CSCE 448/748 – Computational Photography

Color

Nima Kalantari

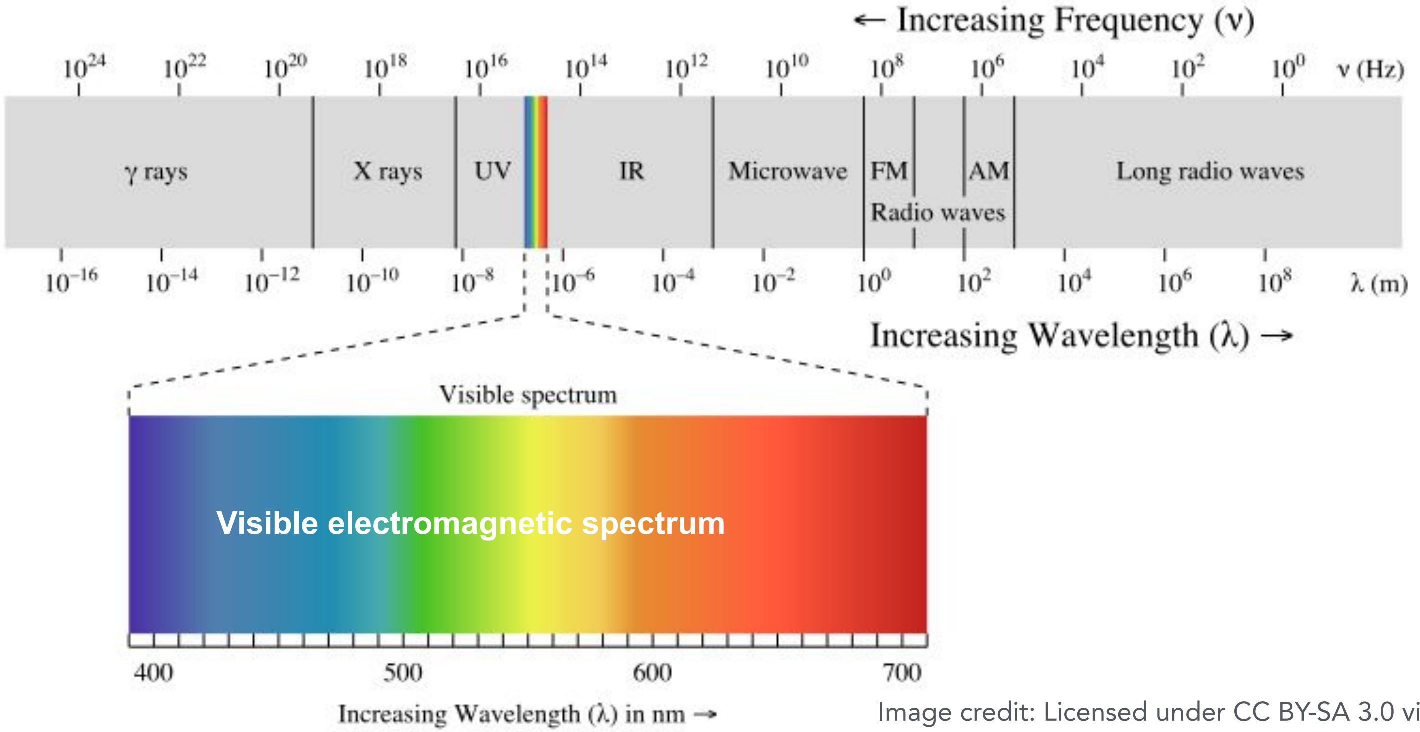
Many slides from Alexei A. Efros, James Hayes, Rob Fergus

Outline

- Physics of color
- Human visual system
- Color reproduction
- Color spaces
- Color in digital cameras

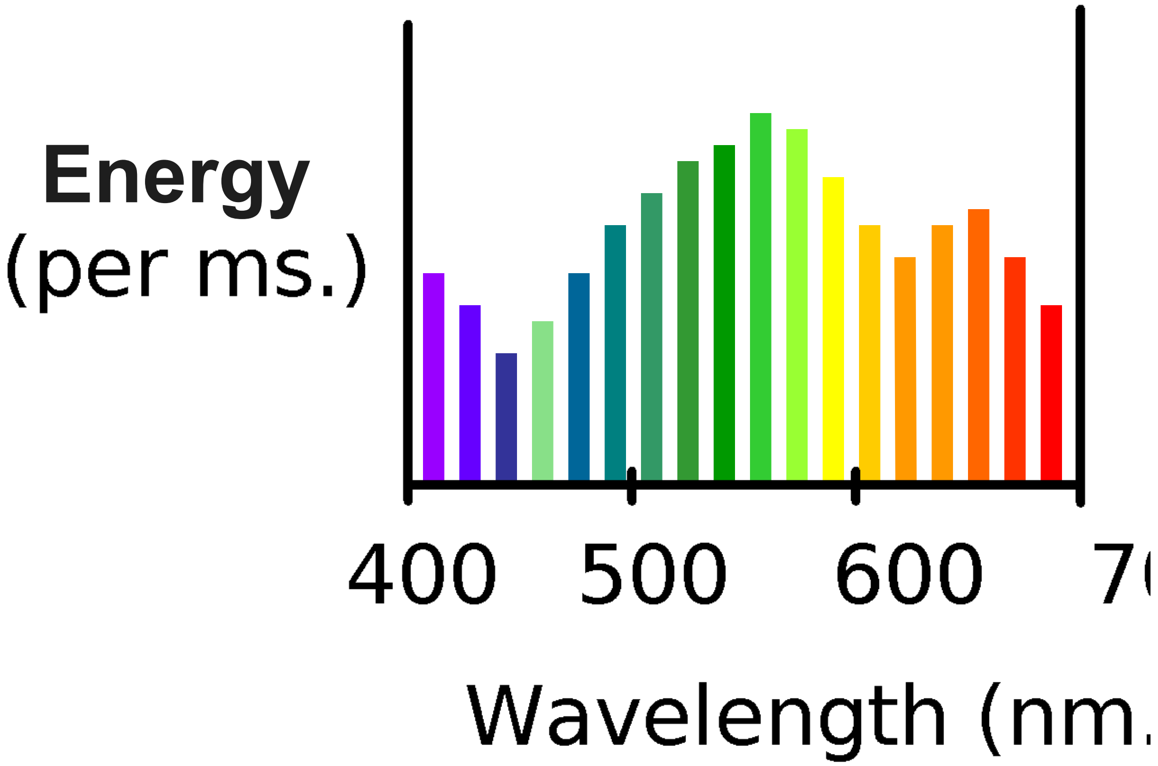
The Visible Spectrum of Light

- **Electromagnetic radiation**
  - **Oscillations of different frequencies (wavelengths)**

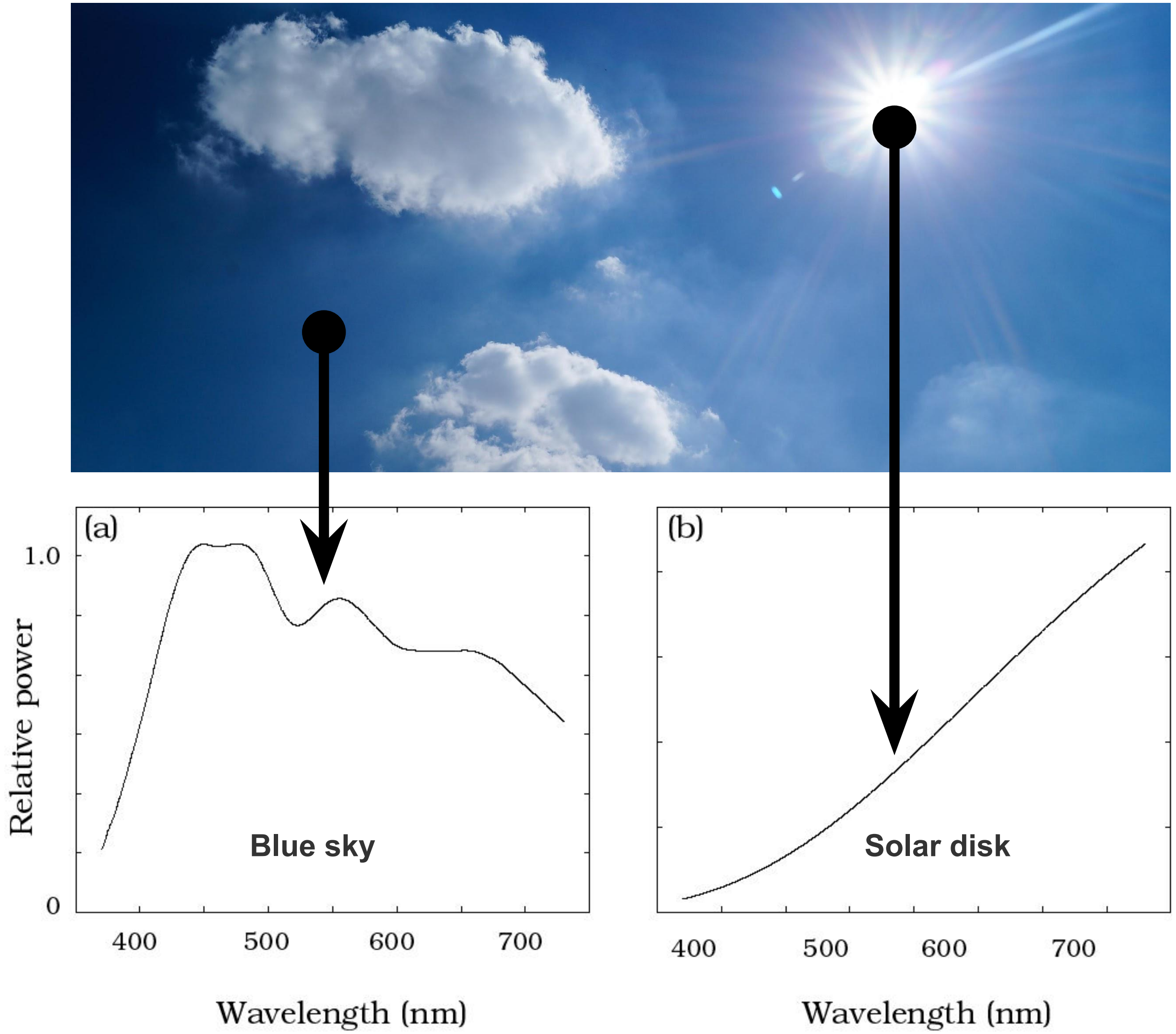


Spectral Power Distribution (SPD)

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



Daylight Spectral Power Distributions Vary



Spectral Power Distribution of Light Sources

- Describes distribution of energy by wavelength

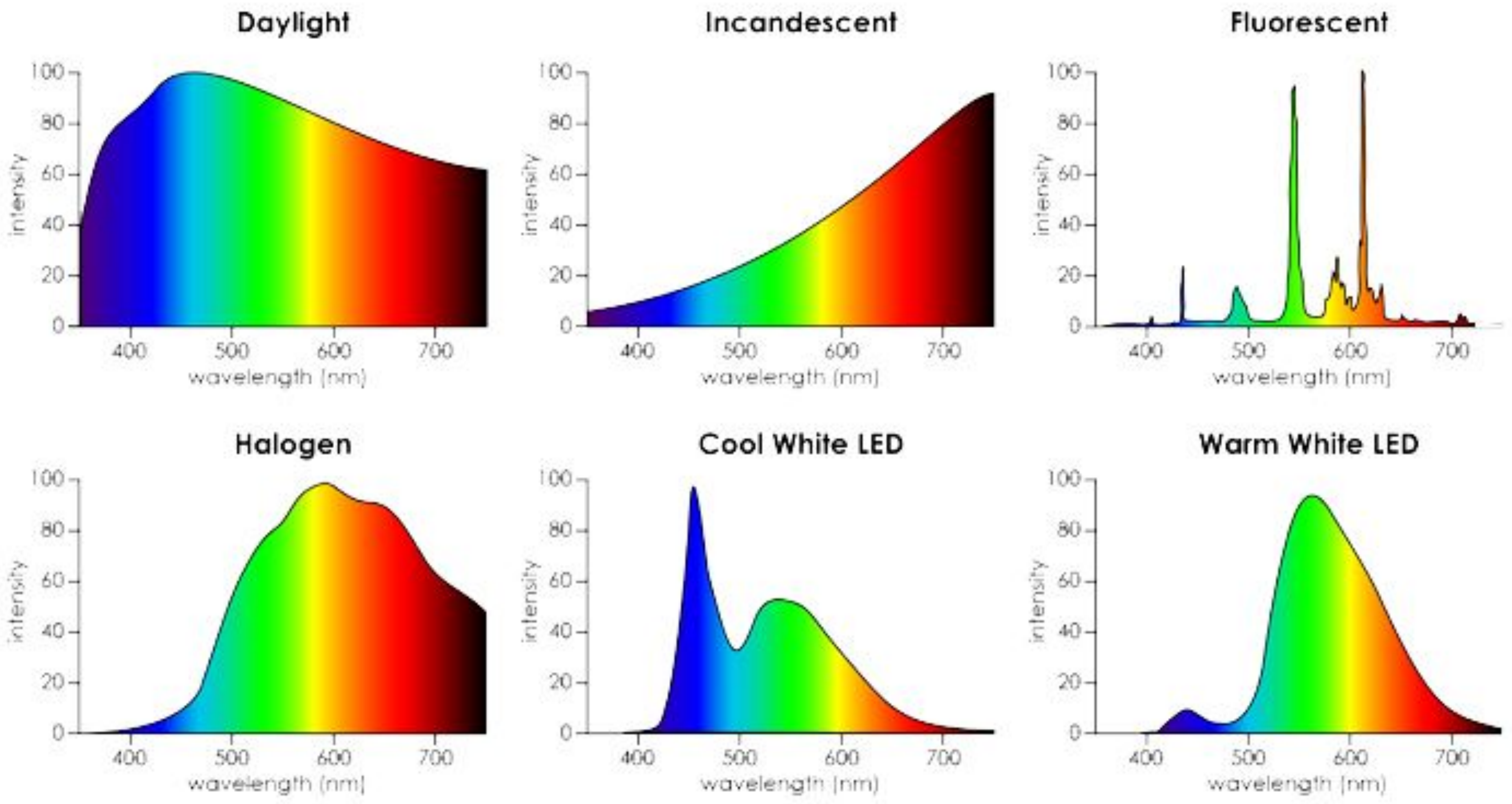
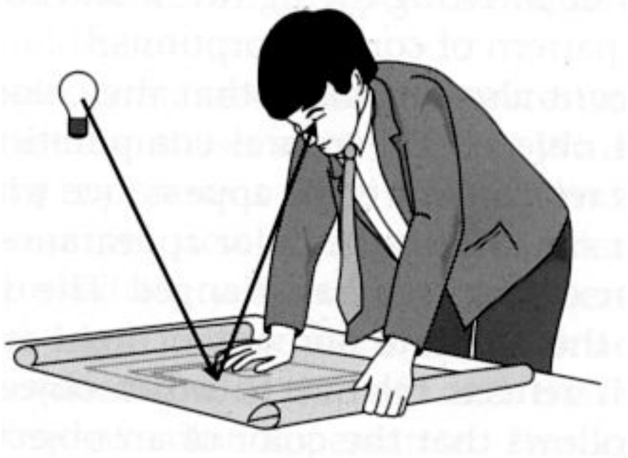
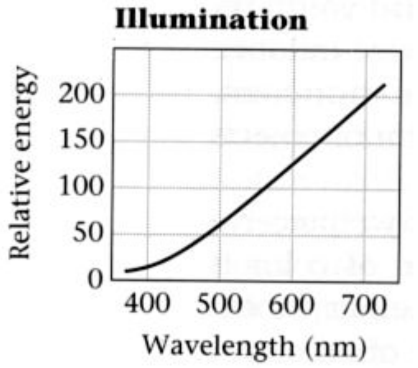


Figure credit:

What about surfaces?

Simplified rendering models: reflectance





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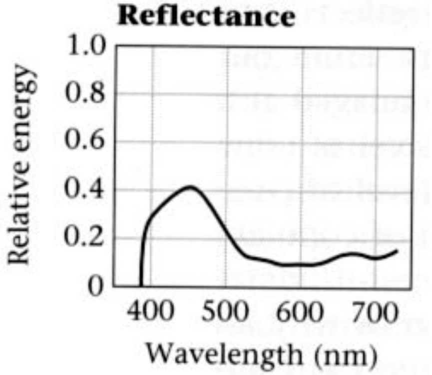

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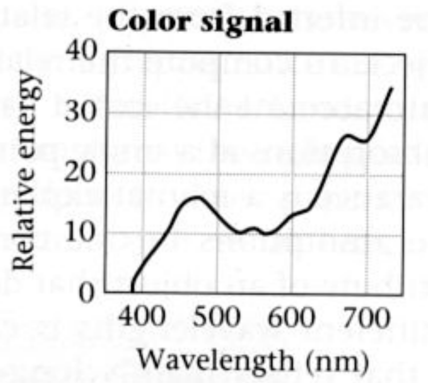
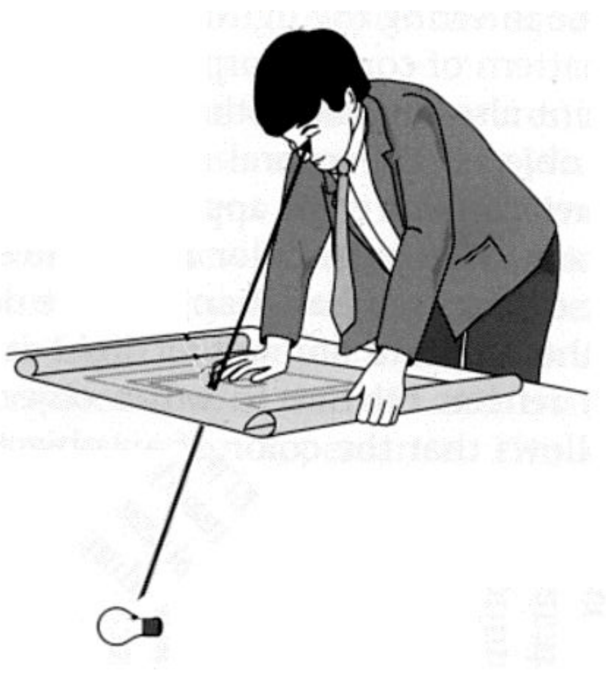
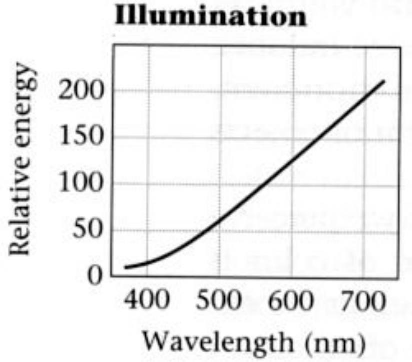


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Simplified rendering models: transmittance





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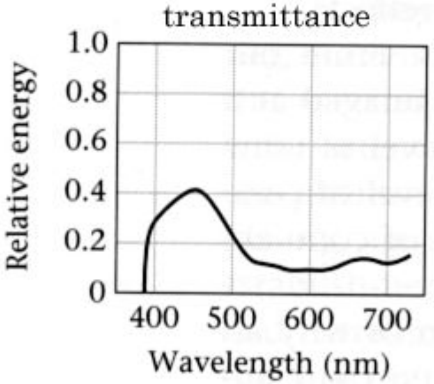

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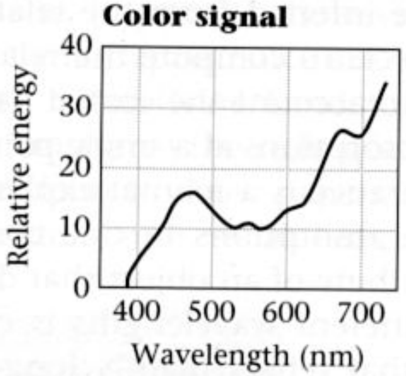
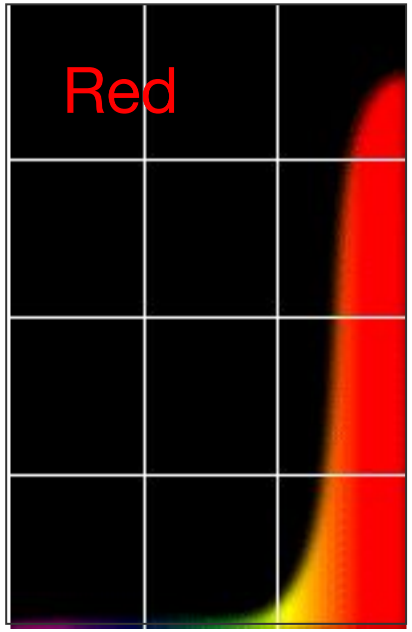
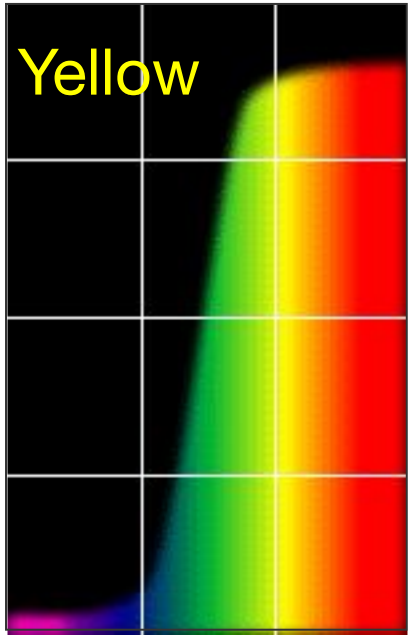
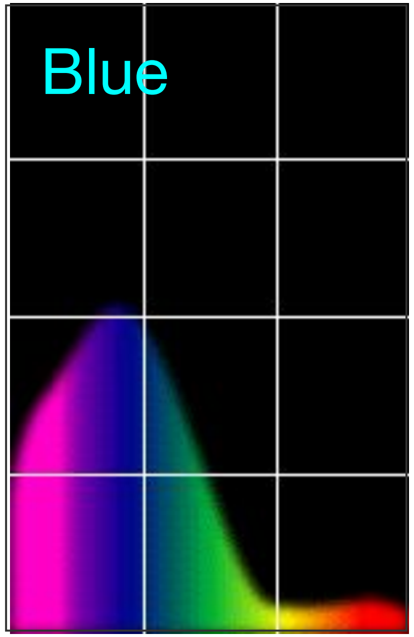


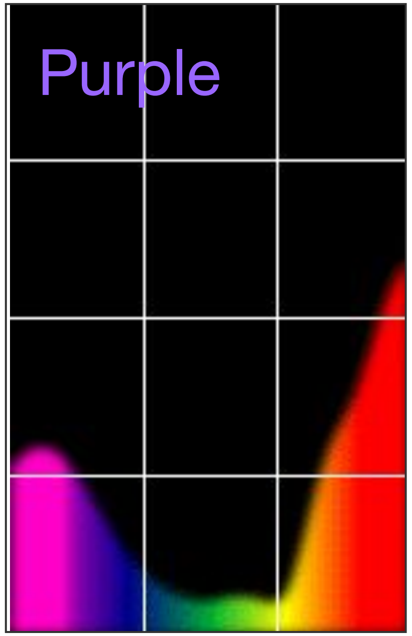
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Example reflectance spectra



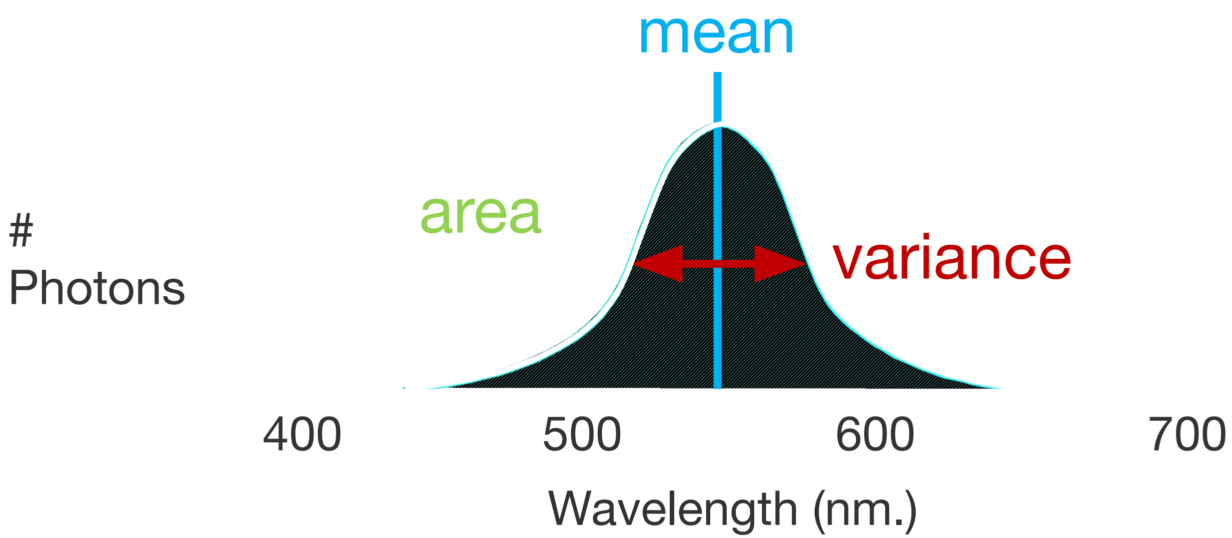






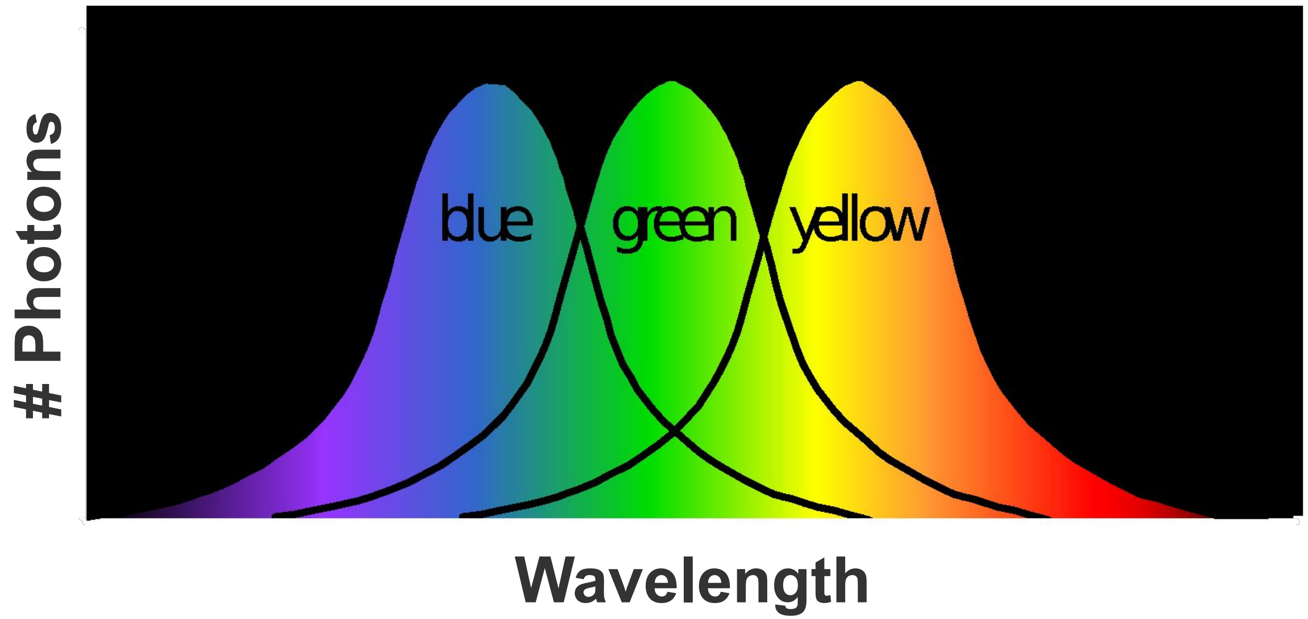
The psychophysical correspondence

- 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

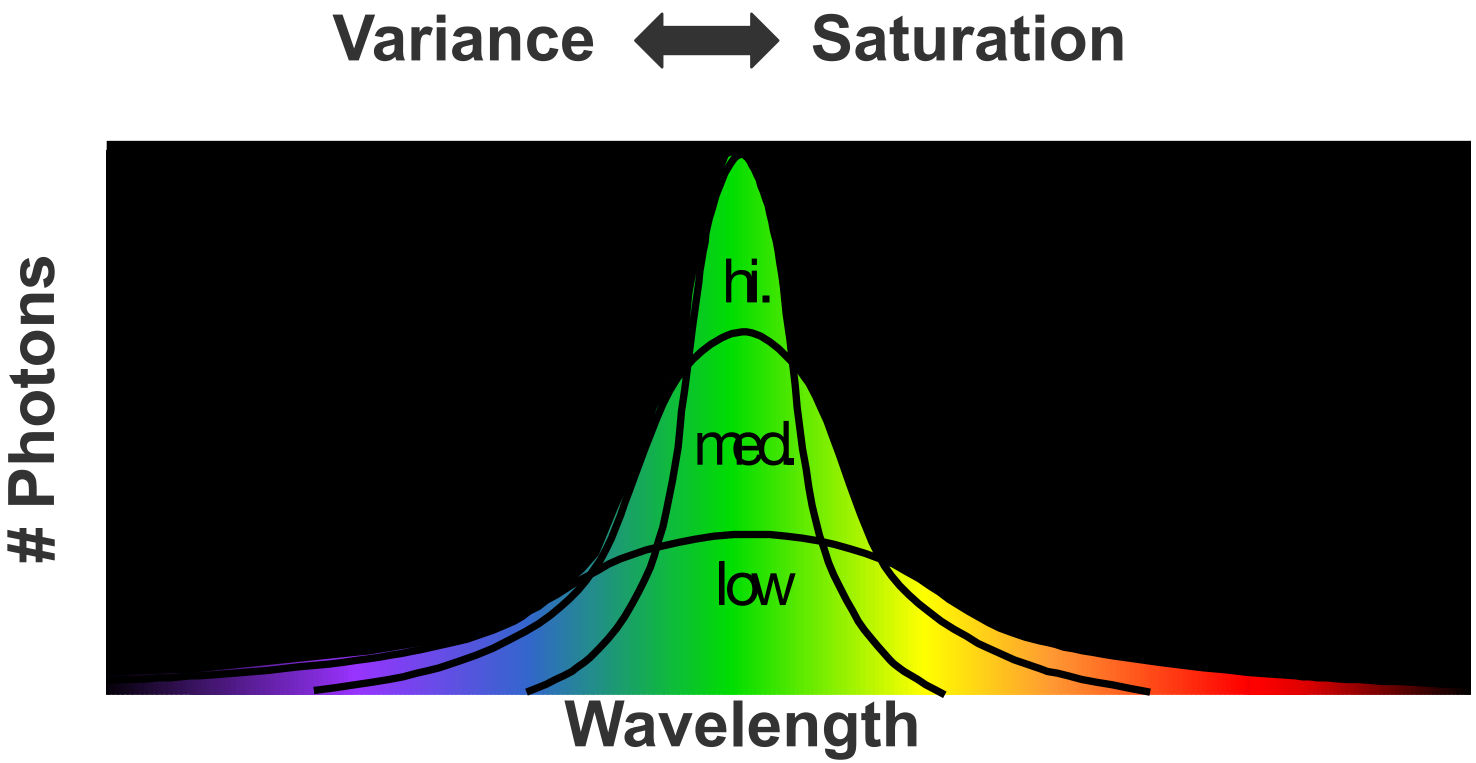


The psychophysical correspondence

Mean ⟷ Hue

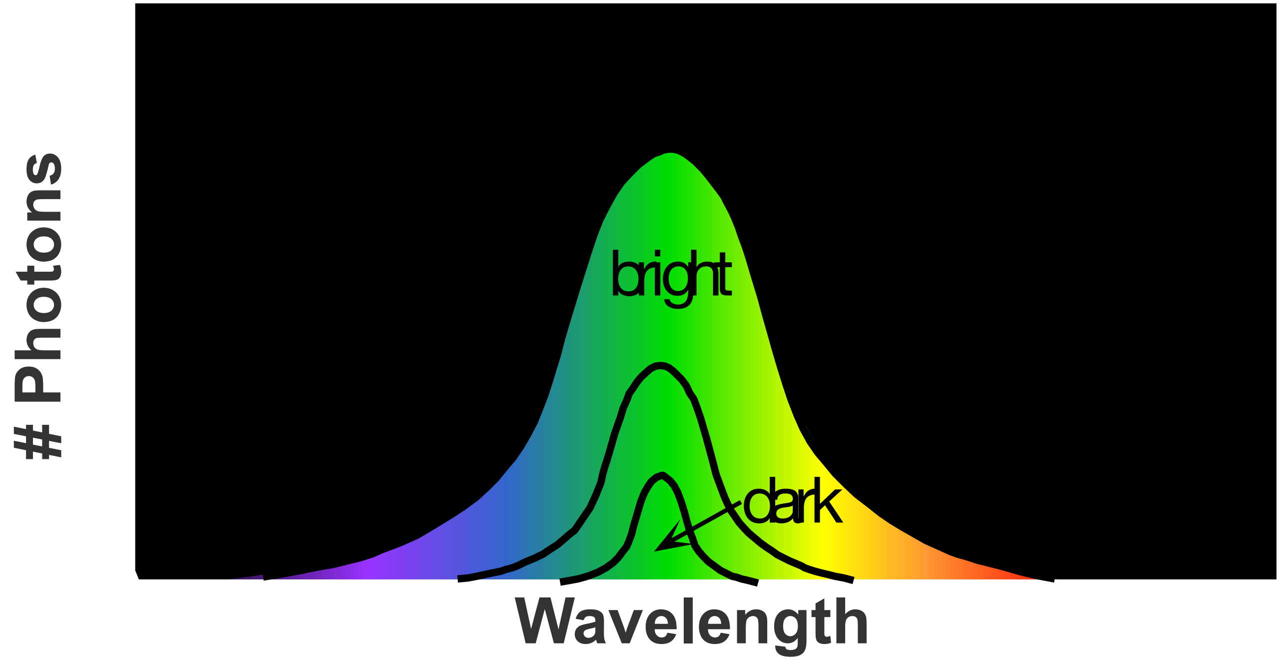


The psychophysical correspondence



The psychophysical correspondence

Area ⟷ Brightness



What is Color?

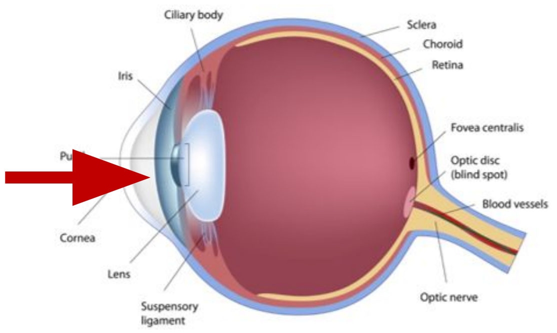
- Color is a phenomenon of human perception; it is not a universal property of light
- Colors are the perceptual sensations that arise from seeing light of different spectral power distributions
- Technically speaking, different wavelengths of light are not “colors”

Outline

- Physics of color
- Human visual system
- Color reproduction
- Color spaces
- Color in digital cameras

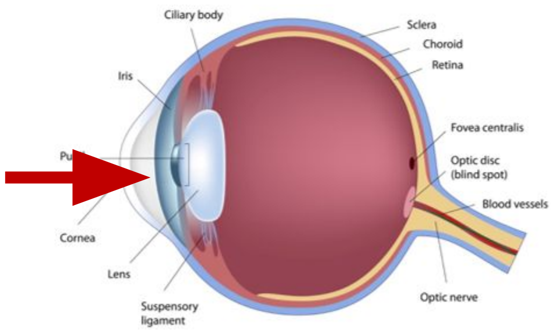
Main Parts of the Eye

- **Cornea**



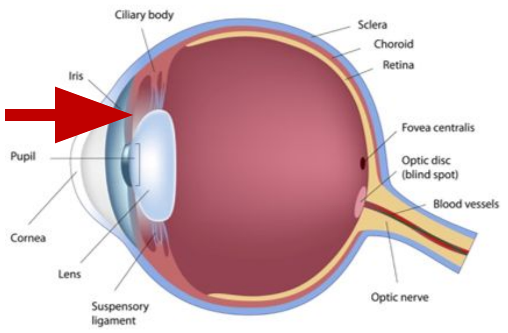
Main Parts of the Eye

- **Cornea**
  - **Provides most refraction**



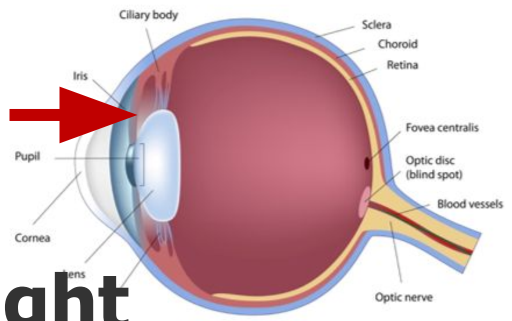
Main Parts of the Eye

- Cornea
- Iris

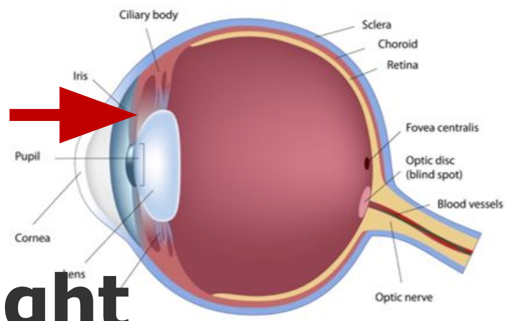


Main Parts of the Eye

- **Cornea**
- **Iris**
  - **Opens/Closes to let in more/less light**



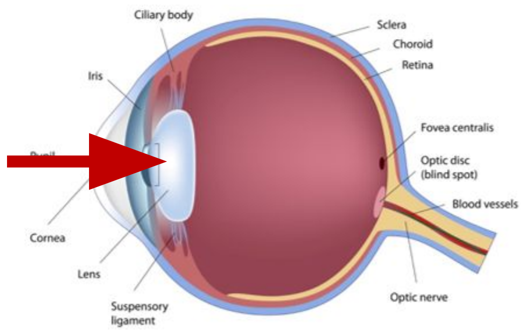
Main Parts of the Eye



- Cornea
- Iris
  - Opens/Closes to let in more/less light
  - Hole is the pupil

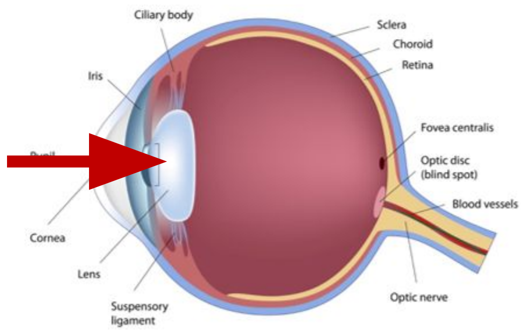
Main Parts of the Eye

- Cornea
- Iris
- Lens



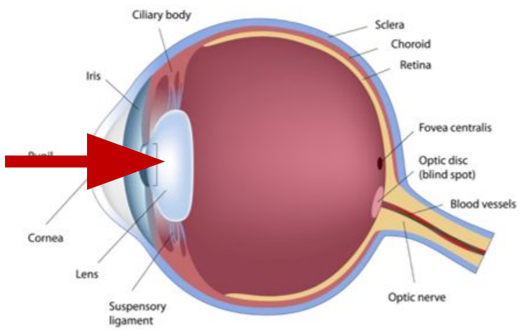
Main Parts of the Eye

- Cornea
- Iris
- Lens
  - Flexible - muscles adjust shape



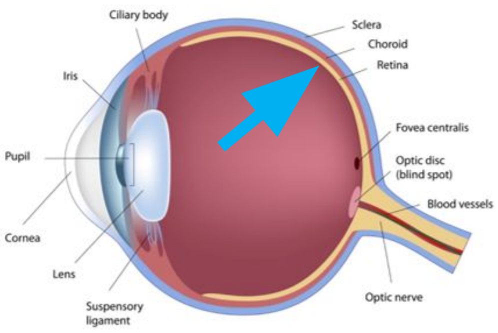
Main Parts of the Eye

- Cornea
- Iris
- Lens
  - Flexible - muscles adjust shape
  - Allows fine-detail focus



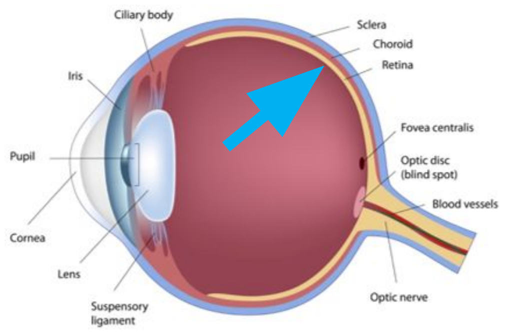
Main Parts of the Eye

- Cornea
- Iris
- Lens
- Retina



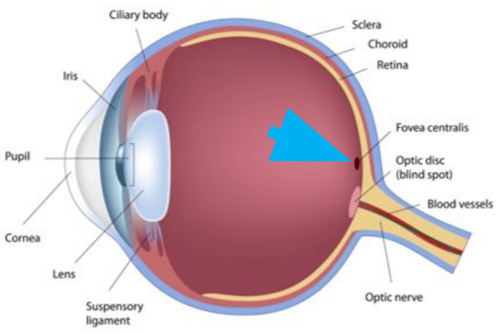
Main Parts of the Eye

- Cornea
- Iris
- Lens
- Retina
  - Layer of receptor cells at back of eye



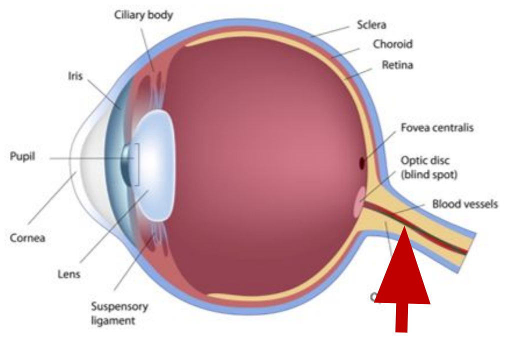
Main Parts of the Eye

- Cornea
- Iris
- Lens
- Retina
  - Layer of receptor cells at back of eye
  - Center of focus is the fovea

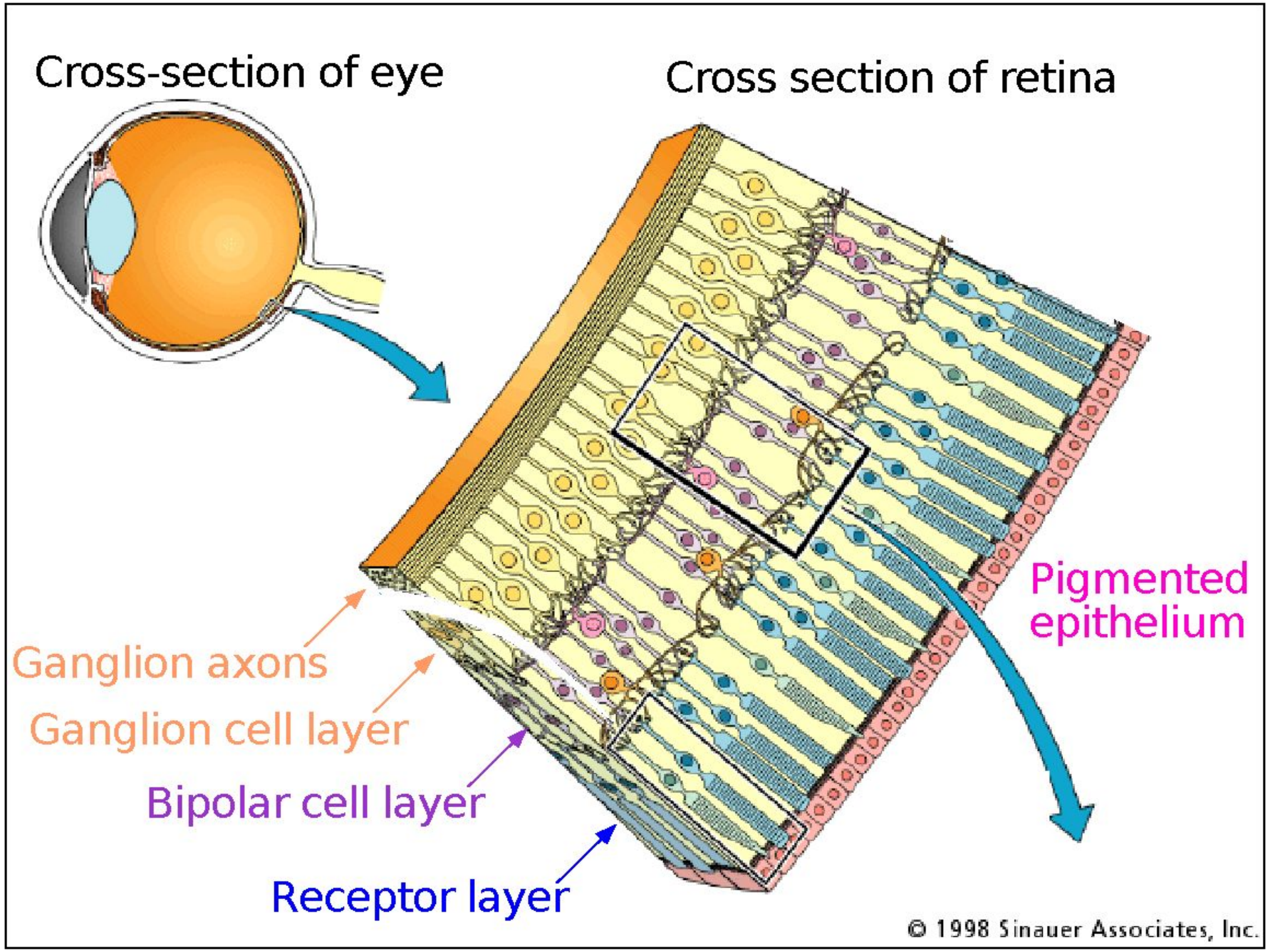


Main Parts of the Eye

- Cornea
- Iris
- Lens
- Retina
  - Layer of receptor cells at back of eye
  - Center of focus is the fovea
  - Optic nerve transfer information from retina to brain
    - Causes a blind spot!

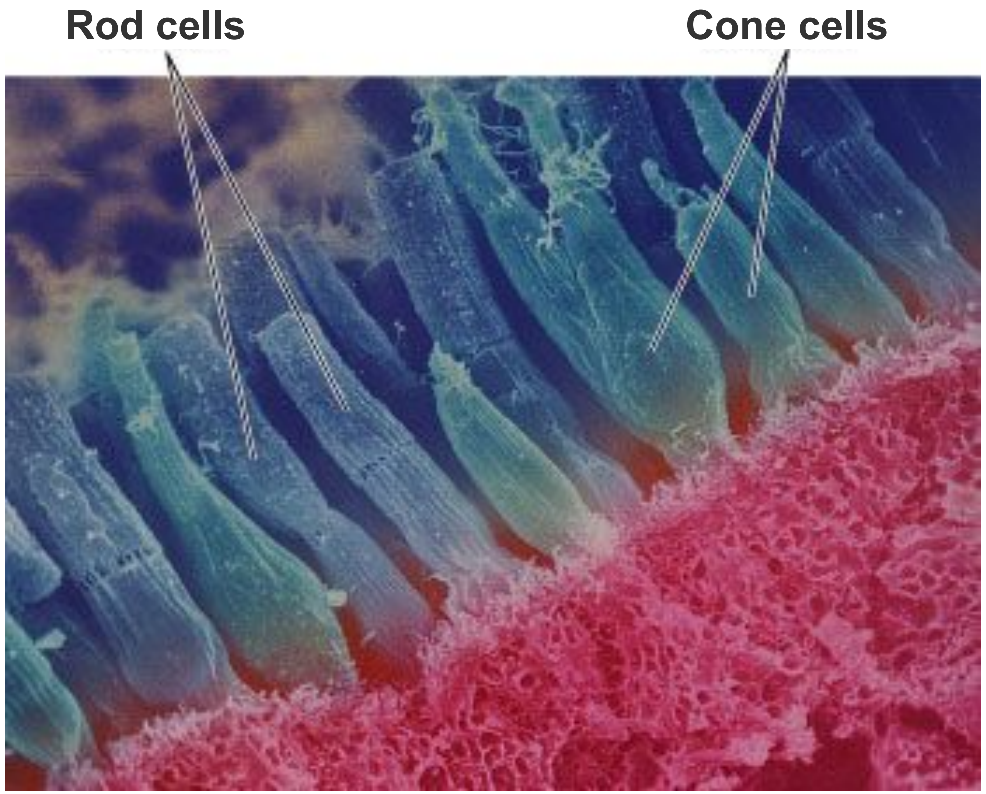


The Retina


Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.

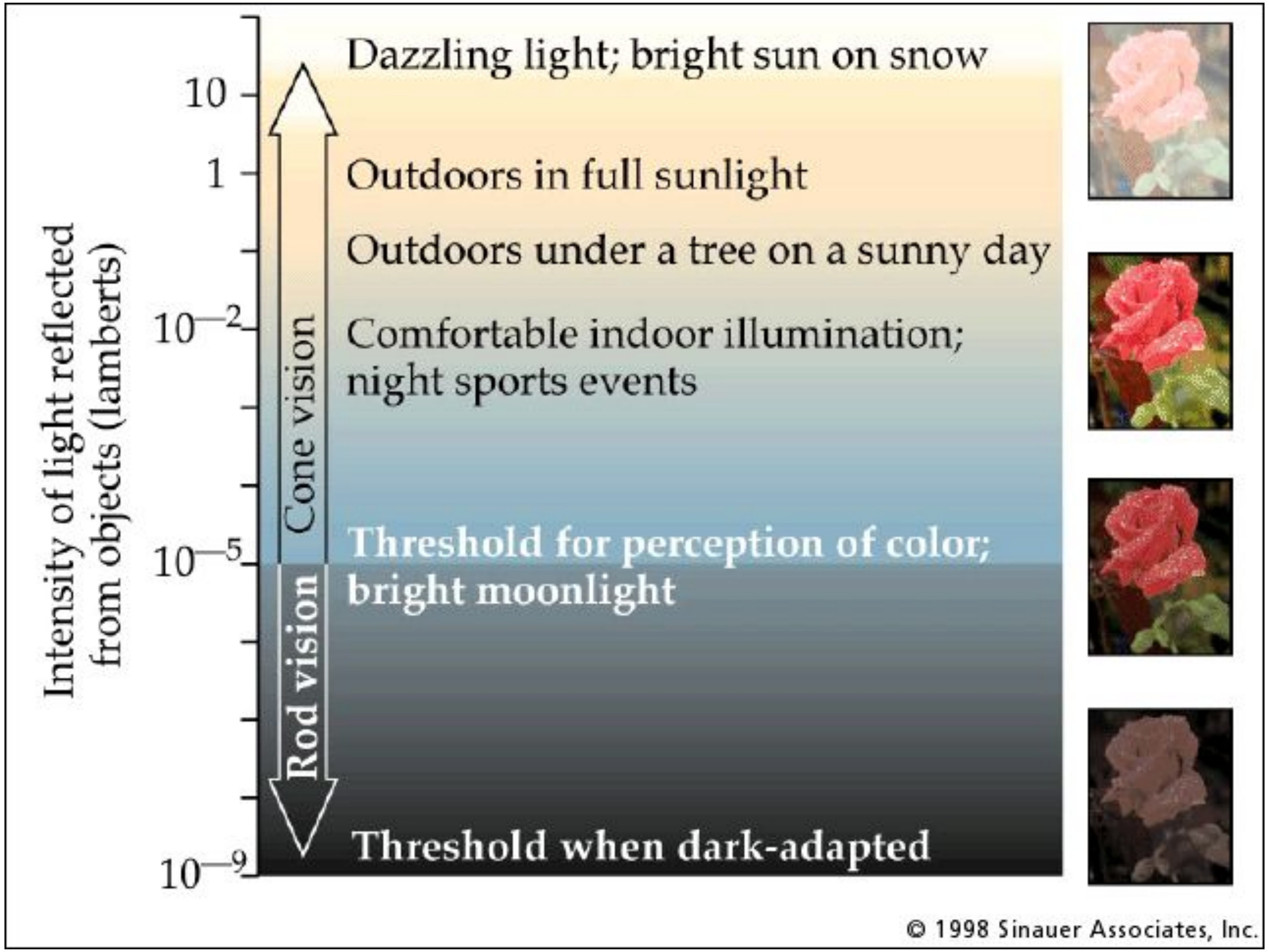
Retinal Photoreceptor Cells: Rods and Cones

- Cones
  - Less sensitive
  - Color vision
  - Operate in high light
- Rods
  - Very sensitive
  - Operate in low light
  - Grayscale vision

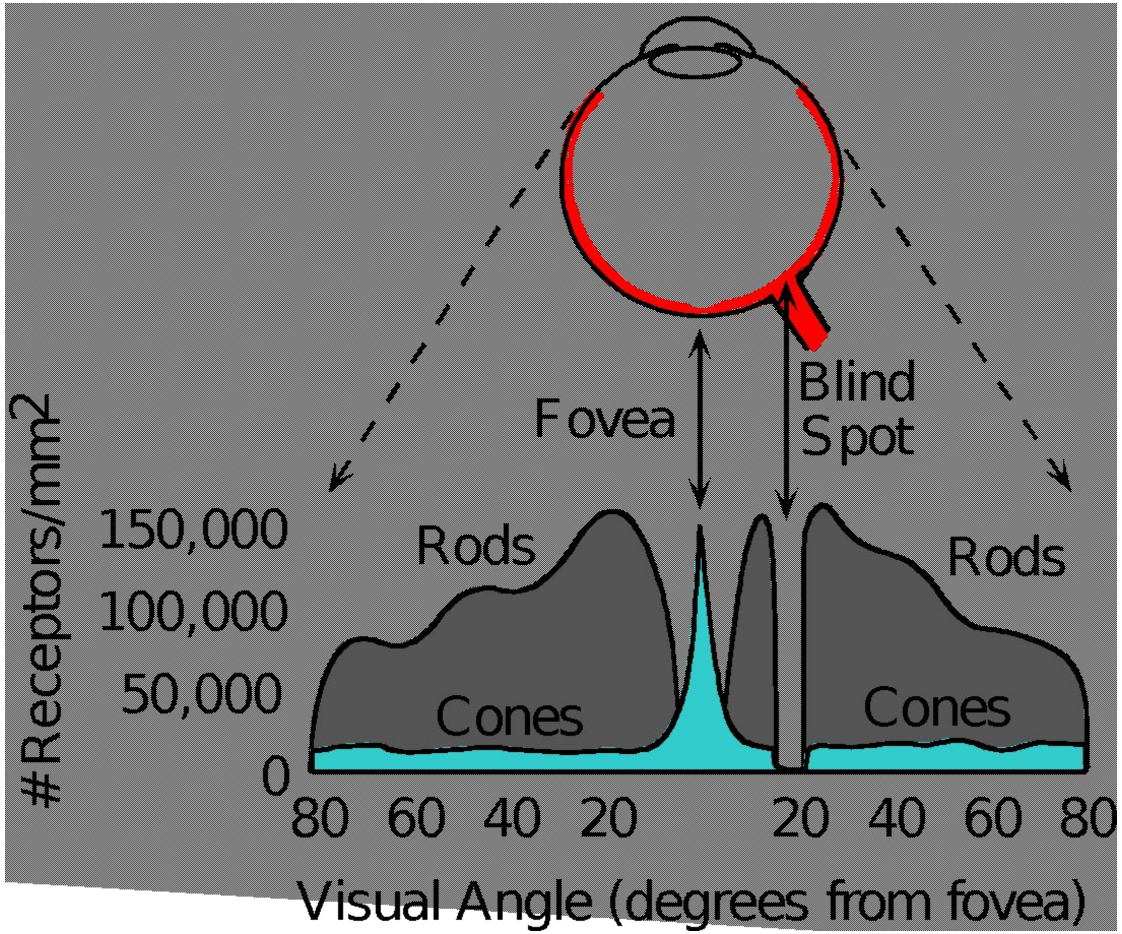


http://ebooks.bfwpub.com/life.php Figure 45.18

Rod / Cone sensitivity



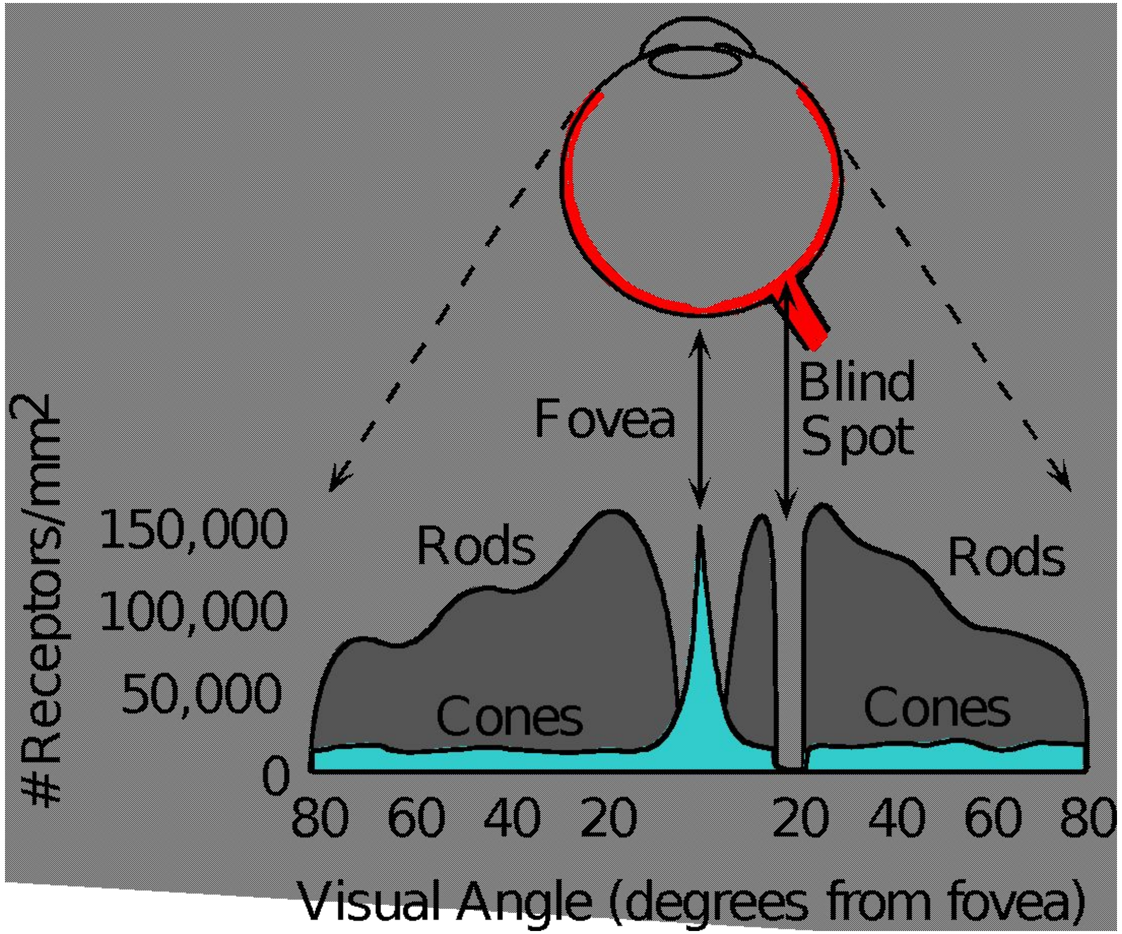
Distribution of Rods and Cones



Blind spot test

From Eric Chudler

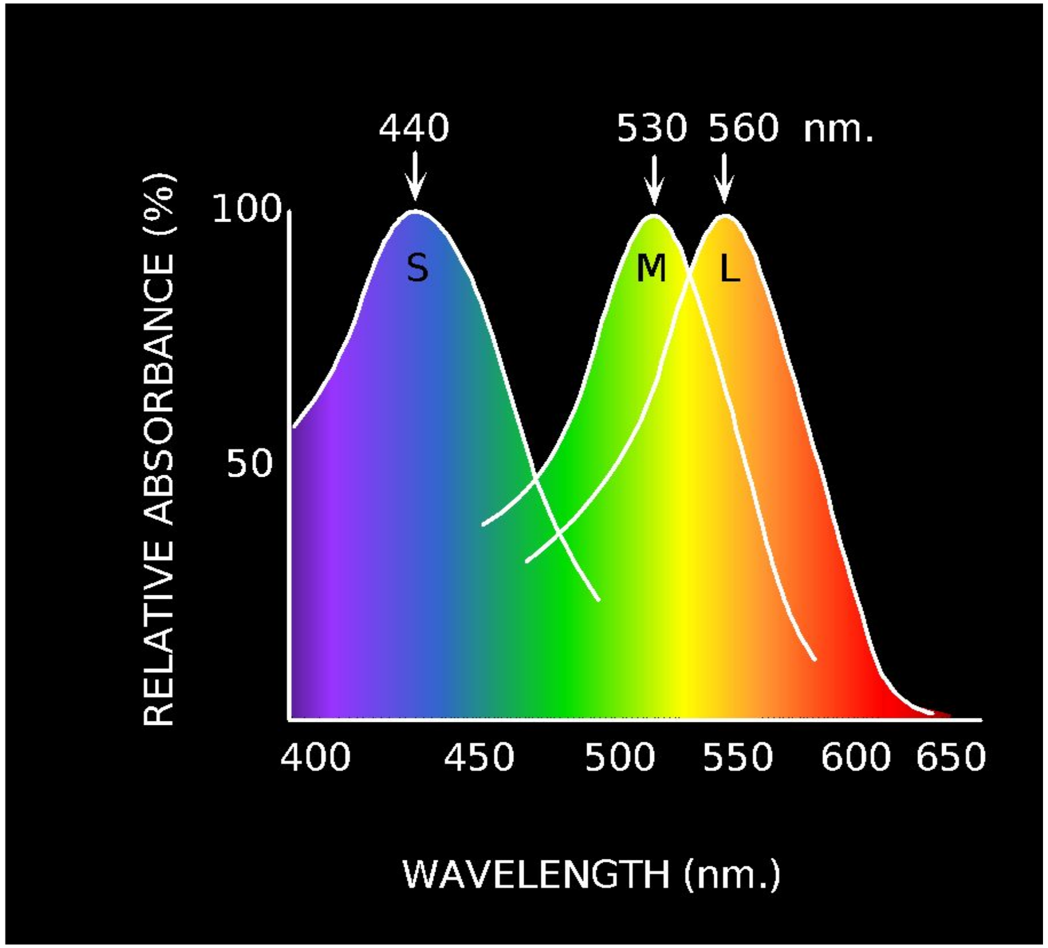
Distribution of Rods and Cones

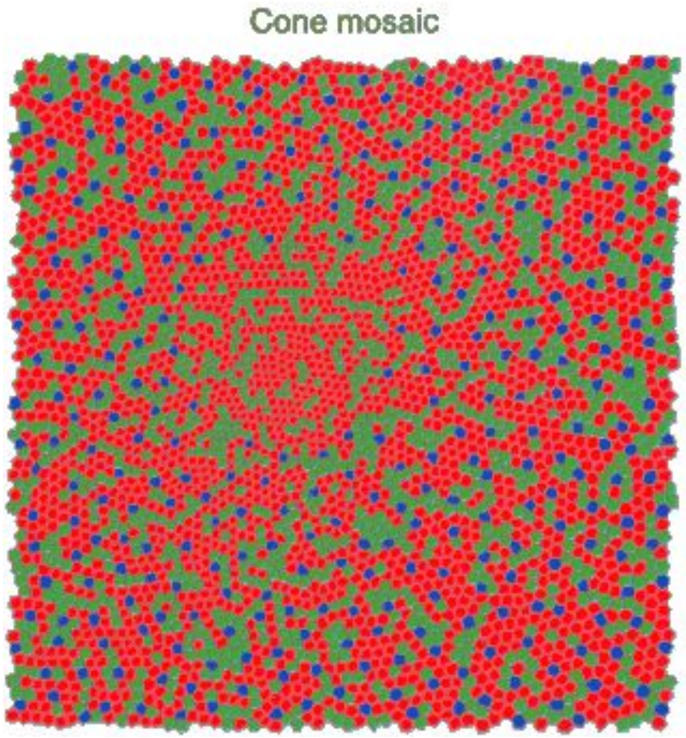


Night Sky: why are there more stars off-center?
Averted vision: http://en.wikipedia.org/wiki/Averted_vision

Different Types of Cones

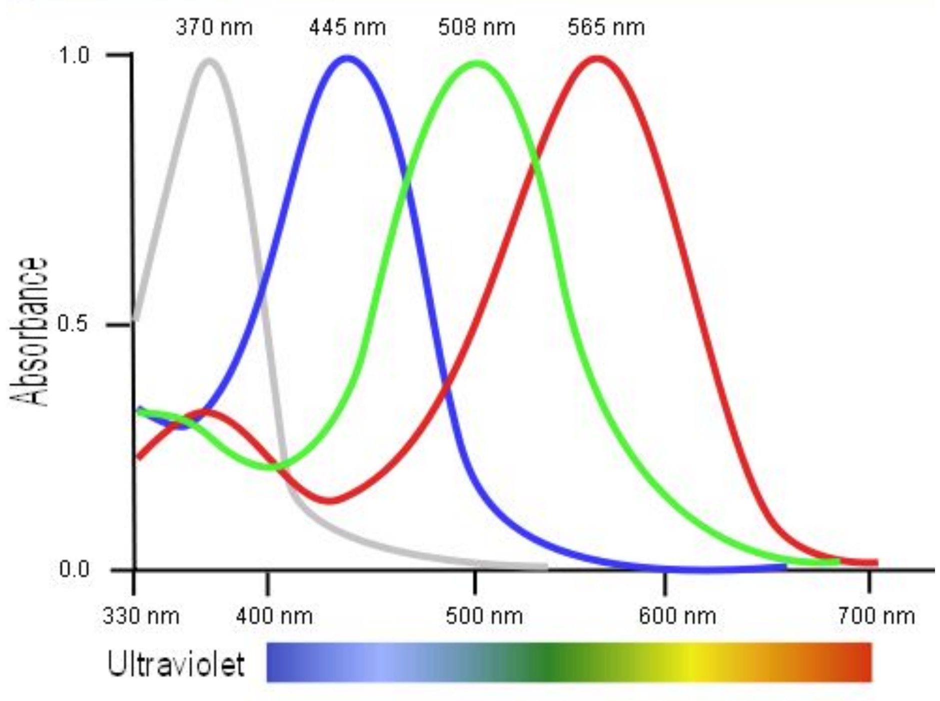
Three kinds of cones:





Tetrachromatism

- Most birds, and many other animals, have cones for ultraviolet light
- Some humans, mostly female, seem to have slight tetrachromatism



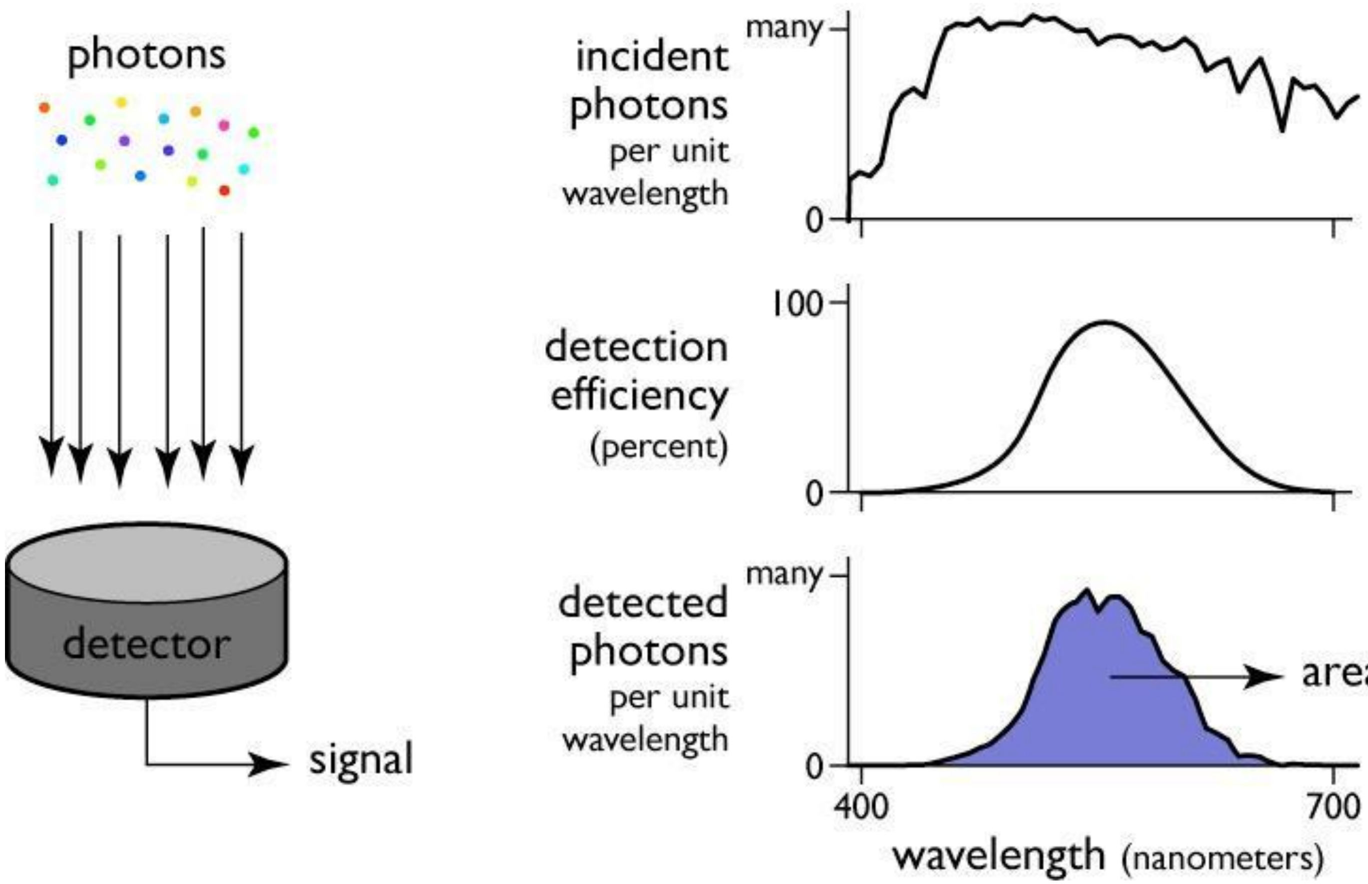
Bird cone responses

Going back to human…

- We have three types of cones
- Each type is a light receptor with specific sensitivity

Measuring Light

A Simple Model of a Light Detector



$n(\lambda)$

$p(\lambda)$

Credit: Marschner

$$X = \int n(\lambda)p(\lambda)\,d\lambda$$

Mathematics of Light Detection

- **Same math carries over to spectral power distributions**
  - **Light entering the detector has its SPD, s(λ)**
  - **Detector has its spectral sensitivity or spectral response, r(λ)**

$$X = \int s(\lambda) r(\lambda)\, d\lambda$$

measured signal

detector's sensitivity

input spectrum

Dimensionality Reduction From ∞ to 1

- At the detector:
  - SPD is a function of wavelength
    - ∞ dimensional signal
  - Detector result is a scalar value
    - 1 dimensional signal

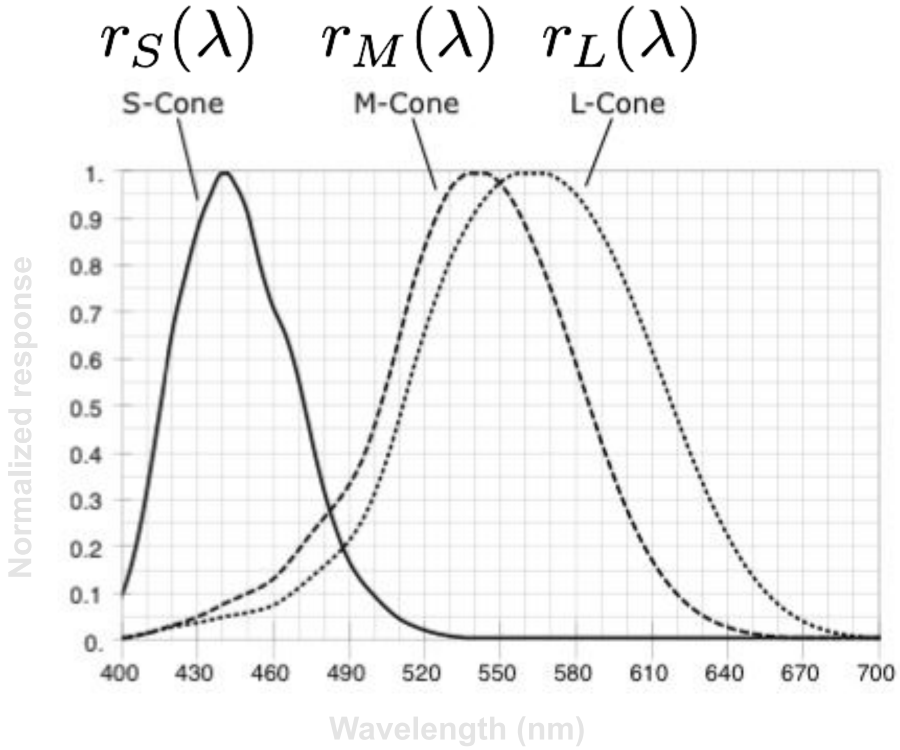
Spectral Response of Human Cone Cells

- Instead of one detector as before, now we have three detectors (S, M, L cone cells), each with a different spectral response curve

$$S = \int r_S(\lambda)s(\lambda)\,d\lambda$$

$$M = \int r_M(\lambda)s(\lambda)\,d\lambda$$

$$L = \int r_L(\lambda)s(\lambda)\,d\lambda$$

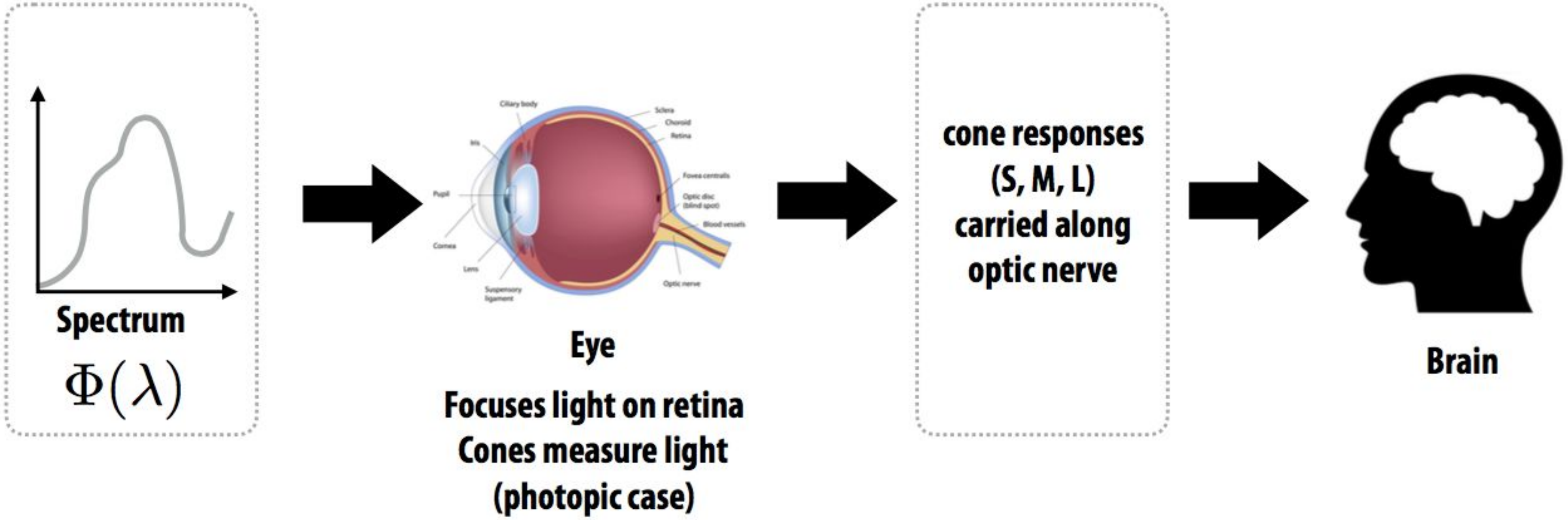


Dimensionality Reduction From ∞ to 3

- At each position on the human retina:
  - SPD is a function of wavelength
    - ∞ dimensional signal
  - 3 types of cones near that position produce three scalar values
    - 3 dimensional signal

The Human Visual System

- Human eye does not measure each wavelength of light
  - Brain does not receive info about each wavelength
- Eye measures three response values only (S, M, L)
  - Three quantities at each position of visual field available to brain

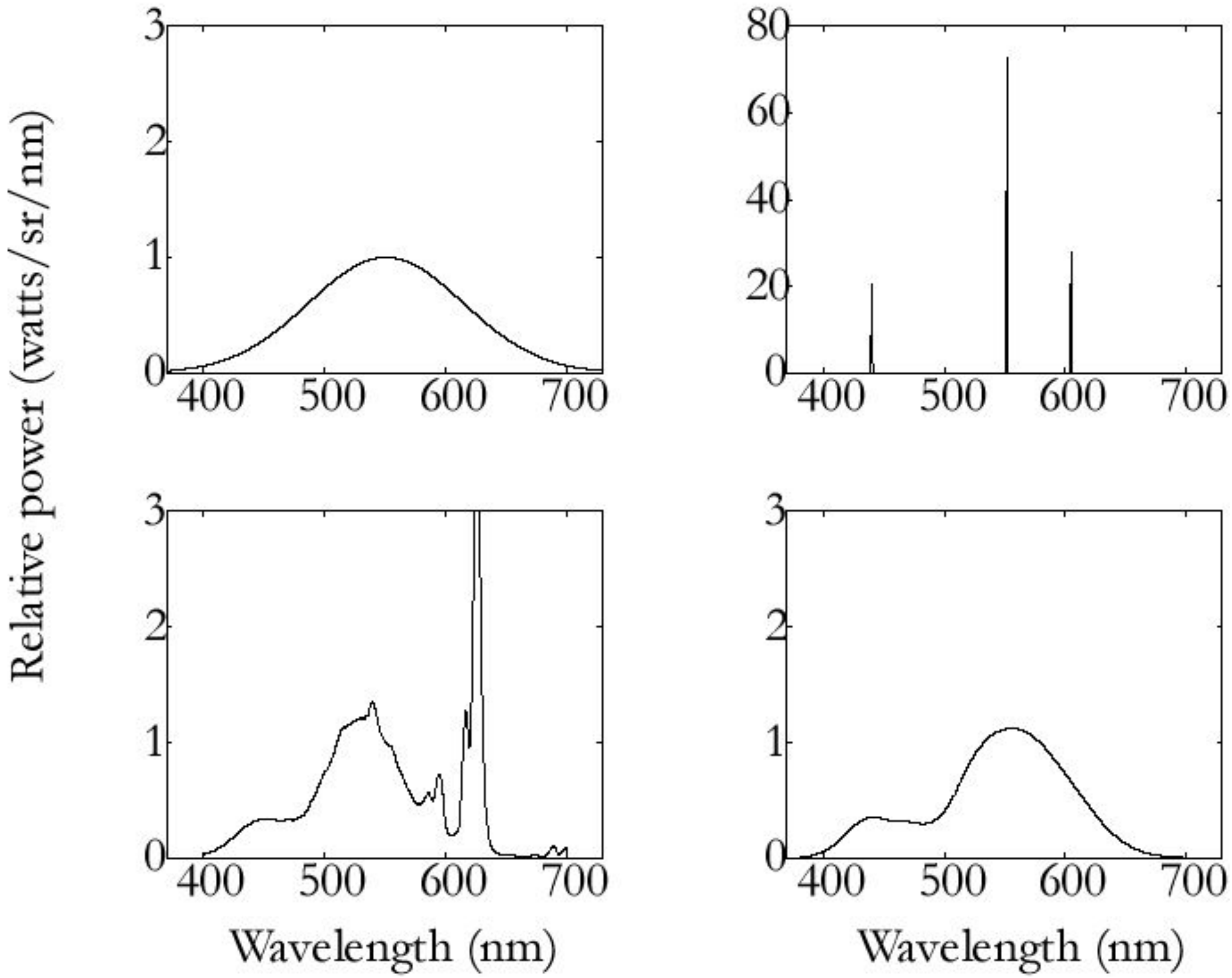


Kayvon Fatahalian

Metamers

- Metameters are two different spectra (∞-dim) that project to the same (S,M,L) (3-dim) response
  - These will appear to have the same color to a human

Metamerism is a Big Effect

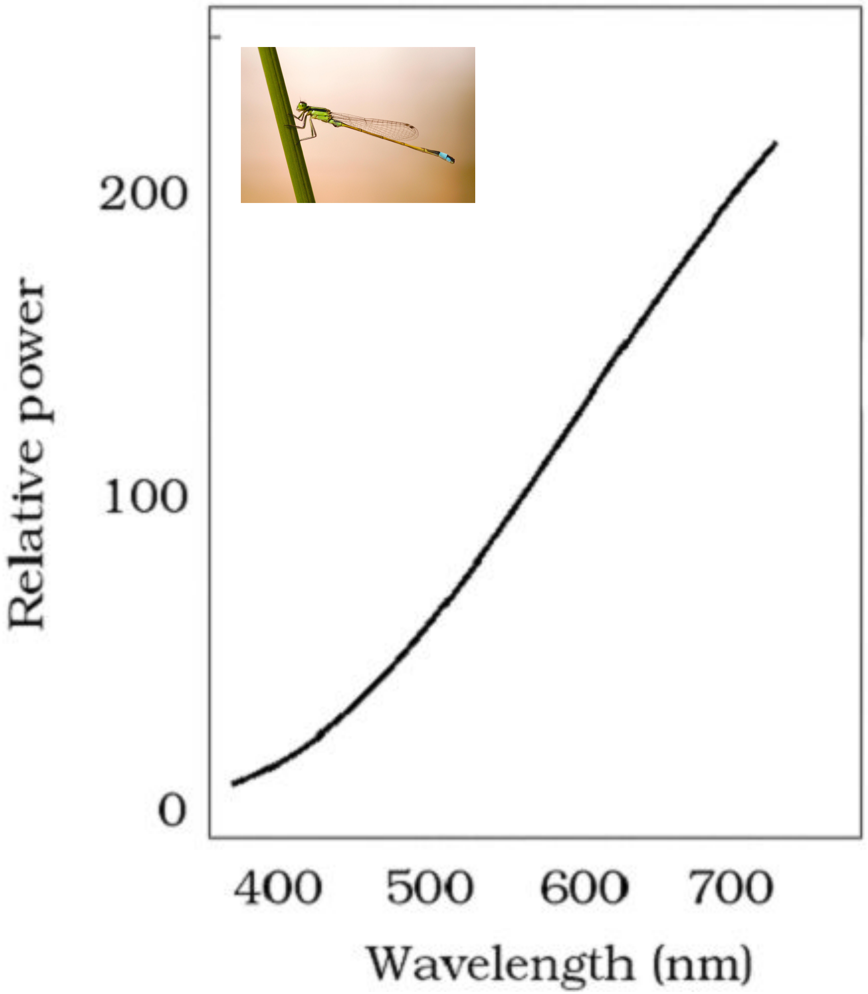


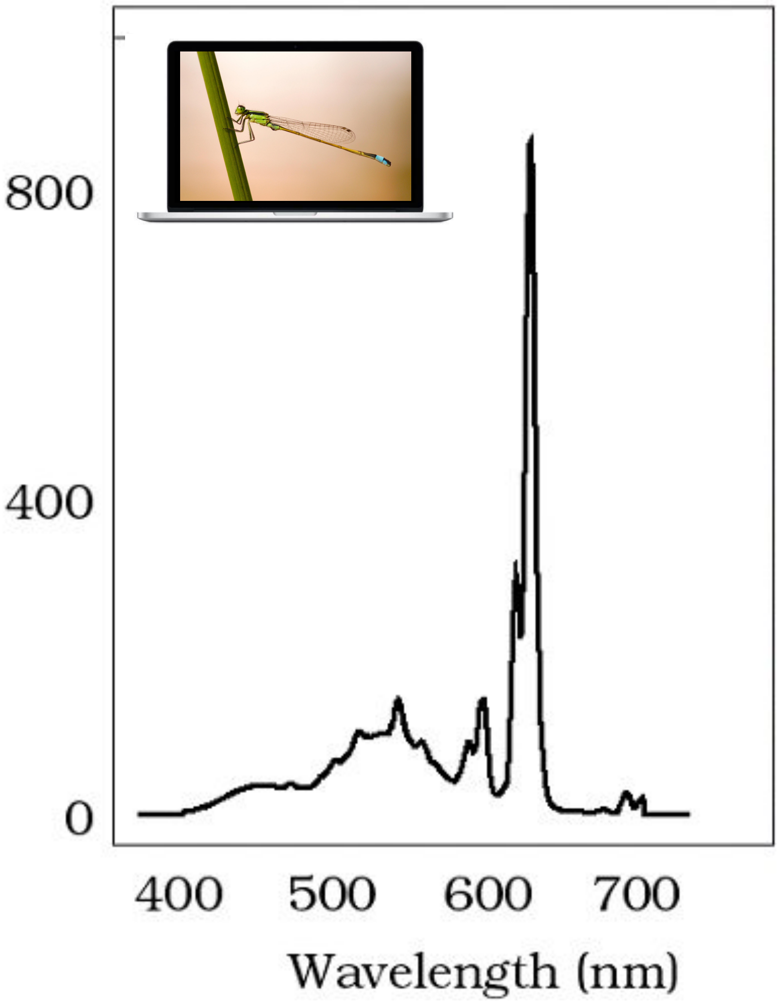
Brian Wandell

Metamers

- Metamers are two different spectra (∞-dim) that project to the same (S,M,L) (3-dim) response
  - These will appear to have the same color to a human
- The existence of metamers is critical to color reproduction
  - Don’t have to reproduce the full spectrum of a real-world scene

Metamerism





Brian Wandell

Outline

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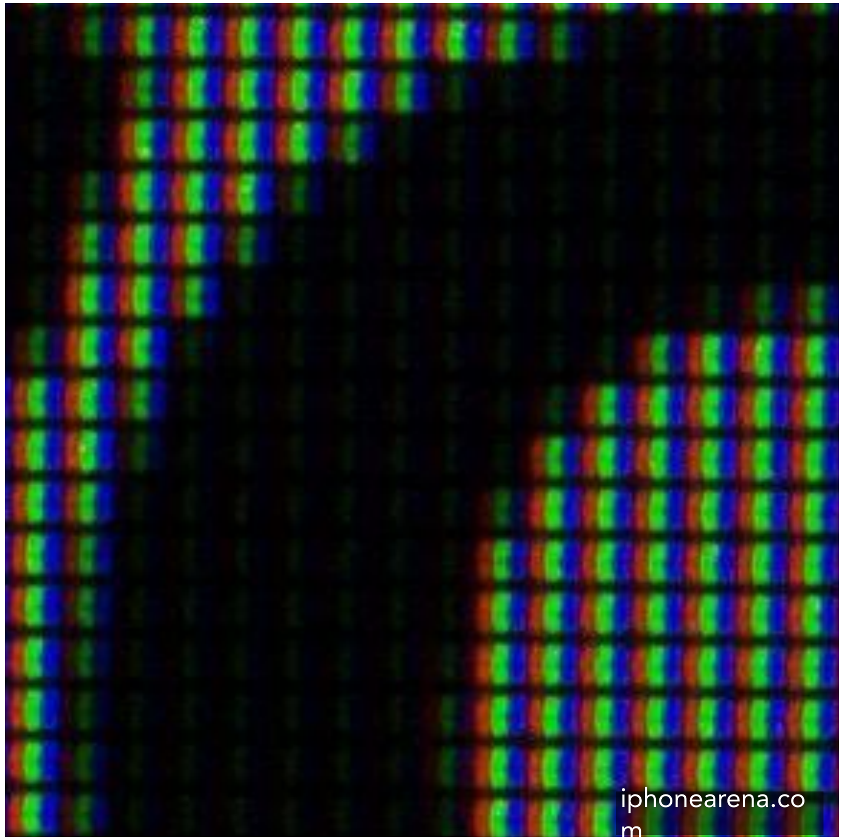
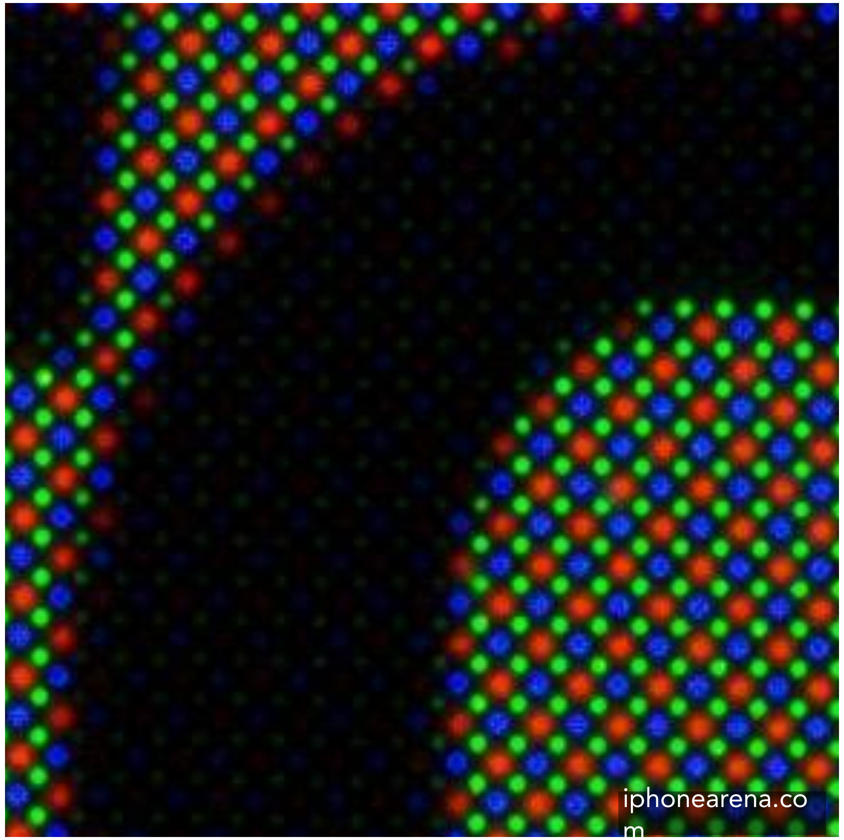
- Color spaces
- Color in digital cameras

Real LCD Screen Pixels (Closeup)



iPhone 6S



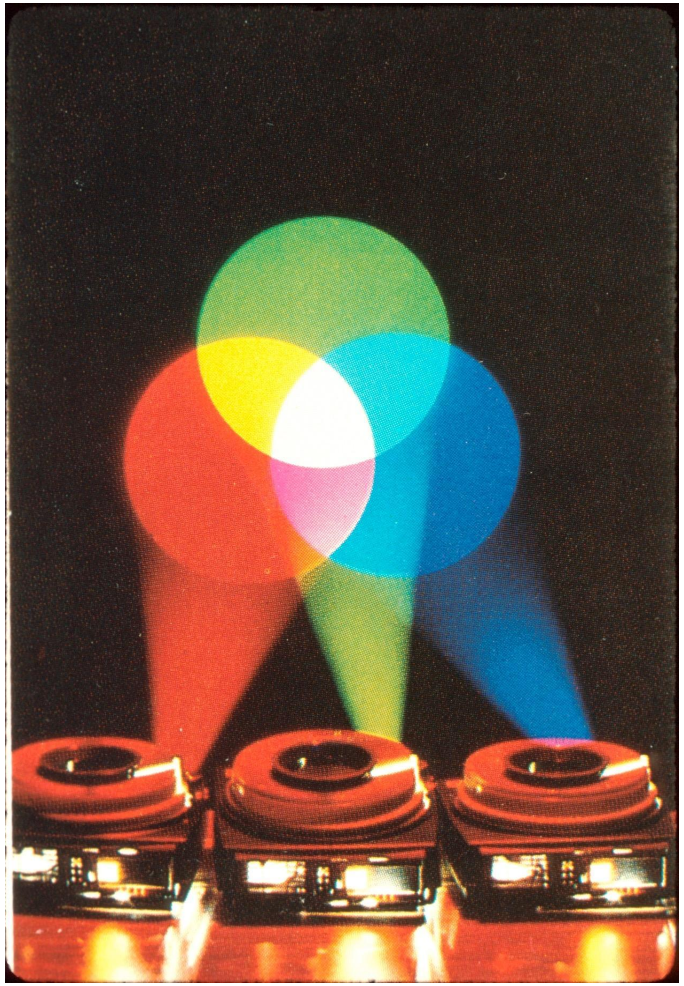
Galaxy S5

Notice R, G, B sub-pixel geometry.
Effectively three lights at each (x,y) location.

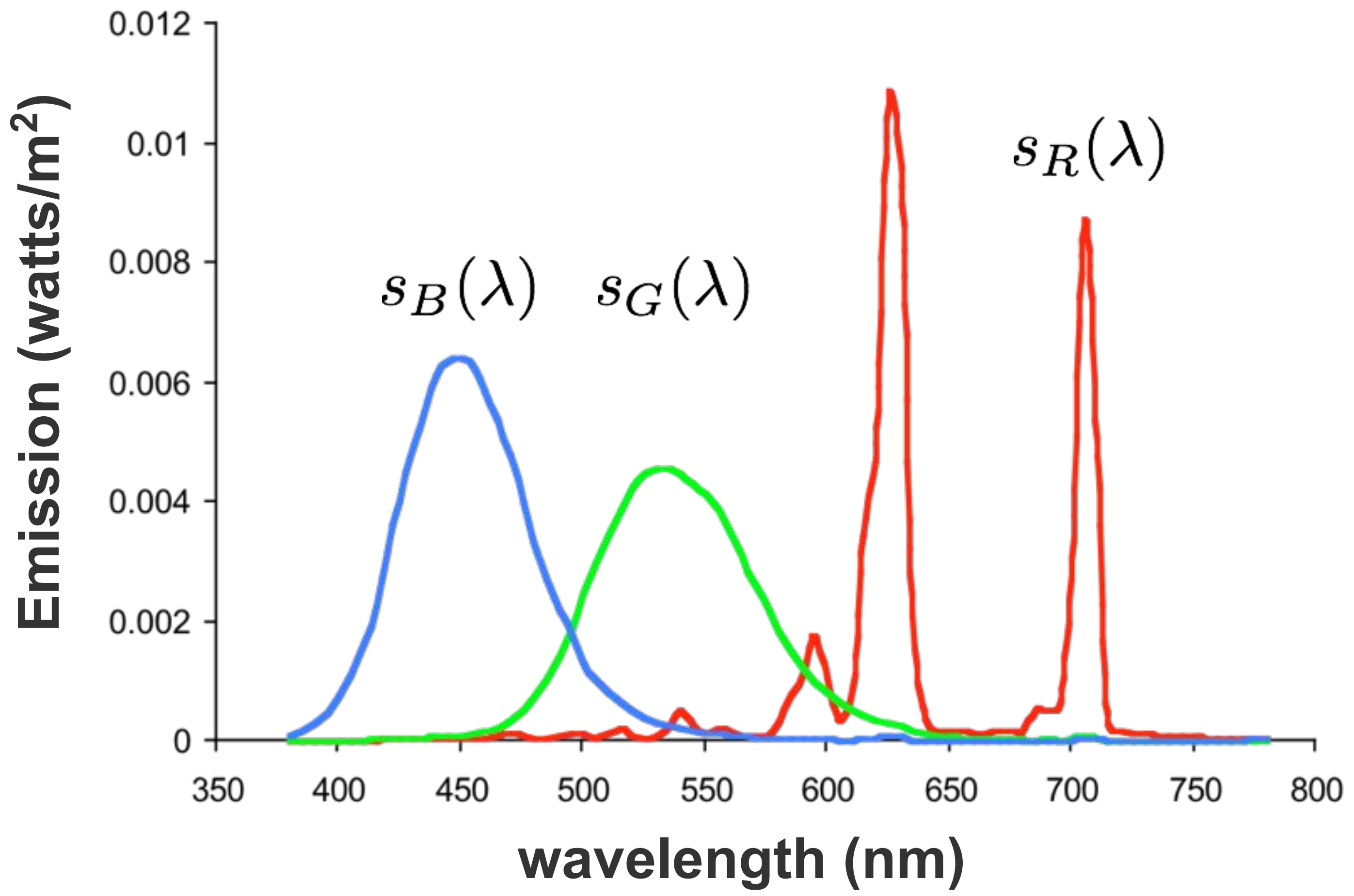
Additive Color

- The set of primary lights have a specific spectral distributions

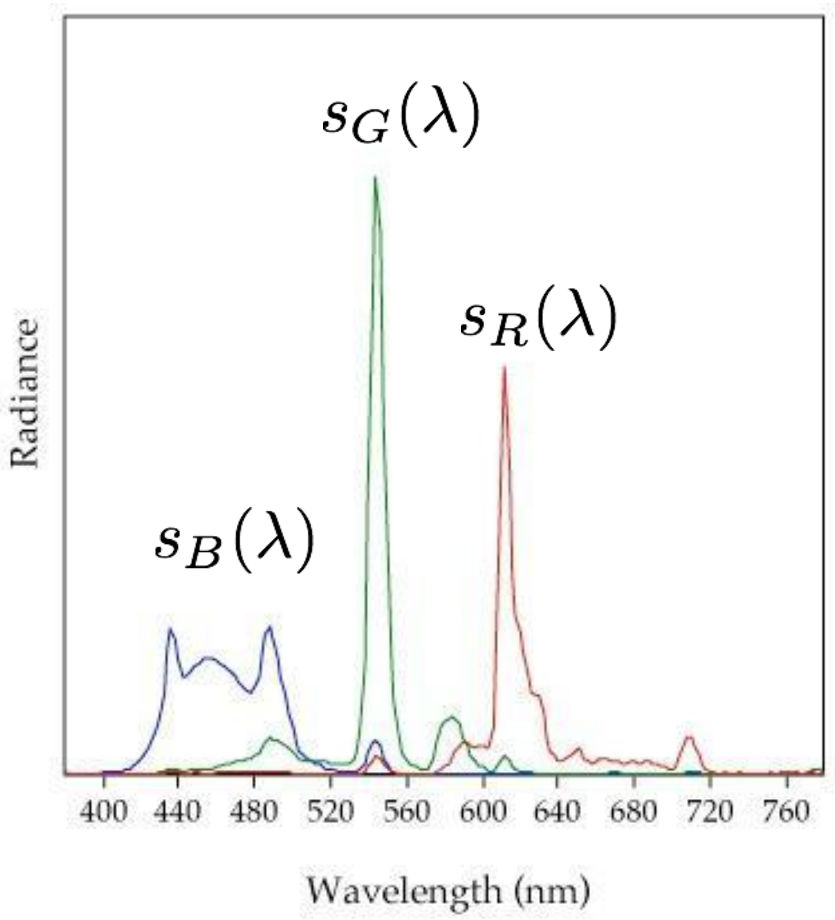
$$s_R(\lambda),\ s_G(\lambda),\ s_B(\lambda)$$



Example Primaries for CRT Display



Example Primaries: LCD Display



[Fairchild 97]

Additive Color

- The set of primary lights have a specific spectral distributions

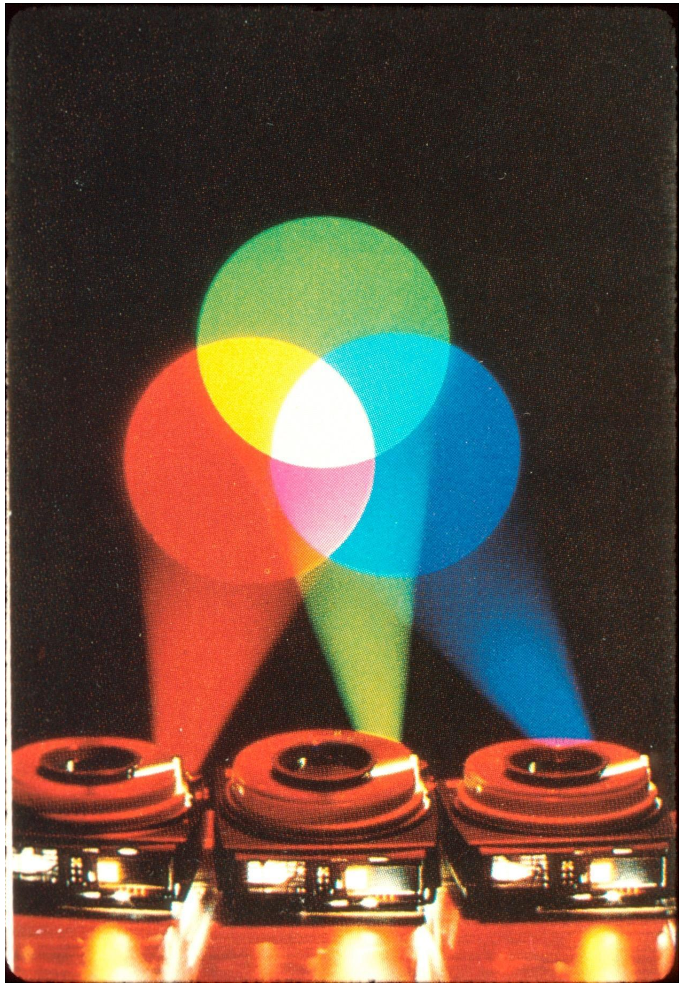
$$s_R(\lambda),\ s_G(\lambda),\ s_B(\lambda)$$

- We can adjust the brightness of these lights and add them together to produce a particular color:

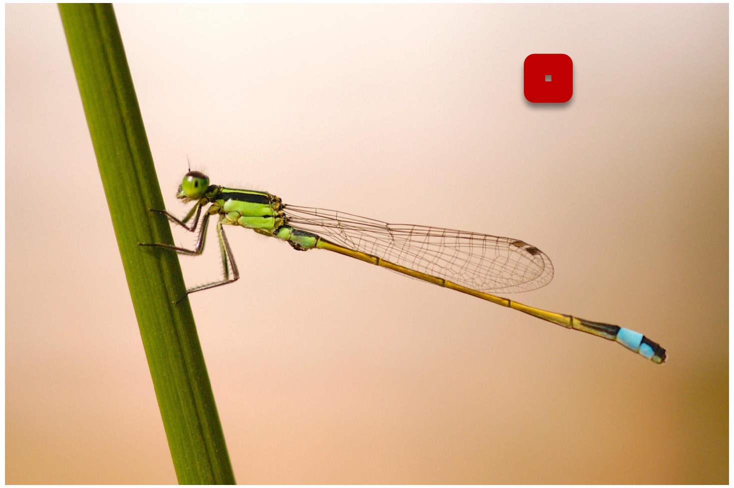
$$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

- The color is now described by the scalar values:

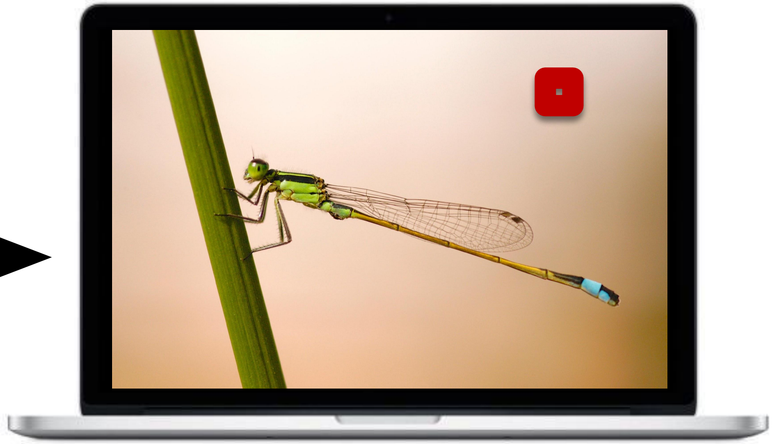
$$R,\ G,\ B$$



Color Reproduction Problem



Target real spectrum $s(\lambda)$



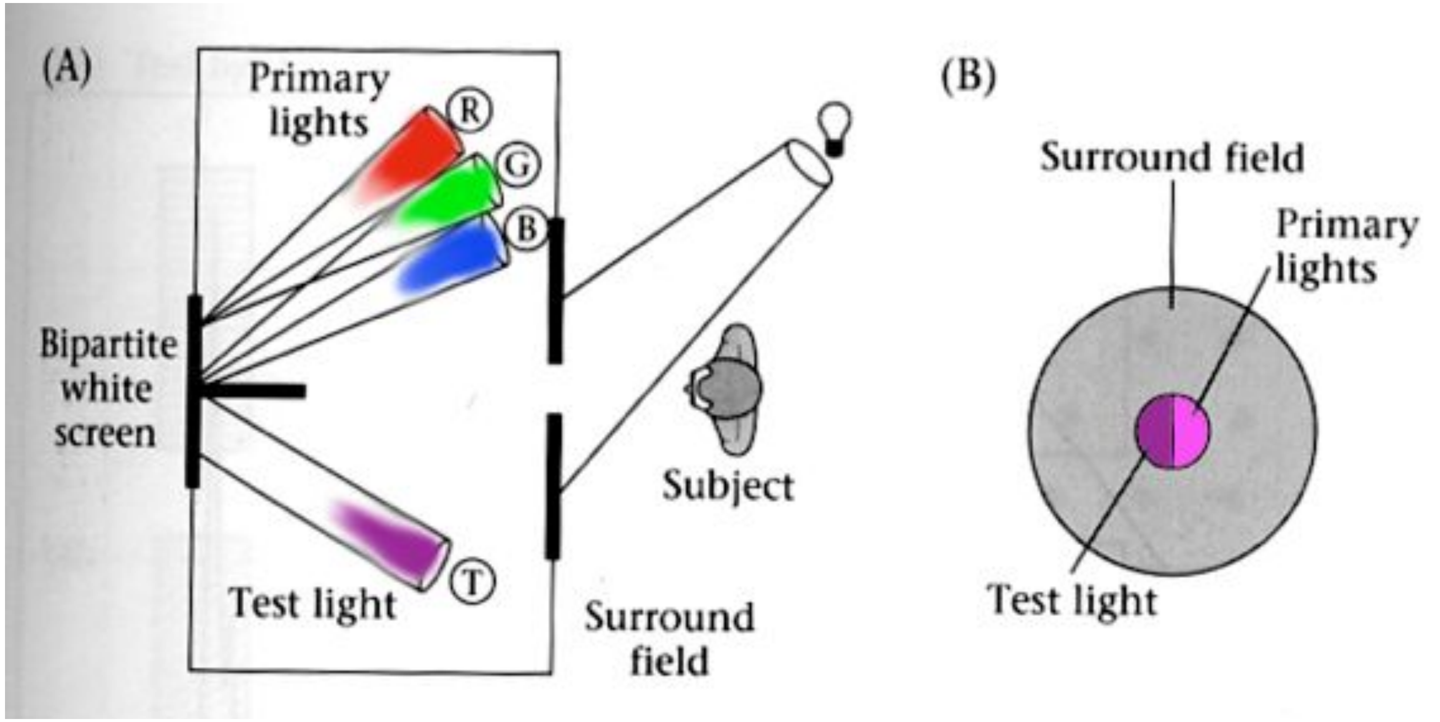
Display outputs spectrum

$$R\, s_R(\lambda) + G\, s_G(\lambda) + B\, s_B(\lambda)$$

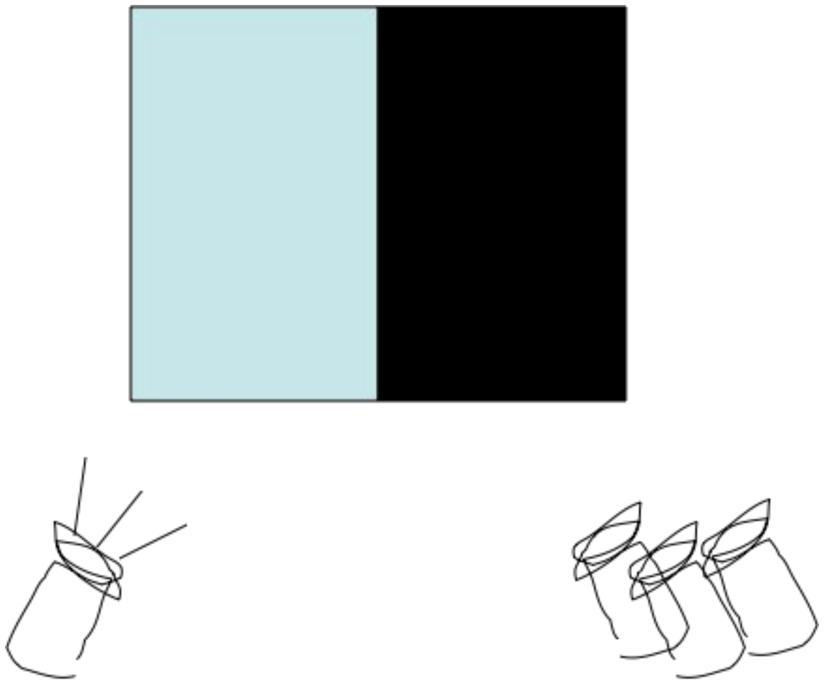
- Goal: at each pixel, choose R, G, B values for display so that the output color matches the appearance of the target color in the real world

Empirical Color Matching Experiment

Additive Color Matching Experiment

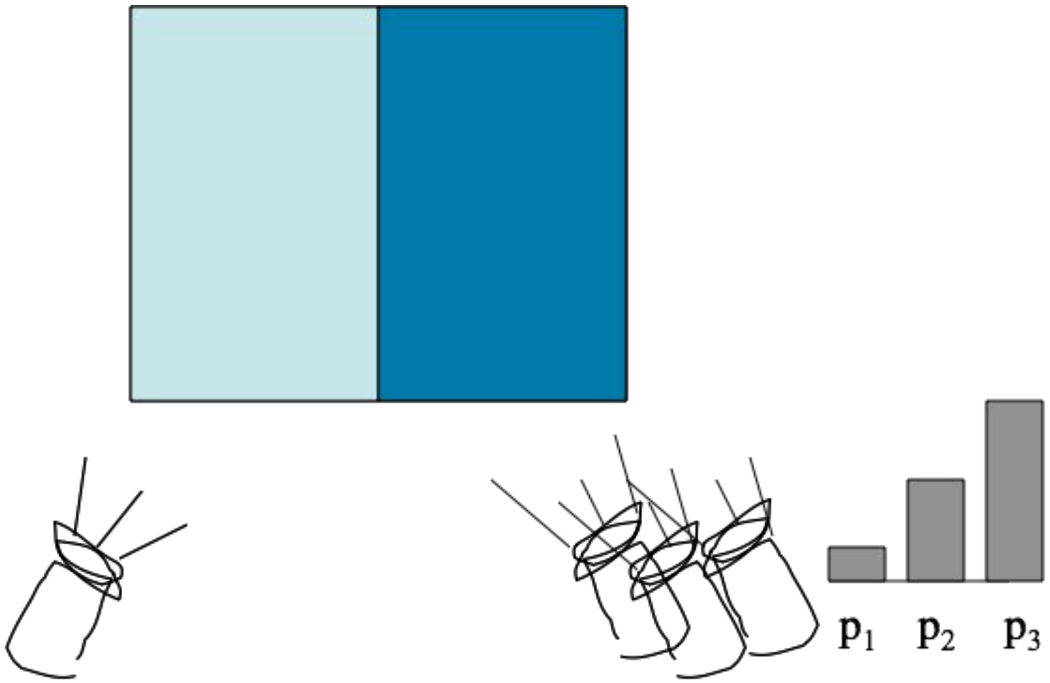


Example Experiment



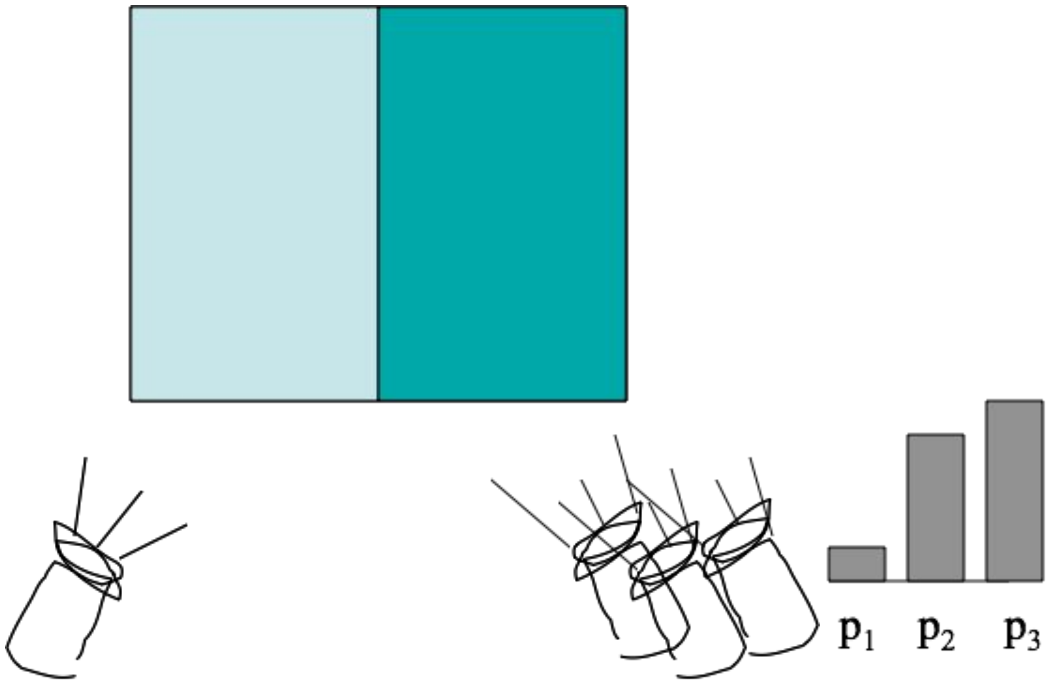
Slide from Durand
and Freeman 06

Example Experiment



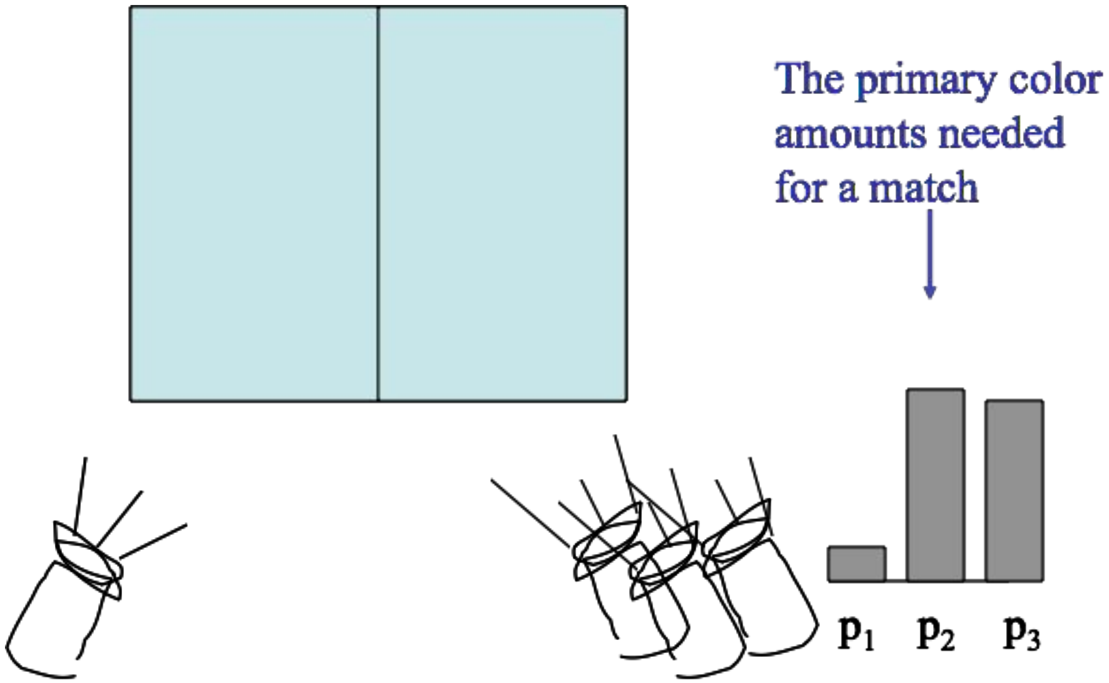
Slide from Durand and Freeman 06

Example Experiment



Slide from Durand and Freeman 06

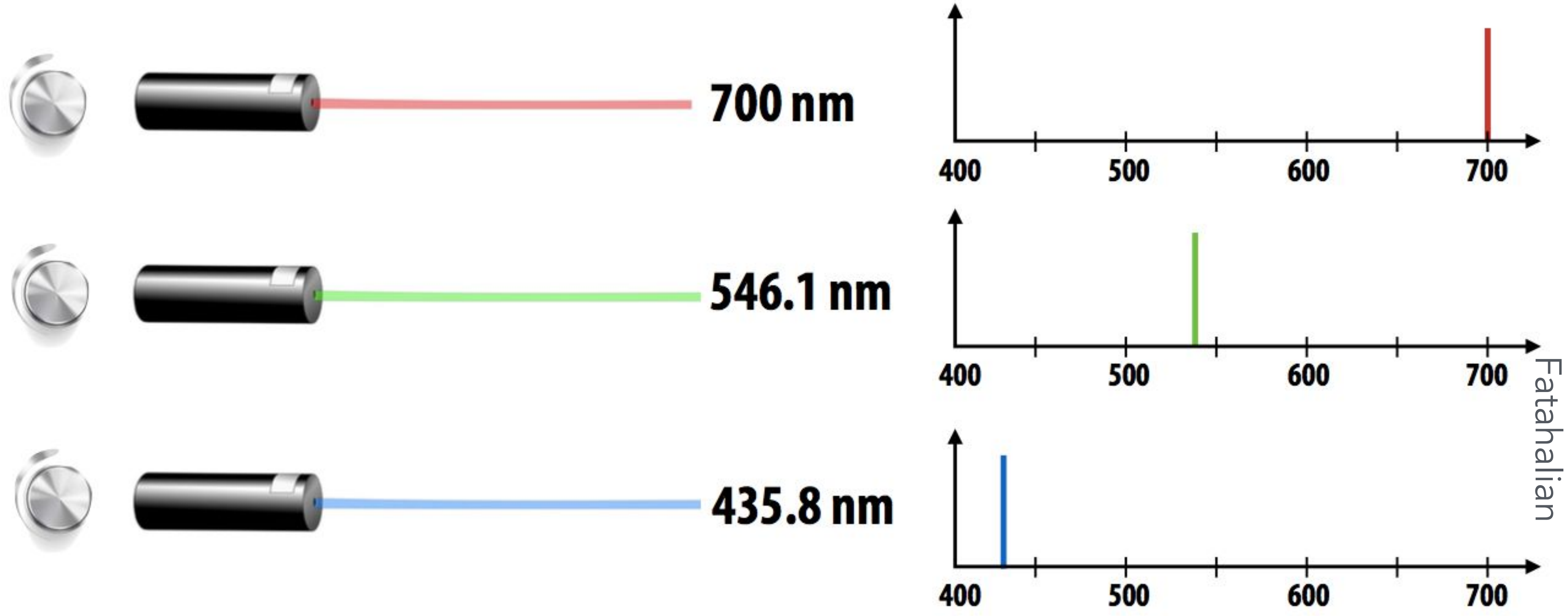
Example Experiment



Slide from Durand
and Freeman 06

CIE RGB Color Matching Experiment

- **Same setup as additive color matching before, but primaries are monochromatic light (single wavelength) of the following wavelengths**

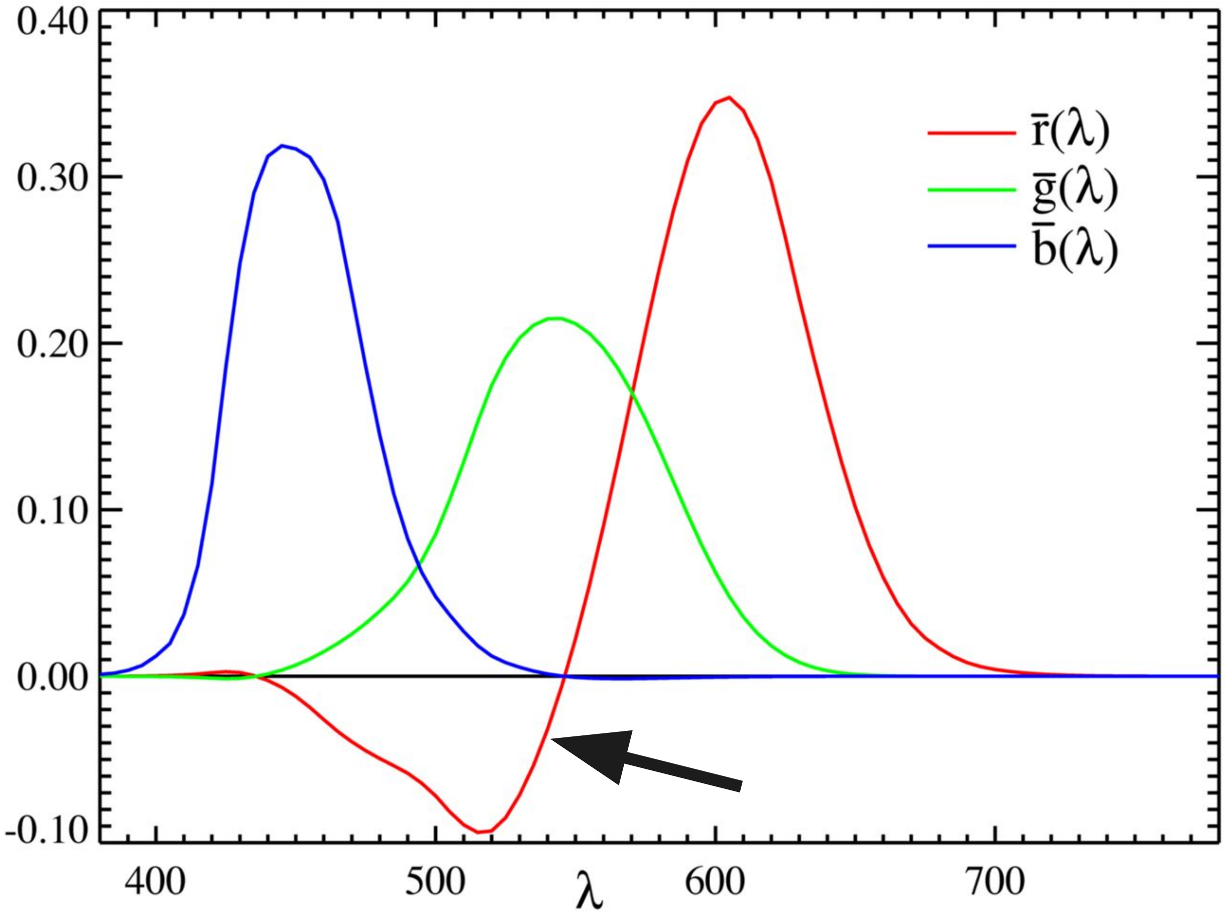


Kayvon Fatahalian

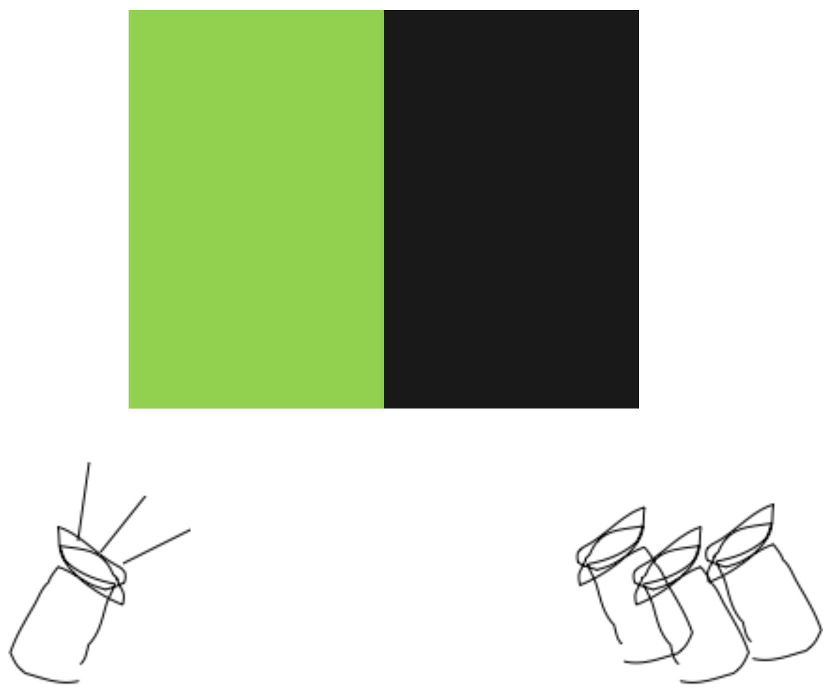
The test light is also a monochromatic light

CIE RGB Color Matching Functions

- Graph plots how much of each CIE RGB primary light must be combined to match a monochromatic light of wavelength given on x-axis

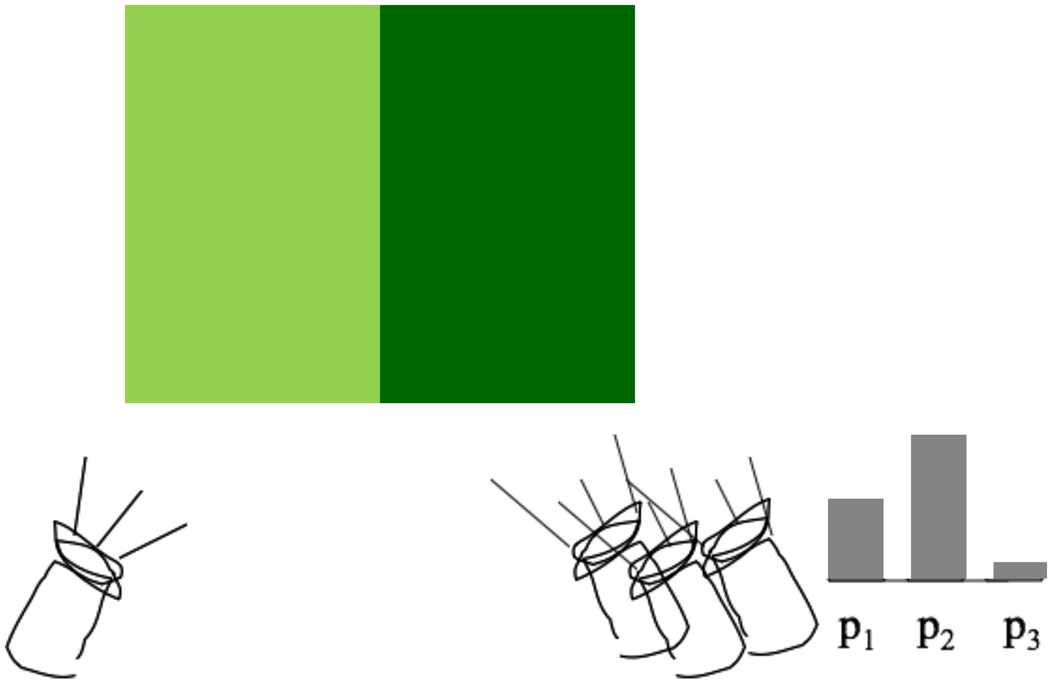


Experiment 2



Slide from Durand
and Freeman 06

Experiment 2

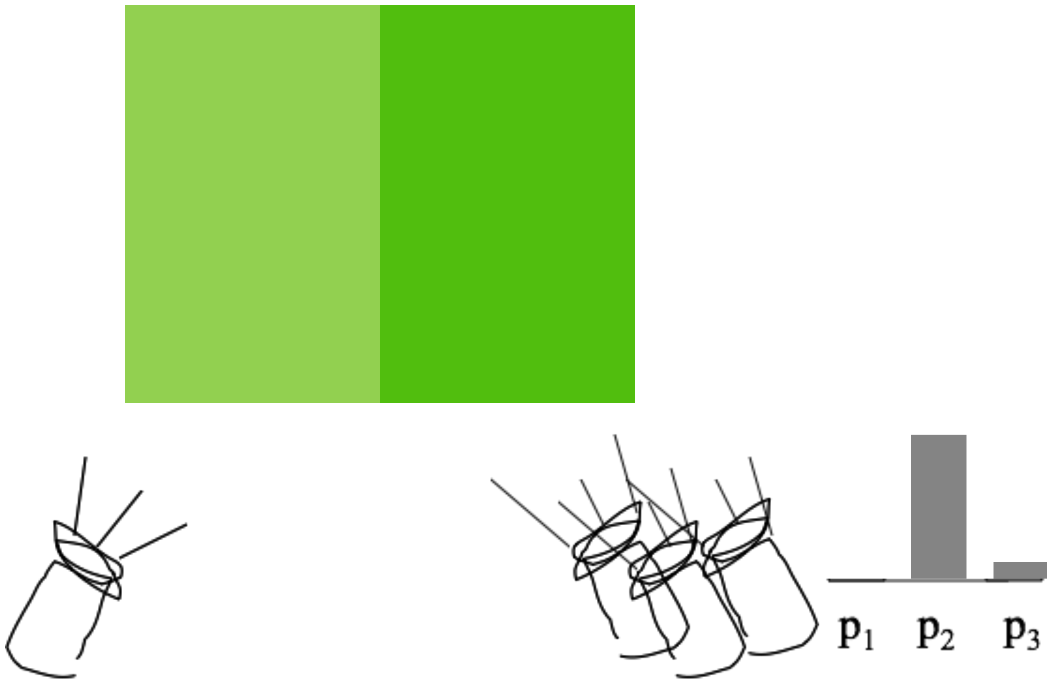


Slide from Durand
and Freeman 06

Experiment 2

Slide from Durand and Freeman 06

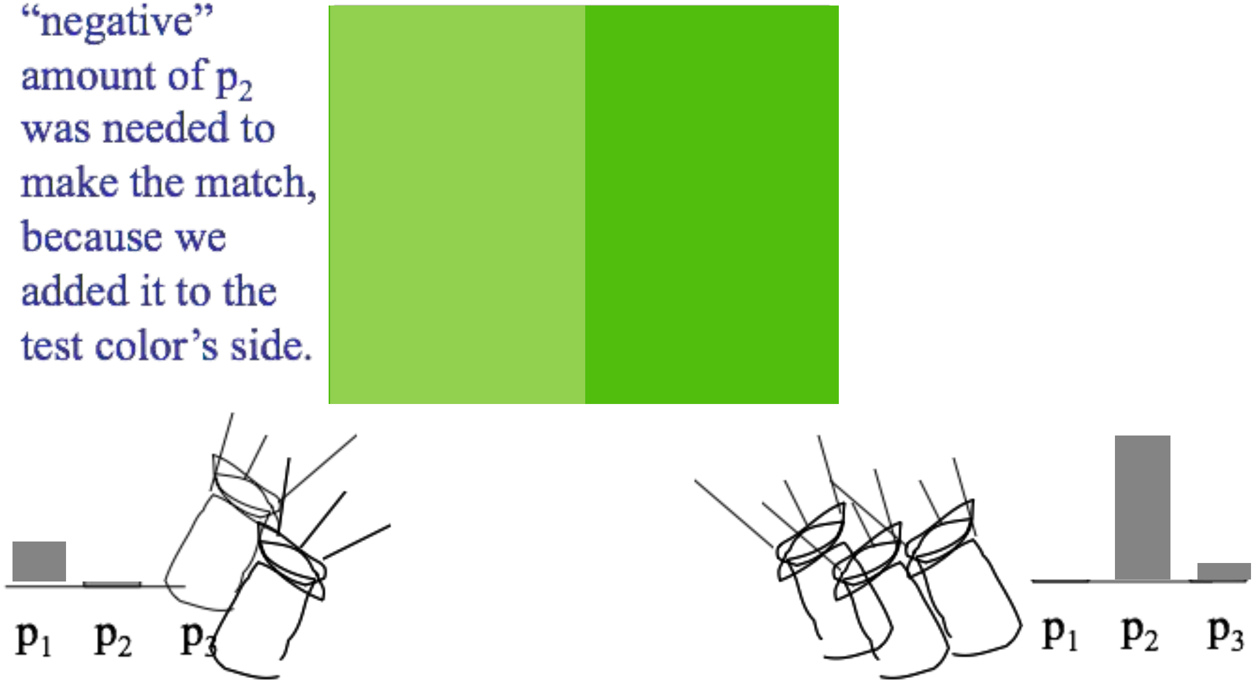
Experiment 2



Slide from Durand
and Freeman 06

Experiment 2

We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

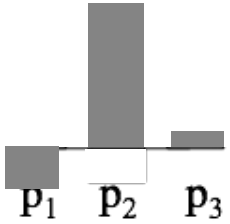


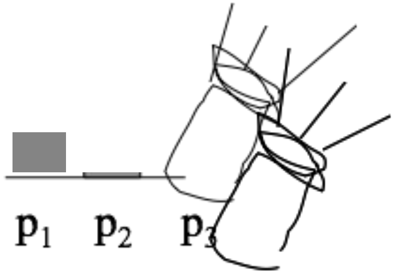
Slide from Durand and Freeman 06

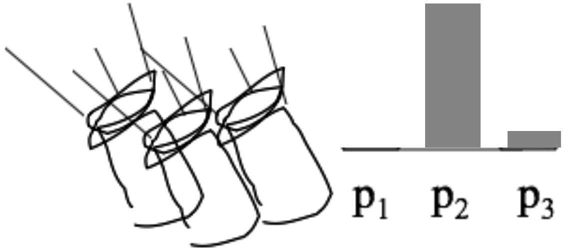
Experiment 2

We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

The primary color amounts needed for a match:



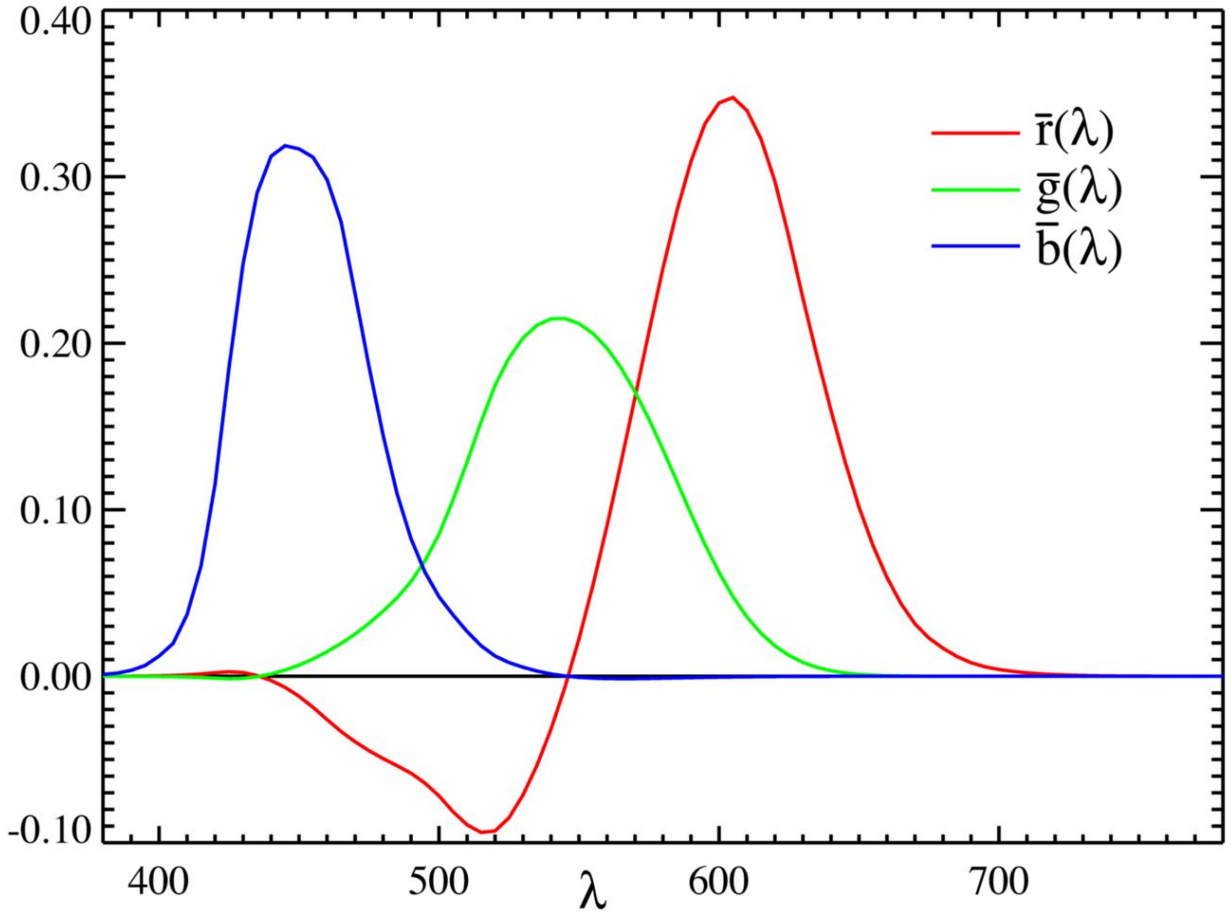




Slide from Durand and Freeman 06

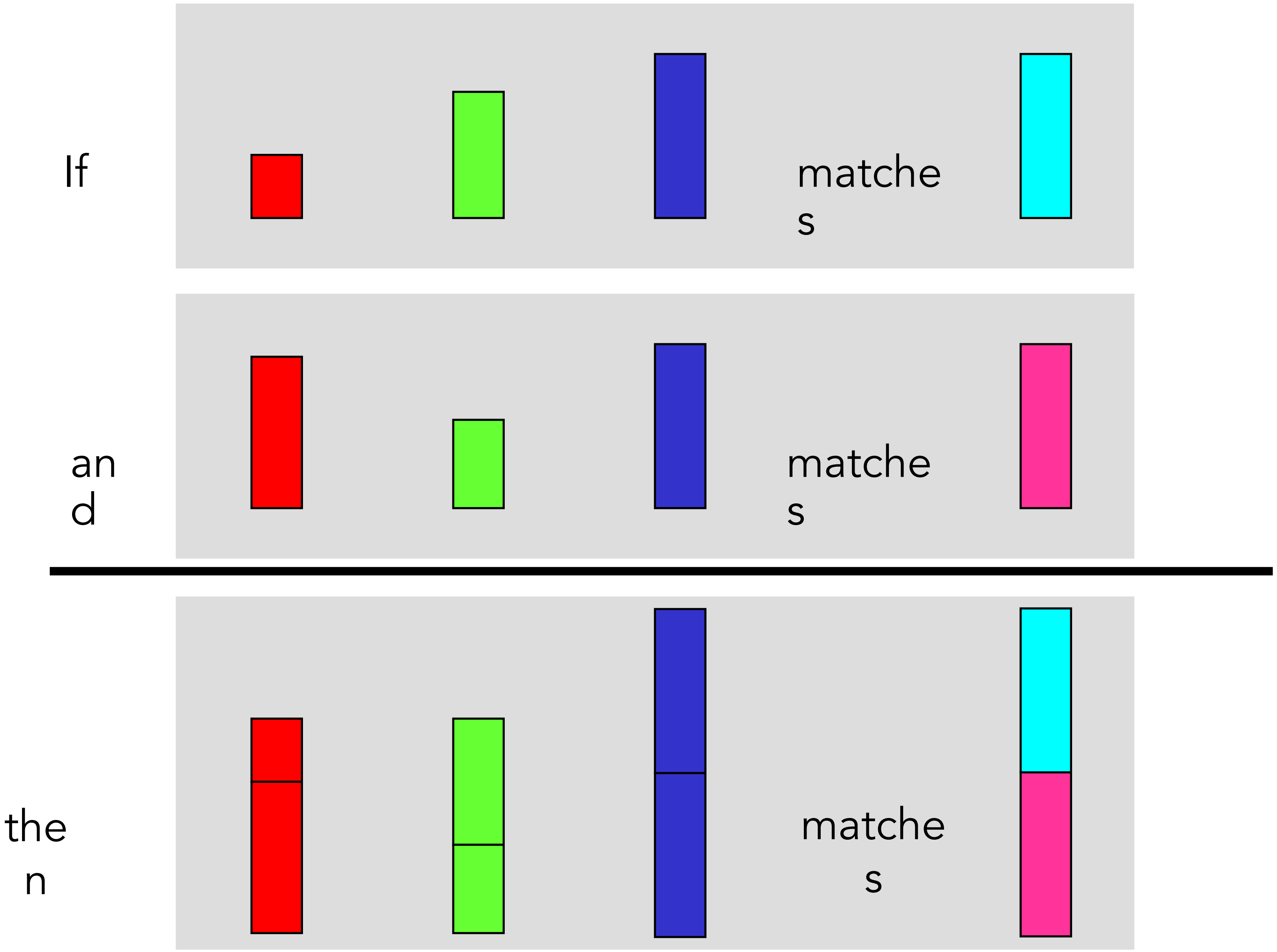
CIE RGB Color Matching Functions

- Graph plots how much of each CIE RGB primary light must be combined to match a monochromatic light of wavelength given on x-axis



What about non monochromatic?

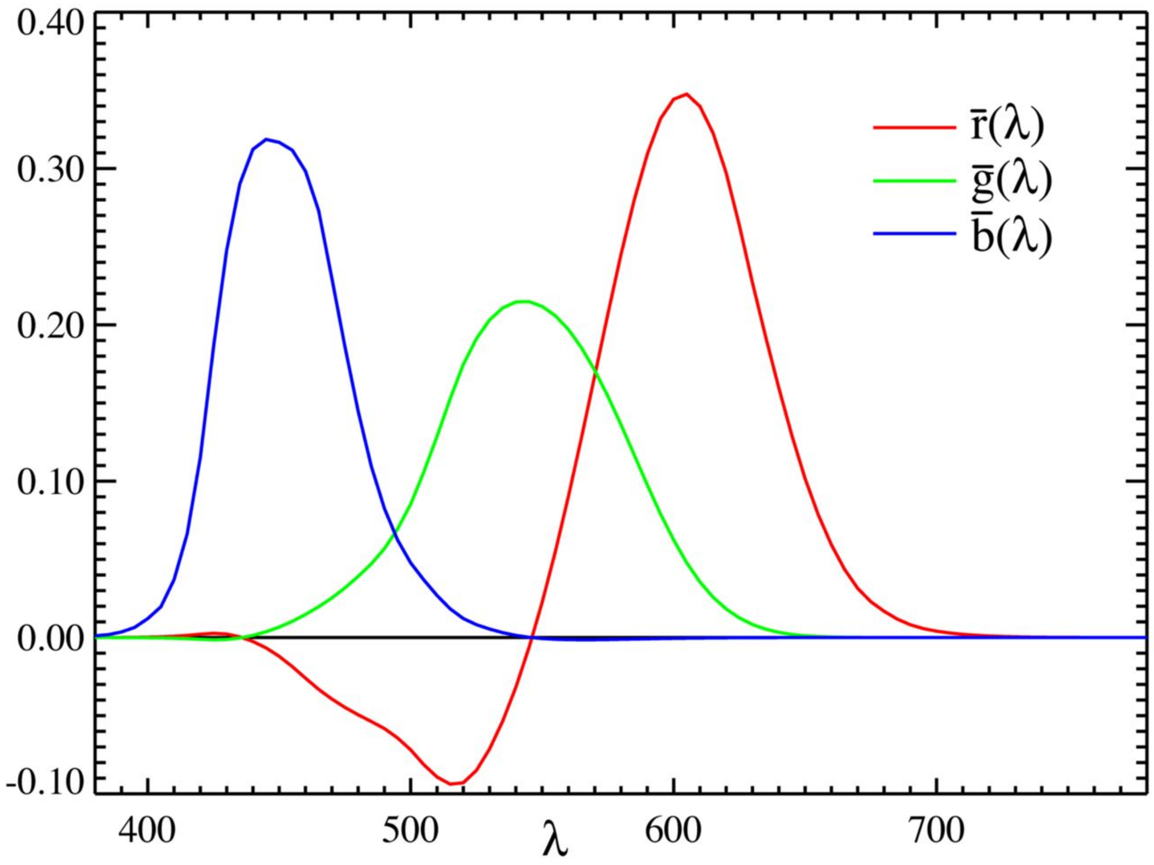
The Color Matching Experiment is Linear



Brian Wandell

CIE RGB Color Matching Functions

- **Certain colors cannot be reproduced by the original primary lights**

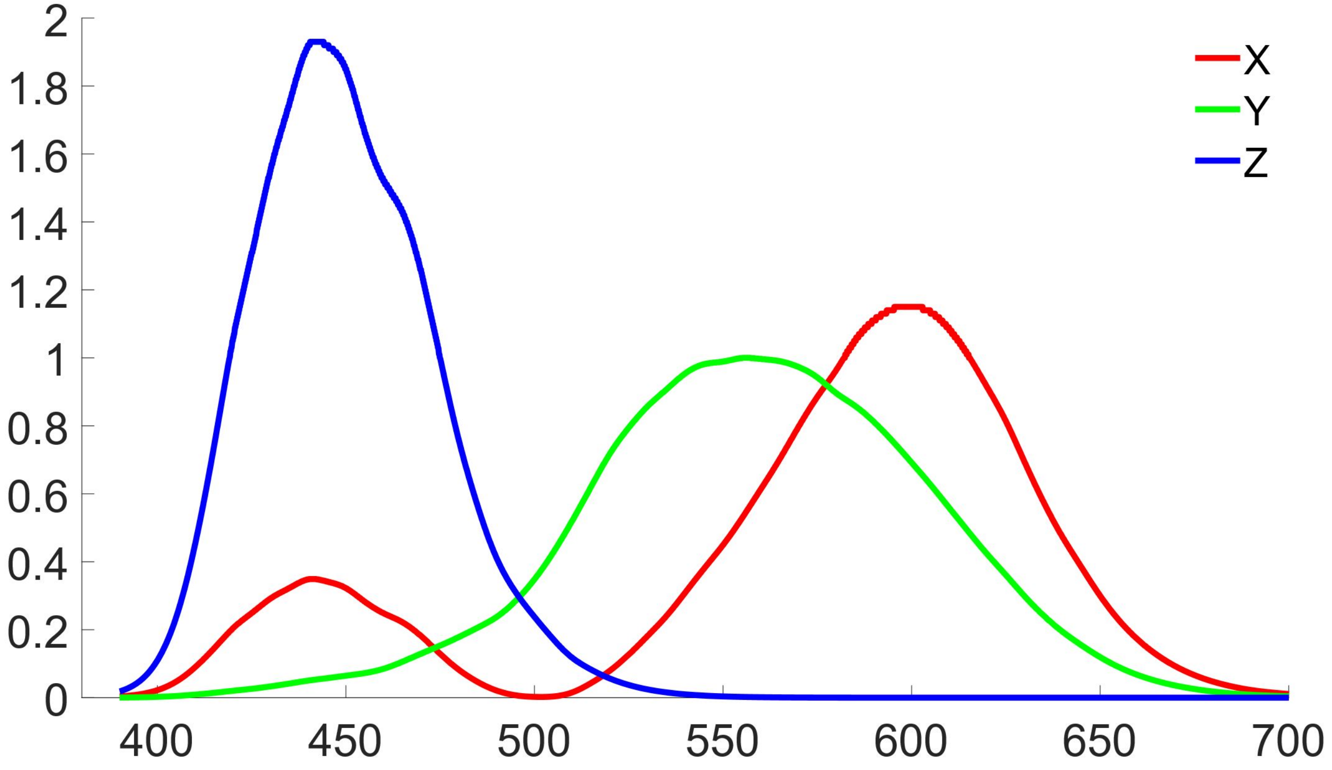


Question

- What is the range of colors that can be represented by these primary lights?

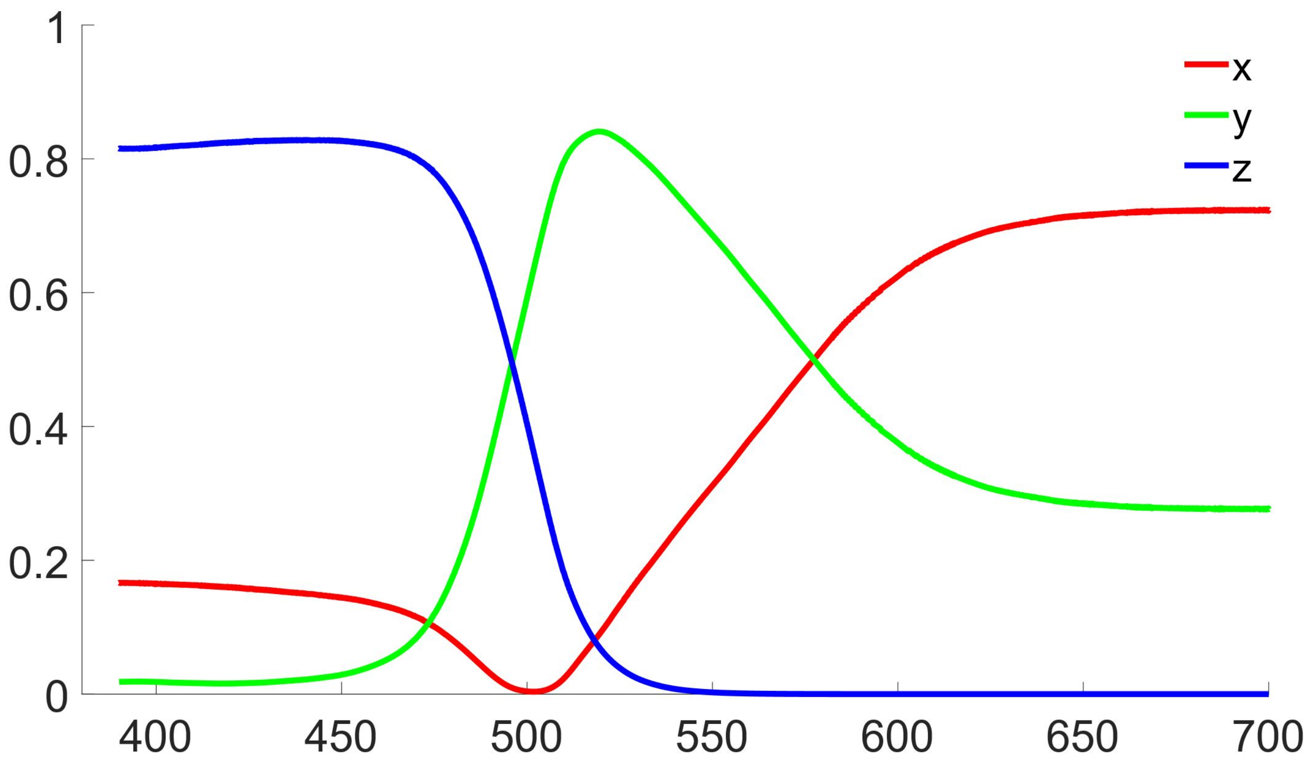
CIE XYZ

- Imaginary primary lights to avoid having negative coefficients

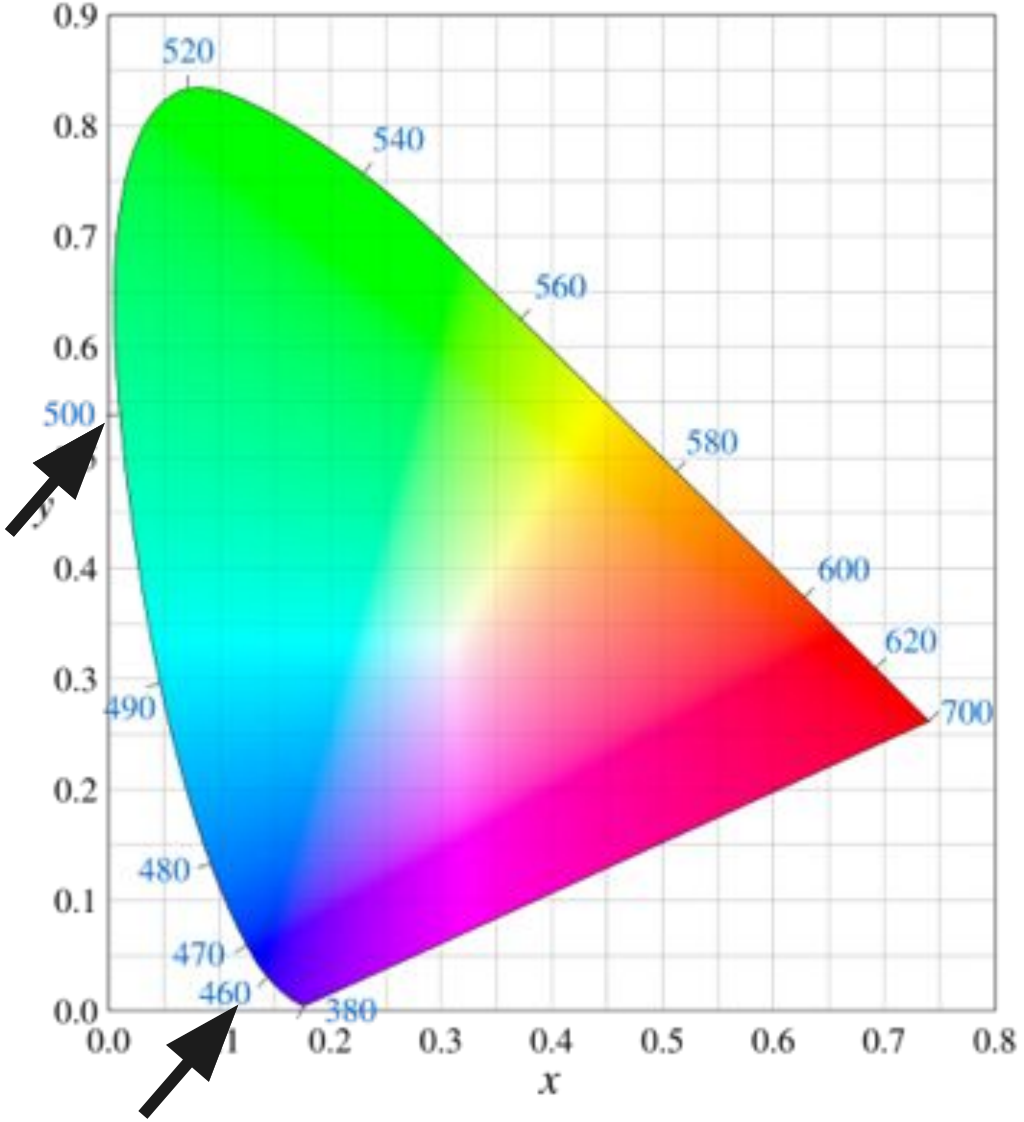


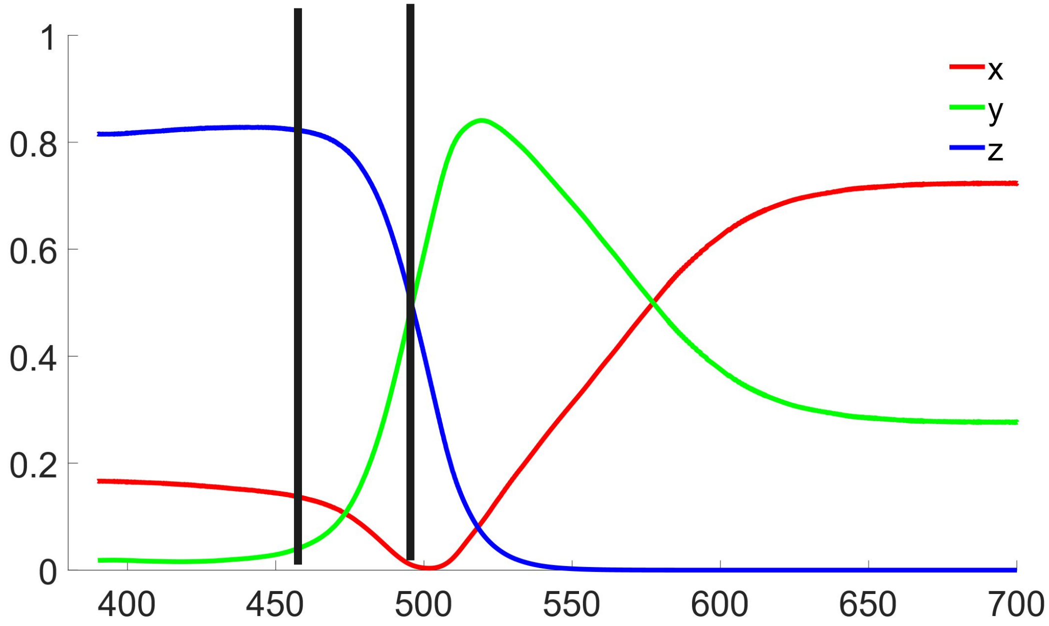
Chromaticity

- $x = X / (X + Y + Z)$
- $y = Y / (X + Y + Z)$
- $z = Z / (X + Y + Z)$
- $x + y + z = 1$

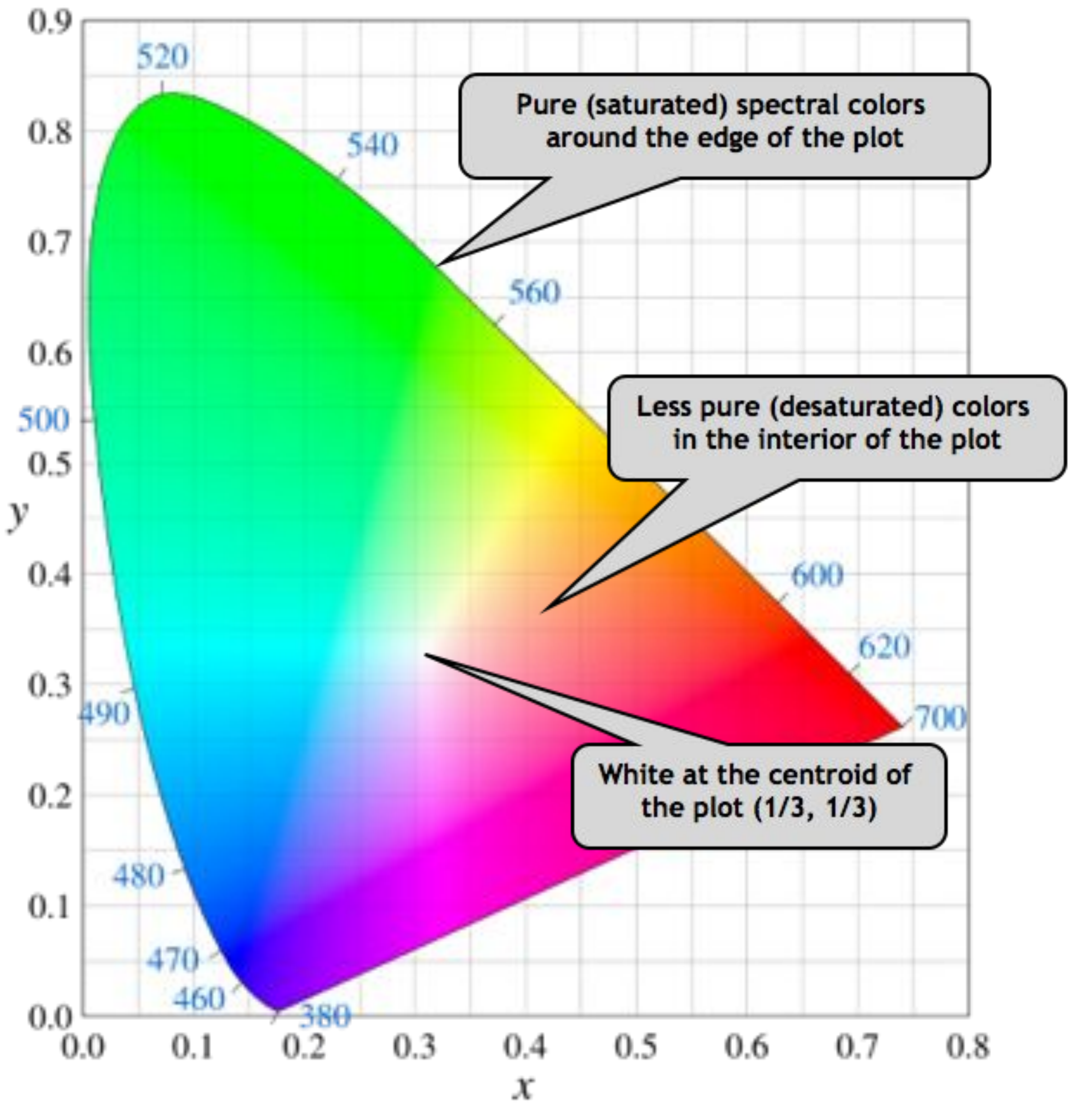


Chromaticity





CIE XYZ



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
y
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
520
540
560
500
490
480
470
460
380
600
620
700
Pure (saturated) spectral colors around the edge of the plot
Less pure (desaturated) colors in the interior of the plot
White at the centroid of the plot (1/3, 1/3)

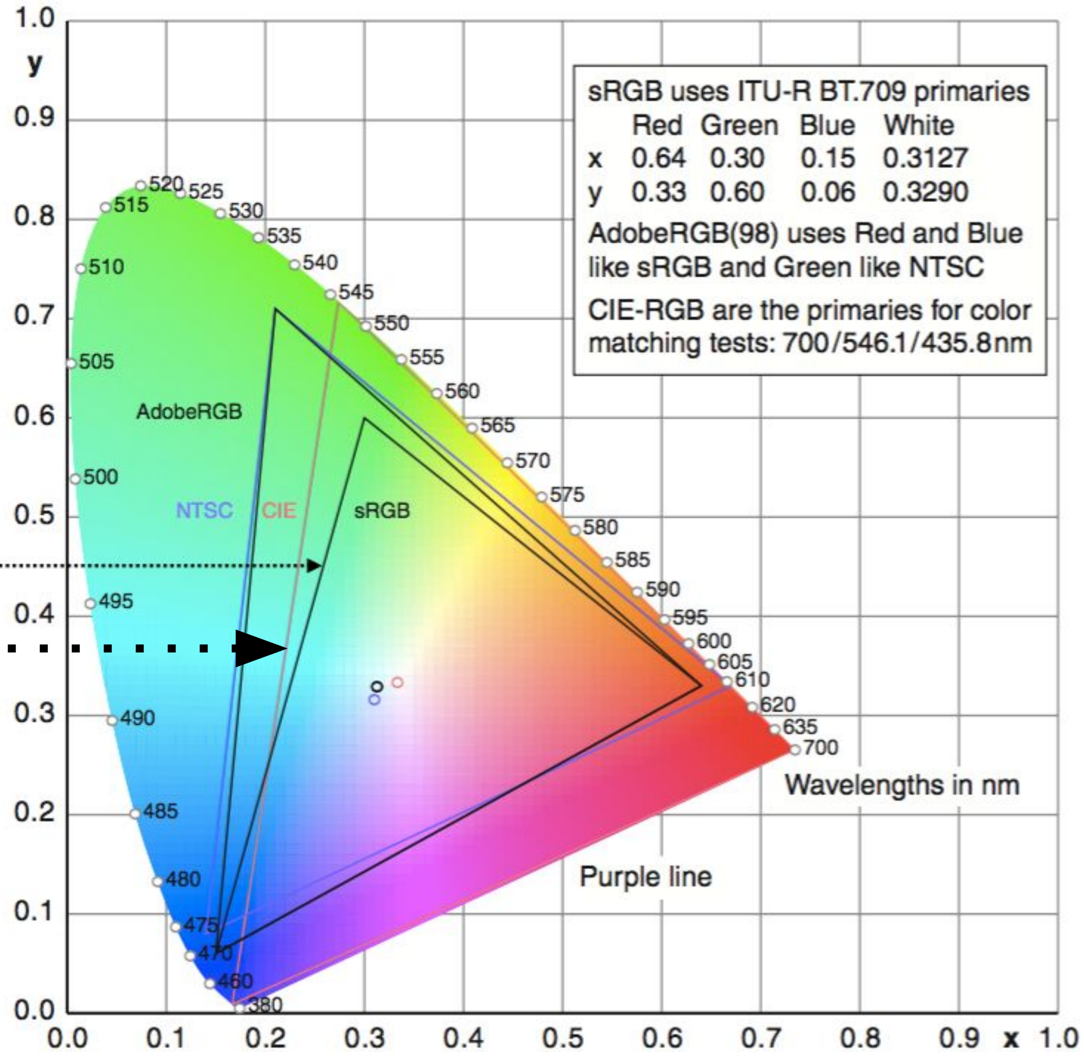
Gamut

- The subset of colors that can be represented within a given display device or color space

Gamut

sRGB is a common color space used throughout the internet

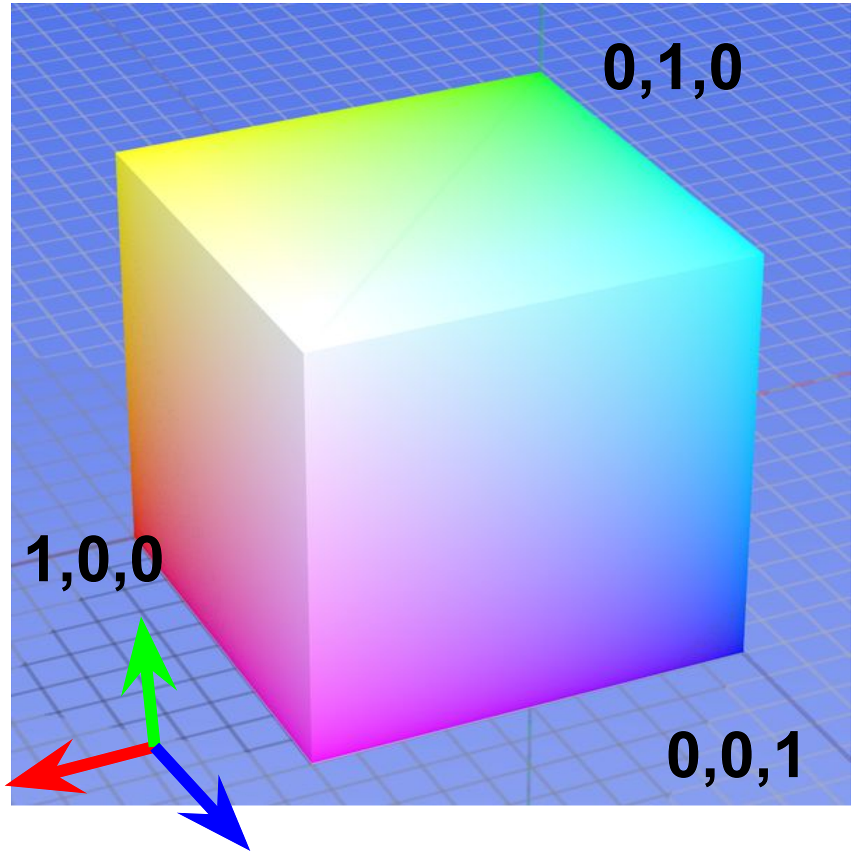
CIE RGB are the monochromatic primaries used for color matching tests described earlier

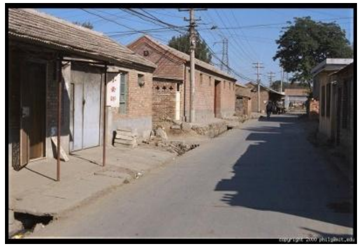


Outline

- Physics of color
- Human visual system
- Color reproduction
- Color spaces
- Color in digital cameras

Color spaces: RGB





R
(G=0,B=0)

G
(R=0,B=0)

B
(R=0,G=0)

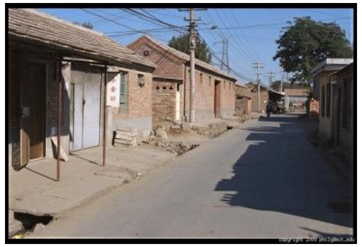
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

RGB

- Red, Green, Blue
- Common specifications for most monitors
  - Tells how much intensity to use for pixels
- Note: Not standard – RGB means different things for different monitors
- Generally used in an *additive* system
  - Each adds additional light (e.g. phosphor)
  - Combine all three colors to get white

RGB

- **Drawbacks**
  - **Strongly correlated channels**
  - **Non-perceptual**



R
(G=0,B=0)

G
(R=0,B=0)

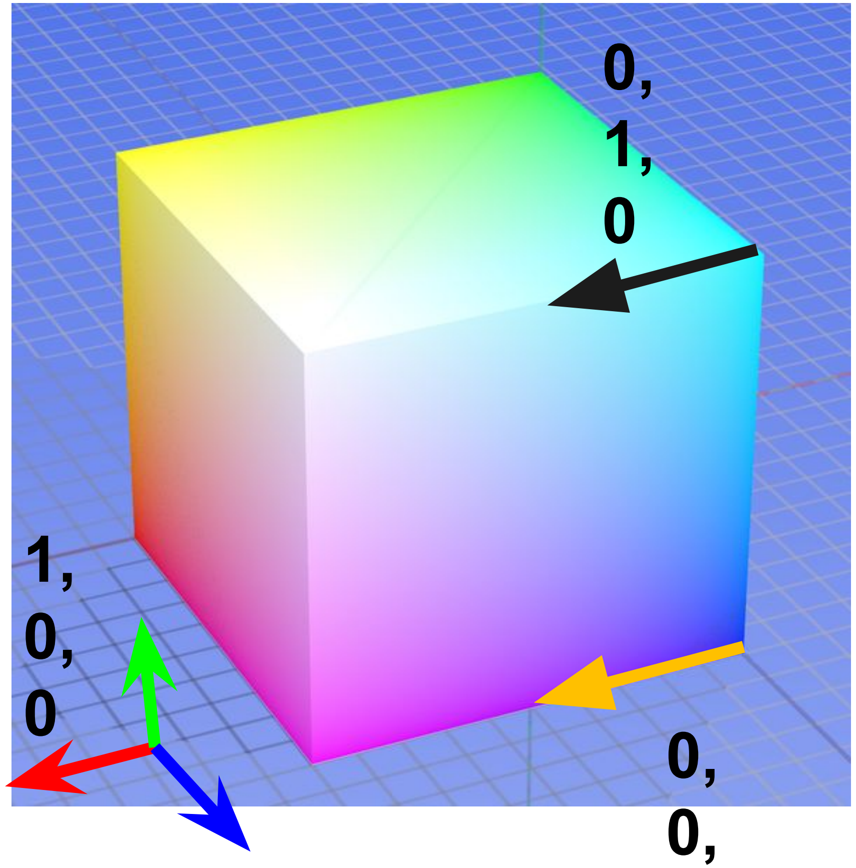
B
(R=0,G=0)

RGB

- Drawbacks
  - Strongly correlated channels
  - Non-perceptual

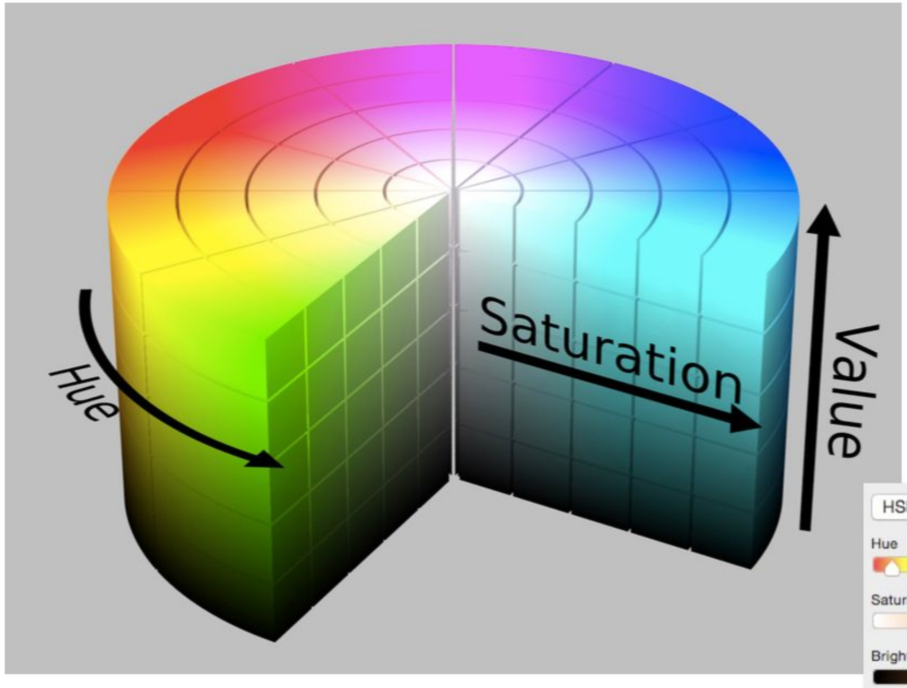
Start	End
R = 0, G = 1, B = 1	R = 0.5, G = 1, B = 1

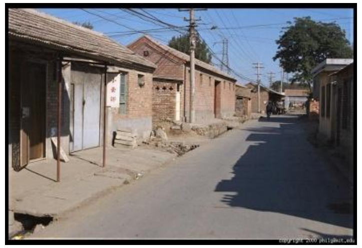
Start	End
R = 0, G = 0, B = 1	R = 0.5, G = 0, B = 1

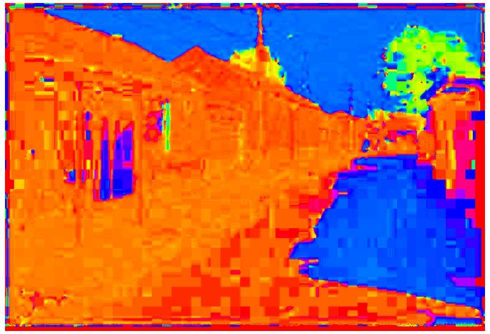


Color spaces: HSV

- Axes correspond to artistic characteristics of color
- Intuitive color model







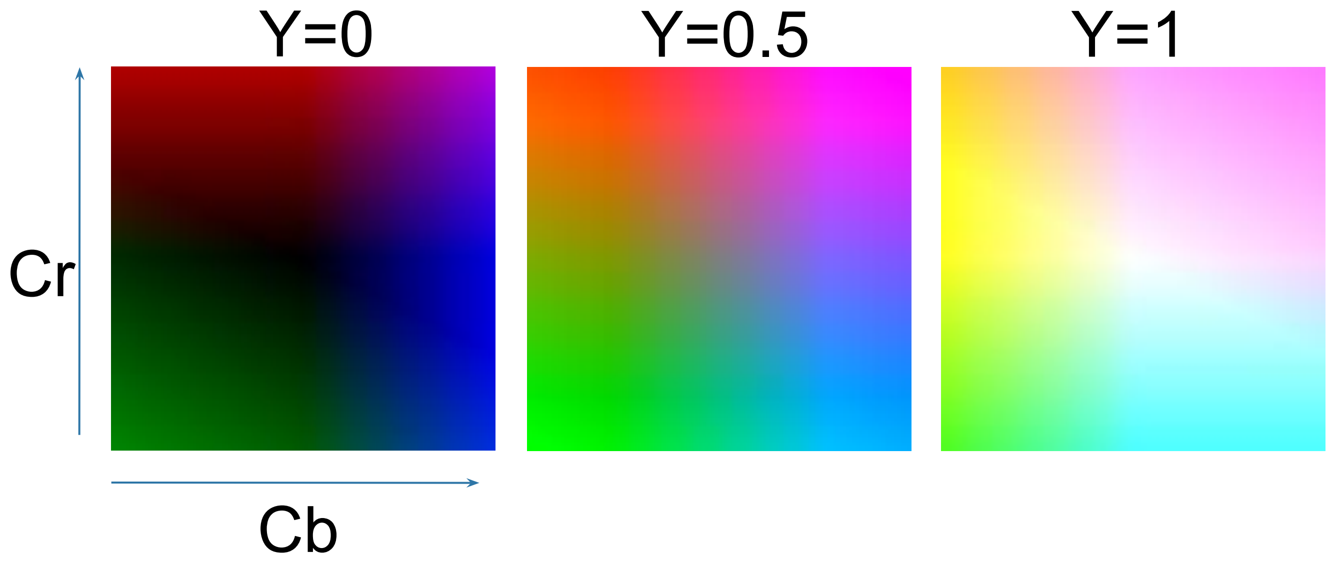
H
(S=1,V=1)

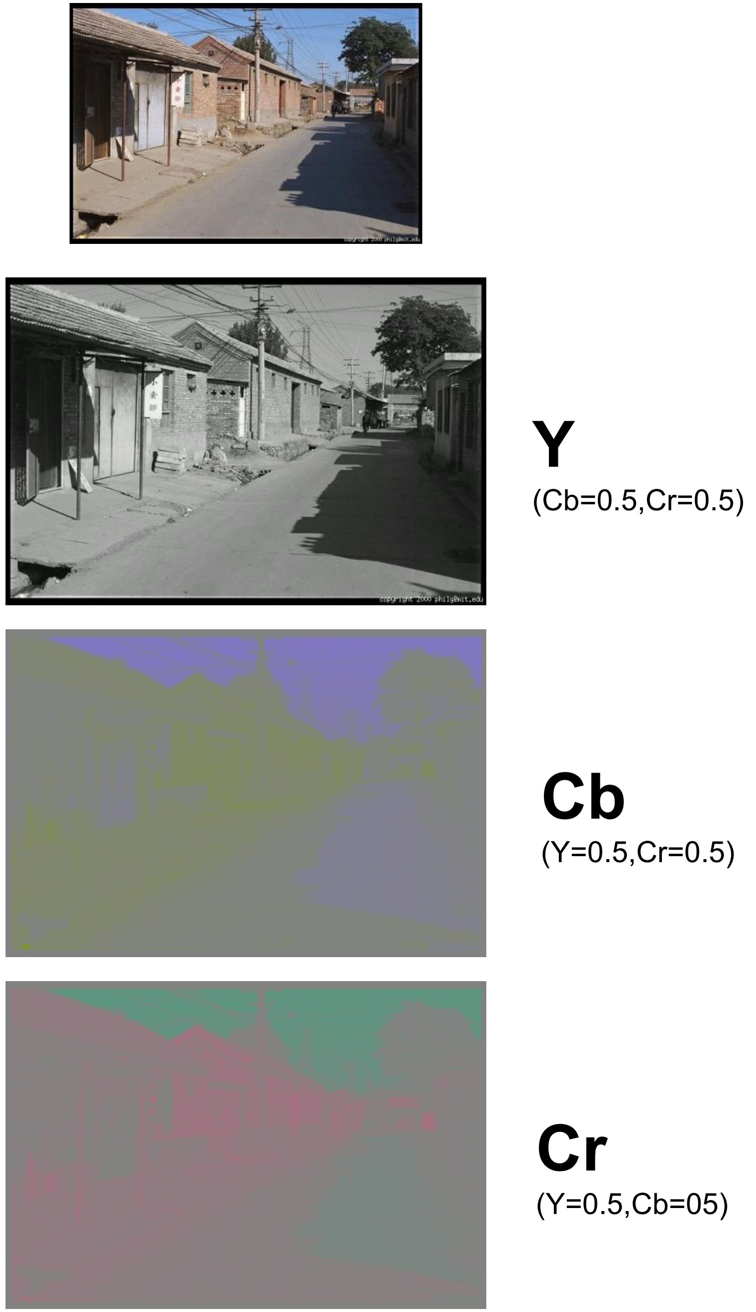
S
(H=1,V=1)

V
(H=1,S=0)

Color spaces: YCbCr

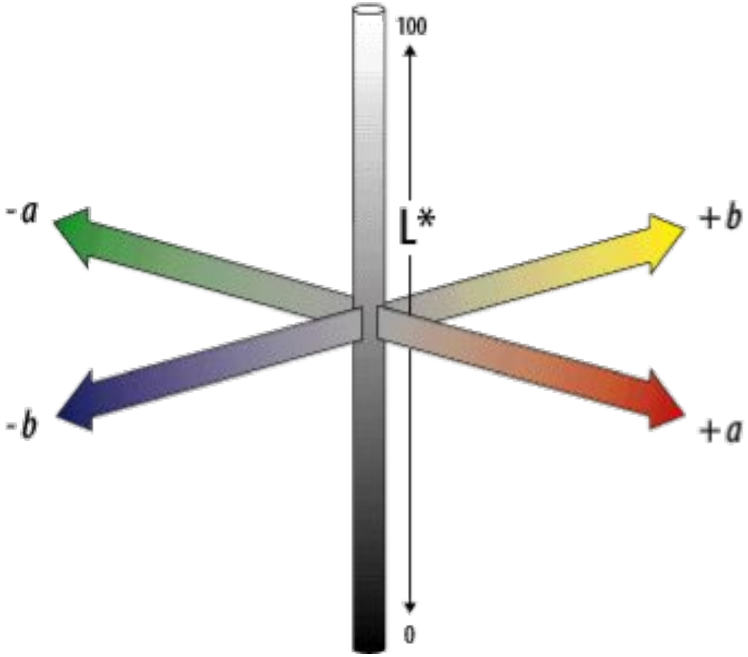
- Fast to compute
- Good for compression
- Used by TV

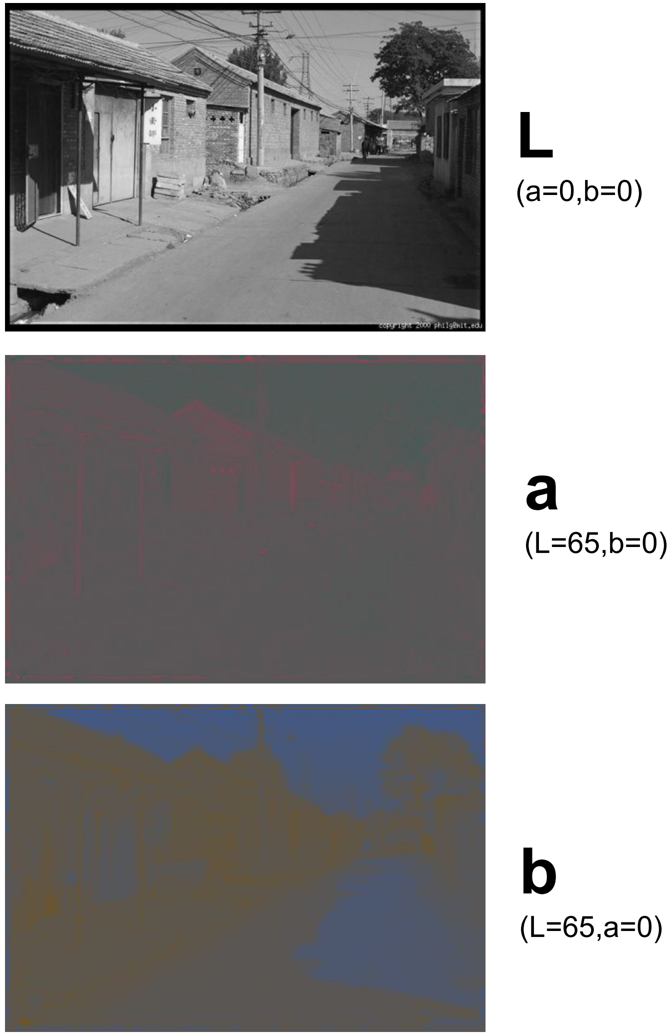




CIELAB model (aka L*a*b*)

- Commonly used
- Strives for perceptual uniformity
- L* is lightness
- a* and b* are color opponent pairs
  - a* is red-green
  - b* is blue-yellow





Outline

- Physics of color
- Human visual system
- Color reproduction
- Color spaces
- Color in digital cameras

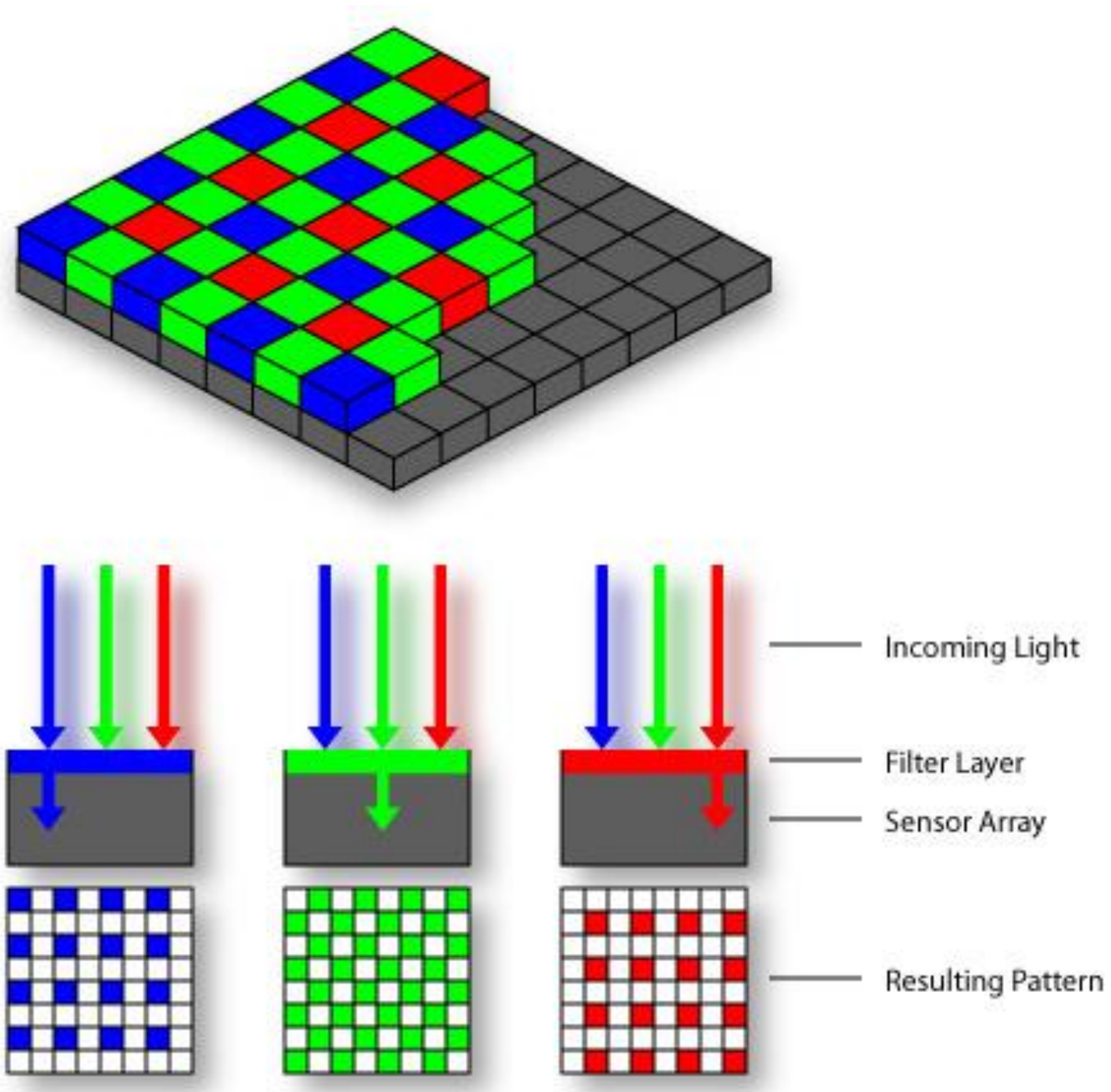
Problem

- Sensor can only record one number
- However, we need three numbers to show color

Solution

- Capture three images at different times
  - Scene motion
- Capture three images using three cameras
  - Change of viewpoint
- Bayer RGB mosaic

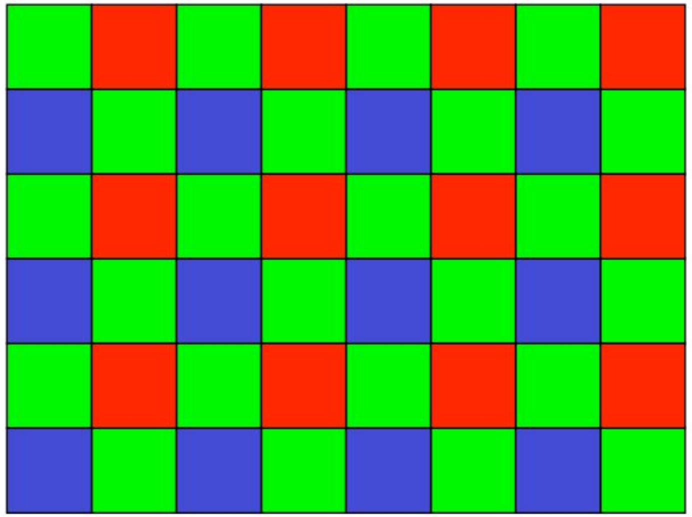
Practical Color Sensing: Bayer Grid



Slide by Steve Seitz

Bayer RGB mosaic

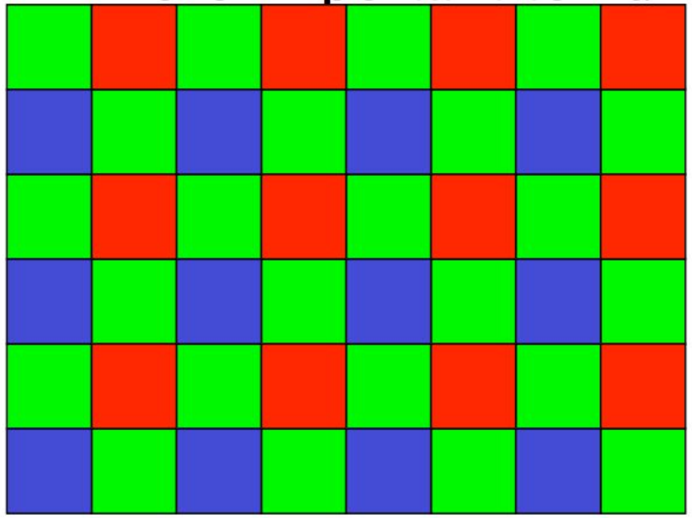
- Each photosite has a different color filter



Slide by Fredo Durand

Bayer RGB mosaic

- Why more green?
  - We have 3 channels and square lattice don't like odd numbers
  - It's the spectrum "in the middle"
  - More important to human perception of luminance

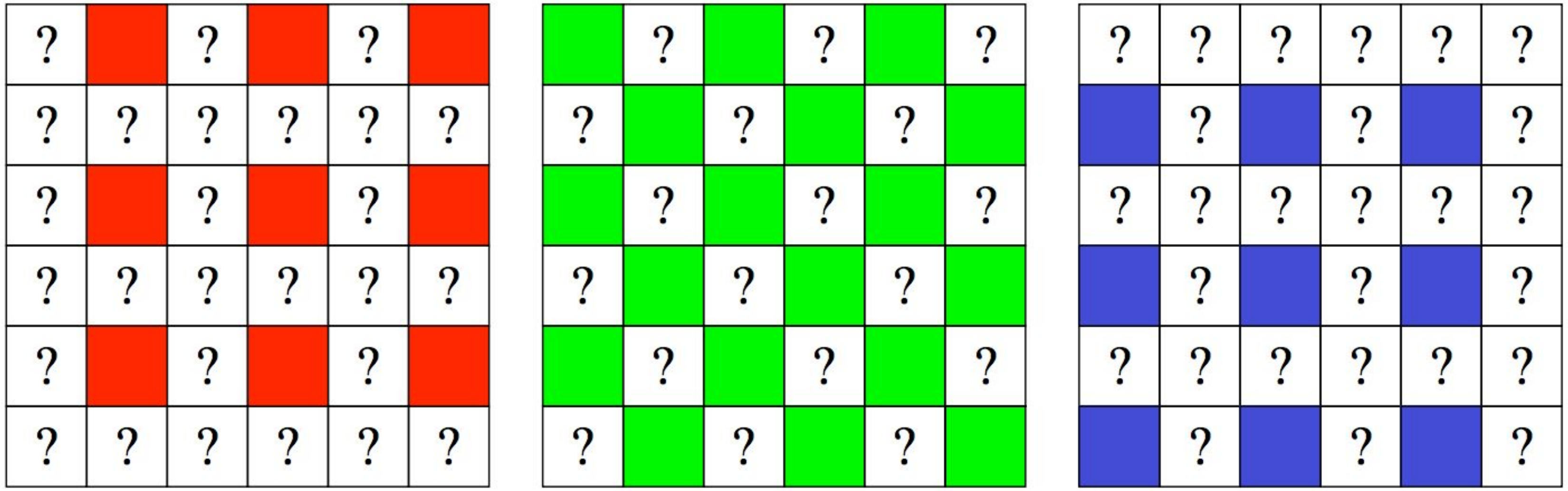


Slide by Fredo Durand

Demosaicing

- Interpolate missing values

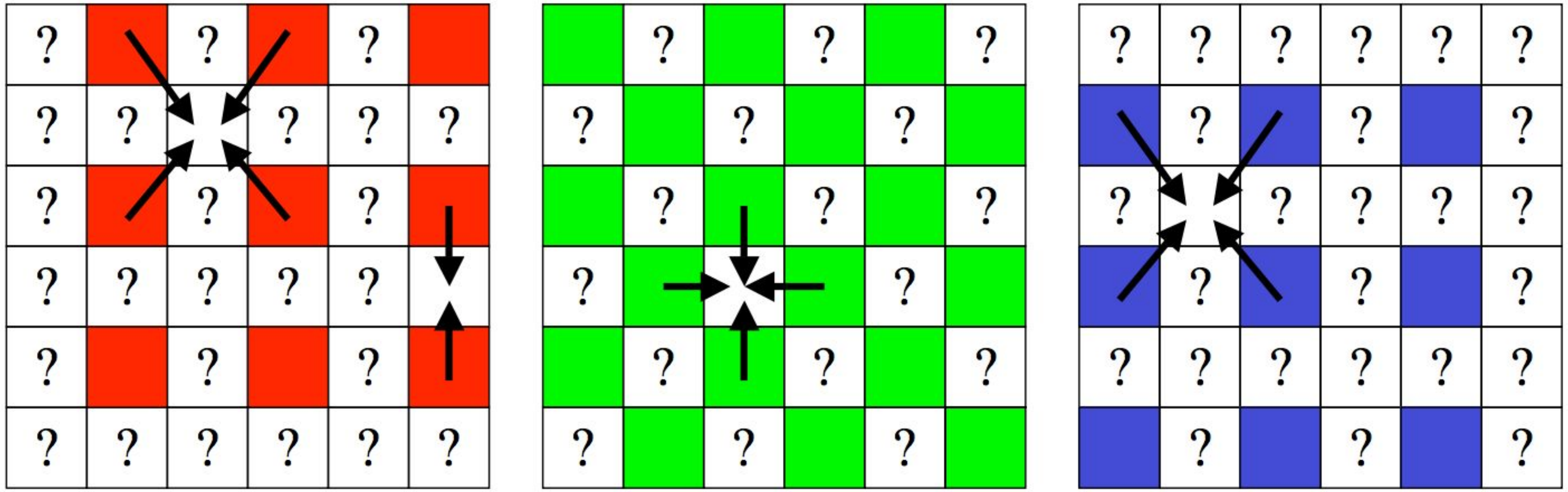
Nearest neighbor



Slide by Fredo Durand

Linear interpolation

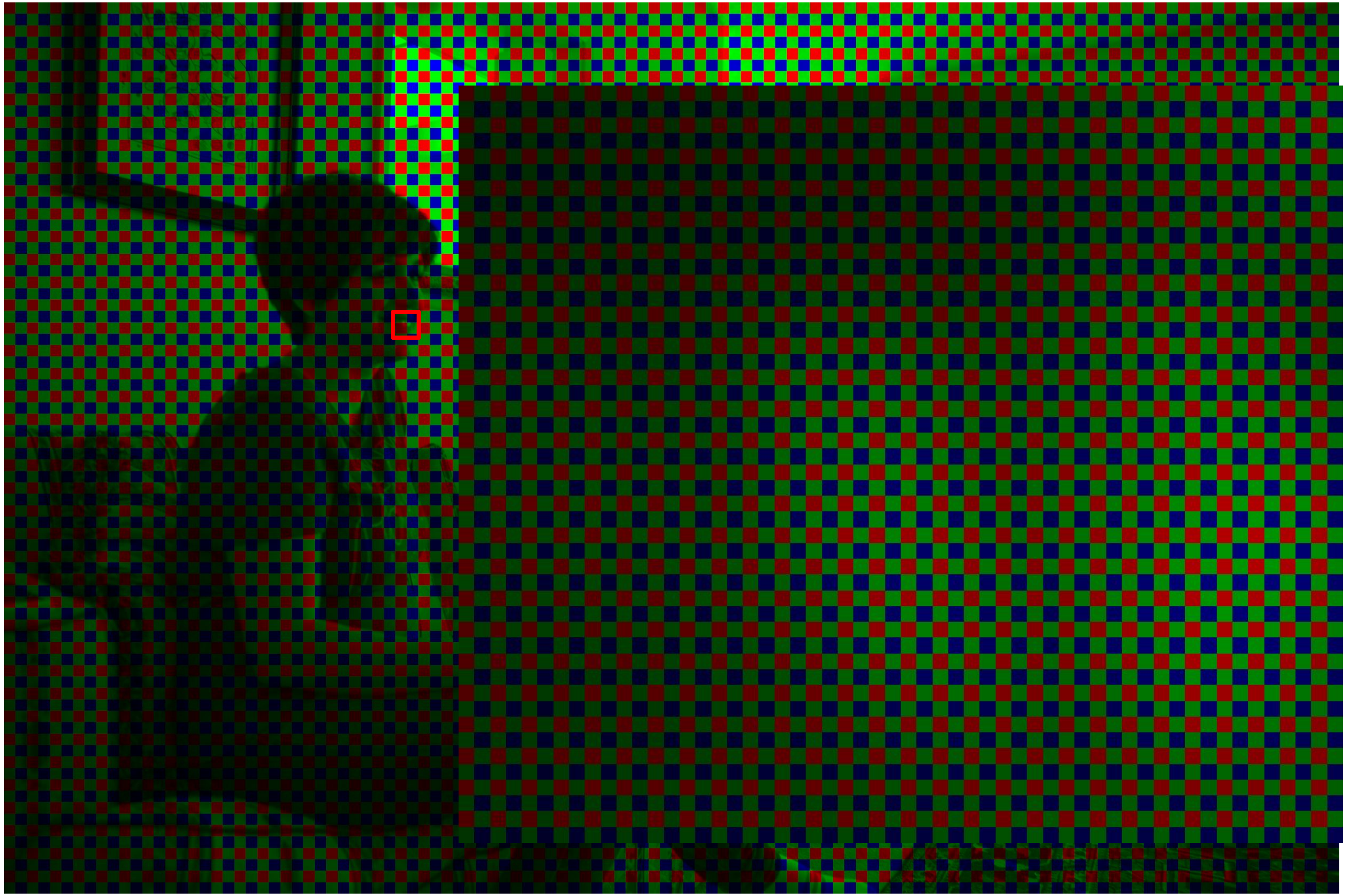
- Average of the 4 or 2 nearest neighbors
  - Linear (tent) kernel
- Smoother kernels can also be used (e.g. bicubic) but need wider support



Slide by Fredo Durand

Example

Example



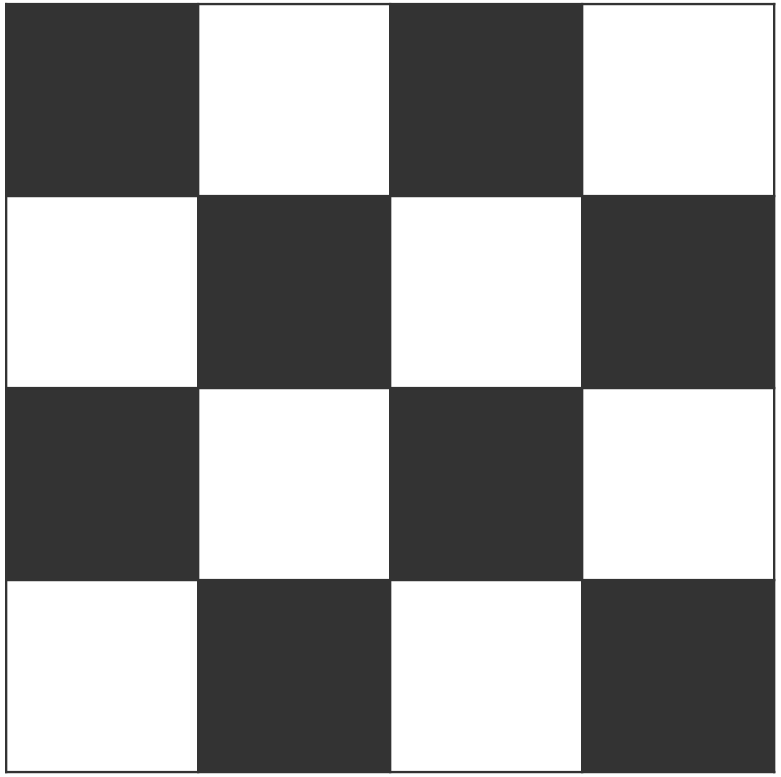
Example

Color Moire patterns

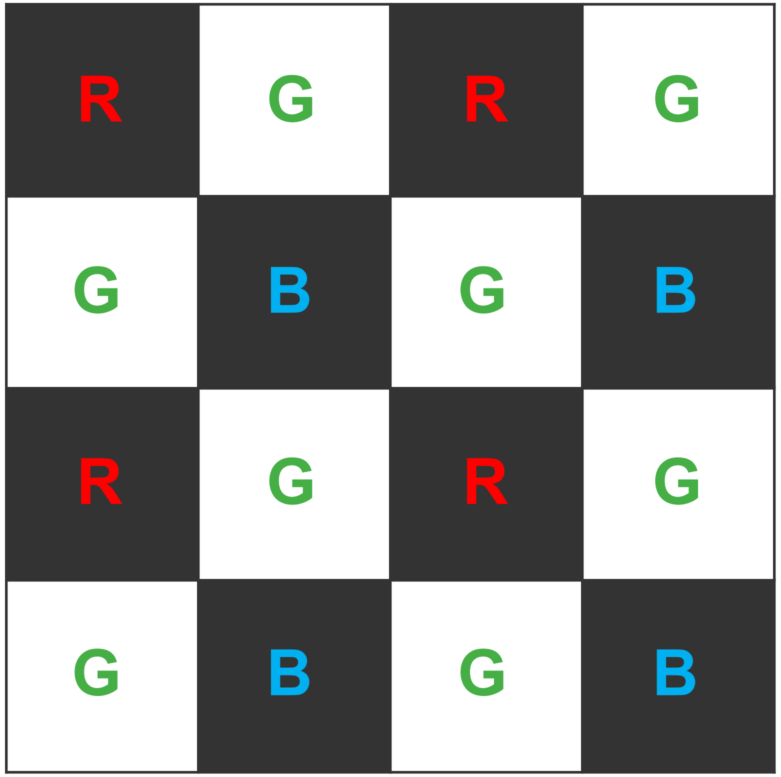
Typical color moire patterns

Slide credit: F. Durand

Moire patterns



Moire patterns



White balancing

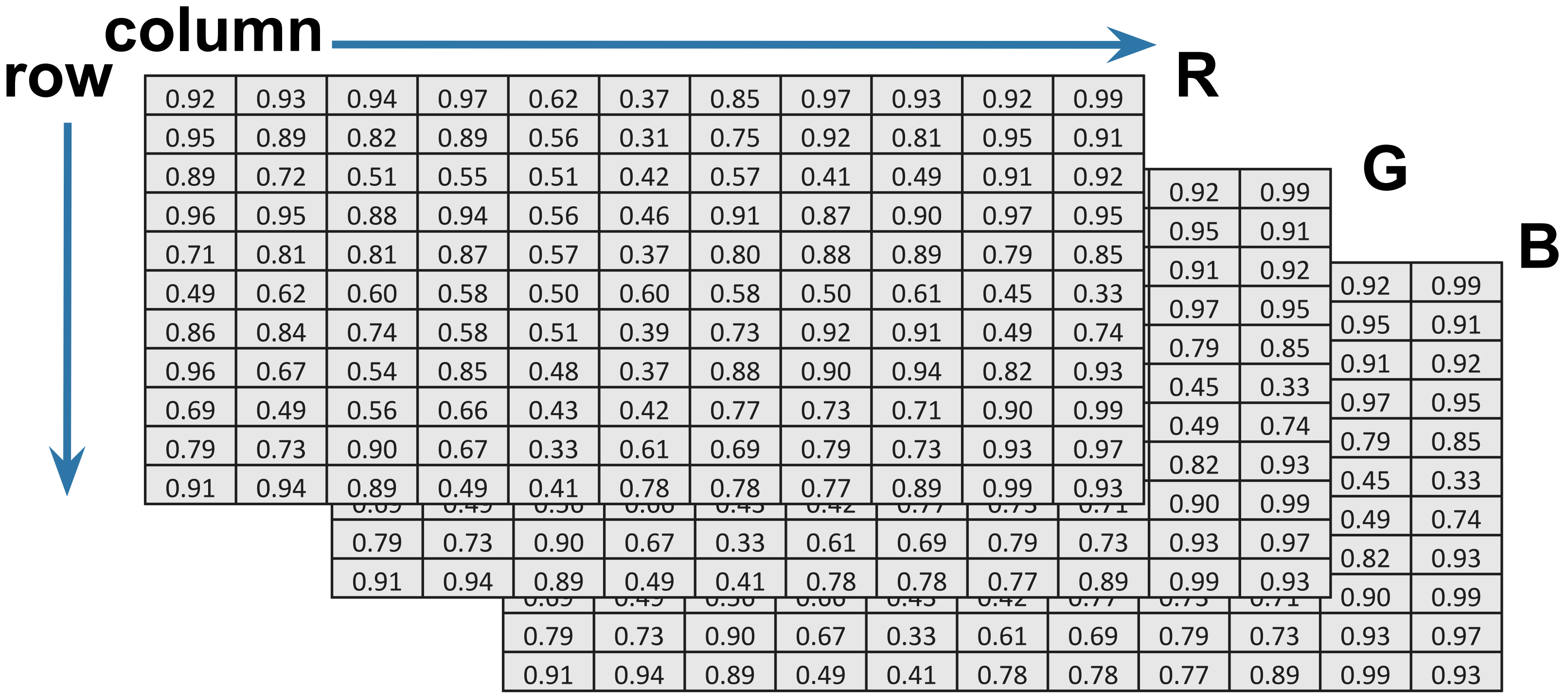
- Manual
  - Choose color-neutral object in the photos and normalize
- Automatic (AWB)
  - Grey World: force average color of scene to grey
  - White World: force brightest object to white

Credit: A. Efros

Project 2

Images in Python

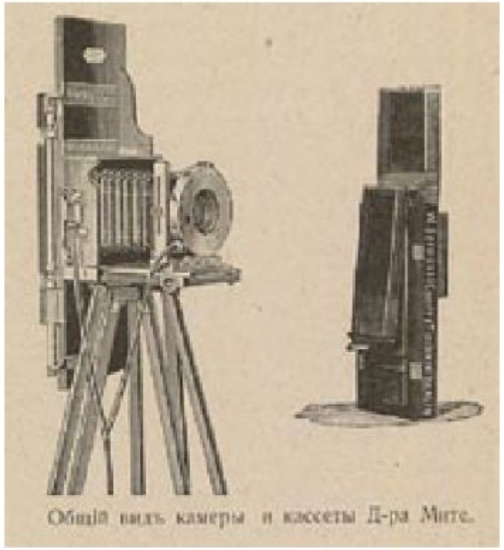
- Images represented as a matrix
- Suppose we have a NxM RGB image called “Im”
  - Im[0,0,0] = top-left pixel value in R-channel
  - Im[y, x, b] = y+1 pixels down, x+1 pixels to right in the bth channel
  - Im[N-1, M-1, 2] = bottom-right pixel in B-channel

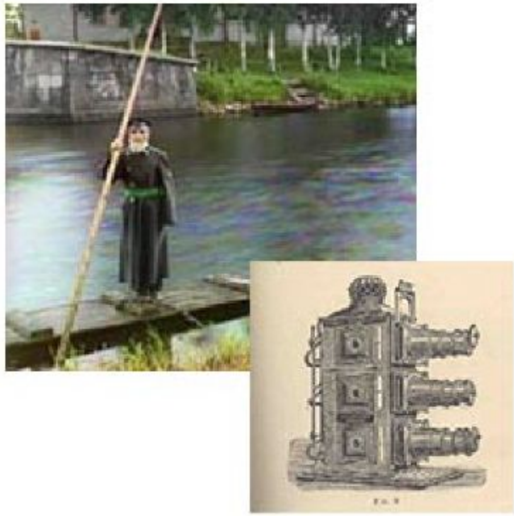


0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60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

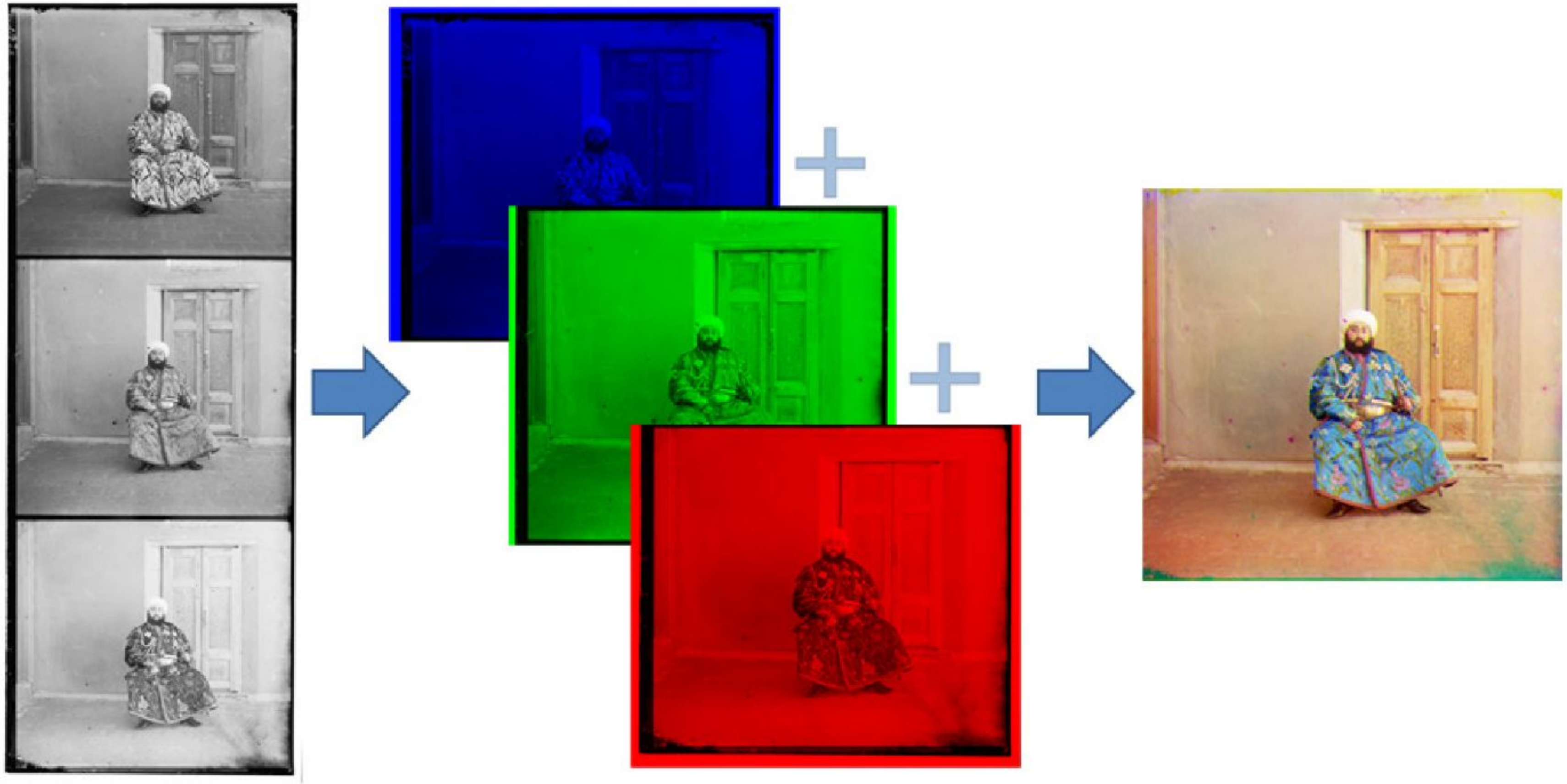
Project 2

Prokudin-Gorskii's Color Photography (1907)





Project 2



Credit: A. Efros

Project 2

R channel

Project 2

G channel

Project 2

B channel

Project 2

- **Goal:** Align R and G channels to B
- **Assumption:** (t_x, t_y) translation aligns the channels
- To align, for example, G to B:
  - For each (t_x, t_y) in a small range
    - Shift G with (t_x, t_y)
    - Check if the shifted G matches B

      Sum of squared differences

$$\mathrm{SSD}(G, B) = \sum_{i=1}^{W} \sum_{j=1}^{H} (G(i,j) - B(i,j))^2$$

  - Return (t_x, t_y) with smallest SSD

Project 2

- For large images, exhaustive search is slow

Example - R

2400

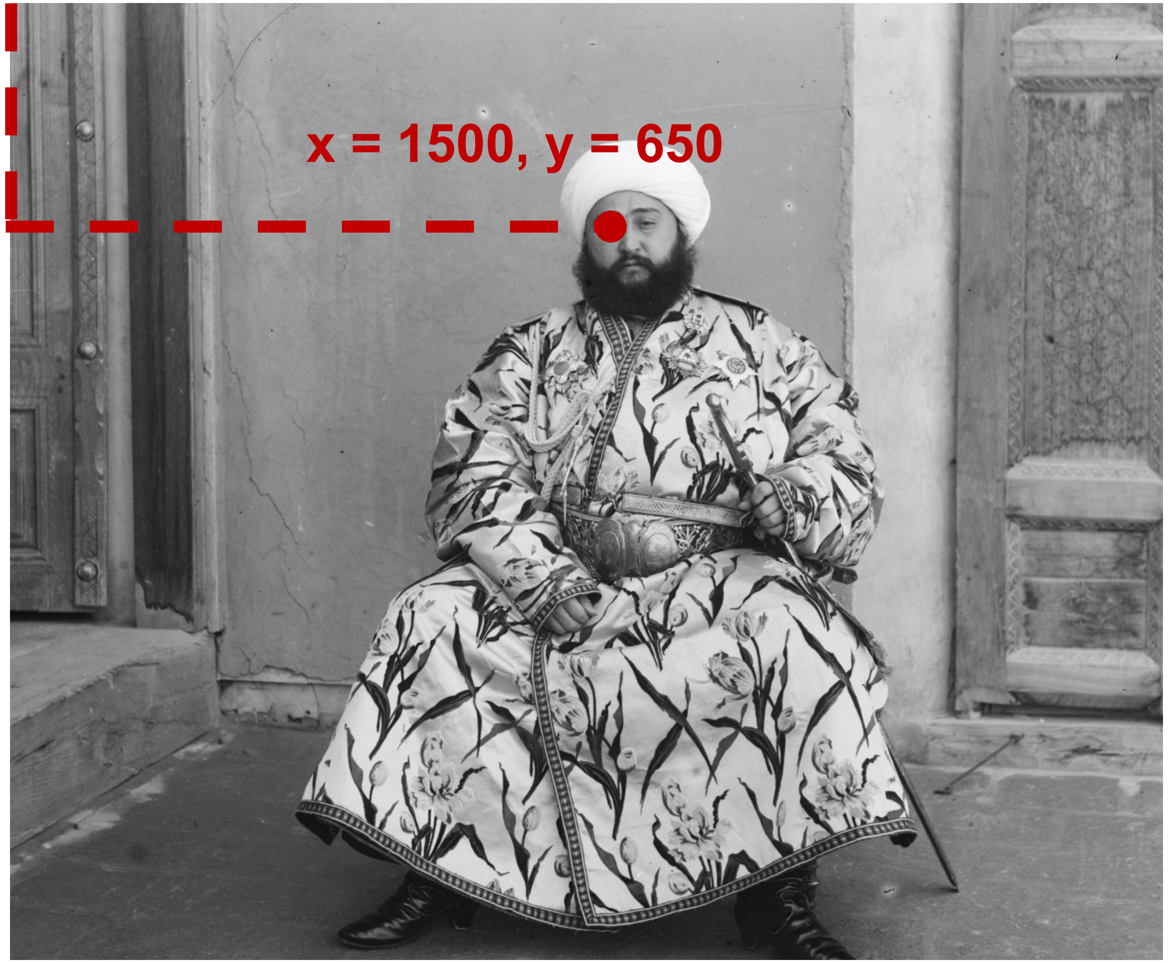
2900

Example - B

2400

2900

Example

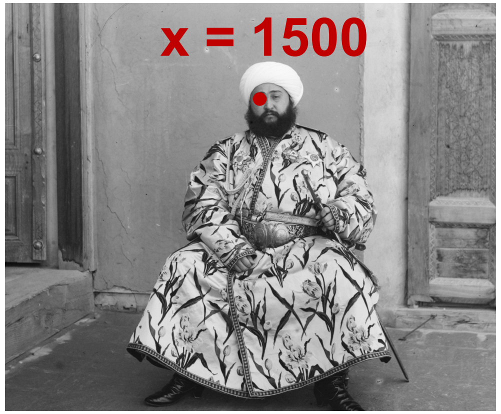


$t_x = 83, t_y = 0$

Project 2

- For large images, exhaustive search is slow
  - We need to compute SSD on high res images
  - Search range is large (eg., -100 to 100)
- Build a pyramid
- Multi-scale search

Multi-scale search



$t_x = 83$

x = 750

x = 791.5

$t_x = 41.5$

x = 375

x = 395.75

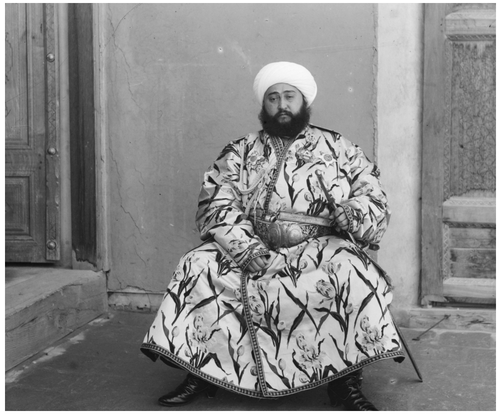
$t_x = 20.75$

x = 187.5

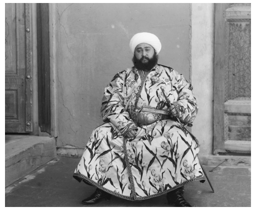
x = 197.875

$t_x = 10.375$

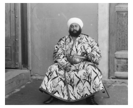
Multi-scale search

Perform local search around 84 (42 * 2) – find t_x = 83

Perform local search around 42 (21 * 2) – find t_x = 42

Perform local search around 20 (10 * 2) – find t_x = 21


Perform search – find t_x = 10