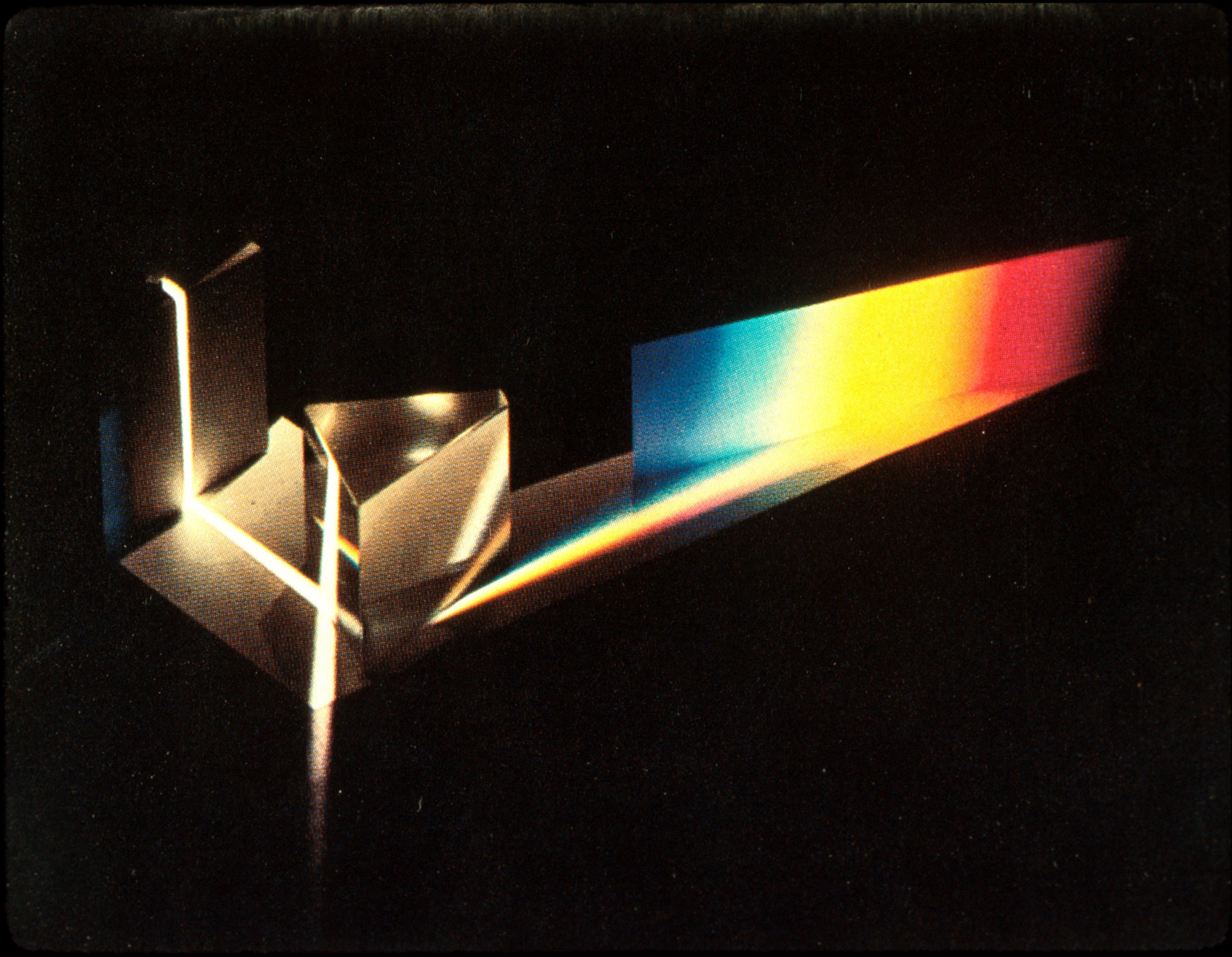
CSE160 – Color

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

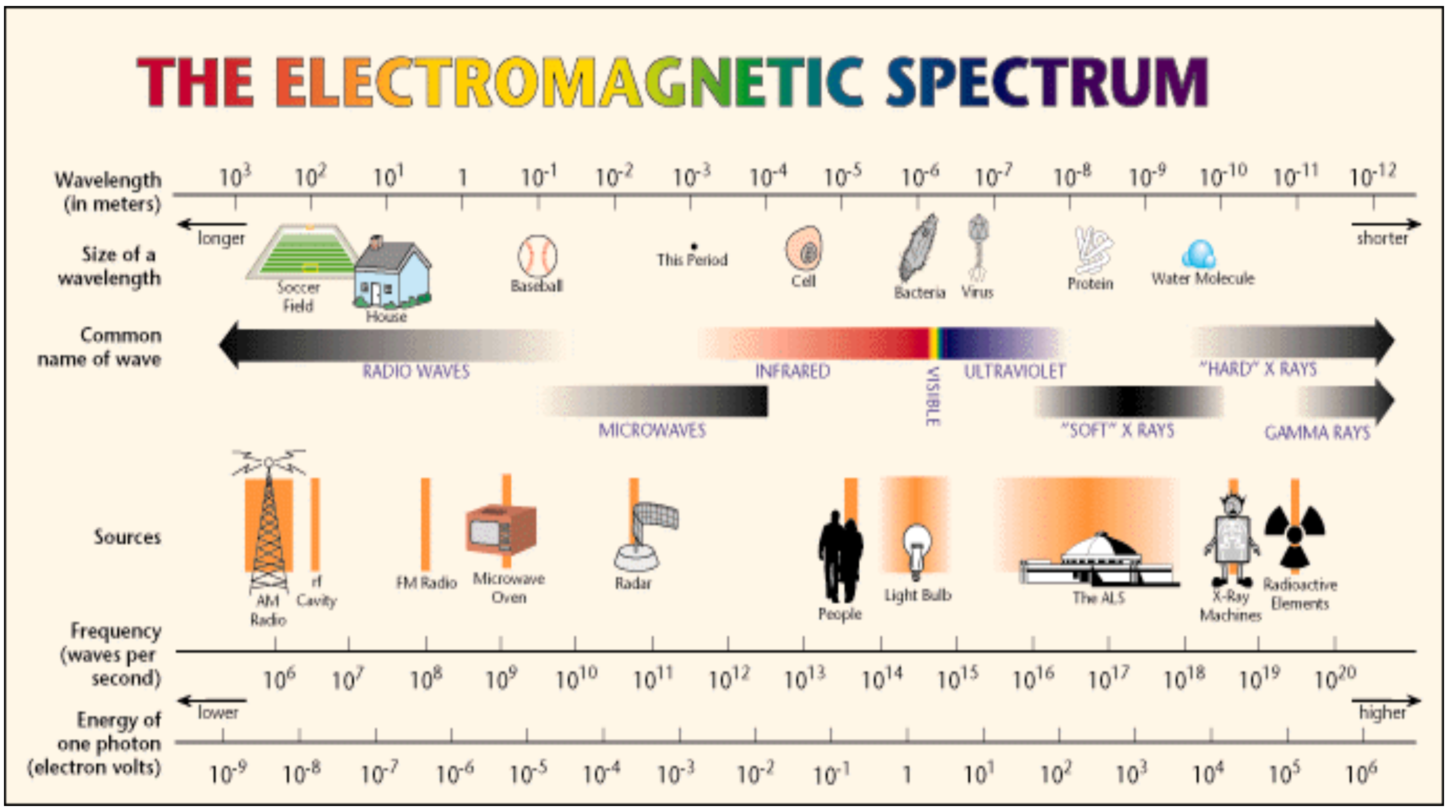
From physics to perception



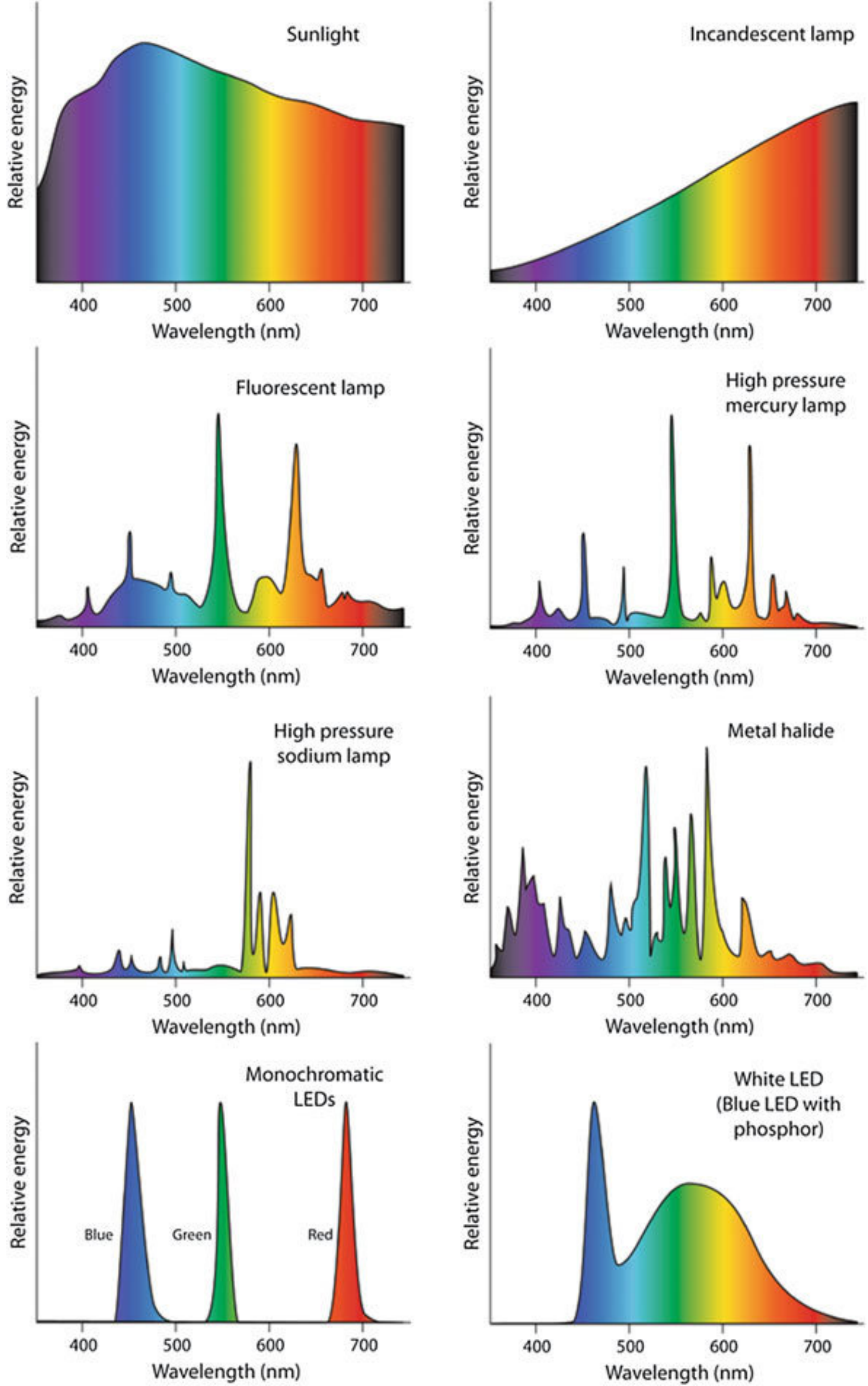
[source unknown]

What light is

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



[Lawrence Berkeley Lab / MicroWorlds]



Sunlight
Incandescent lamp
Fluorescent lamp
High pressure mercury lamp
High pressure sodium lamp
Metal halide
Monochromatic LEDs
Blue
Green
Red
White LED (Blue LED with phosphor)
Relative energy
Wavelength (nm)
400
500
600
700

Superposition (linearity) of spectral power distributions

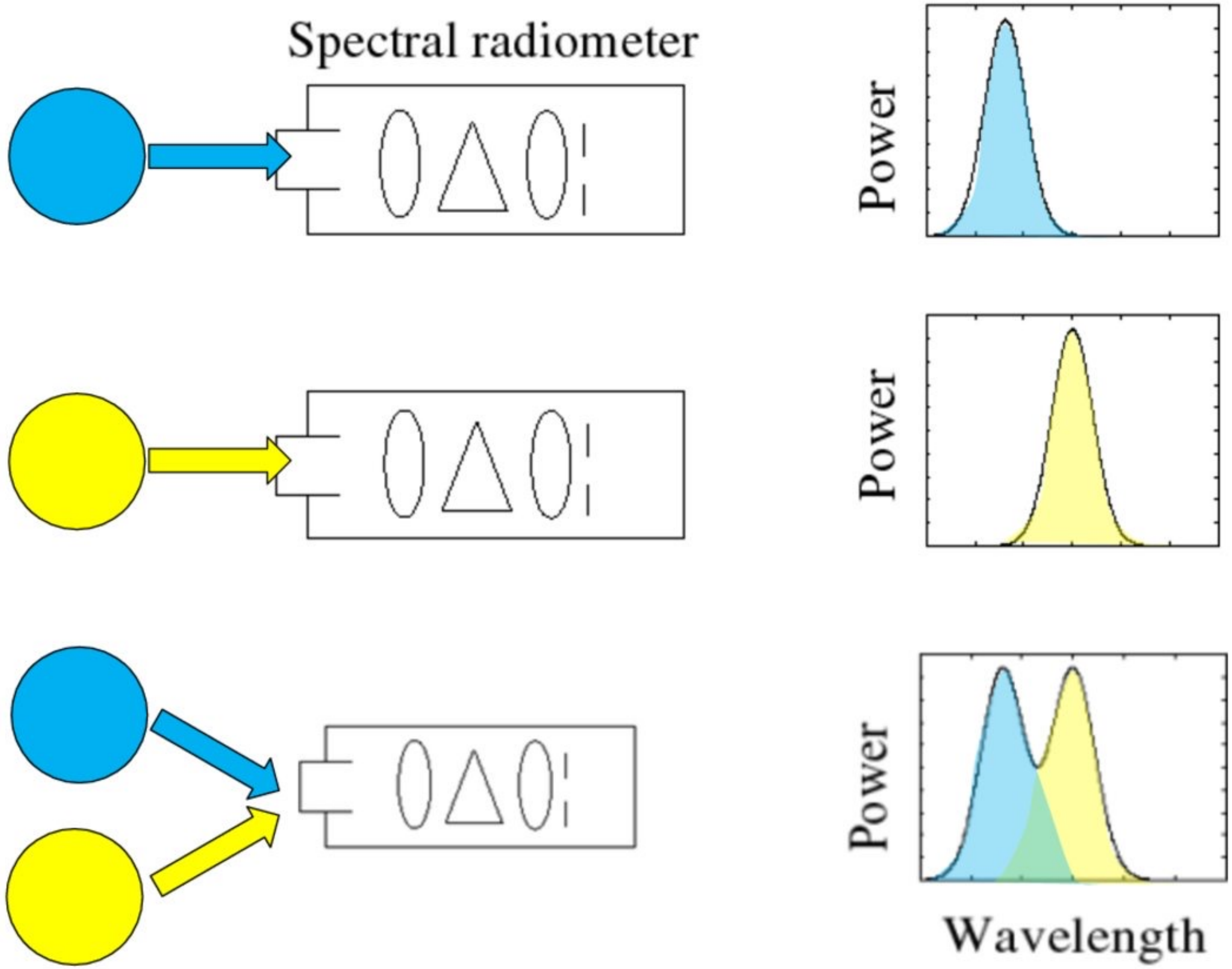
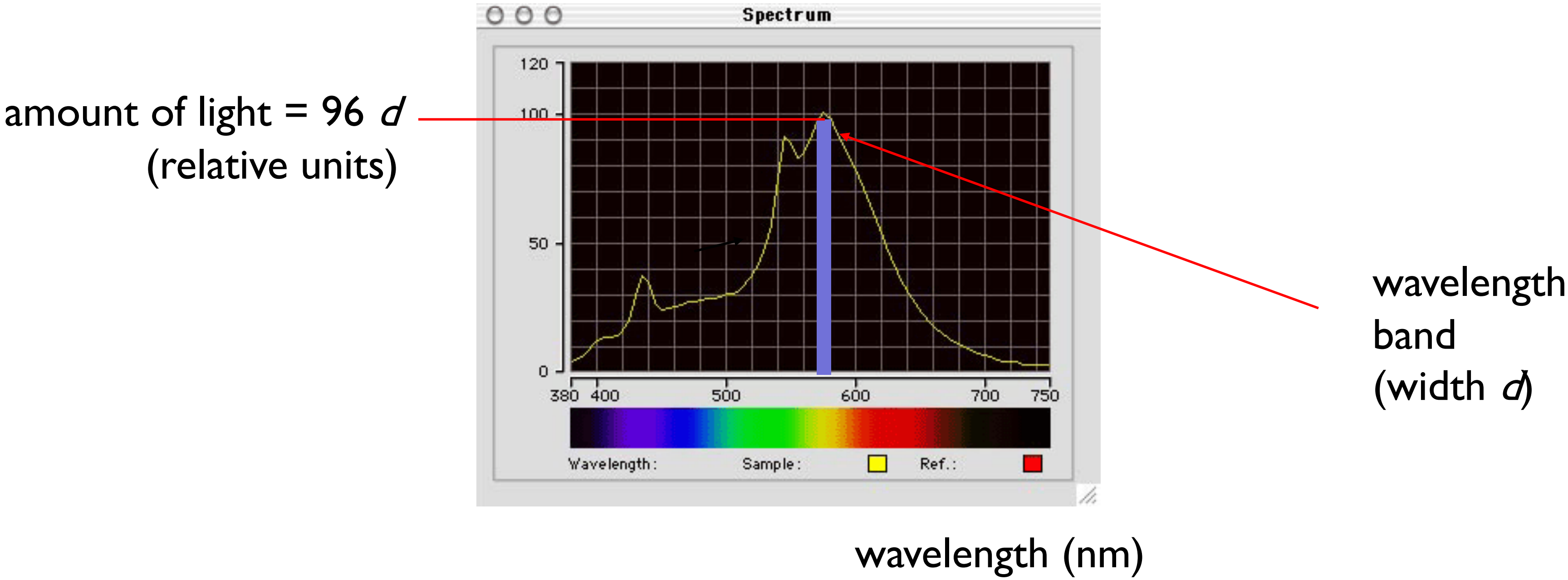


Figure credit: Brian Wandell

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)

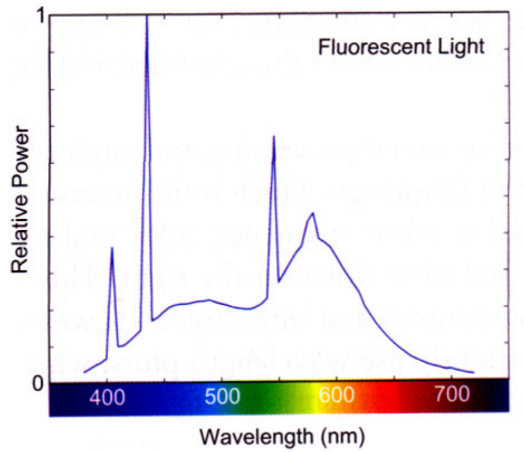


[modified JED]

But why do we see "color"?

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

[Stone 2003]

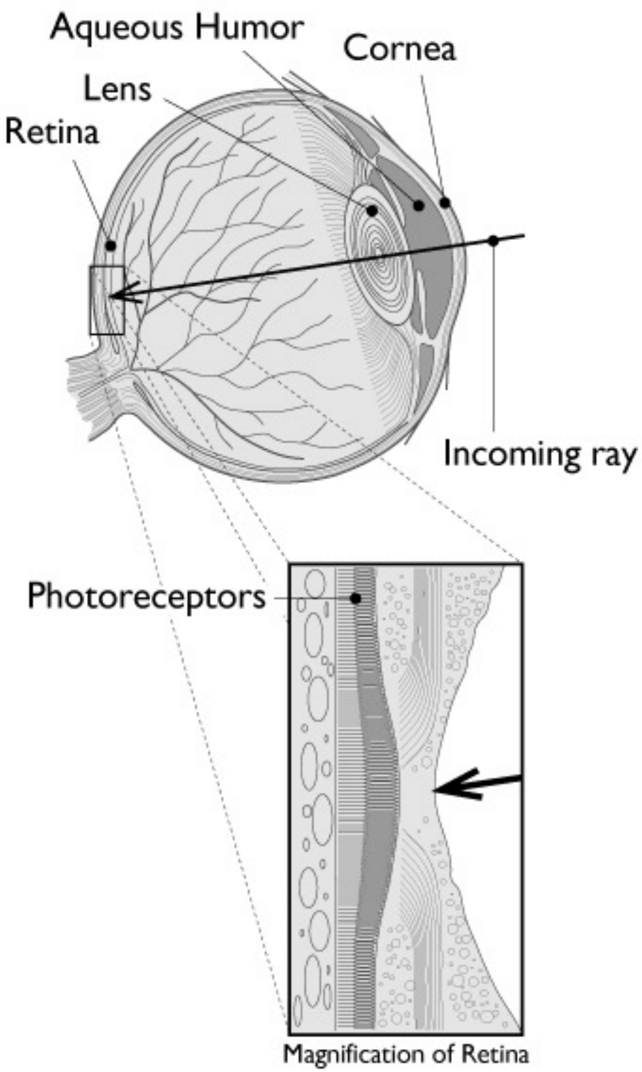


Physical

?

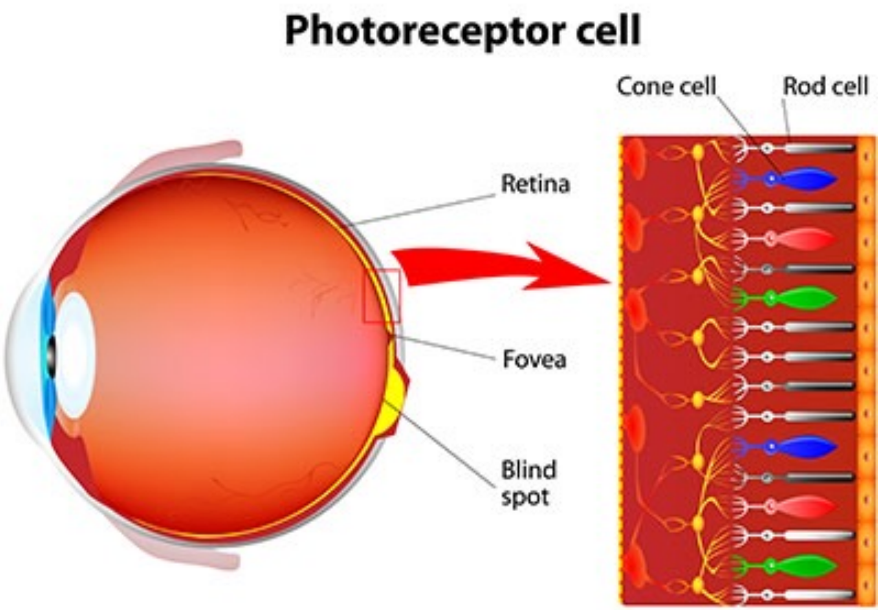
Perceptual

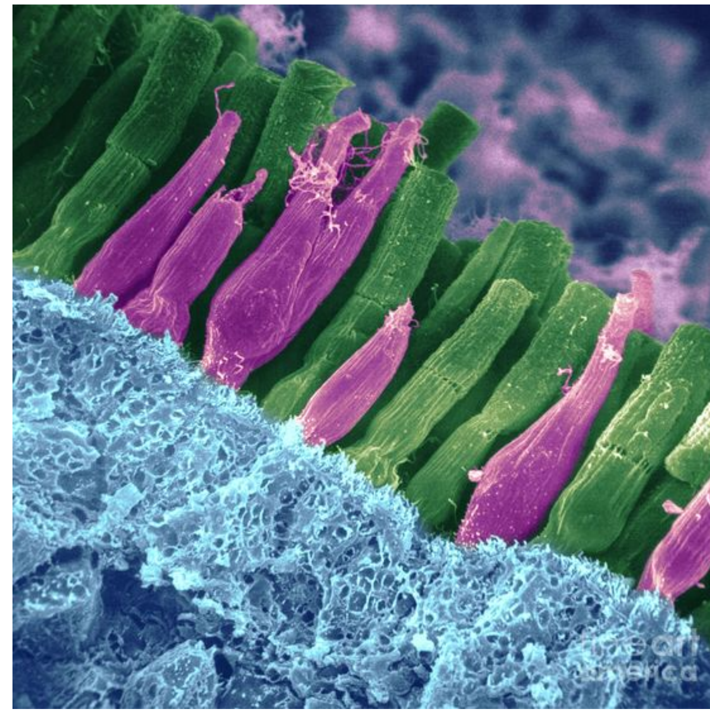
The eye as a measurement device



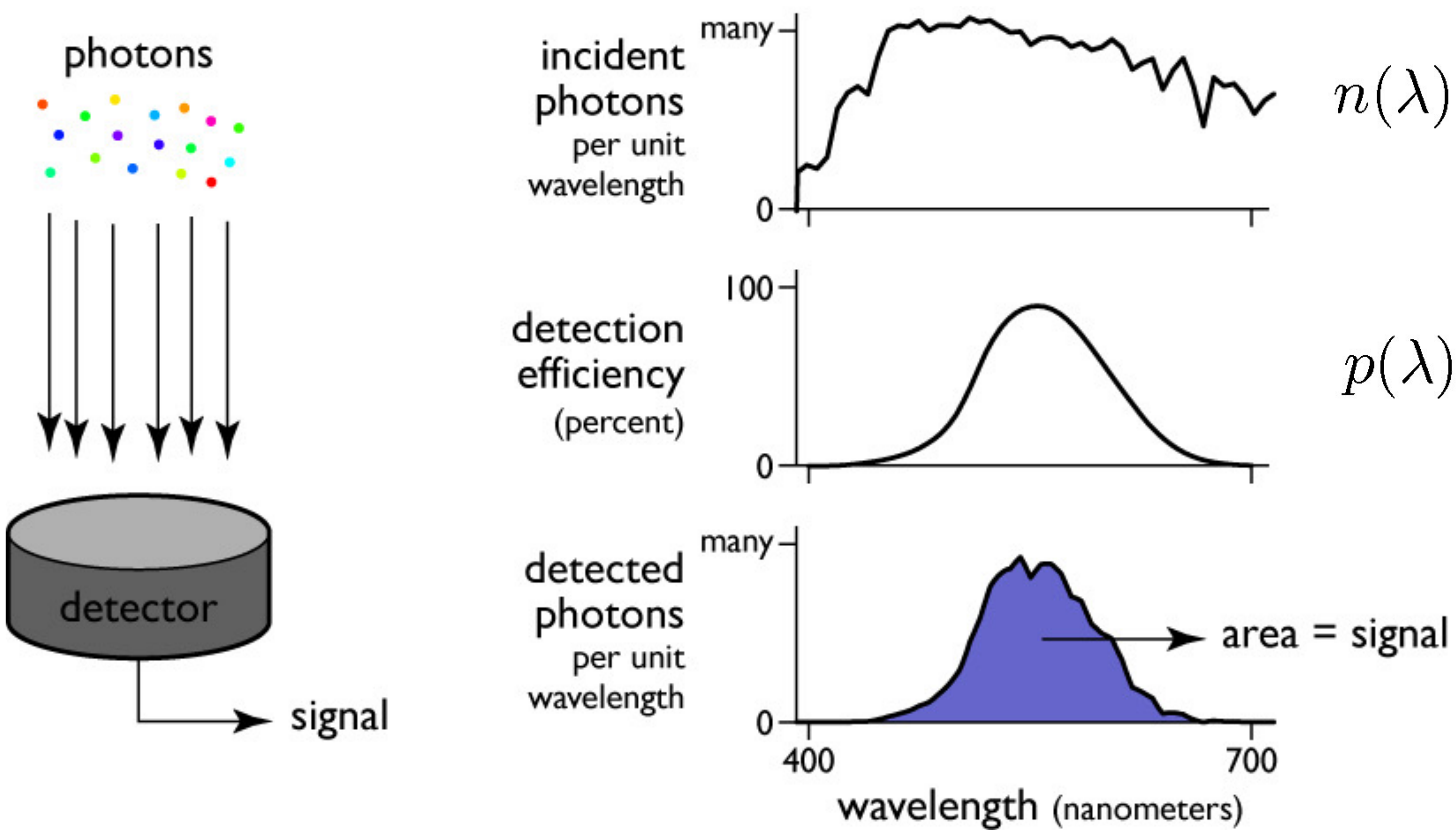
[Greger et al. 1995]

- 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
Cone cell
Rod cell
Retina
Fovea
Blind spot



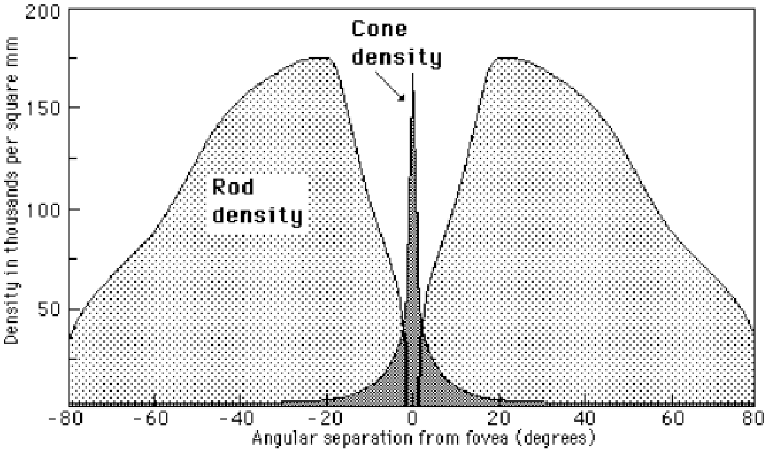
A simple light detector



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

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

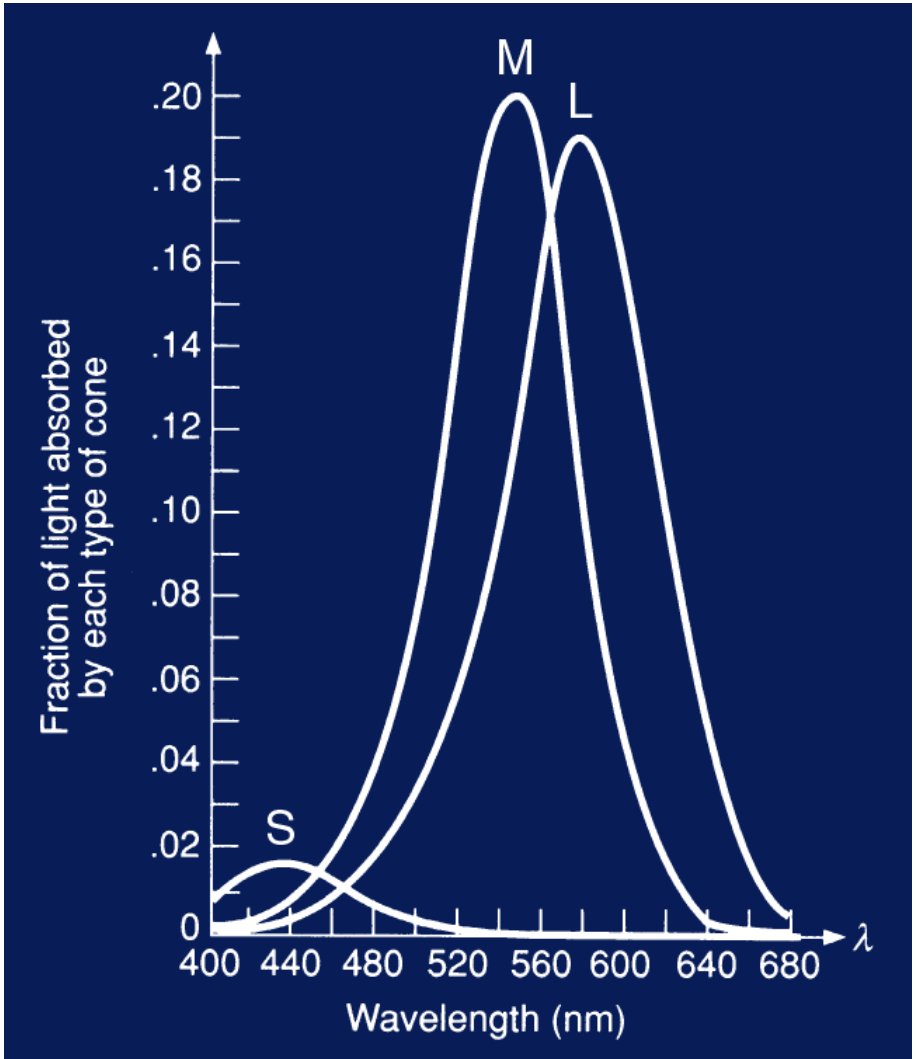


Rods

- 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

[Talton]

Cone Responses

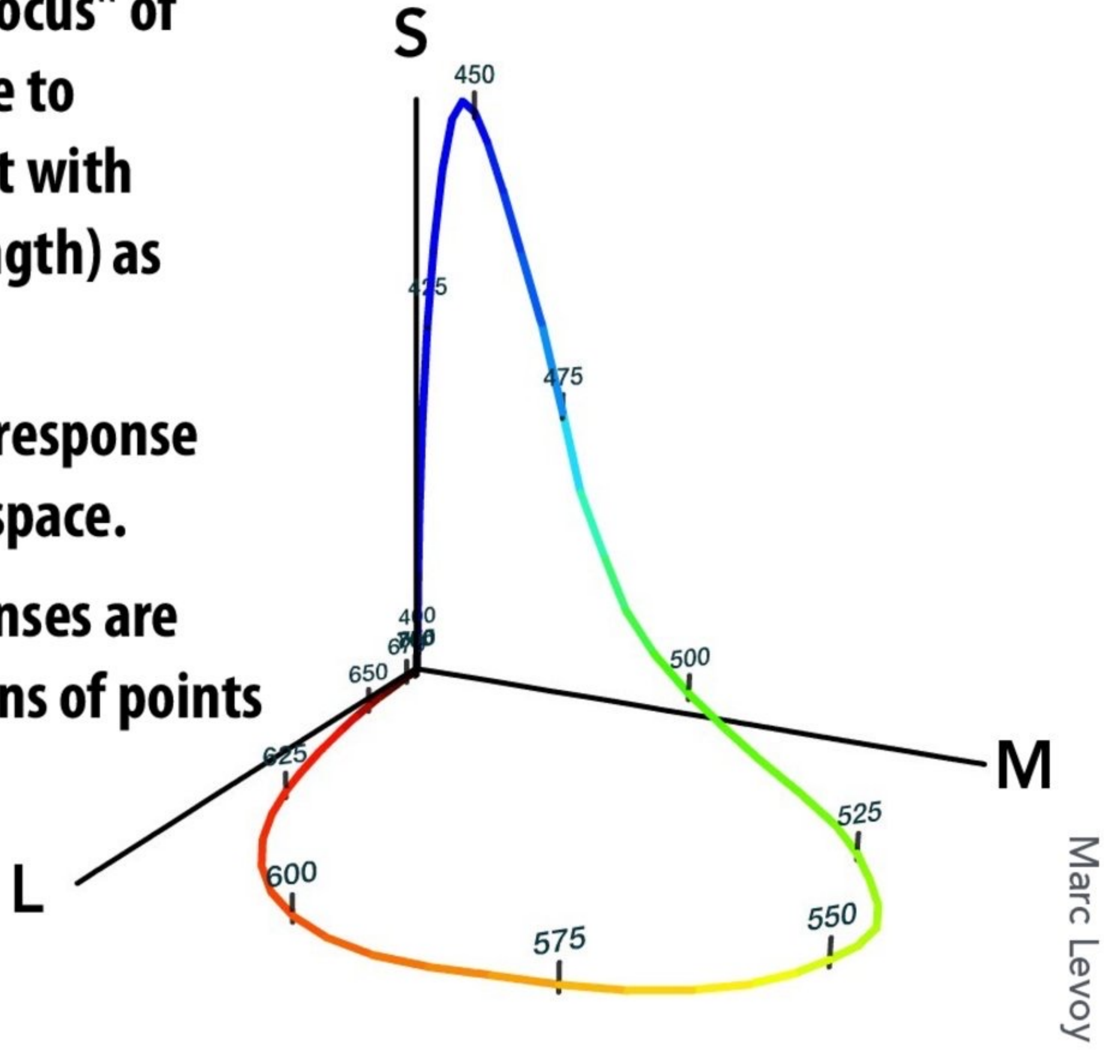


- S,M,L cones have broadband spectral sensitivity
- S,M,L neural response is integrated w.r.t. λ
  - we'll call the response functions r_S, r_M, r_L
- Results in a trichromatic visual system
- S, M, and L are *tristimulus values*

[source unknown]

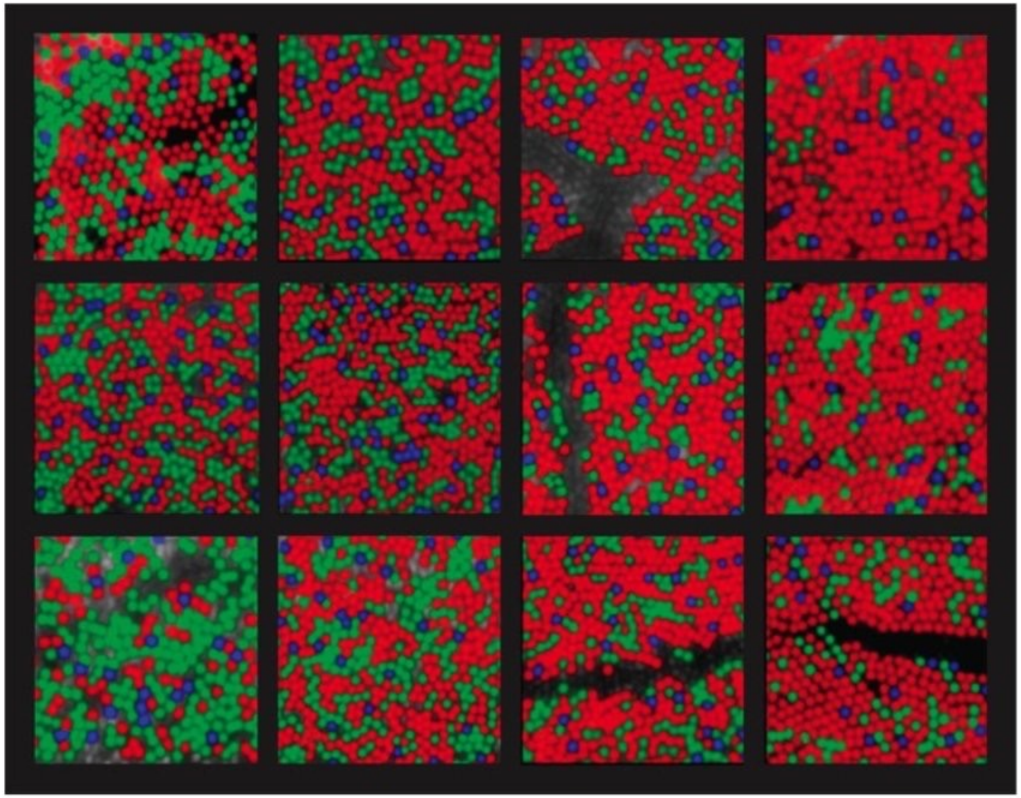
LMS responses plotted as 3D color space

- 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.



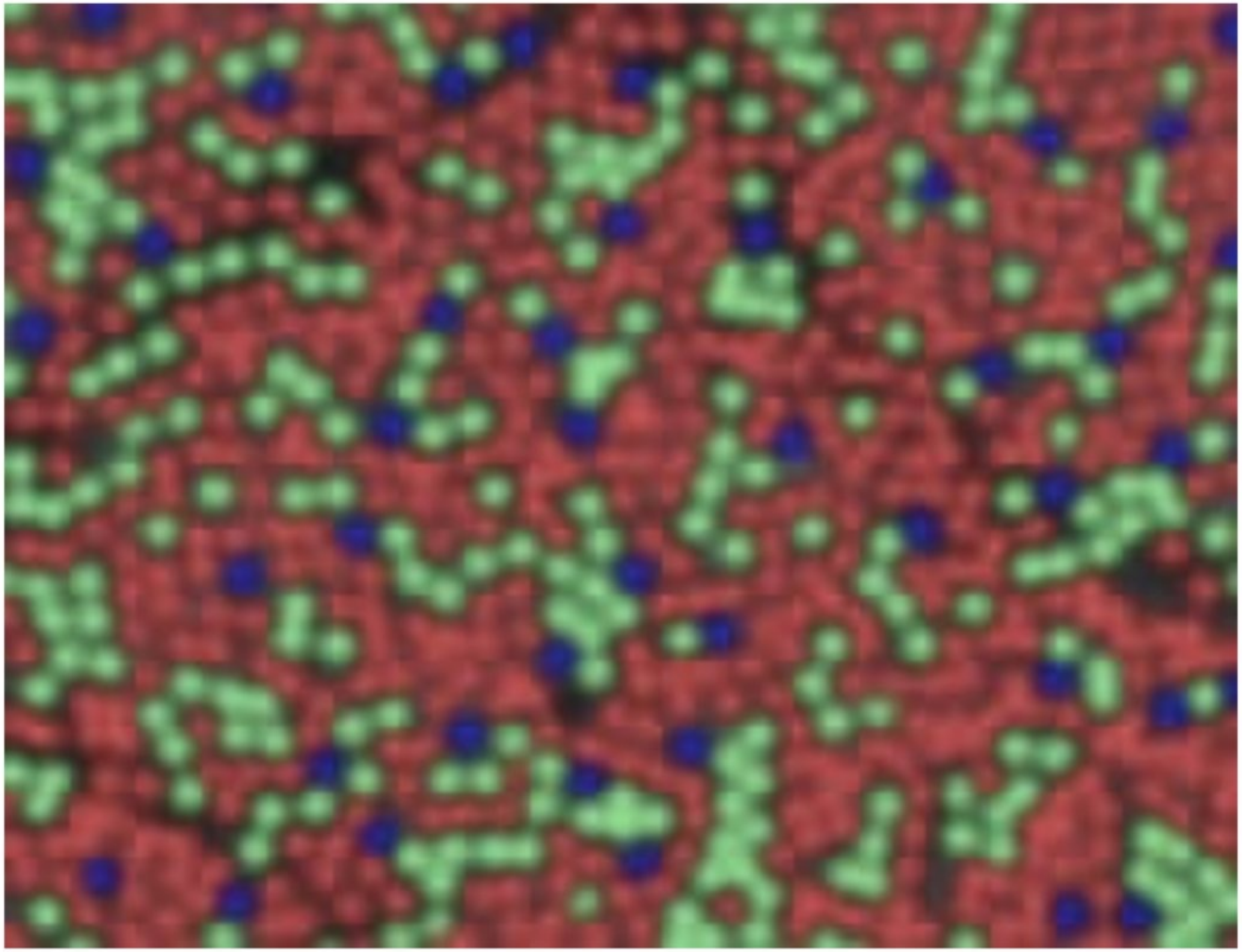
Fraction of three cone cell types varies widely

Hofer, H. et al. J. Neurosci. 2005;25:9669-9679



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)

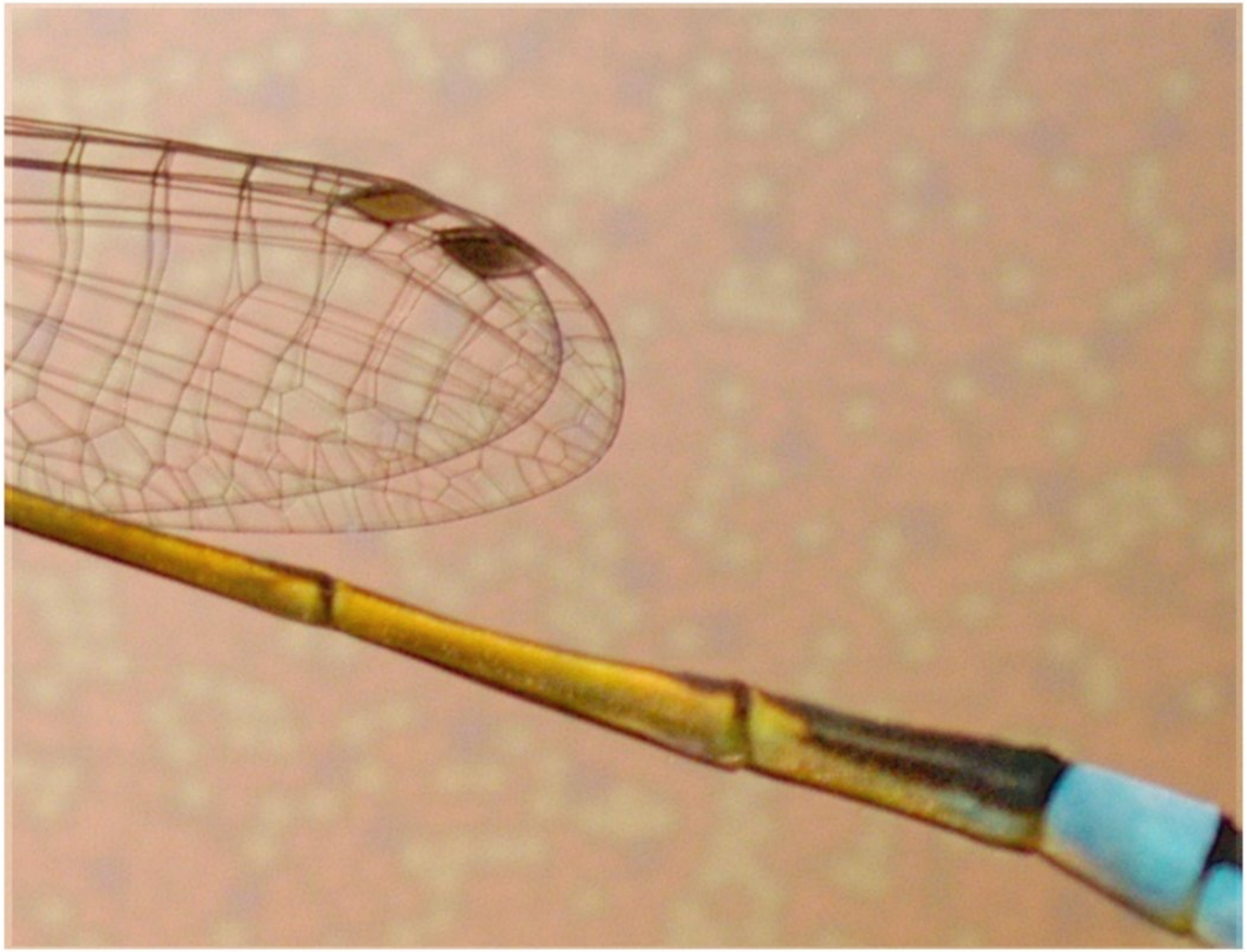
Example: spectral response of human cone cells



Scene projected onto retina

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

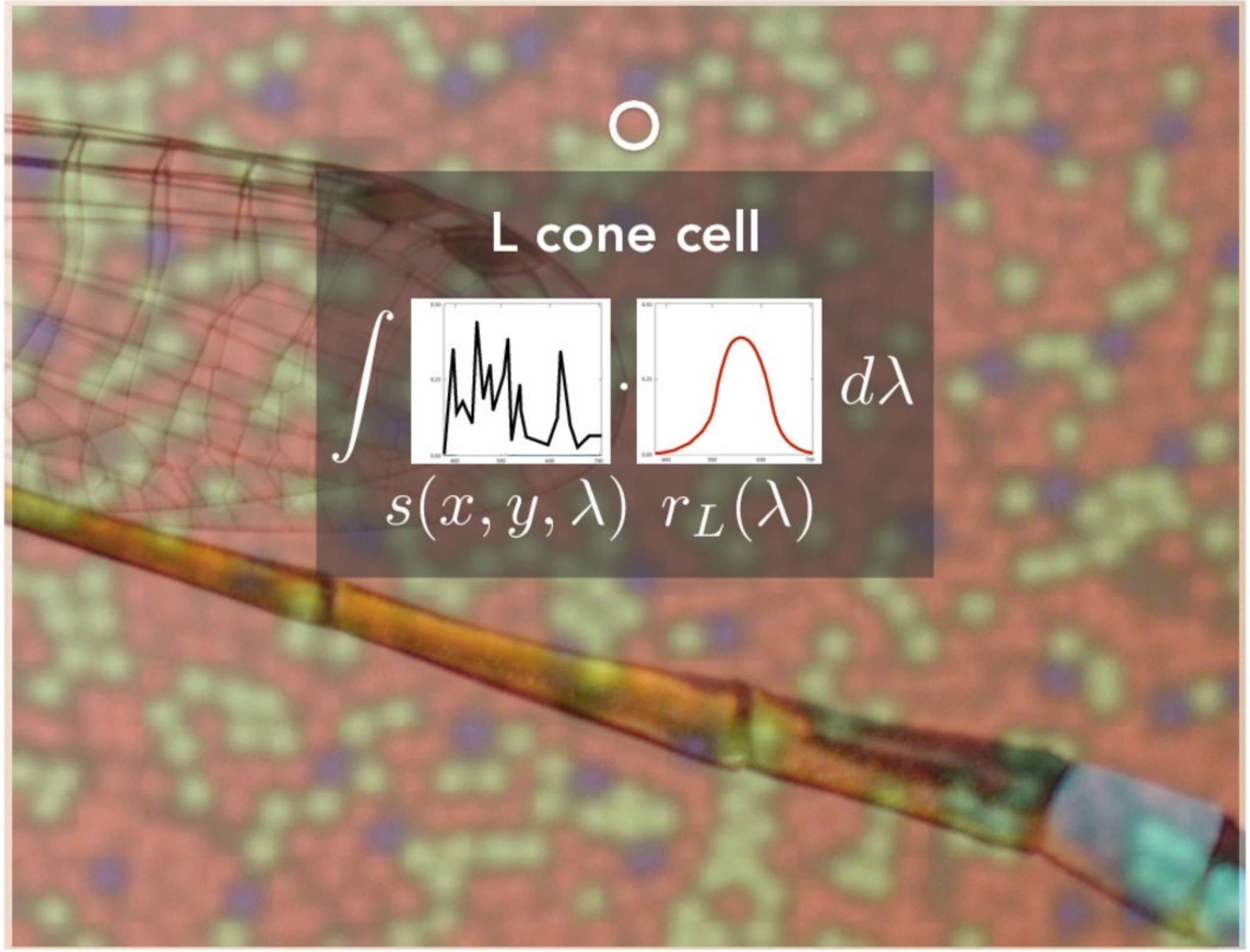
Example: spectral response of human cone cells



Scene projected onto retina

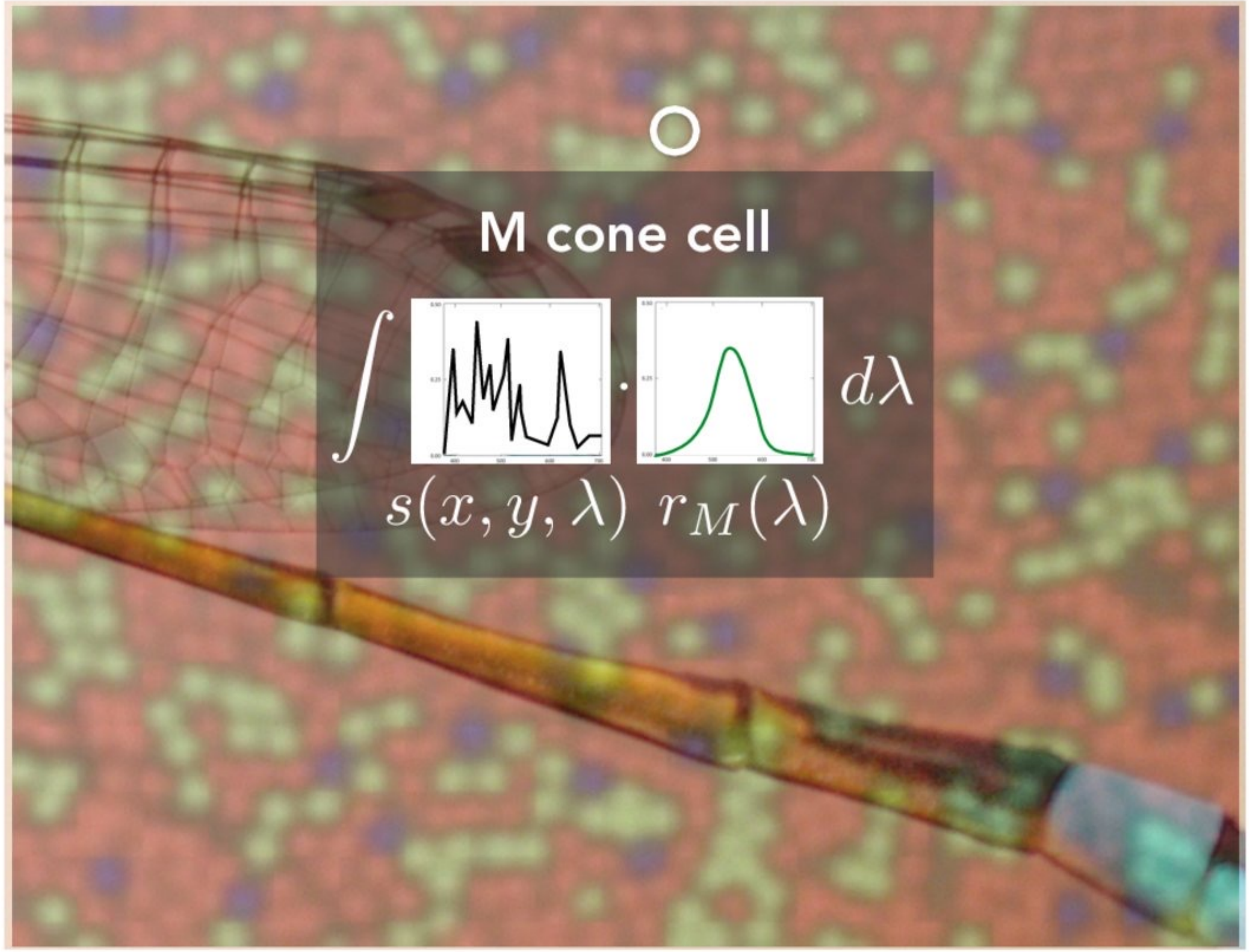
Credit: Sabesan, http://depts.washington.edu/sabaolab

Example: spectral response of human cone cells



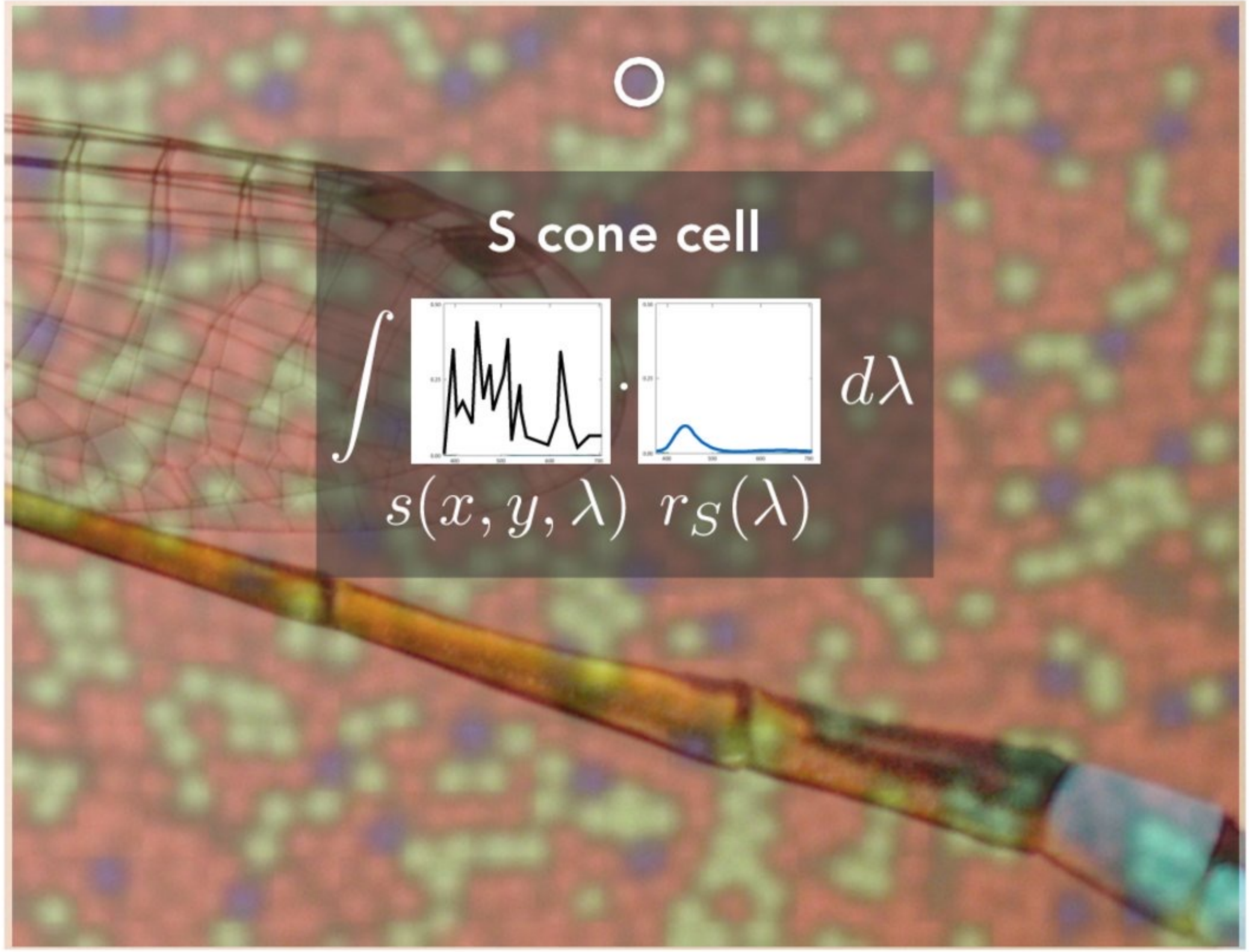
Credit: Sabesan, http://depts.washington.edu/sabaolab

Example: spectral response of human cone cells



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

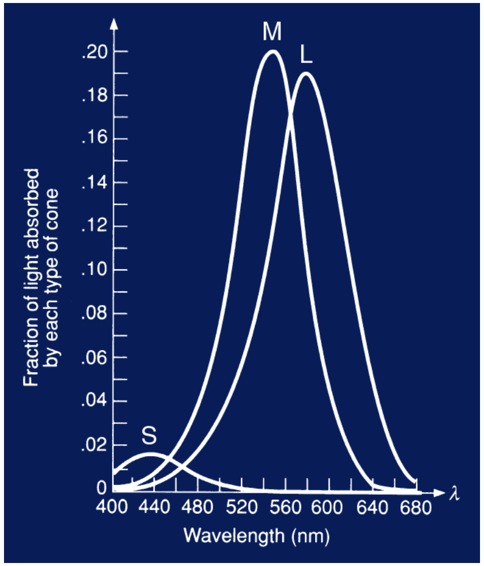
Example: spectral response of human cone cells

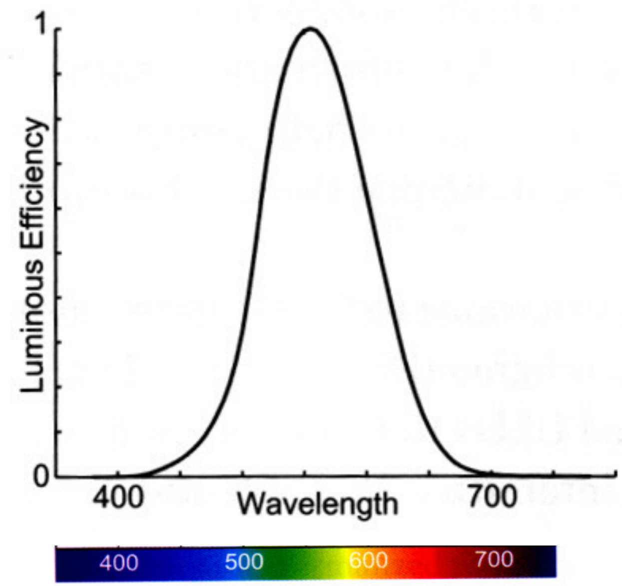


Credit: Sabesan, http://depts.washington.edu/sabaolab

Luminance (brightness)

– Combined visual response to a spectrum

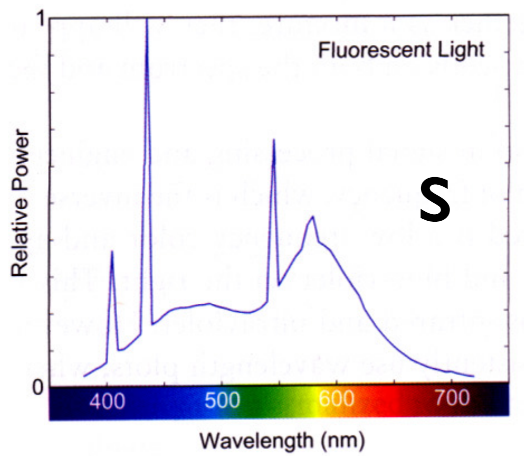




[Stone 2003]

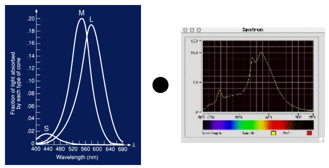
Colorimetry: an answer to the problem

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



Physical

[Stone 2003]



$$S = r_S \cdot s$$

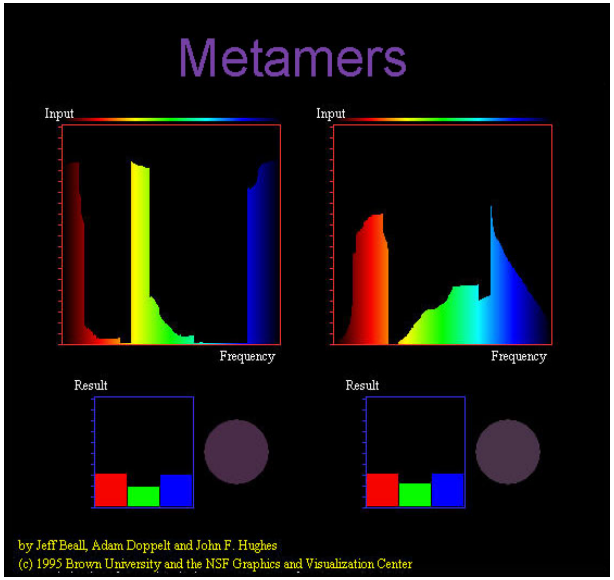
$$M = r_M \cdot s$$

$$L = r_L \cdot s$$

Perceptual

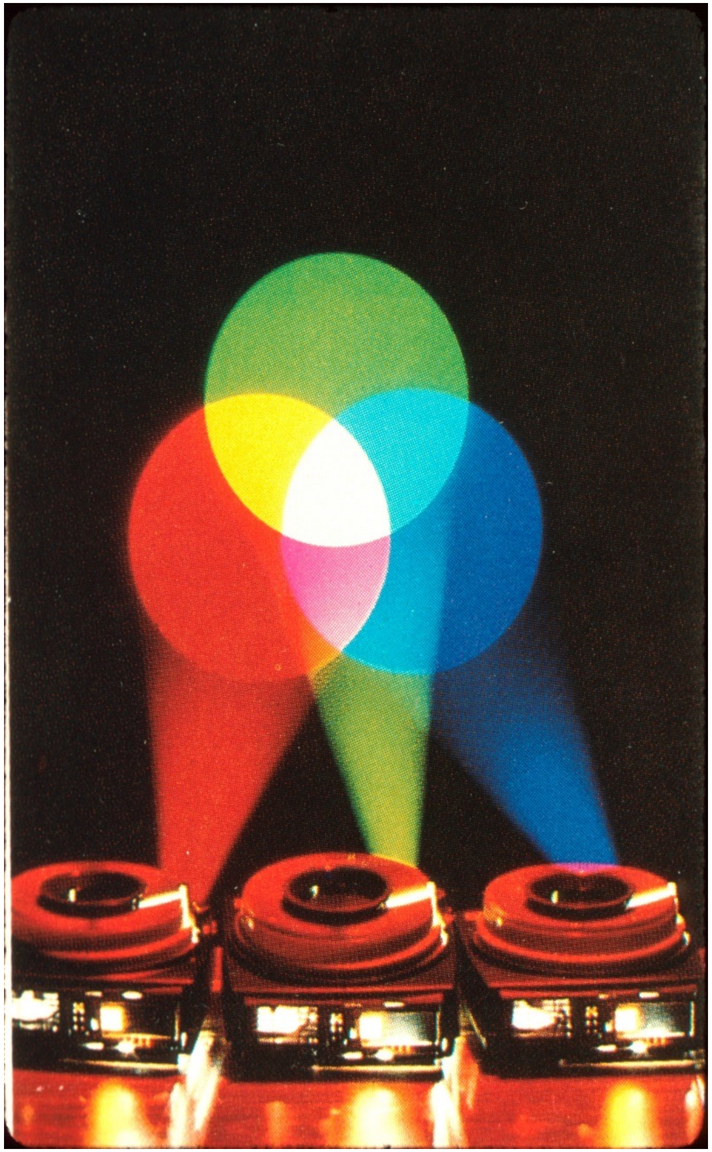
Metamers

- 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*



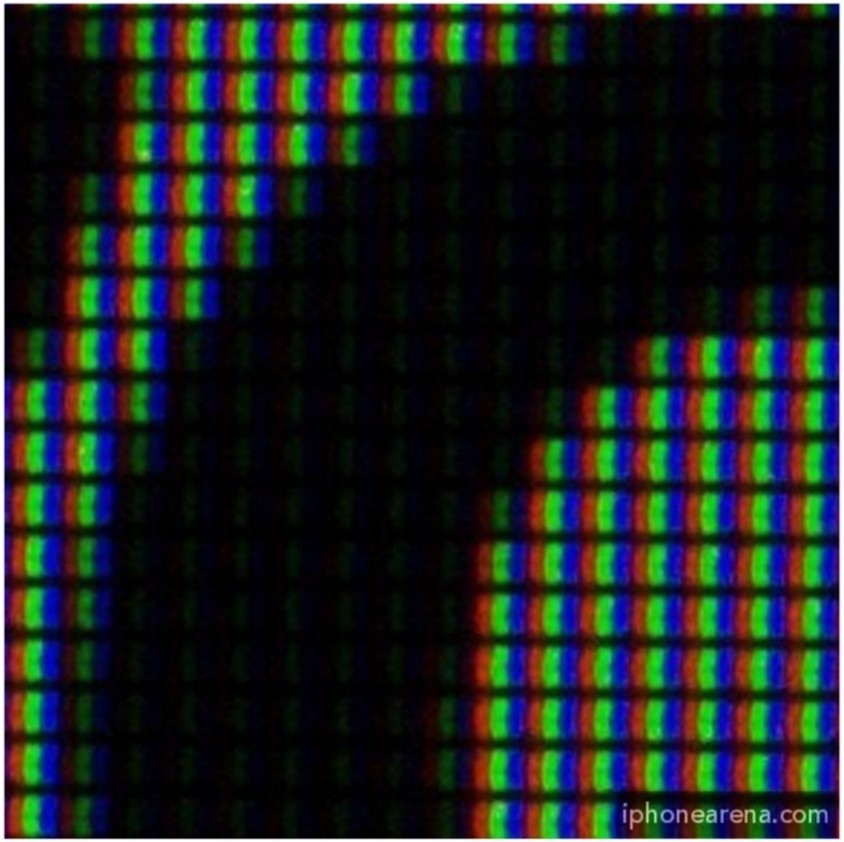
Additive Color

Additive Color

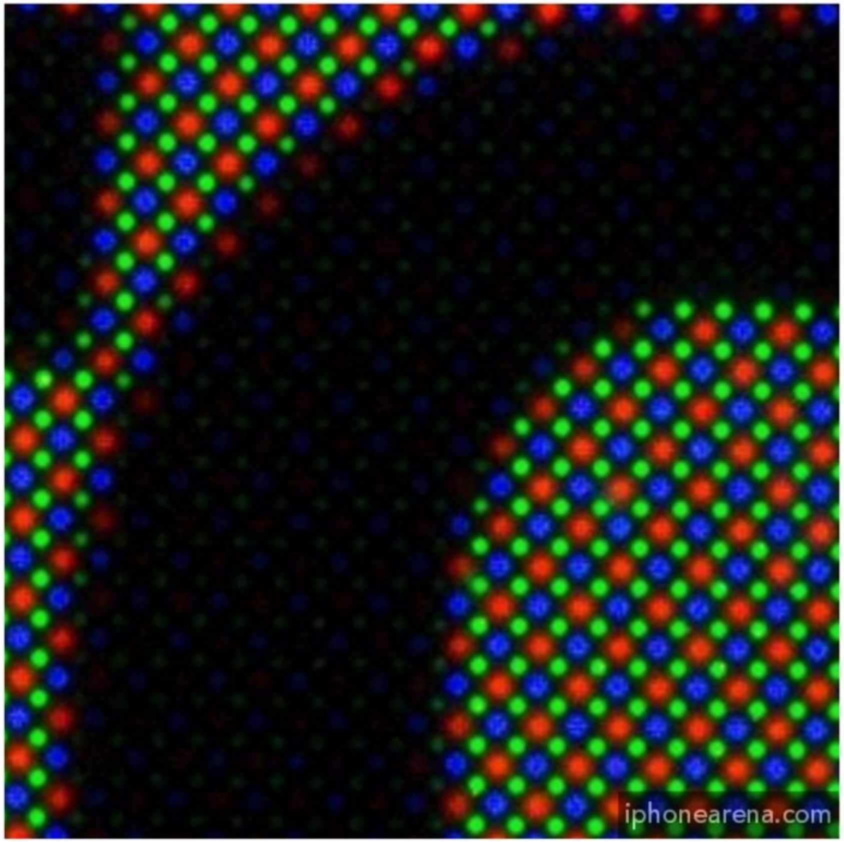


[source unknown]

Recall: real LCD screen pixels (closeup)



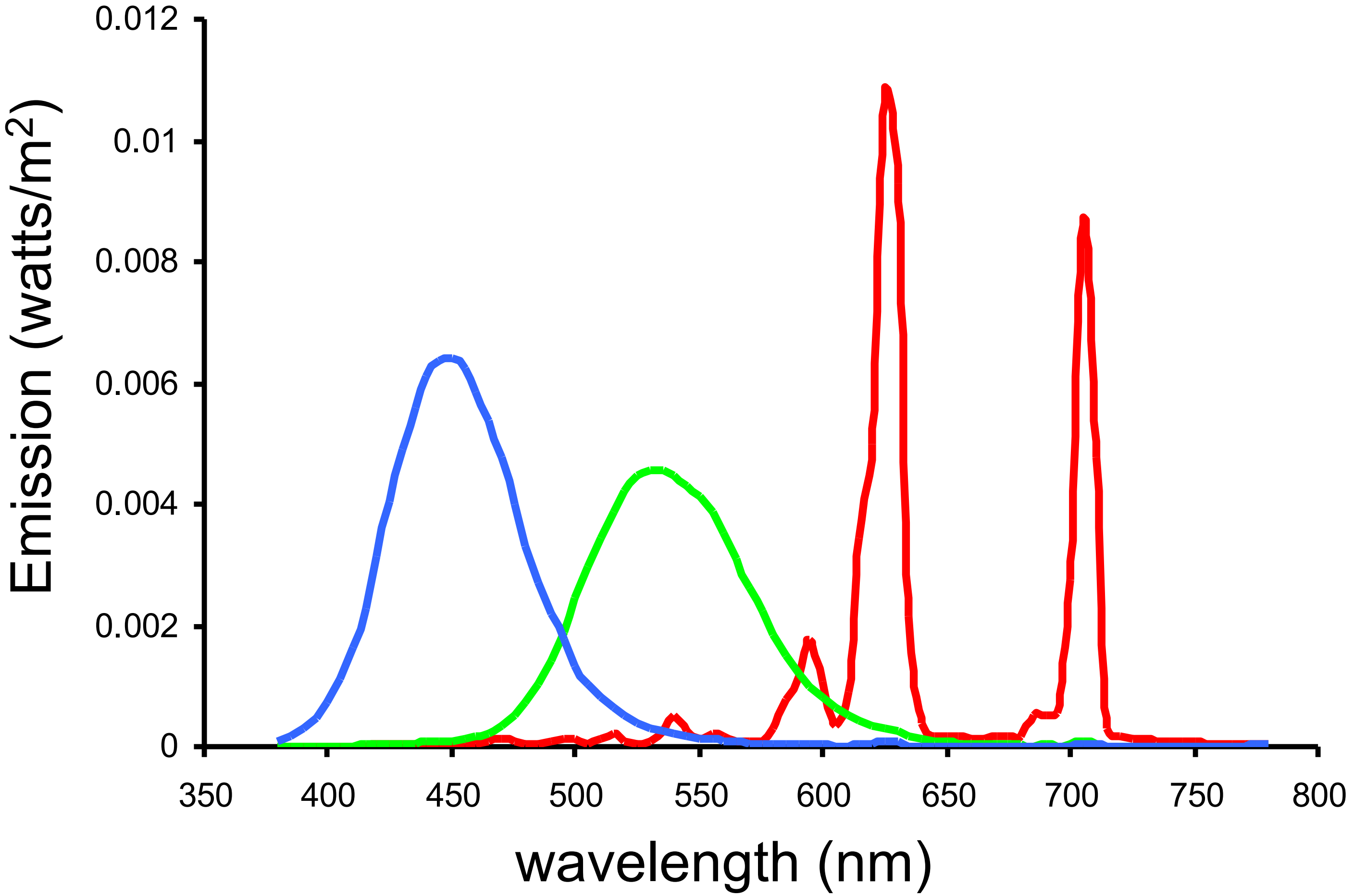
iPhone 6S



Galaxy S5

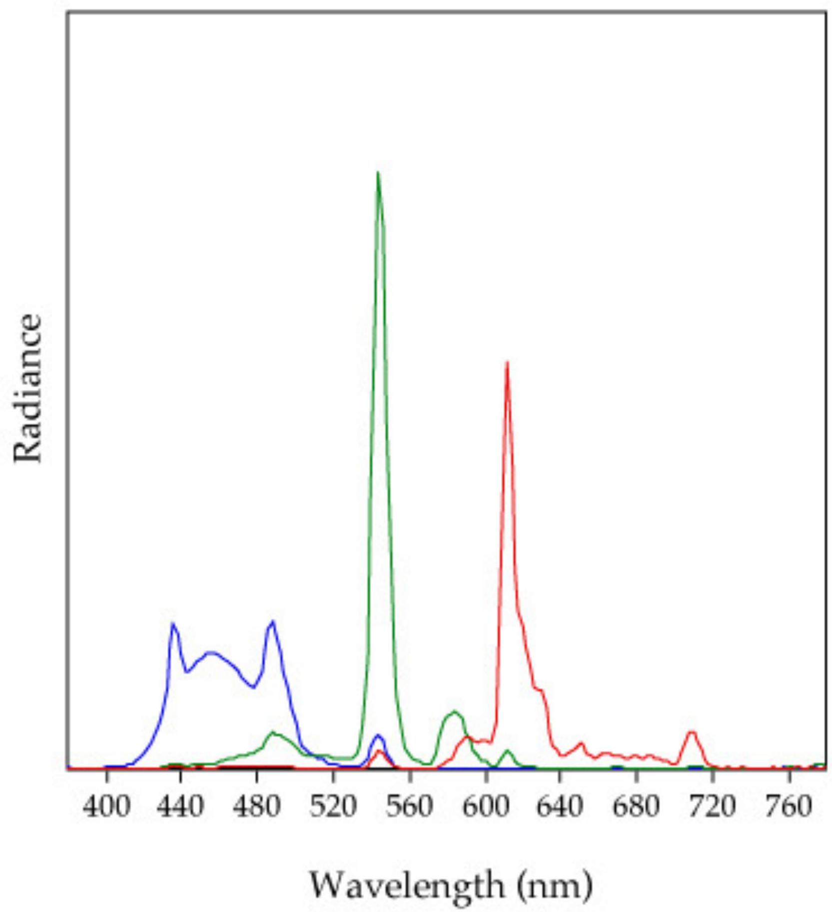
Notice R, G, B sub-pixel geometry.
Effectively three lights at each (x,y) location.

CRT display primaries



– Curves determined by phosphor emission properties

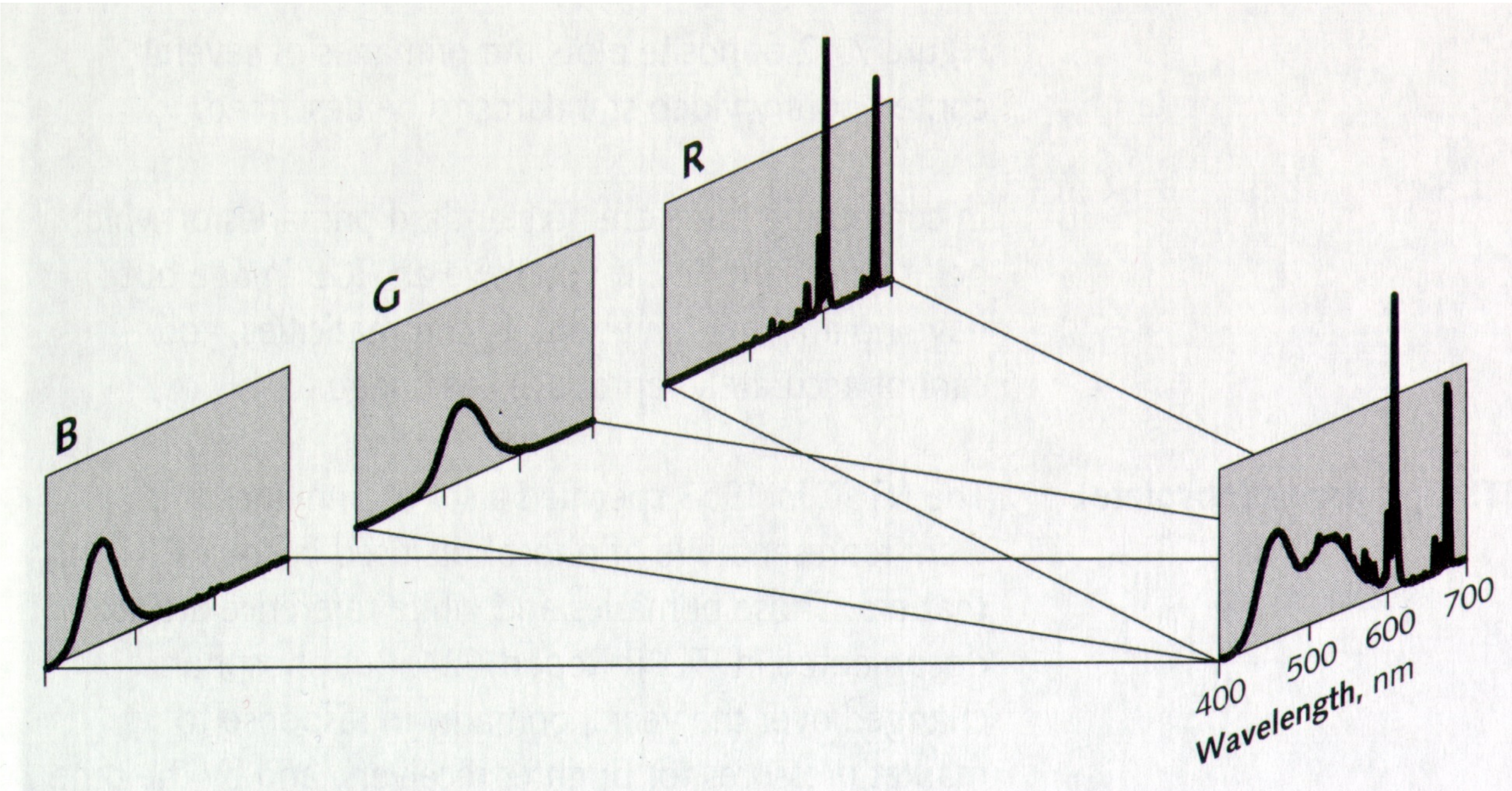
LCD display primaries



[Fairchild 97]

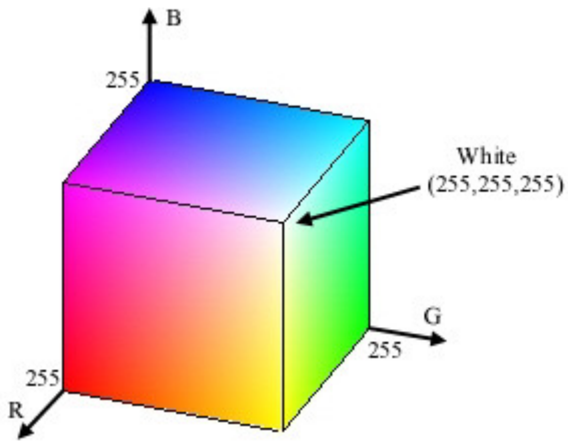
– Curves determined by (fluorescent) backlight and filters

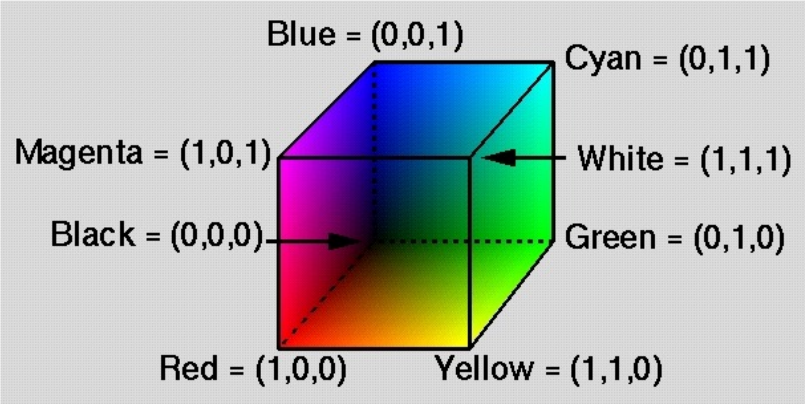
Combining Monitor Phosphors with Spatial Integration

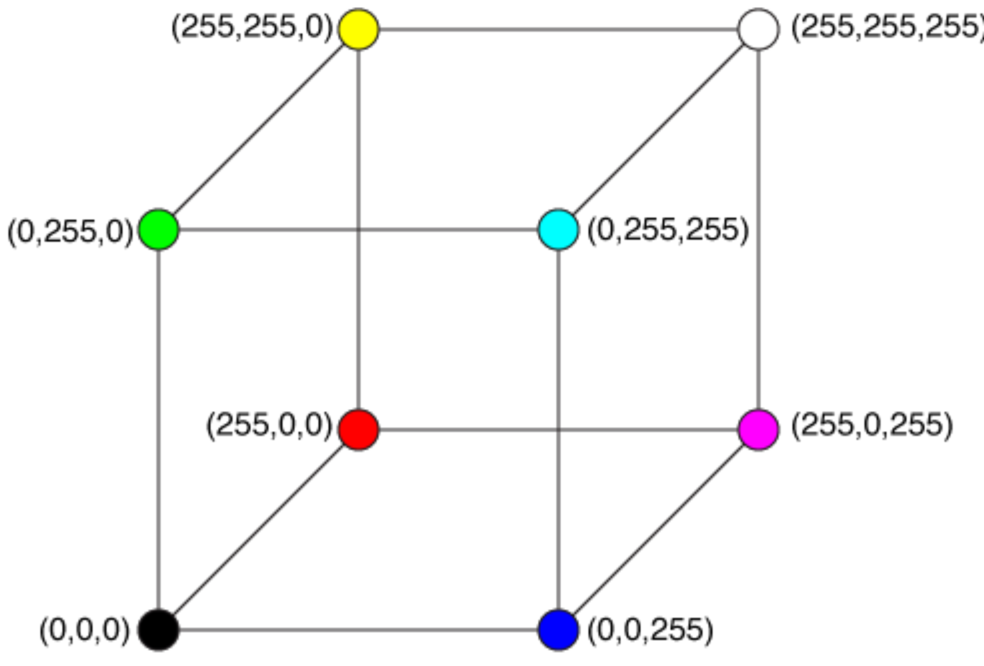


[source unknown]

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)

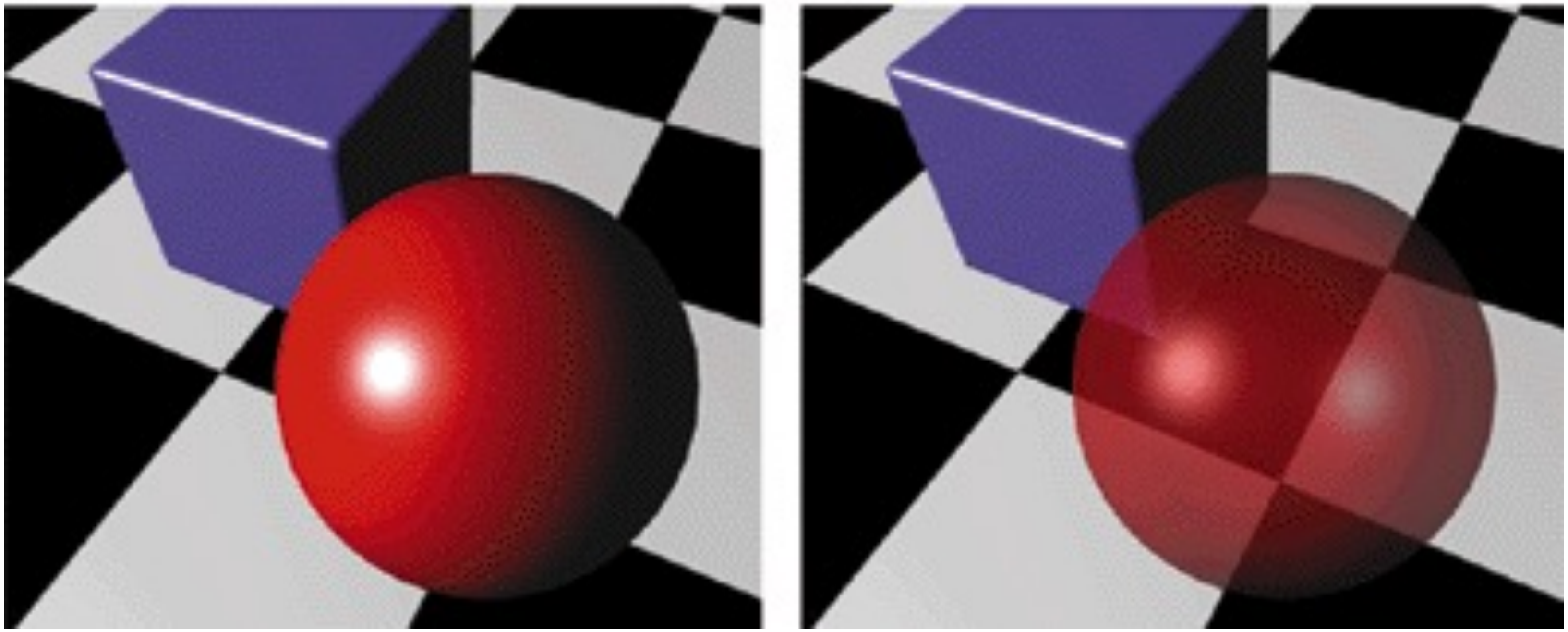
What color is “Yellow” in RGB color space?

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?

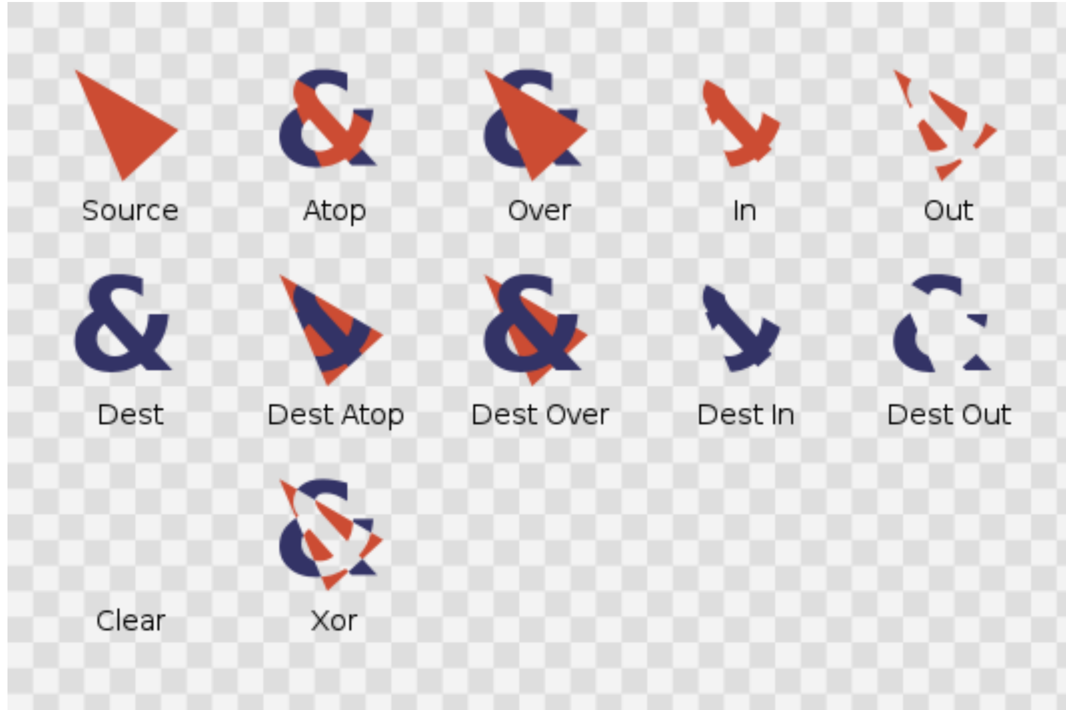
A) (1,0,0)
B) (0,1,0)
C) (1.0,0.5,0.5)
D) (0.5,0.5,0.5)
E) (1.0,1.0,0.0)

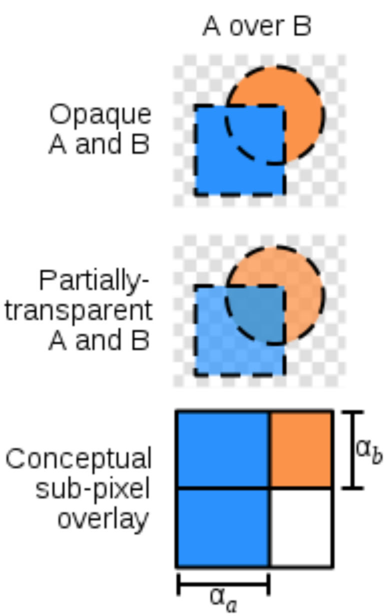
RGB-Alpha



ITFILM EXPRESS
File
Untitled Project
Home
Project
Edit
Export
Viewer
Layer
View: 2D
Local
Effects
Controls
History
Text
Editor
JCVD Green Screen [00:00:10:04] (Video)
00:14:01
00:00:14:01
Tracks
JCVD
JCVD Green Screen
Video 1
Thunderbird
Audio 1
Audio 2
Master
Color Difference Key
Screen Color
Green
Min
0.65
Max
1.00
Gamma
1.00
View Matte

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





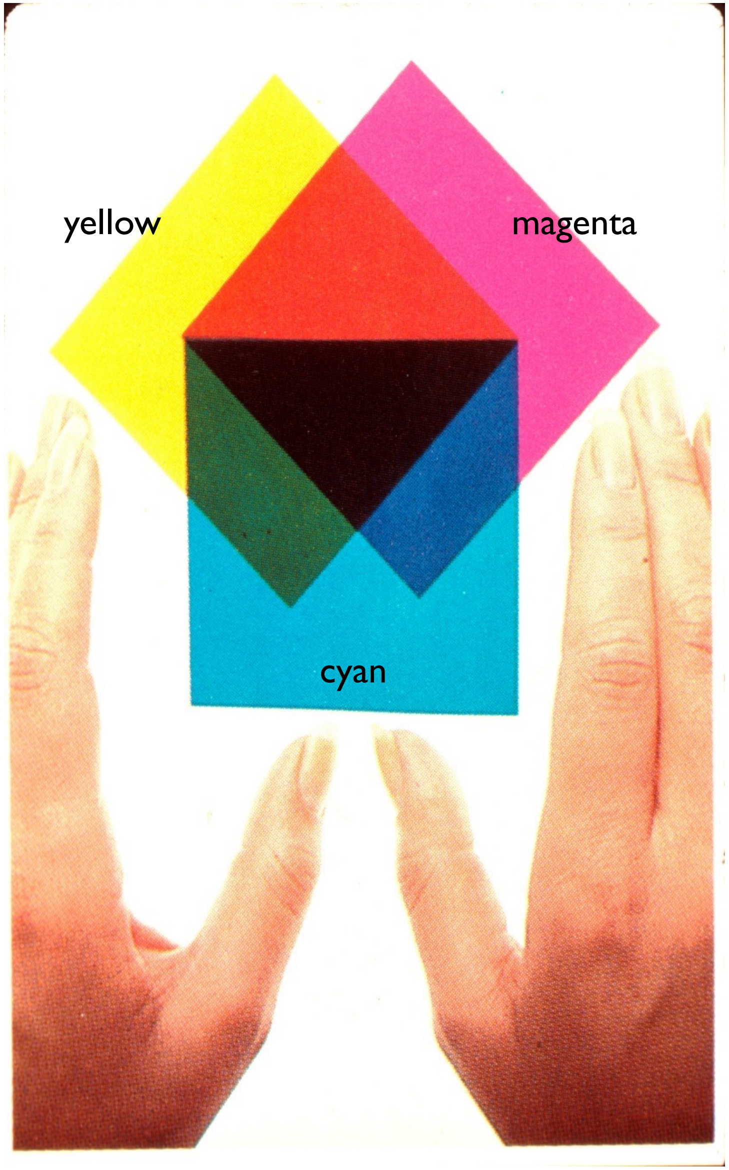
As an example, the **over** operator can be accomplished by applying the following formula to each pixel value:

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

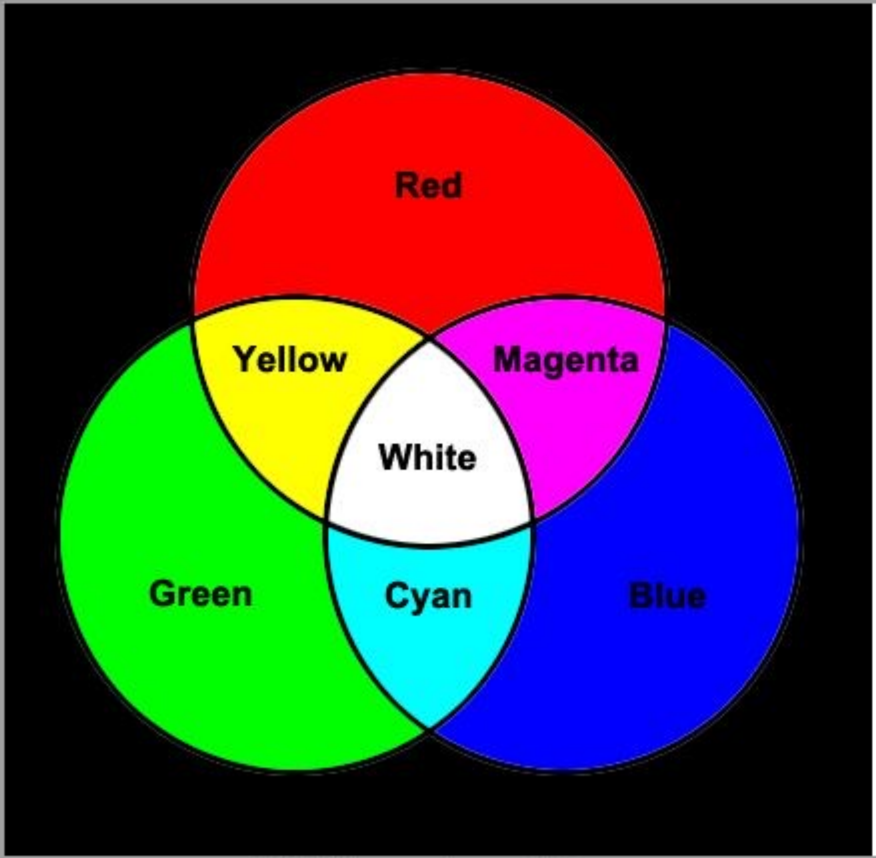
where C_o is the result of the operation, C_a is the color of the pixel in element A, C_b is the color of the pixel in element B, and α_a and α_b are the alpha of the pixels in elements A and B respectively. If it is assumed

Subtractive Color

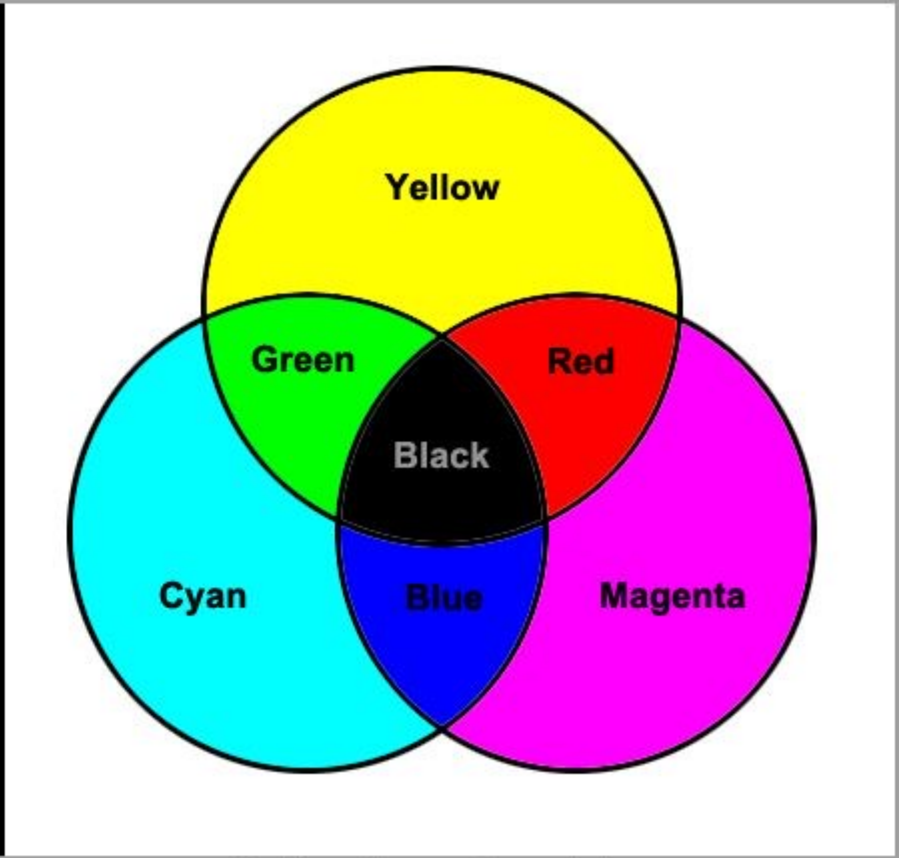
Subtractive Color



[source unknown]



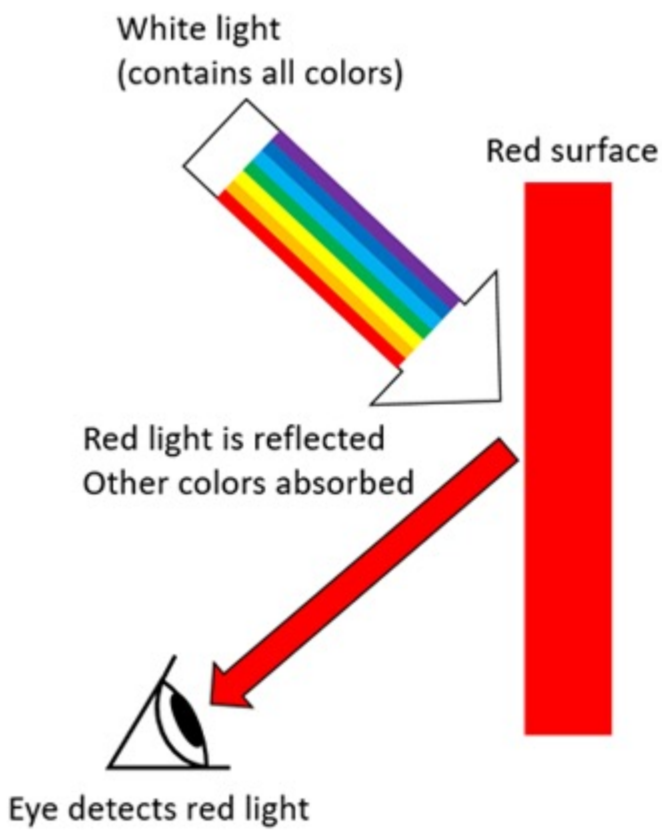
Additive color mixing

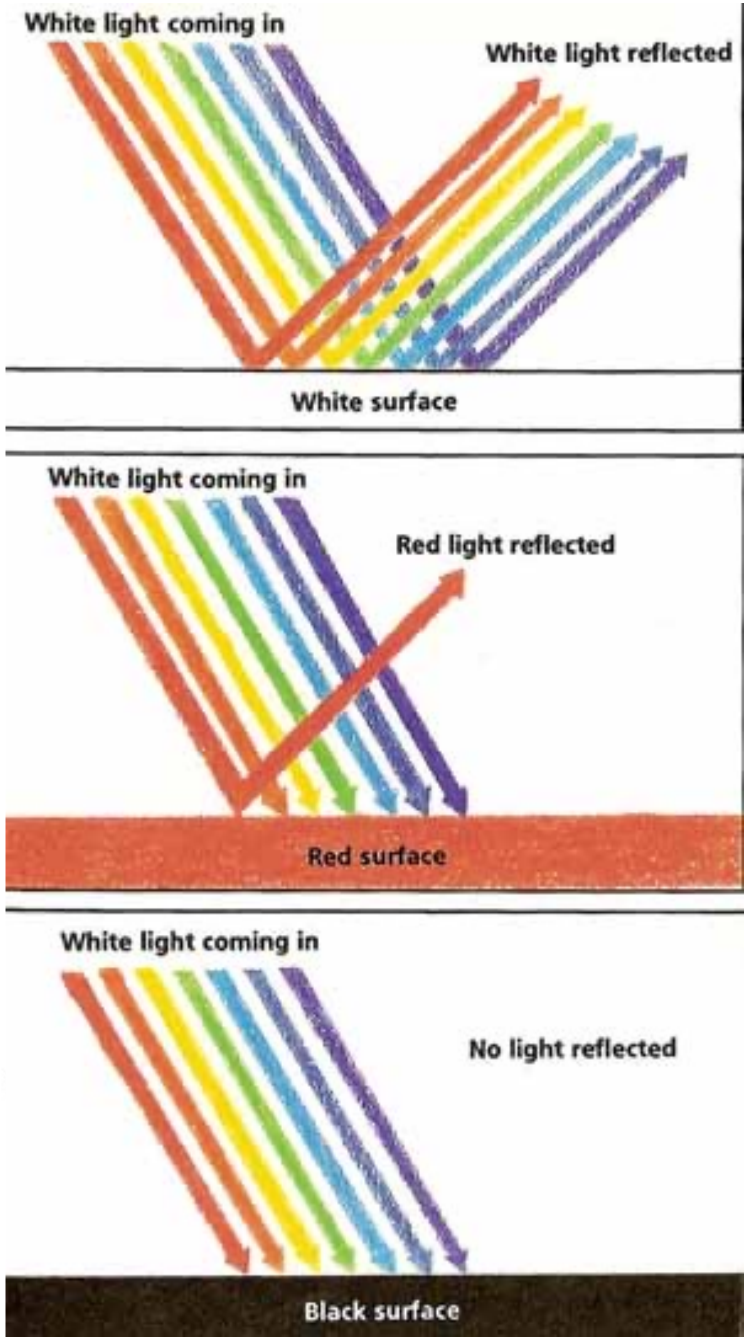


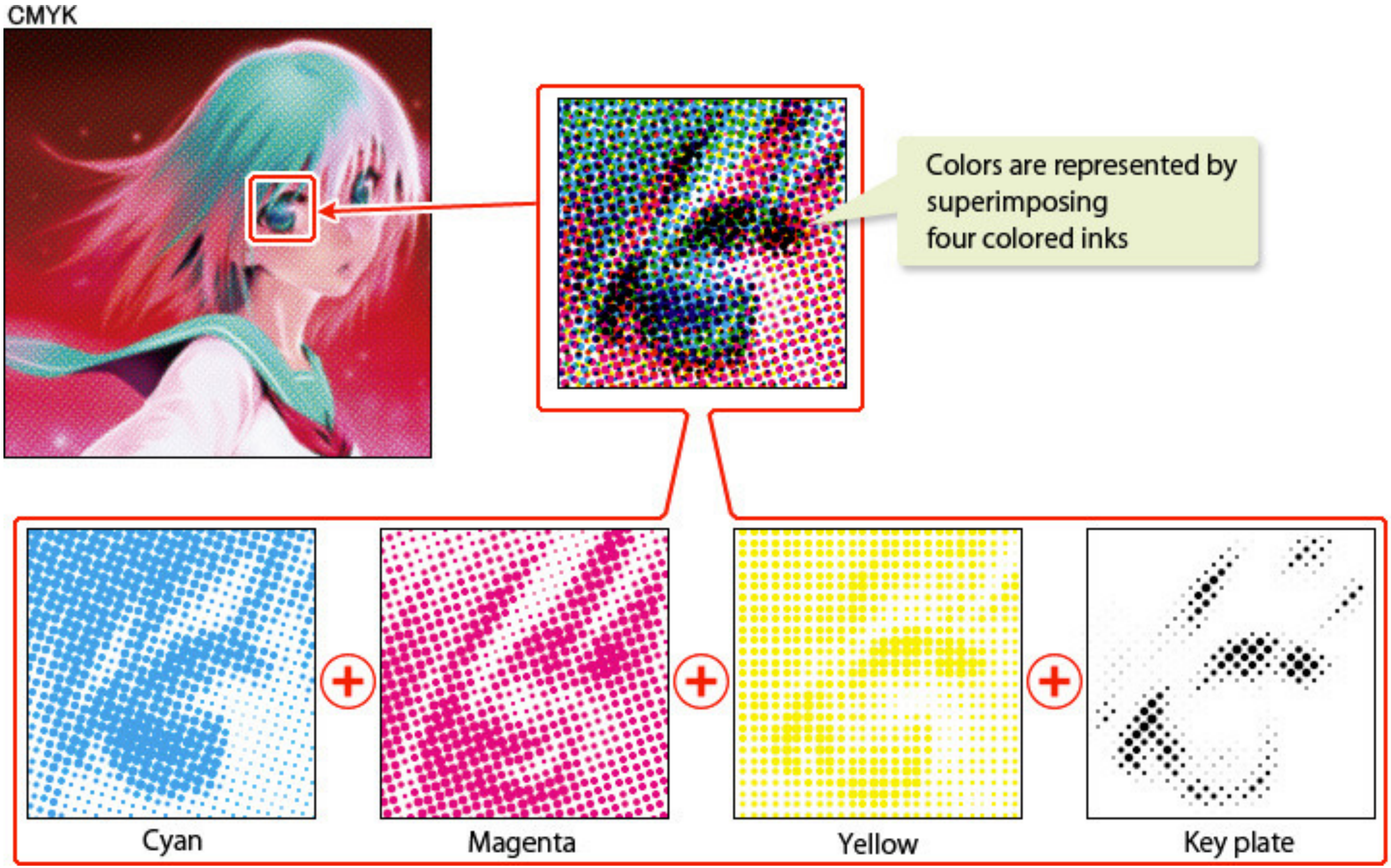
Subtractive color mixing

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

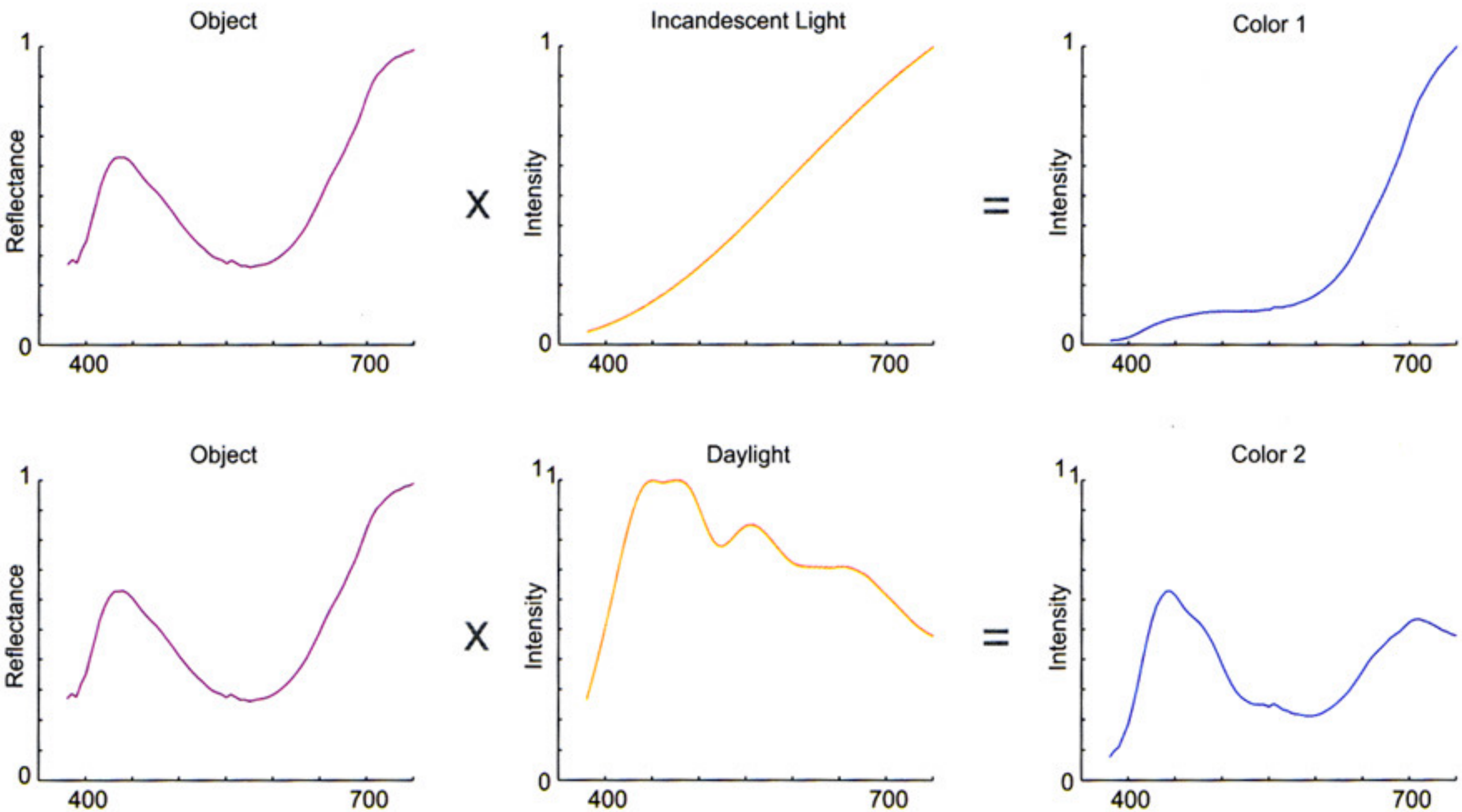
Subtractive color systems start with light (white). Colored inks, paints, or filters between the viewer and the light source or reflective surface subtract wavelengths from the light, giving it color.


White light
(contains all colors)
Red surface
Red light is reflected
Other colors absorbed
Eye detects red light

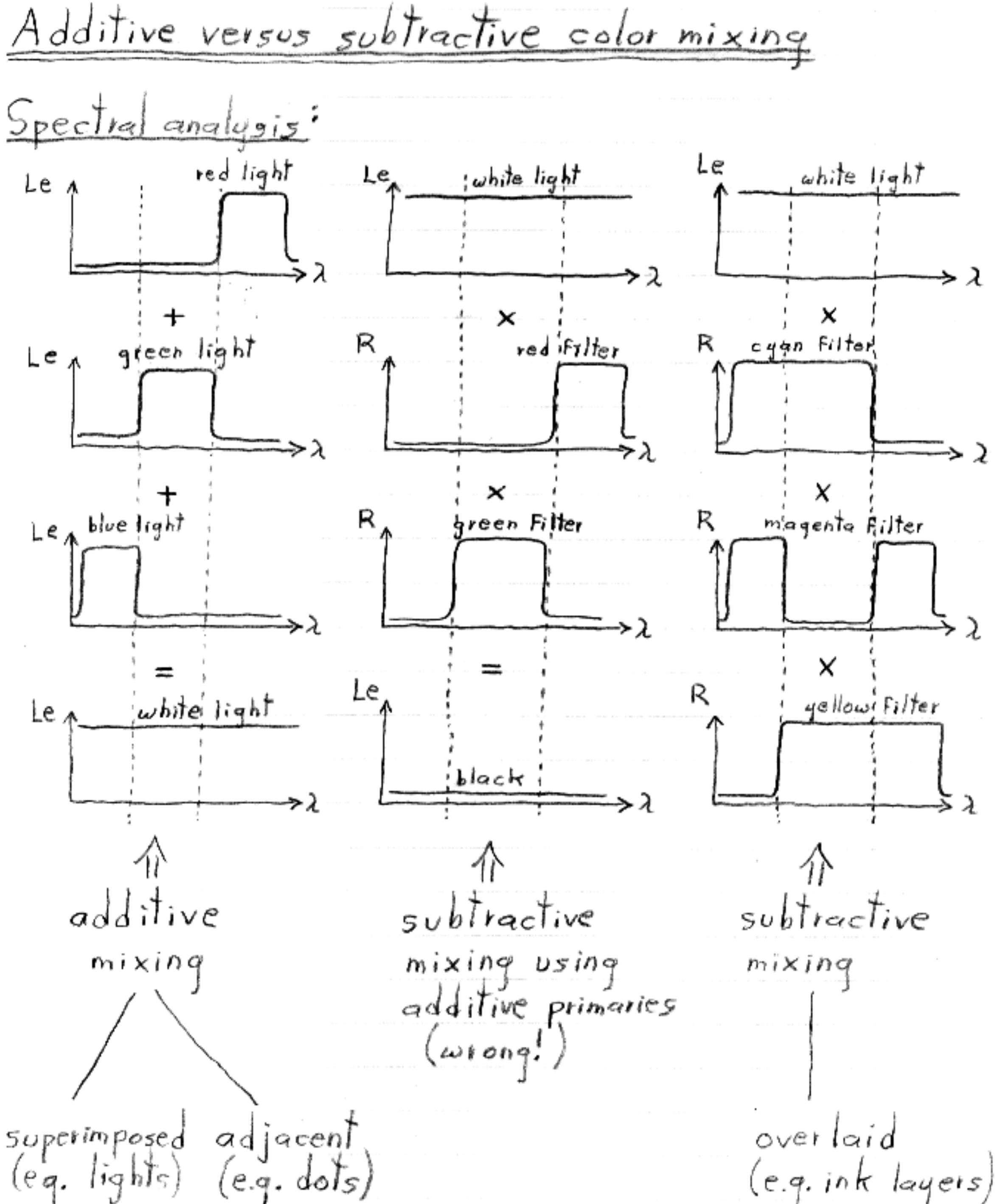

White light coming in
White light reflected
White surface
White light coming in
Red light reflected
Red surface
White light coming in
No light reflected
Black surface



CMYK
Colors are represented by superimposing four colored inks
Cyan
Magenta
Yellow
Key plate

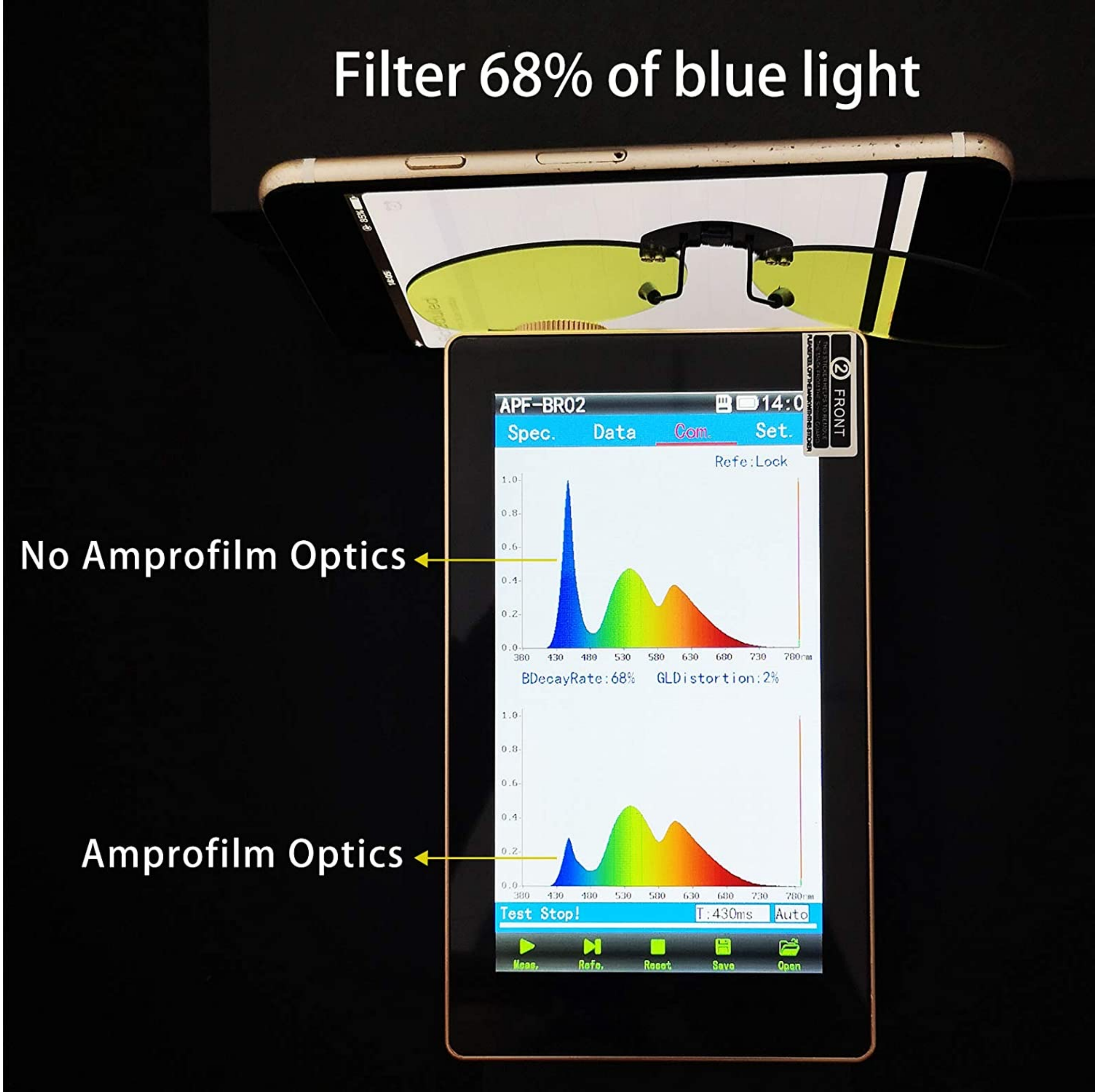
Reflection from colored surface



[Stone 2003]


Additive versus subtractive color mixing
Spectral analysis:
Le
red light
λ
+
green light
blue light
=
white light
white light
×
R
red filter
green filter
black
cyan filter
magenta filter
yellow filter
additive mixing
subtractive mixing using additive primaries (wrong!)
subtractive mixing
superimposed (e.g. lights)
adjacent (e.g. dots)
overlaid (e.g. ink layers)

[levoy]



Filter 68% of blue light
No Amprofilm Optics
Amprofilm Optics
APF-BR02
Spec.
Data
Com.
Set.
Refe:Lock
BDecayRate:68%
GLDistortion:2%
Test Stop!
T:430ms
Auto
FRONT

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), C := C - K, M := M - K, Y := Y - K.

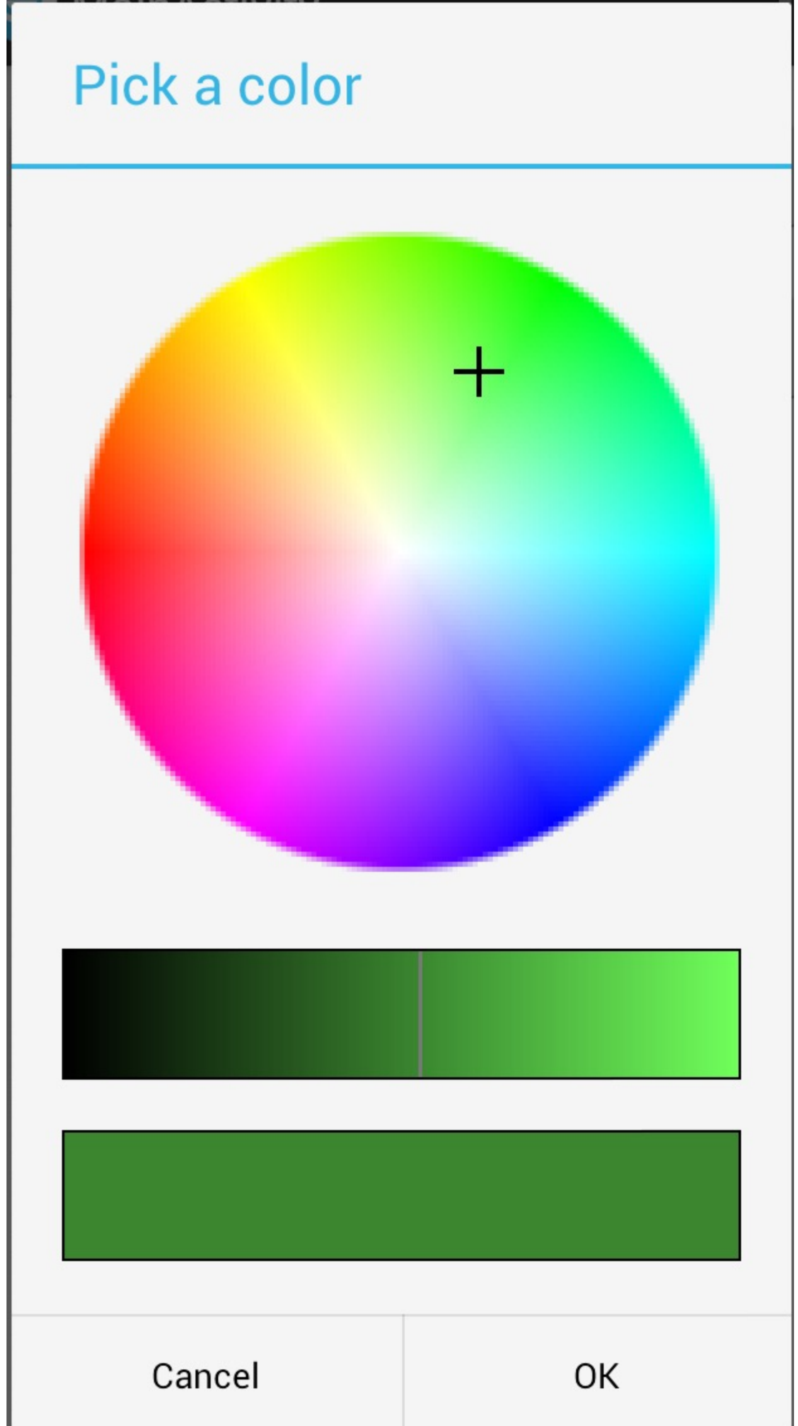
What color is “Yellow” in CMY color space?

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)

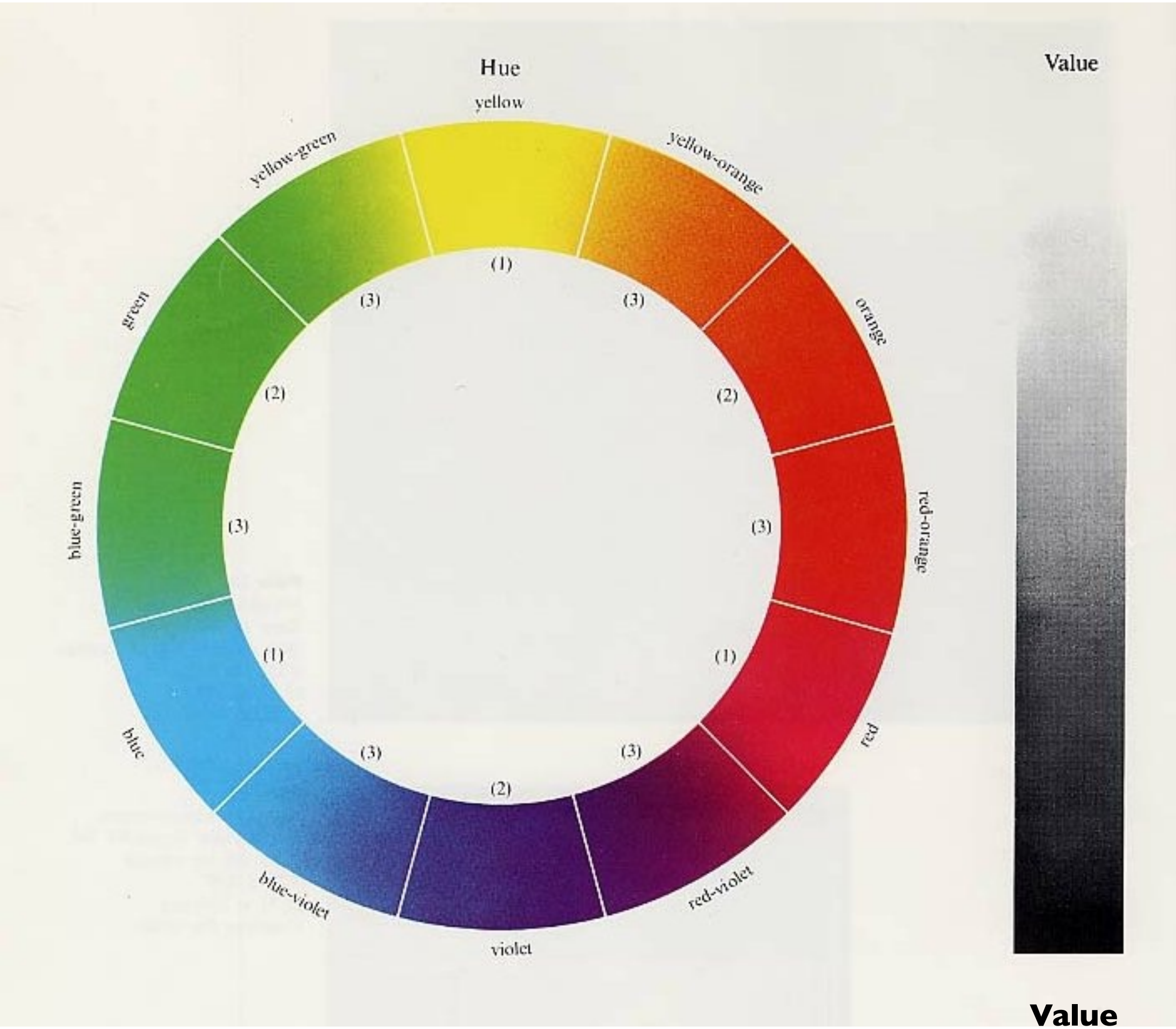
What color is “Red” in CMY color space?

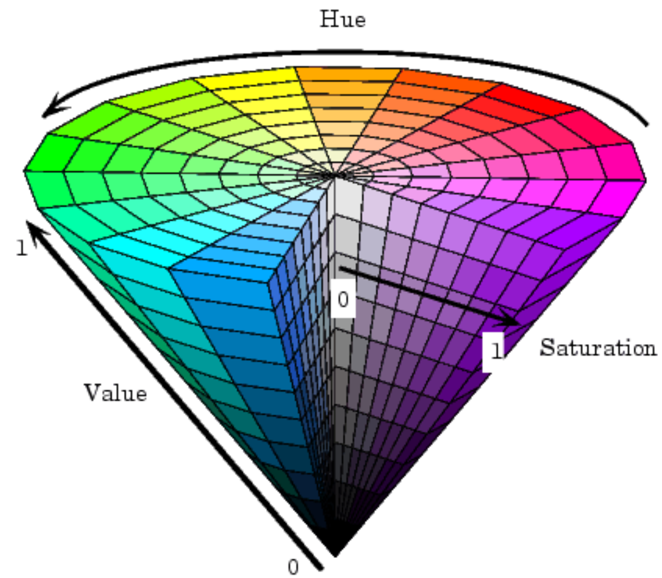
A) (0,1,1)
B) (0,1,0)
C) (1.0,0.5,0.5)
D) (0.5,0.5,0.5)
E) (1.0,1.0,0.0)

HSV Color


Pick a color
Cancel
OK

Perceptual dimensions of color - HSV



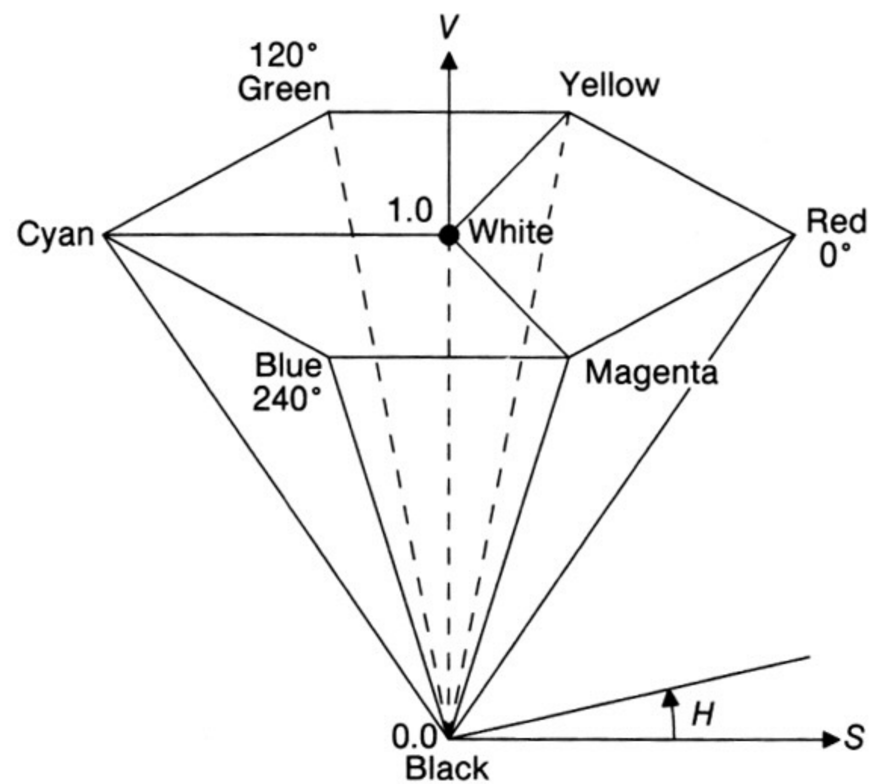


Hue

Value
Intensity
Lightness
Y

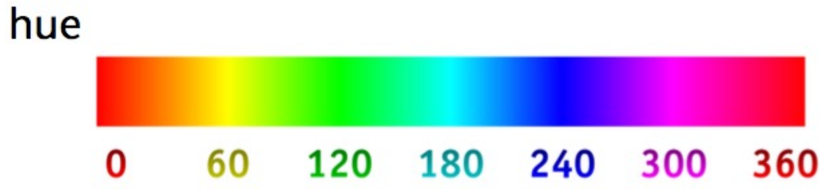
Perceptual organization for RGB: HSV

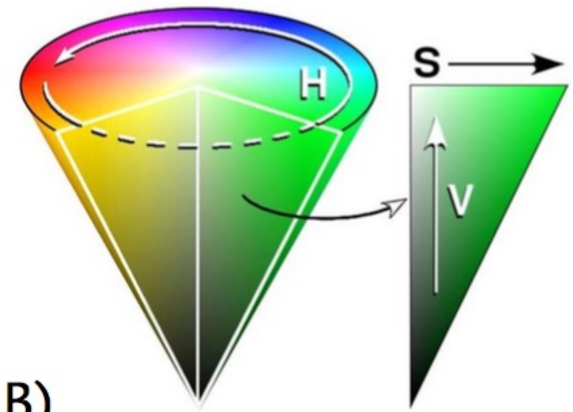
- hue (an angle, 0 to 360)
- saturation (0 to 1)
- value (0 to 1)



[FvDFH]

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



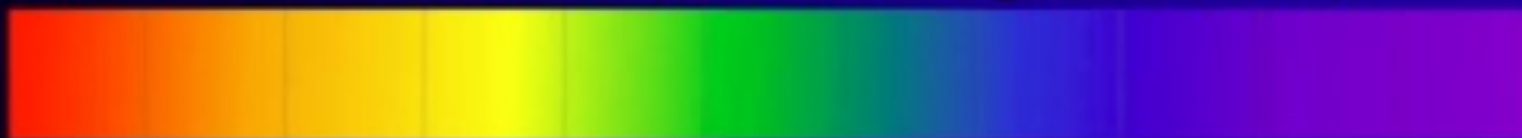


- conversion RGB $\rightarrow$ HSV
  - $V = \max = \max(R, G, B), \qquad \min = \min(R, G, B)$
  - $S = (\max - \min) / \max \qquad (\text{or } S = 0, \text{ if } V = 0)$
  - $$H = 60 \times \begin{cases} 0 + (G - B) / (\max - \min), & \text{if } \max = R \\ 2 + (B - R) / (\max - \min), & \text{if }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

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

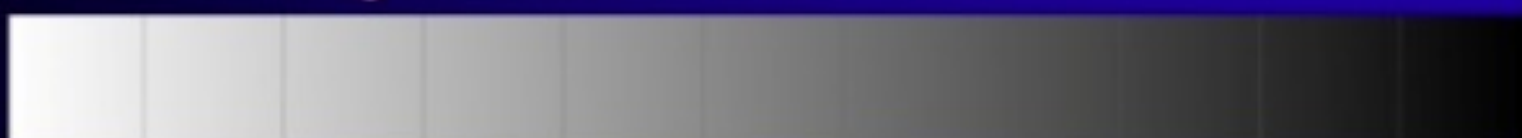
Dimension of Color (HSL/HSV/HVC)

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



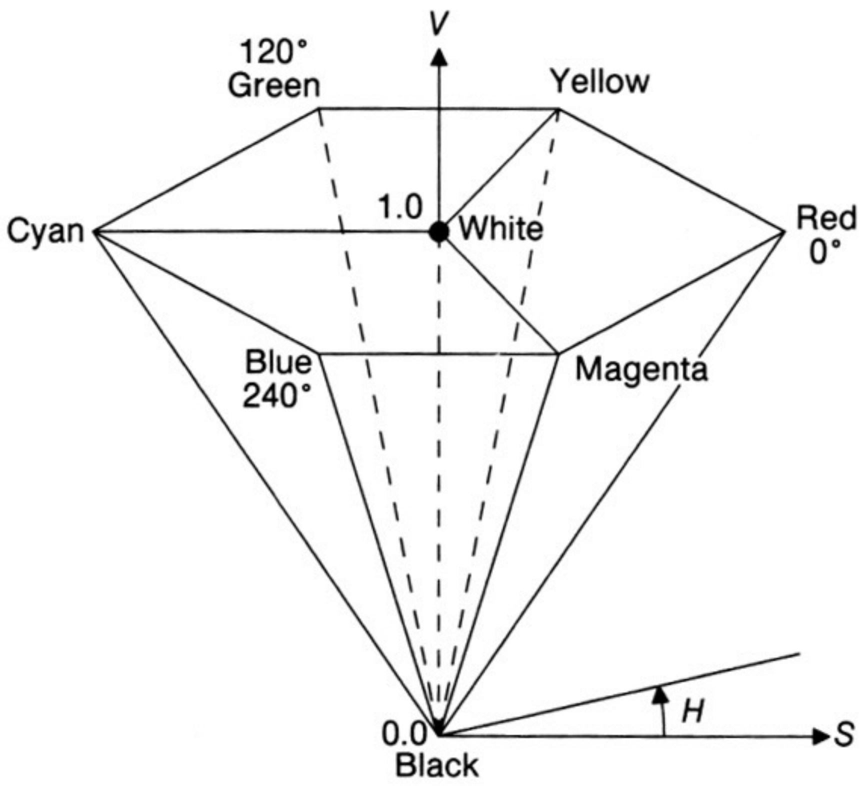
- Saturation = Density (purity) of the color

- Value = Lightness & Darkness

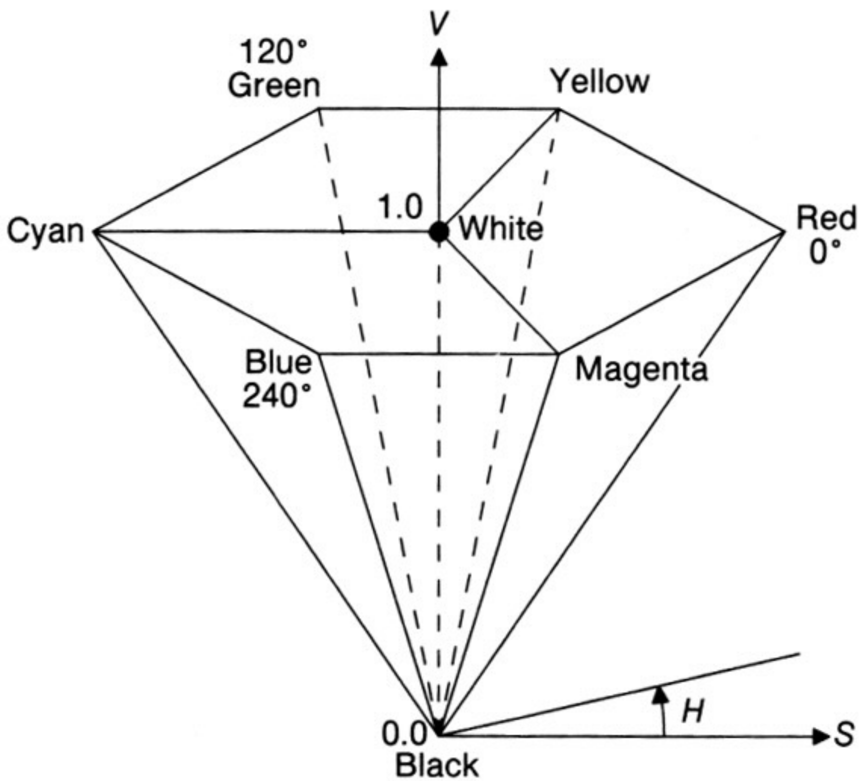


What color is "Red" in HSV color space?

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

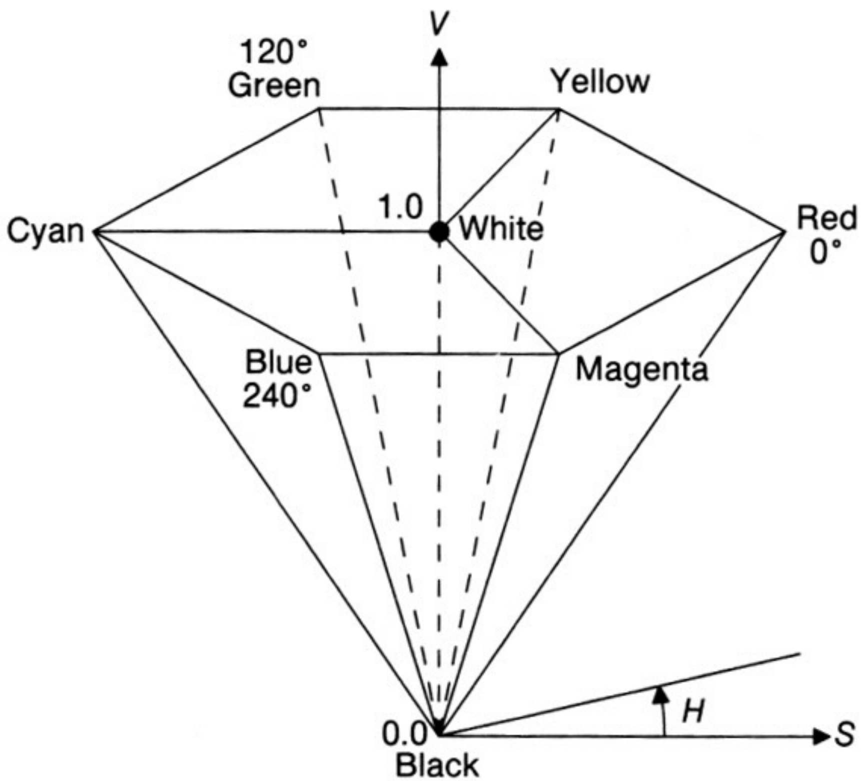


What color is "Yellow" in HSV color space?



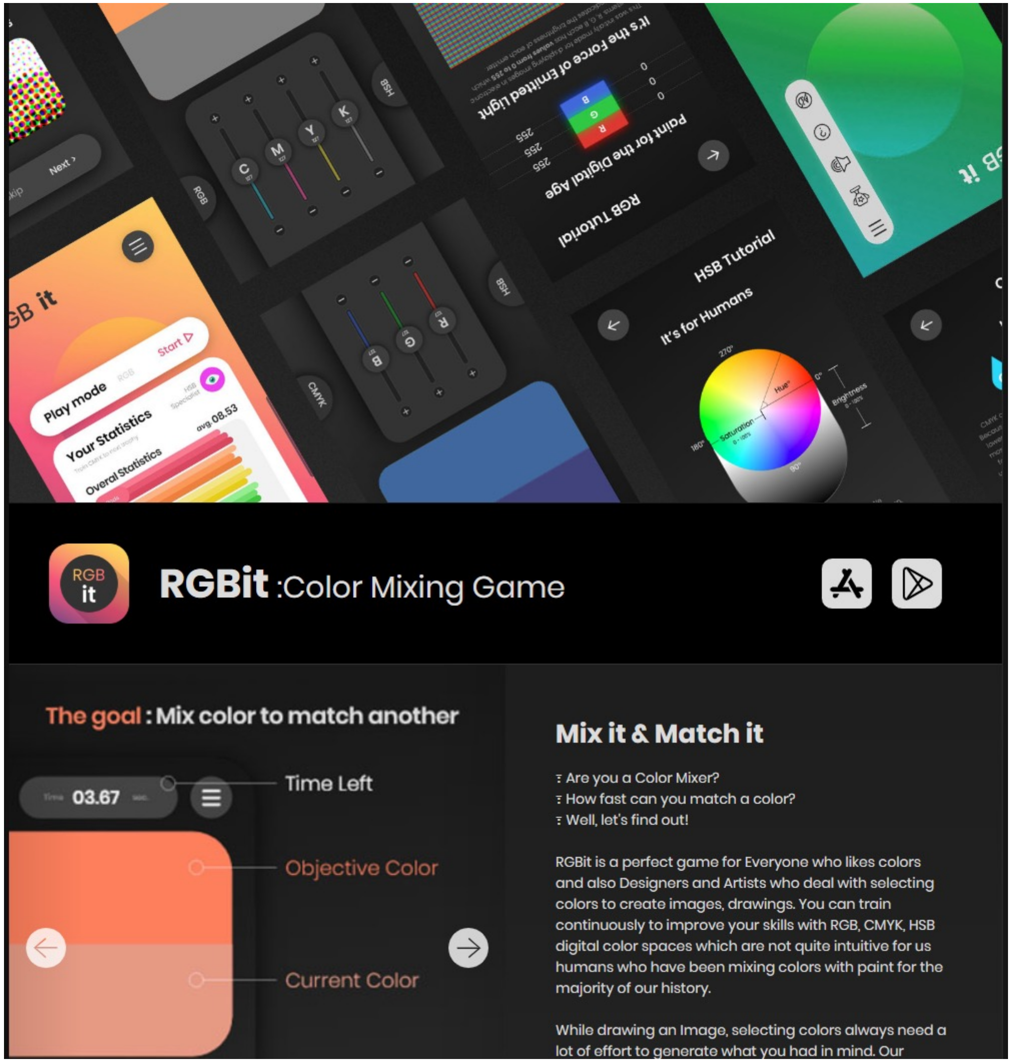
A) (0,1,1)
B) (0,0,0)
C) (60,1,1)
D) (0,0.2,1.0)
E) (0,1.0,0.0)

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



YIQ/YUV Color

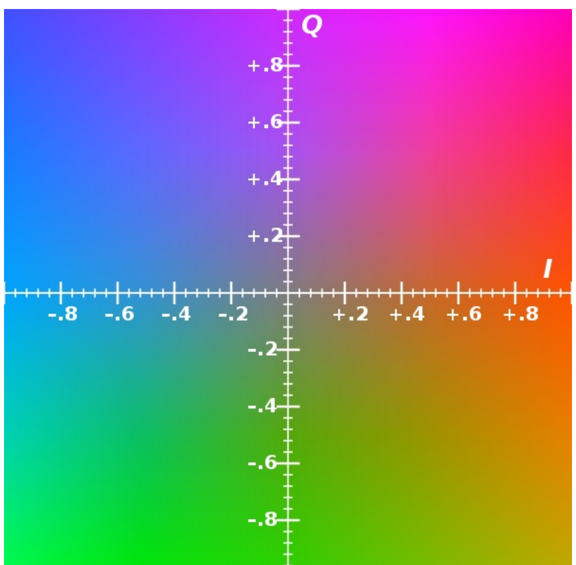
NTSC TV

quadrature amplitude modulation

- YIQ color space (Wandell pg 304)

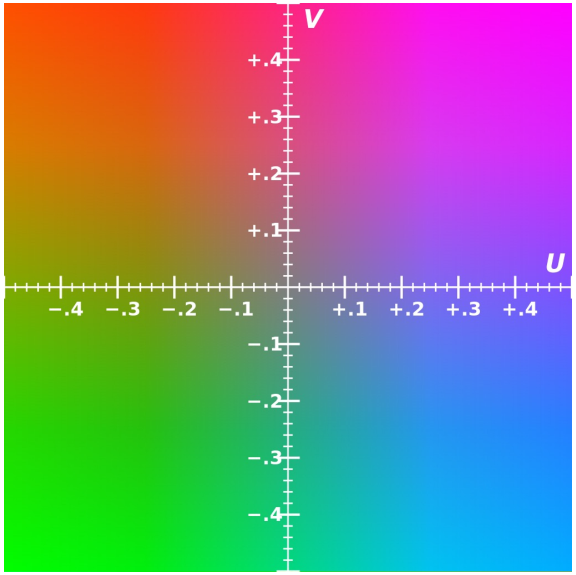
(Y) luminance

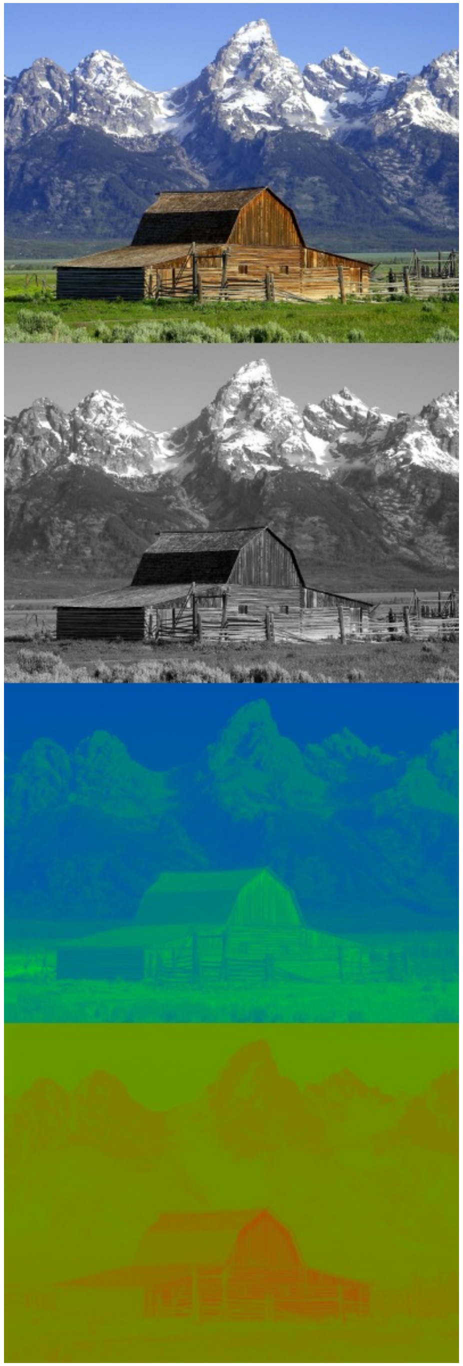
(IQ) chroma



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

YUV / YCbCr





Humans care about intensity more than chroma

Blur just one channel of image and compare

Y **Chroma** **Chroma**

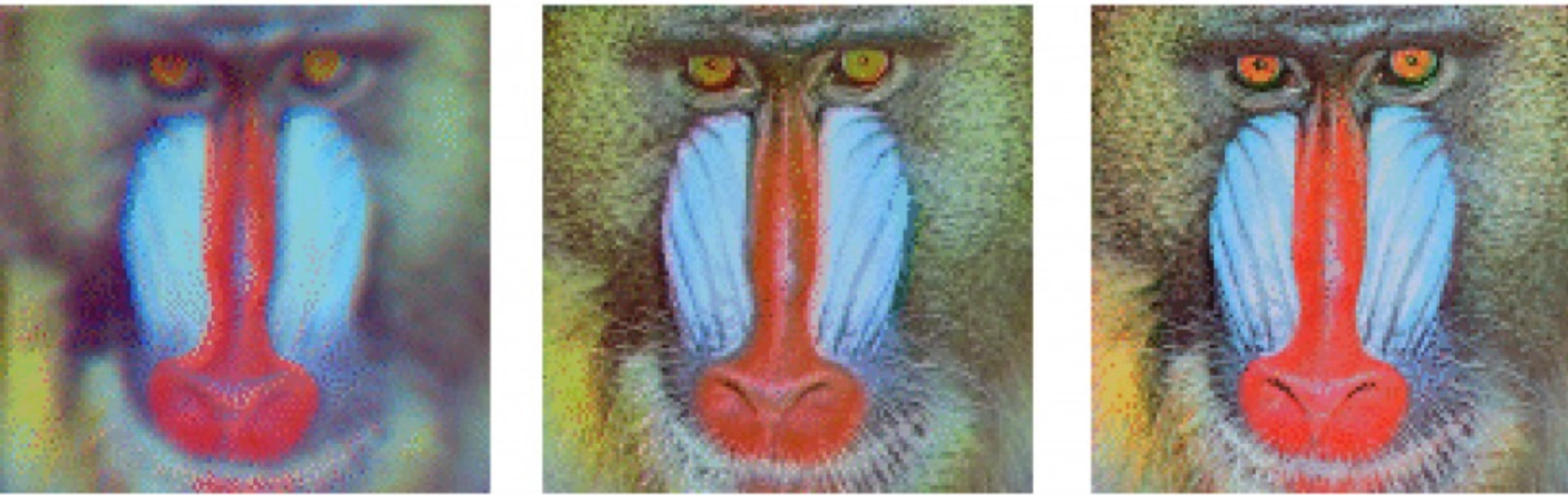
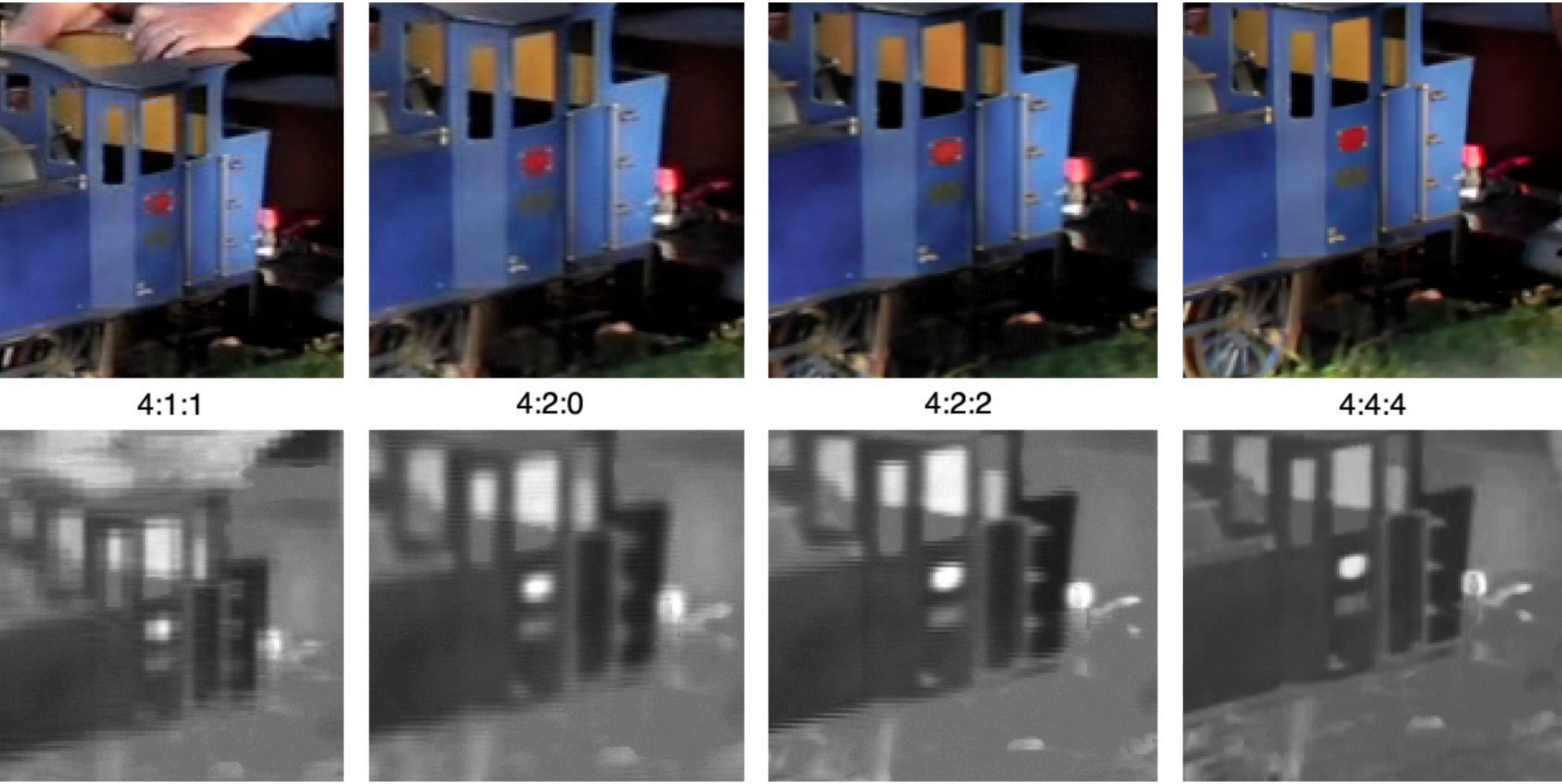


Figure 9.23: The apparent spatial sharpness (focus) of a color image depends mainly on the light-dark component of the image, not the opponent-colors components. A colored image was converted to a light-dark, red-green and blue-yellow representation. To create the three images, the light-dark (a), red-green (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).

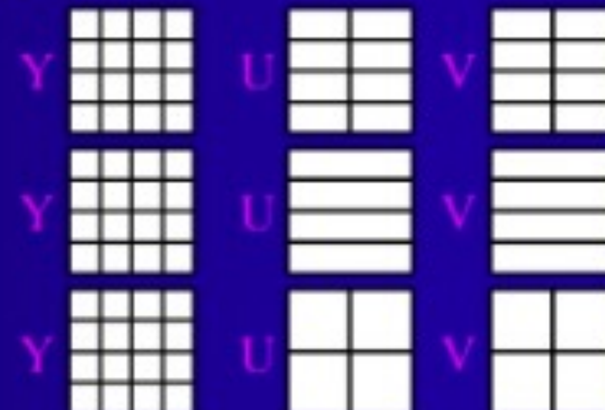
[From Wandell – Foundations of Vision]

Full resolution luminance (Y)
Chroma (IQ) subsampling



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)

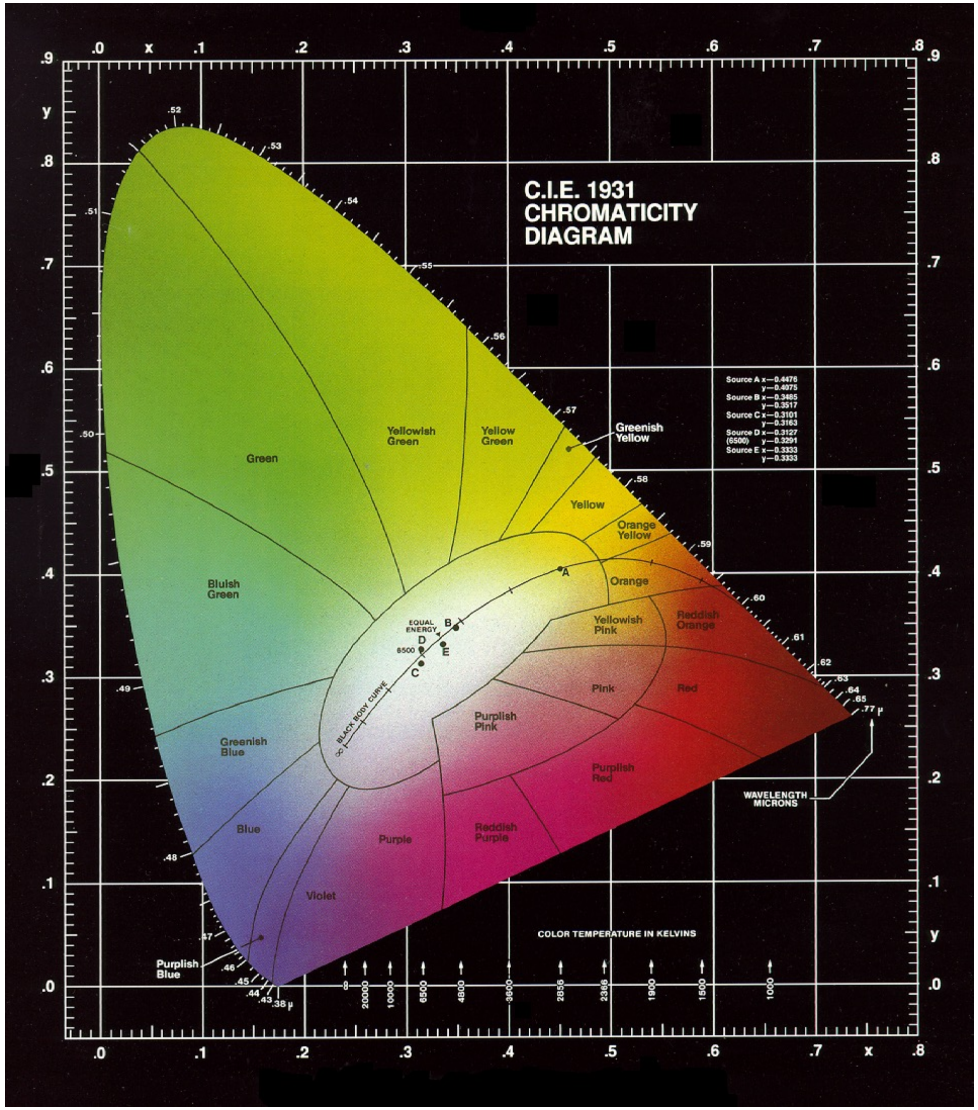
Y

U

V

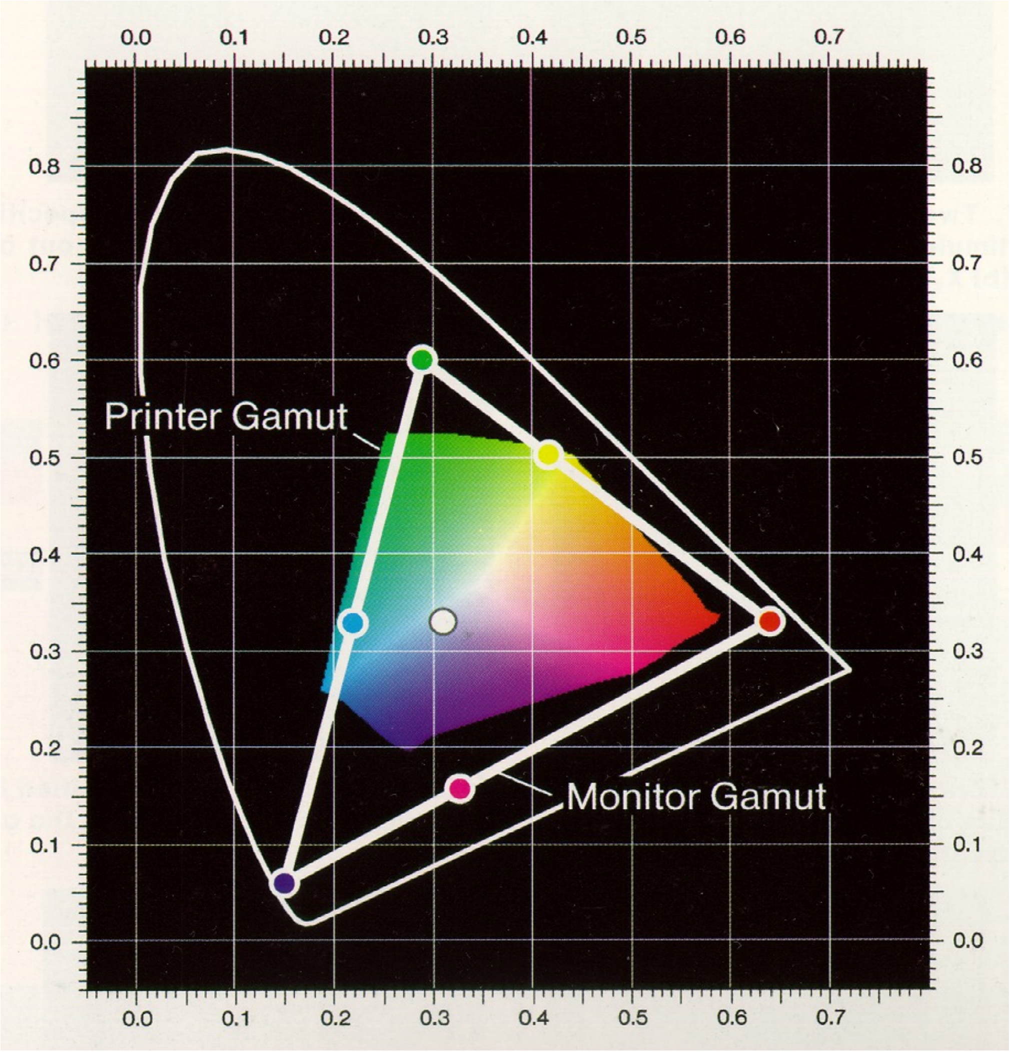
Color Gamuts, Color Matching, and XYZ

Chromaticity Diagram



[source unknown]

Color Gamuts

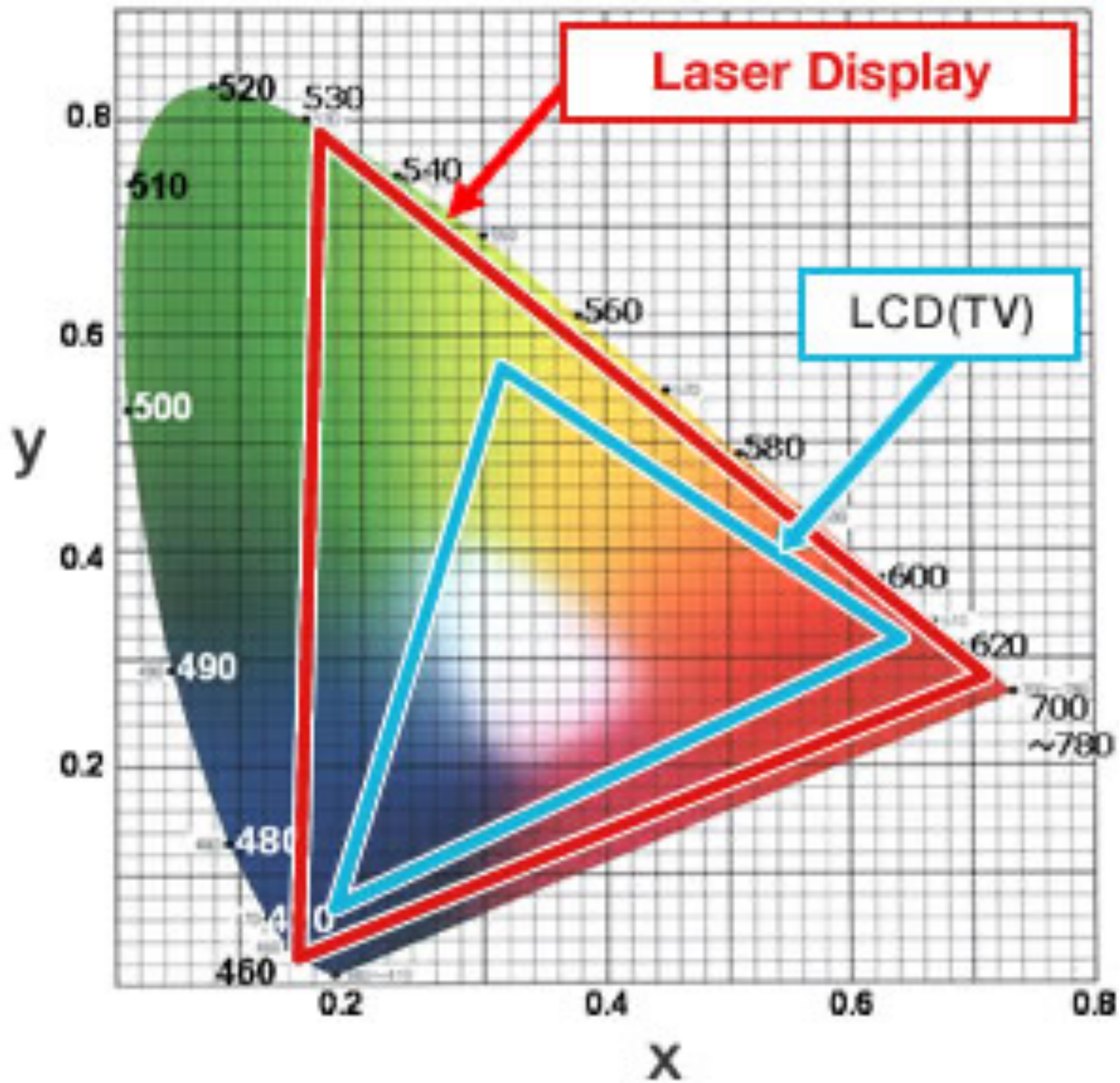


[source unknown]

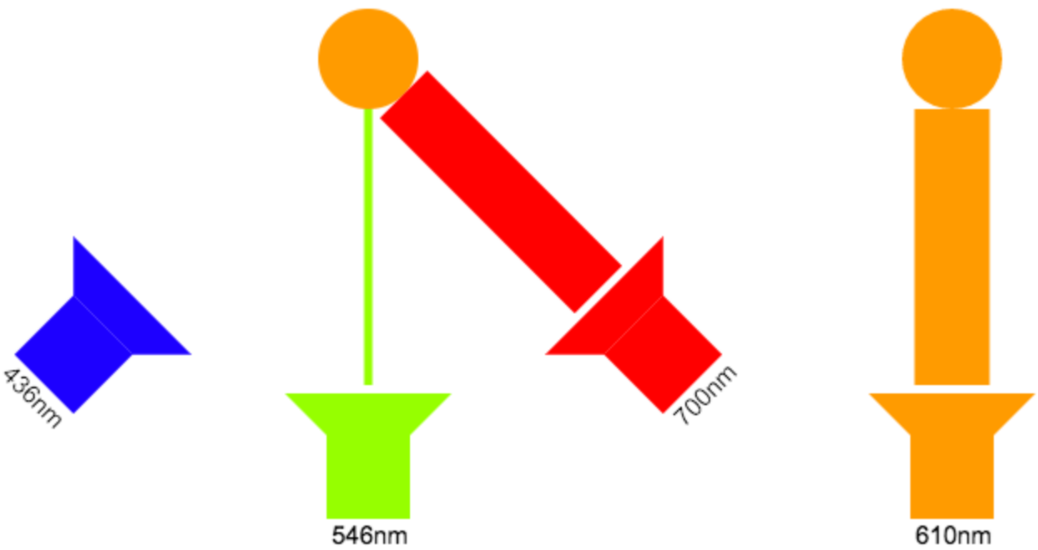
Monitors/printers can't produce all visible colors

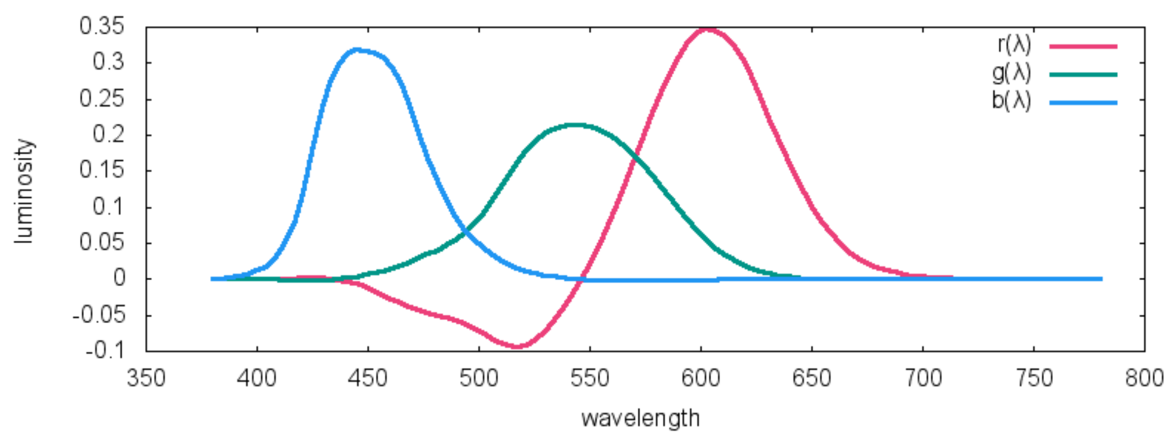
Reproduction is limited to a particular domain

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


Laser Display
LCD(TV)
y
x
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
520
530
510
540
560
500
580
600
490
620
700
~780
480
460

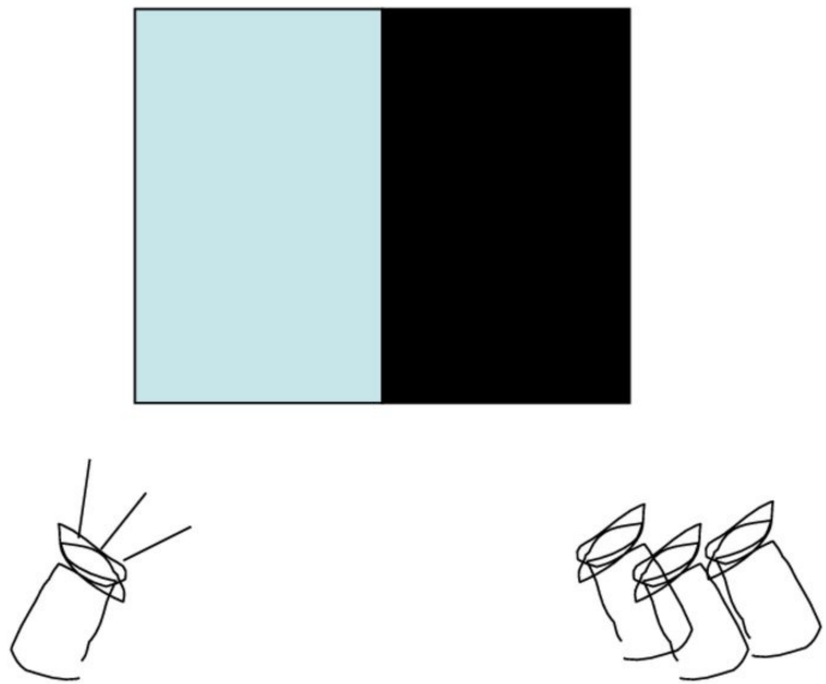
Color matching experiment (CIE 1931)





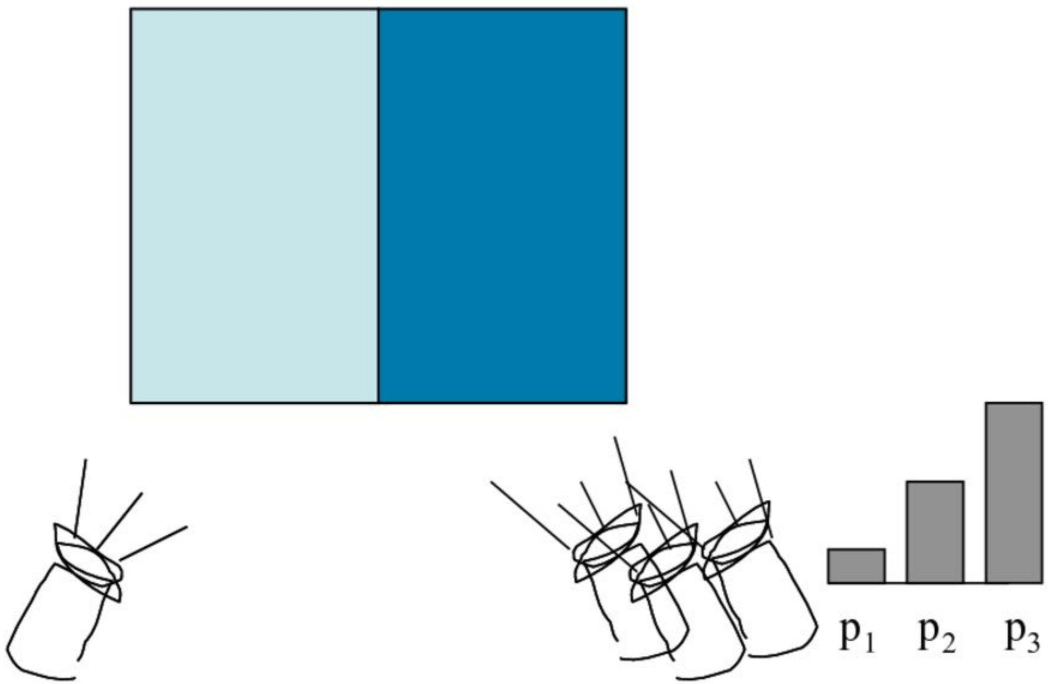
[https://medium.com/hipster-color-science/a-beginners-guide-to-colorimetry-401f1830b65a]

Example experiment



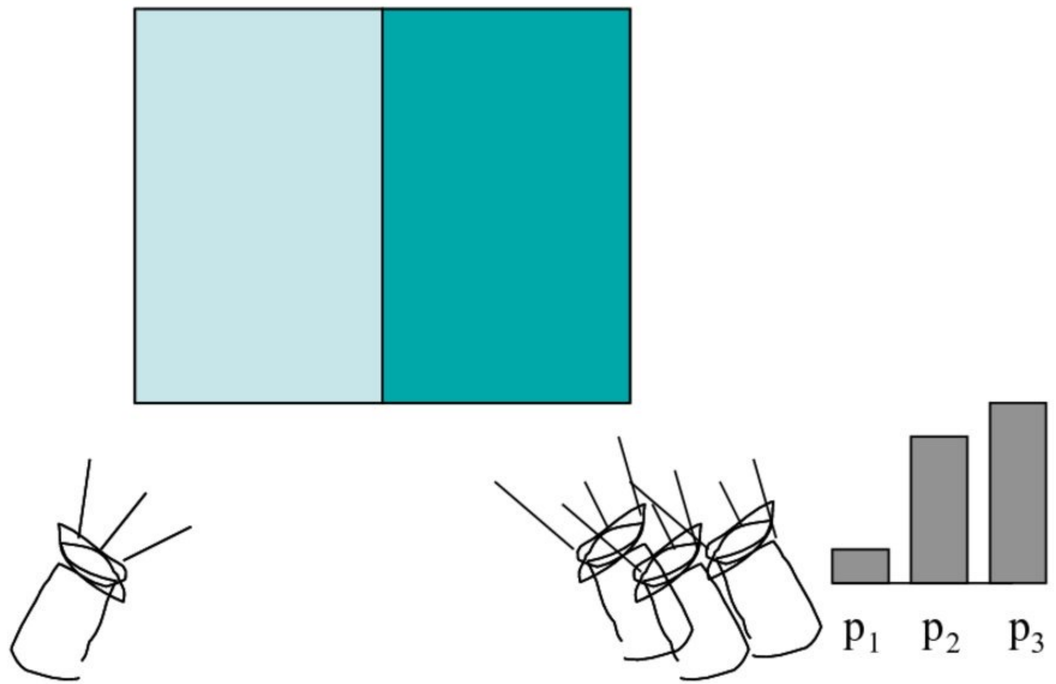
Slide from Durand
and Freeman 06

Example experiment



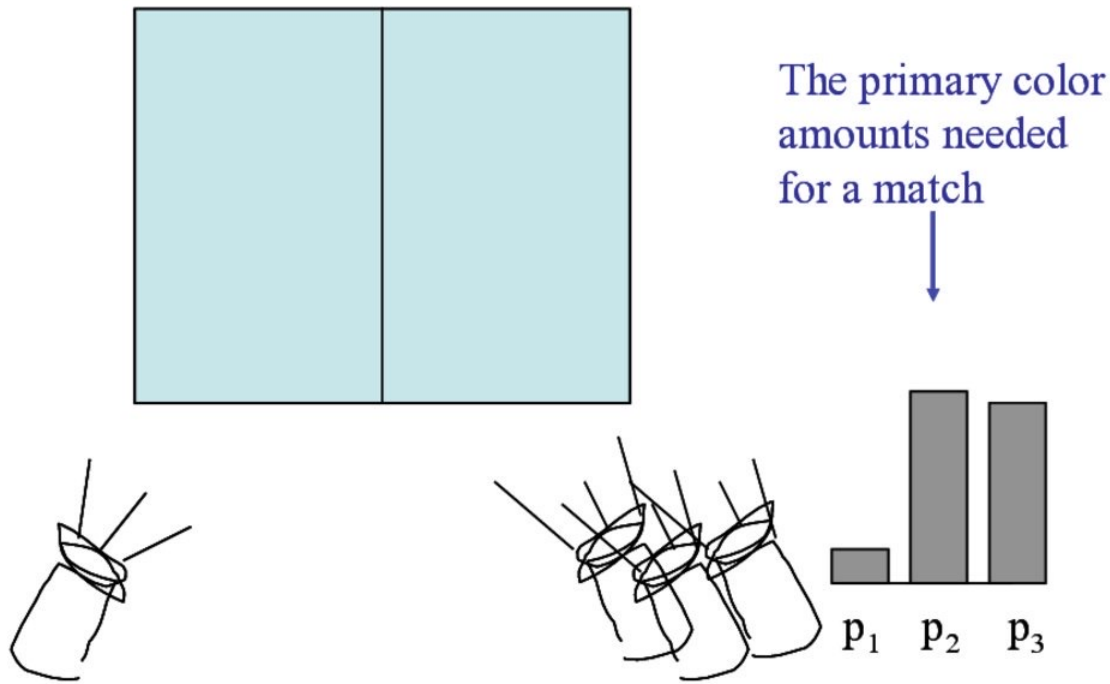
Slide from Durand and Freeman 06

Example experiment



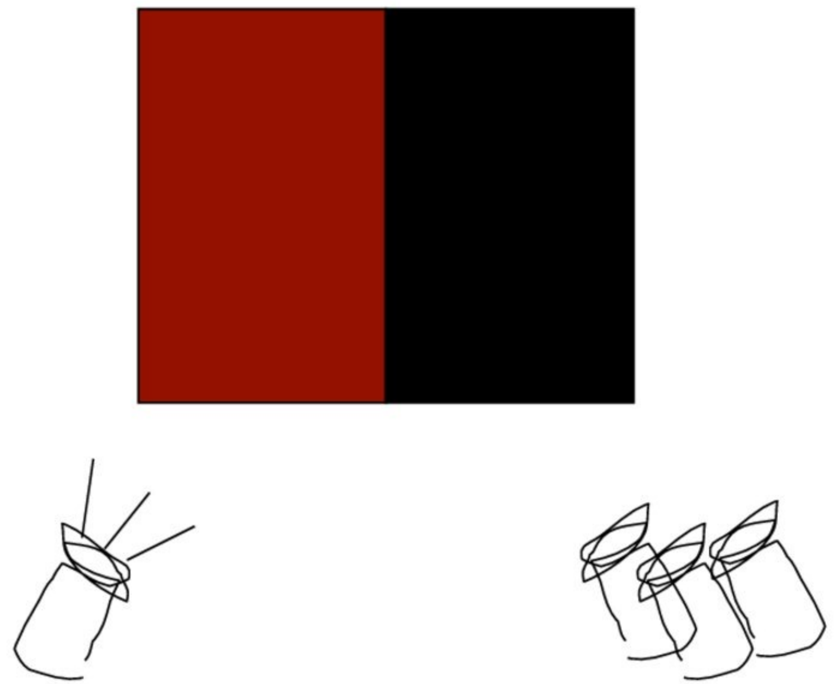
Slide from Durand and Freeman 06

Example experiment



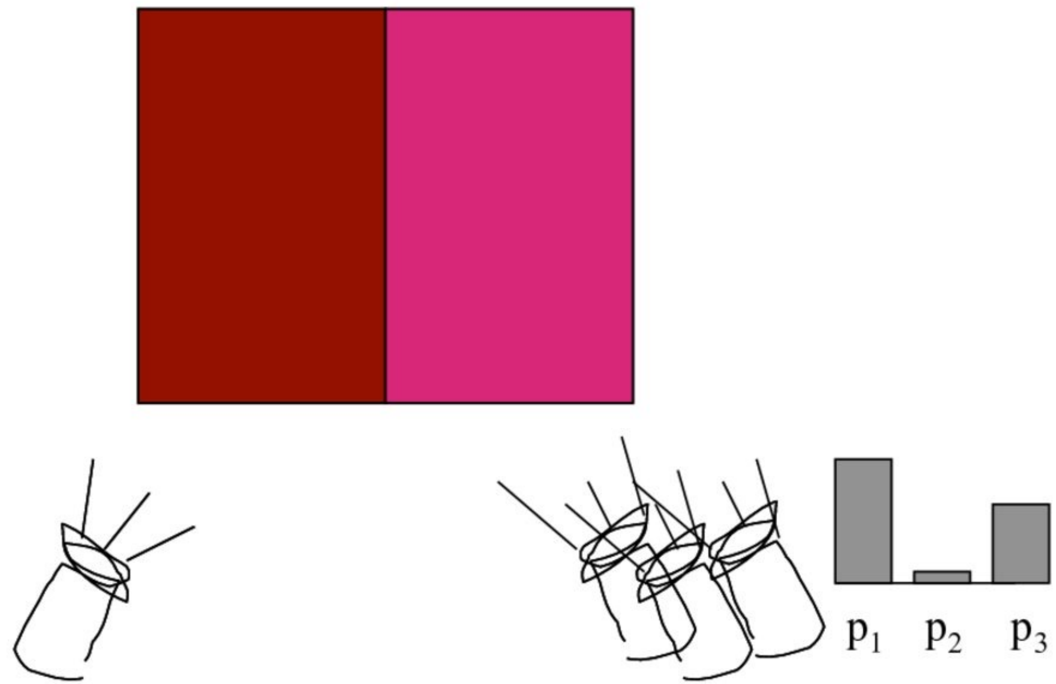
Slide from Durand and Freeman 06

Experiment 2: out of gamut target



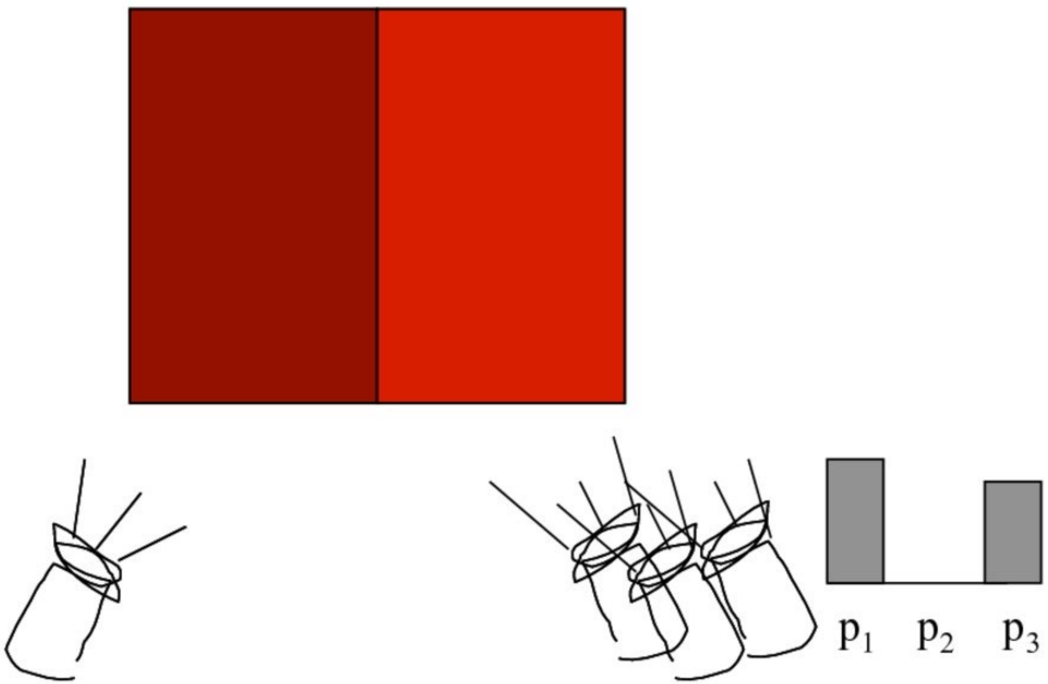
Slide from Durand
and Freeman 06

Experiment 2: out of gamut target



Slide from Durand and Freeman 06

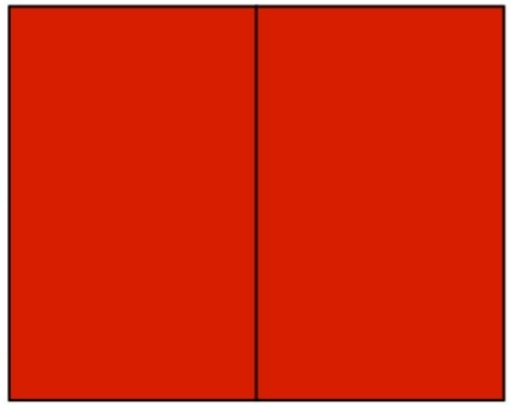
Experiment 2: out of gamut target



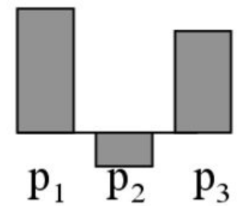
Slide from Durand
and Freeman 06

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.

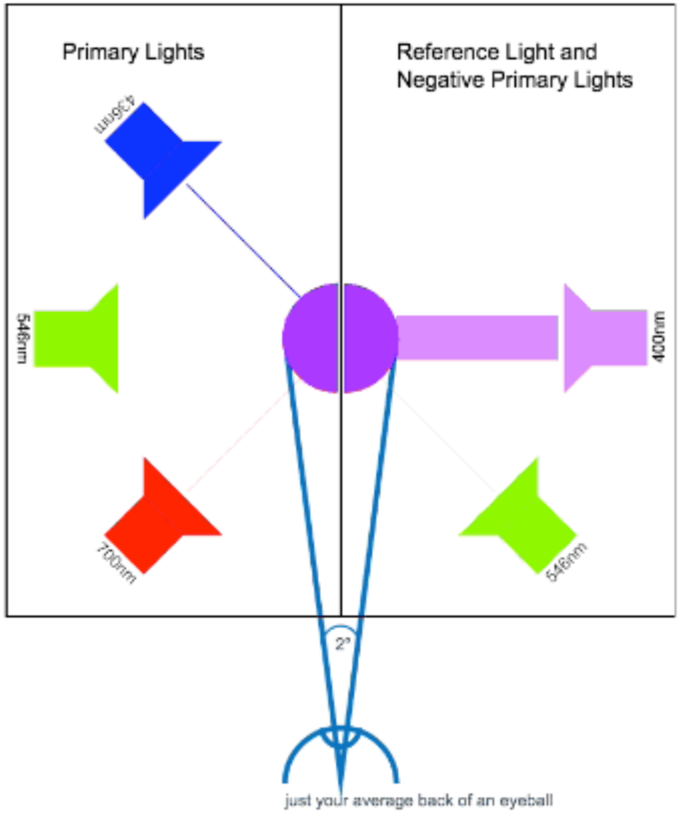


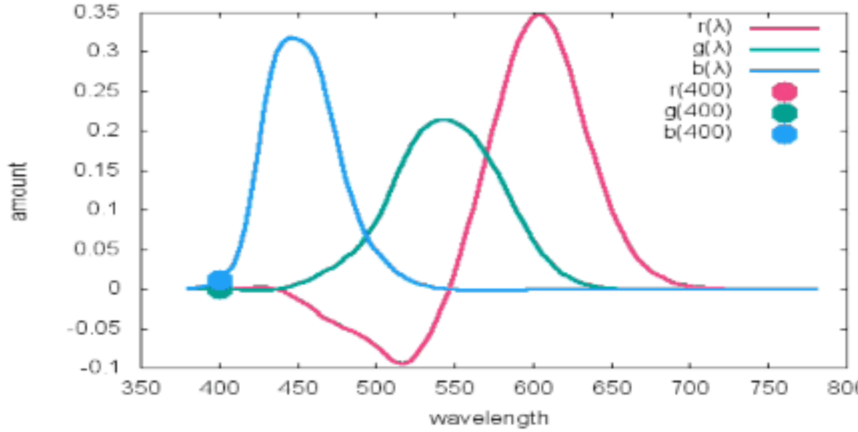
The primary color amounts needed for a match:



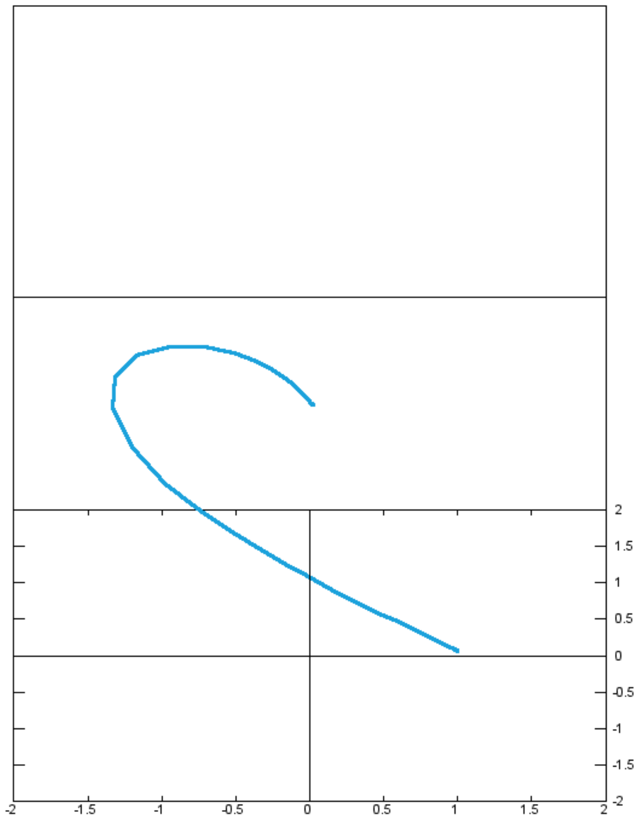
Slide from Durand and Freeman 06

Color matching experiment (CIE 1931)

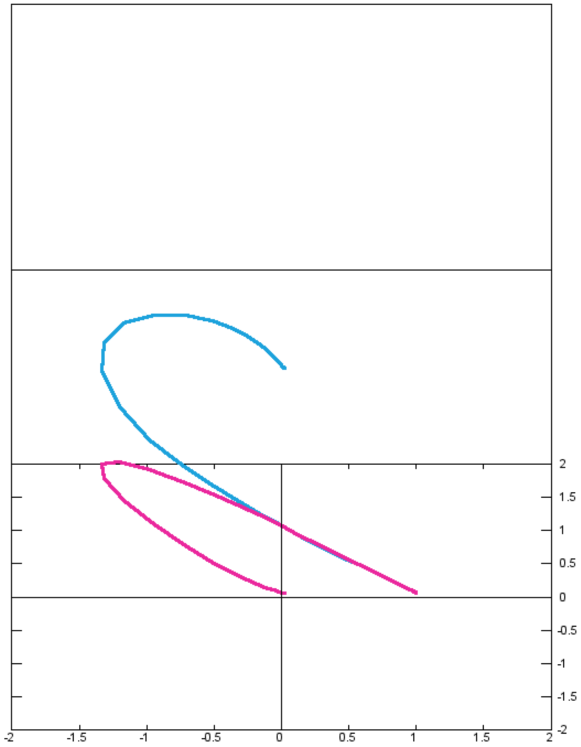


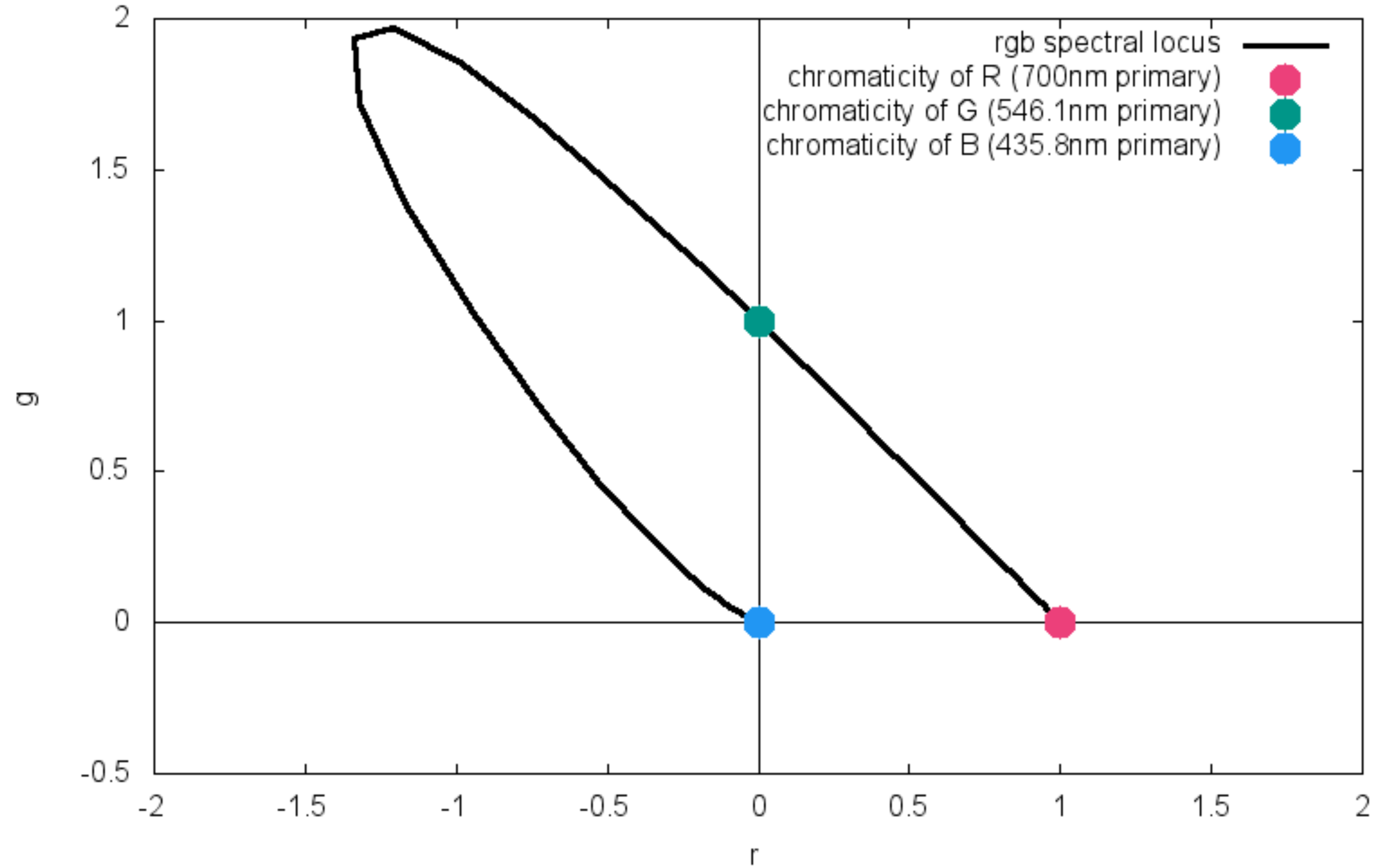


Spectral locus plotted in RGB

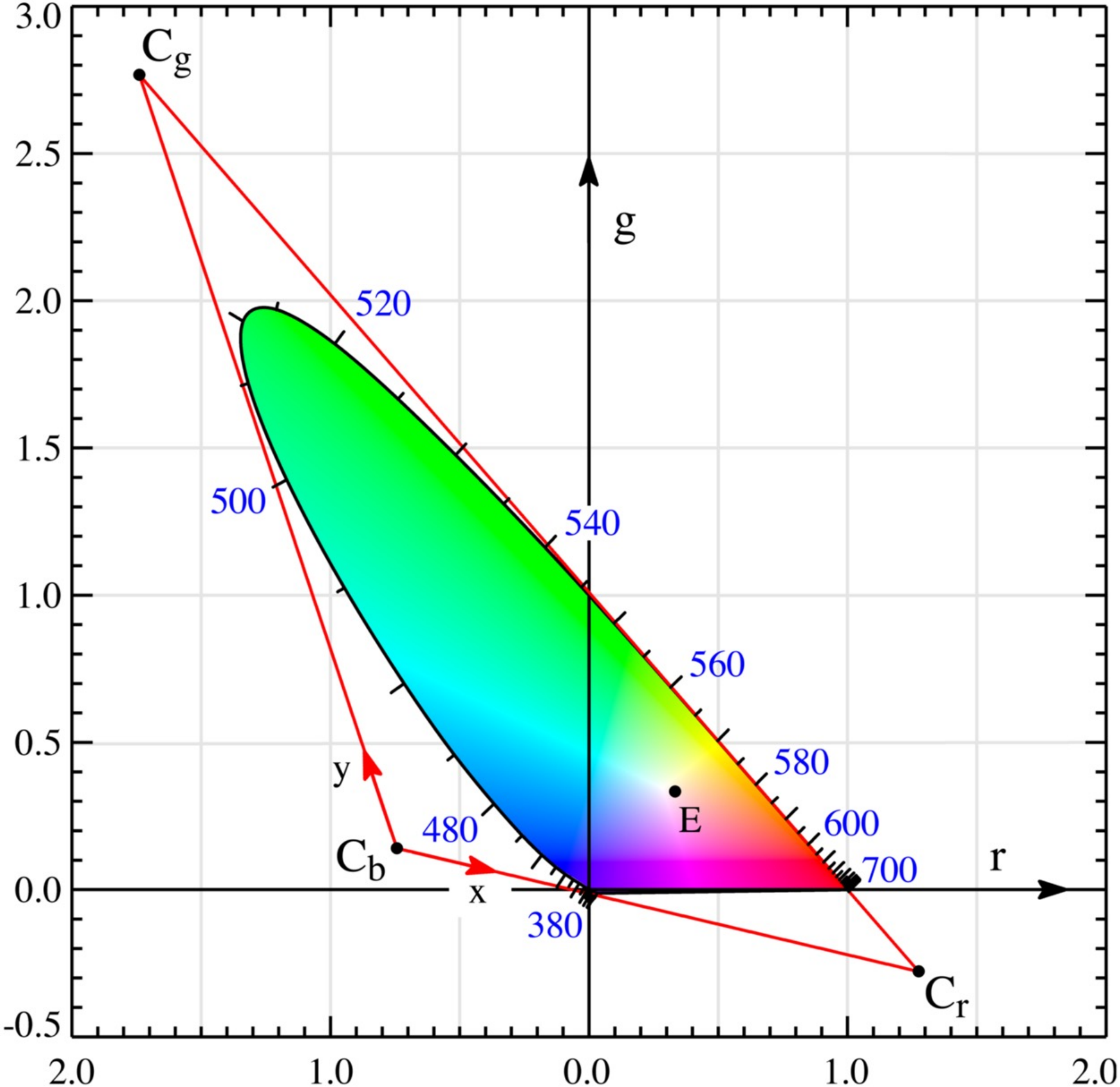


Projected onto RG plane





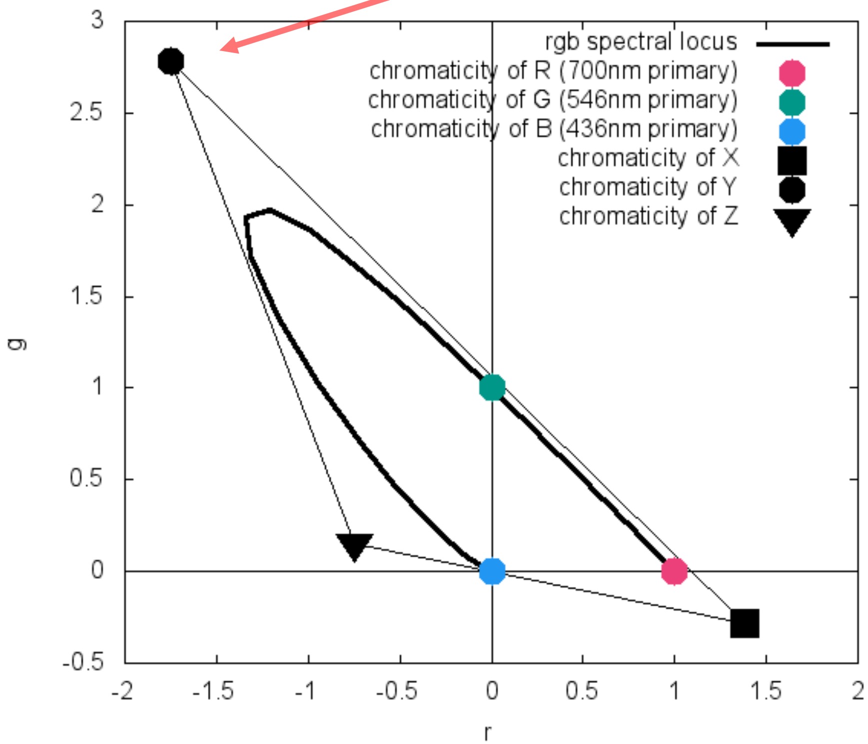
rgb spectral locus
chromaticity of R (700nm primary)
chromaticity of G (546.1nm primary)
chromaticity of B (435.8nm primary)
g
r
2
1.5
1
0.5
0
-0.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2



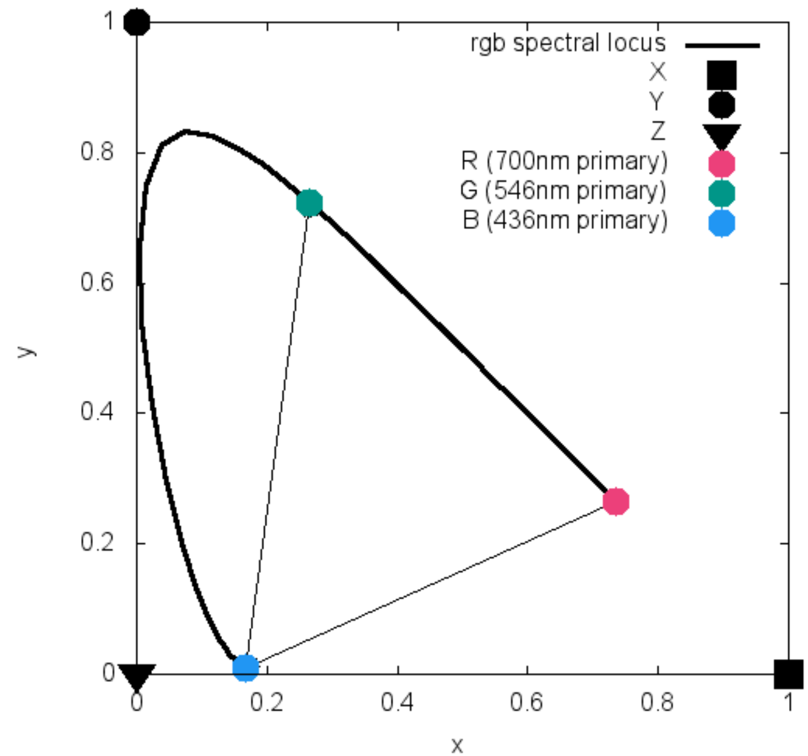
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
2.0
1.0
0.0
1.0
2.0
C_g
C_b
C_r
g
r
x
y
E
520
500
540
560
580
600
700
480
380

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

RGB

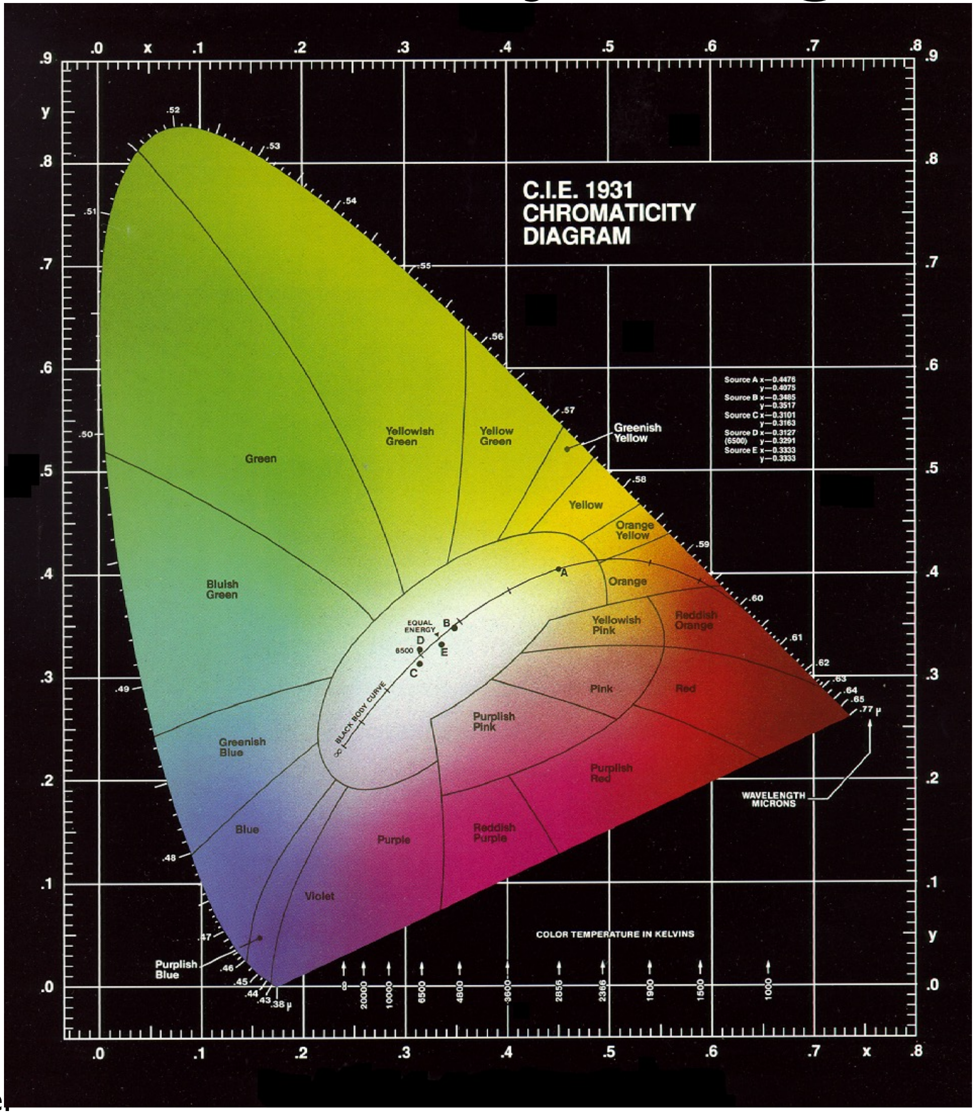


XYZ



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

Chromaticity Diagram



[source unknown]

Administrative

Q&A

End