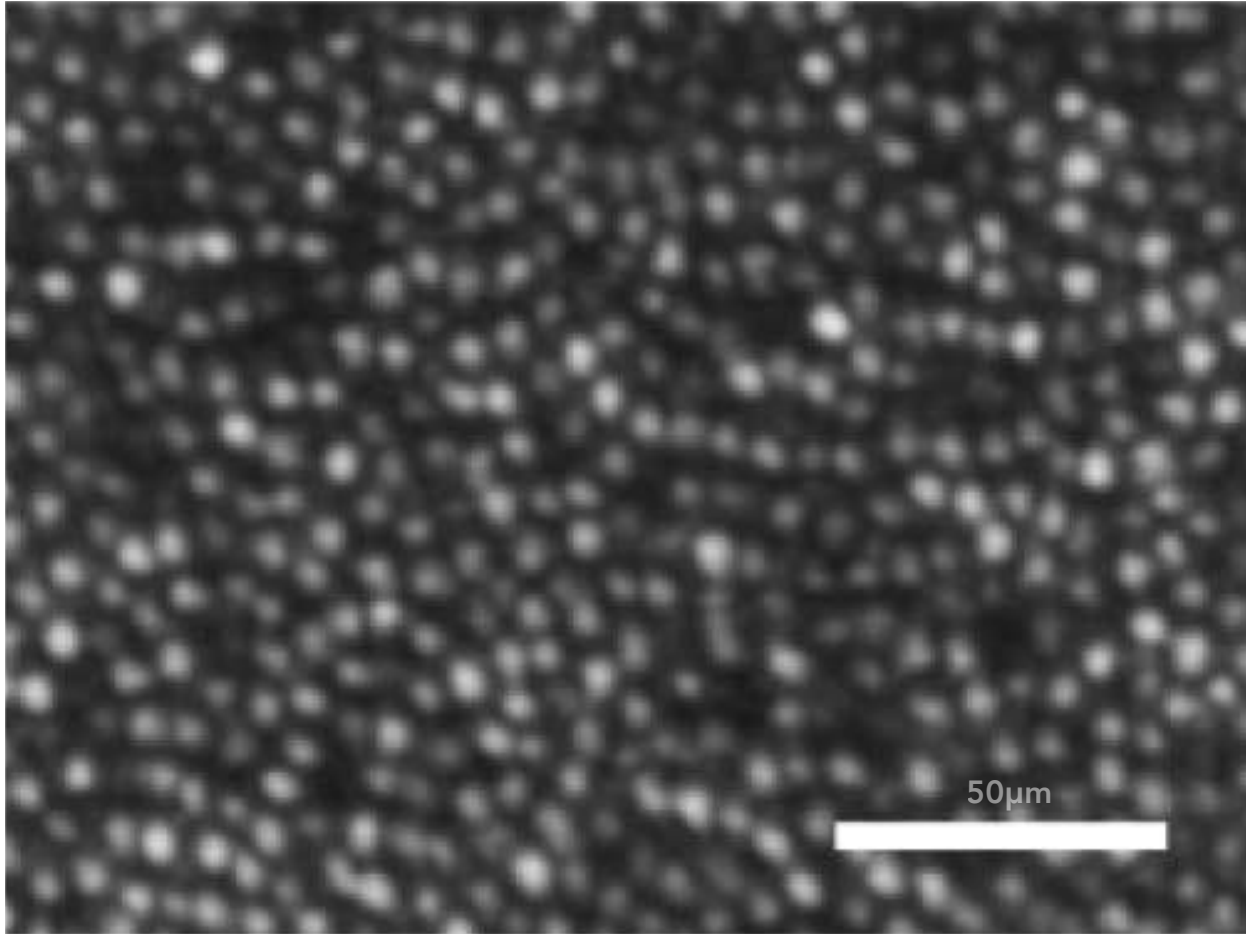
a b

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



CMOS sensor

Eye: Photoreceptor Cell Mosaic



Sabesan Lab, UW. Pandiyan et al. 2020.

Dynamics of Sensing Light

Camera Stabilization

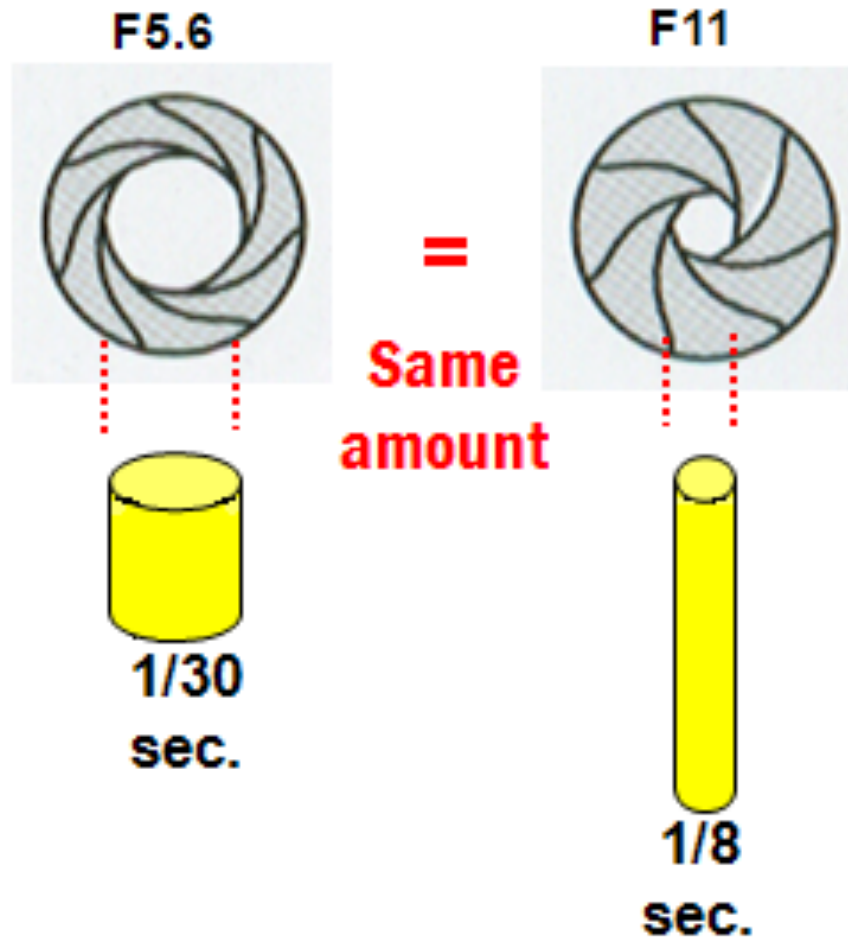


Shutter Speed



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

Exposure: Shutter Speed vs. Aperture



Exposure: Shutter Speed vs. Aperture



f / 4
0.01 sec



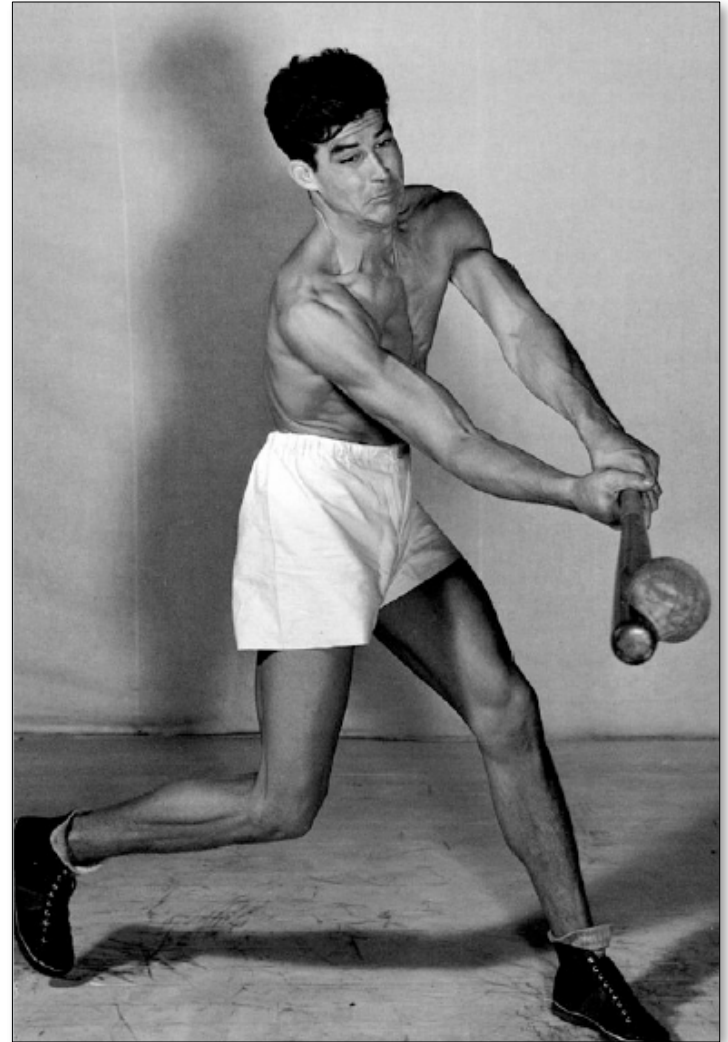
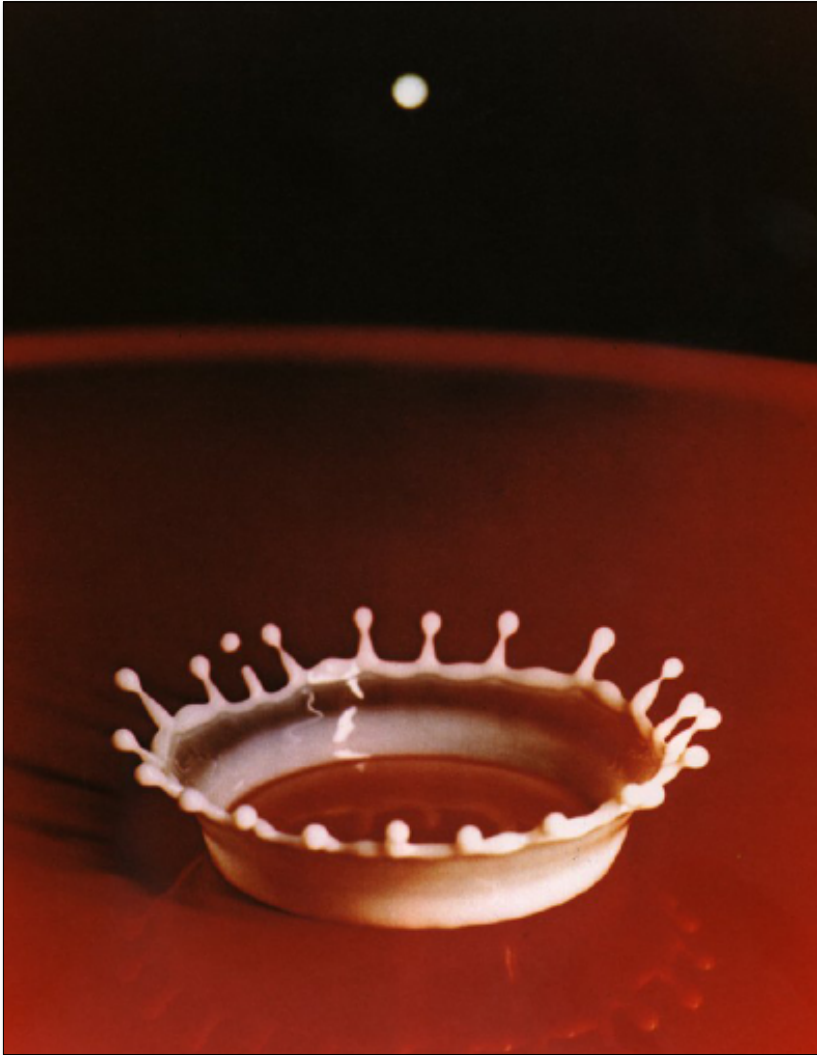
f / 11
0.1 sec



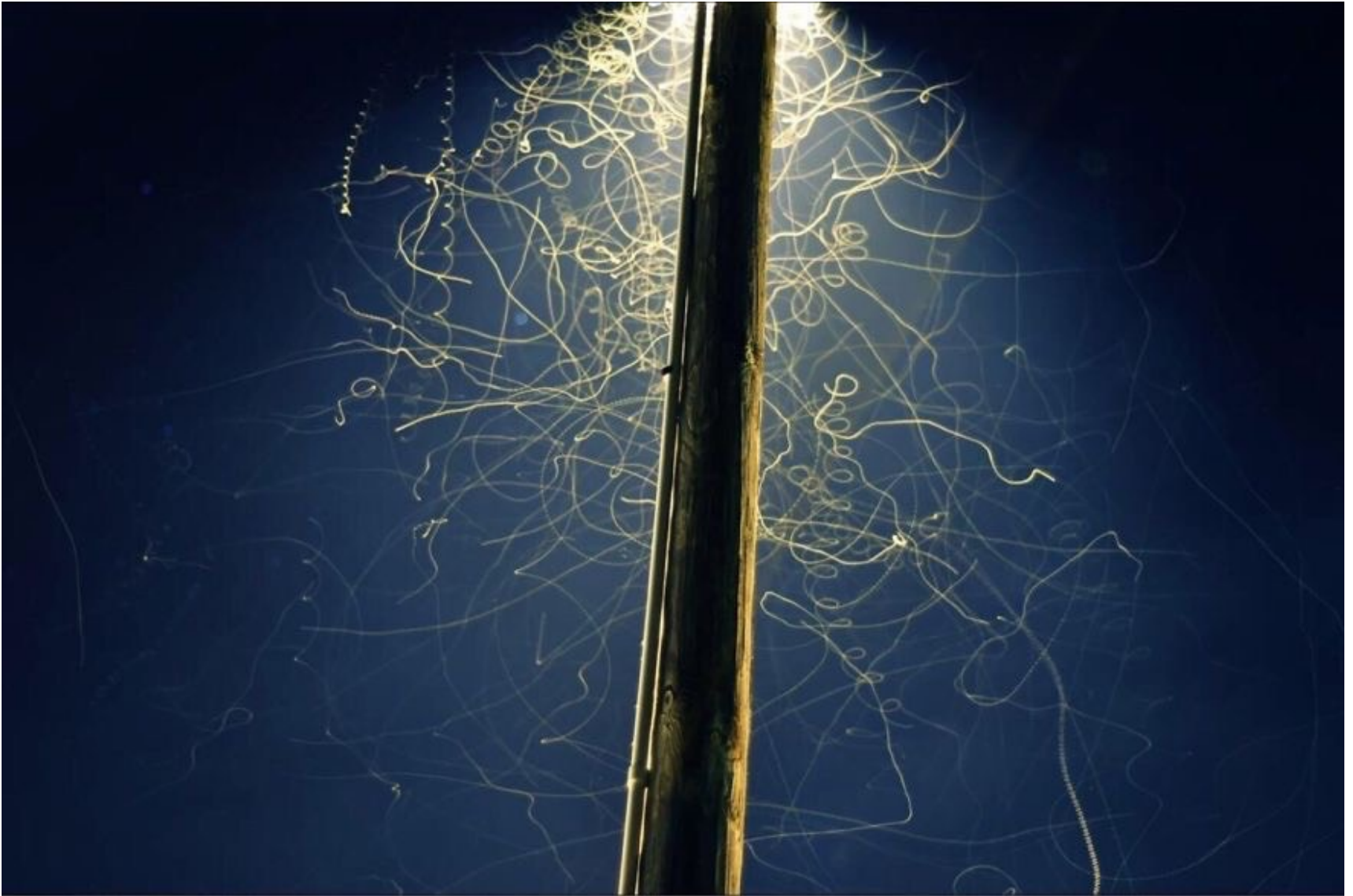
f / 32
0.8 sec

- Photographers must trade off depth of field and motion blur for moving subjects

High-Speed Photography (Short Shutter)

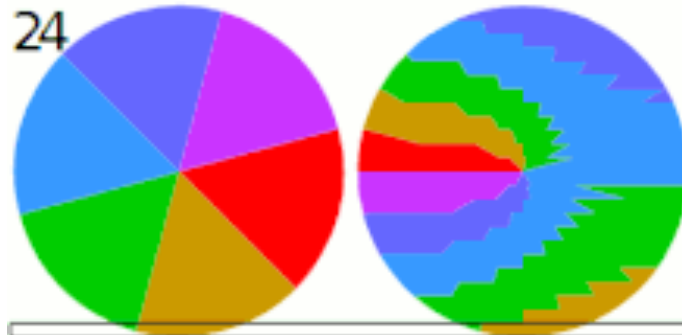
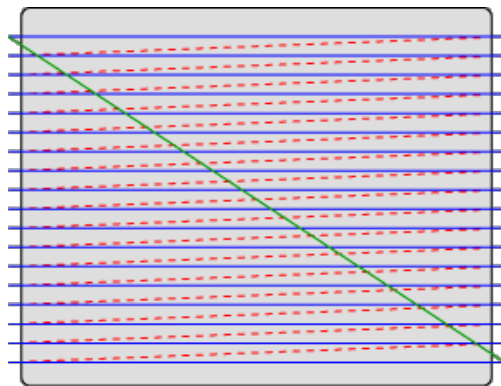


Long-Exposure Photography



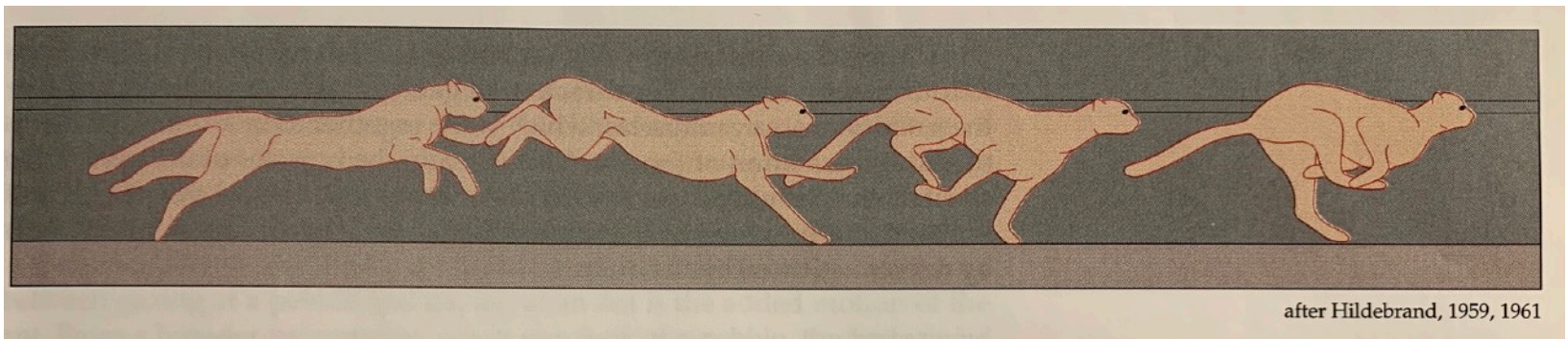
<https://www.demilked.com/best-long-exposure-photos/>

Camera Rolling Shutter



Eye Stabilization

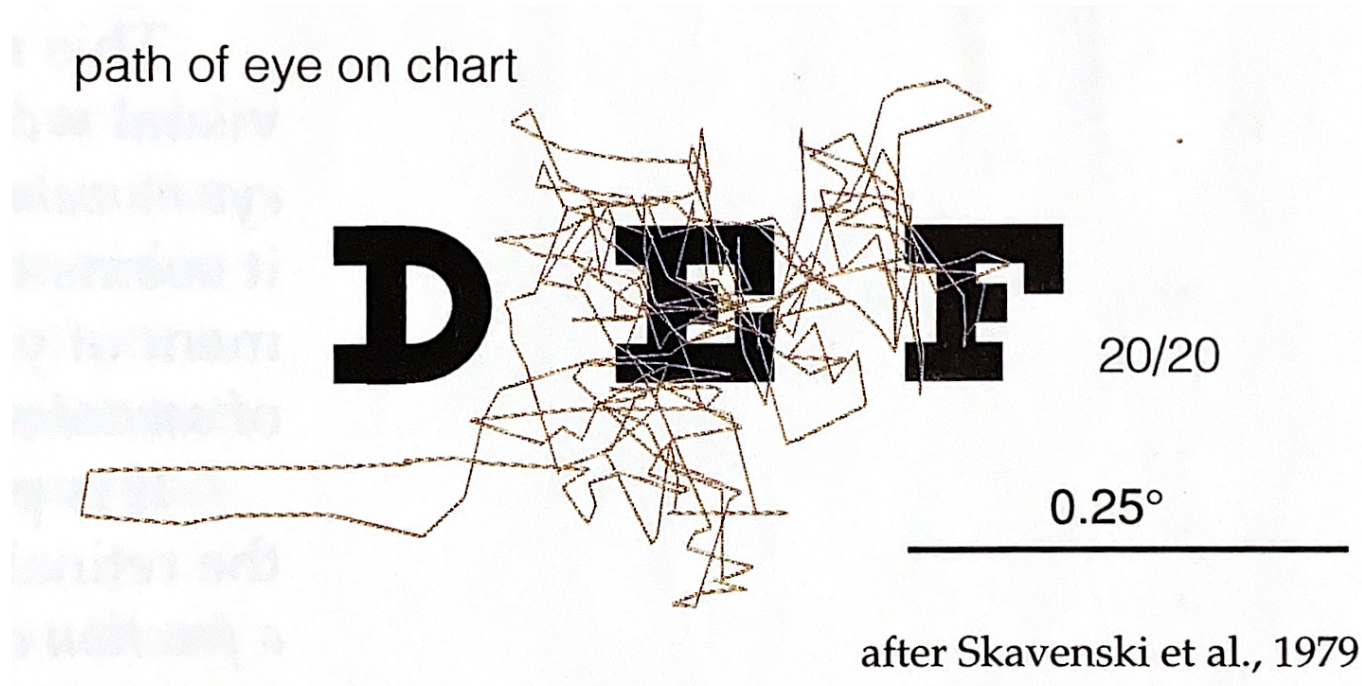
“Eye movements catch images and hold them steady on the retina” — Rodieck



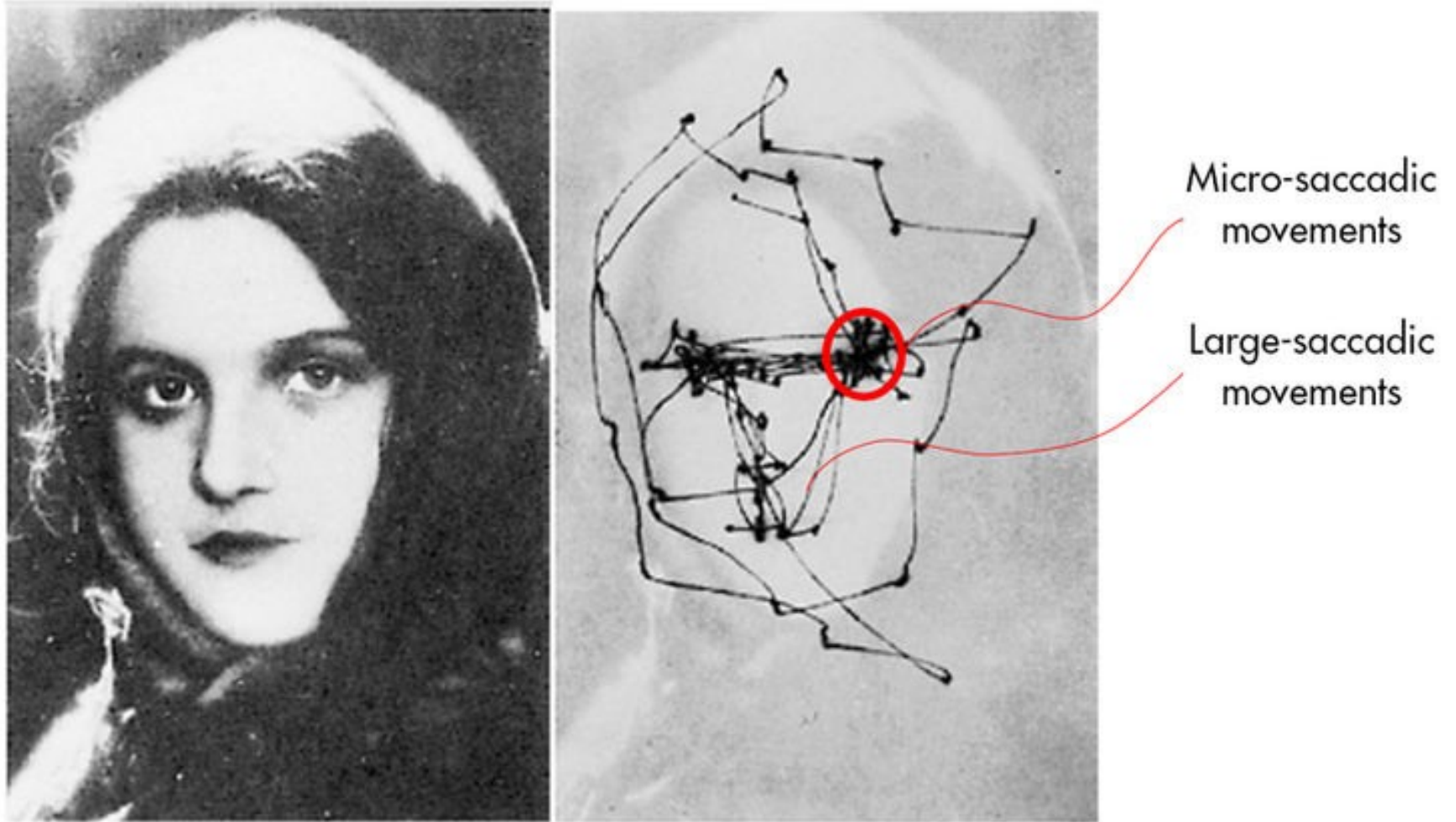
Source: Rodieck, *The First Steps in Seeing*, p. 6, 9

Yet Eye Gaze is Never Fixed

“The image of the visual world is always moving on the retina” — Rodieck



Saccadic Eye Movements



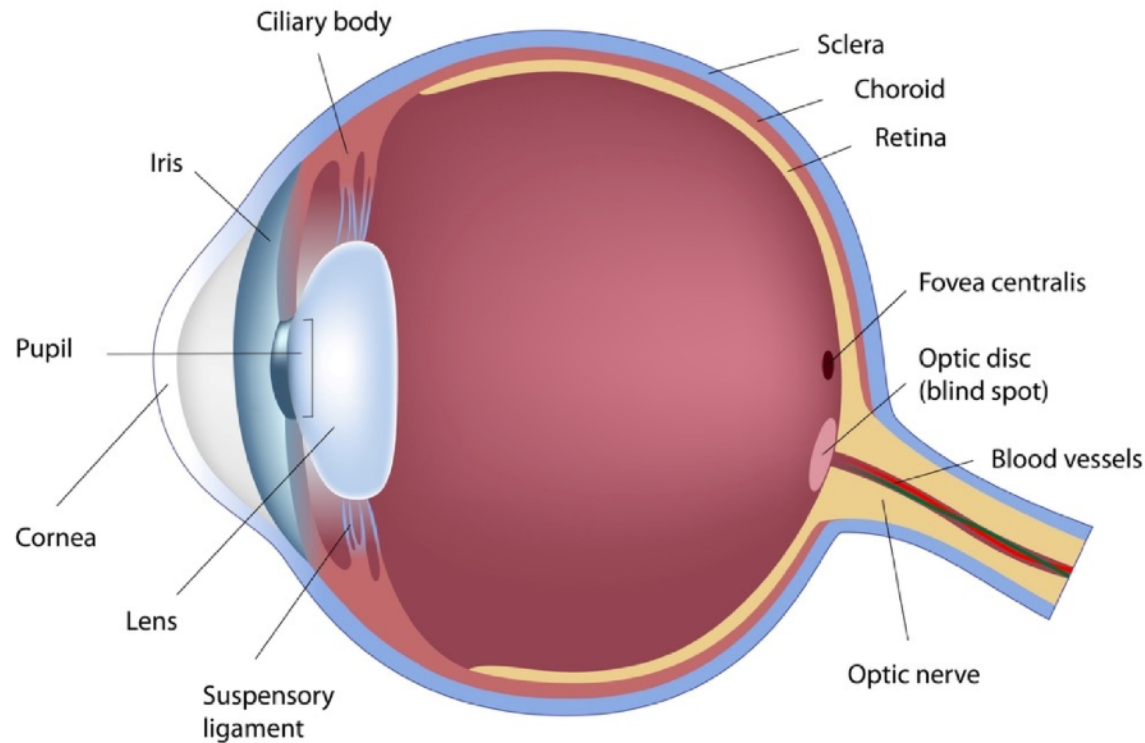
Yarbus, 1967

Saccadic Eye Movements



Visual Physiology of the Eye

Anatomy of The Human Eye



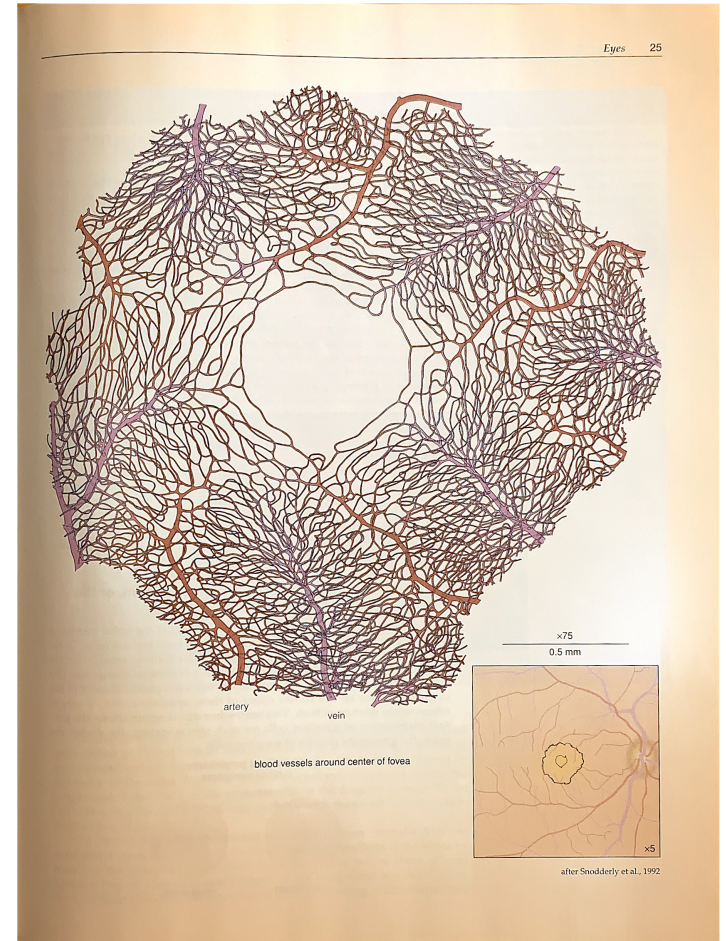
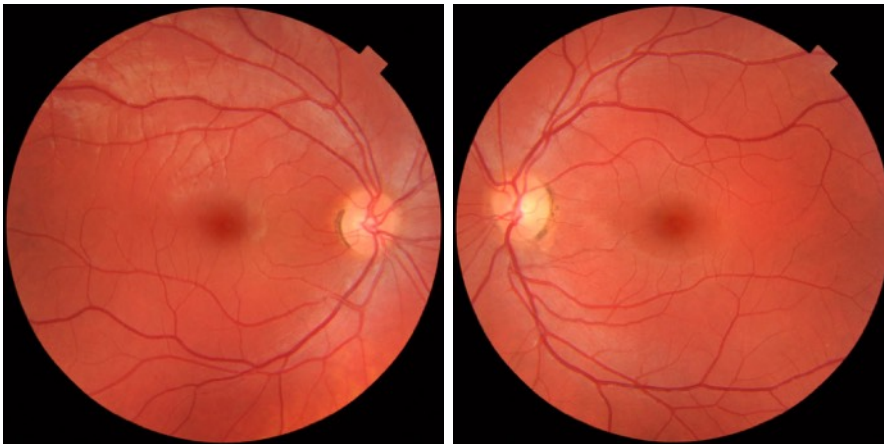
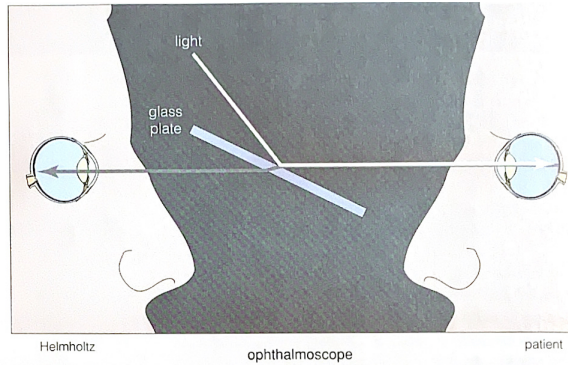
The human eye is like a camera

- Iris - colored annulus with radial muscles
- Pupil - the hole (aperture) whose size is controlled by the iris
- Retina - the “film”

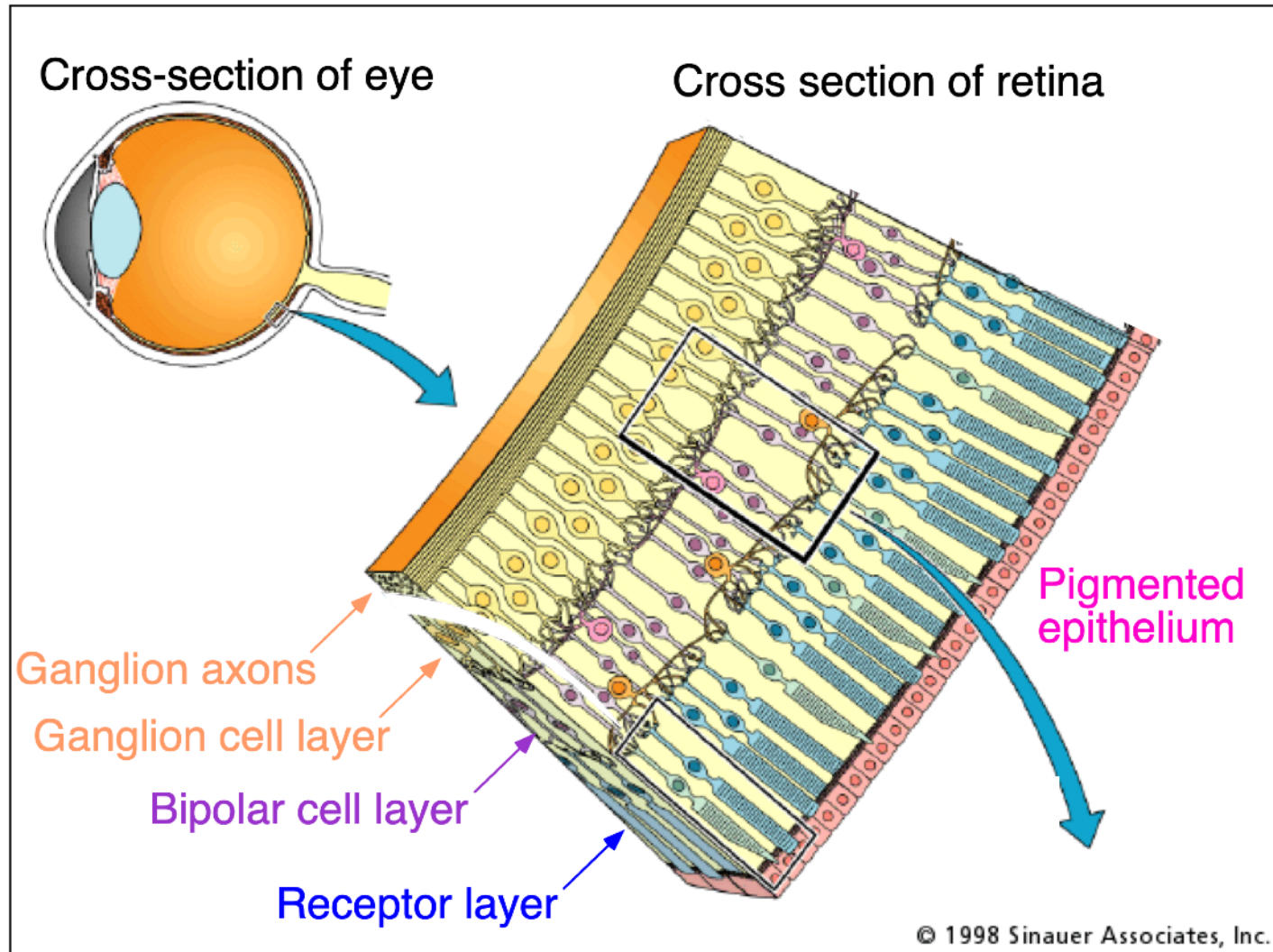
Fundus View of the Eye



Hermann von Helmholtz



The Retina



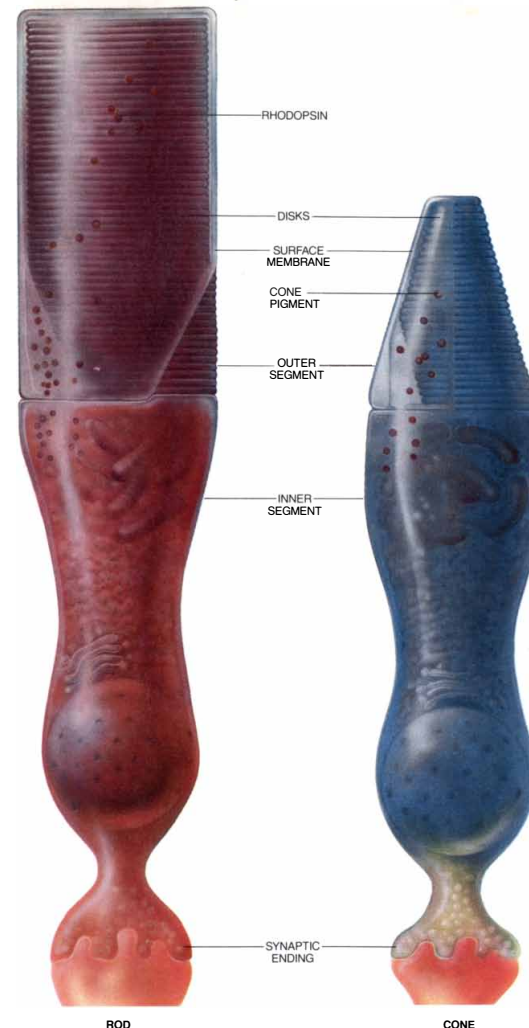
Two Types of Light-Sensitive Receptor Cells

Cones

cone-shaped
less sensitive
operate in high light
color vision

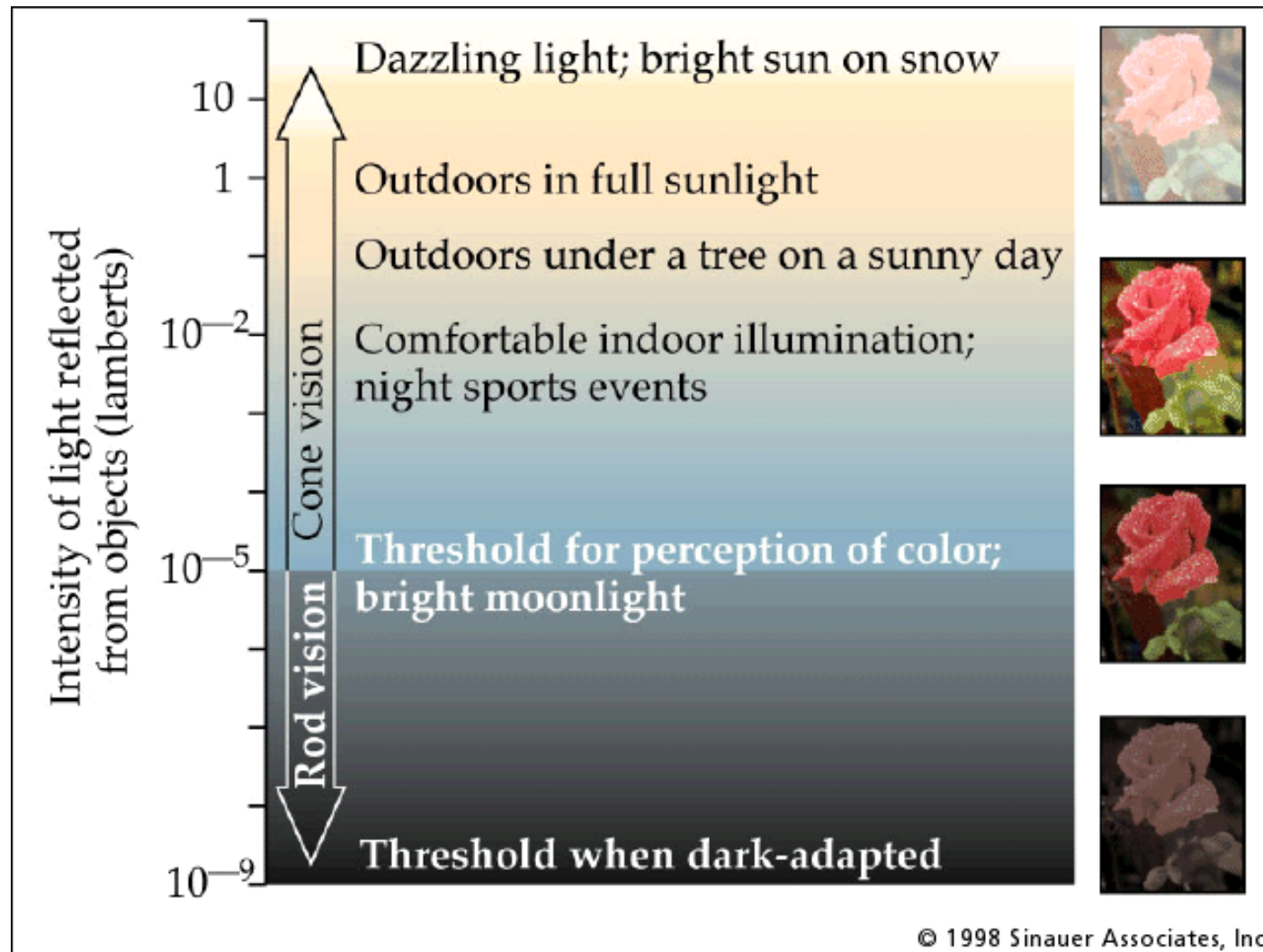
Rods

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



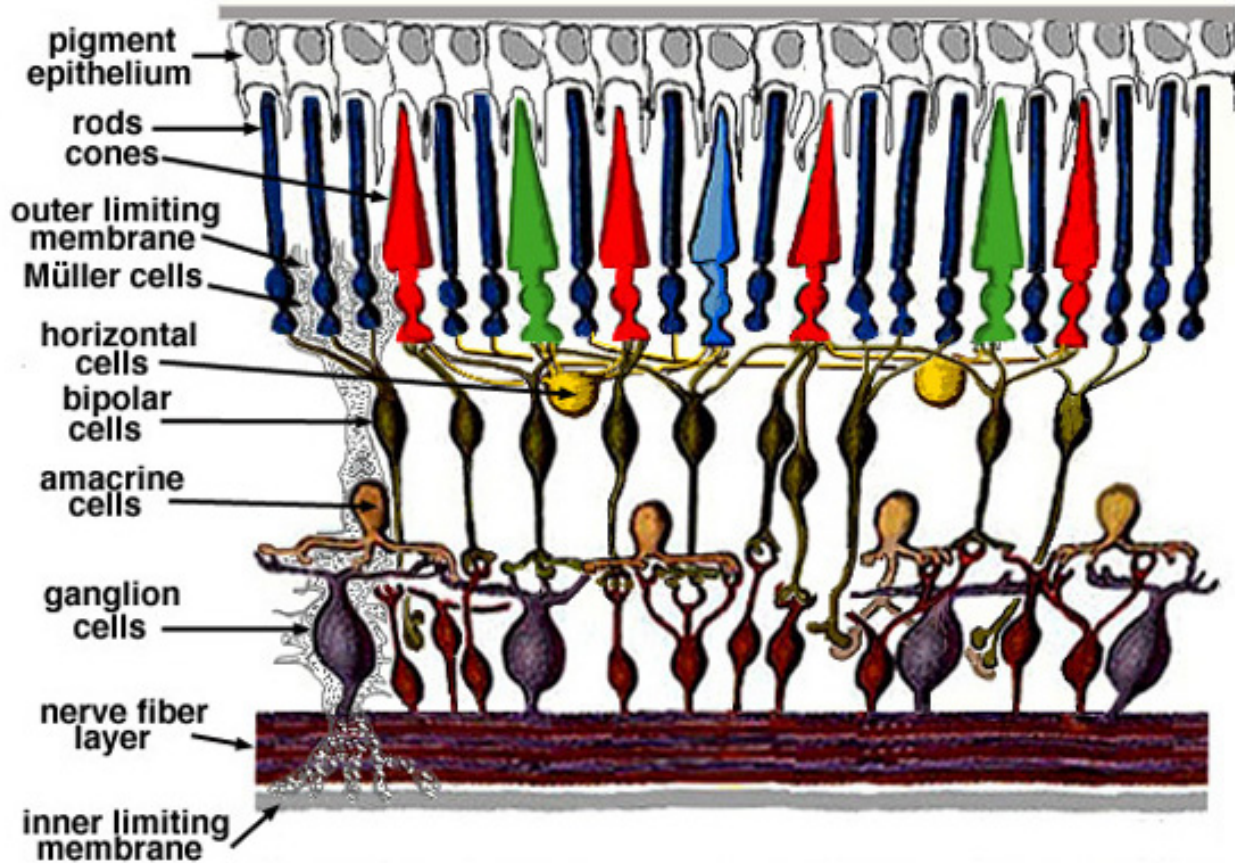
Schnapf & Baylor, 1987

Rod / Cone Sensitivity



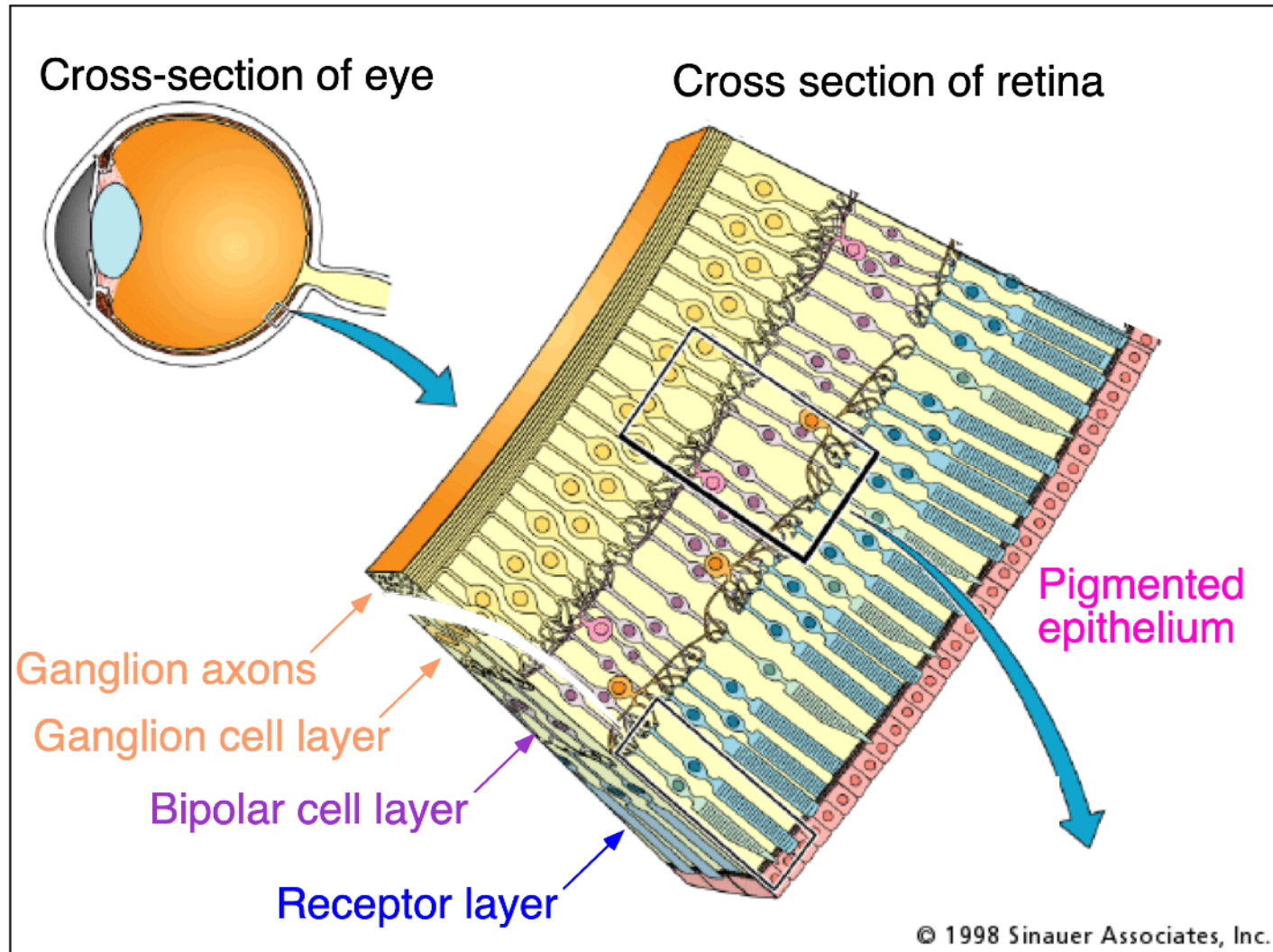
The famous sock-matching problem...

Retina Up-Close

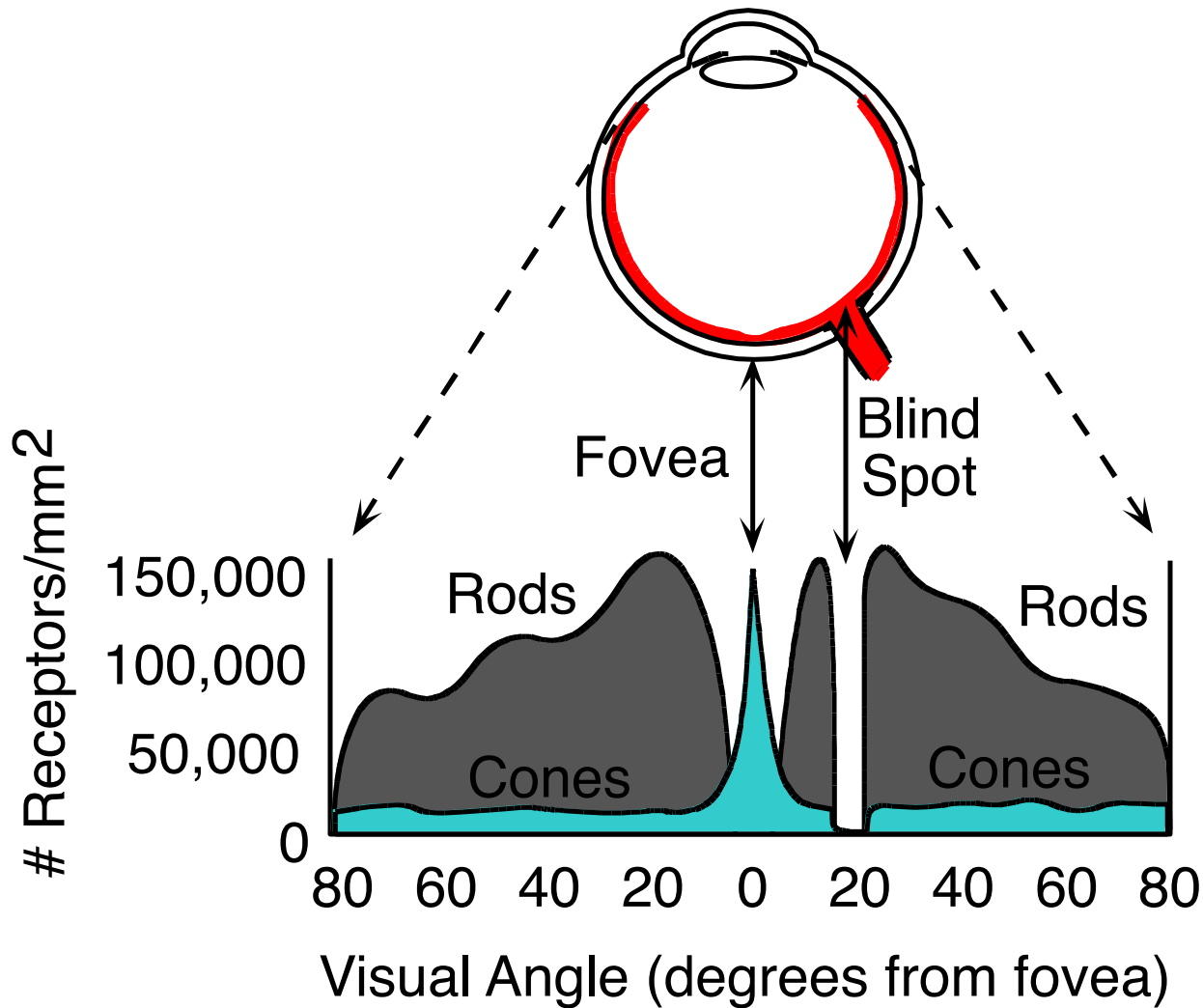


↑ ↑ ↑
Light

The Retina

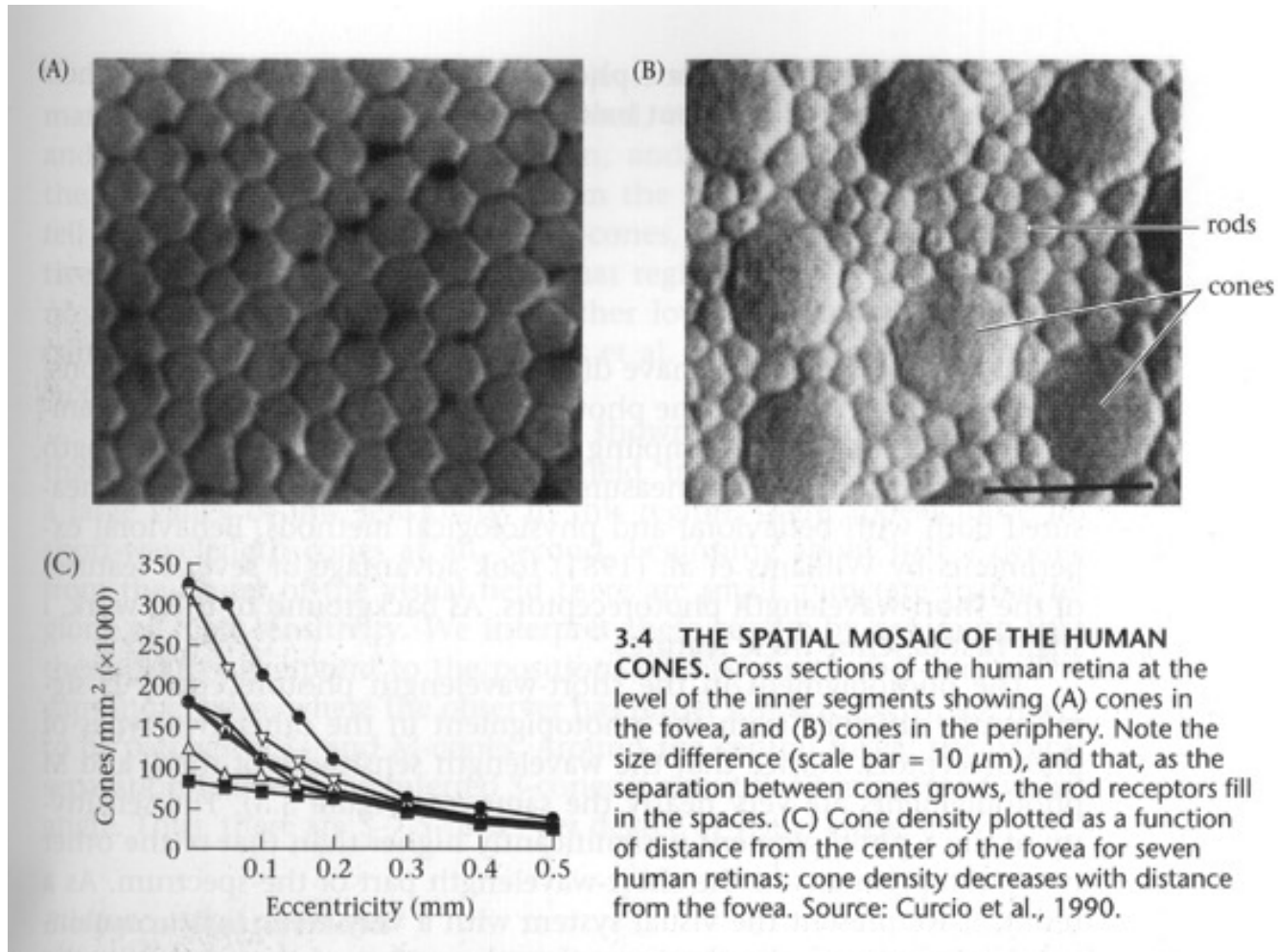


Distribution of Rods and Cones



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

Distribution of Rods and Cones



Color Vision

The Visible Spectrum of Light

Electromagnetic radiation

- Oscillations of different frequencies (wavelengths)

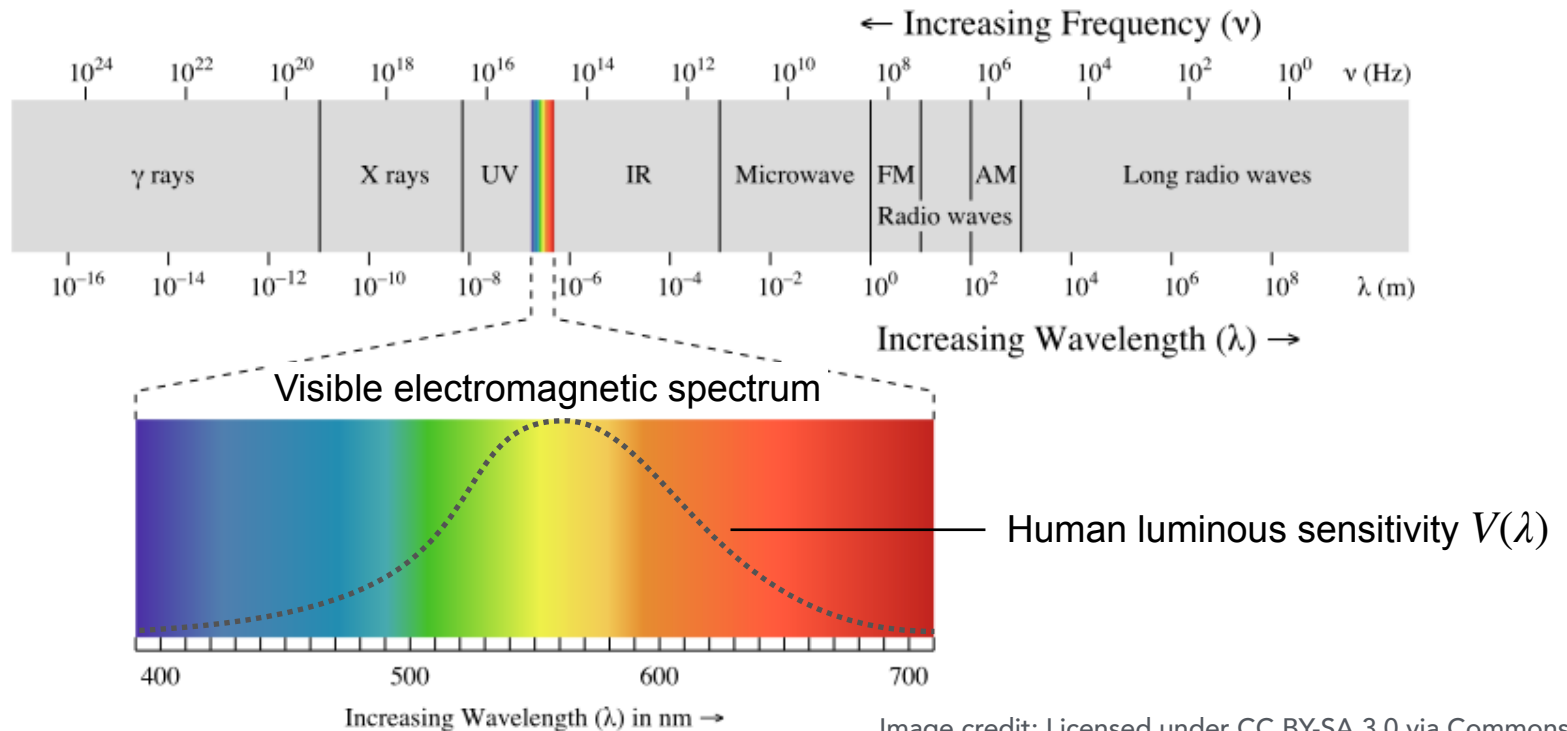
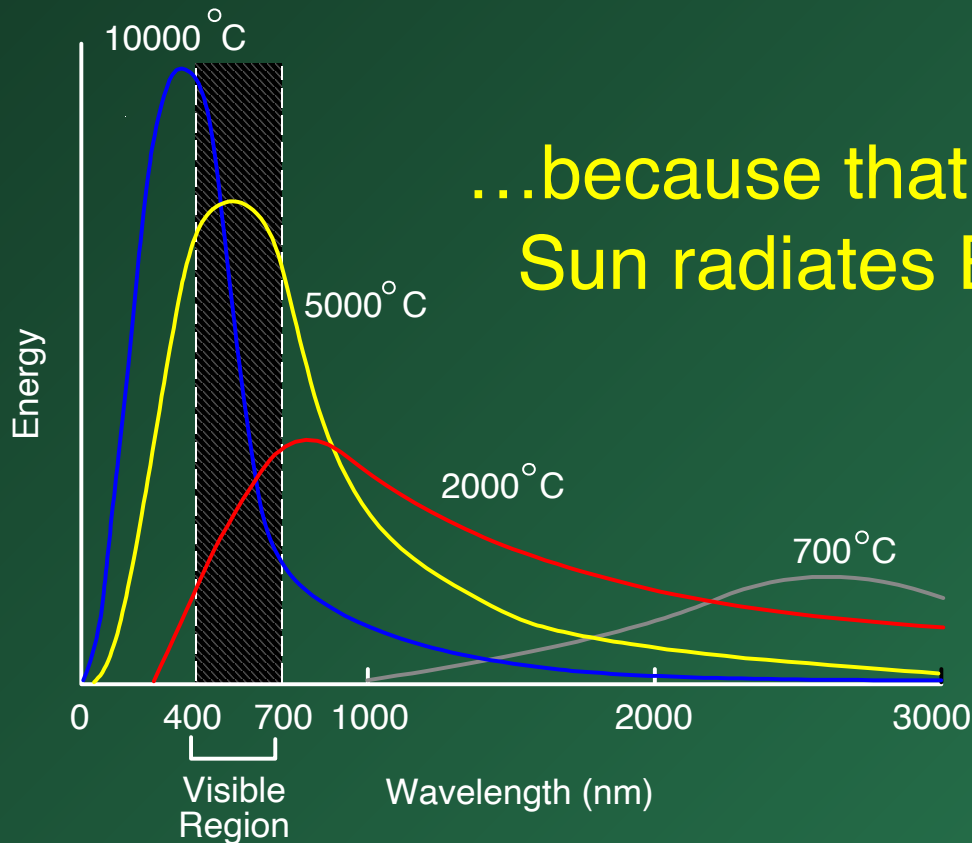


Image credit: Licensed under CC BY-SA 3.0 via Commons
https://commons.wikimedia.org/wiki/File:EM_spectrum.svg#/media/File:EM_spectrum.svg

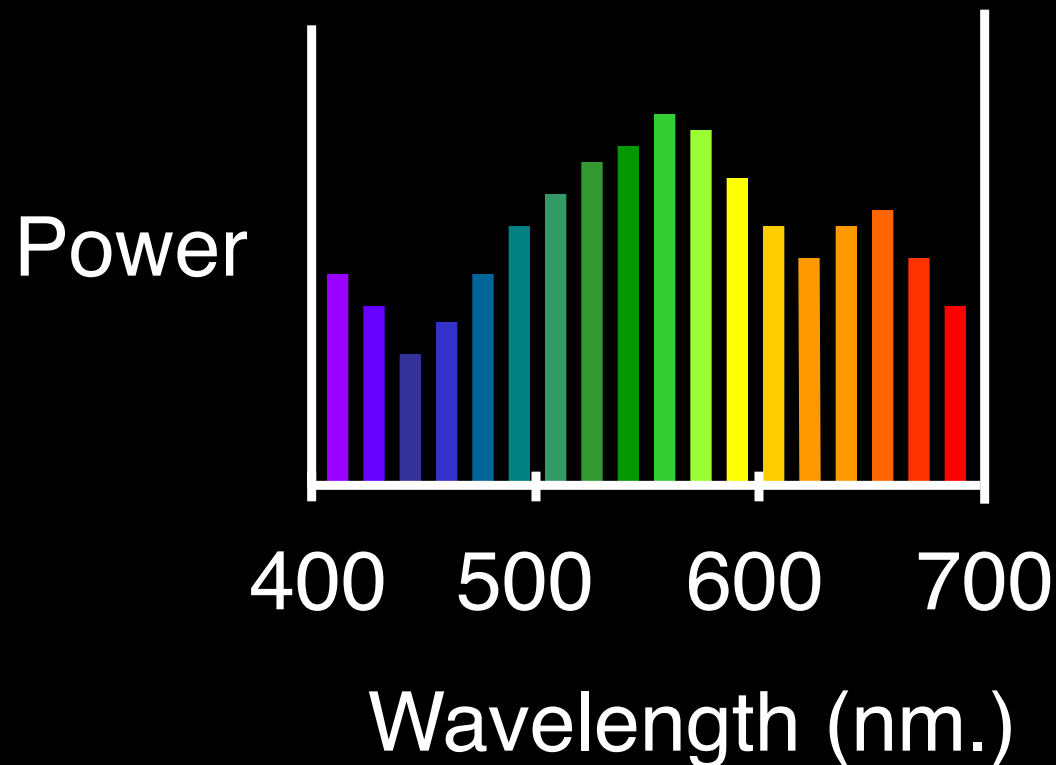
The Visible Spectrum of Light

Why do we see light of these wavelengths?



The Physics of Light

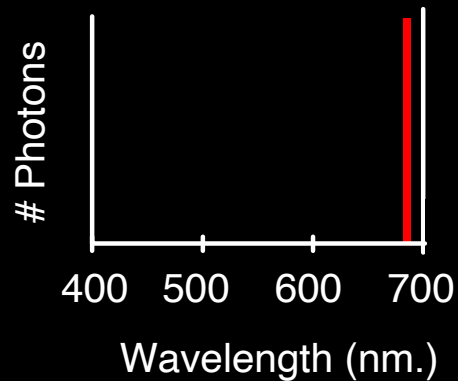
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



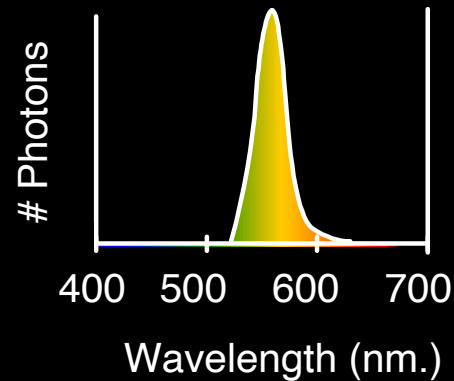
The Physics of Light

Some examples of the spectra of light sources

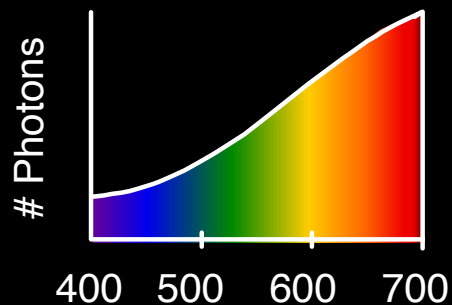
A. Ruby Laser



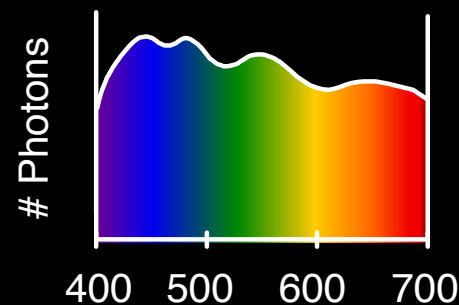
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb

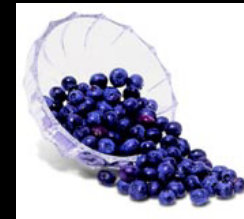


D. Normal Daylight

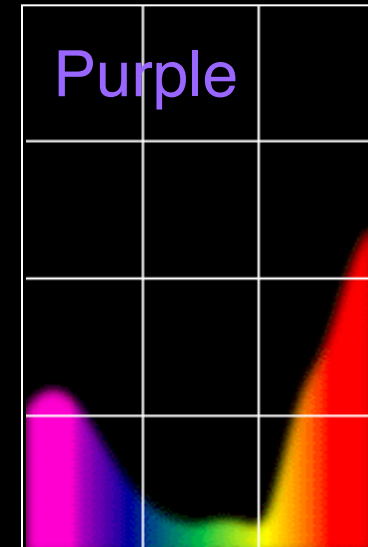
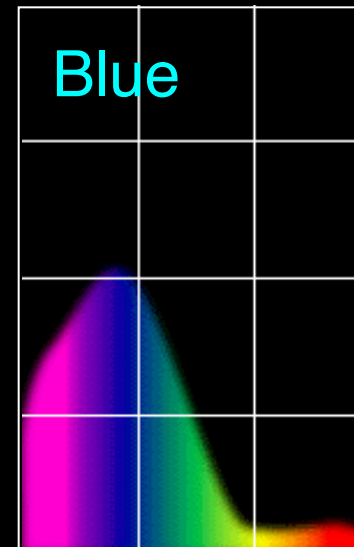
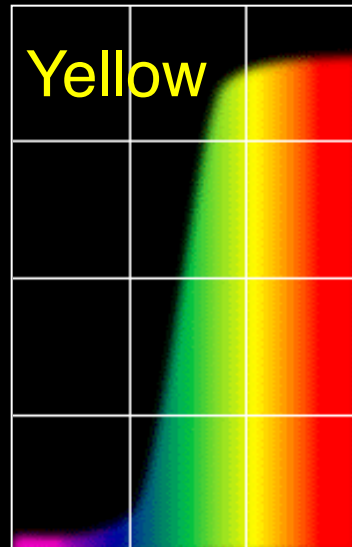
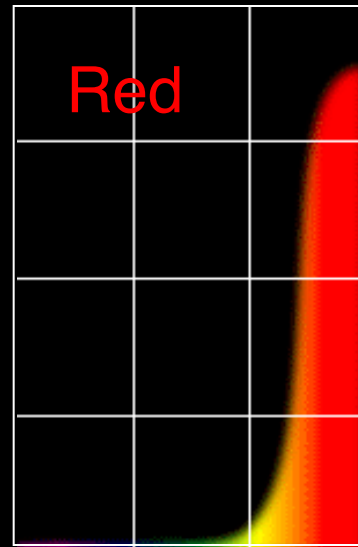


The Physics of Light

Some examples of the reflectance spectra of surfaces



% Photons Reflected



400

700

400

700

400

700

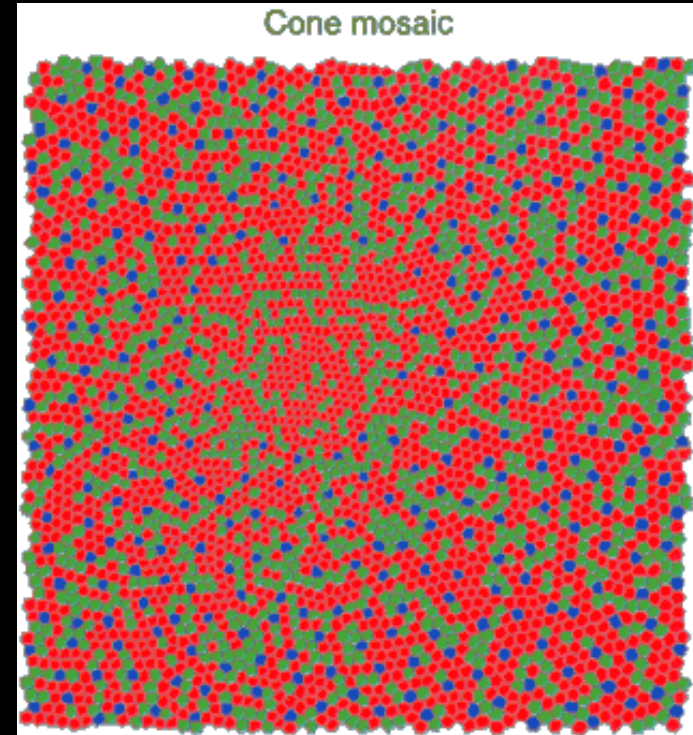
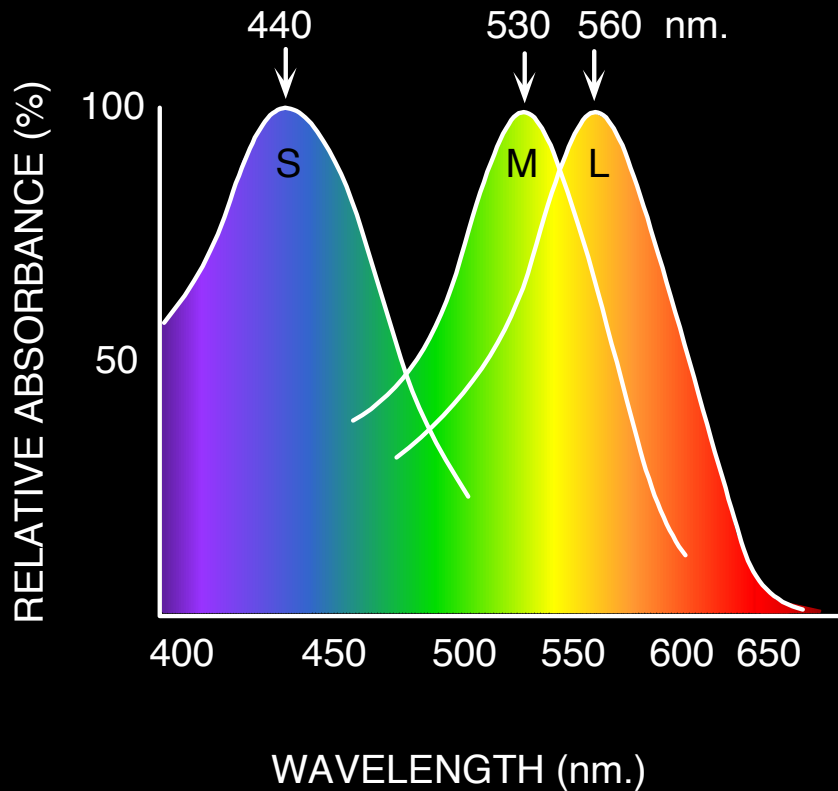
400

700

Wavelength (nm)

Physiology of Color Vision

Three kinds of cones:



- What's up with S cones?
- Why are there 3?

The Dimensionality of Color Vision



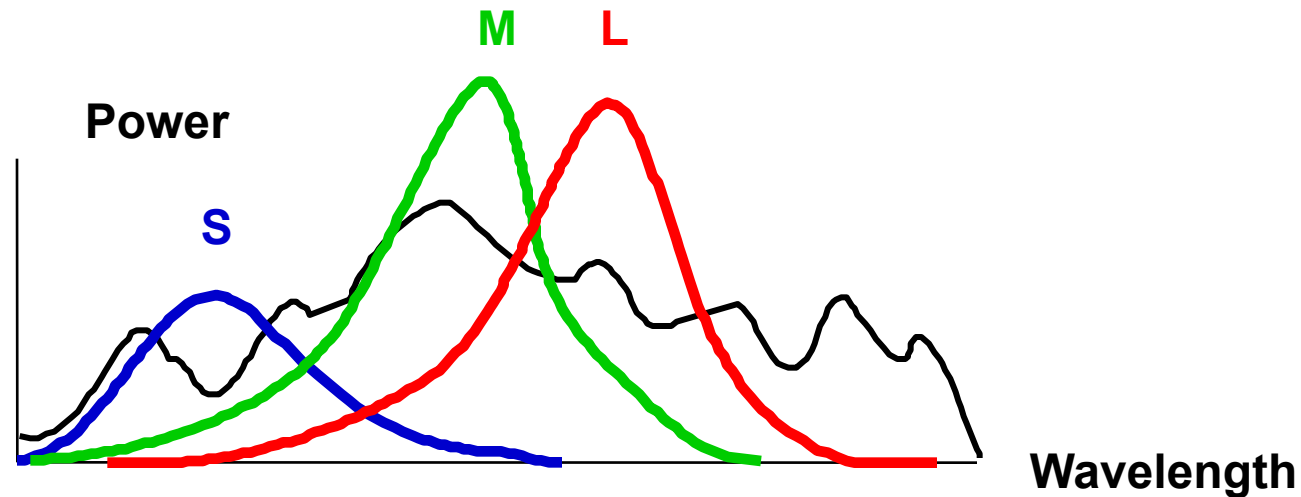
Maxwell's color matching experiment

- To match a set of test colors:
 - Most people need three color primaries
 - Some people need only two primaries

<http://designblog.rietveldacademie.nl/?p=68422>

Portrait: <http://rsta.royalsocietypublishing.org/content/366/1871/1685>

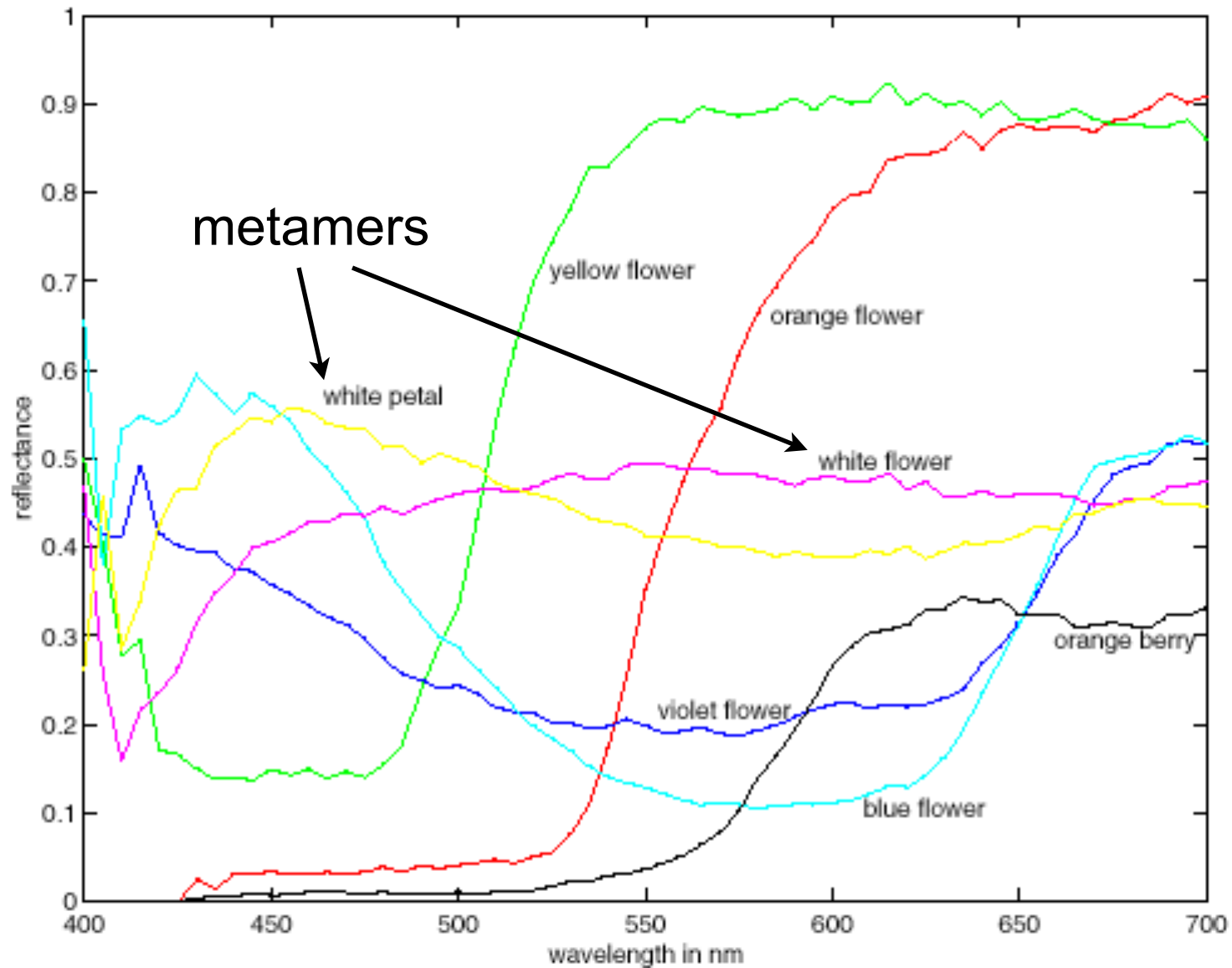
Trichromacy = Three Dimensional Color



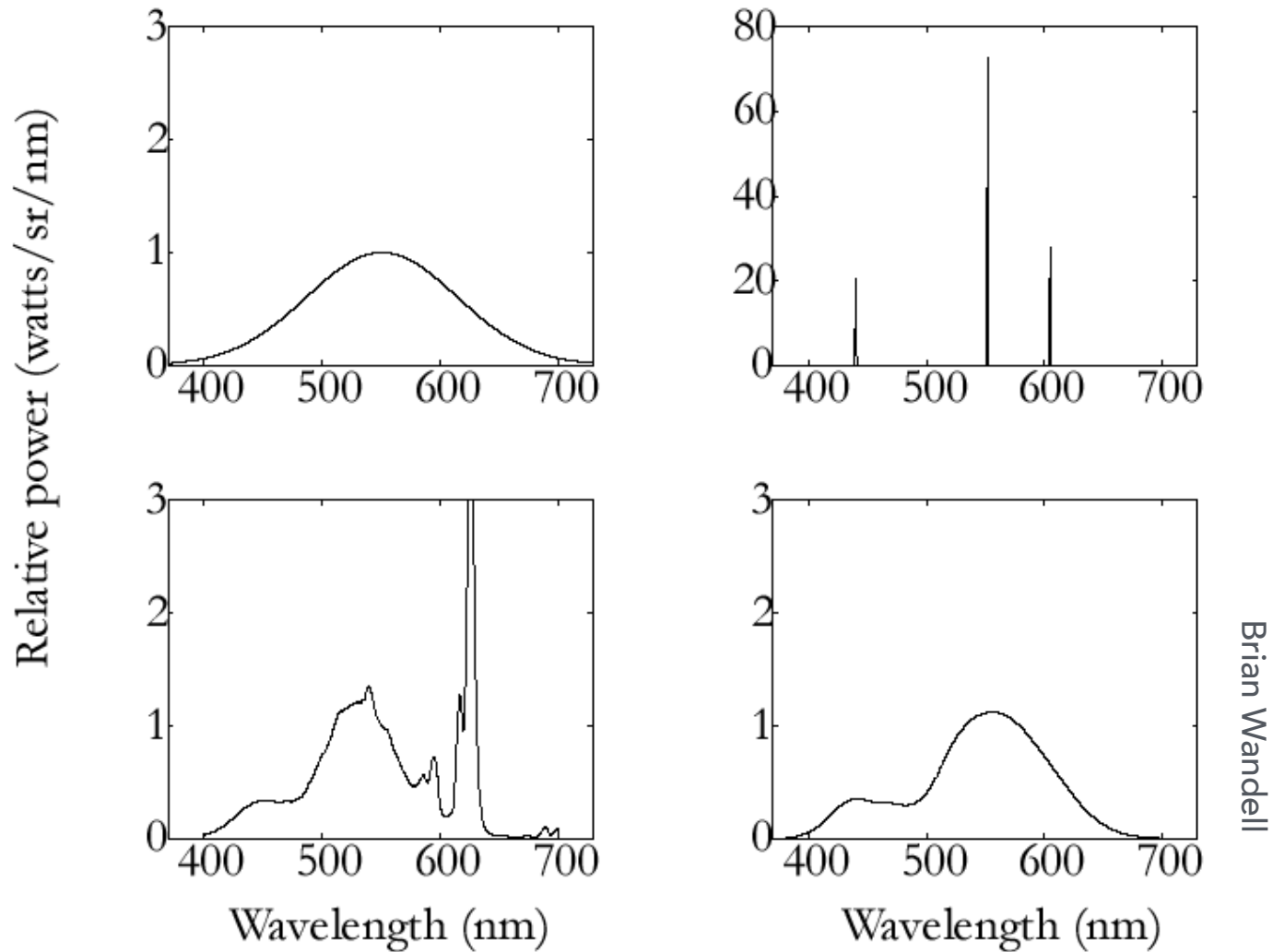
Cone cells act as *filters* on the spectrum

- 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”!



Metamerism is a Big Effect



Color Vision Diversity

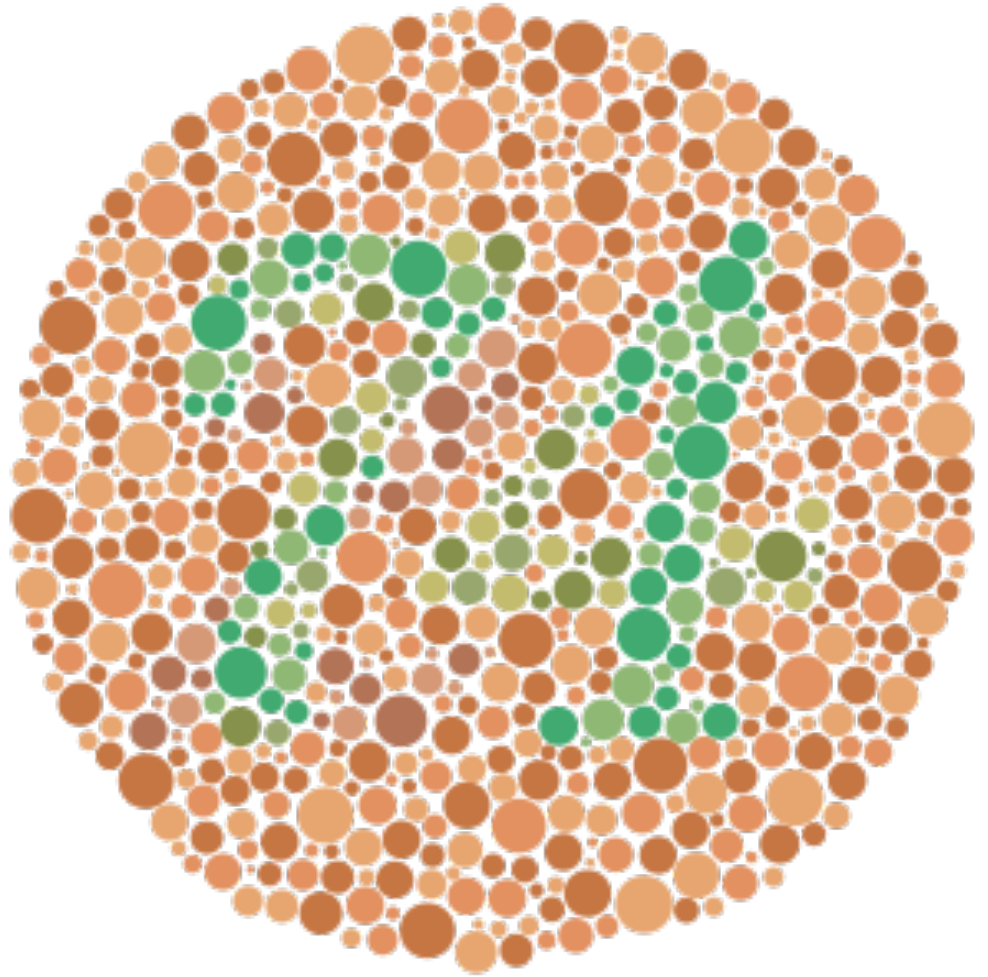
Red-Green Color Blindness is Common in Men

5-8% in males (XY)

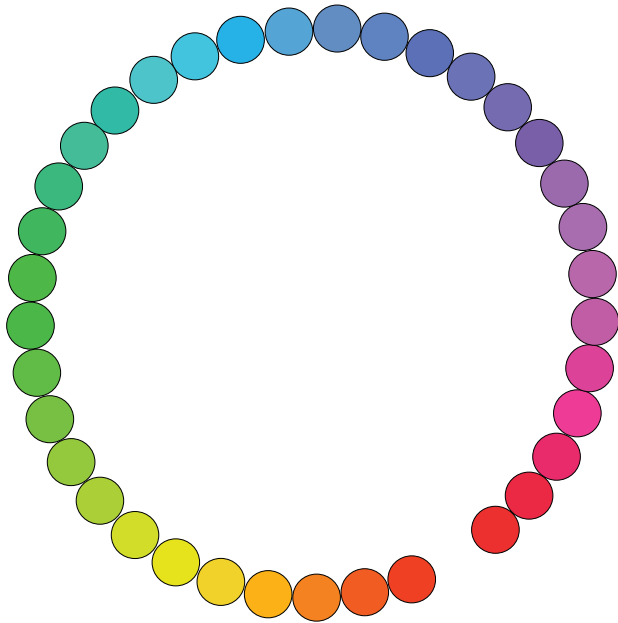
0.5% to 1.0% in
females (XX)

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.



Color Naming

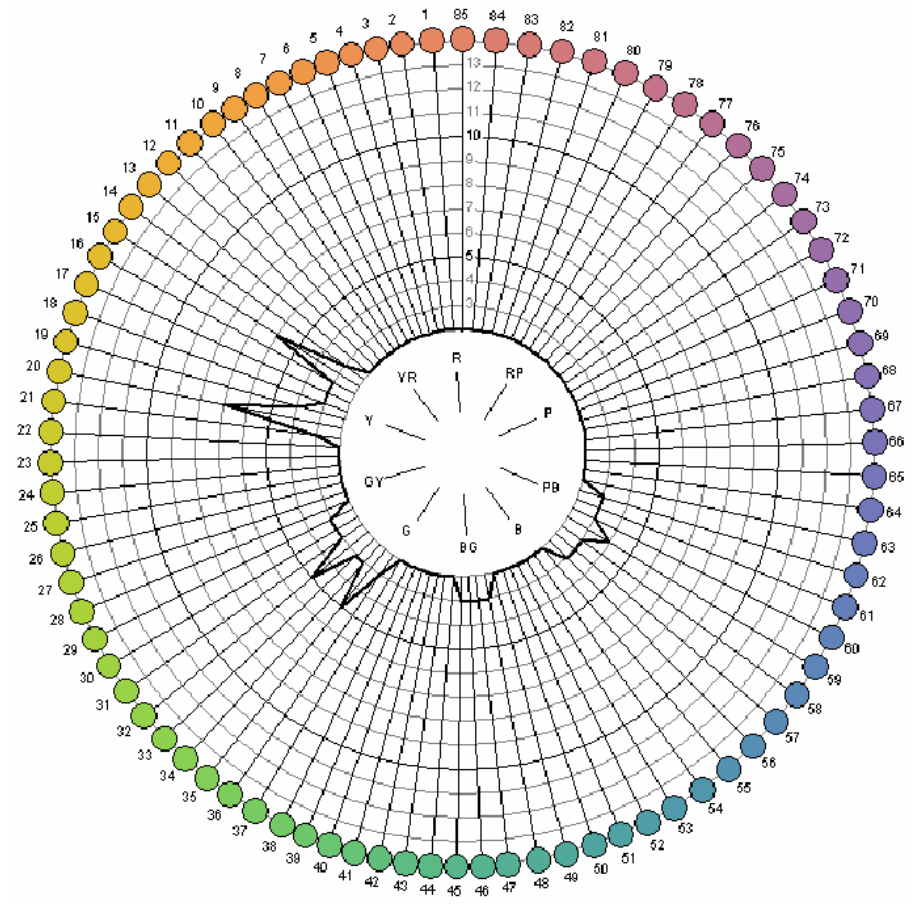


A Person With One Trichromatic Eye and One Dichromatic Eye



Neitz and Neitz 2017, Colorblindness confined to one eye.
Courtesy of Jay Neitz

Farnsworth-Munsell Hue 100 Test (FM-100)



Source: RP Imaging

Simulation of Dichromatic Color Perception



Normal



Protan



Deutan



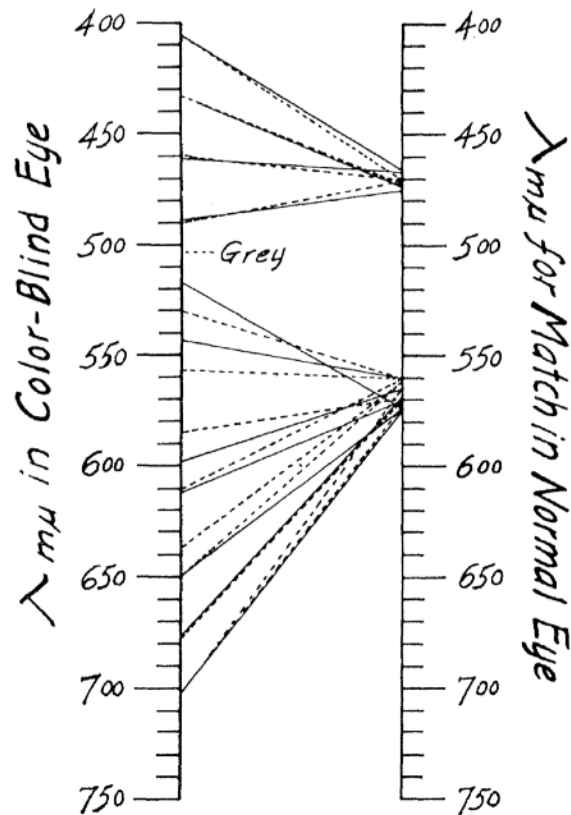
Tritan

Created with Coblis — Color Blindness Simulator

A Person With One Trichromatic Eye and One Deuteranopic Eye

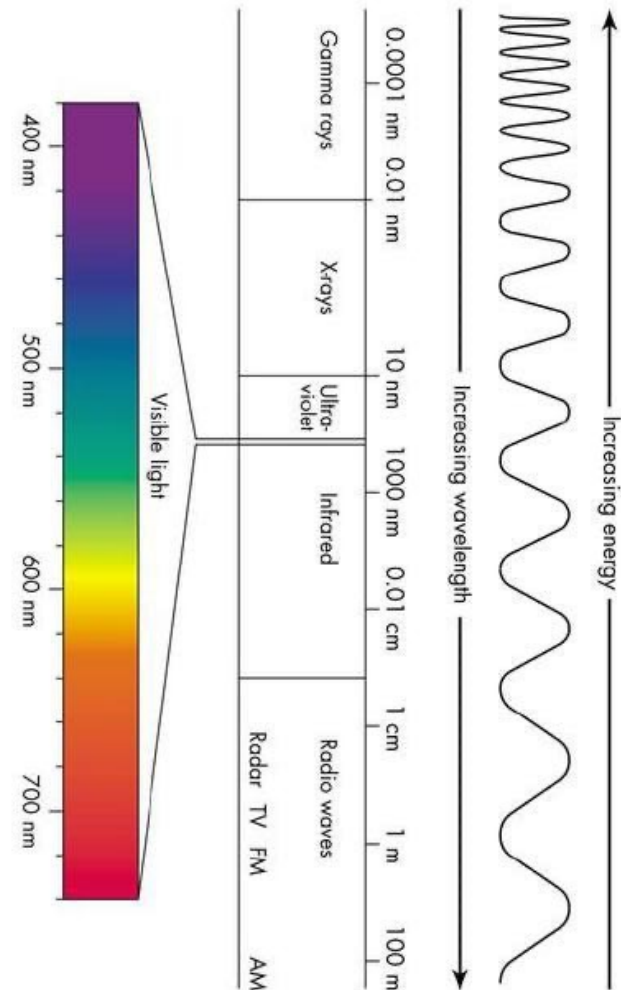
Graham and Hsia, 1959.

"A unilaterally dichromatic subject".



----- 7/11/57 New London
 ————— 7/19/57 New York

FIG. 2.—Results of the experiment on binocular matching



Source: Munsell



Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Normal



Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Protan



Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Deutan



Steve McCurry | Reza | Walter Iooss | Steve McCurry
Harold Edgerton | NASA | National Geographic

Tritan

Not Everyone is Trichromat

Types of Dichromacy:

- Deuteranopia: missing M cones
- Protanopia: missing L cones
- Tritanopia: missing S cones
- Deuteranomaly: Anomalous trichromacy where M cone is shifted toward L

“M” and “L” are on the X-chromosome

- Males (XY) are more likely to be color blind
- “L” has high variation, so some females (XX) are genetically tetrachromatic

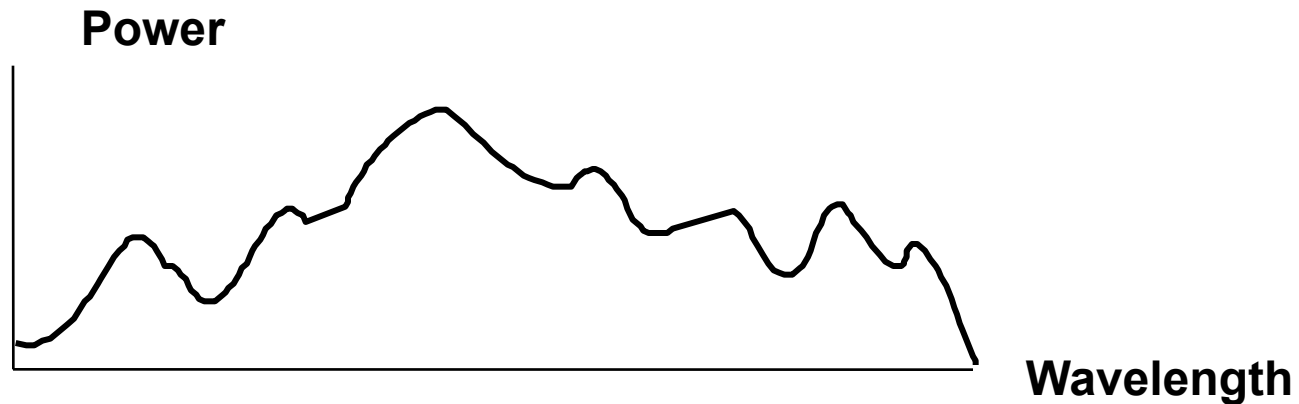
How many color receptor classes in different species?

- 1 (night animals)
- 2 (e.g. dogs)
- 4 (fish, birds)
- 5 (pigeons, some reptiles/ amphibians)
- 12+ (mantis shrimp)



Perceived Colors (Back to Trichromacy)

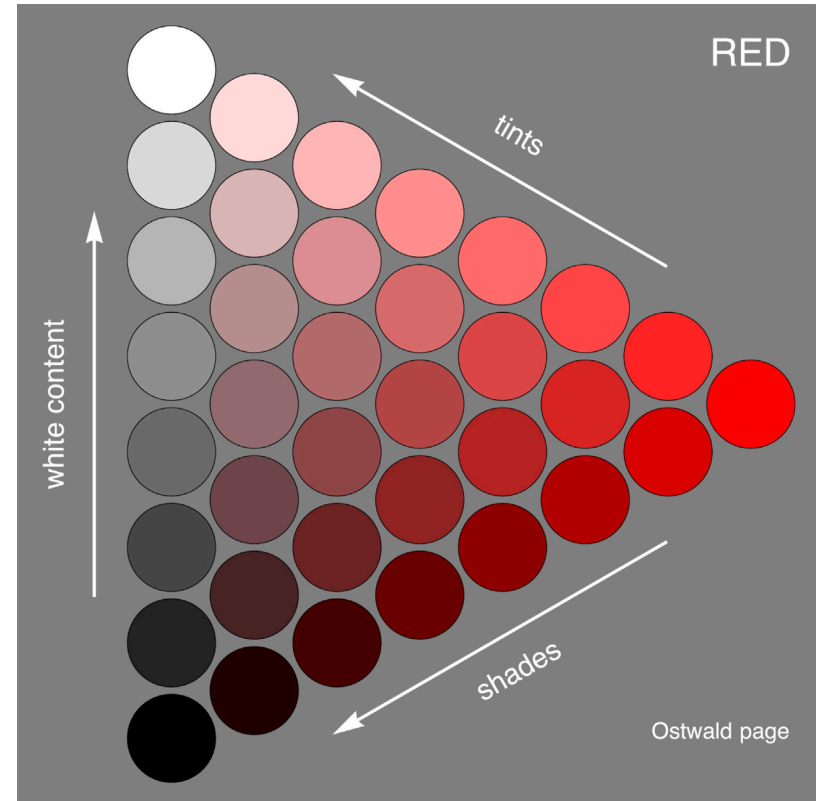
Given a Spectrum, What is the Color?



How to Organize Color?



Ostwald's color atlas



One branch of atlas

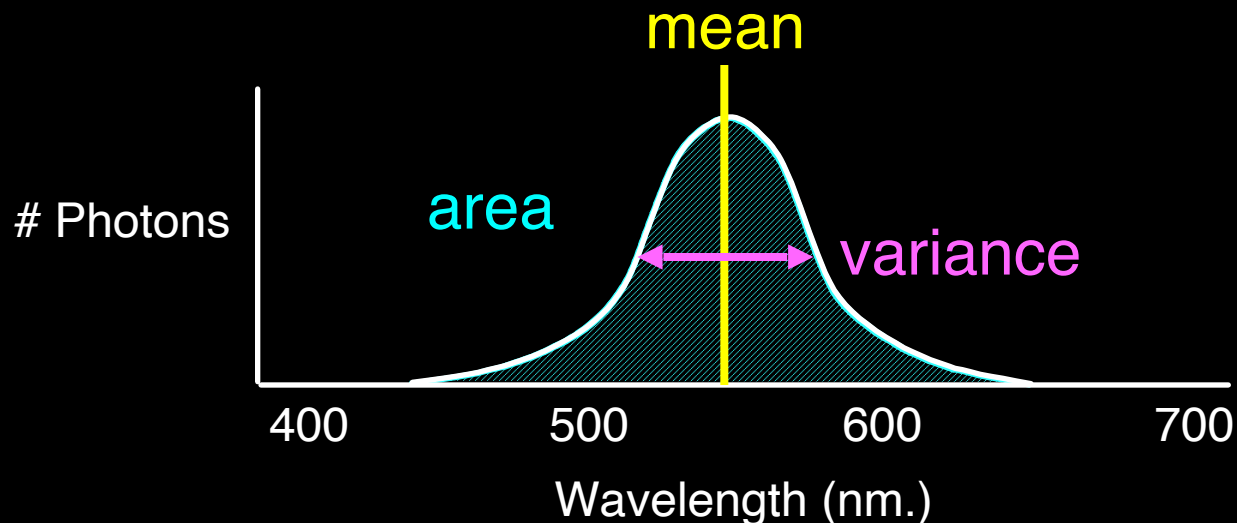
Enables mapping a color by its hue, saturation and brightness.

The Psychophysics of “Color”

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

An helpful* conceptual model:

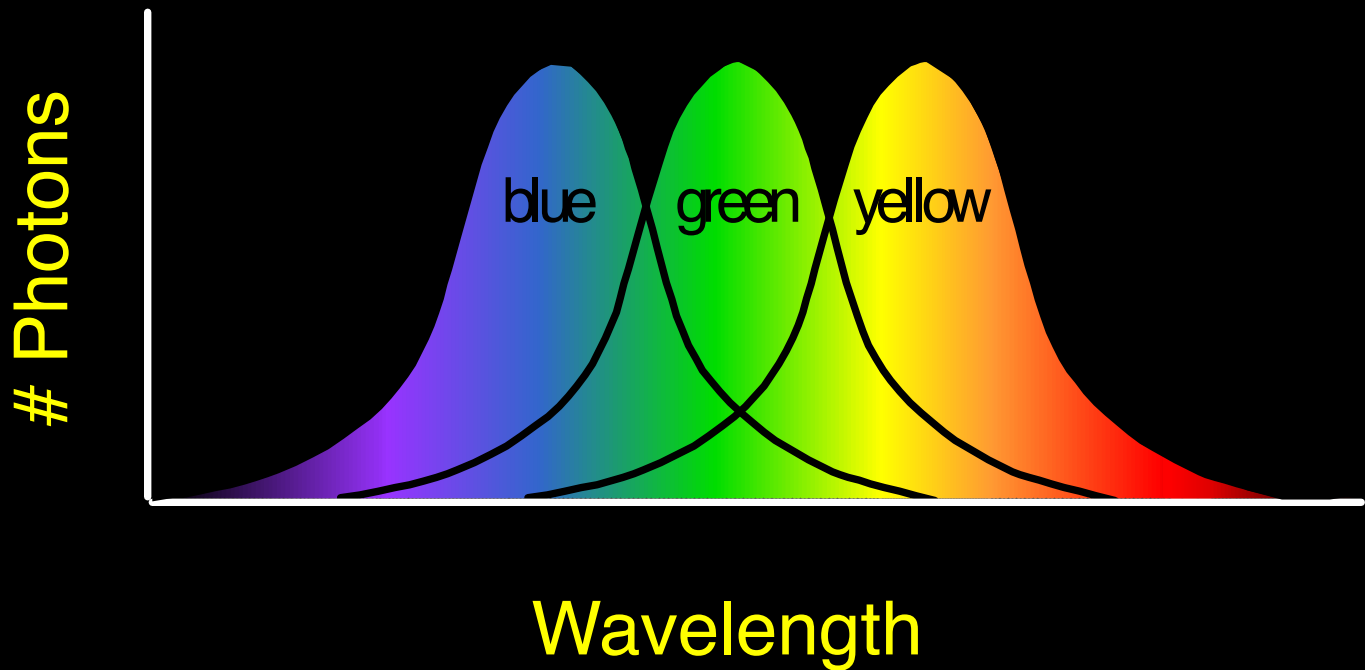
Consider only physical spectra with normal distributions



* But limited, e.g. neglects purples

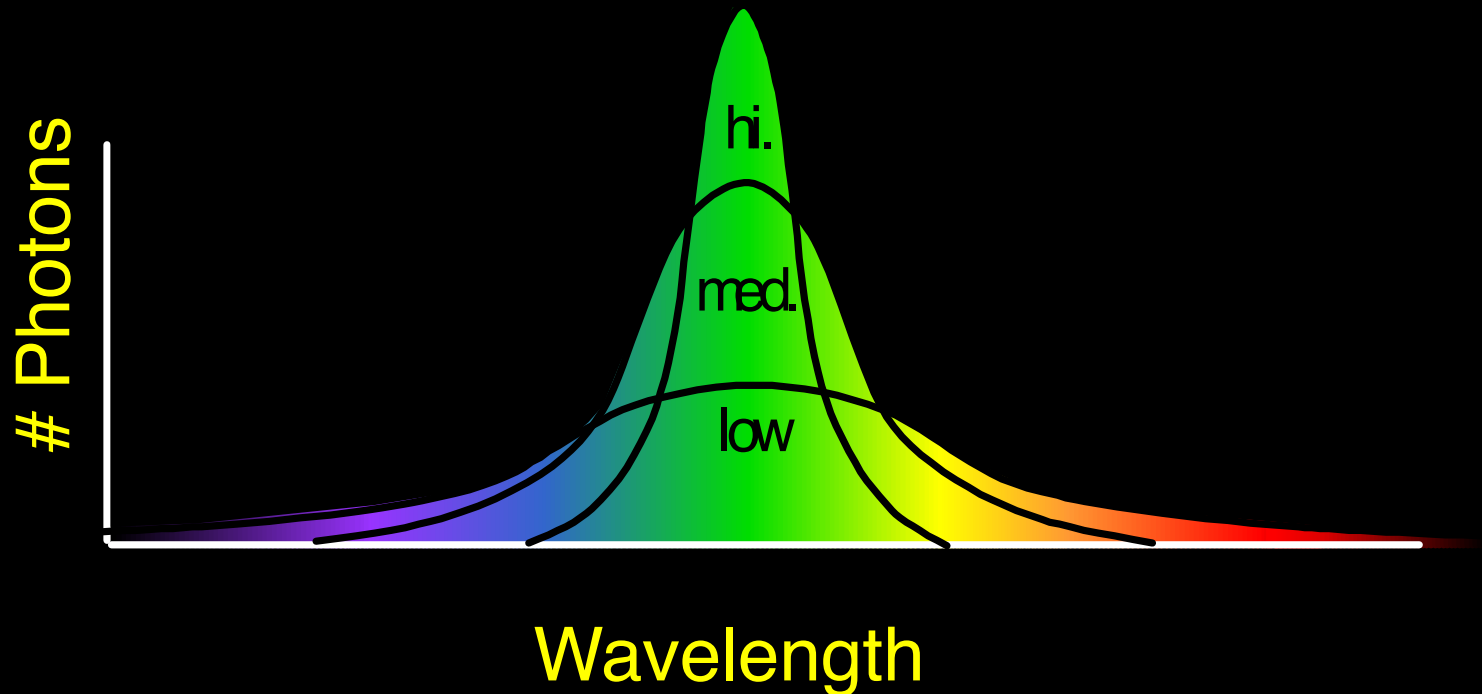
The Psychophysical Correspondence

Mean $\longleftrightarrow$ Hue



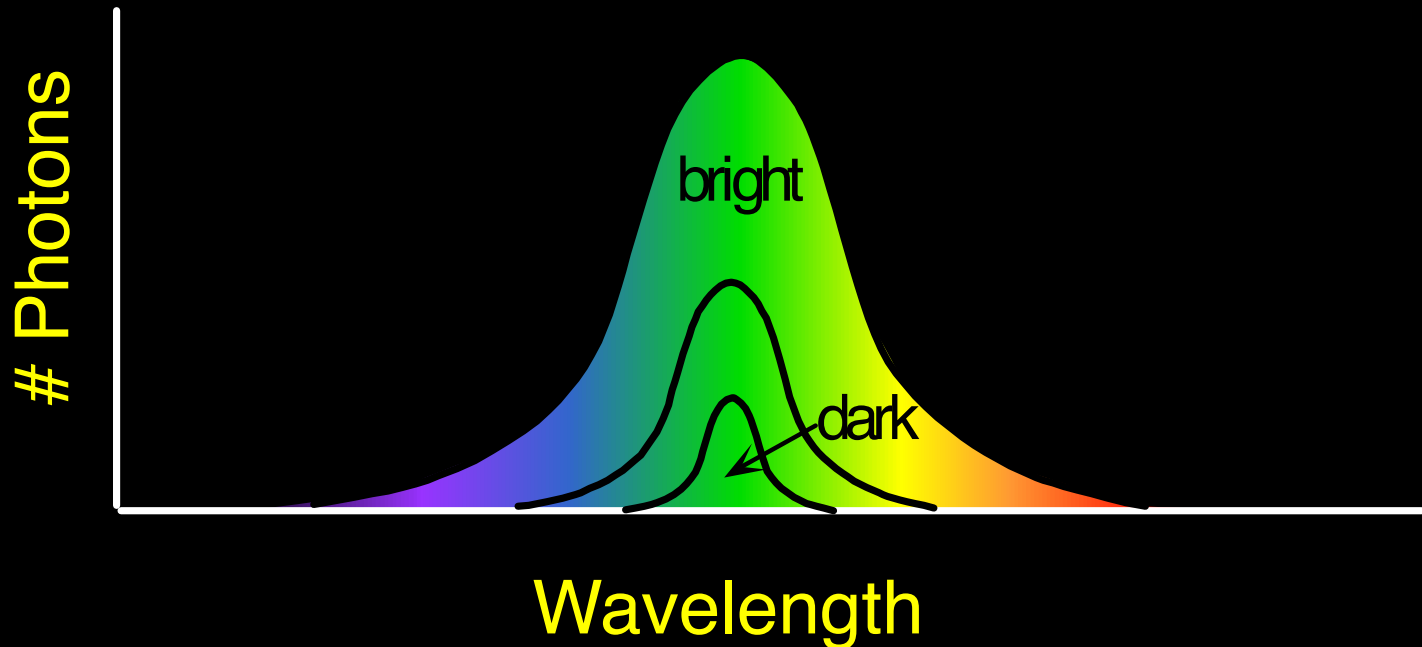
The Psychophysical Correspondence

Variance $\longleftrightarrow$ Saturation



The Psychophysical Correspondence

Area $\longleftrightarrow$ **Brightness**



So Spectrum Determines Perceived Color?

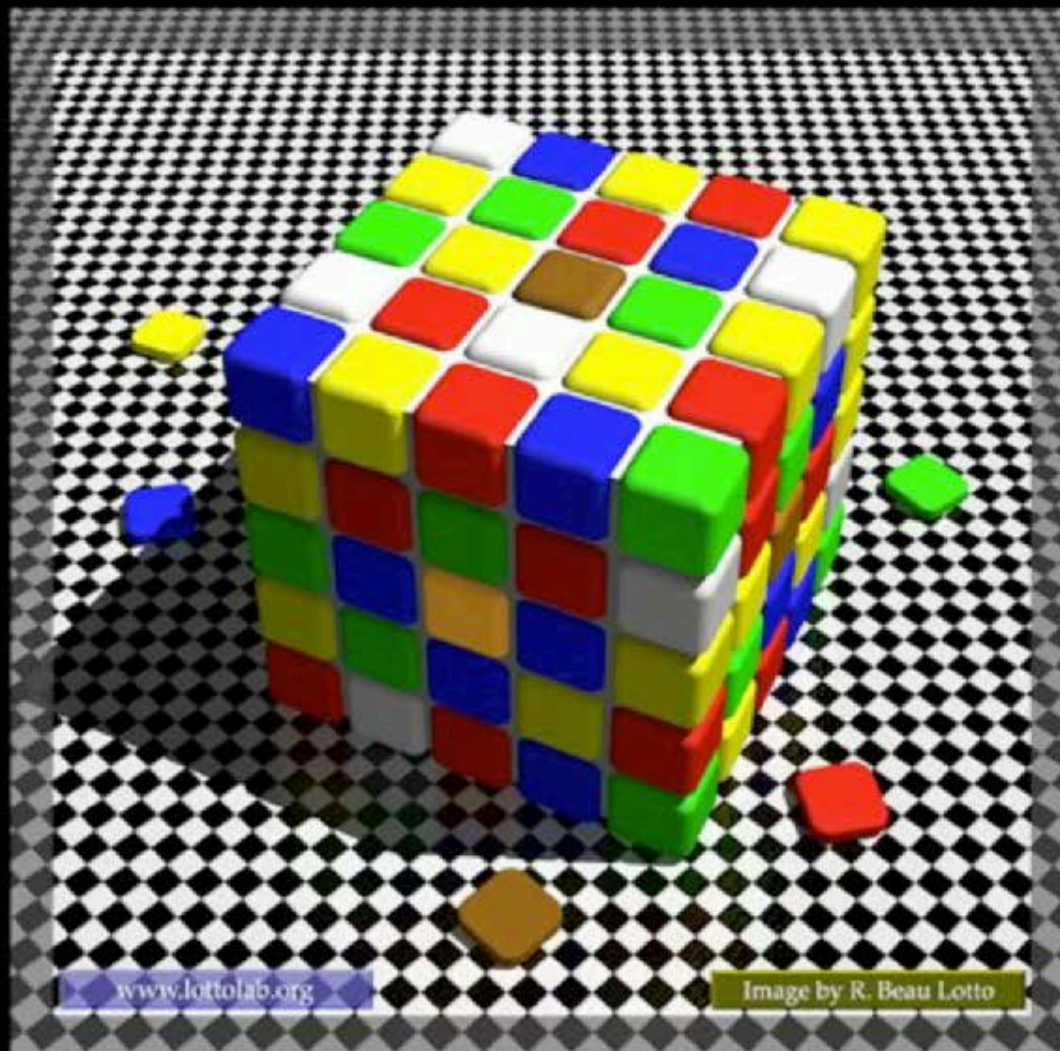
The “photometer metaphor” of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).



No! Color Perception is Contextual

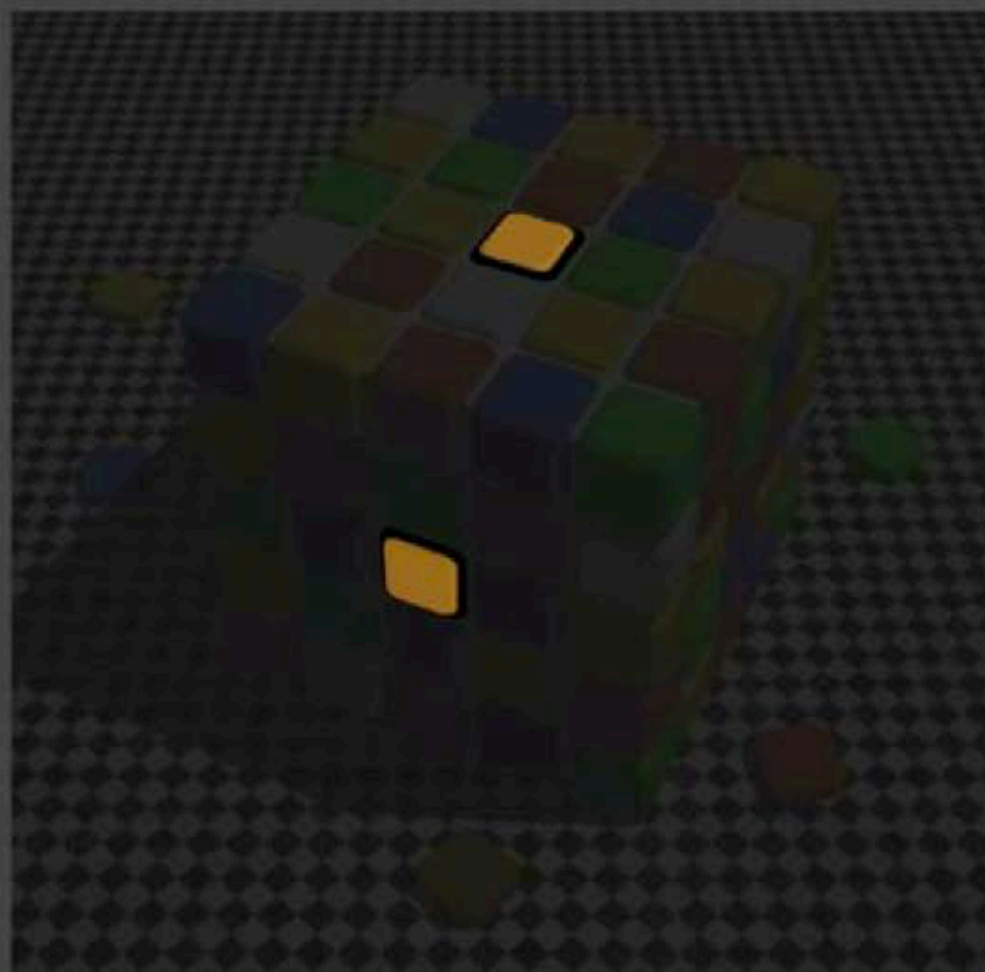
~~The “photometer metaphor” of color perception:
Color perception is determined by the spectrum of light
on each retinal receptor (as measured by a photometer).~~



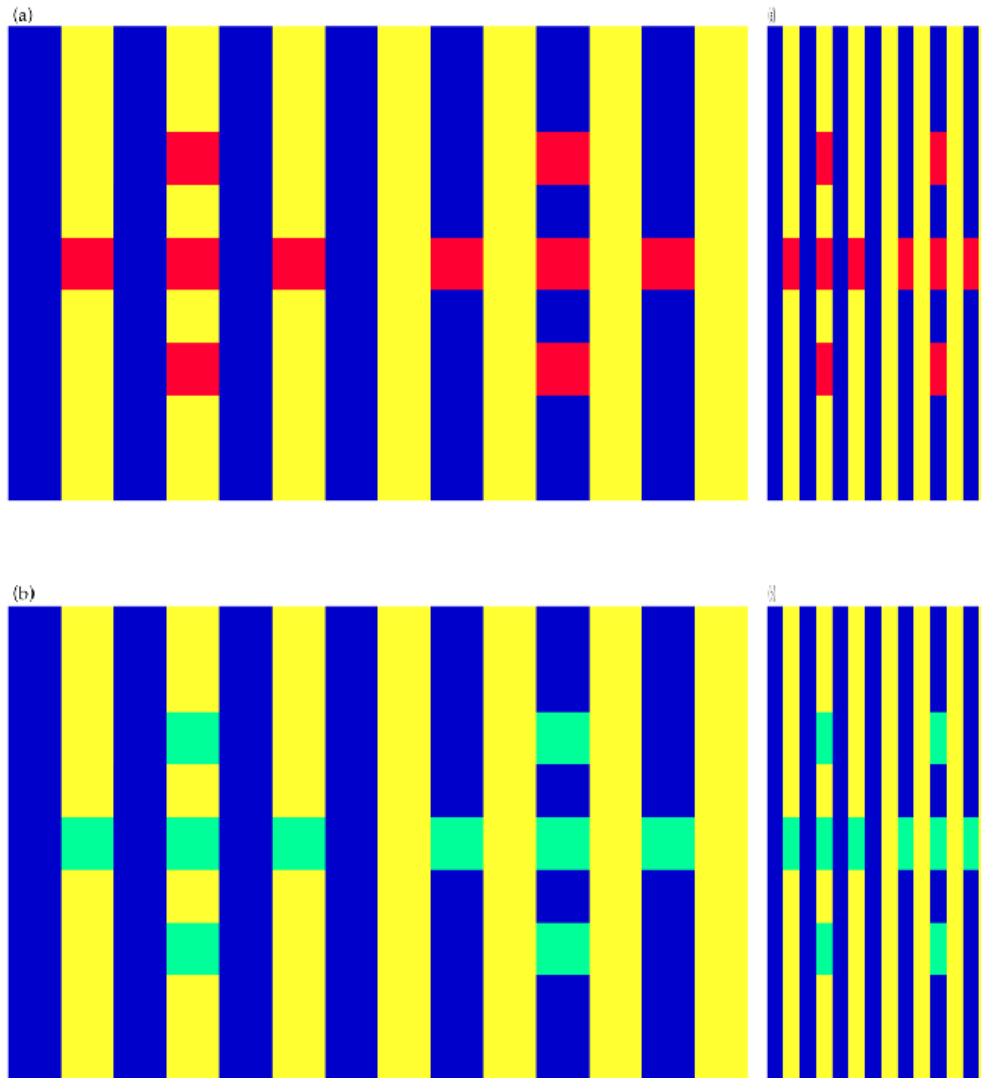


www.lottolab.org

Image by R. Beau Lotto



Surround Effects



Roberts (1996)

Studying Chromatic Adaptation / Color Constancy



Slide credit: Mark Fairchild



Slide credit: Mark Fairchild

A CYAN FILTER



Slide credit: Mark Fairchild



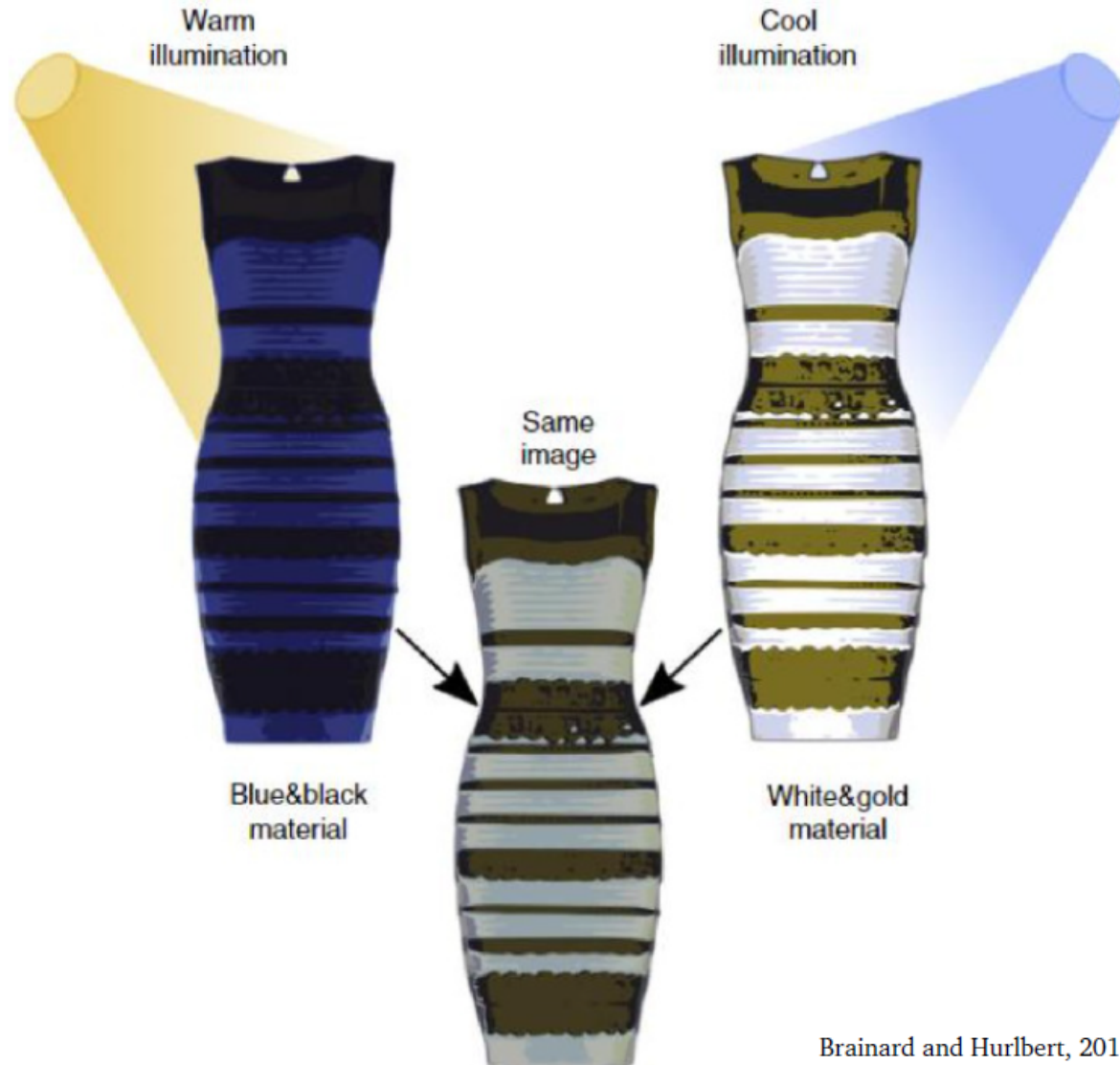
Slide credit: Mark Fairchild

What Color Was “The Dress”?



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

Two Scene Interpretations of “The Dress”



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

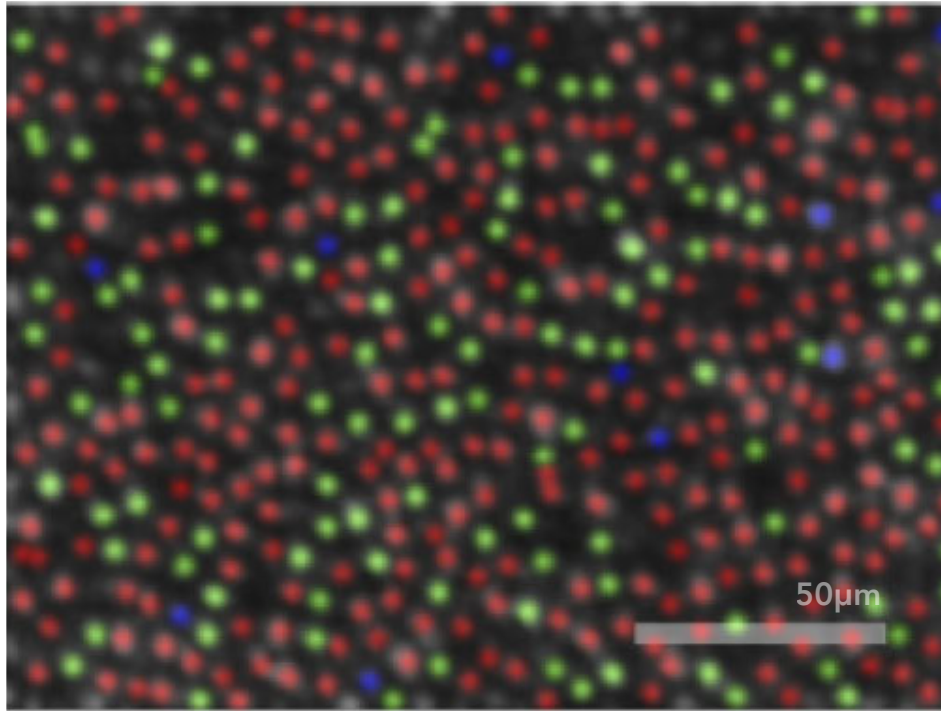
Camera White Balancing



- 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 Cameras

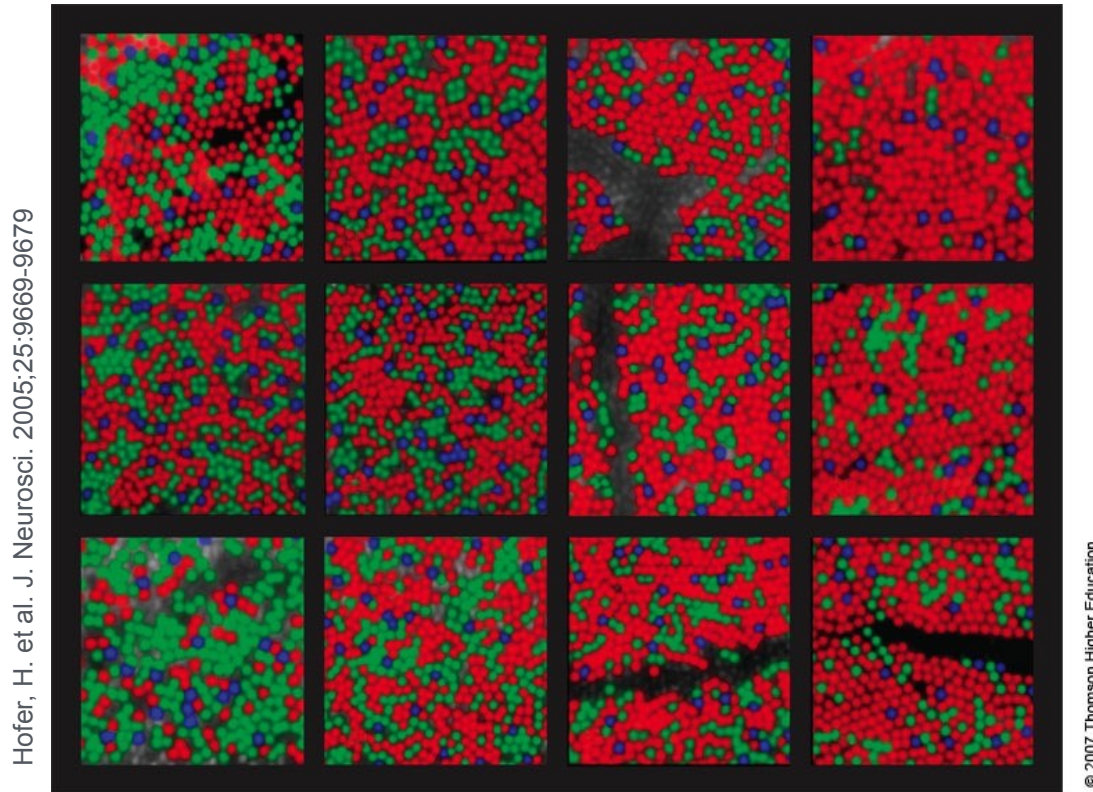
Retina: Three Types of Cone Cells



Sabesan Lab, UW. Pandiyan et al. 2020.

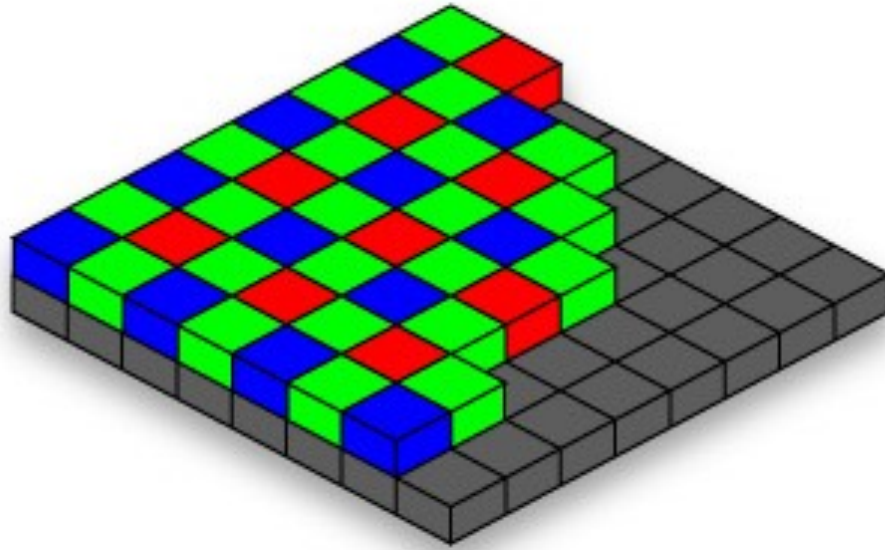
Mosaic of S, M, L cone cells in human retina

Retina: Three Types of Cone Cells



Distribution of cone cells at edge of fovea in 12 different humans with normal color vision. Note high variability of percentage of different cone cell types. (false color image)

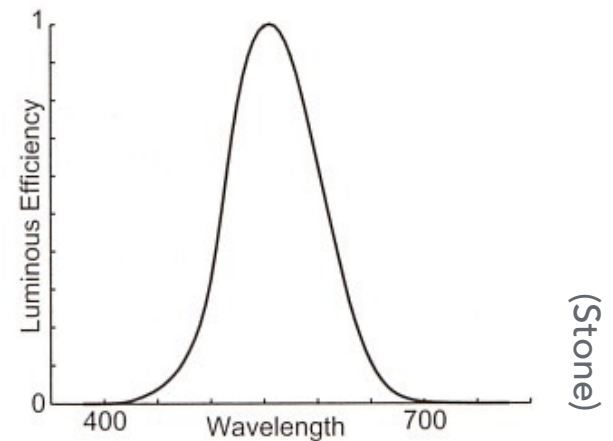
Cameras: Color Filter Arrays (R, G, B)



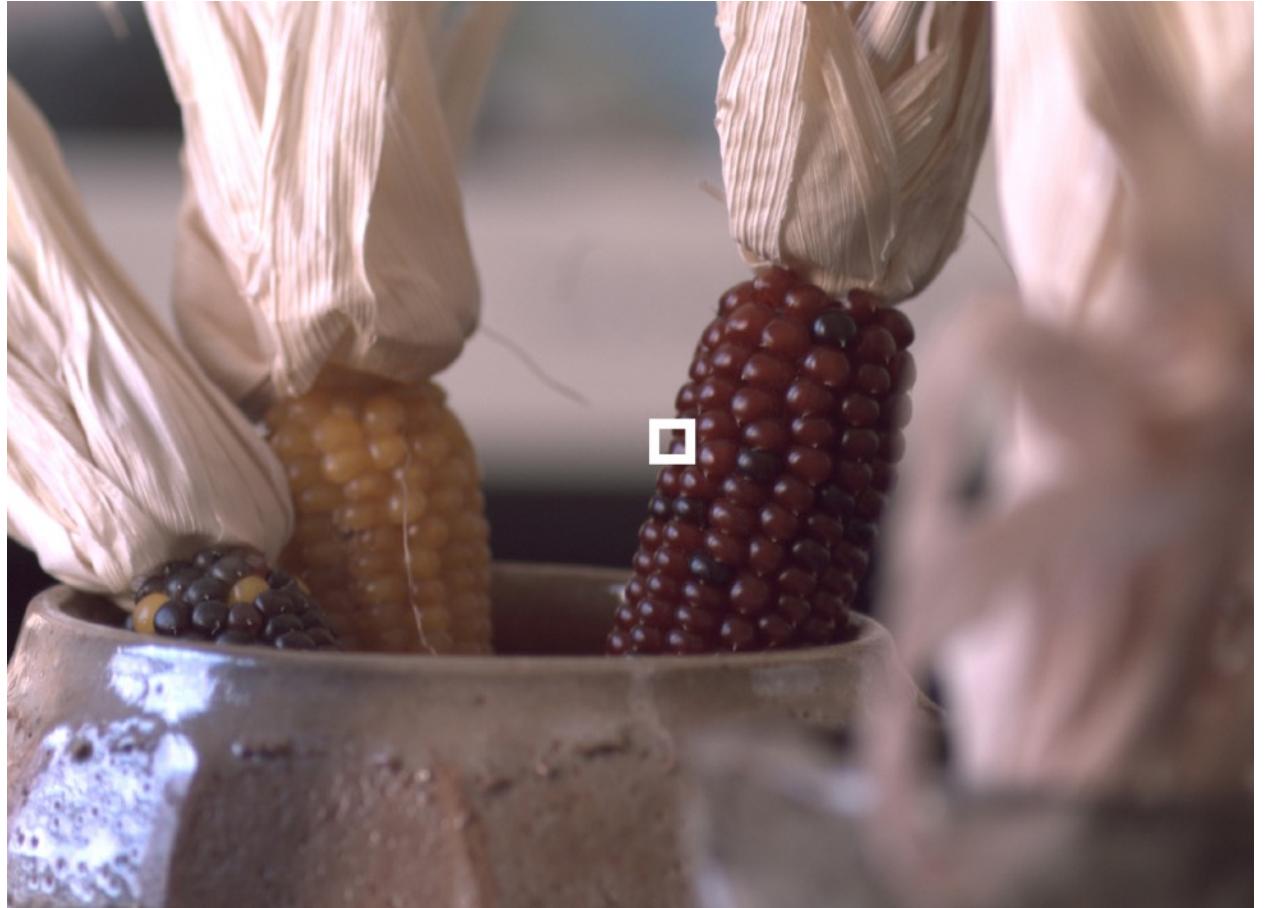
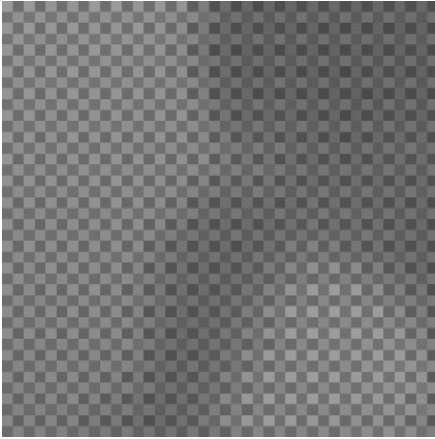
Bayer CFA

Why more green pixels than red or blue?

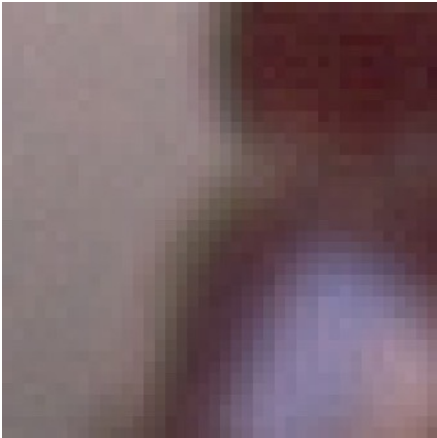
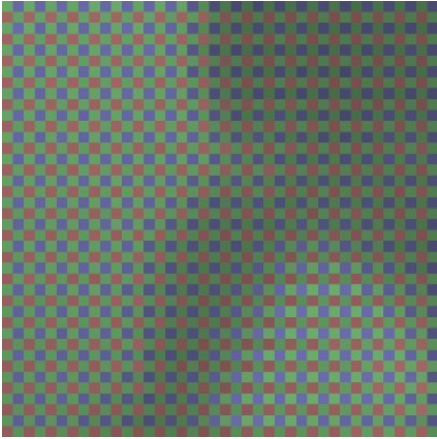
- Because humans are most sensitive in the green portion of the visible spectrum
- Sensitivity given by the human luminous efficiency curve



Demosaicking Algorithms



Demosaicking Algorithms



Demosaicking Algorithms

Interpolate sparse color samples into RGB at every output image pixel

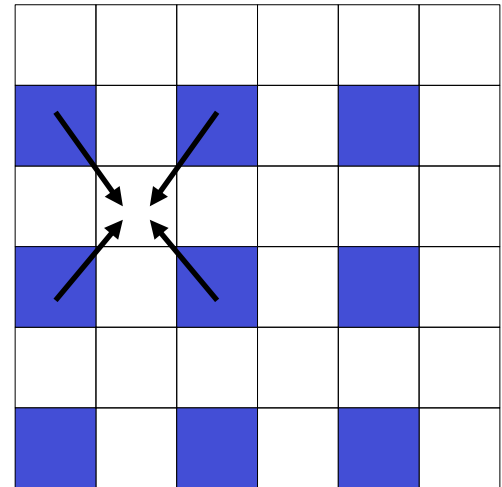
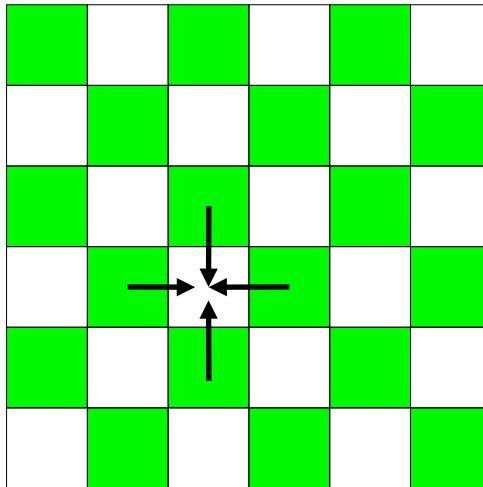
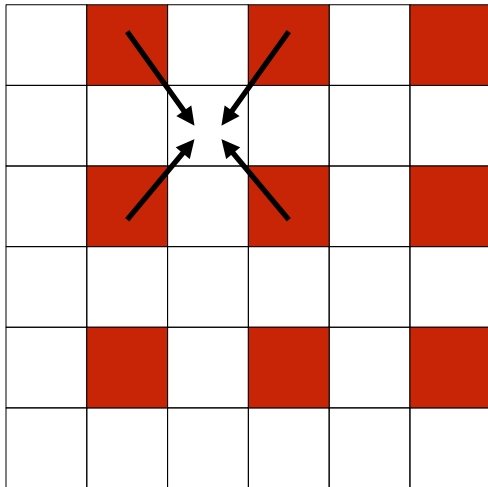
Simple algorithm: bilinear interpolation

- Average 4 nearest neighbors of the same color

Consumer cameras use more sophisticated techniques

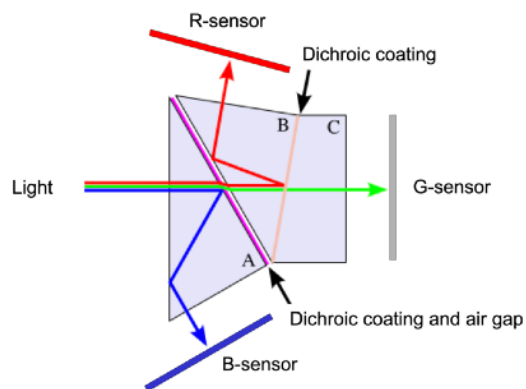
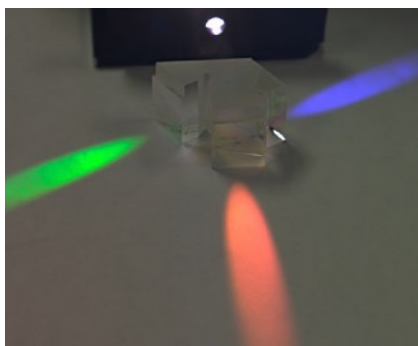
- Try to avoid interpolating across edges
- Data-driven / ML approaches

Due to demosaicking, 2/3 of image data is “made up”!



Some Cameras Detect R,G,B at Every Pixel

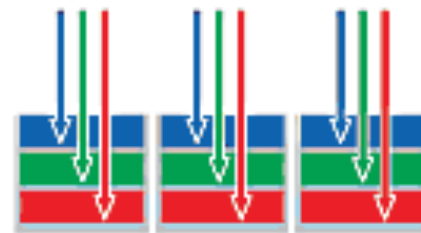
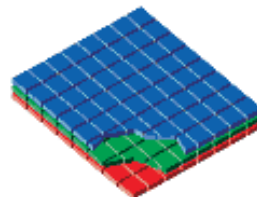
3-Chip Architecture



Stacked-Pixel Sensors



Foveon X3[®] Capture



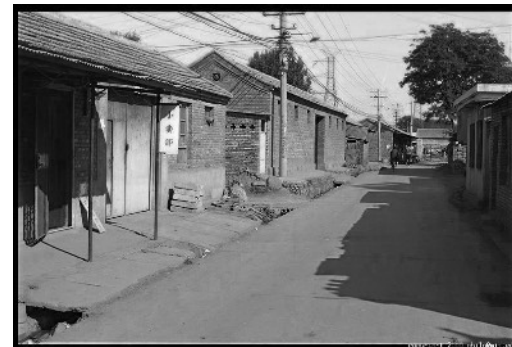
Color Image



R



G



B

Image Representation

Images represented as a matrix

Suppose we have an NxM RGB image called “im”

- $\text{im}(1,1,1)$ = top-left pixel value in R-channel
- $\text{im}(y, x, b)$ = y pixels down, x pixels to right in the bth channel
- $\text{im}(N, M, 3)$ = bottom-right pixel in B-channel

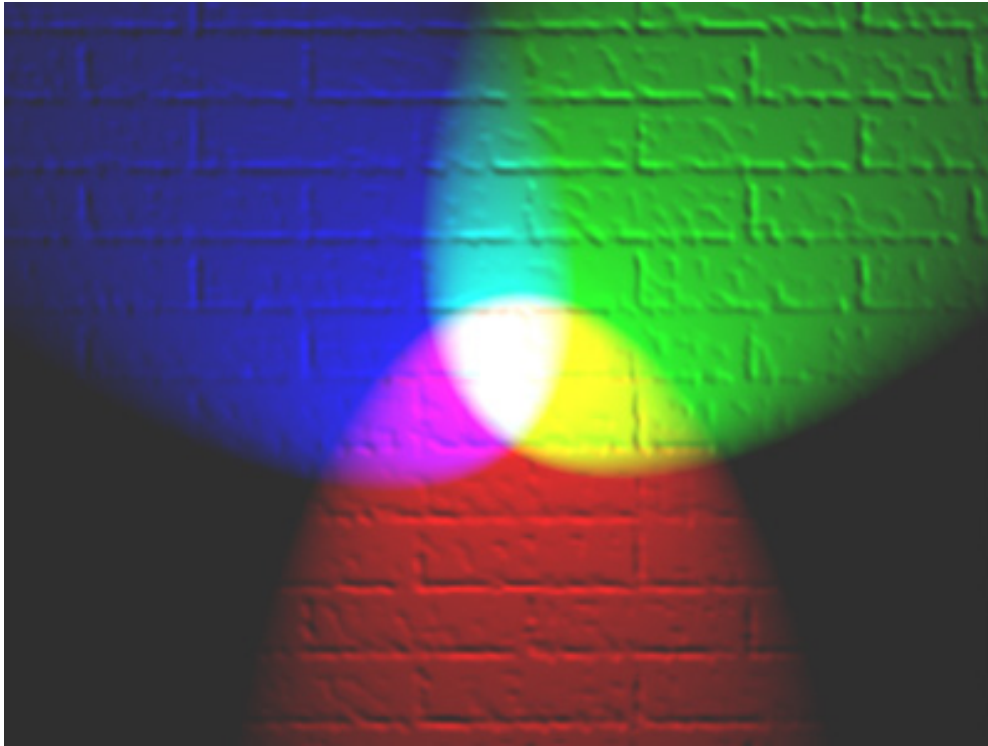
Diagram illustrating the representation of an RGB image as a 3D matrix. The main matrix is 10x10x3, with the first 10 columns representing the R-channel, the next 10 columns representing the G-channel, and the final 10 columns representing the B-channel. The matrix is labeled with 'row' (vertical arrow) and 'column' (horizontal arrow).

0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99	0.92	0.99	0.92	0.99	0.92	0.99	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91	0.95	0.91	0.97	0.95	0.95	0.91	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92	0.91	0.92	0.79	0.85	0.79	0.85	0.79	0.85
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95	0.45	0.33	0.45	0.33	0.45	0.33	0.45	0.33
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85	0.82	0.93	0.82	0.93	0.82	0.93	0.82	0.93
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93	0.93	0.97	0.93	0.97	0.93	0.97	0.93	0.97

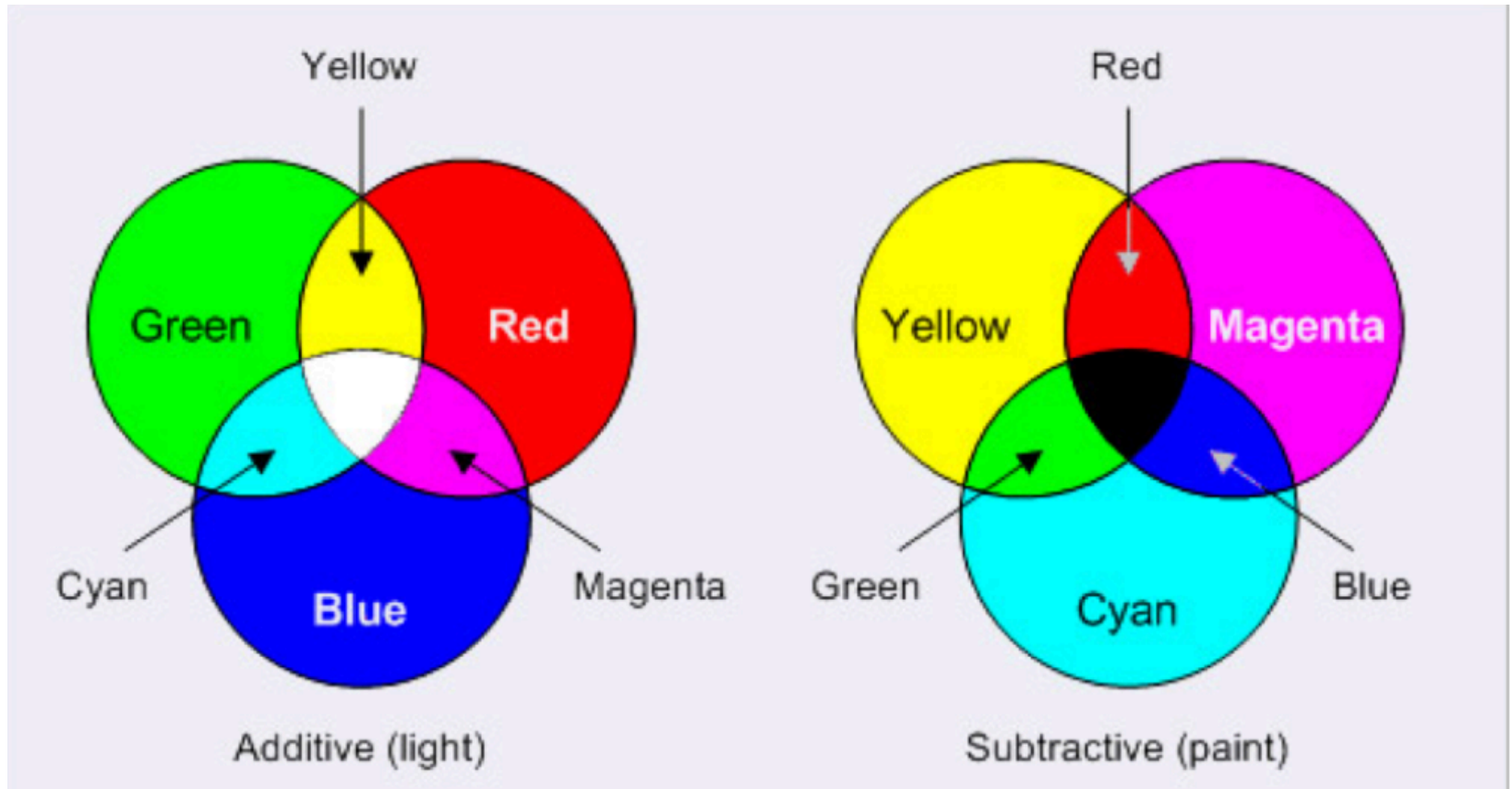
Color Representation

Color Spaces

How can we represent color?



Color Spaces: RGB vs. CMY(K)

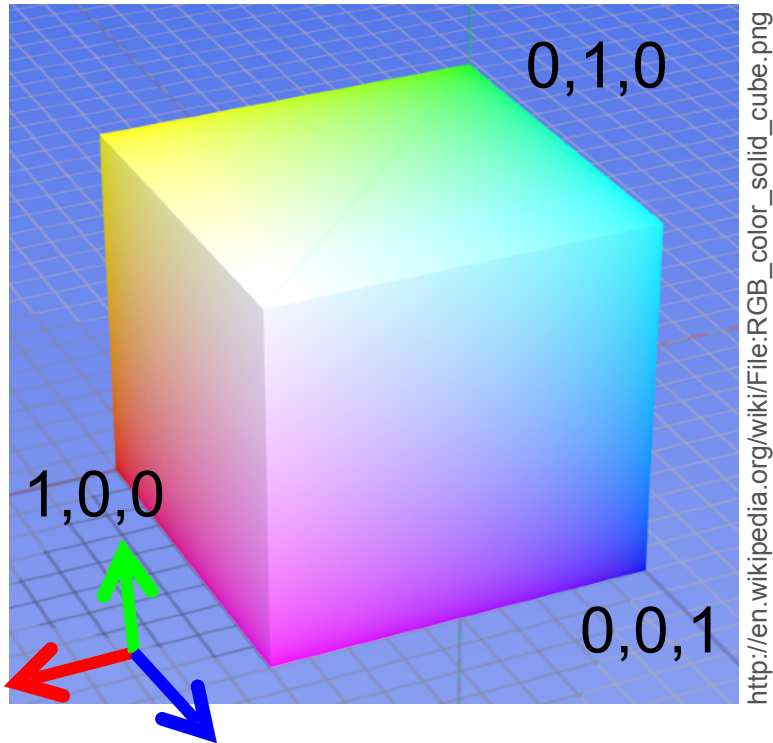


Source: <https://intranet.mcad.edu/kb/cmyk-vs-rgb-what-color-space-should-i-work>

Colored primary lights
(emission spectra sum)

Colored primary inks
(absorption spectra multiply)

Color Spaces: RGB



RGB cube - default color space

- 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)

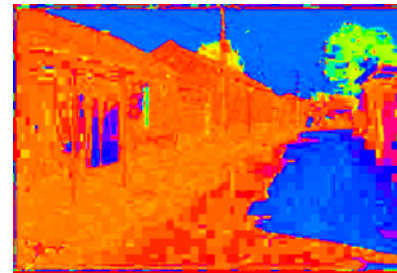


B
(R=0,G=0)

Color Spaces: RGB to HSV



RGB 2 HSV conversion with grid — VerbaGleb, Wikimedia Commons, CC BY-SA 4.0. Converted from Ogg/Theora to H.264/MP4; no visual changes.



H
(S=1,V=1)

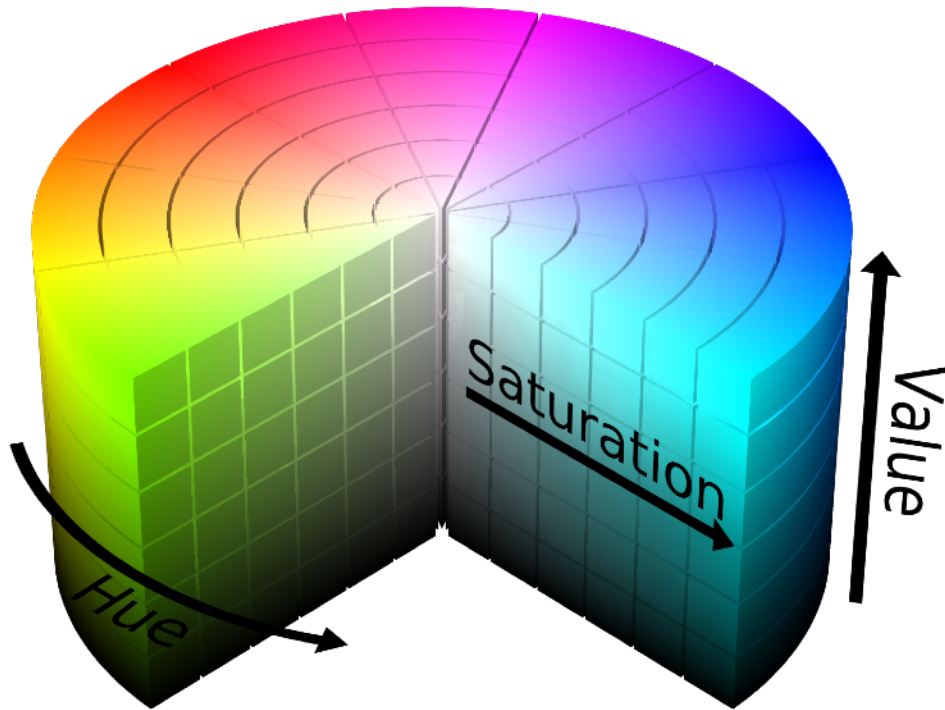


S
(H=1,V=1)



V
(H=1,S=0)

Color Spaces: HSV



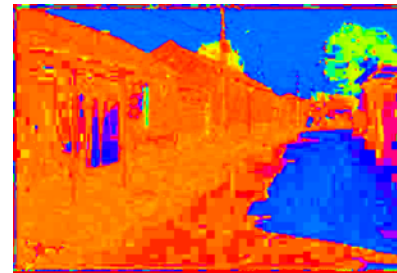
Source: https://commons.wikimedia.org/wiki/File:HSV_color_solid_cylinder.png, Datumizer

Hue, Saturation, Value (Intensity)

- RGB cube on its vertex

Decouples the three components (a bit)

Use `rgb2hsv()` and `hsv2rgb()`



H

(S=1,V=1)



S

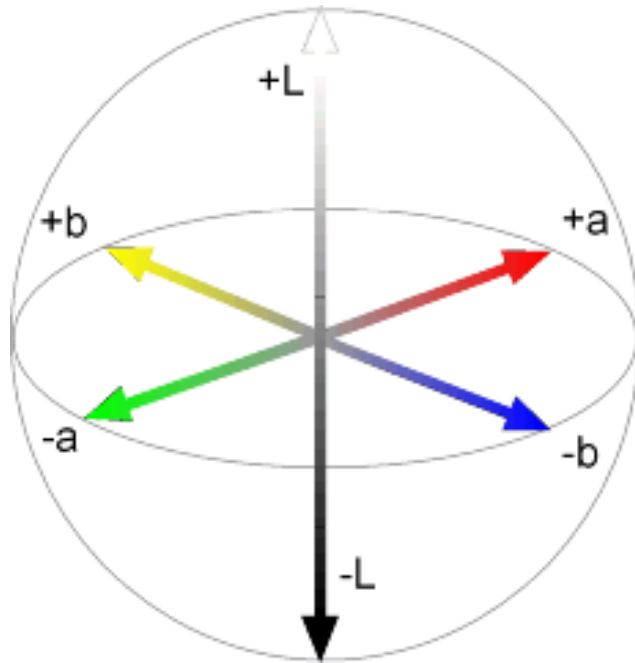
(H=1,V=1)



V

(H=1,S=0)

Color Spaces: CIELAB (AKA “Lab” or $L^*a^*b^*$)



A perceptually-organized color space that acts as a simple and useful color appearance model

- Chromatic adaptation (white balance)
- Predicts color appearance (hue, saturation, etc)
- Aims for perceptual uniformity (non-linear warping)
- Gives a useful color error metric



L^*
($a^*=0, b^*=0$)



a^*
($L=65, b=0$)



b^*
($L^*=65, a^*=0$)

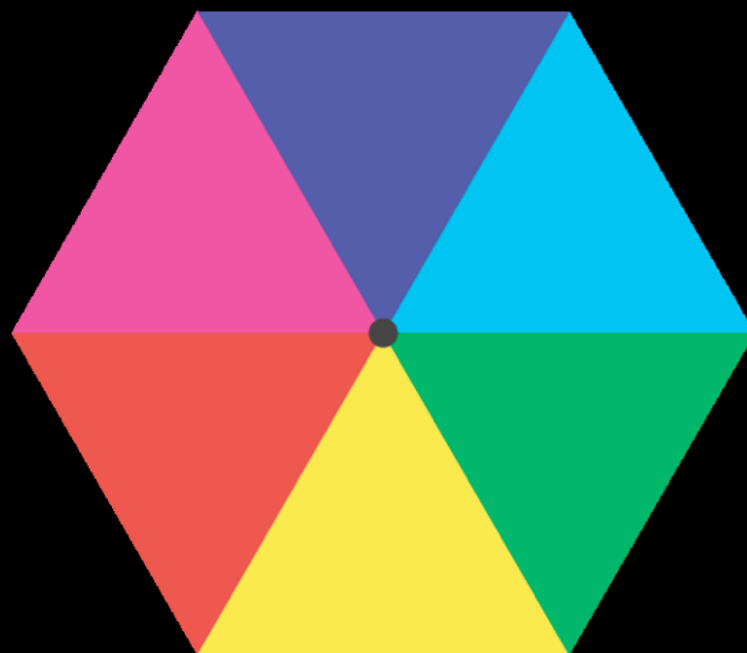
Perceptual Color Opponency







Image



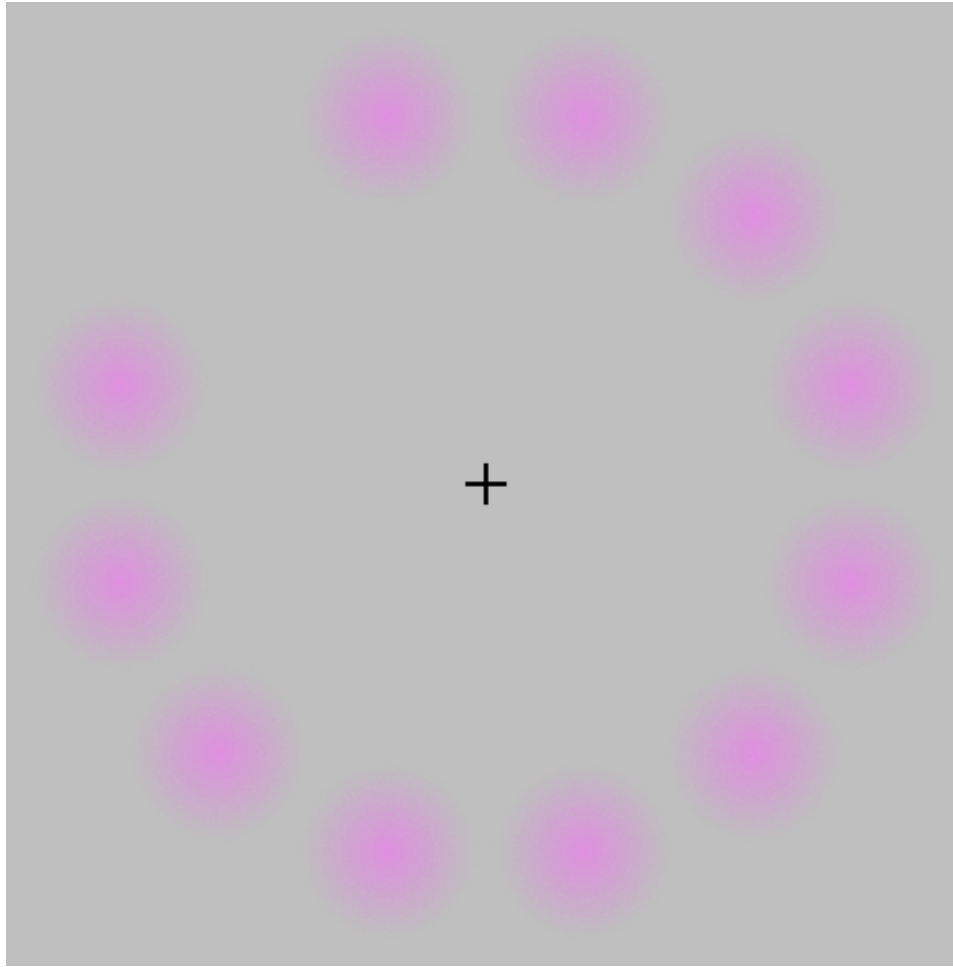
Afterimage



keep staring at the black dot.



Lilac Chaser Illusion

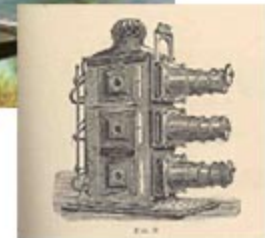


- After-image
- Troxler fading

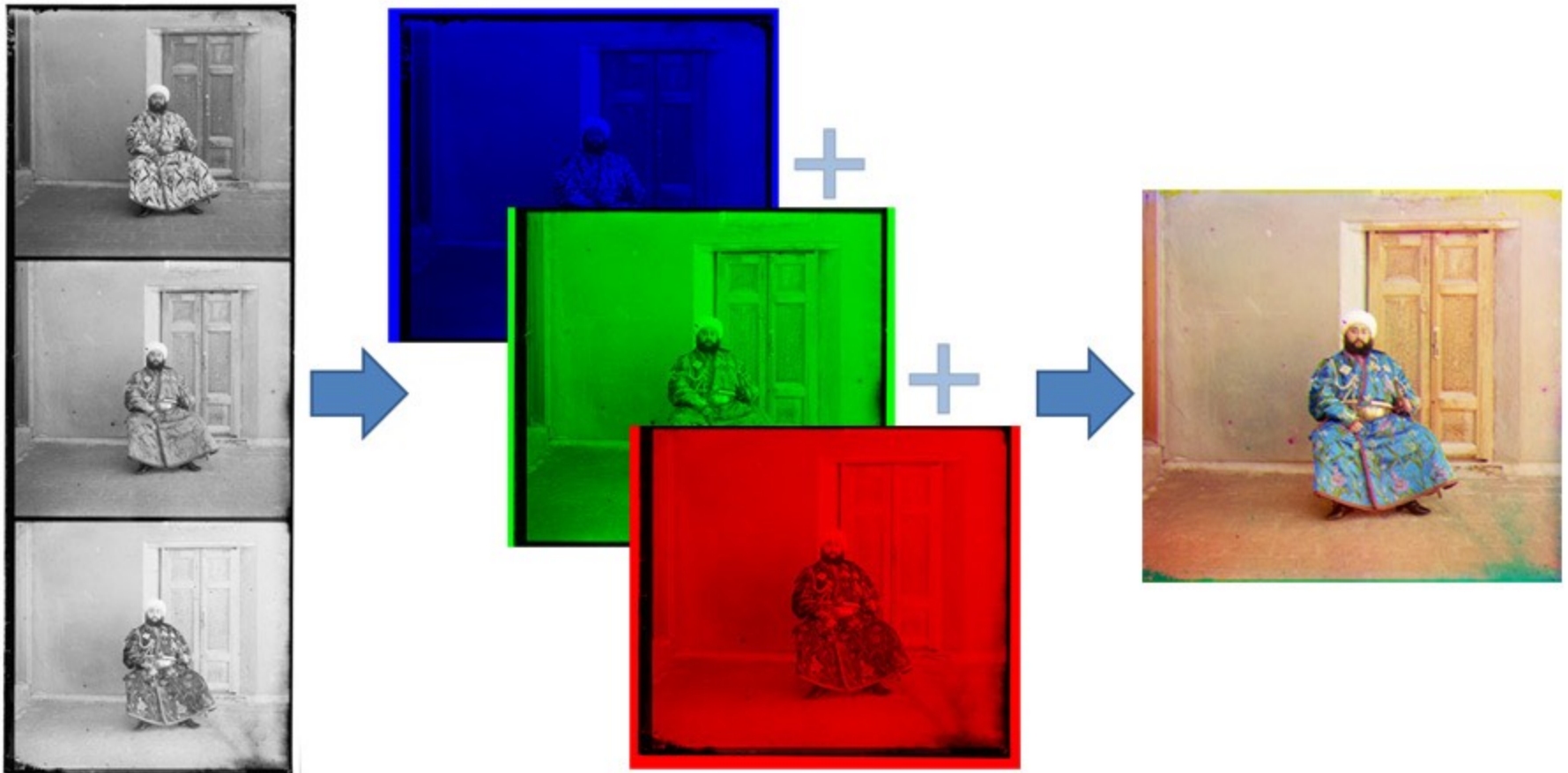
Programming Project #1

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
 - L2 norm / Euclidian Distance (sqrt dropped):

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

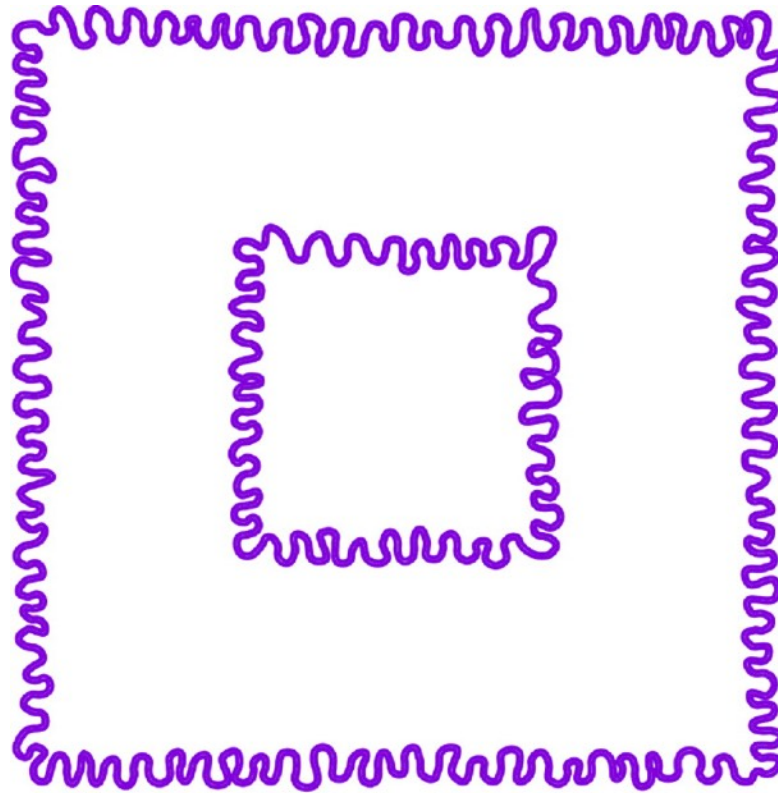
- Normalized Correlation (NCC):

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



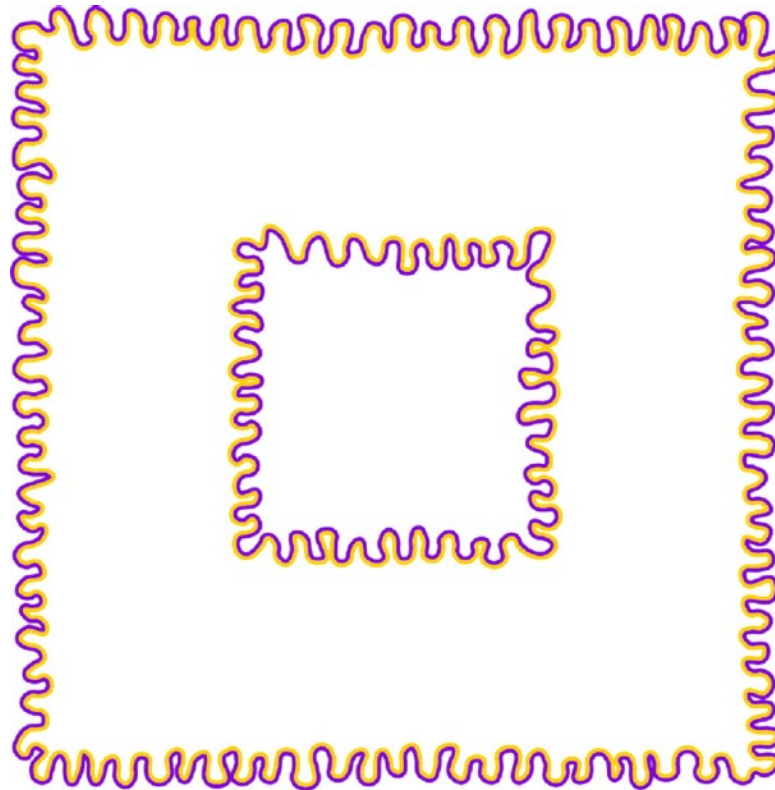
Weird and Wonderful Human Vision

Watercolor Illusion



Pinna & Tanca, *JOV*, 2008

Watercolor Illusion



Pinna & Tanca, *JOV*, 2008

Watercolor Illusion

