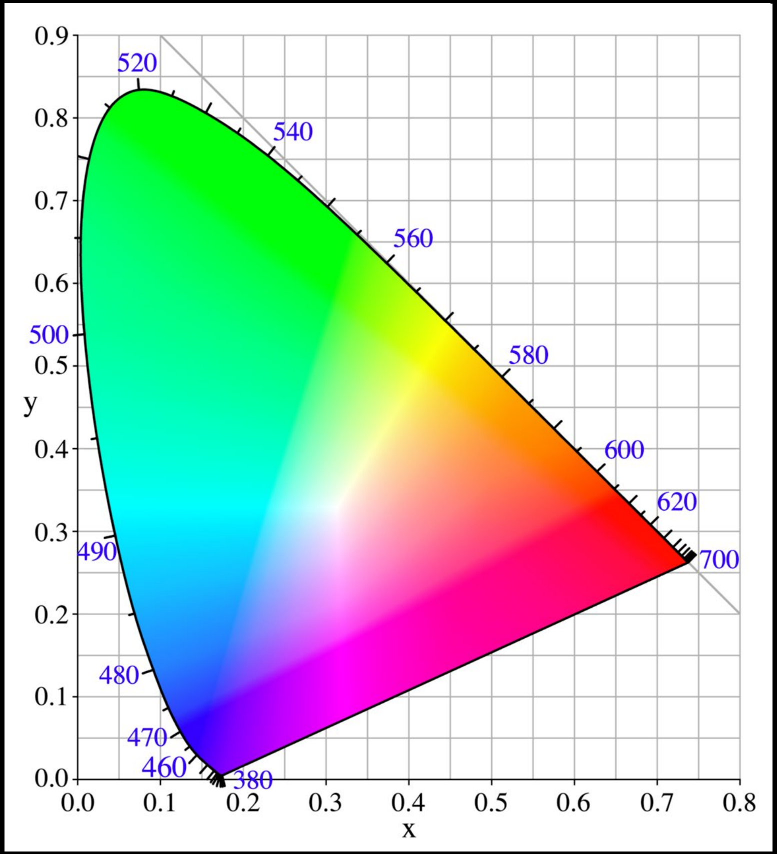
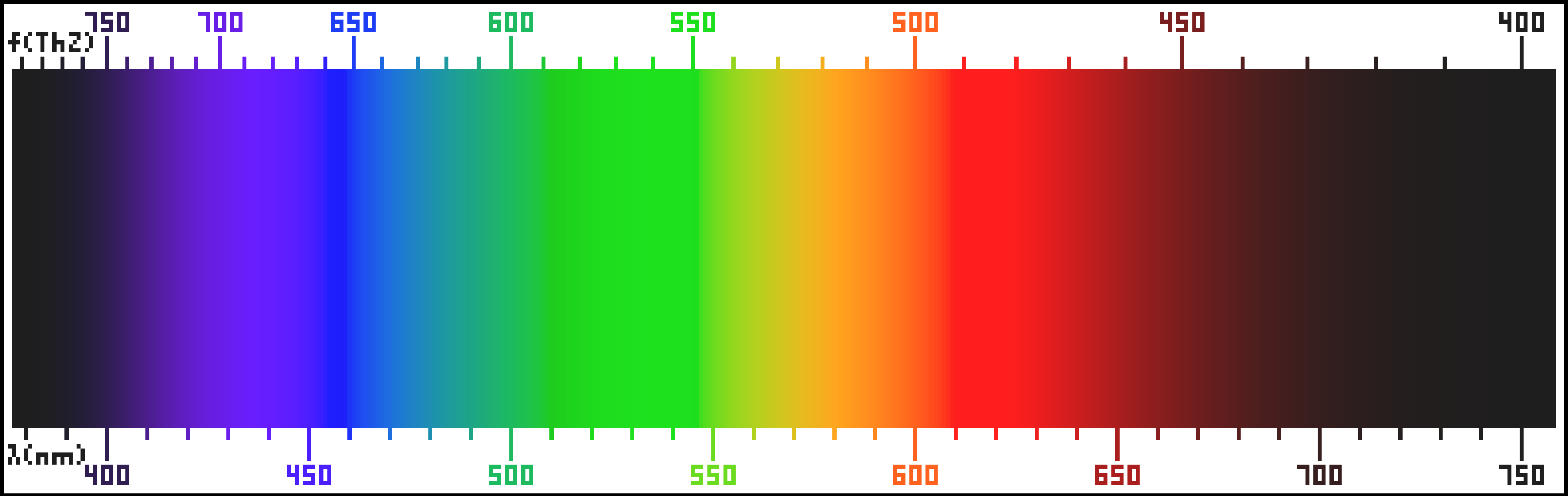
Color! Main Goals:

- Understand this thing: "Chromaticity diagram"



- Given a spectrum, how to predict what color the spectrum will seem to you

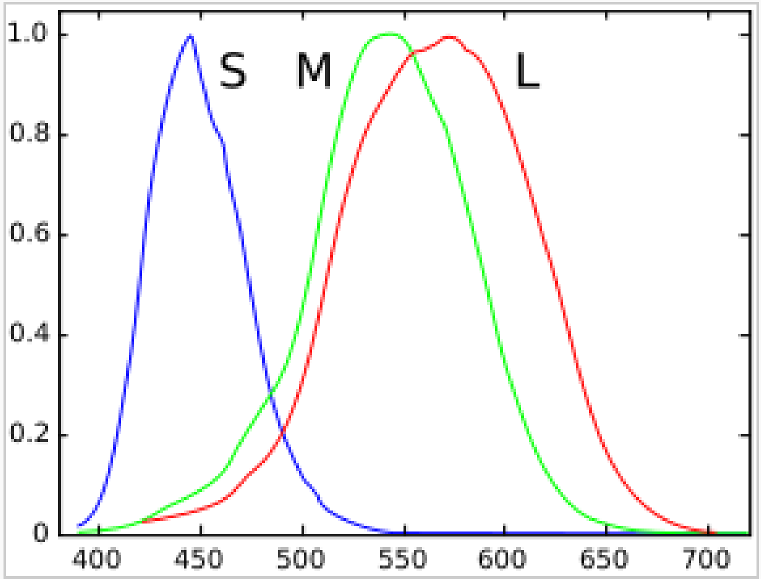
Visible Spectrum



From Wikipedia, “Visible Spectrum”

- “All the colors of the rainbow…”
  → Where is brown?? Where is pink?? Where is turquoise??

Cone cells

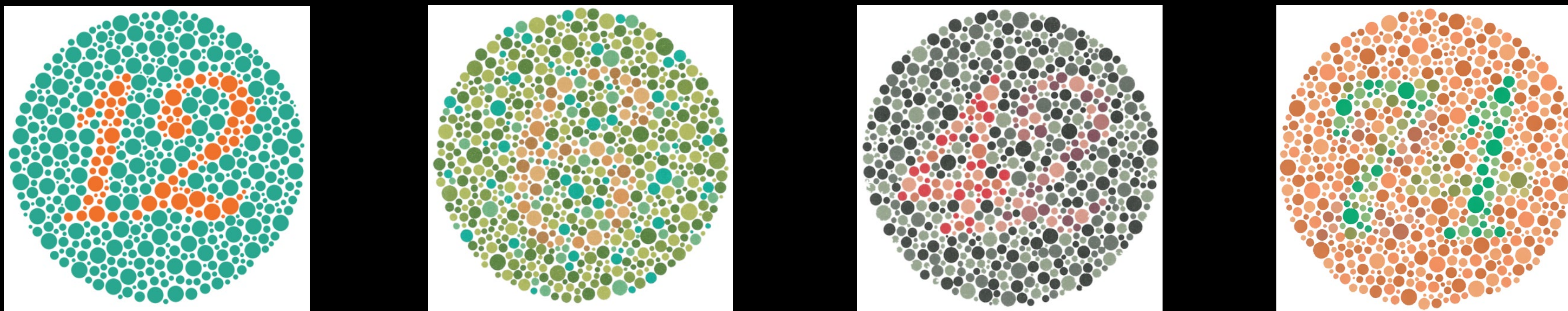


Normalized response spectra of human cones, S, M, and L types, to monochromatic spectral stimuli

"Short" "Medium" "Long"

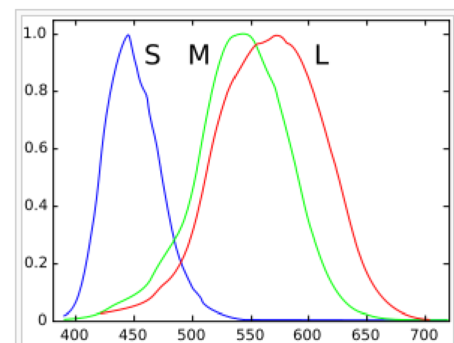
From Wikipedia, "Color Vision"

Color blindness



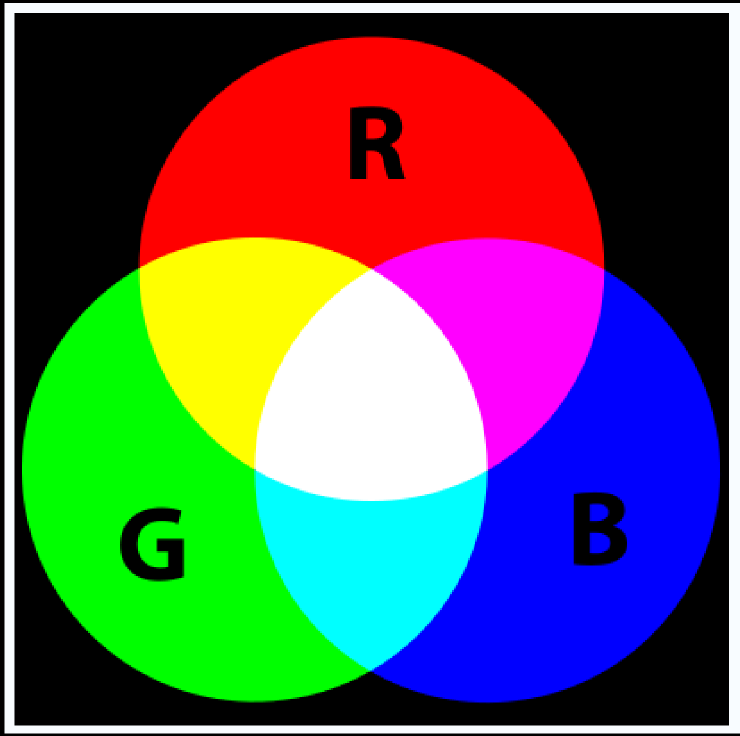
From Wikipedia, “Ishihara test”

Name	Cause	Prevalence
tritanopia	lacks S cones	<1% of males and females
tritanomaly	S cones mutated	~0.01% of males and females
deuteranopia	lacks M cones	~1% of males
deuteranomaly, standard “red-green color blindness”	M cones mutated	~5% of European males; far fewer females
protanopia	lacks L cones	~1% of males
protanomaly	L cones mutated	~3% of European males; far fewer females
achromatopsia	total color blindness	0.003% of males and females (1 in 33,333)

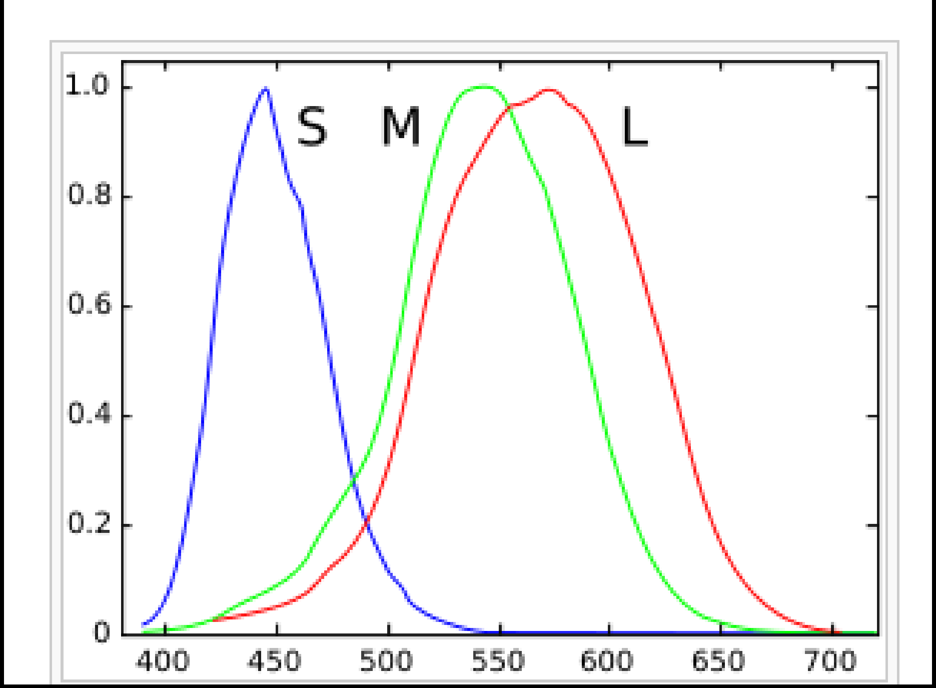


Normalized response spectra of human cones, S, M, and L types, to monochromatic spectral stimuli

Primary Colors



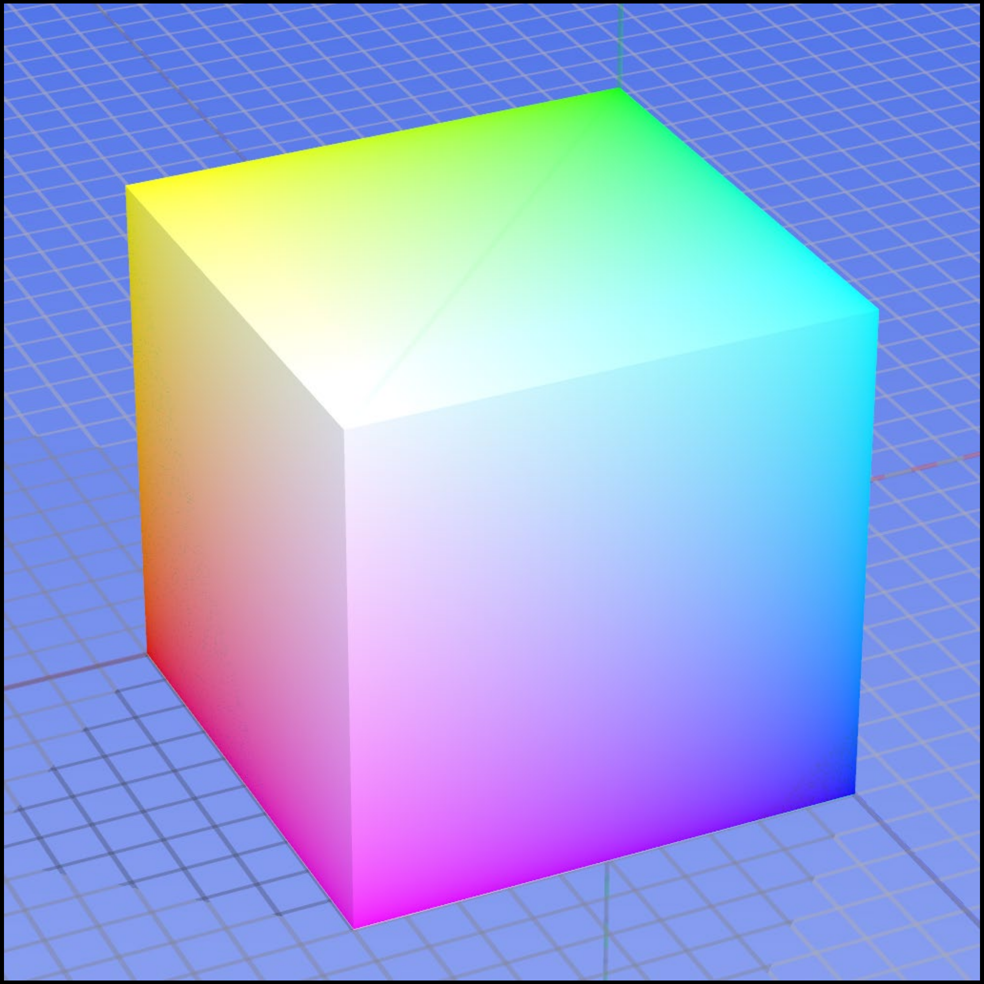
From Wikipedia,
"RGB Color Model"



Cone cell response

- How the primary song *should* go
- "Additive color mixing"
- (Pigments: "subtractive color mixing")

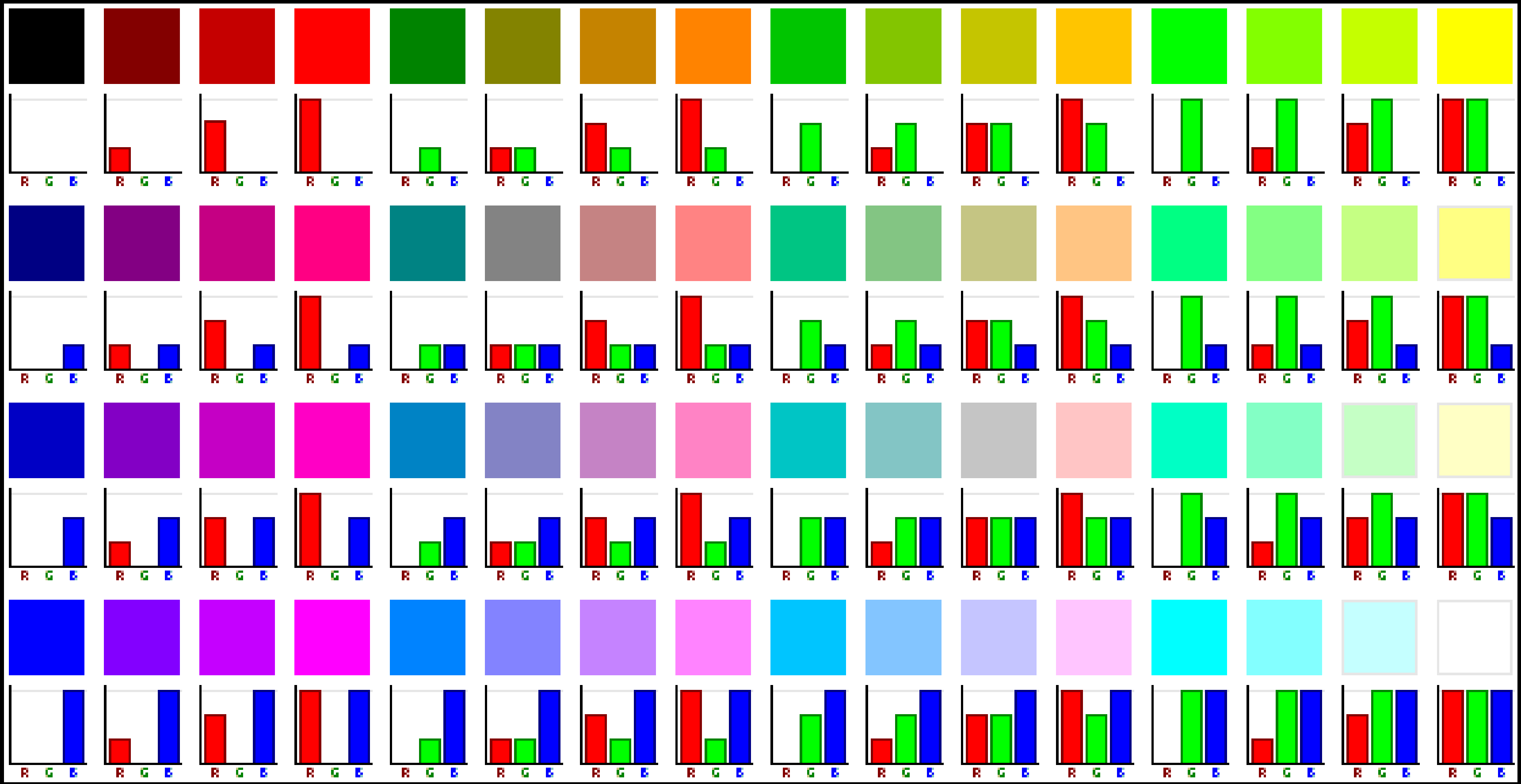
Components of R, G, B: Plot in 3D "color space"



From Wikipedia,
"RGB Color Model"
(old version)

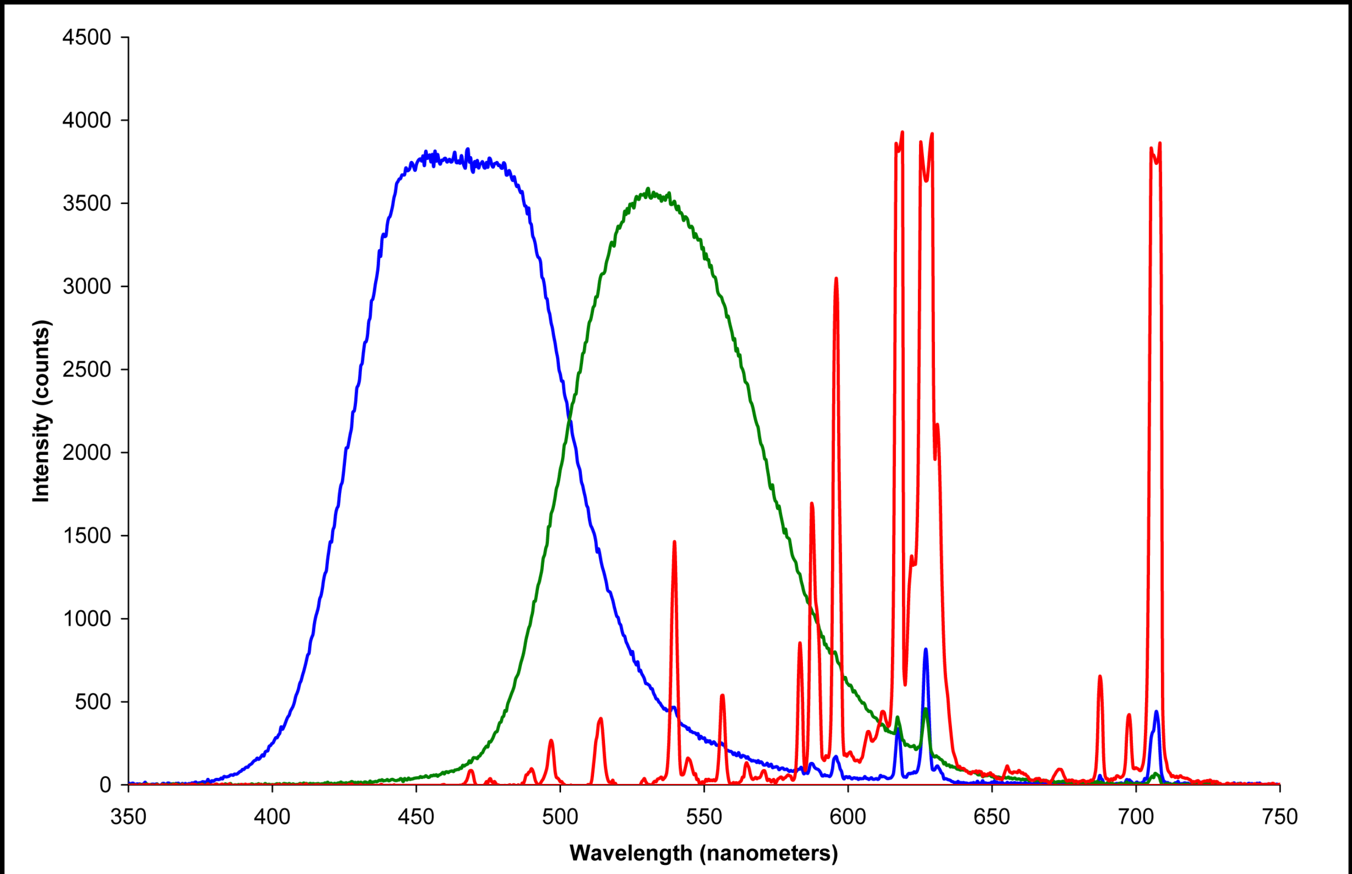
Viewing slices of the cube:
https://programmingdesignsystems.com/color/color-models-and-color-spaces/index.html

Components of R, G, B



From Wikipedia,
“RGB Color Model”
(old version)

How to Display Colors



The emission spectra of the three phosphors that define the **additive primary colors** of a CRT color video display. Other electronic color display technologies (LCD, Plasma display, OLED) have analogous sets of primaries with different emission spectra.

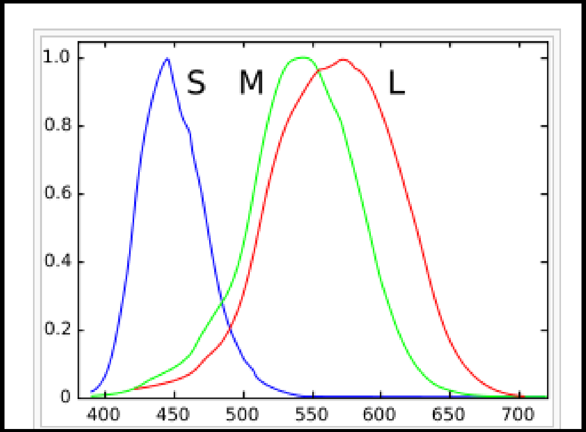
From Wikipedia, “Primary Color”

1920's Color Matching Experiments

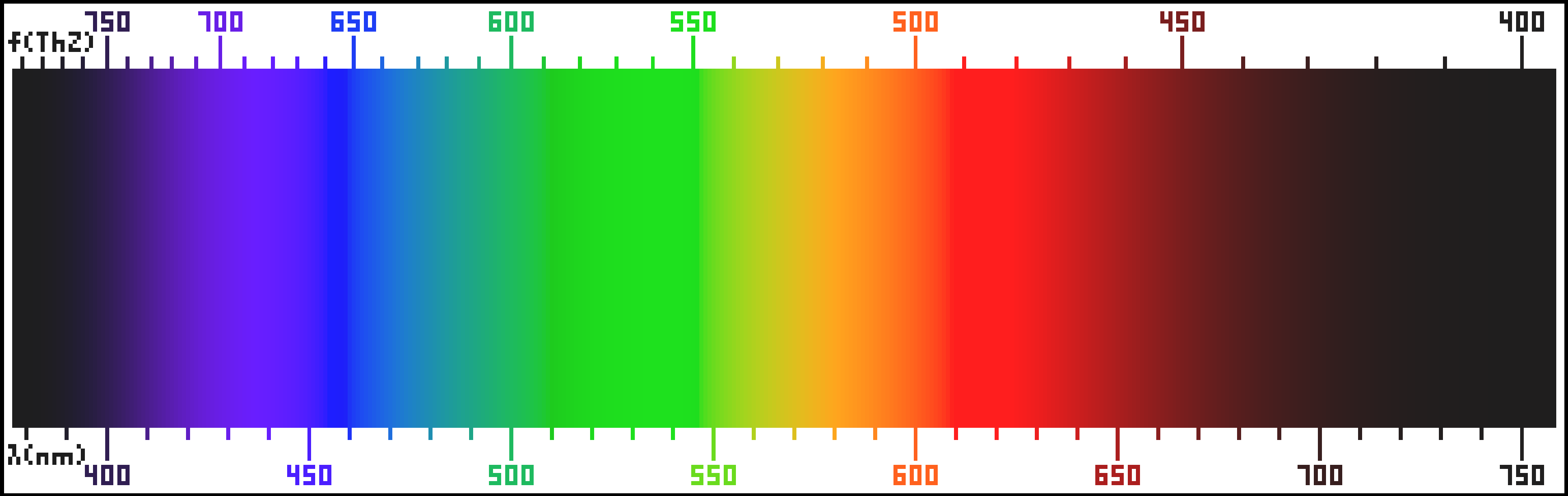
Using combinations of these three:

- Narrow red source at 700 nm
- Narrow green source at 546.1 nm
- Narrow blue source at 435.8 nm

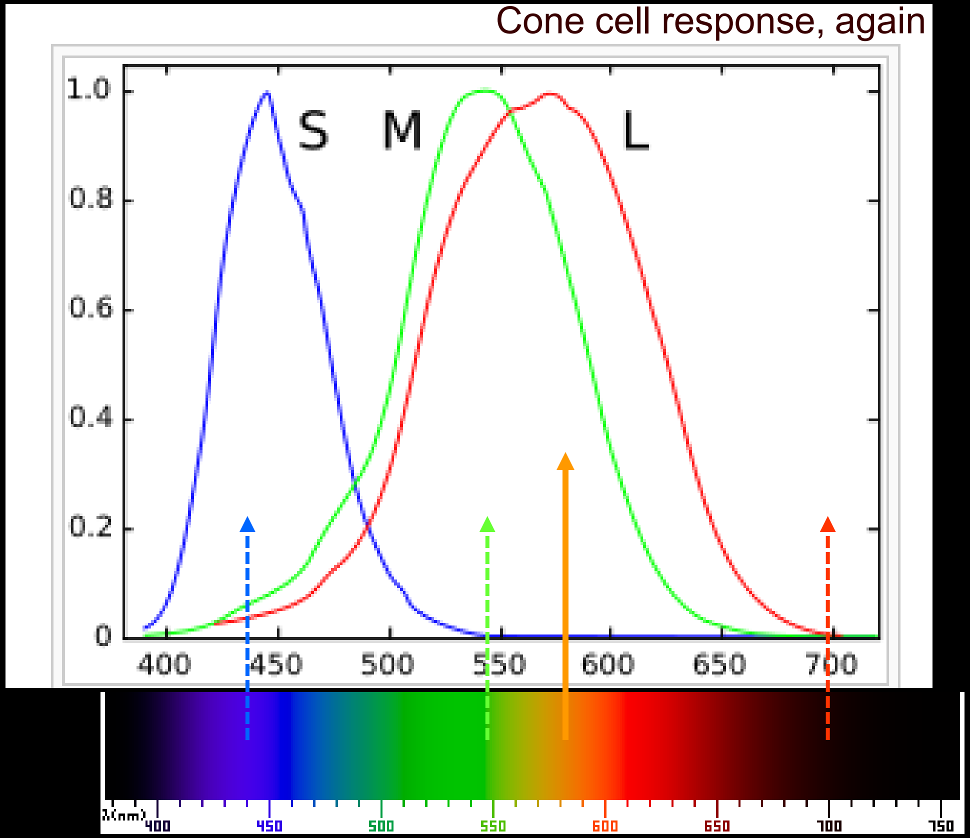
How much of each is required to match the wavelengths in the visible spectrum ("pure colors")?



Cone cell response, again



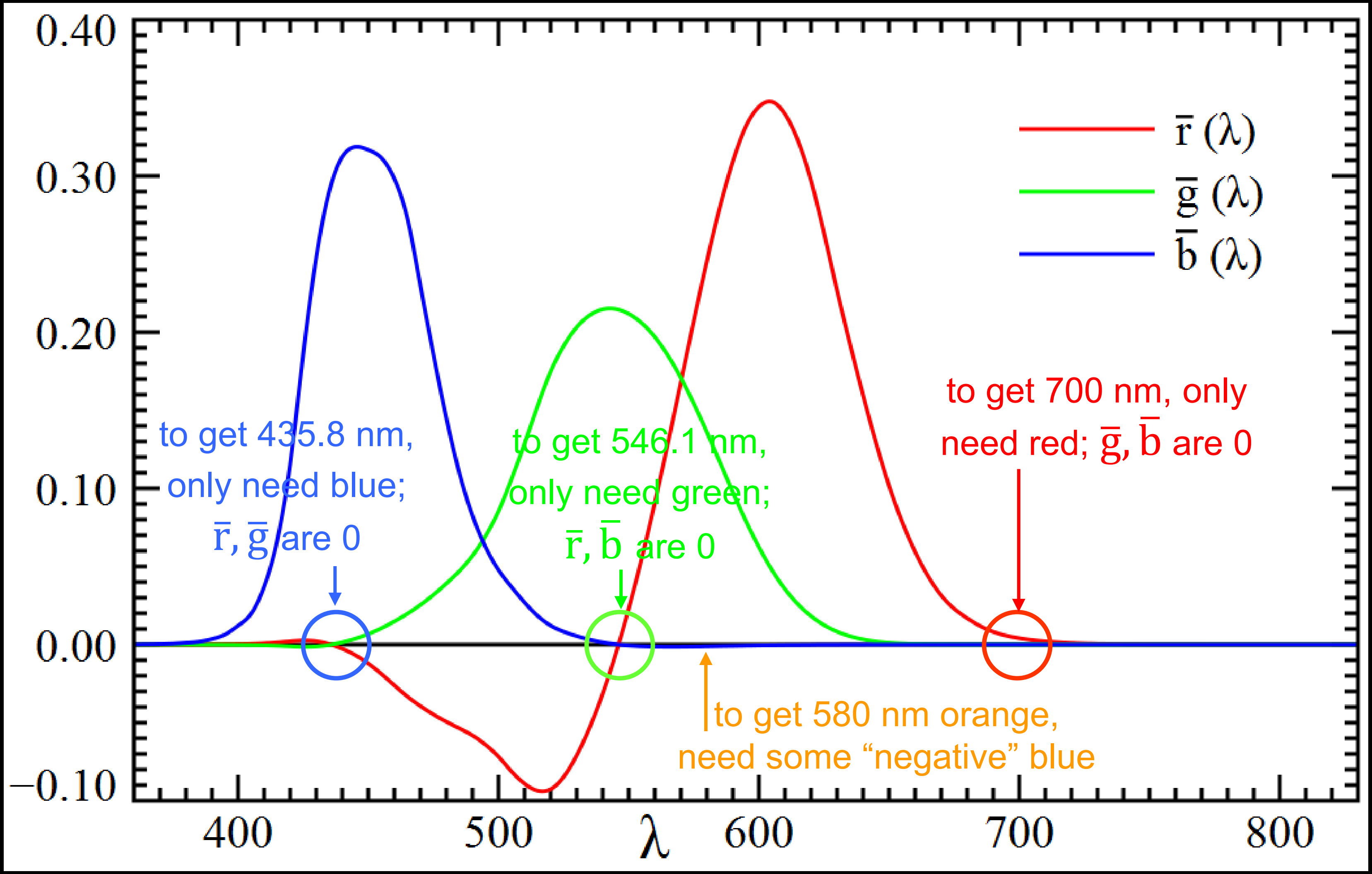
A Concern



- Say you want to mix the dashed lines to look the same as 580 nm orange line.
- You may start by turning up the red light. But soon you also need to turn up the green light. However…
  - → Green light will excite some S! (a small amount, but nonzero)
  - → 580 nm alone will never excite S! Therefore 580 nm cannot be matched.
  - → You need some "negative blue" to counteract

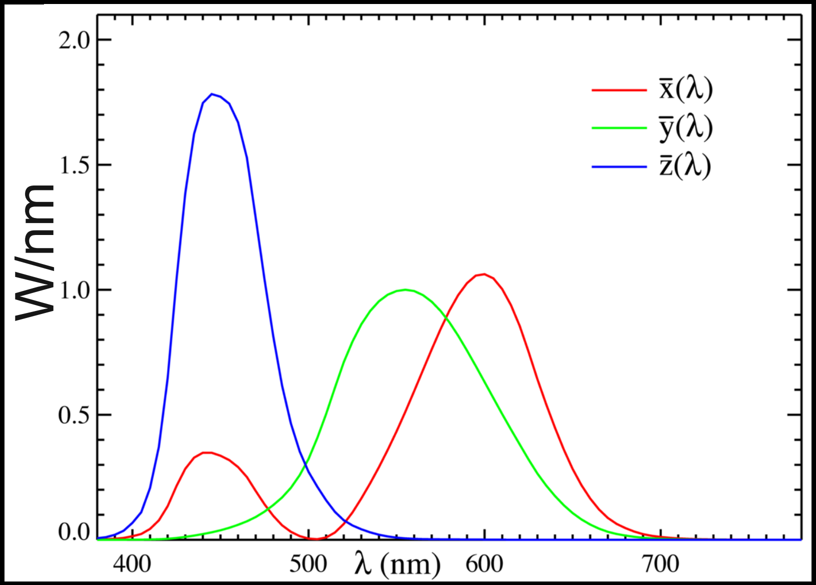
Results: $\bar{r}, \bar{g}, \bar{b}$ functions

red source = 700 nm green source = 546.1 nm blue source at 435.8 nm

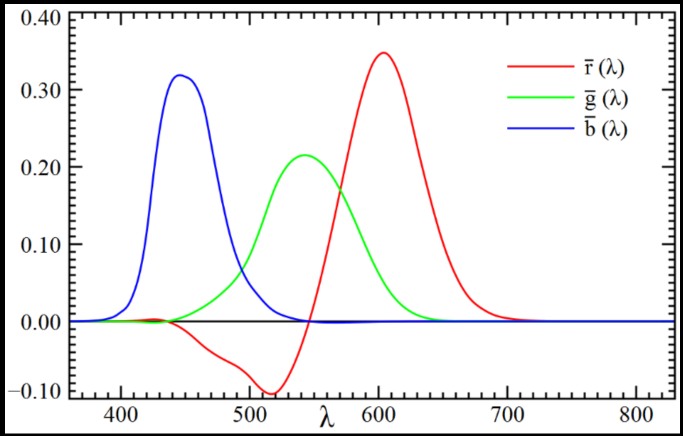


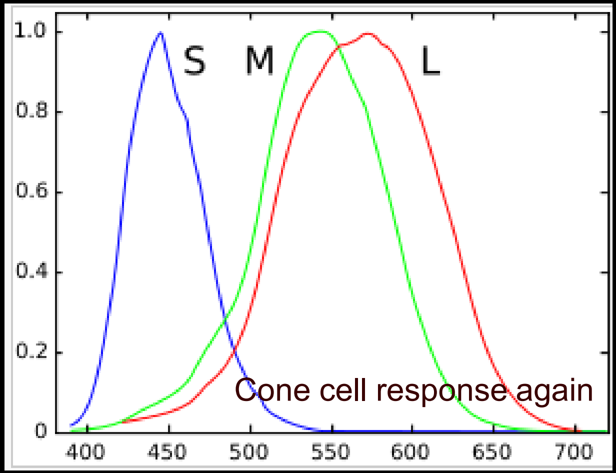
From Wikipedia, "1931 Color Space" (also in P&W)

Better!! $\bar{x}, \bar{y}, \bar{z}$ functions



From Wikipedia, "CIE 1931 Color Space"
(<u>Very Important</u>, but not in Peatross & Ware)





<u>$\bar{x}, \bar{y}, \bar{z}$ properties</u>

- all are positive
- $\bar{z}$ = close to S cones, close to $\bar{b}$
- $\bar{y}$ = matches intensity response of eye, close to M cones. Normalized to 1.
- $\bar{x}$ = chosen so that white is equal parts of all three

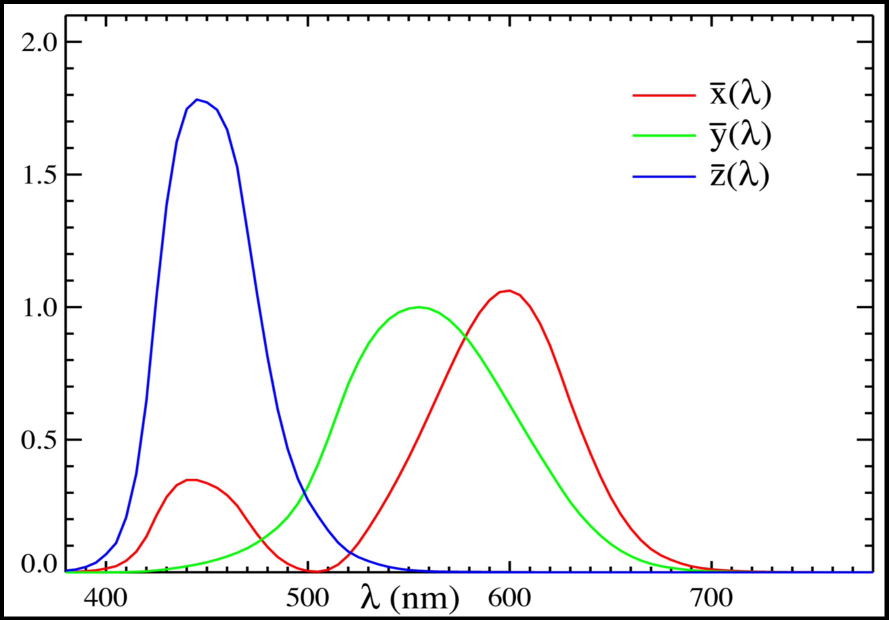
Projections

- Given a spectrum I(λ), how much $\bar{x}$, $\bar{y}$, and $\bar{z}$ does it have?

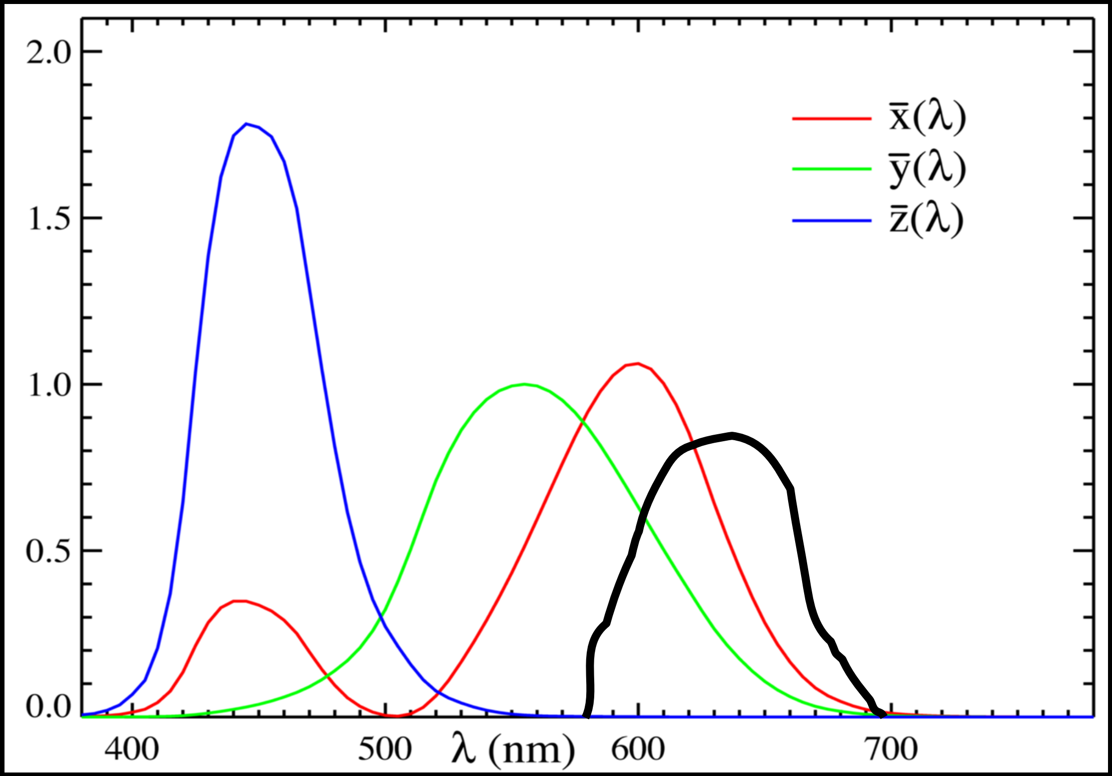
$$X = \int I(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int I(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int I(\lambda)\bar{z}(\lambda)d\lambda$$



Worked Example, Like P2.13



Note 1: the functions were changed in 2006. For HW problem, use functions given on **https://optics.byu.edu/resources** (link provided in textbook)

Note 2: as explained in my instructions for P2.13, "luminous power" (in lumens) $= 683 \times \int I(\lambda)\bar{y}(\lambda)d\lambda$ $= 683 \times Y$

- X = ~15
- Y = ~12
- Z = 0

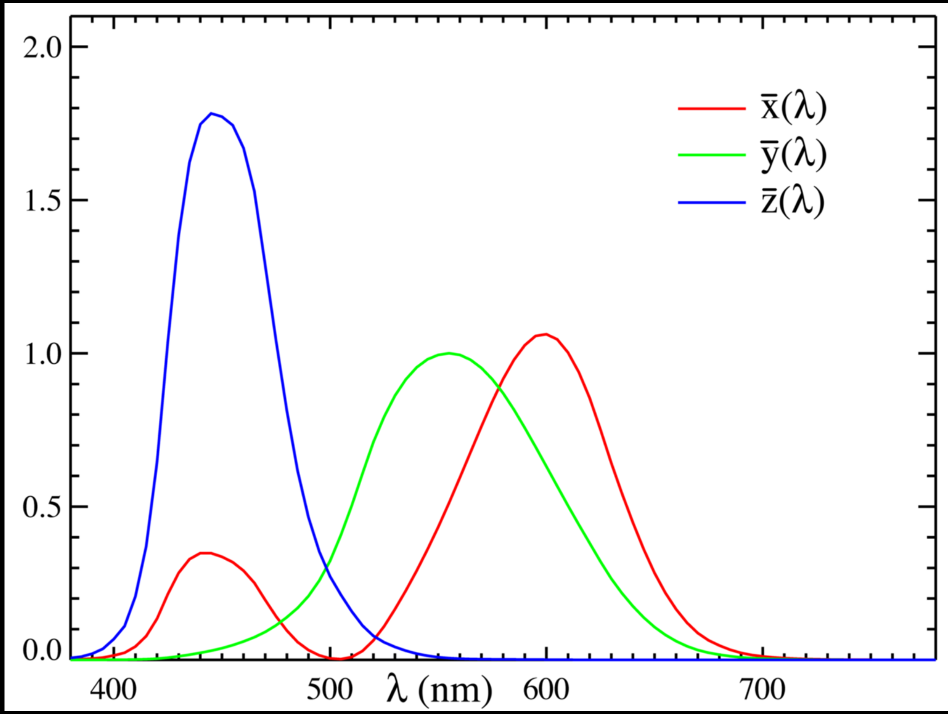
Normalize so they add up to 1 ("color" should not depend on overall intensity)

- x = 15/27 = 0.56
- y = 12/27 = 0.44
- z = 1 − x − y = 0

These are the chromaticity coordinates!!

Another Worked Example

- What is (x,y) for a delta function at 560 nm?



<u>My estimates:</u>

X = 0.59

Y = 0.98

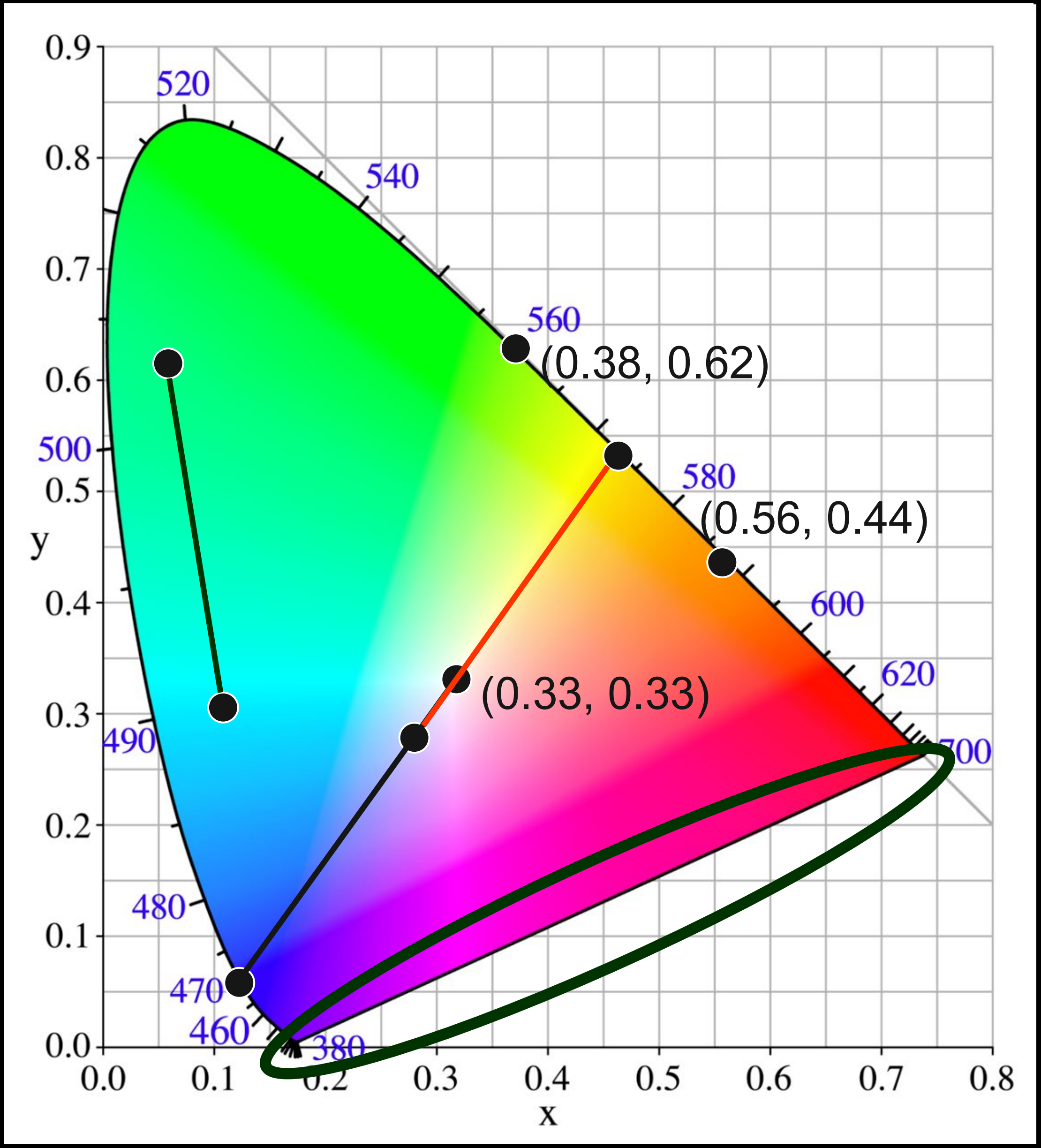
Z = 0

x = 0.38

y = 0.62

Do that for every wavelength → the "locus" curve

Chromaticity Diagram



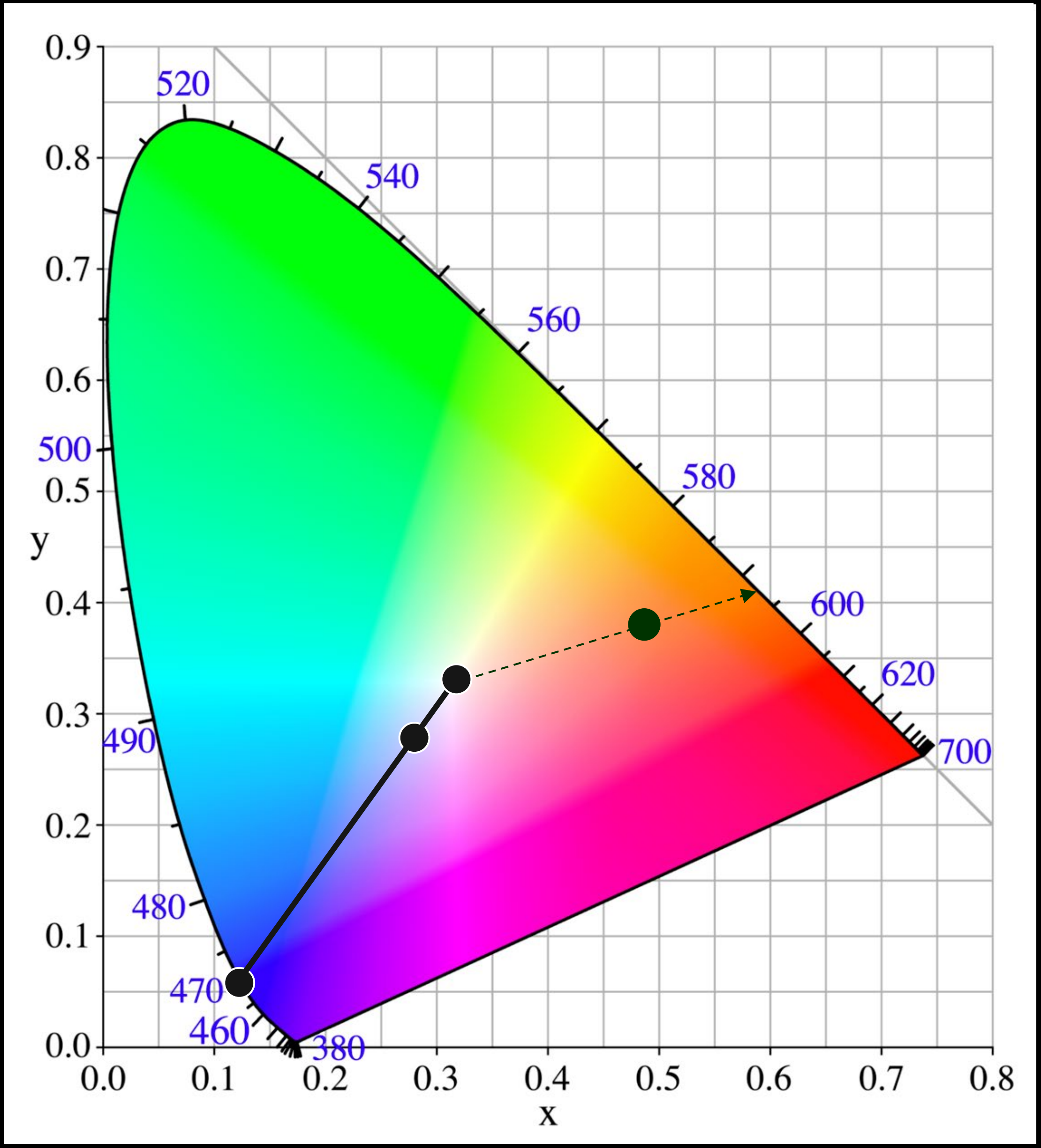
Things to observe

- Example 2: 560 nm = (0.38, 0.62)
- The locus curve
- Example 1: (0.56, 0.44)
- The white point = (0.33, 0.33)
- "Line of purples"

Linear effects

- Color mixing along line connecting two points
- "Hue": pure wavelength which can mix with white to get the point. Example: 470 nm
- "Complementary color": color that can mix with the point to get white. Example: $\lambda_C = 573$ nm

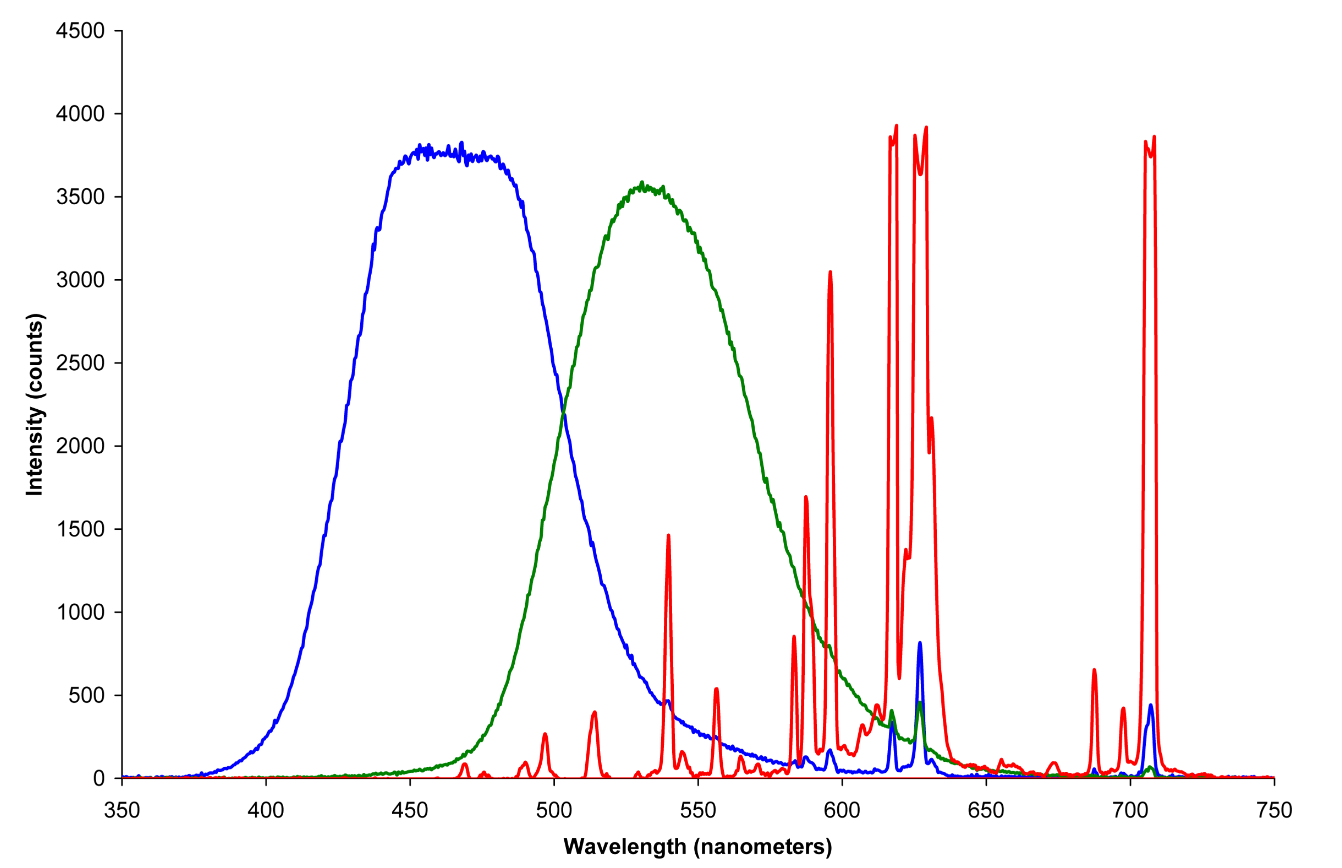
Chromaticity Diagram



- Saturation: How close is the point to its hue?
  a. Example 1: 18%
  b. Example 2: 65%

- Brightness
  a. Overall intensity, Not on this diagram

Remember this?

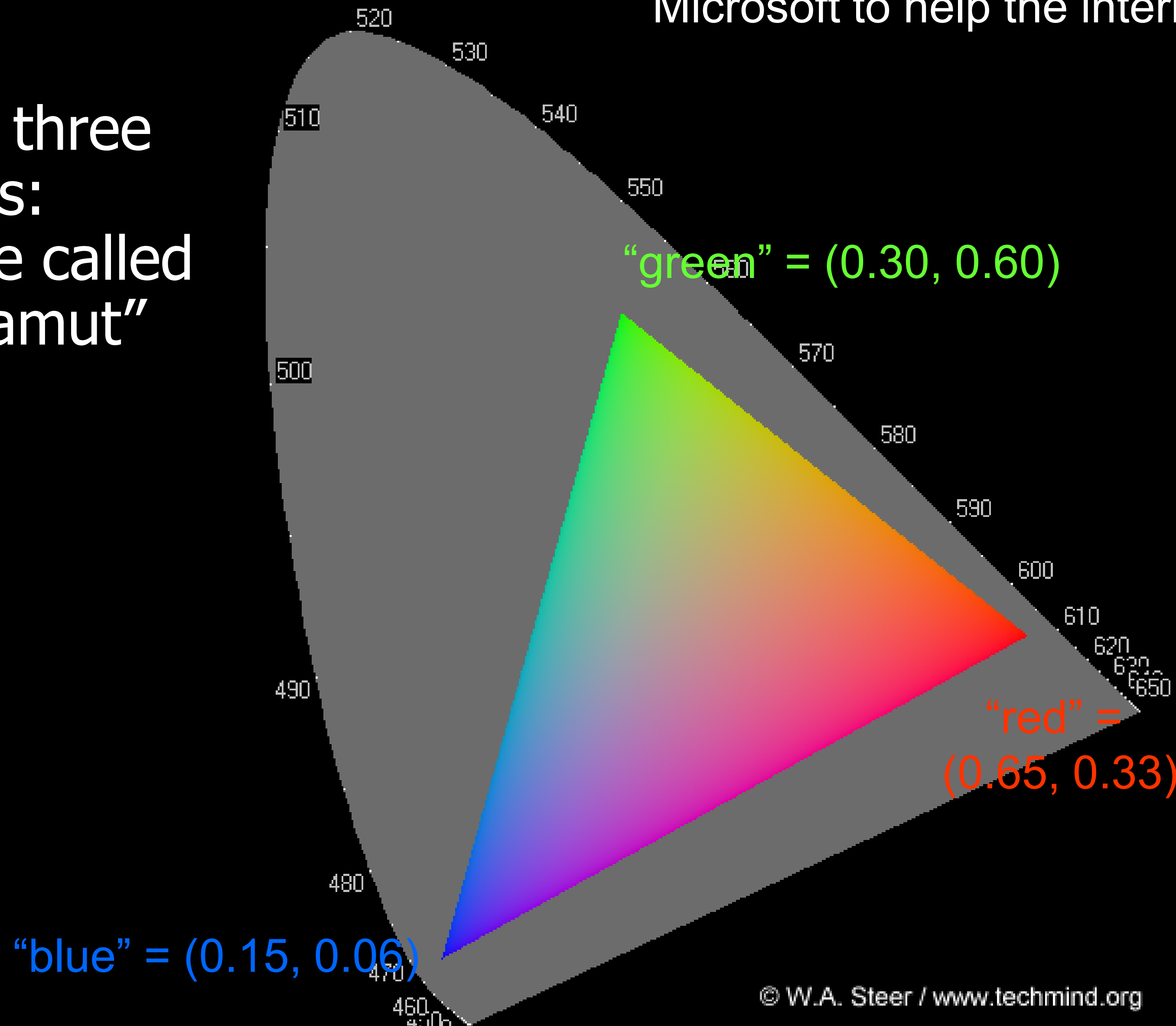


The emission spectra of the three phosphors that define the **additive primary colors** of a CRT color video display. Other electronic color display technologies (LCD, Plasma display, OLED) have analogous sets of primaries with different emission spectra.

sRGB: three specific color sources

Standard created in 1996 by HP and Microsoft to help the internet

- Mixing three sources: triangle called the "gamut"

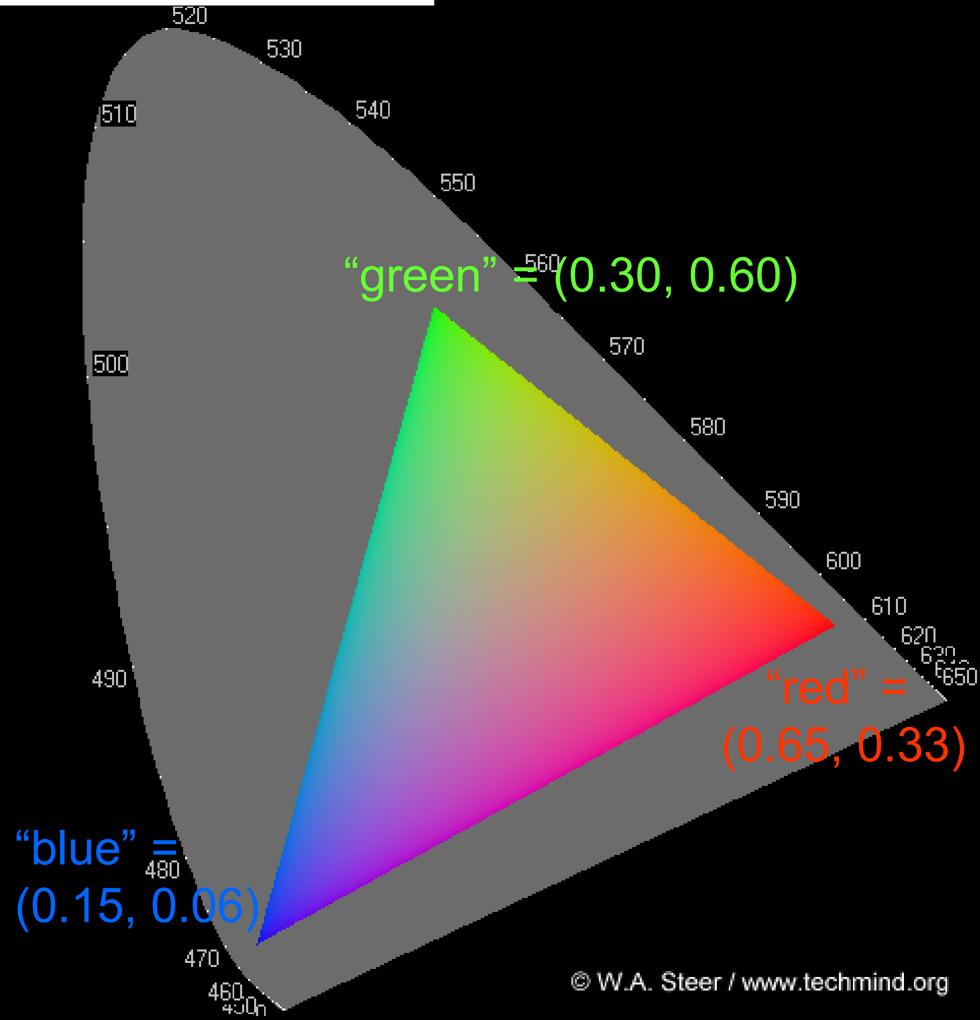


XYZ to sRGB

$$\begin{bmatrix} \tilde{R} \\ \tilde{G} \\ \tilde{B} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

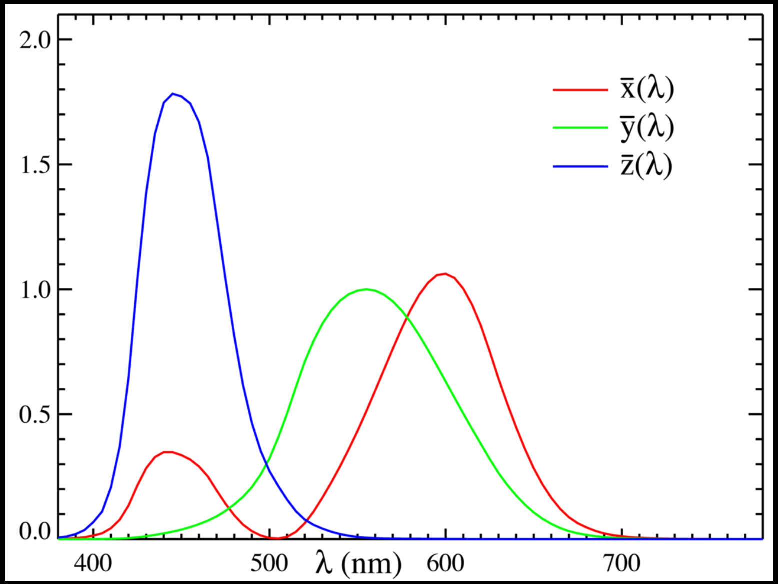
From P&W P2.14

- Step 1: linear transformation
- Step 2: apply nonlinear function because eyes respond logarithmically (given in P2.14)
- Normalize R,G,B values to be integers from 0 to 255
   a. 256×256×256 = 16,777,216 possible colors



xyY

- Reminder: what was Y?



- all are positive
- $\bar{z}$ = close to S cones, close to $\bar{b}$
- $\bar{y}$ = matches intensity response of eye, close to M cones
- $\bar{x}$ = chosen so that white is equal parts of all three

XYZ ↔ xyY Transformations

$$\begin{bmatrix} x \\ y \\ Y \end{bmatrix} = \begin{bmatrix} \dfrac{X}{X+Y+Z} \\ \dfrac{Y}{X+Y+Z} \\ Y \end{bmatrix}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \dfrac{x}{y} Y \\ Y \\ \dfrac{1-x-y}{y} Y \end{bmatrix}$$

"Hue, brightness, saturation"

- Hue – use RGB values to turn locus into a hexagon, then written as 0 to 360°
- Saturation called "chroma", as before
- Brightness from Y, scaled as 0 to 1

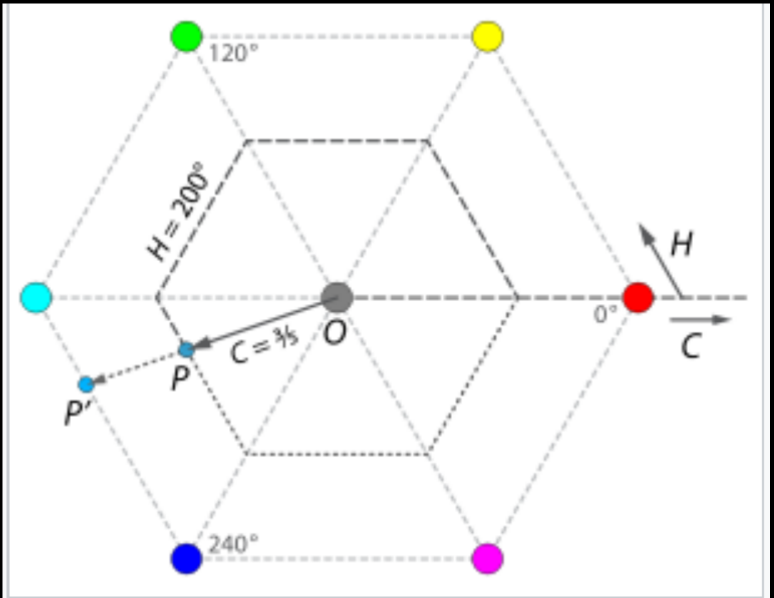
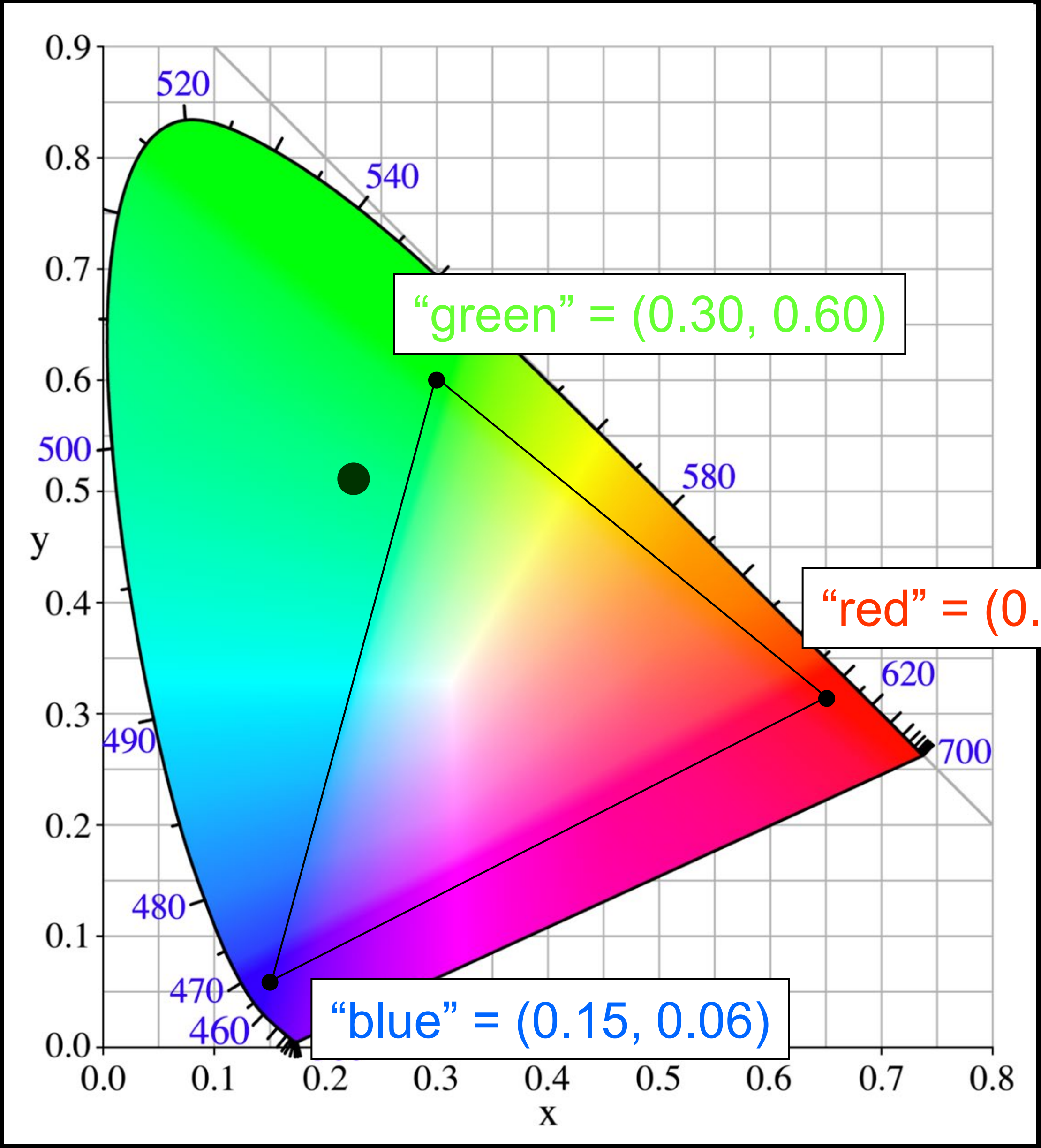


Fig. 9. Both hue and chroma are defined based on the projection of the RGB cube onto a hexagon in the "chromaticity plane". Chroma is the relative size of the hexagon passing through a point, and hue is how far around that hexagon's edge the point lies.

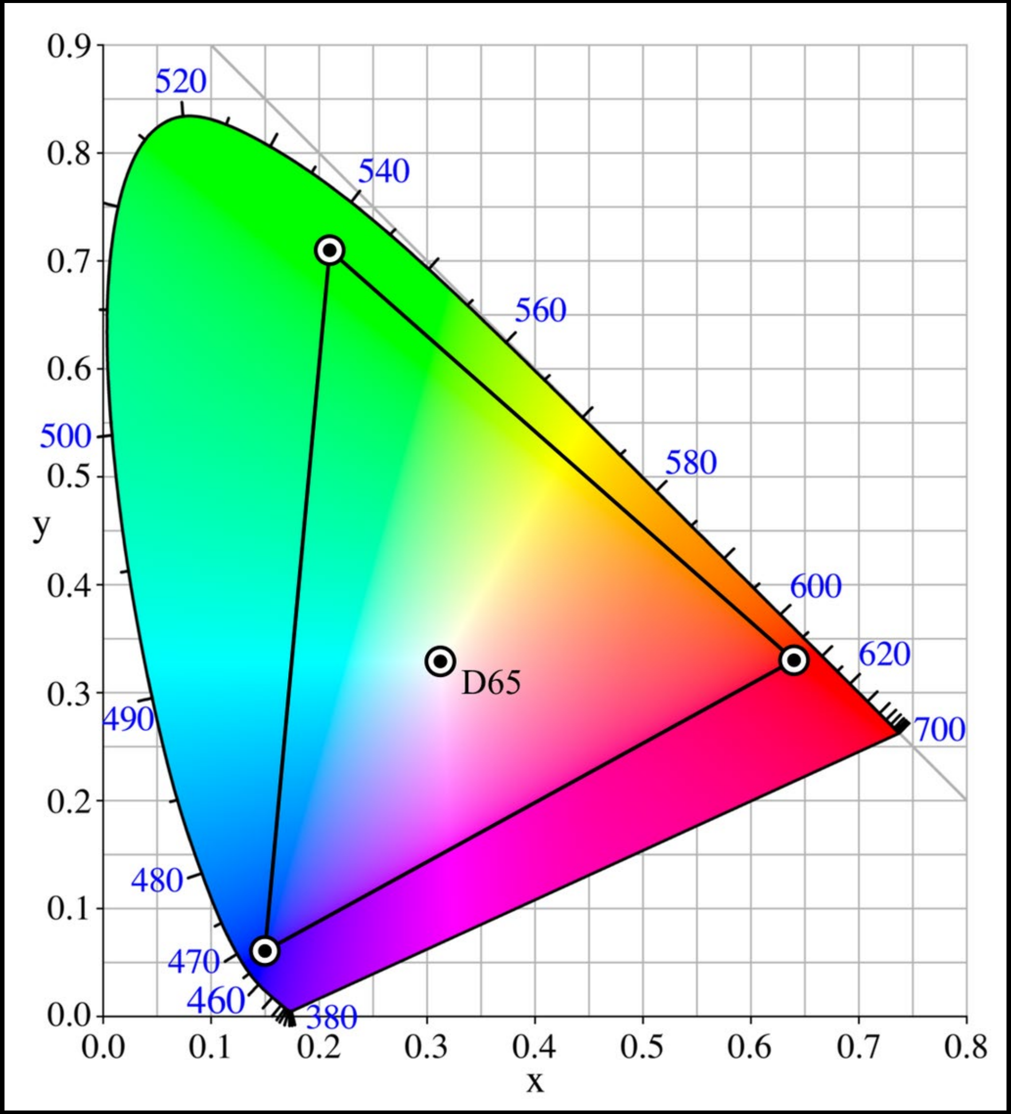
From Wikipedia "HSL and HSV"

sRGB gamut, again



- How would you get this color using sRGB?
- What would be the ideal set of three light sources for your monitor to give you as many colors as possible in the gamut?

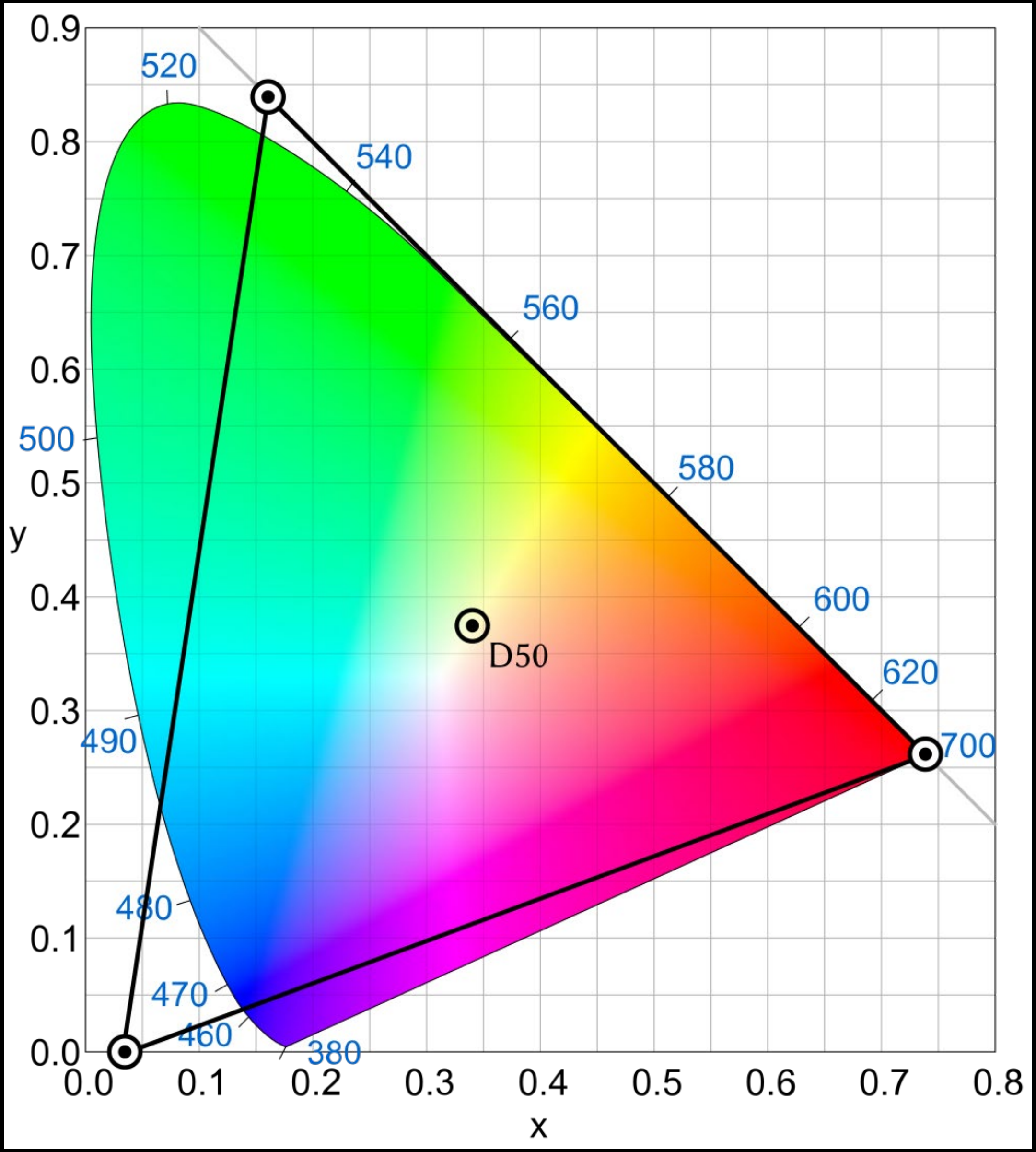
Adobe RGB



- Better than sRGB?
- Only if your camera/display/ printer are all calibrated for it
- Not for use on internet
- Also: there's a wider range of possible colors, but the difference between individual colors is bigger than in sRGB (still 256×256×256)

From Wikipedia, "Adobe RGB color space"

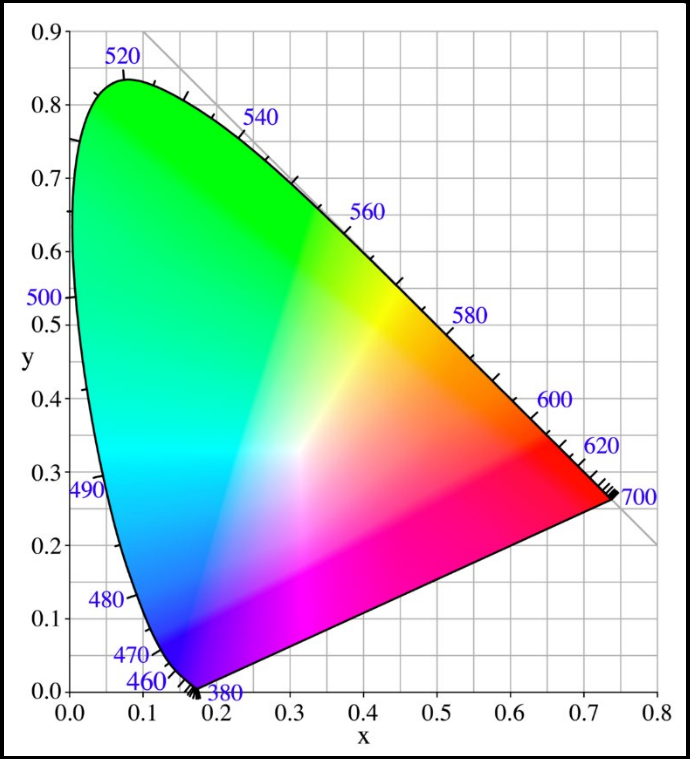
ProPhoto RGB



"One of the downsides to this color space is that approximately 13% of the representable colors are imaginary colors that do not exist and are not visible colors."

From Wikipedia, "ProPhoto RGB color space"

Summary



- Three types of cones: short, medium, long
- Three dimensional color space: RGB
- "Color matching functions": $\bar{r}, \bar{g}, \bar{b}$
- Alternate functions: $\bar{x}, \bar{y}, \bar{z}$
  - $\bar{y}$ = overall response
  - $\bar{z}$ is basically $\bar{b}$
  - $\bar{x}$ makes white light have equal parts
- Projections of spectrum: X,Y,Z values
- Normalized X,Y,Z values: x,y,z
- Chromaticity coordinates: x,y
- Chromaticity diagram
  - $\rightarrow$ Locus, gamut, linear effects, complementary colors, etc.
- Other ways to specify coordinate in 3d space:
  - x,y,Y; hue, saturation, Y; hue, brightness, saturation; sRGB coordinates; other color spaces