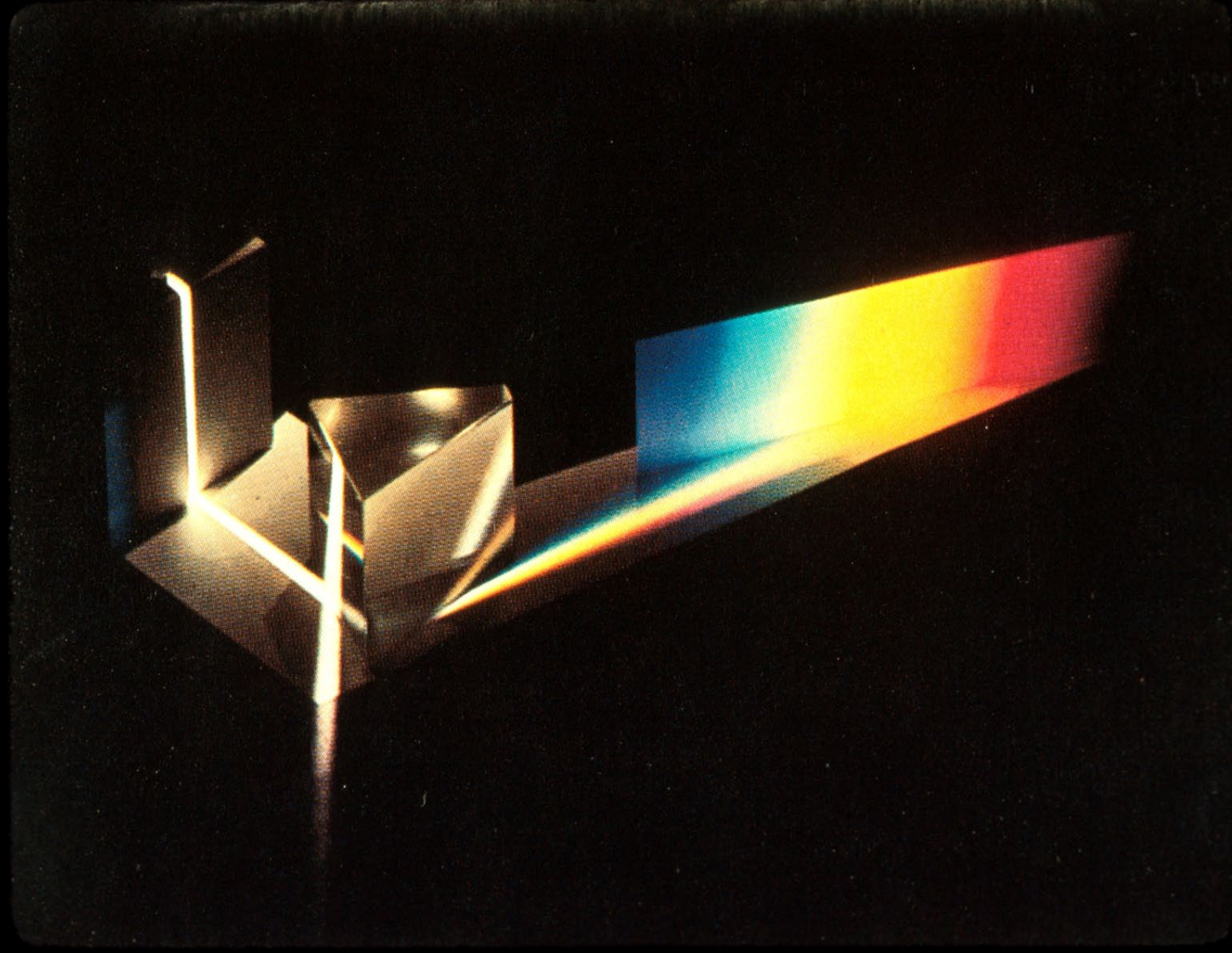


CSE160 – Color - Oct 22

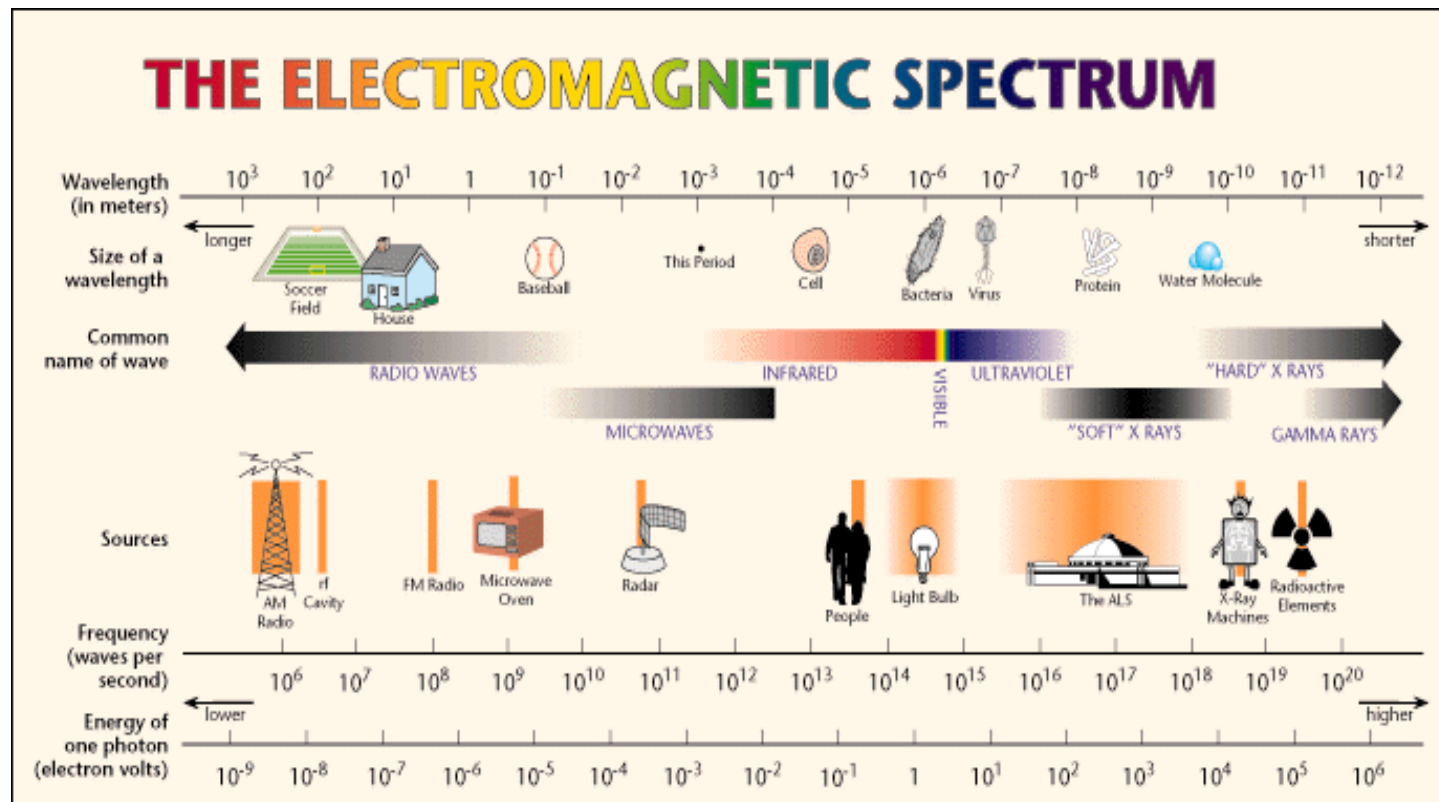
- From physics to perception
- Additive color
- RGB-Alpha
- Subtractive color
- HSV color
- YIQ/YUV color
- Color Gamuts, Color Matching, and XYZ
- Administrative
- Q&A

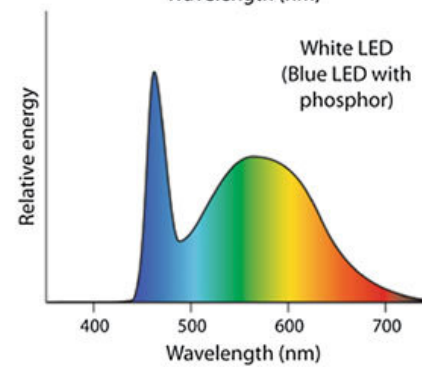
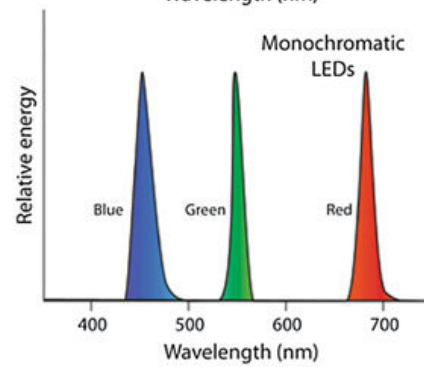
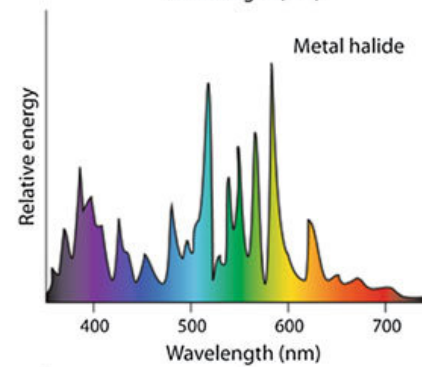
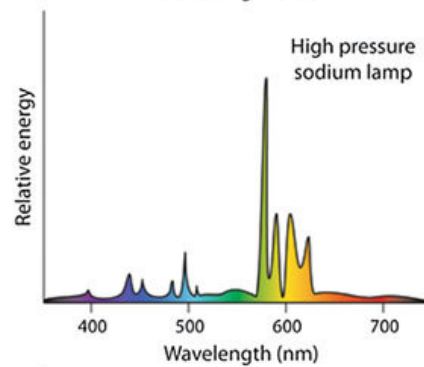
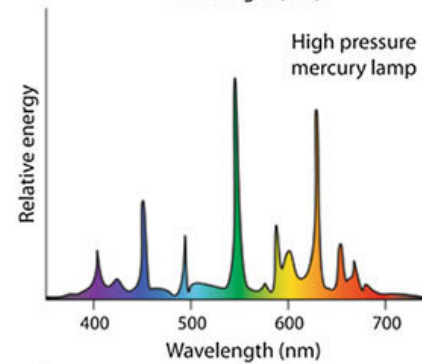
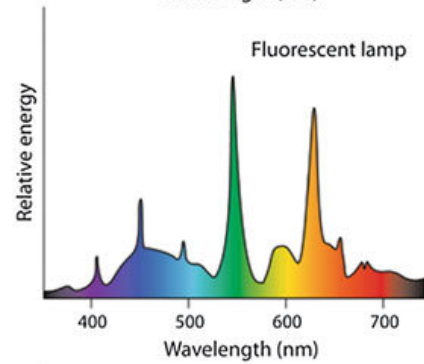
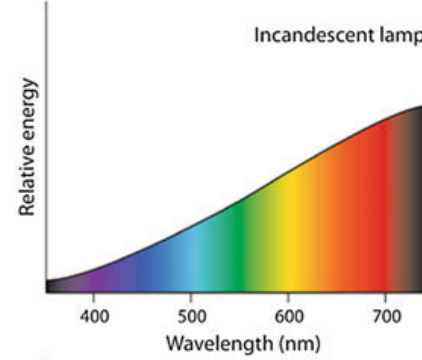
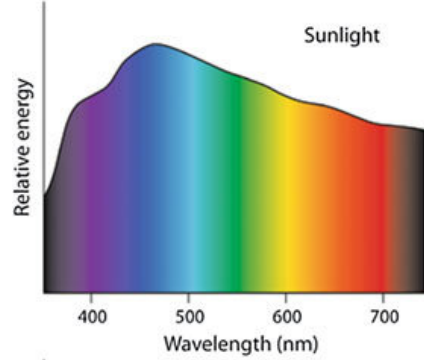
From physics to perception



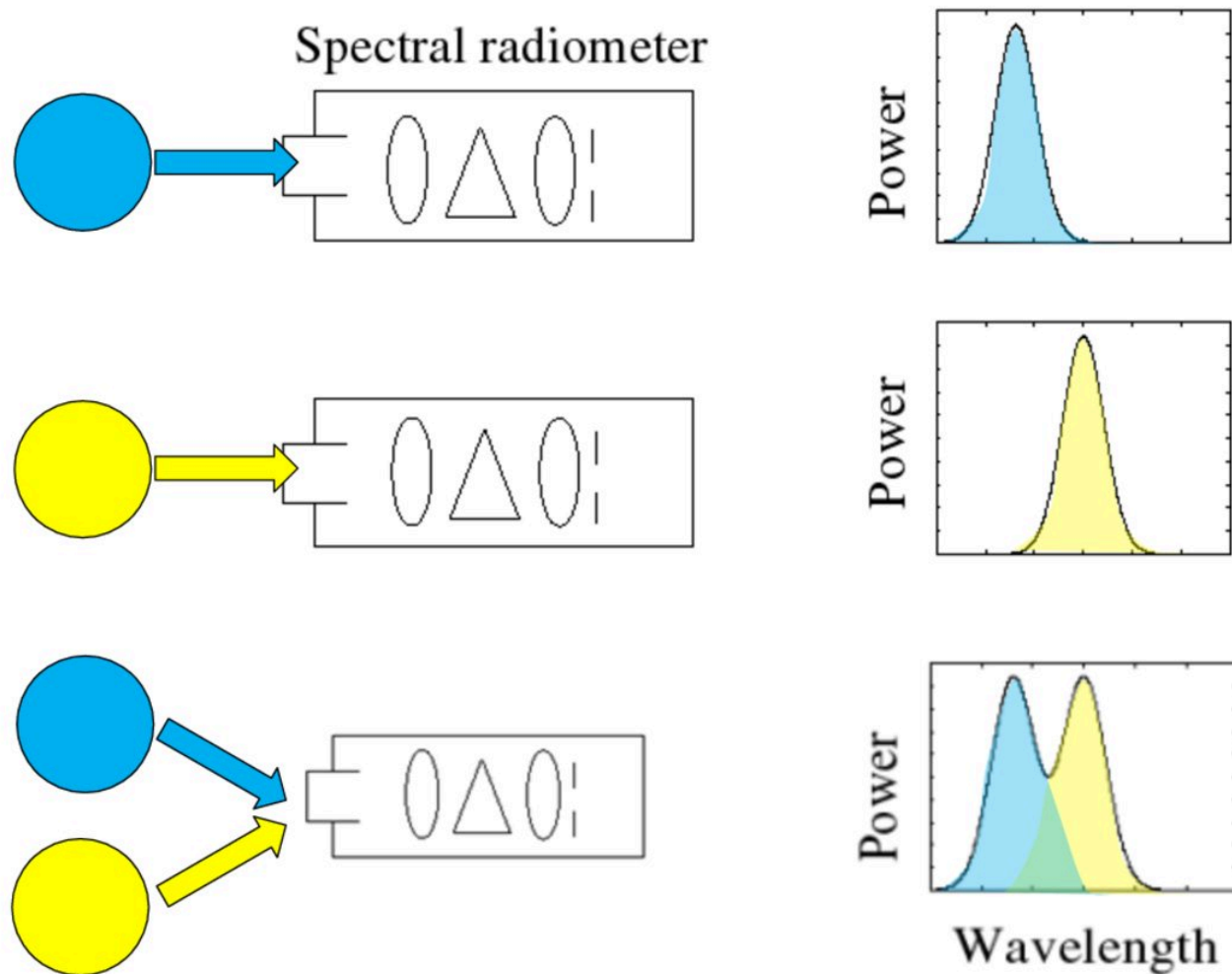
What light is

- Light is electromagnetic radiation
 - exists as oscillations of different frequency (or, wavelength)





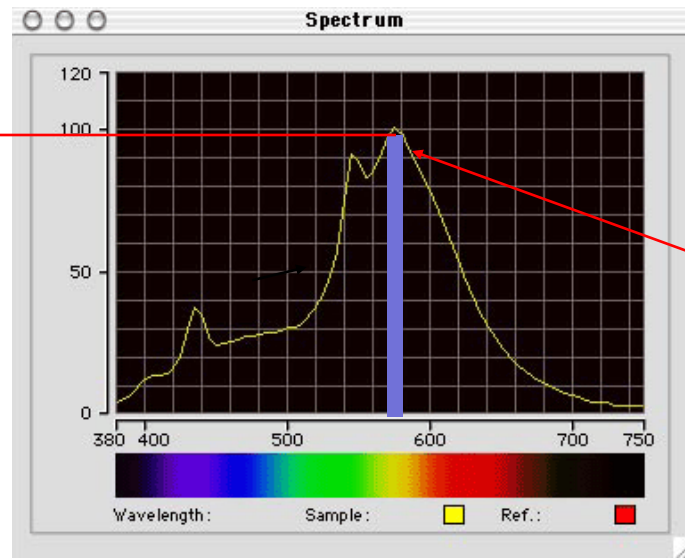
Superposition (linearity) of spectral power distributions



Measuring light

- Salient property is the *spectral power distribution (SPD)*
 - the amount of light present at each wavelength
 - units: Watts per nanometer (tells you how much power you'll find in a narrow range of wavelengths)

amount of light = $96\ d$
(relative units)

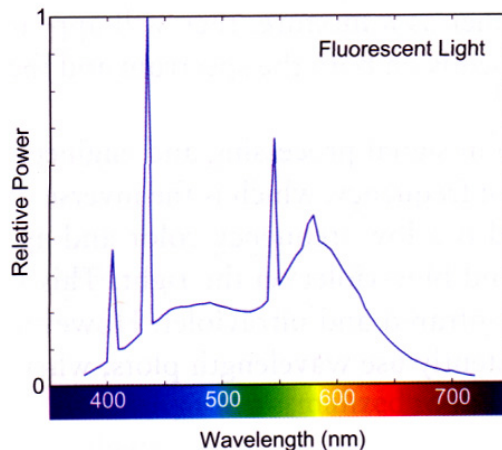


wavelength
band
(width d)

wavelength (nm)

But why do we see “color”?

- Map a *Physical light description* to a *Perceptual color sensation*



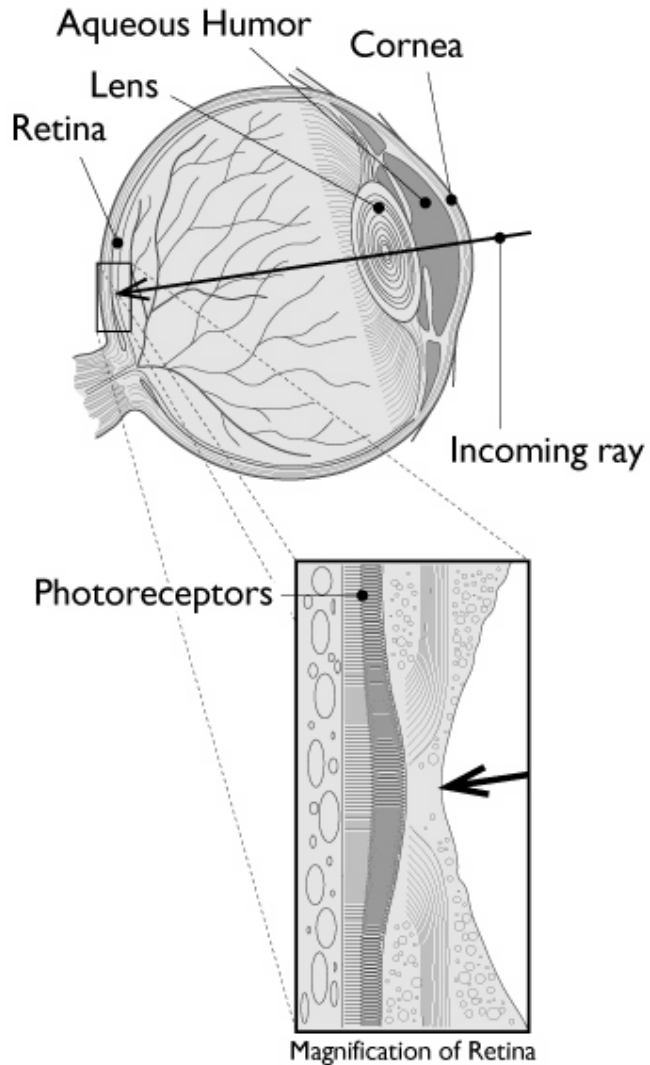
Physical



?

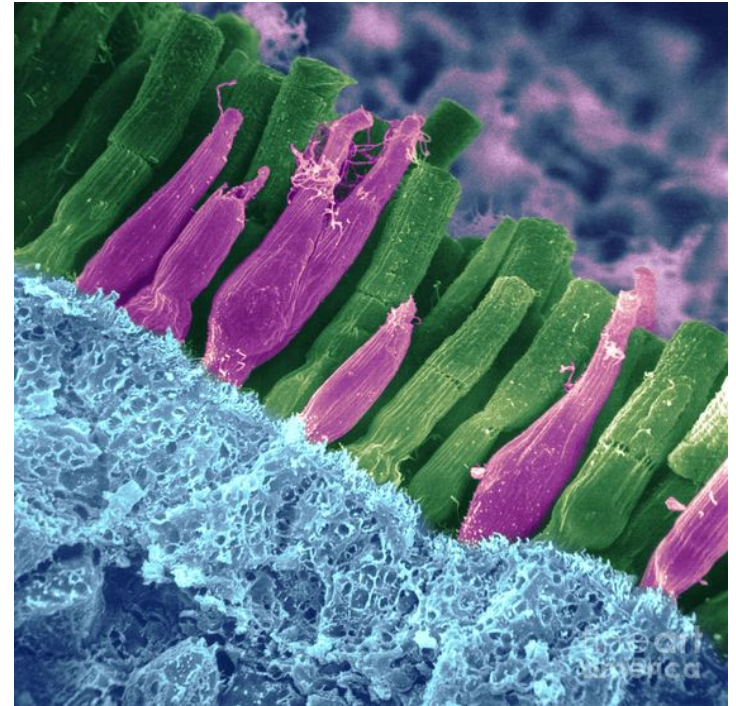
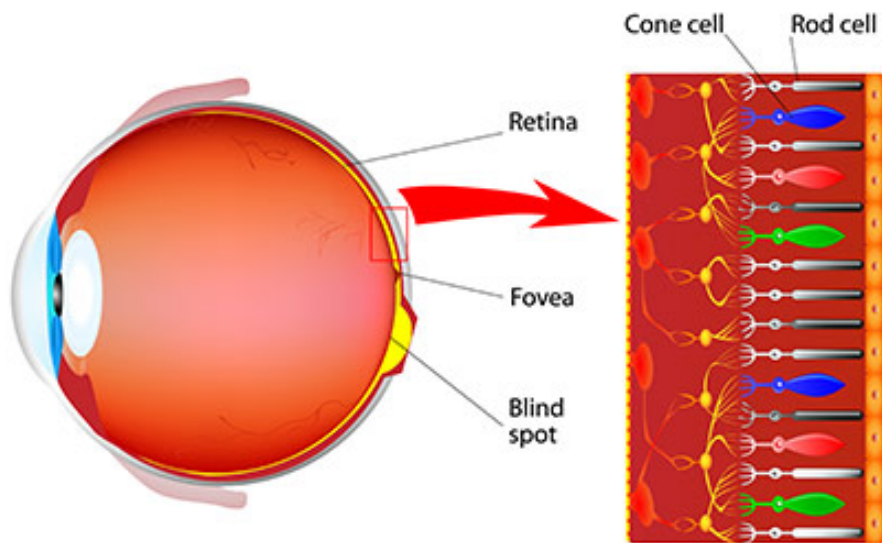
Perceptual

The eye as a measurement device

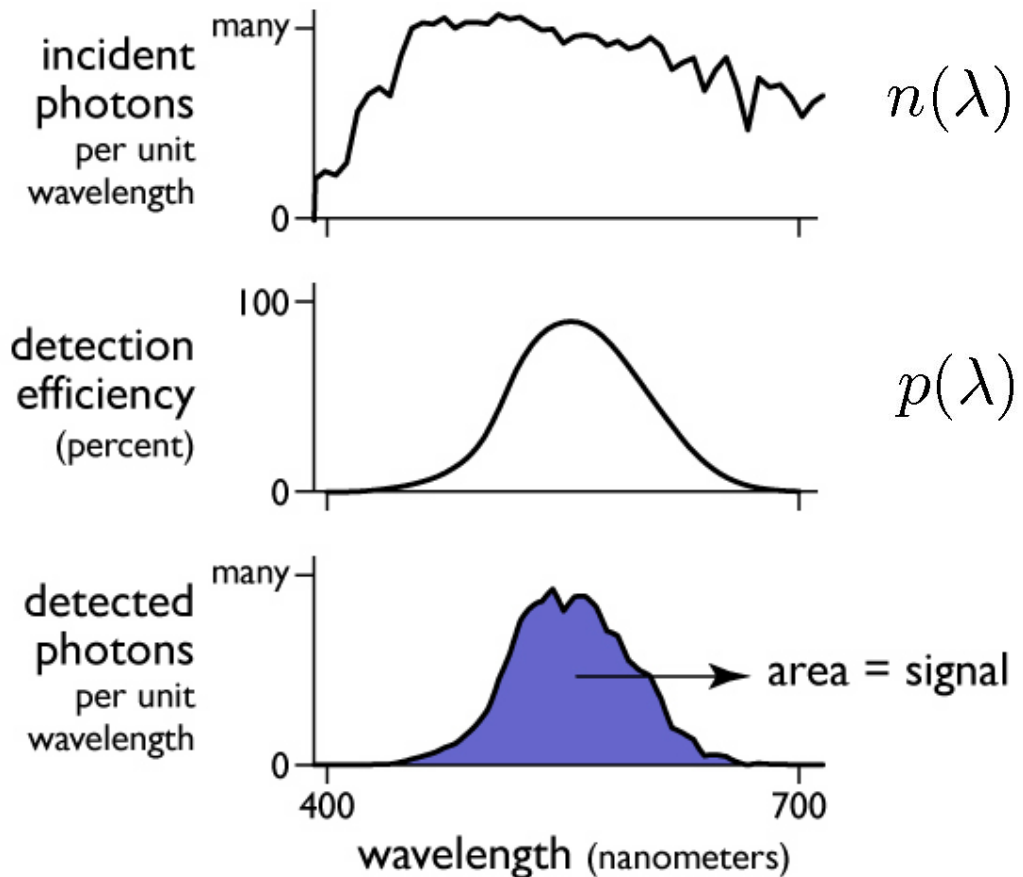
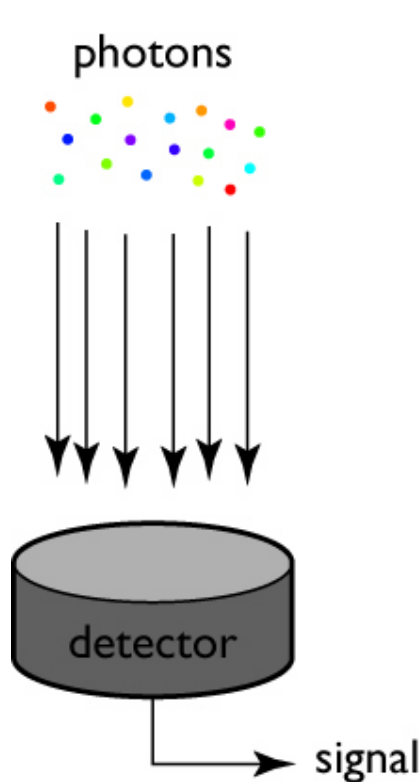


- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
 - its optics are much like a camera
 - its detection mechanism is also much like a camera
- Light is measured by the *photoreceptors* in the retina
 - they respond to visible light
 - different types respond to different wavelengths

Photoreceptor cell



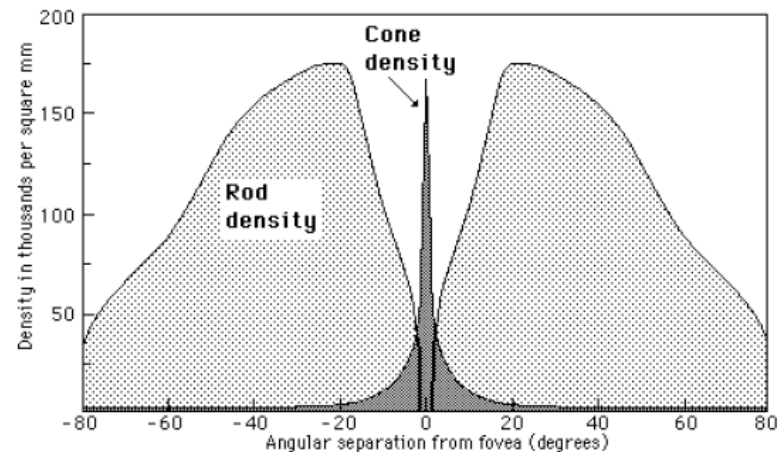
A simple light detector



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

Cones

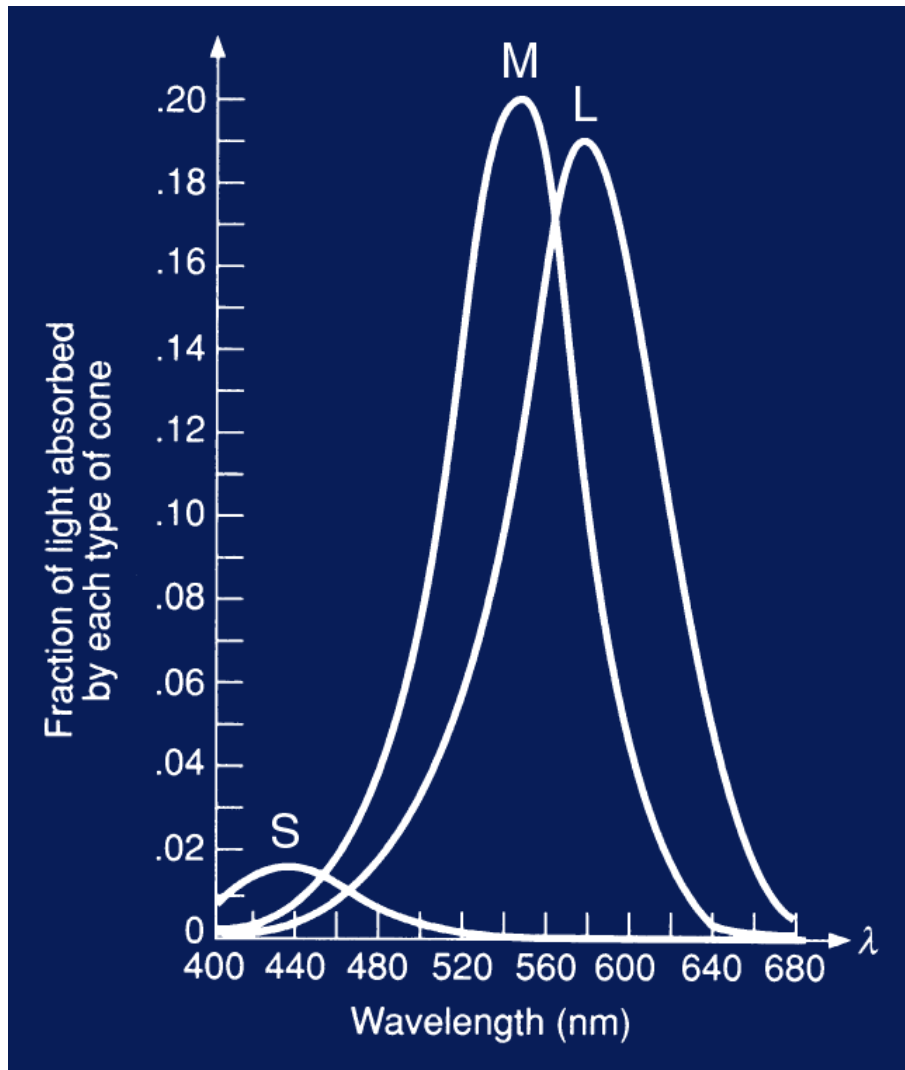
- Responsible for photopic (light-adjusted) vision and color perception
- 7 million total concentrated in narrow band around the fovea
- Three distinct types:
 - S (2%) correspond to blue
 - M (32%) correspond to green
 - L (64%) correspond to red
- Provide the physiological basis for trichromatic color theory



Rods

- Monochromatic perception
- Responsible for scotopic (dim-light) vision and motion sensing
- 120 million total concentrated in mid-periphery
- One-thousand times more sensitive than cones
- Tetrachromacy in mesopic vision during intermediate lighting conditions

Cone Responses

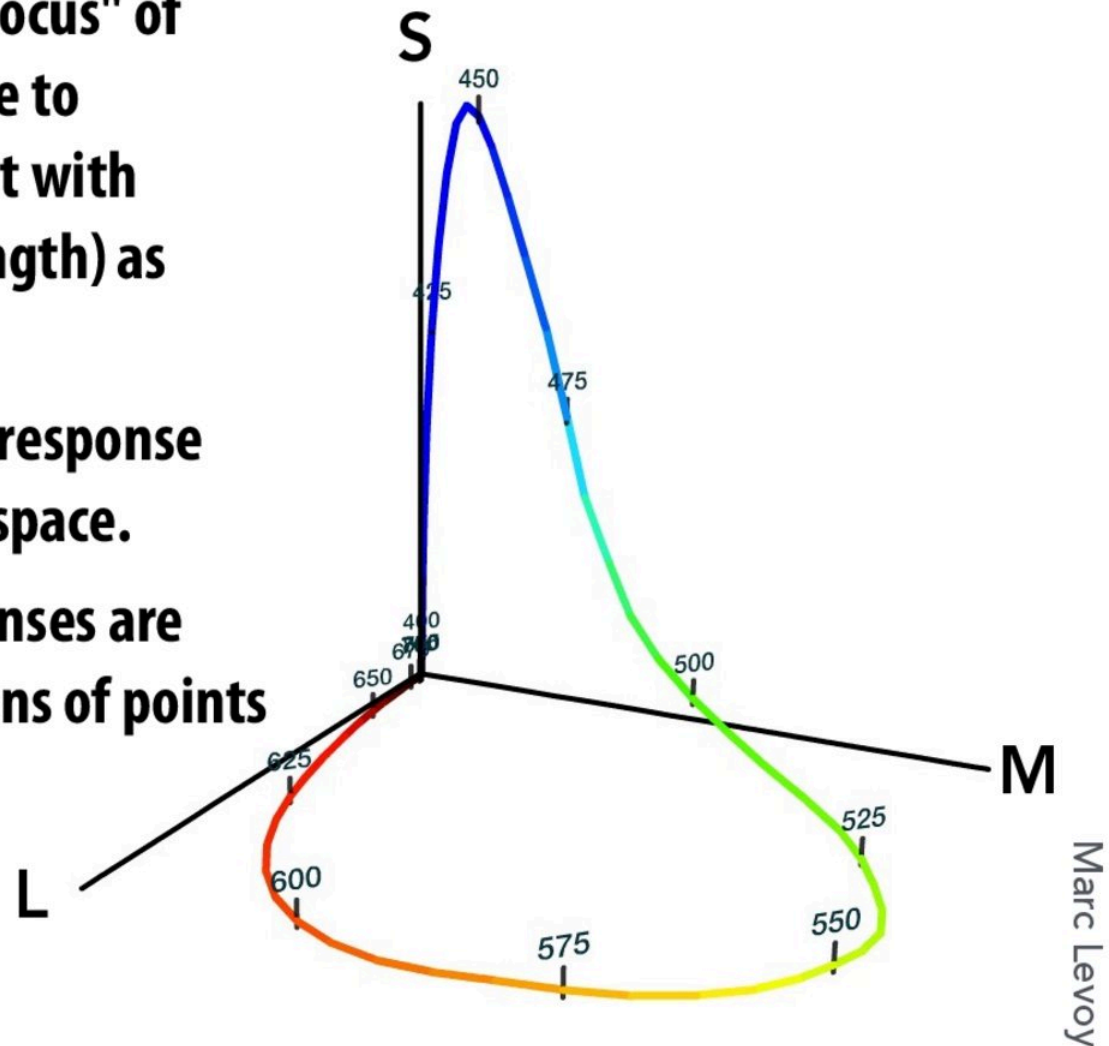


- S, M, L cones have broadband spectral sensitivity
- S, M, L neural response is integrated w.r.t. λ
 - we'll call the response functions r_S, r_M, r_L
- Results in a trichromatic visual system
- S, M, and L are *tristimulus values*

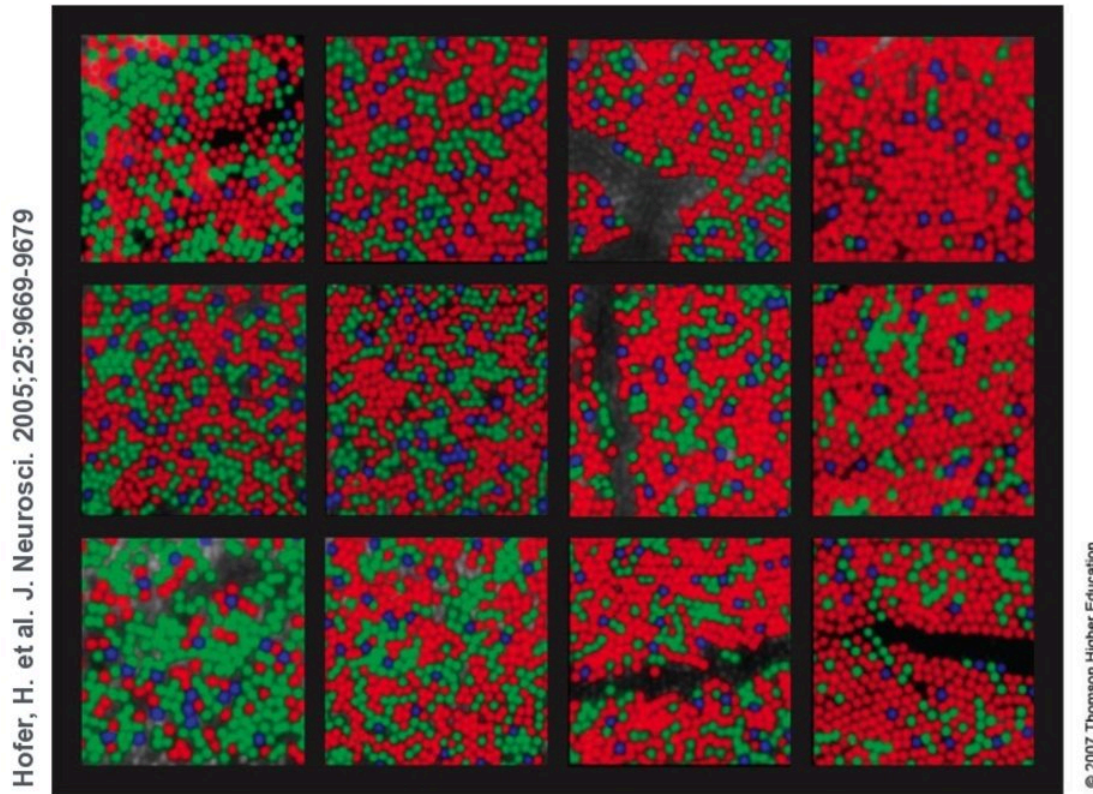
[source unknown]

LMS responses plotted as 3D color space

- Visualization of "spectral locus" of human cone cells' response to monochromatic light (light with energy in a single wavelength) as points in 3D space.
- This is a plot of the S, M, L response functions as a point in 3D space.
- Space of all possible responses are positive linear combinations of points on this curve.

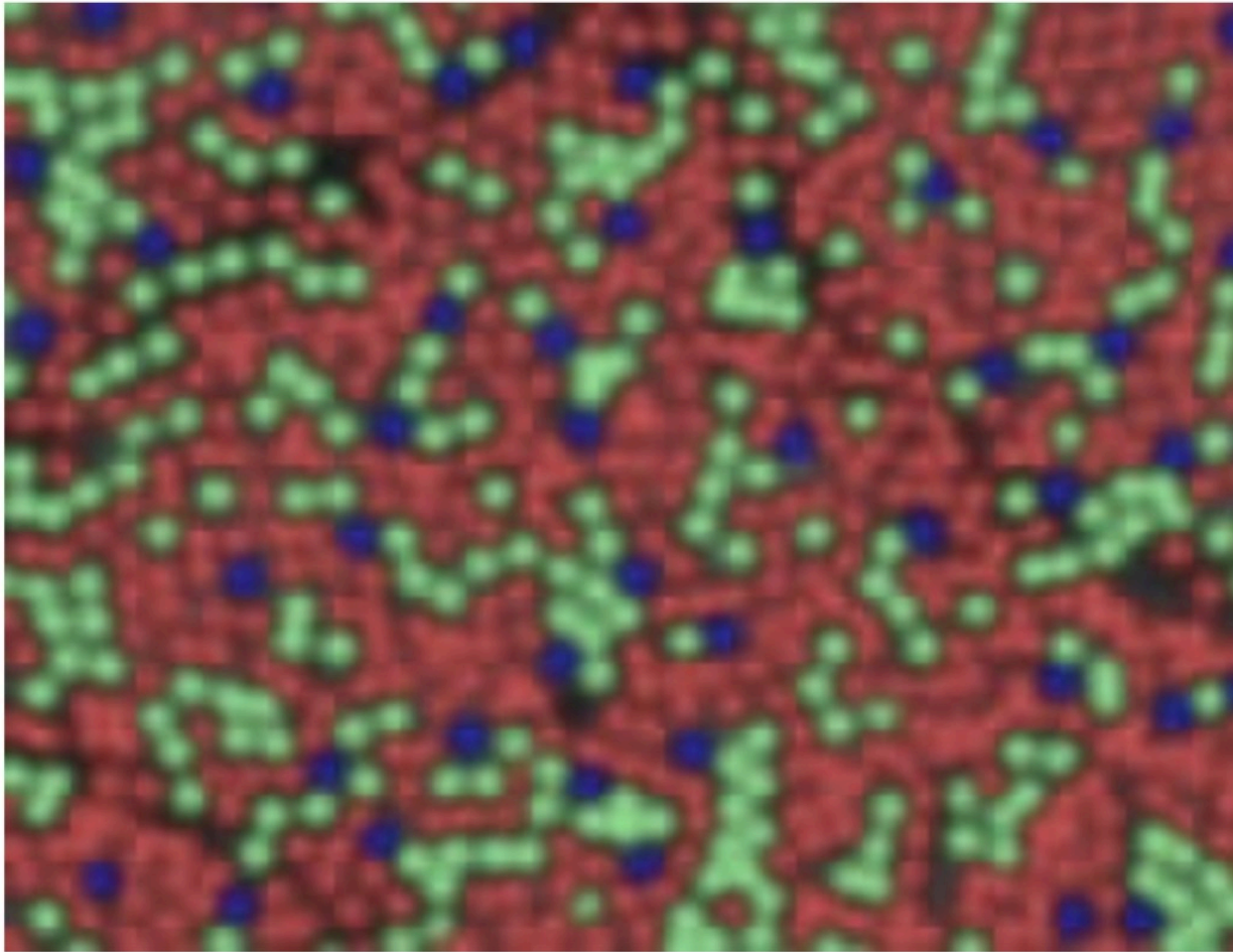


Fraction of three cone cell types varies widely



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)

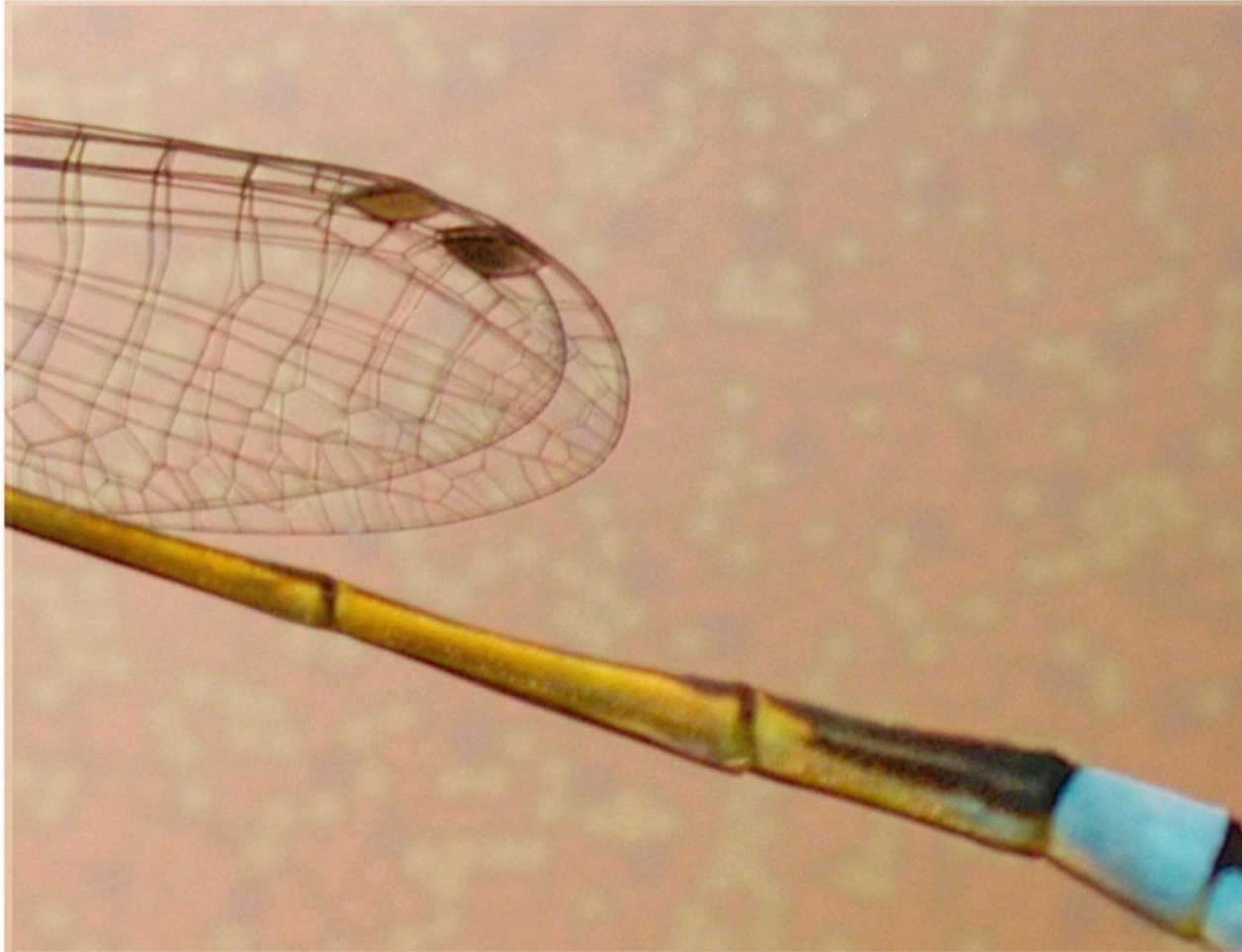
Example: spectral response of human cone cells



Scene projected onto retina

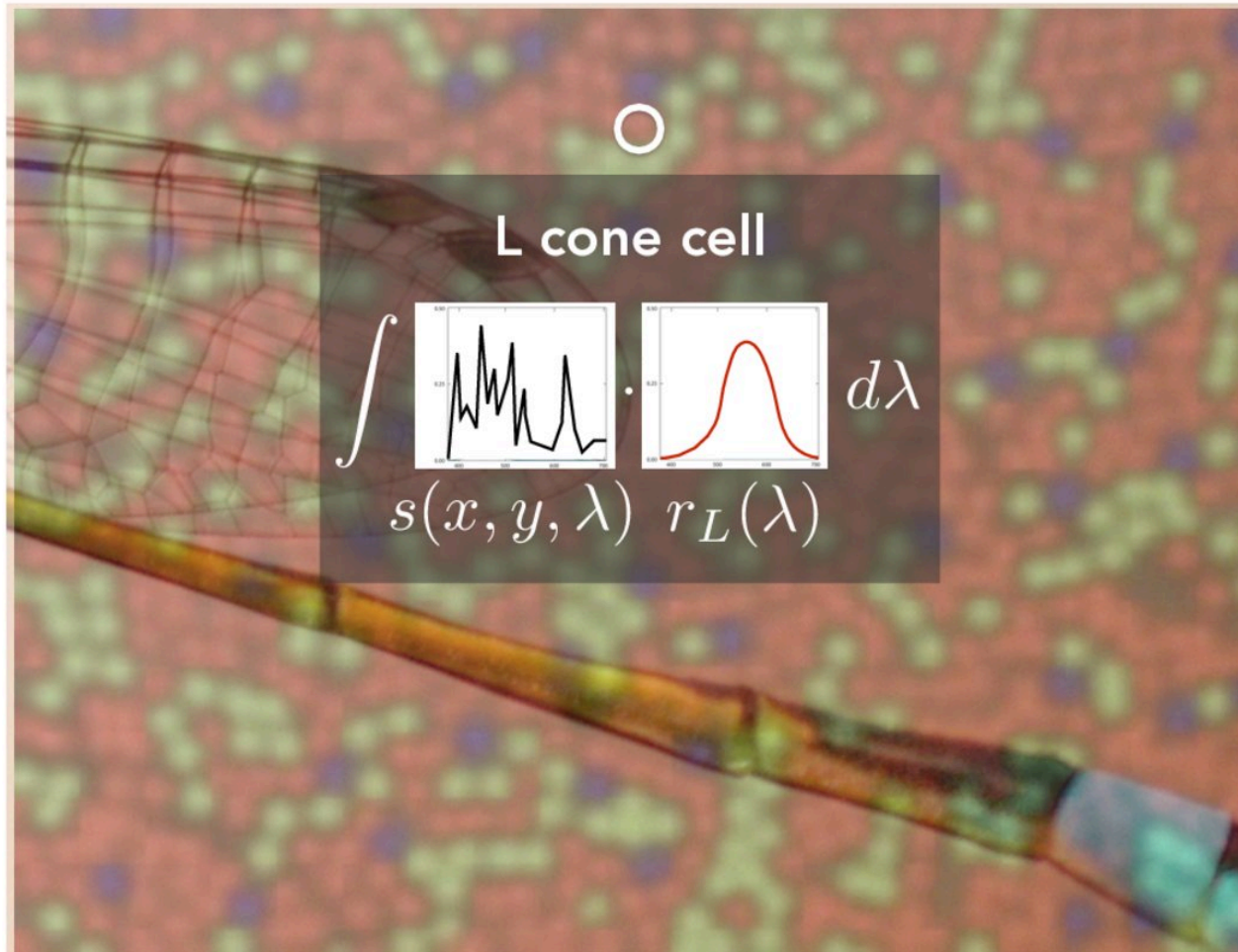
Credit: Sabesan, <http://depts.washington.edu/sabaolab/>

Example: spectral response of human cone cells

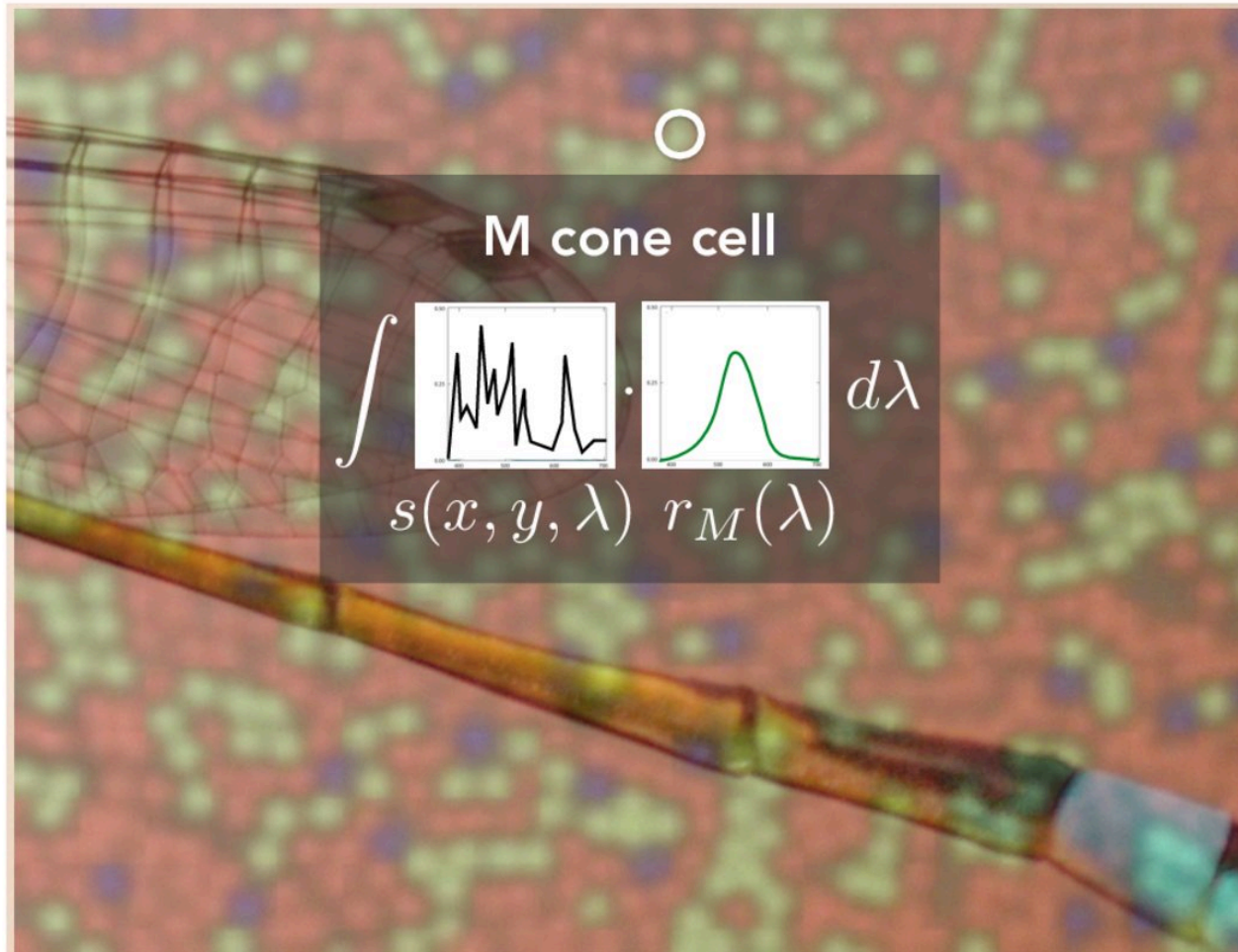


Scene projected onto retina

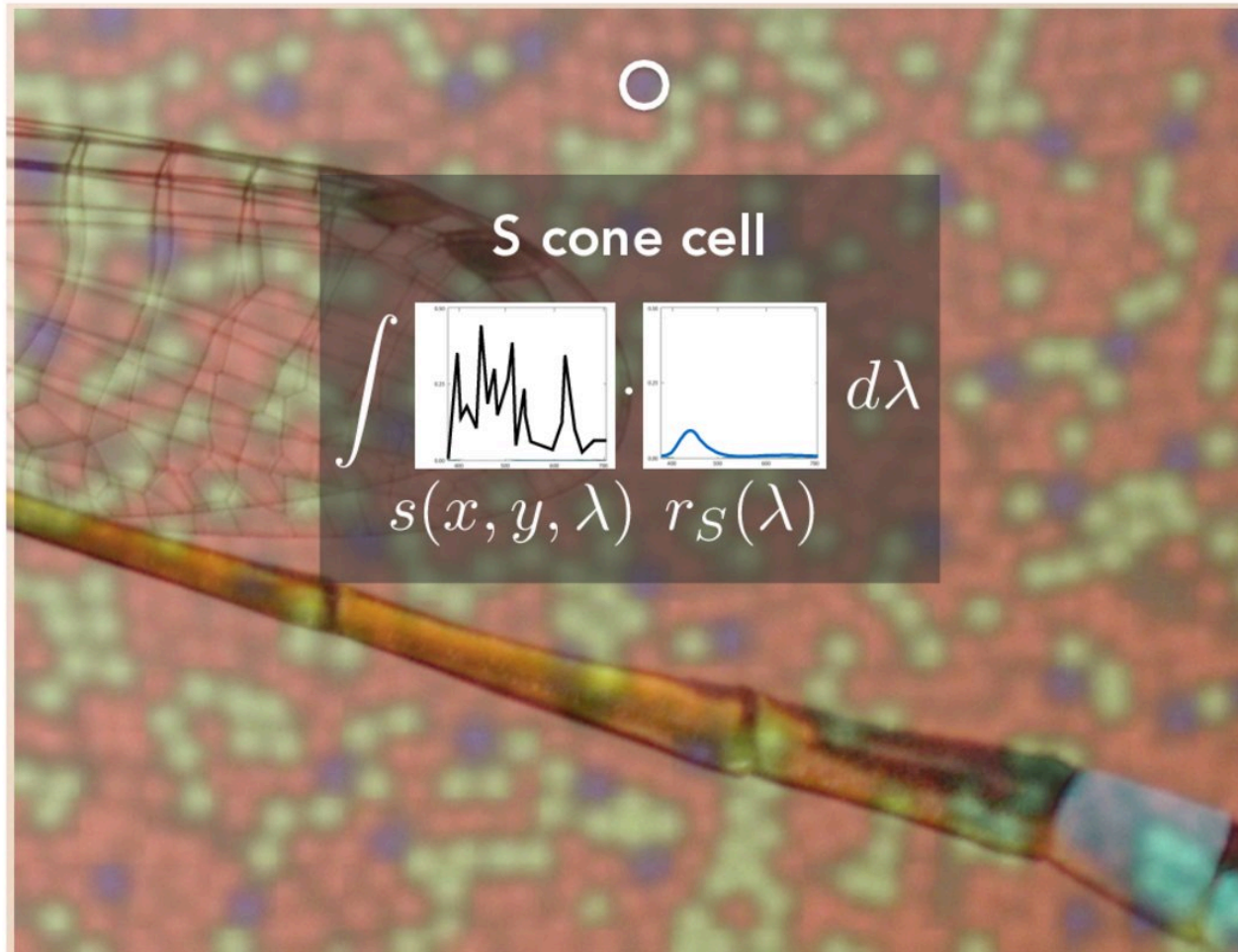
Example: spectral response of human cone cells



Example: spectral response of human cone cells

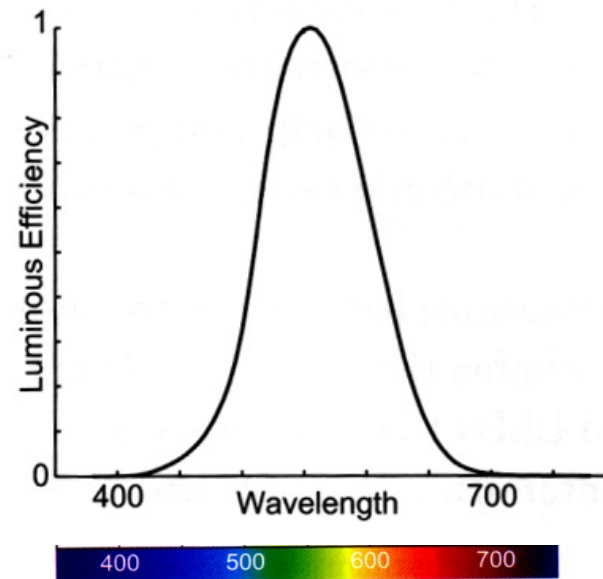
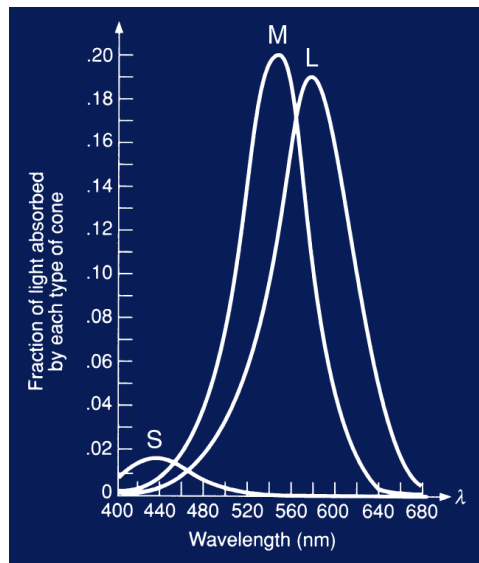


Example: spectral response of human cone cells



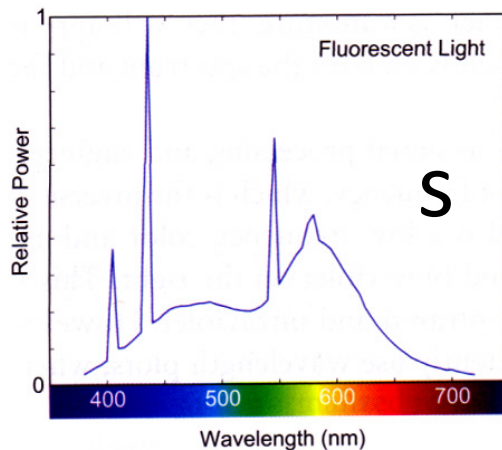
Luminance (brightness)

- Combined visual response to a spectrum

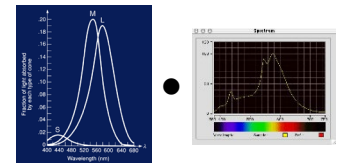


Colorimetry: an answer to the problem

- Wanted to map a *Physical light description* to a *Perceptual color sensation*
- Basic solution was known and standardized by 1930



Physical

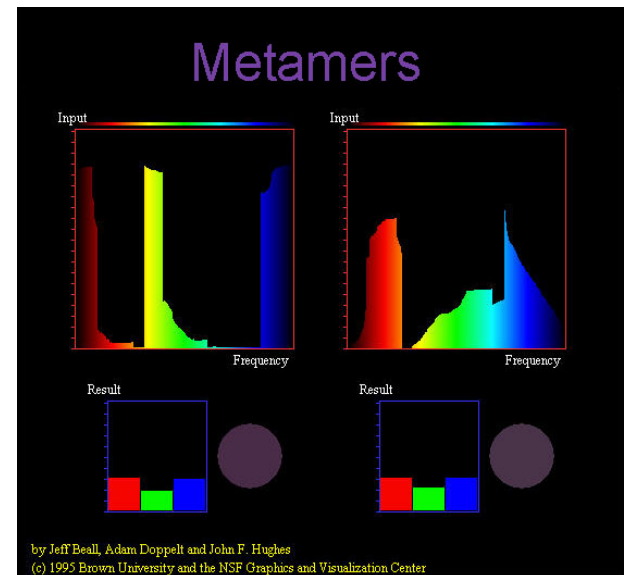


$$\begin{aligned} S &= r_S \cdot s \\ M &= r_M \cdot s \\ L &= r_L \cdot s \end{aligned}$$

Perceptual

Metamers

- Take a spectrum (which is a function)
- Eye produces three numbers
- This throws away a lot of information!
 - Quite possible to have two different spectra that have the same S, M, L tristimulus values
 - Two such spectra are *metamers*



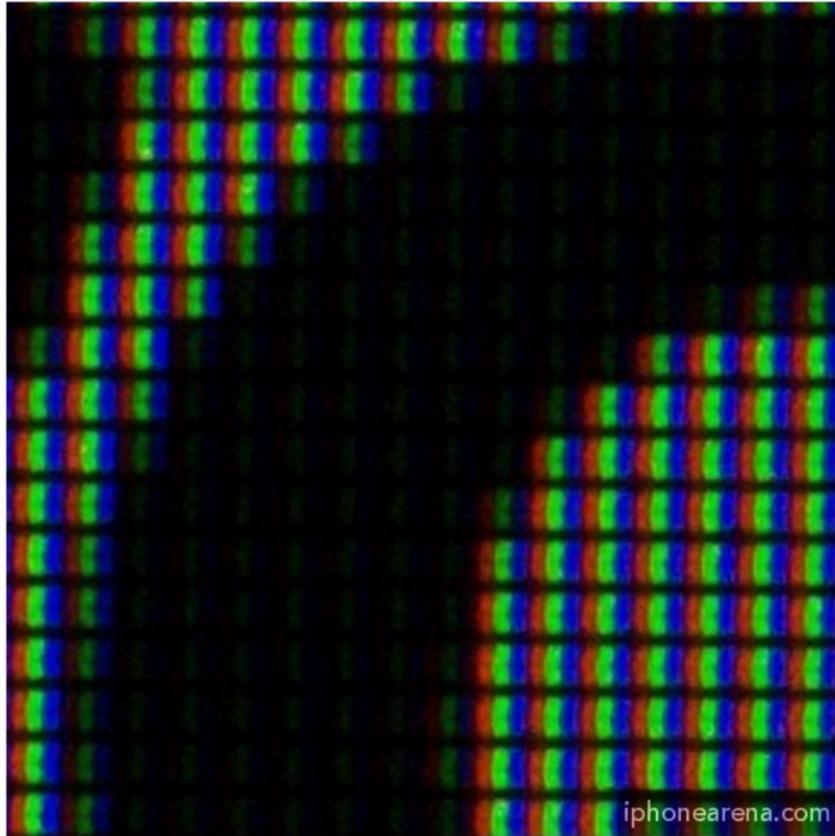
Additive Color

Additive Color

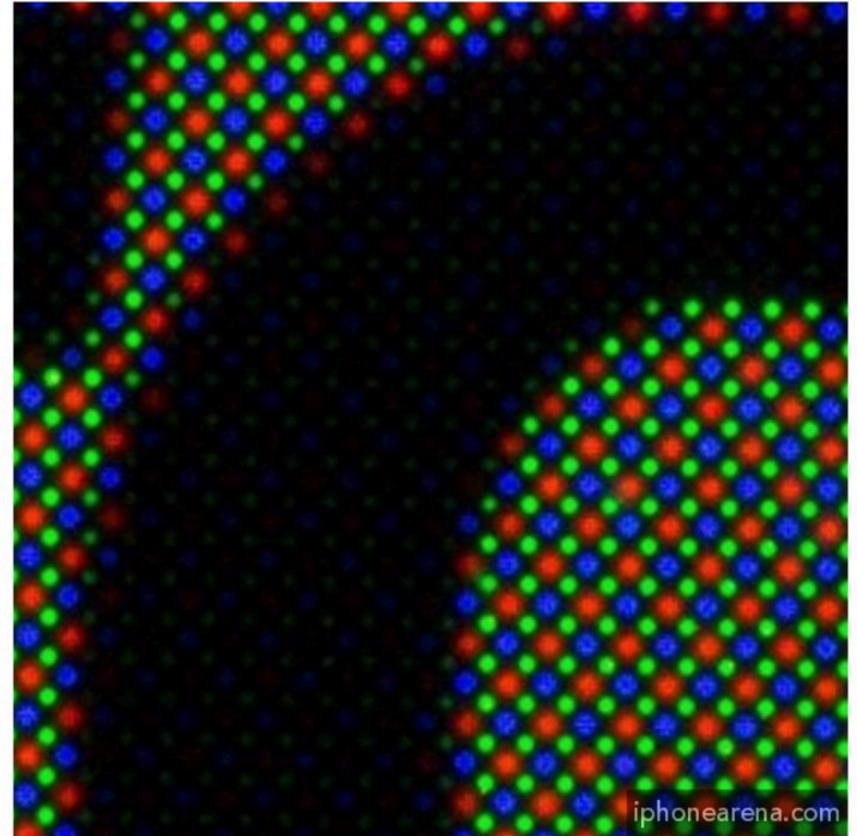


[source unknown]

Recall: real LCD screen pixels (closeup)



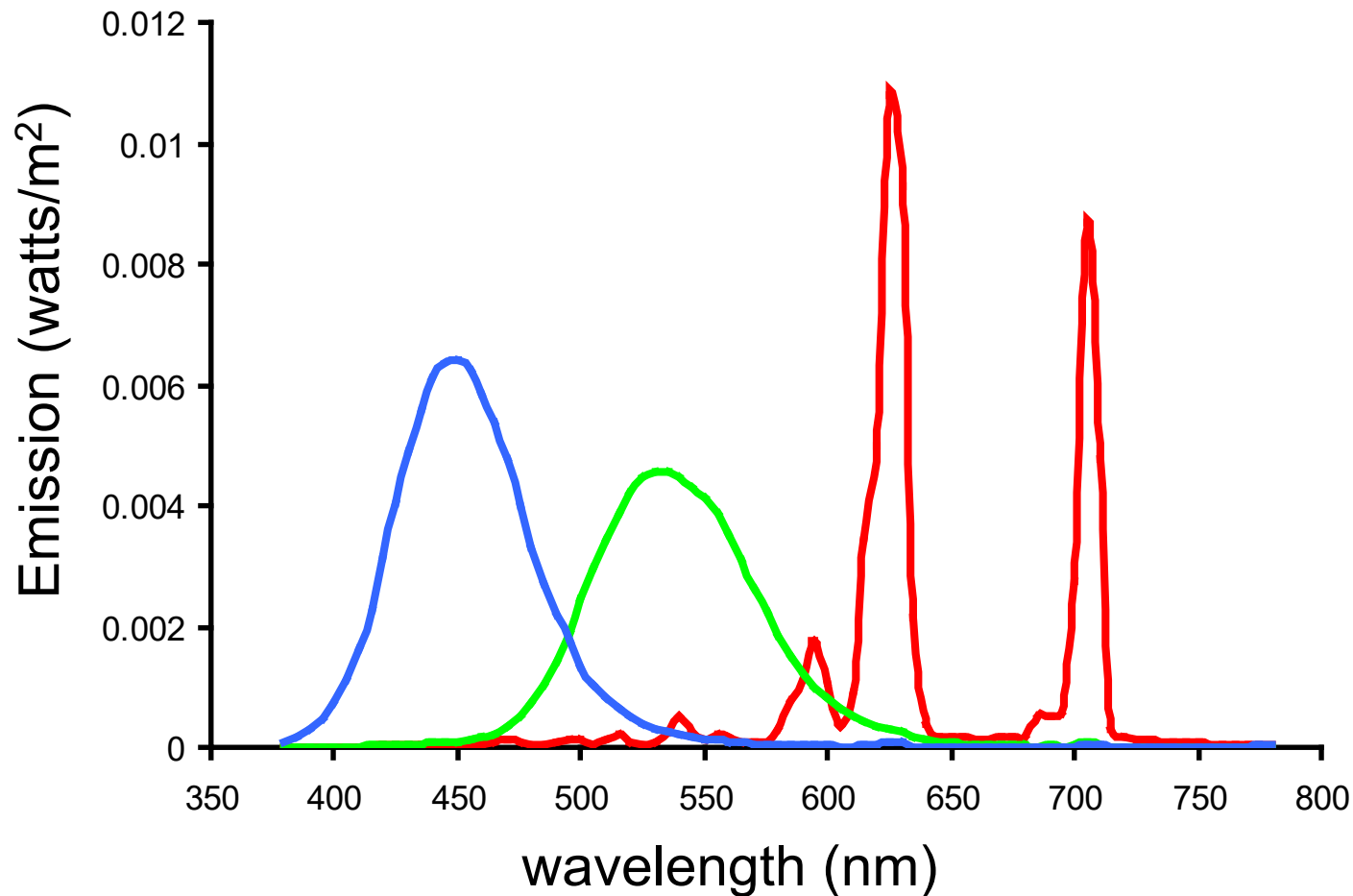
iPhone 6S



Galaxy S5

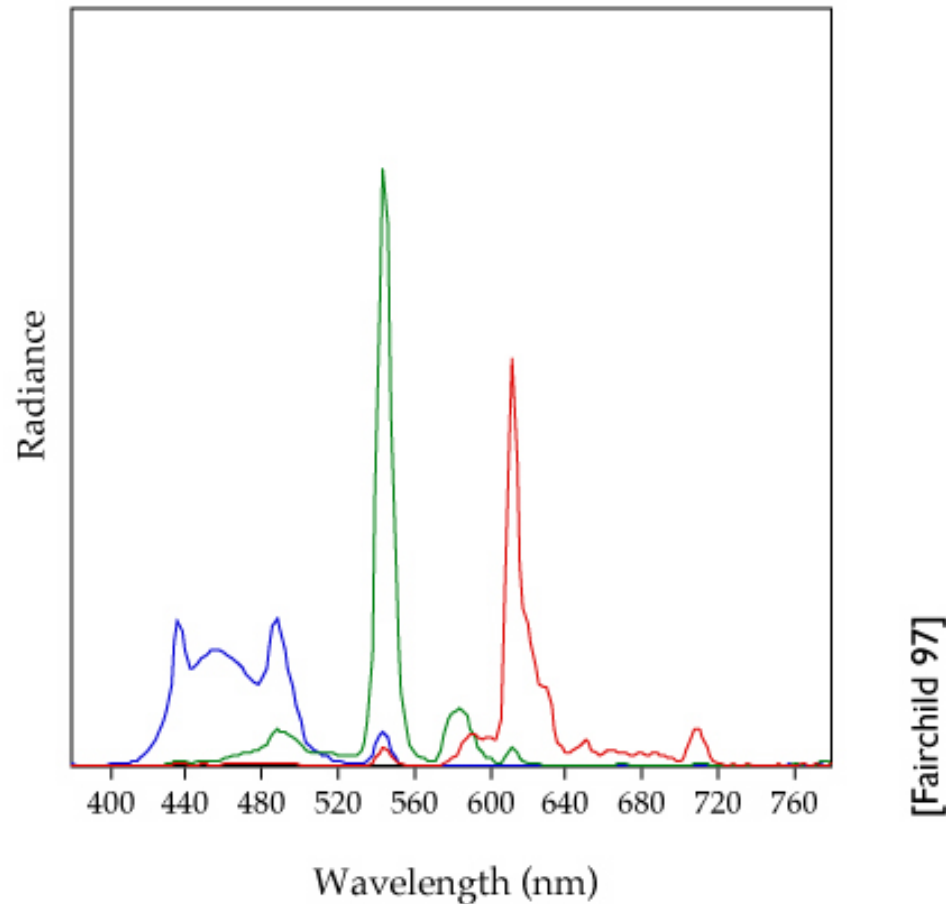
**Notice R, G, B sub-pixel geometry.
Effectively three lights at each (x,y) location.**

CRT display primaries



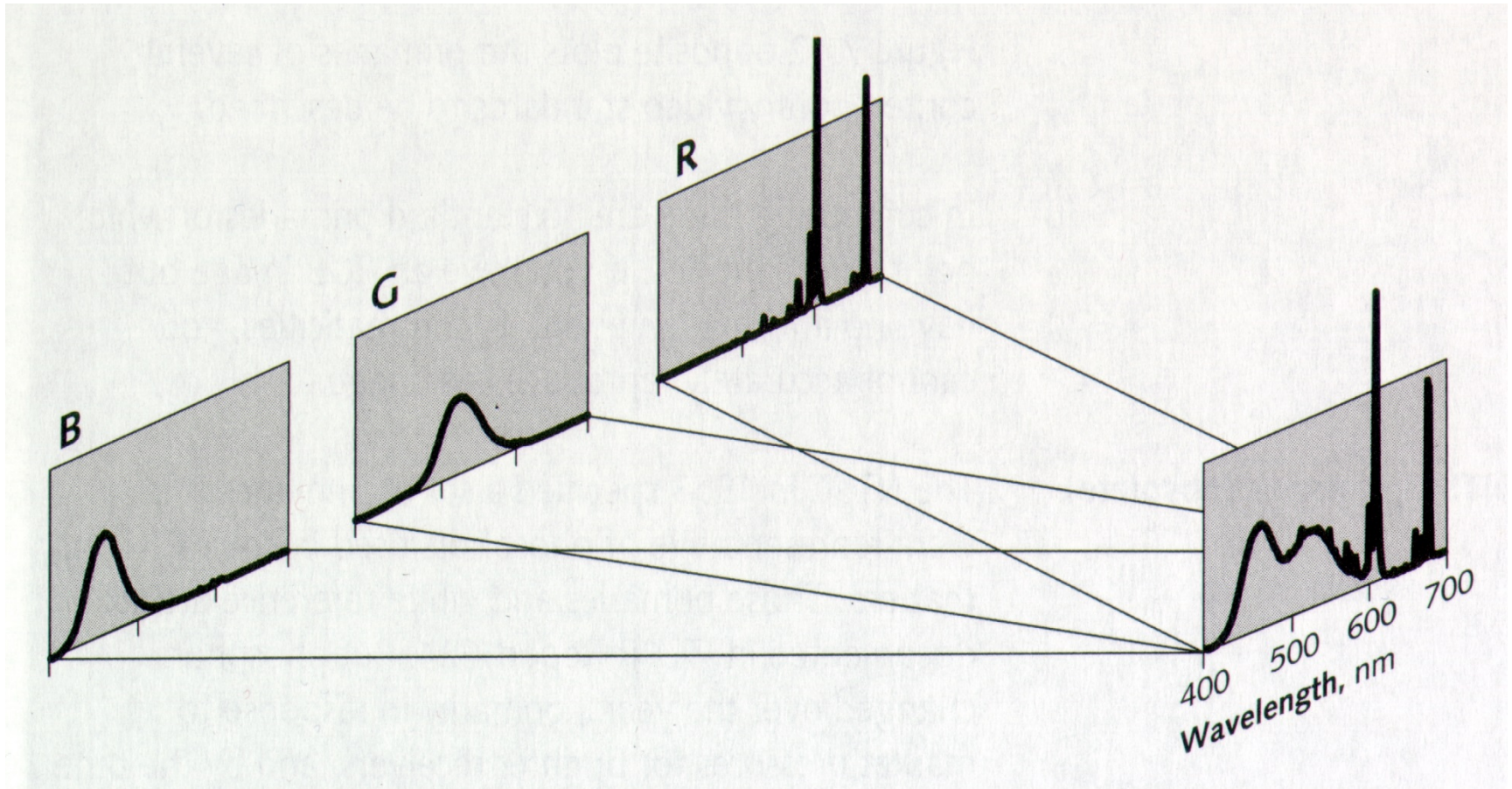
- Curves determined by phosphor emission properties

LCD display primaries



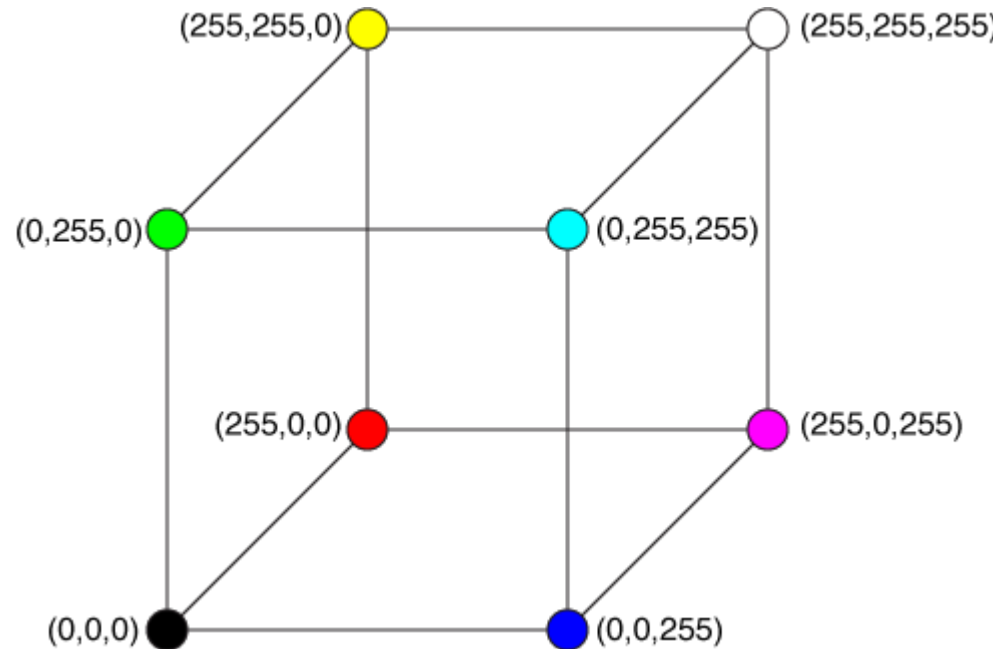
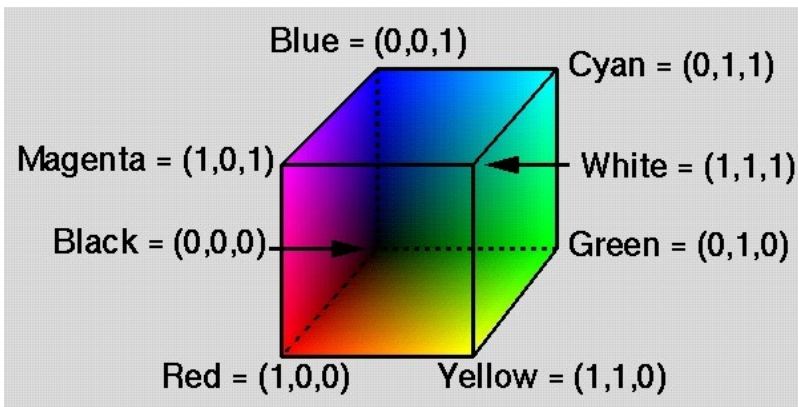
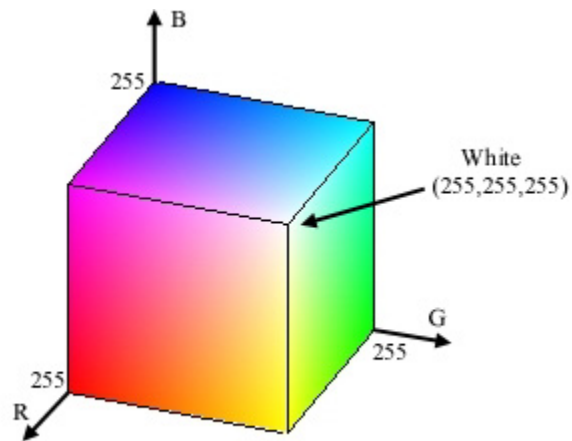
- Curves determined by (fluorescent) backlight and filters

Combining Monitor Phosphors with Spatial Integration



[source unknown]

RGB as a 3D space



What color is “Red” in RGB color space?

- A) (1,0,0)
- B) (0,1,0)
- C) (1.0,0.5,0.5)
- D) (0.5,0.5,0.5)
- E) (1.0,1.0,0.0)

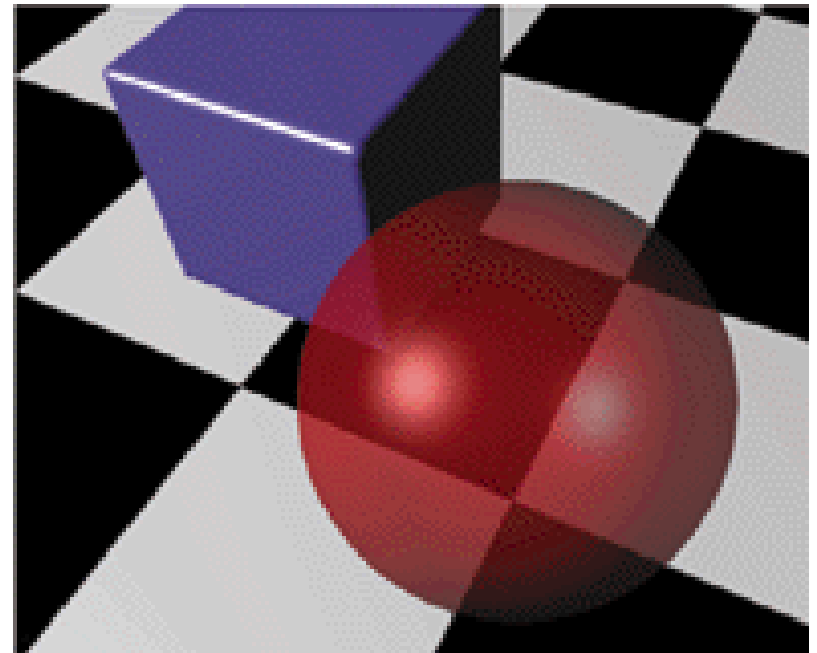
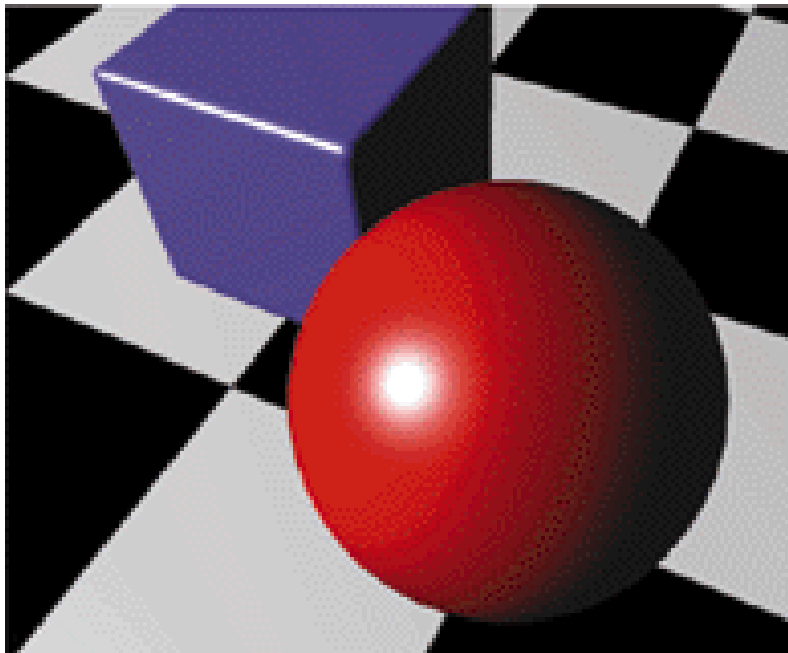
What color is “Yellow” in RGB color space?

- A) (1,0,0)
- B) (0,1,0)
- C) (1.0,0.5,0.5)
- D) (0.5,0.5,0.5)
- E) (1.0,1.0,0.0)

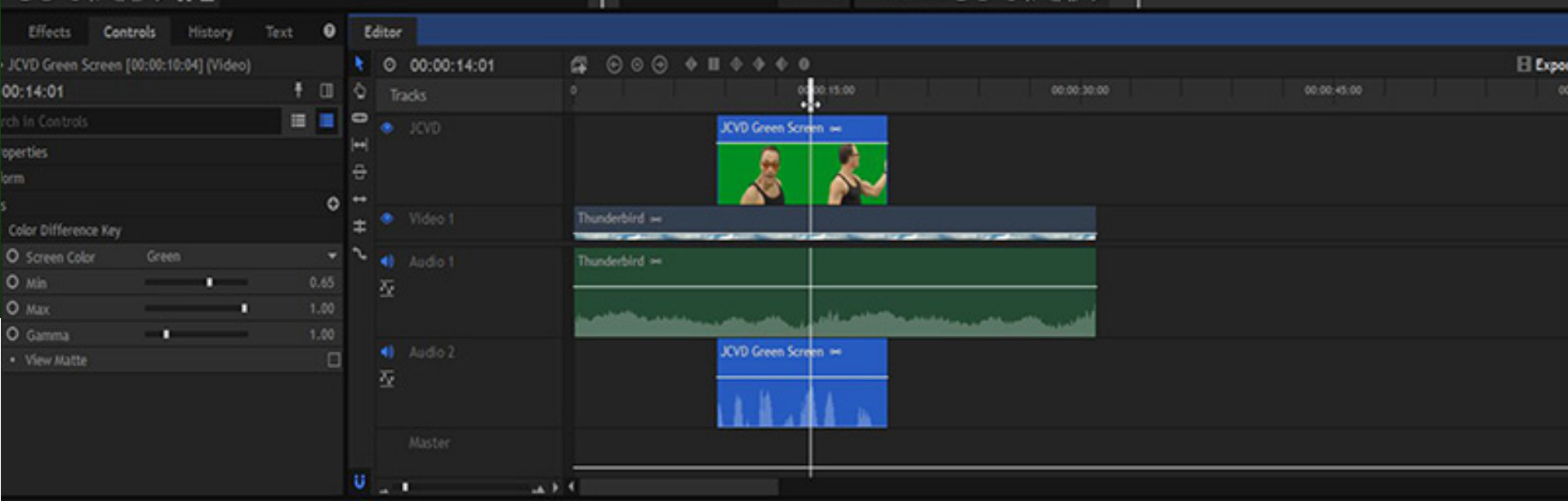
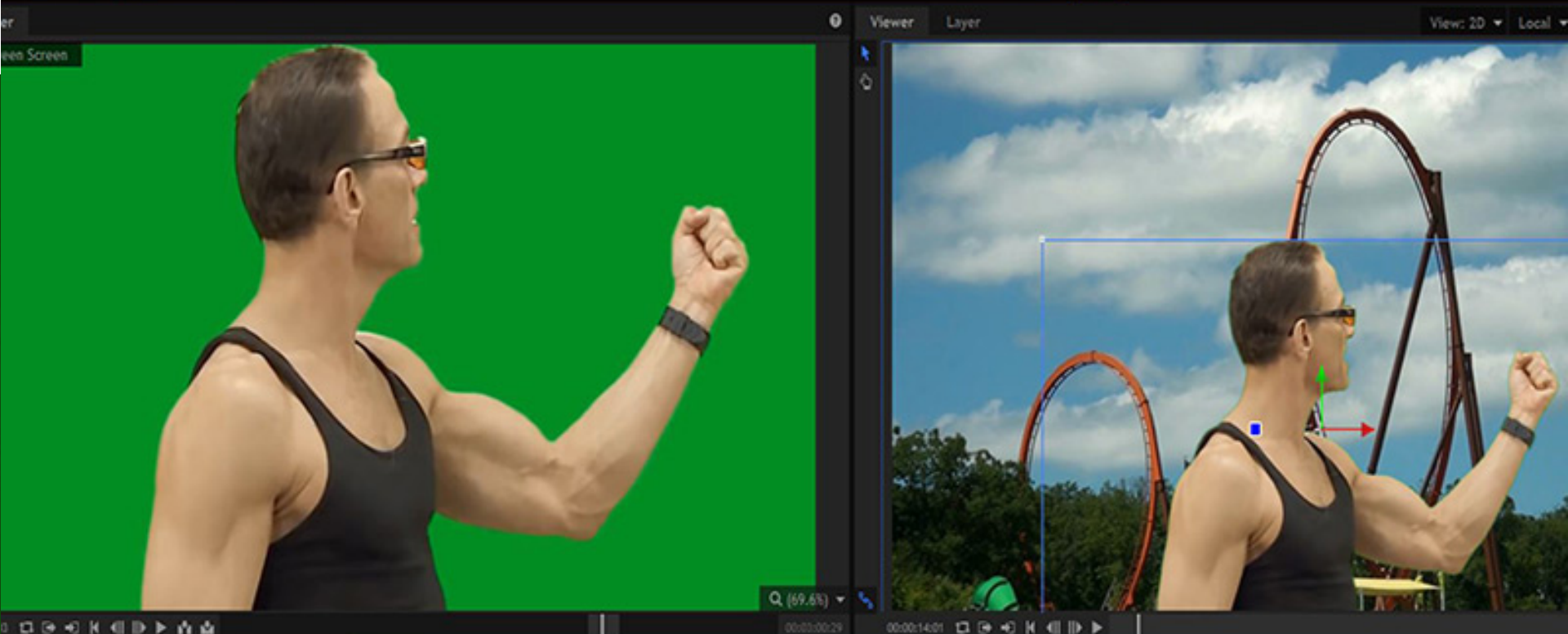
What color is “Pink” in RGB color space?

- A) (1,0,0)
- B) (0,1,0)
- C) (1.0,0.5,0.5)
- D) (0.5,0.5,0.5)
- E) (1.0,1.0,0.0)

RGB-Alpha

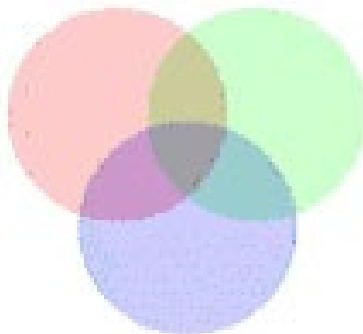




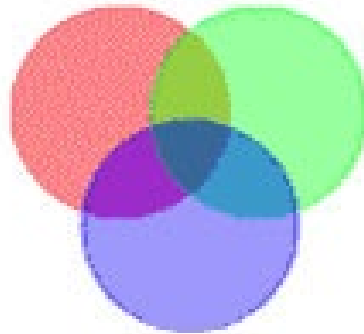


Alpha Blend - three layers over white. Blend order: Red, Green, and Blue

alpha = 64



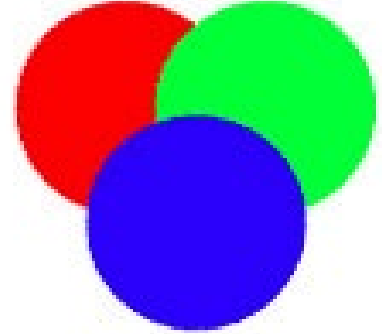
alpha = 127

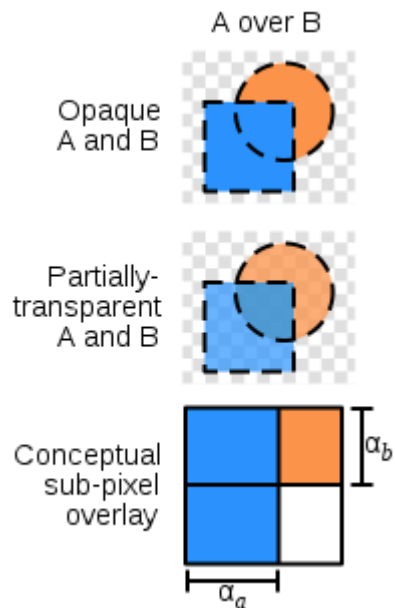
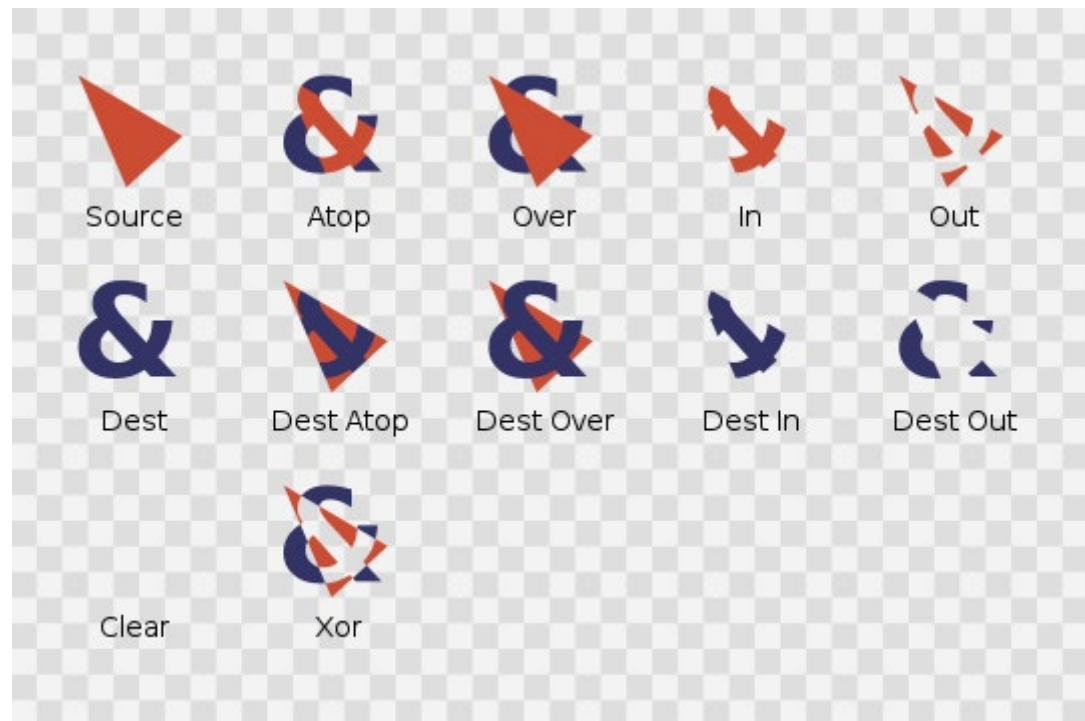


alpha = 191



alpha = 255





As an example, the **over** operator can be accomplished by applying the following formula to each pixel value:

$$C_o = \frac{C_a \alpha_a + C_b \alpha_b (1 - \alpha_a)}{\alpha_a + \alpha_b (1 - \alpha_a)}$$

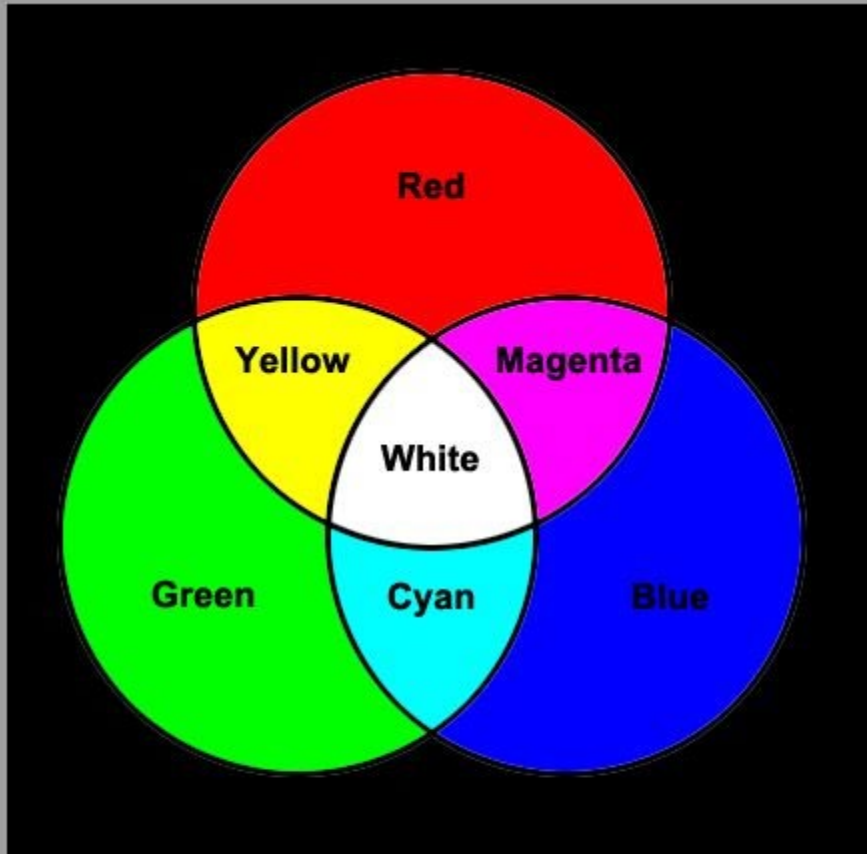
where C_o is the result of the operation, C_a is the color of the pixel in element A, C_b is the color of the pixel in element B, and α_a and α_b are the alpha of the pixels in elements A and B respectively. If it is assumed

Subtractive Color

Subtractive Color

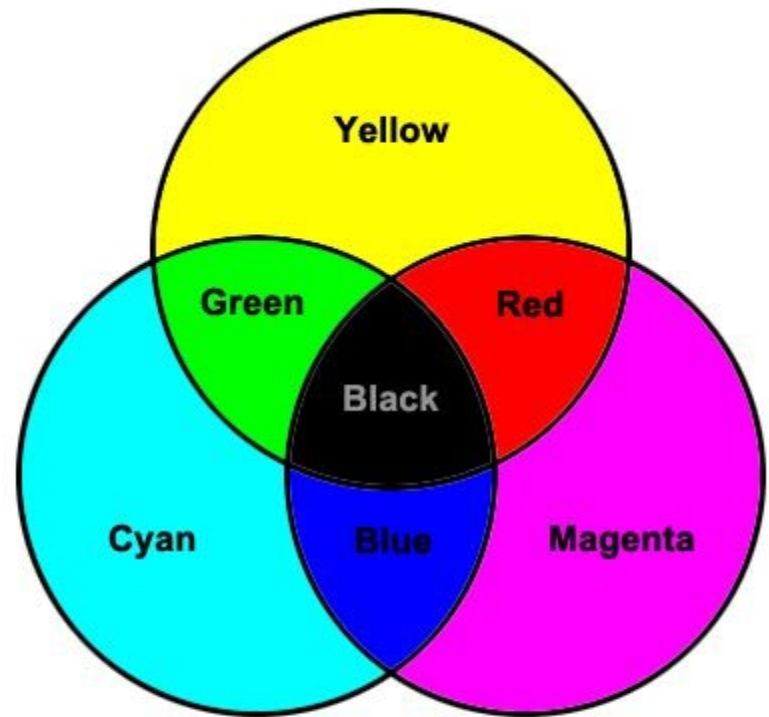


[source unknown]



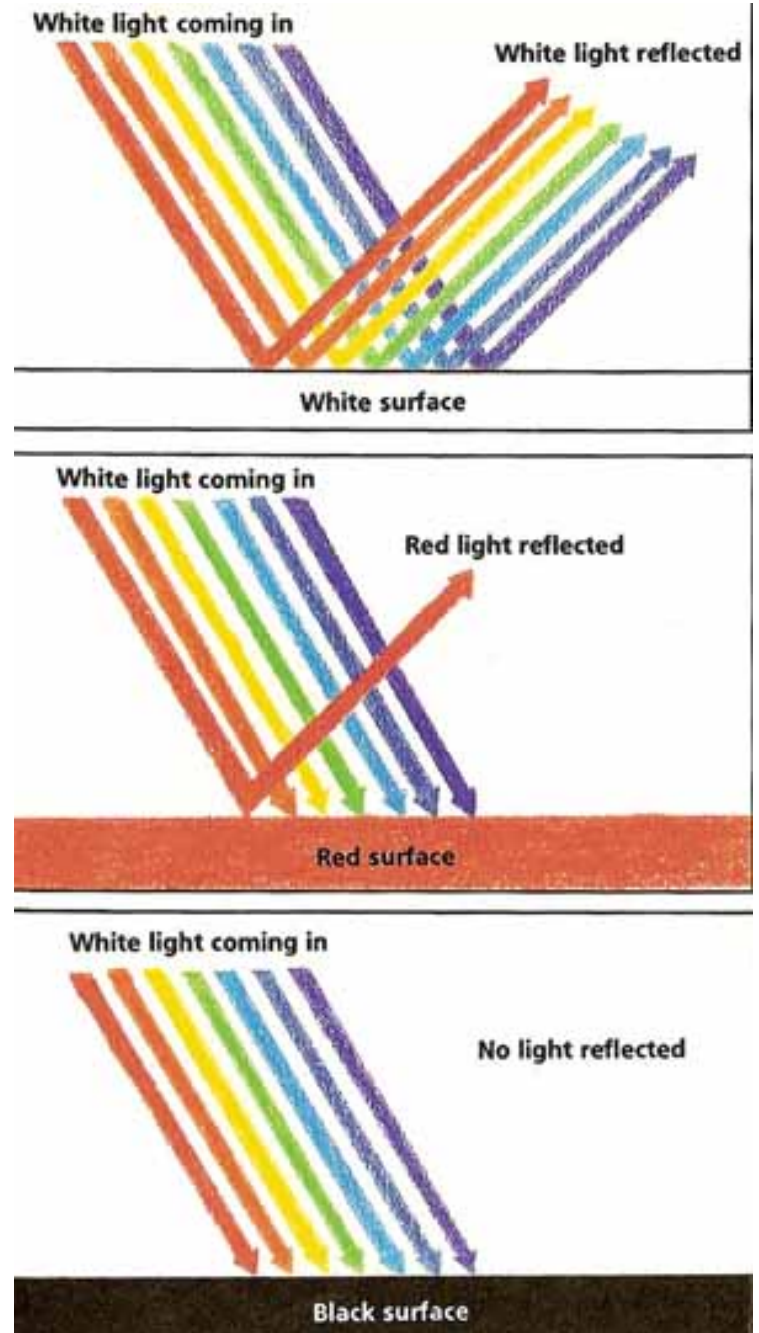
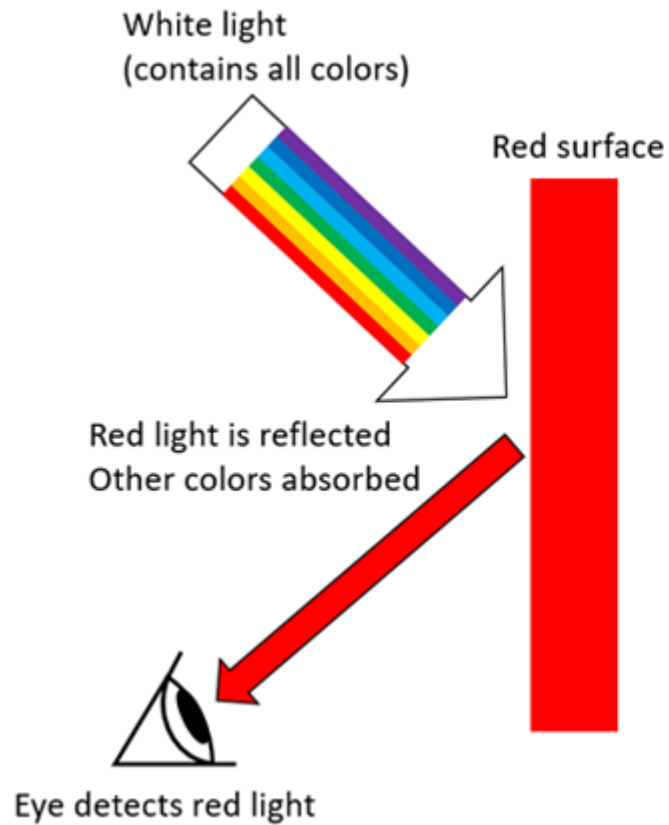
Additive color mixing

Additive color systems start without light (black). Light sources of various wavelengths combine to make a color.



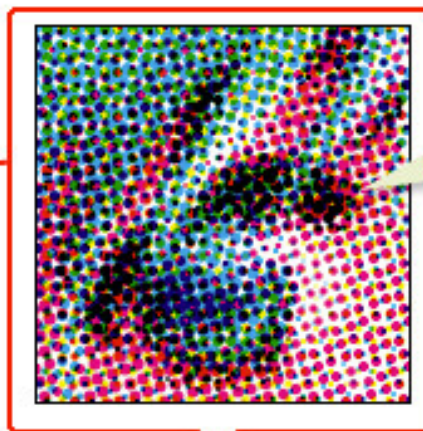
Subtractive color mixing

Subtractive color systems start with light (white). Colored inks, paints, or filters between the viewer and the light source or reflective surface subtract wavelengths from the light, giving it color.

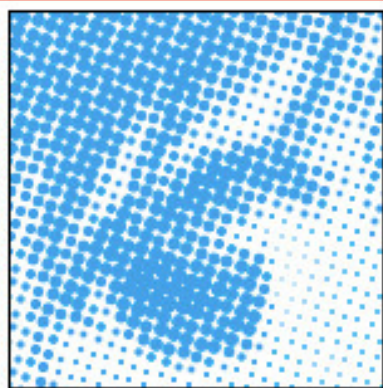




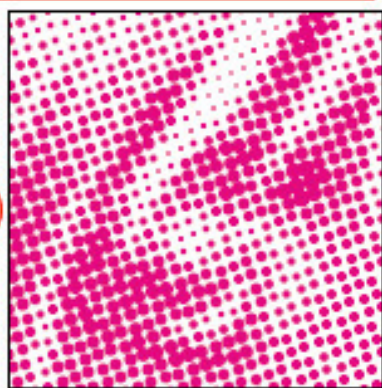
CMYK



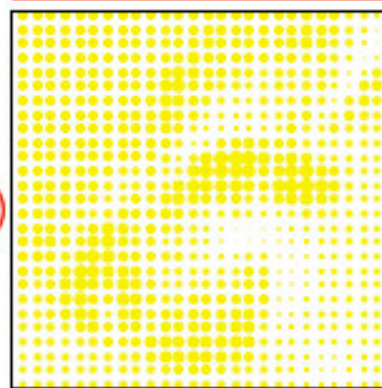
Colors are represented by superimposing four colored inks



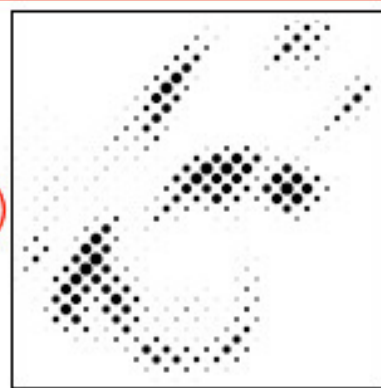
Cyan



Magenta

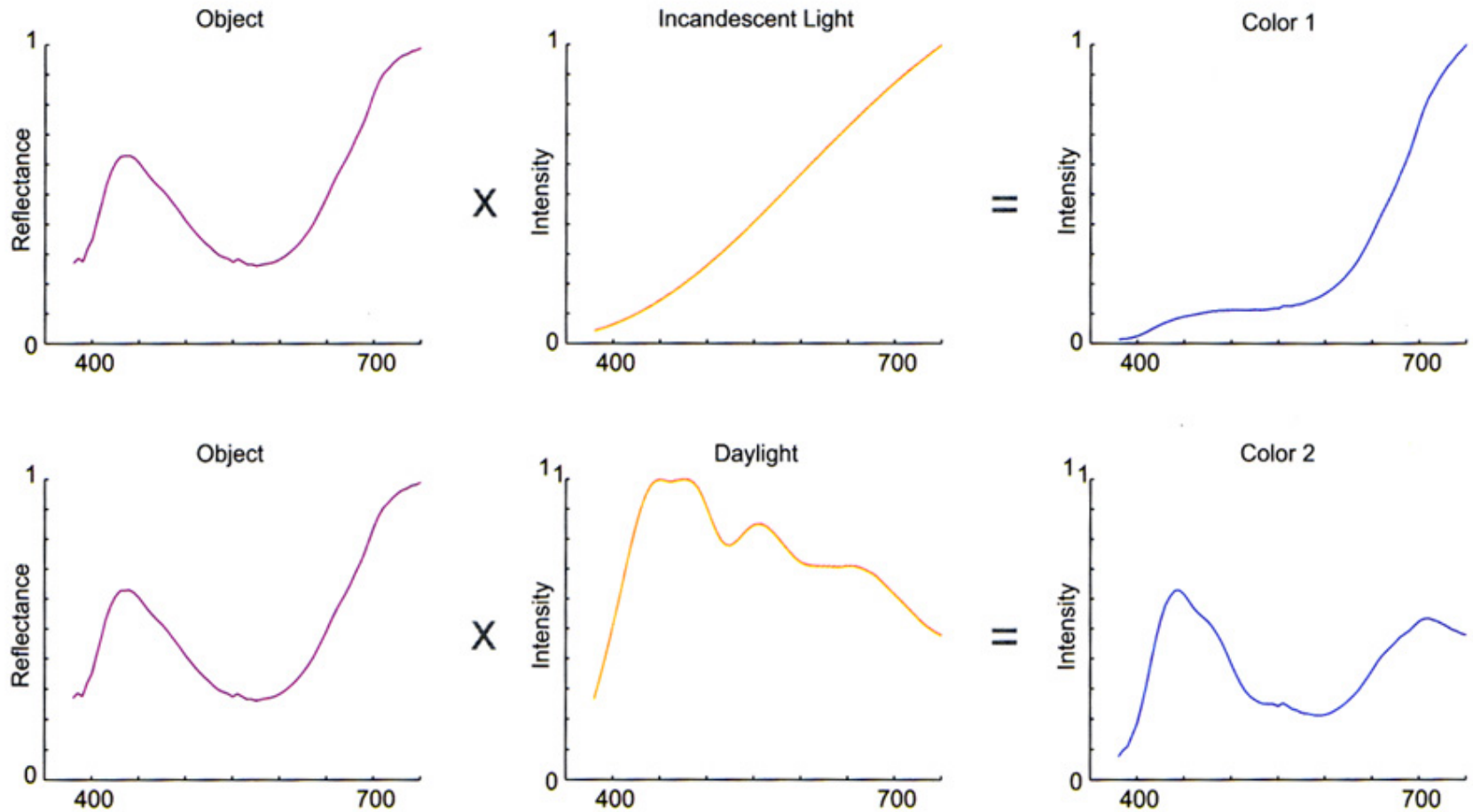


Yellow



Key plate

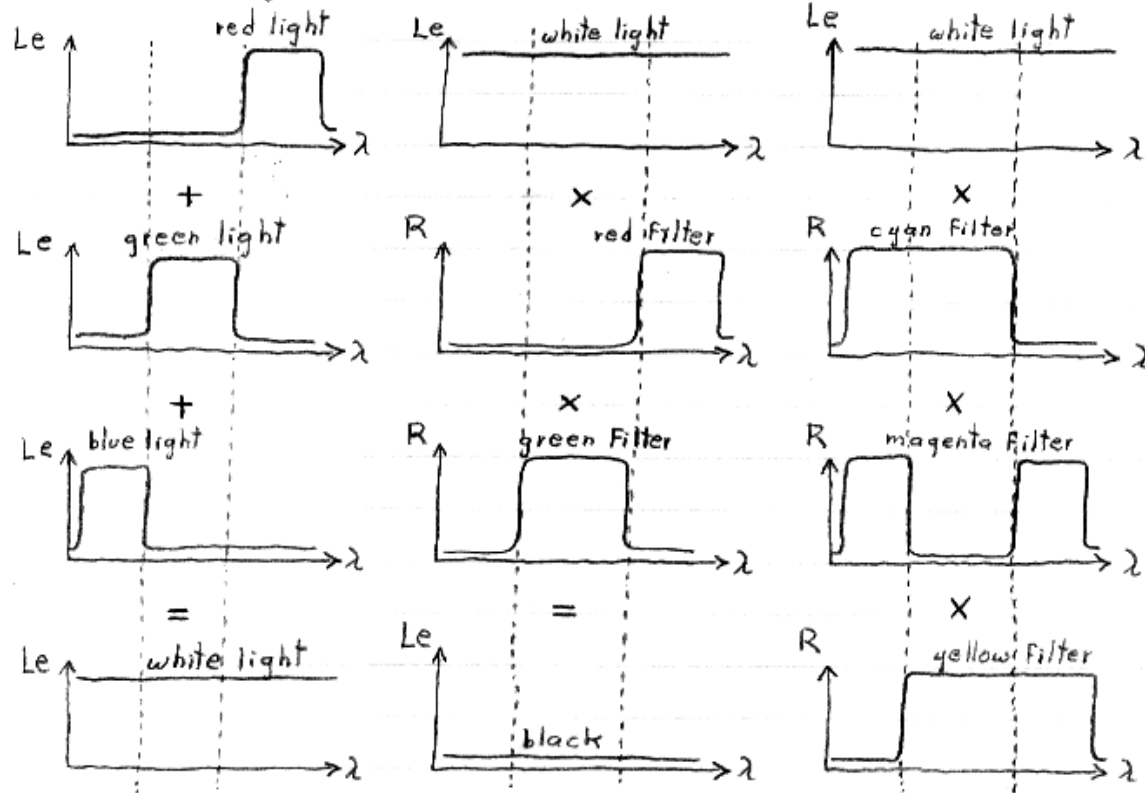
Reflection from colored surface



[Stone 2003]

Additive versus subtractive color mixing

Spectral analysis:



↑↑
additive
mixing

superimposed
(e.g. lights) adjacent
(e.g. dots)

↑↑
subtractive
mixing using
additive primaries
(wrong!)

↑↑
subtractive
mixing

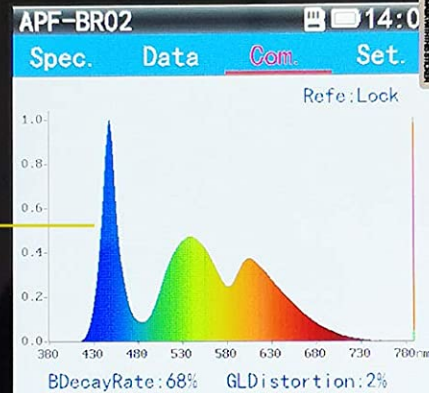
overlaid
(e.g. ink layers)

[levoy]

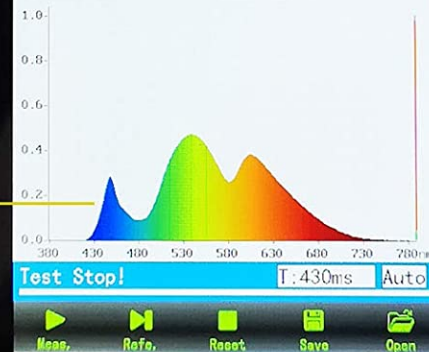
Filter 68% of blue light



No Amprofilm Optics



Amprofilm Optics



Conversion between RGB and CMY

- Convert White from (1, 1, 1) in RGB to (0, 0, 0) in CMY:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}$$

- Sometimes, an alternative CMYK model (K stands for *Black*) is used in color printing (e.g., to produce darker black than simply mixing CMY).

$$K := \min (C, M, Y), \quad C := C - K, \quad M := M - K, \quad Y := Y - K.$$

What color is “Yellow” in CMY color space?

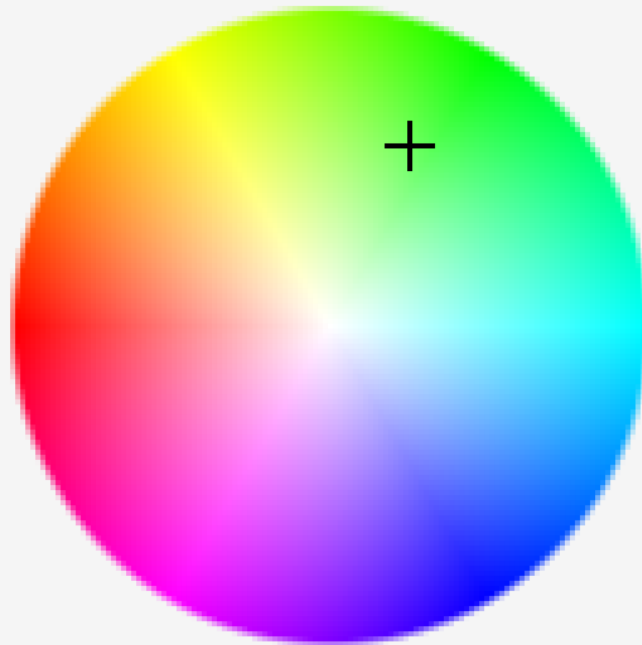
- A) (0,1,1)
- B) (0,0,1)
- C) (1.0,0.5,0.5)
- D) (0.5,0.5,0.5)
- E) (1.0,1.0,0.0)

What color is “Red” in CMY color space?

- A) (0,1,1)
- B) (0,1,0)
- C) (1.0,0.5,0.5)
- D) (0.5,0.5,0.5)
- E) (1.0,1.0,0.0)

HSV Color

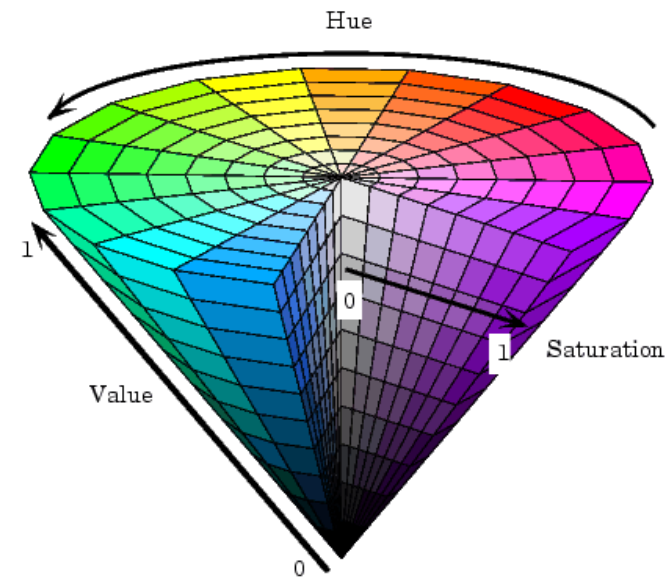
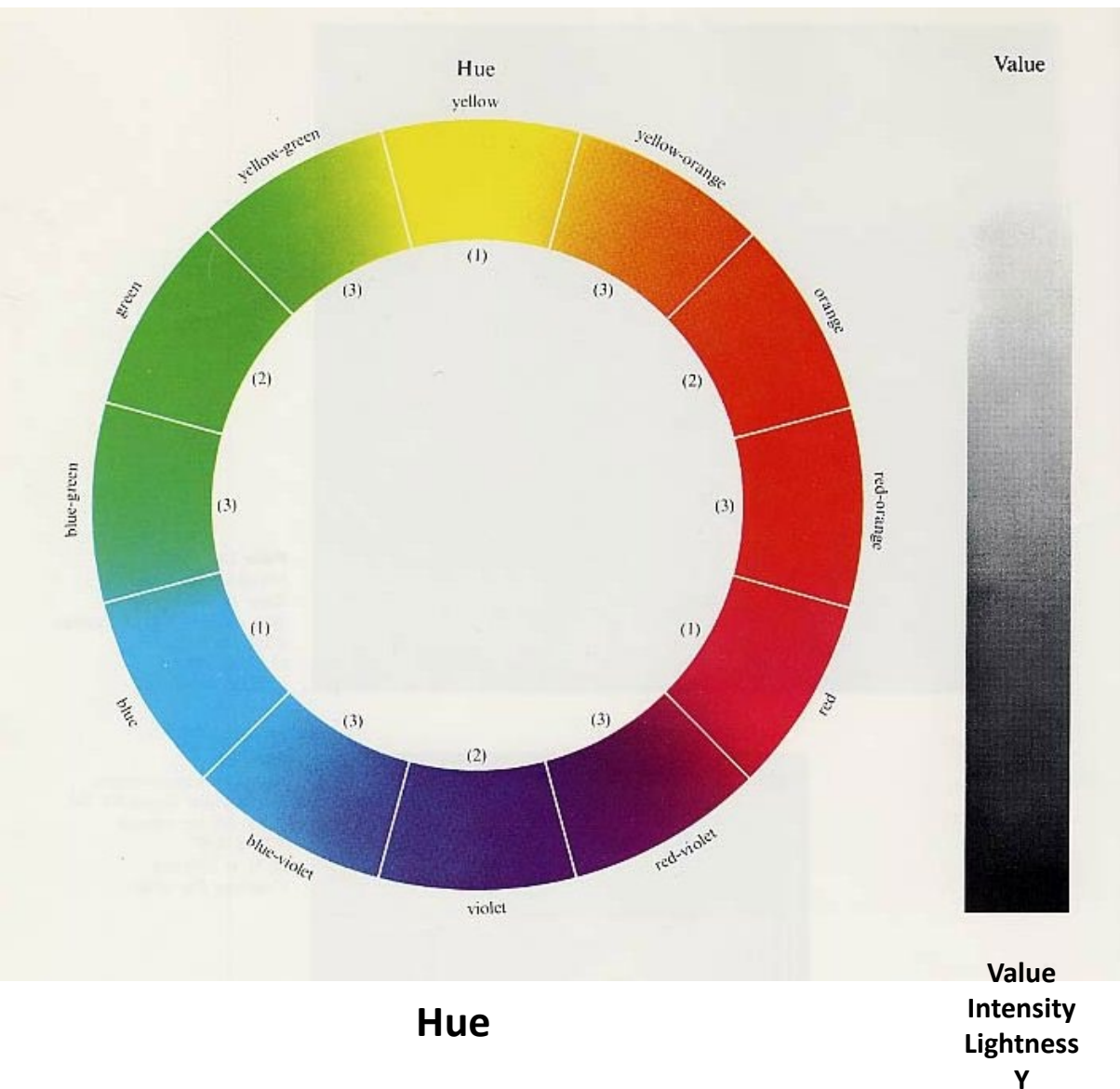
Pick a color



Cancel

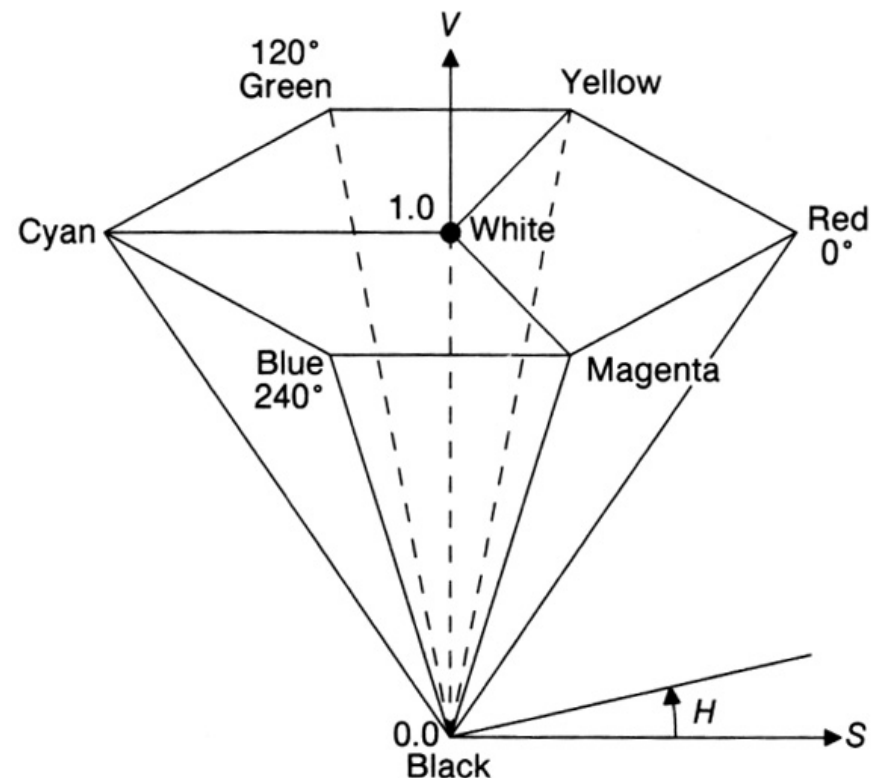
OK

Perceptual dimensions of color - HSV



Perceptual organization for RGB: HSV

- hue (an angle, 0 to 360)
- saturation (0 to 1)
- value (0 to 1)



[FvDFH]

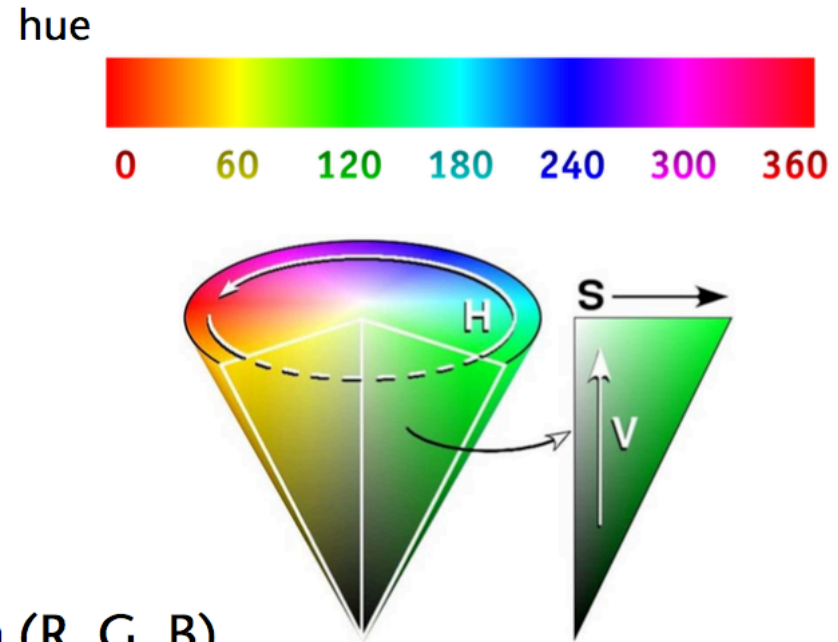
- colour cone

- $H = \text{hue} / \text{colour in degrees} \in [0, 360]$
- $S = \text{saturation} \in [0, 1]$
- $V = \text{value} \in [0, 1]$

- conversion RGB $\rightarrow$ HSV

- $V = \max = \max(R, G, B), \quad \min = \min(R, G, B)$
- $S = (\max - \min) / \max \quad (\text{or } S = 0, \text{ if } V = 0)$
- $H = 60 \times \begin{cases} 0 + (G - B) / (\max - \min), & \text{if } \max = R \\ 2 + (B - R) / (\max - \min), & \text{if } \max = G \\ 4 + (R - G) / (\max - \min), & \text{if } \max = B \end{cases}$

$H = H + 360, \text{ if } H < 0$



Dimension of Color (HSL/HSV/HVC)²²

- ◆ Hue = Color name (red, blue, green, etc.)



- ◆ Saturation = Density (purity) of the color

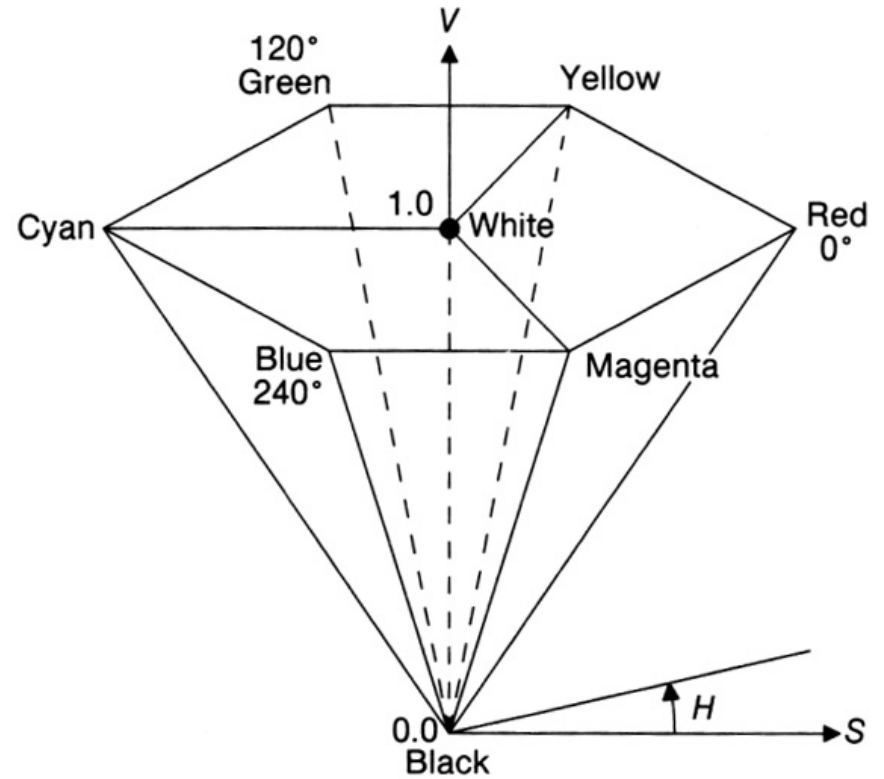


- ◆ Value = Lightness & Darkness



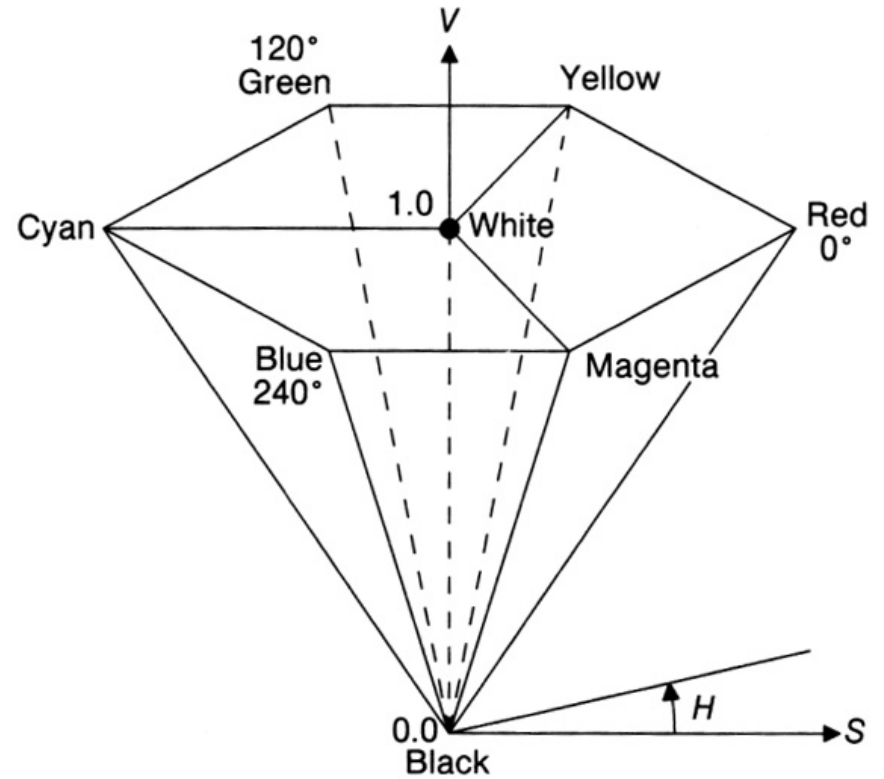
What color is “Red” in HSV color space?

- A) (0,1,1)
- B) (0,0,0)
- C) (60,1,1)
- D) (0,0.2,1.0)
- E) (0,1.0,0.0)



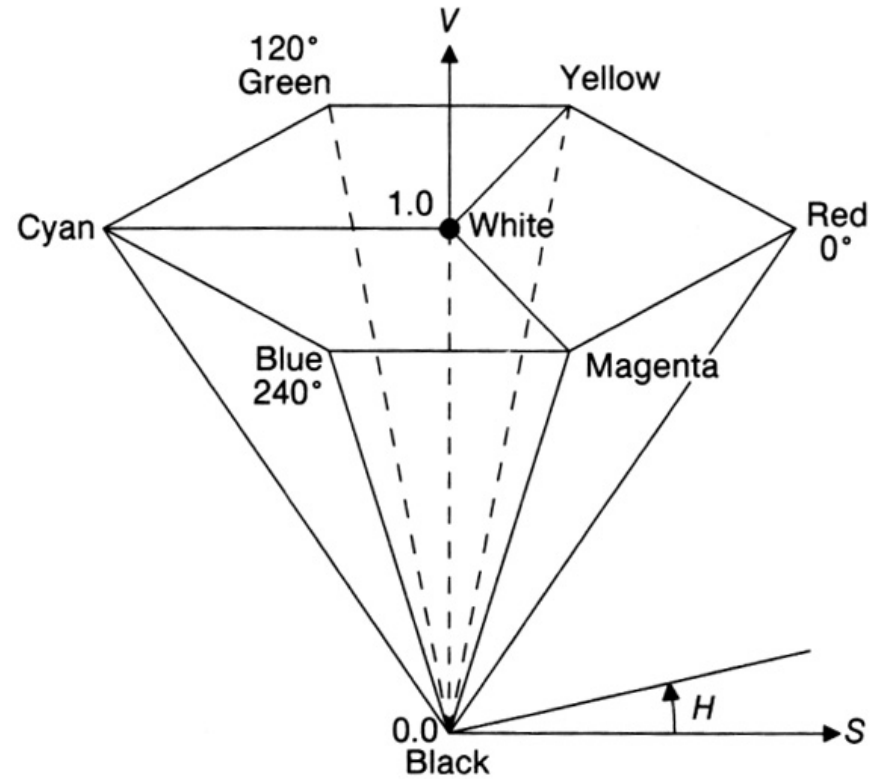
What color is “Yellow” in HSV color space?

- A) (0,1,1)
- B) (0,0,0)
- C) (60,1,1)
- D) (0,0.2,1.0)
- E) (0,1.0,0.0)



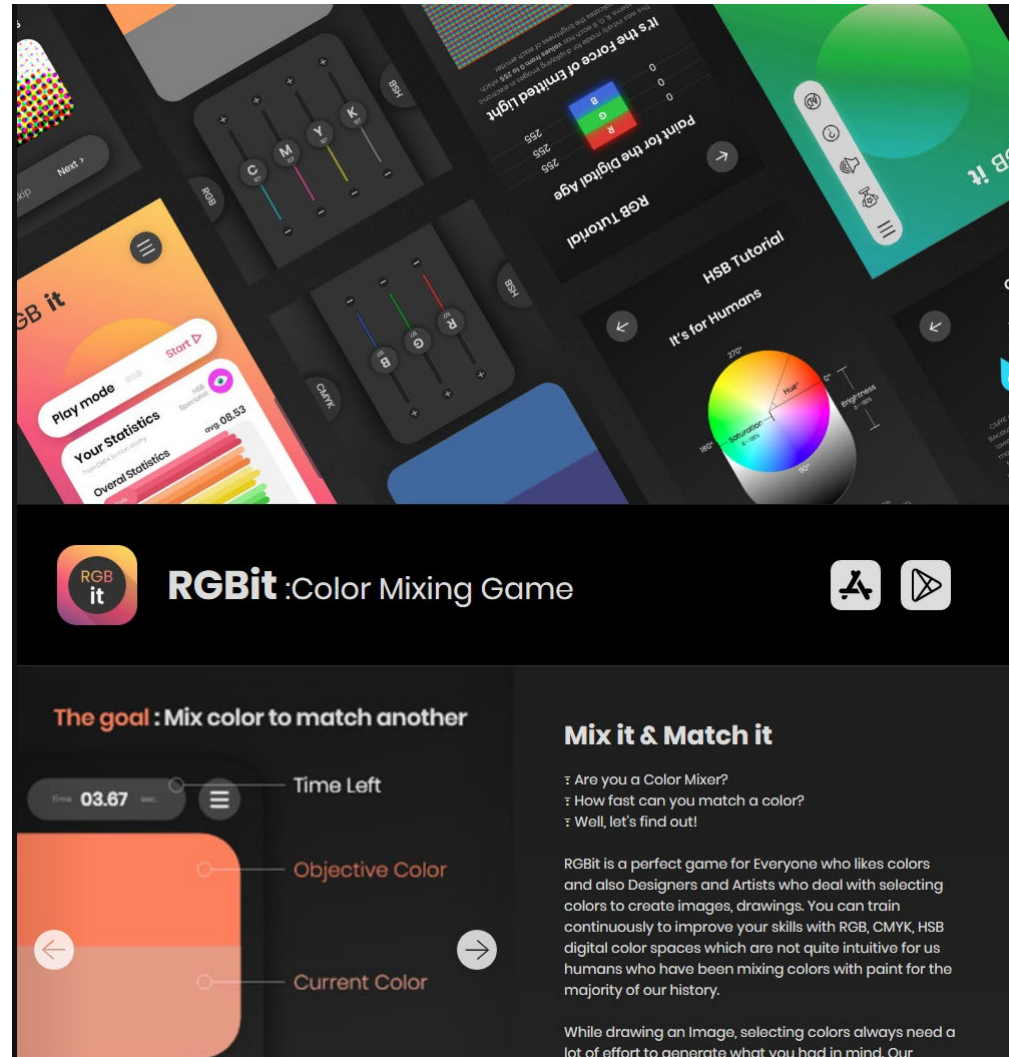
What color is “Pink” in HSV color space?

- A) (0,1,1)
- B) (0,0,0)
- C) (60,1,1)
- D) (0,0.2,1.0)
- E) (0,1.0,0.0)



Attendance and survey

[Tiny.cc/cse160421](https://tiny.cc/cse160421)

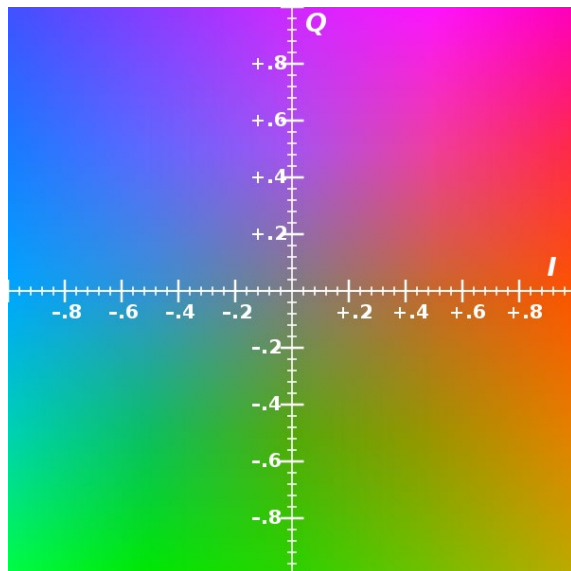


YIQ/YUV Color

NTSC TV

quadrature amplitude modulation

- YIQ color space (Wandell pg 304)



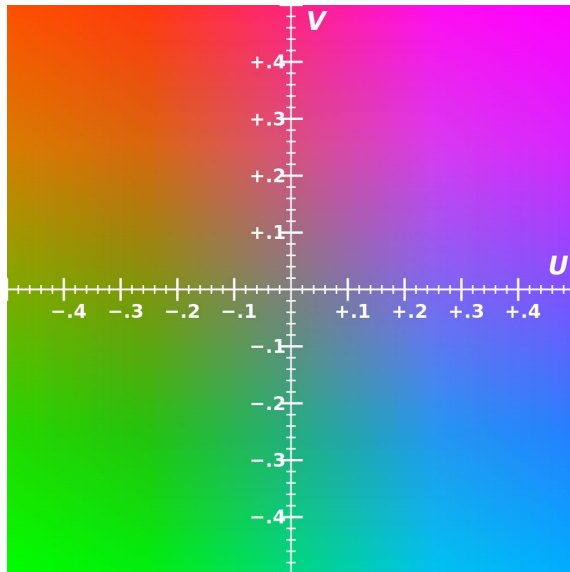
$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0,299 & 0,587 & 0,114 \\ 0,596 & -0,275 & -0,321 \\ 0,212 & -0,523 & 0,3111 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

(Y) luminance

(IQ) chroma



YUV / YCbCr

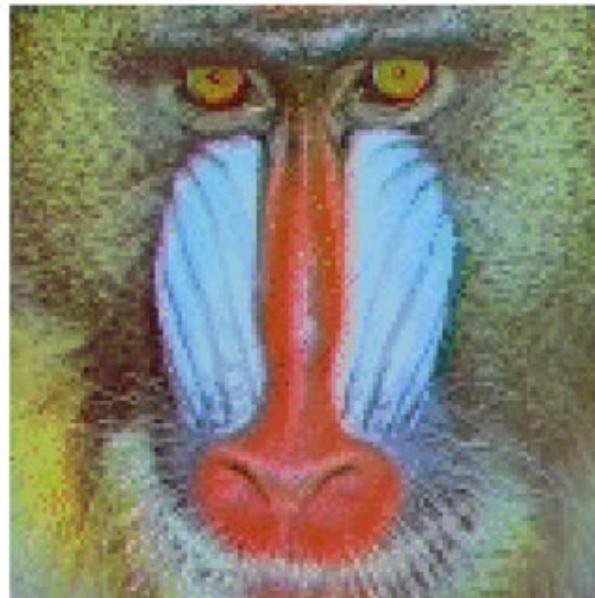


Humans care about intensity more than chroma

Y



Chroma



Chroma



Figure 9.23: The apparent spatial sharpness (focus) of a color image depends mainly on the light-dark component of the image, not the opponent-colors components. A colored image was converted to a light-dark, red-green and blue-yellow representation. To create the three images, the light-dark (a), red-green (b), or blue-yellow (c) components were spatially blurred and then the image was reconstructed. The light-dark image looks defocused, but the same amount of blurring does not make the other two images look defocused. (Source: H. Hel-Or, personal communication).

Full resolution luminance (Y) Chroma (IQ) subsampling



4:1:1



4:2:0



4:2:2



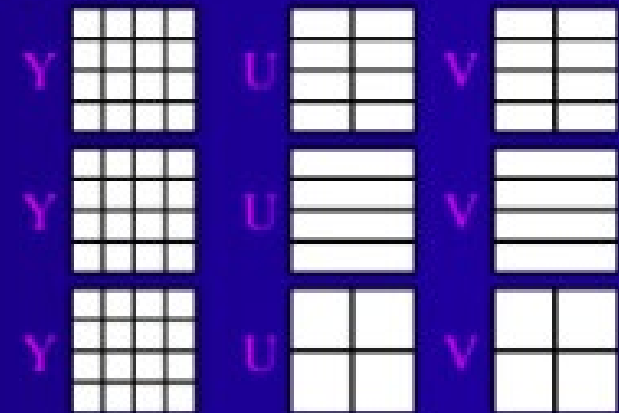
4:4:4



Color space compression

■ Typical data assignment to YUV

- ◆ $Y:U:V = 4:2:2$ (TV)
- ◆ $Y:U:V = 4:1:1$ (JPEG)
- ◆ $Y:U:V = 4:2:0$ (JPEG)



JPEG (1:50)



Y



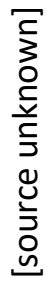
U



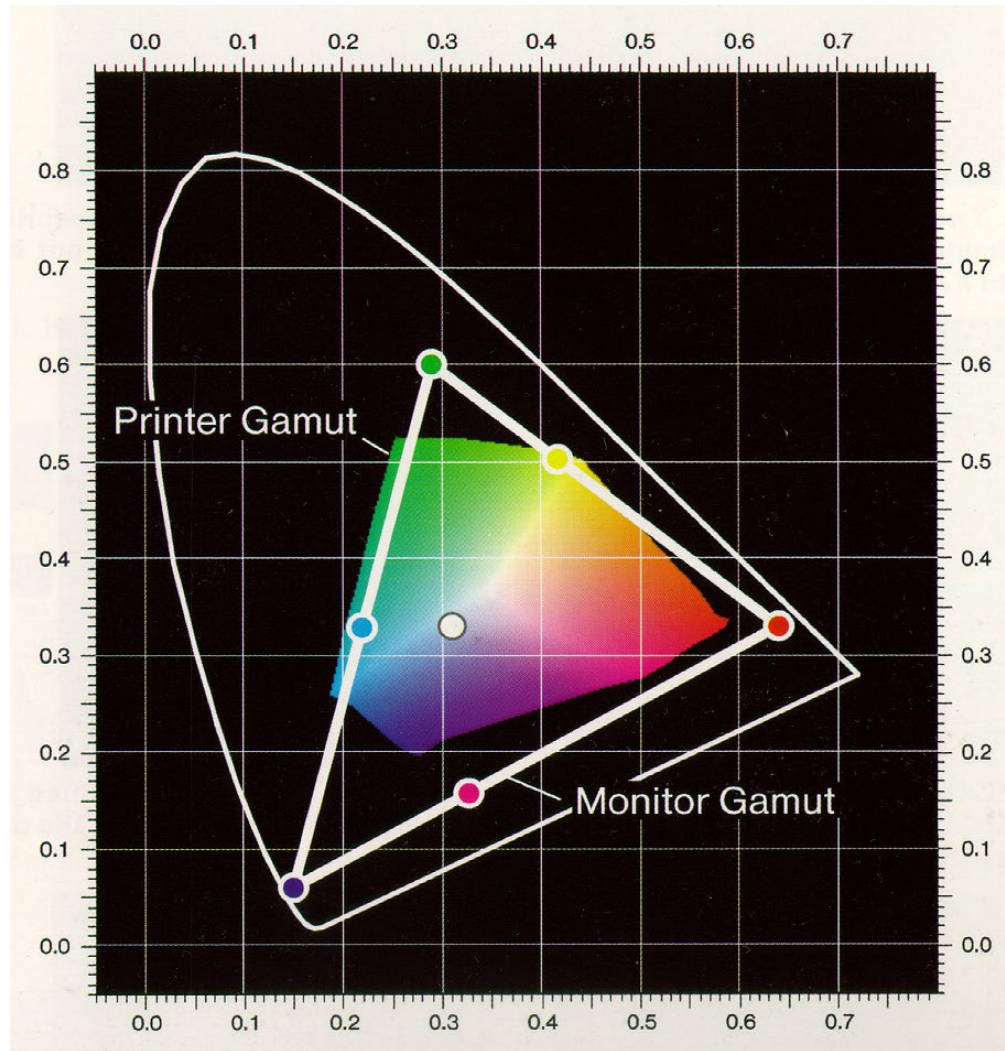
V

Color Gamuts, Color Matching, and XYZ

[source unknown]



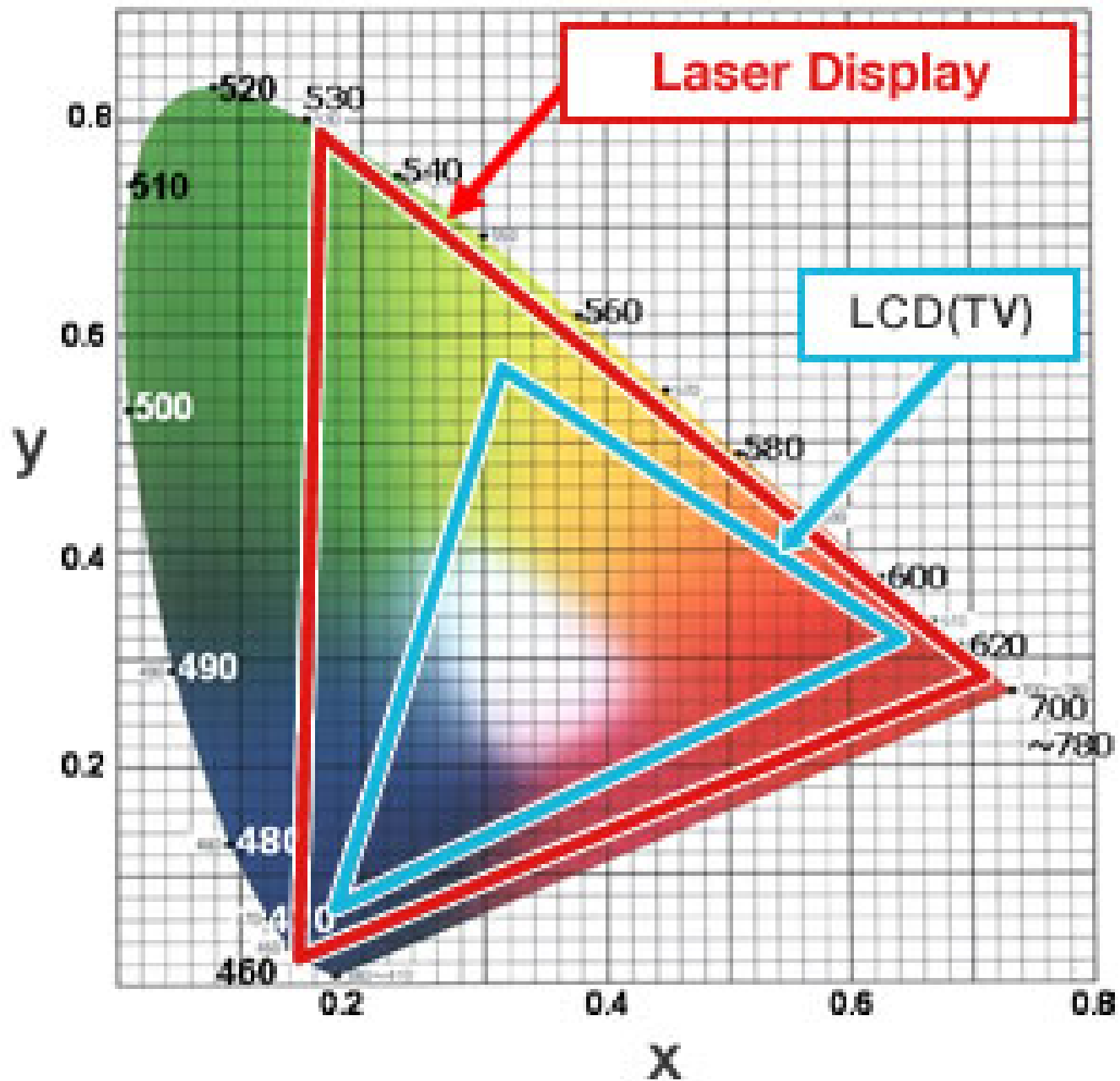
Color Gamuts



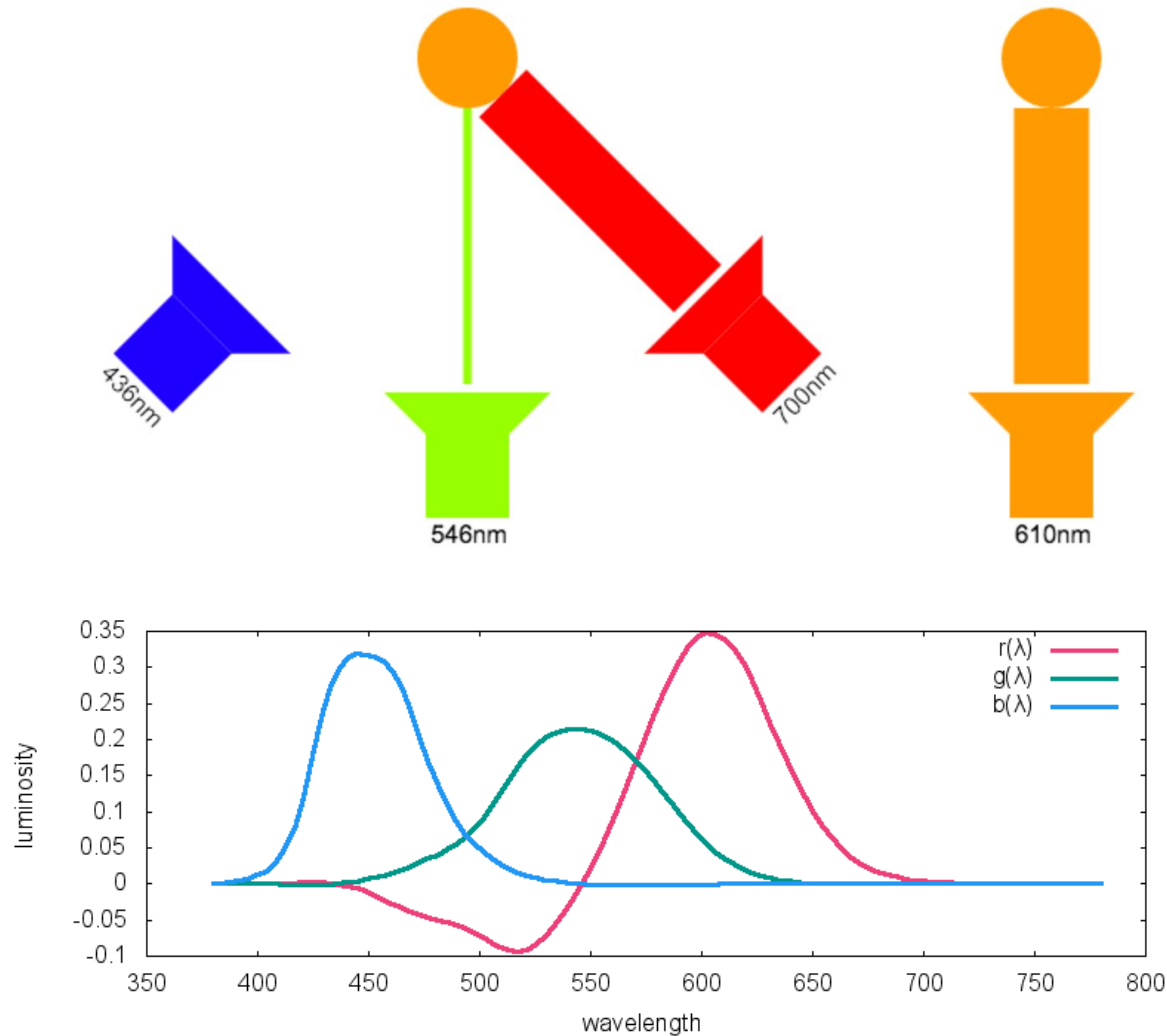
Monitors/printers can't produce all visible colors

Reproduction is limited to a particular domain

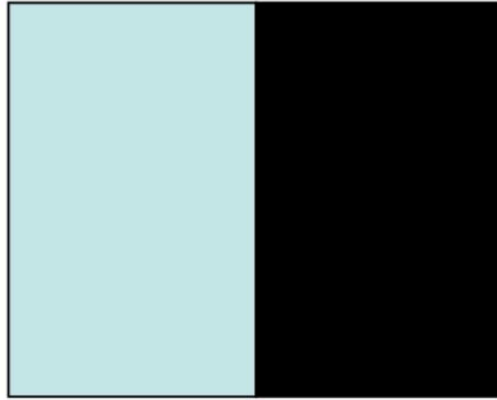
For additive color (e.g. monitor) gamut is the triangle defined by the chromaticities of the three primaries.



Color matching experiment (CIE 1931)

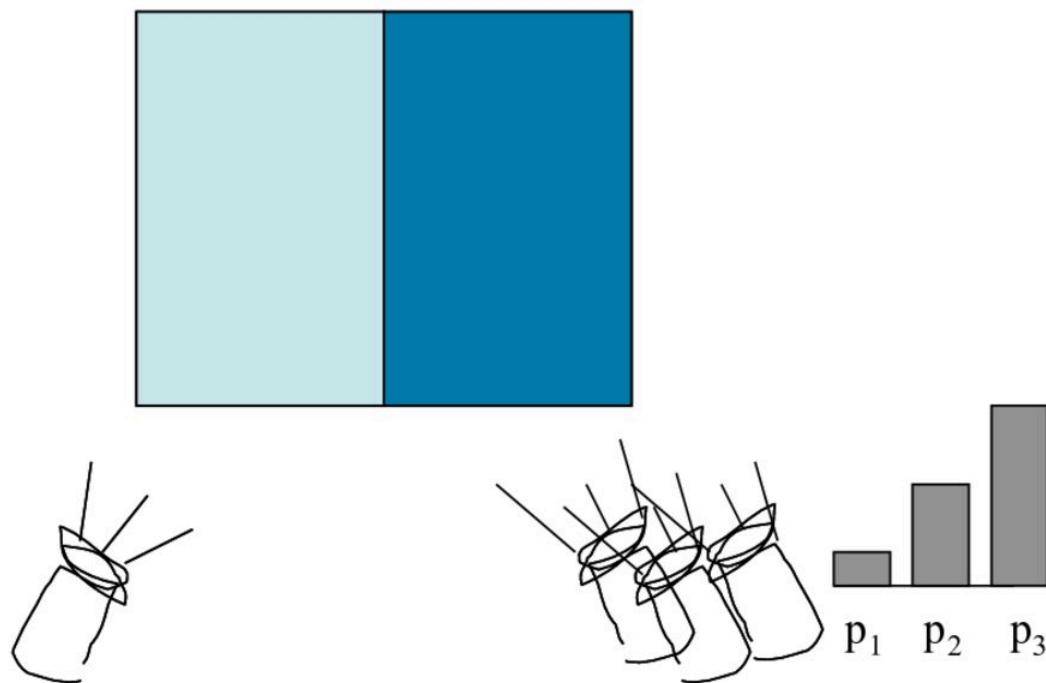


Example experiment



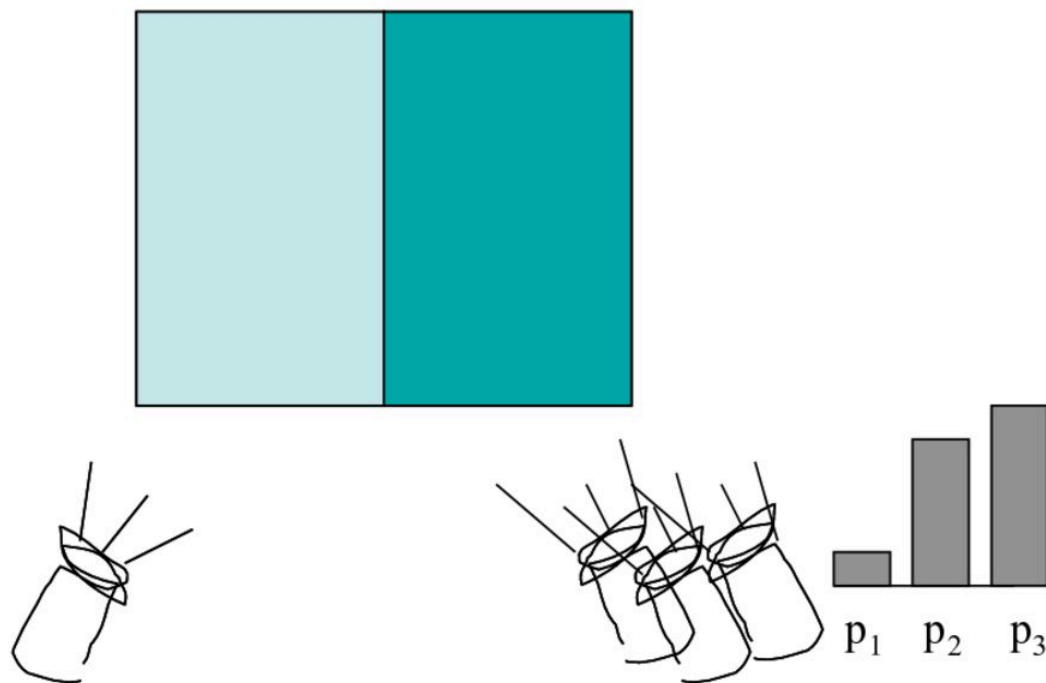
Slide from Durand
and Freeman 06

Example experiment



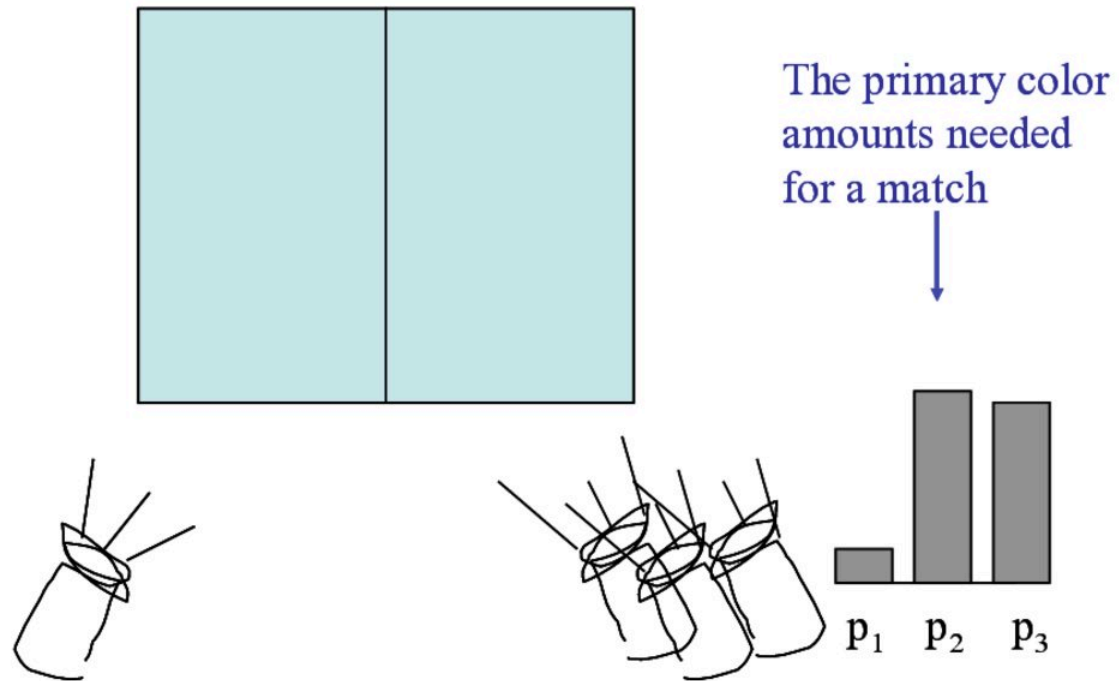
Slide from Durand
and Freeman 06

Example experiment



Slide from Durand
and Freeman 06

Example experiment



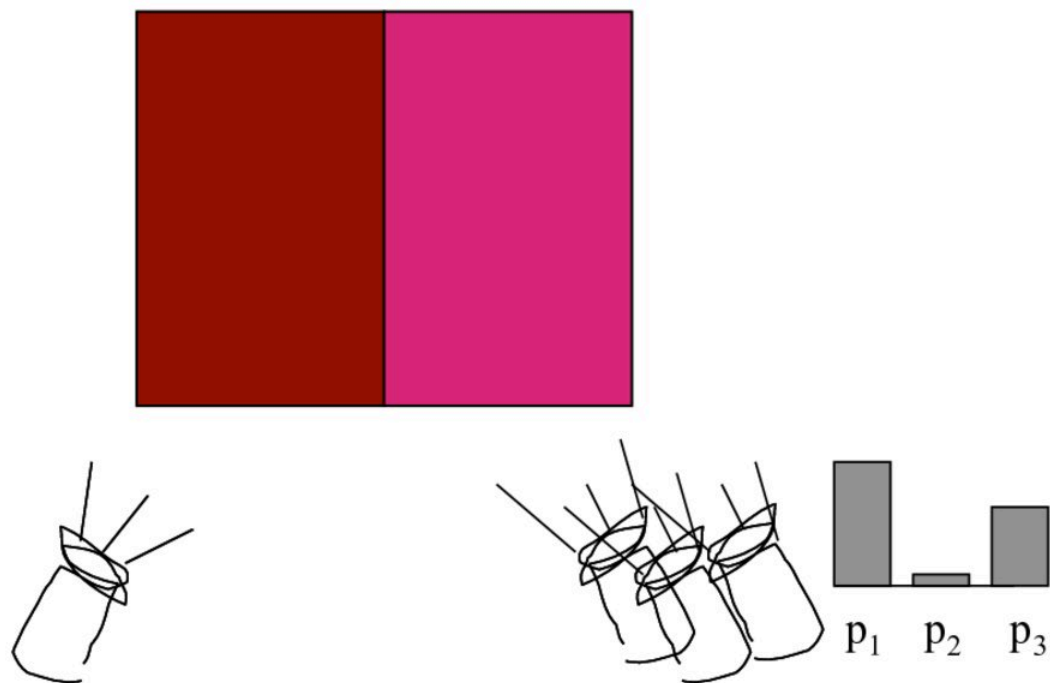
Slide from Durand
and Freeman 06

Experiment 2: out of gamut target



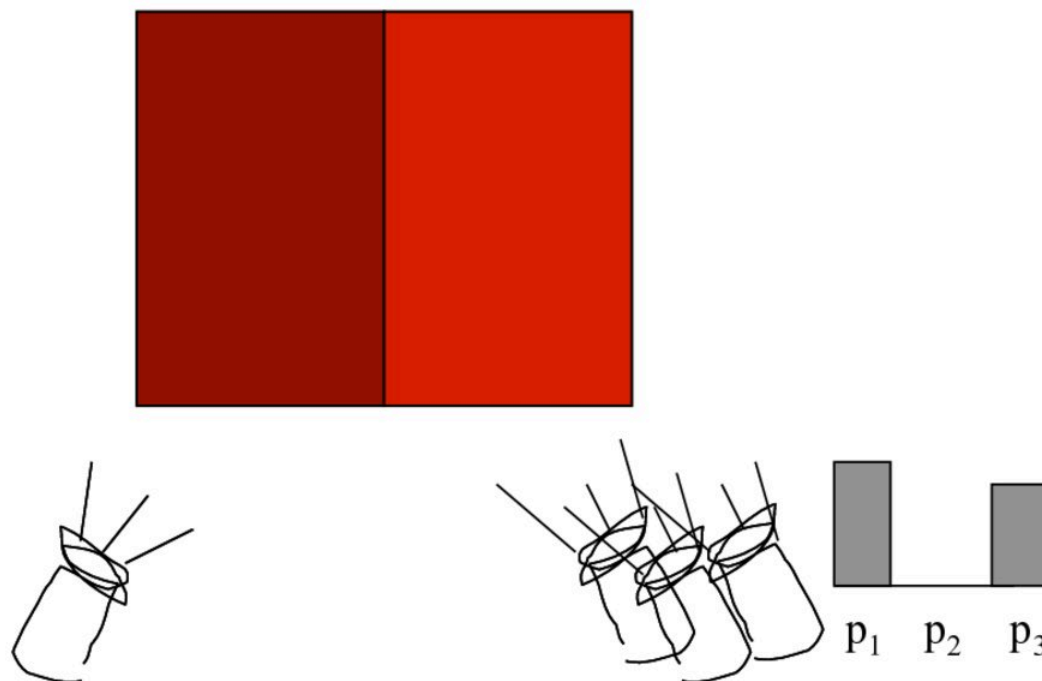
Slide from Durand
and Freeman 06

Experiment 2: out of gamut target



Slide from Durand
and Freeman 06

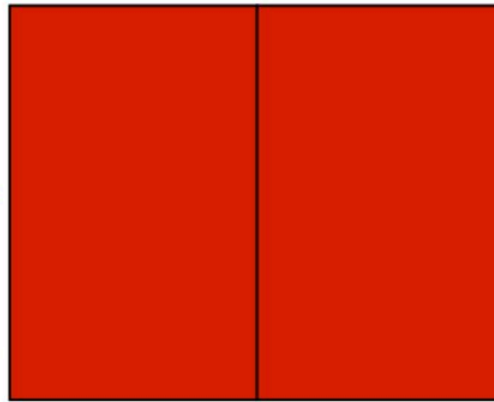
Experiment 2: out of gamut target



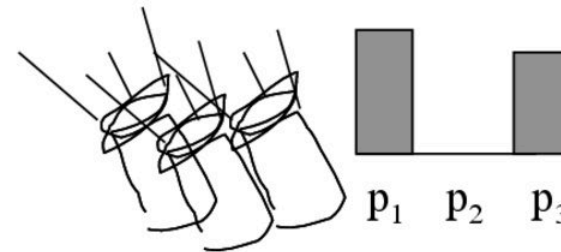
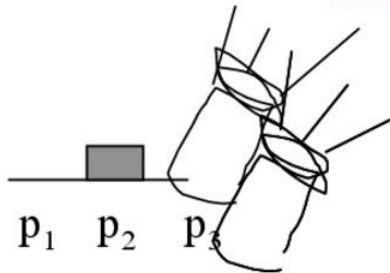
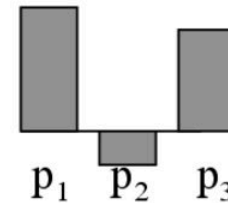
Slide from Durand
and Freeman 06

Experiment 2: out of gamut target

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

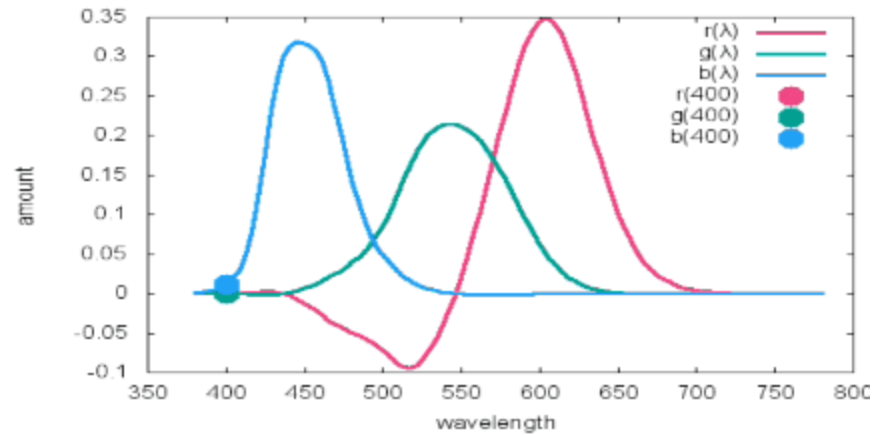
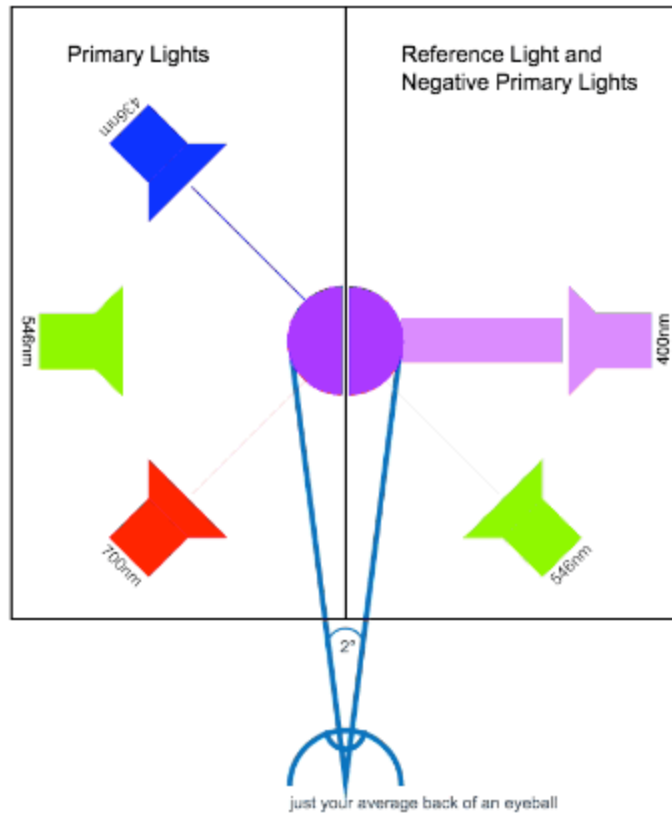


The primary color amounts needed for a match:

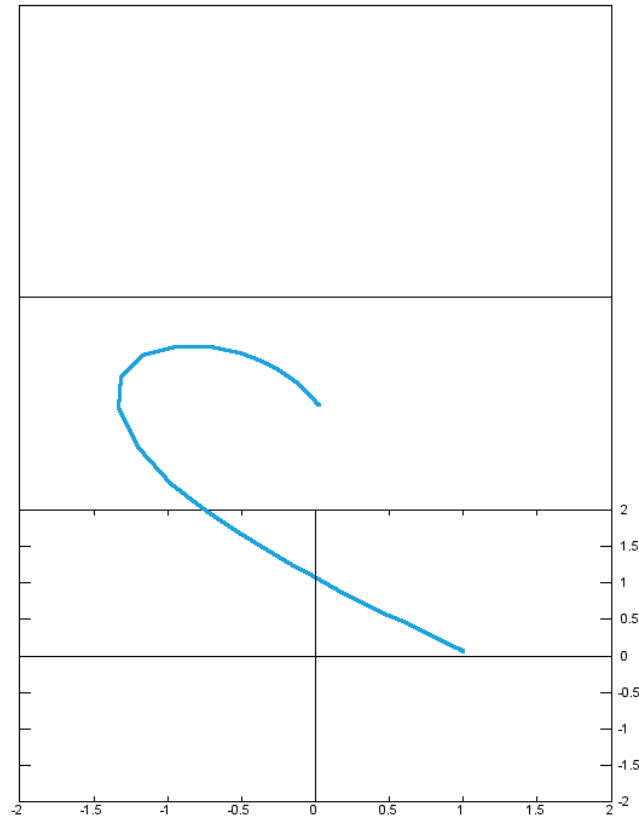


Slide from Durand
and Freeman 06

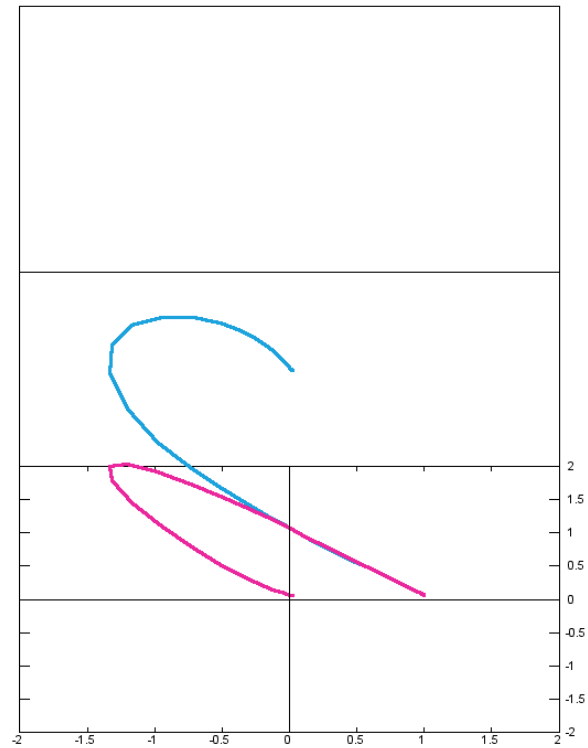
Color matching experiment (CIE 1931)

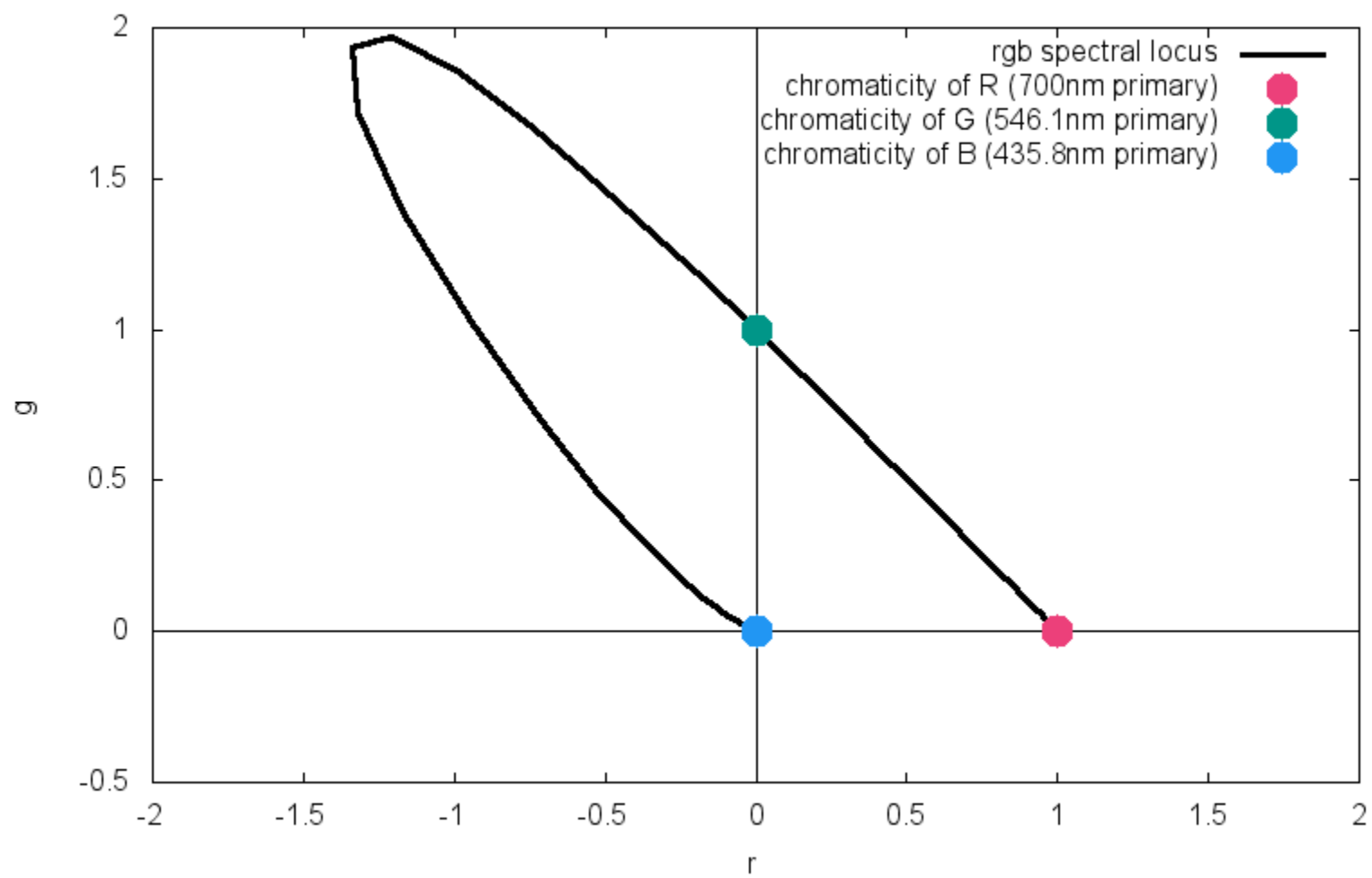


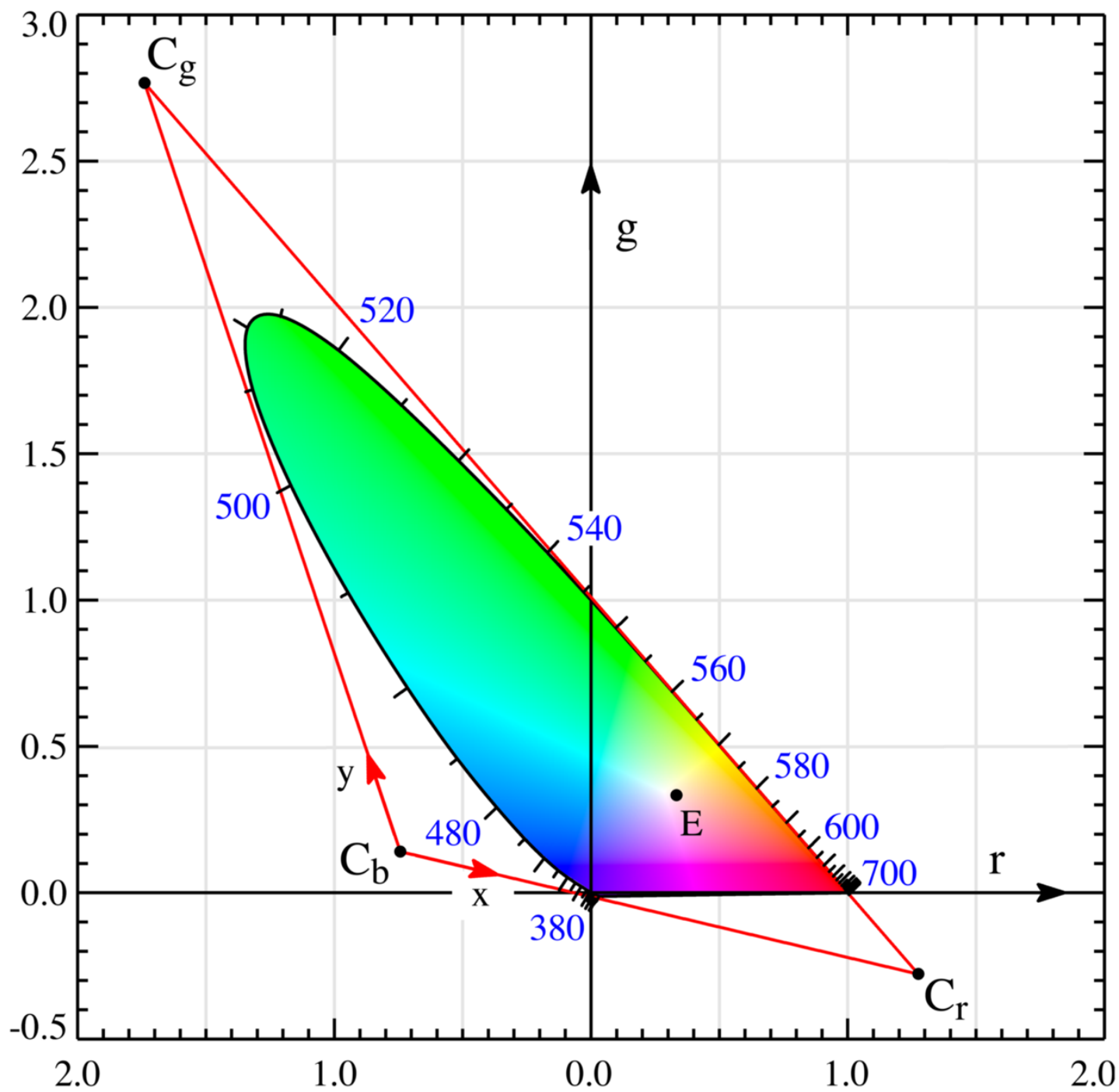
Spectral locus plotted in RGB



Projected onto RG plane

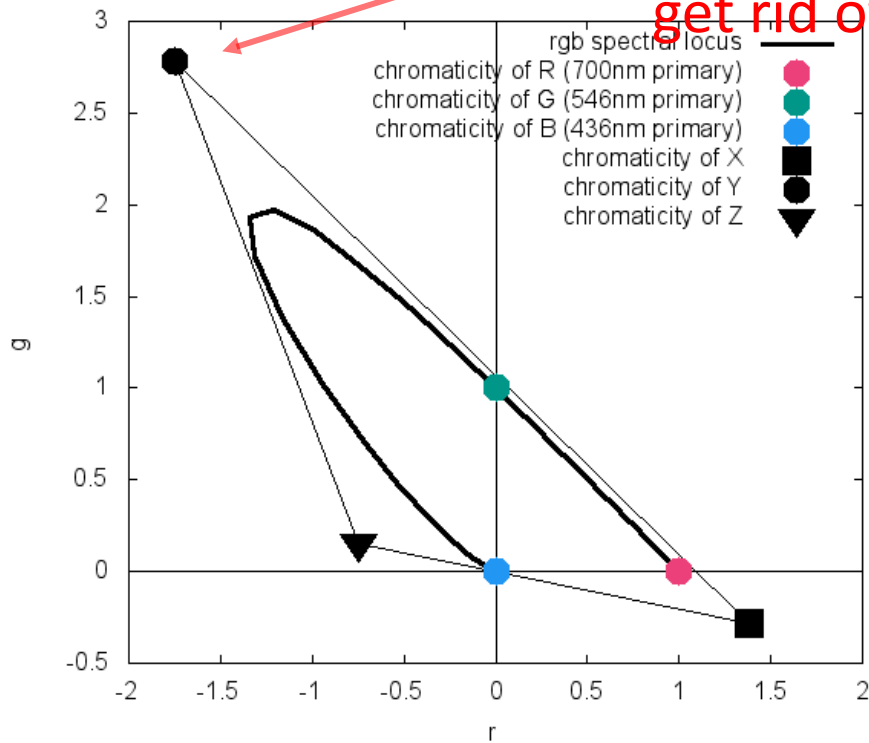




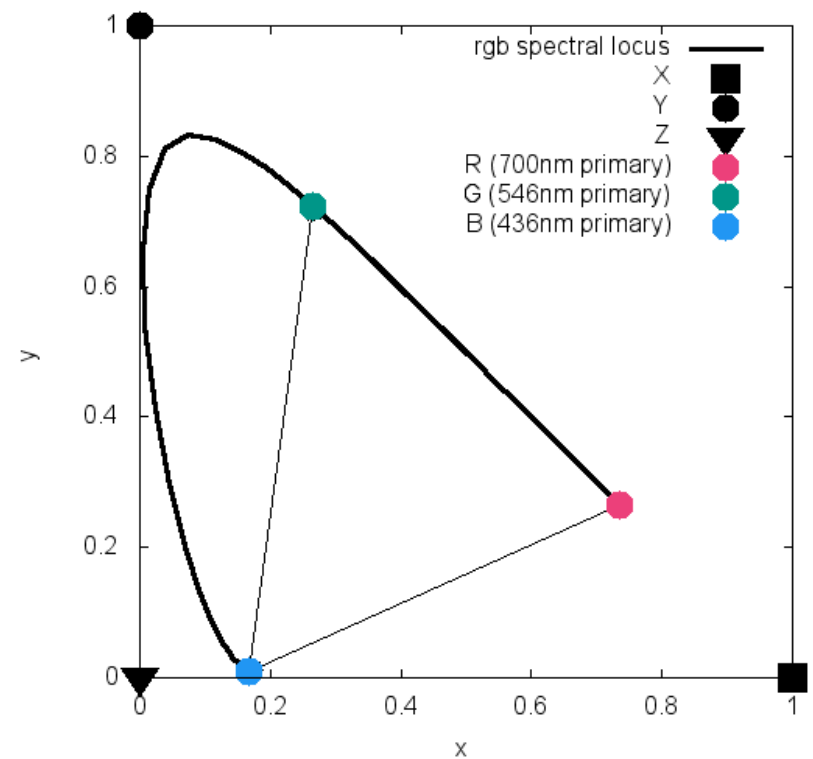


We hate negative
mixing, so let's make up
imaginary primaries to
get rid of it

RGB

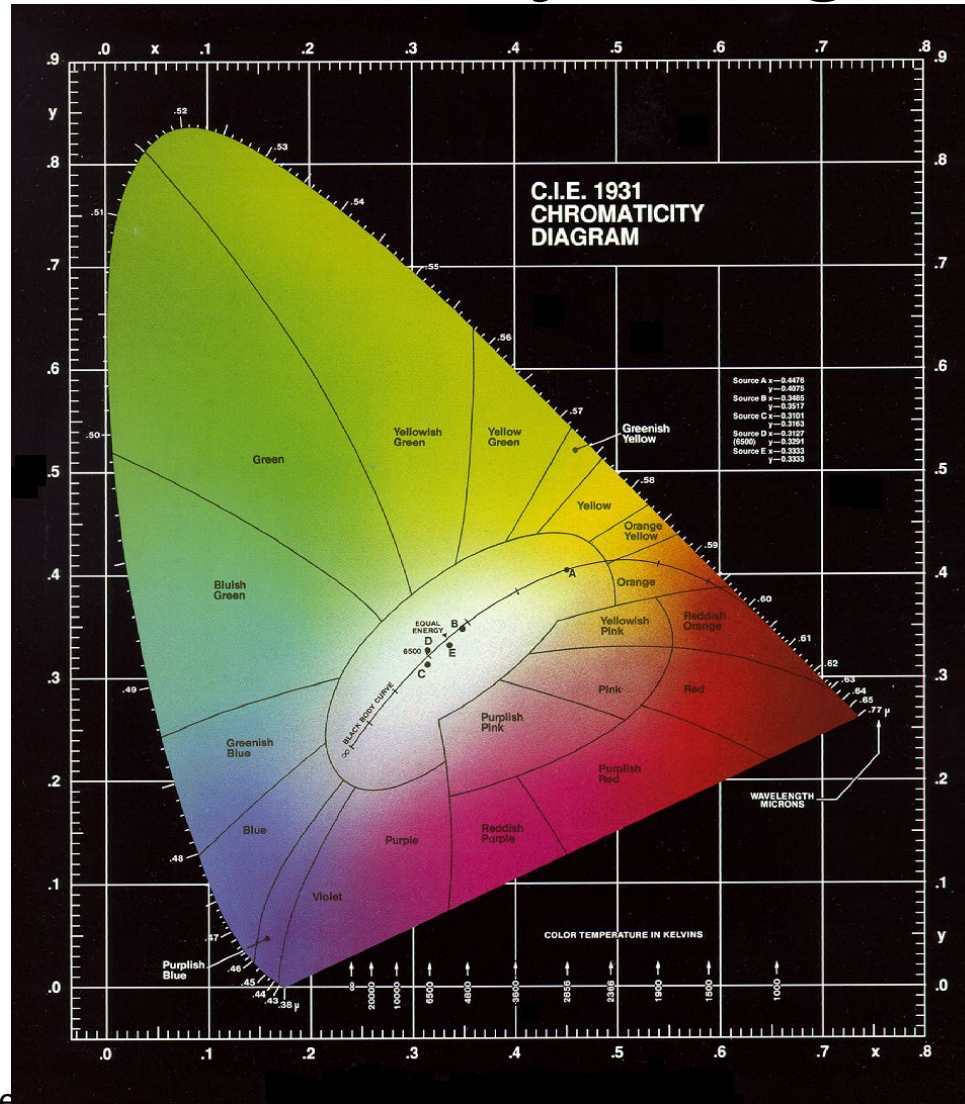


XYZ



$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.41847 & -0.15866 & -0.082835 \\ -0.091169 & 0.25243 & 0.015708 \\ 0.00092090 & -0.0025498 & 0.17860 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Chromaticity Diagram



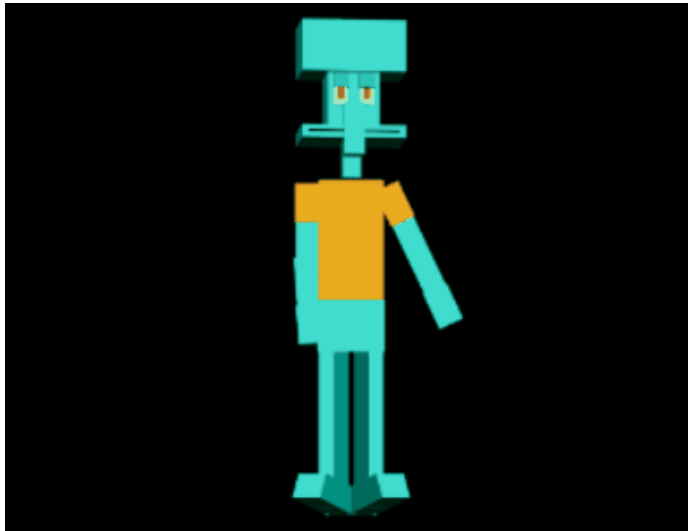
[source unknown]

Administrative

Due Dates

- Yesterday
 - Add/drop passed, so now have late policy
- Due Mon
 - HW2 – Object Modeling, Transforms
- Due Wed
 - (Quiz 2)
- Due following Monday
 - Lab Assignment 2 (Blocky Animal)

Assignment 2



Your name here.

UCSC CSE-160-01 Pages Hall of Fame

2020 Spring Quarter View All Pages

Hall of Fame

Spring 2020

Winter 2020

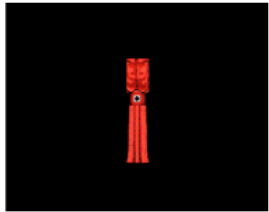
Assignment 2 - Bloody Animal



1st Place - Dragon - Herman Wu



2nd Place - Squidward by Sehej Singh Sohal - <https://people.ucsc.edu/~sssohal/A2/>



2nd Place - Squid by Kevin Macnair Pinney - <https://people.ucsc.edu/~kpinney/cse160/ps2>

Q&A

End