Introduction to Color Science: Additive Color for Computer Graphics

CS 465, Prof. Steve Marschner
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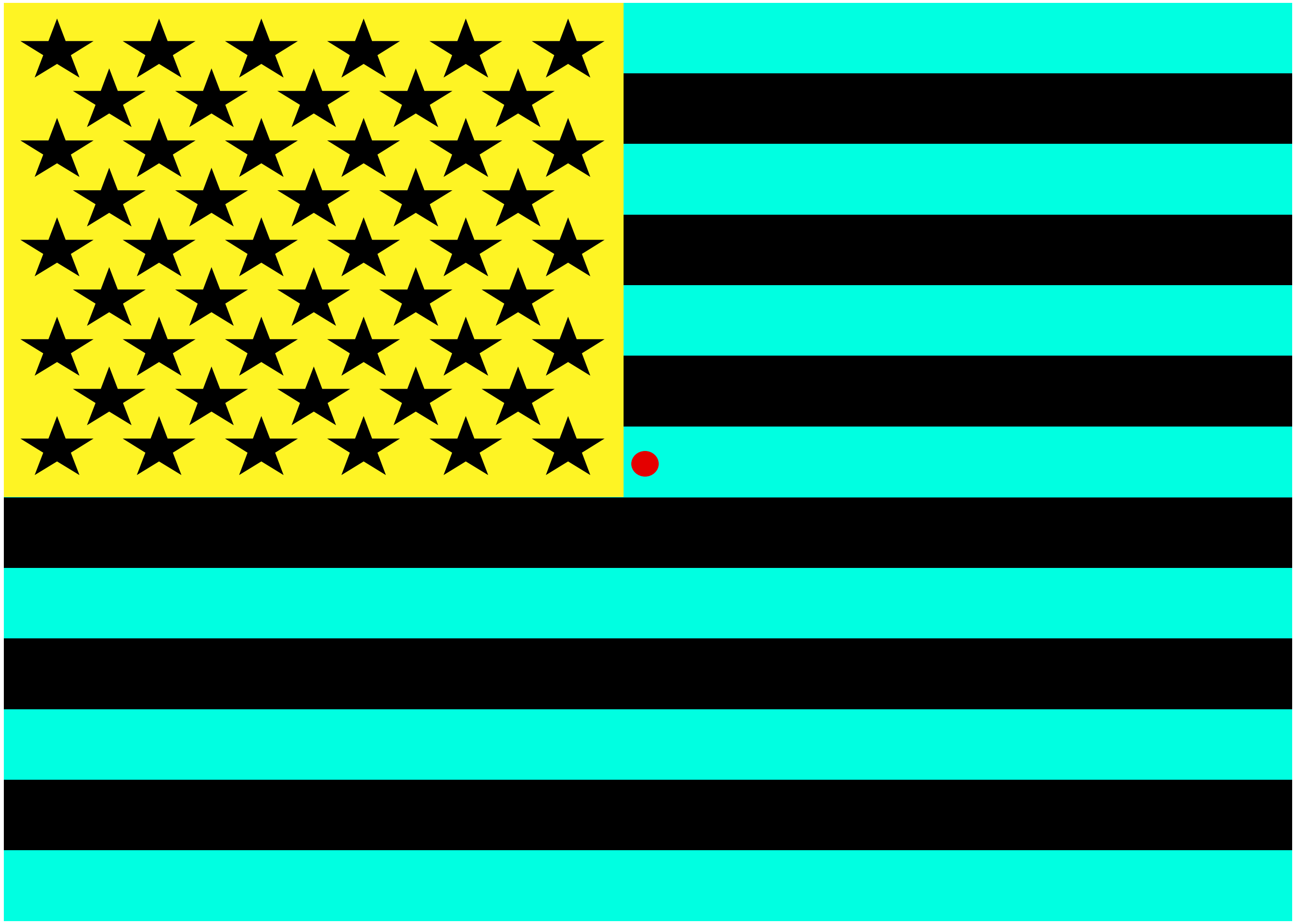
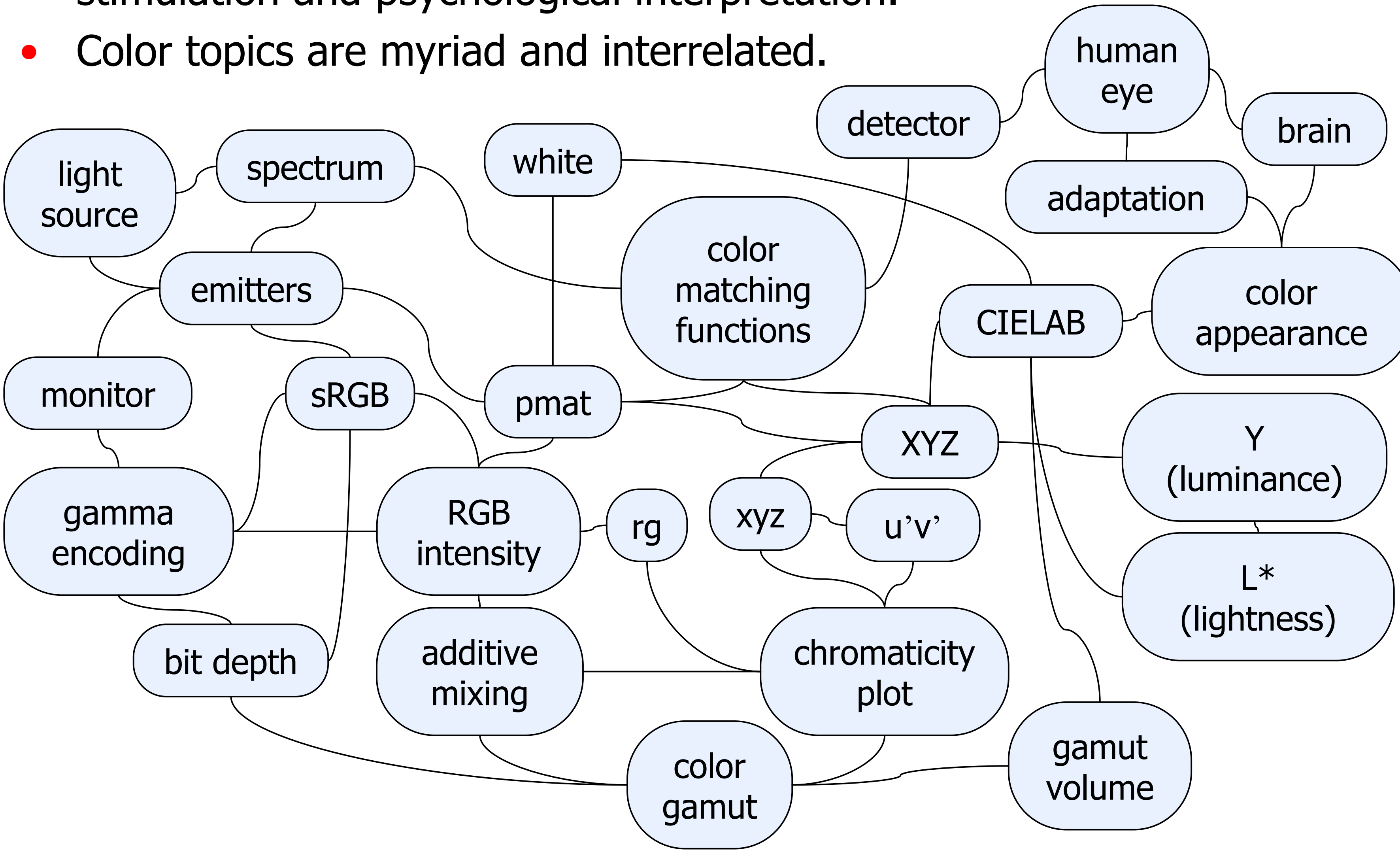
Eastman Kodak Company

Stare at the Red Dot.



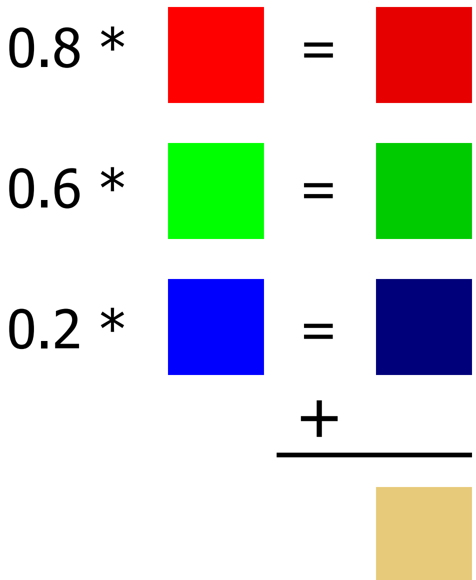
Color

- Color is a perception resulting from a combination of physical stimulation and psychological interpretation.
- Color topics are myriad and interrelated.



Additive RGB Intensity

- Primaries: Red , Green , and Blue
- A monitor is an additive system, meaning colors may be synthesized using **linear** combinations of the primaries.
- Example:



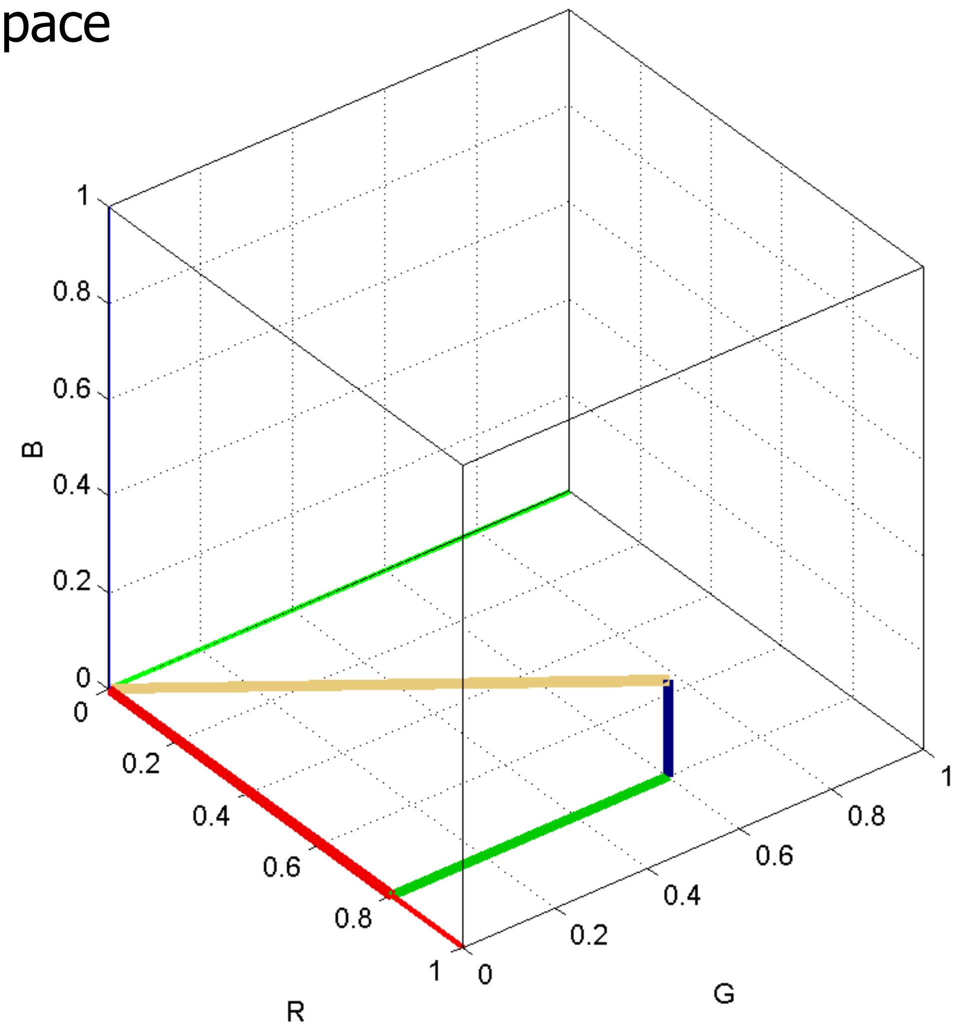
- Perhaps you recall that Code Values are **nonlinear**?
Using an sRGB monitor, linear intensity values (0.8, 0.6, 0.2) correspond to 8-bit nonlinear code values (231, 203, 124).

Additive Color Using Component Vectors

- In a 3-D (R,G,B) intensity space
  R unit vector is (1,0,0)
  G unit vector is (0,1,0)
  B unit vector is (0,0,1)

- 0.8 **R** + 0.6 **G** + 0.2 **B** = (0.8, 0.6, 0.2)

- Black is (0, 0, 0)
- White is (1, 1, 1)



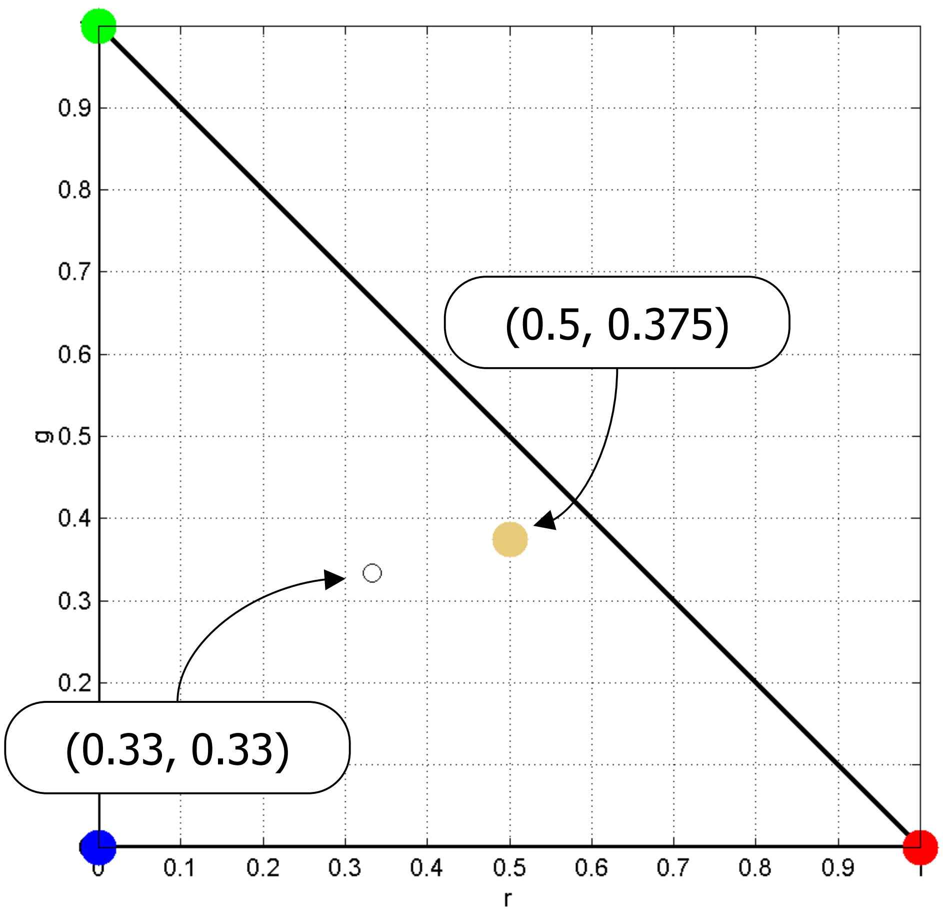
Chromaticity Diagram

- Chromaticity: how much of each primary, relative to the others.

  $r = R / (R+G+B)$

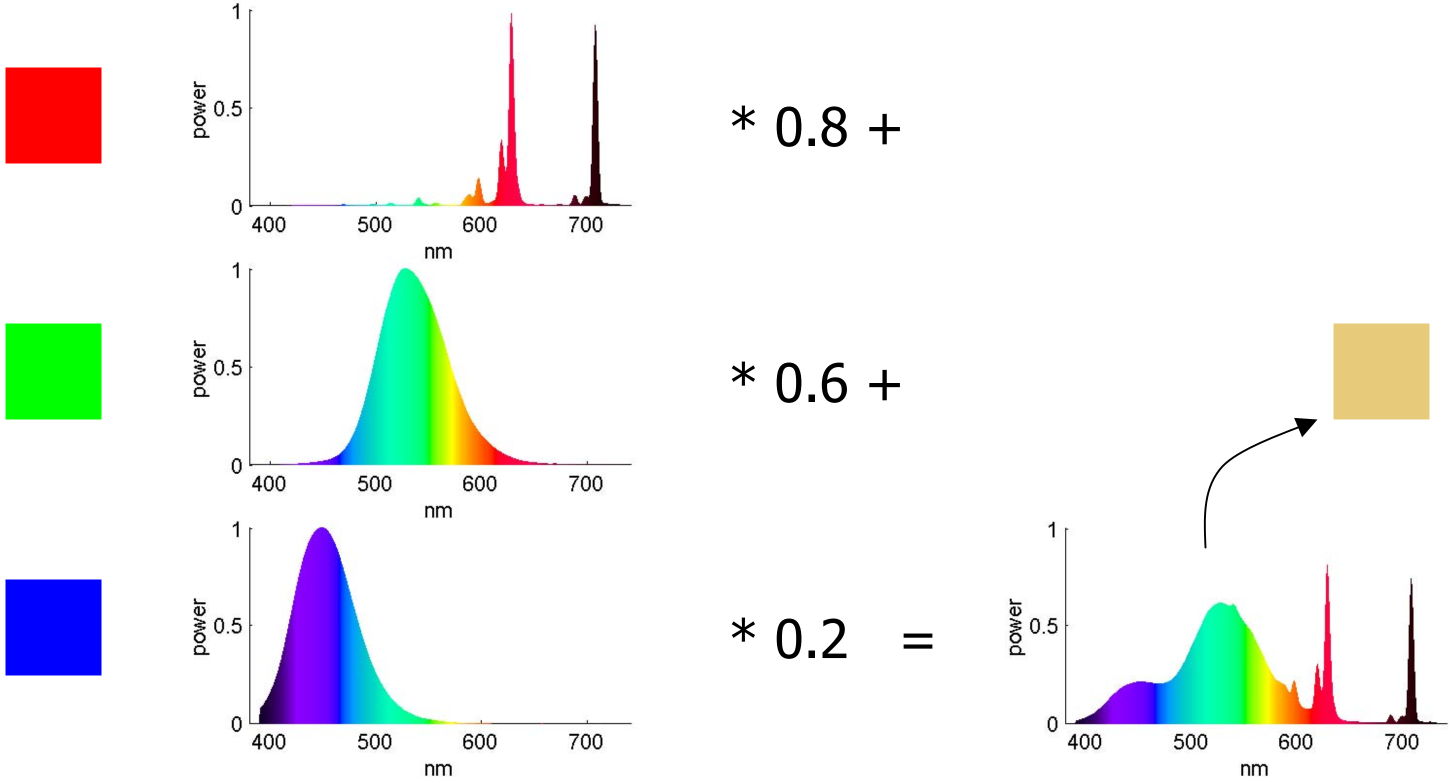
  $g = G / (R+G+B)$

  $b = 1 - r - g$
- Chromaticity is inherently 2-D, thus it has less information than RGB.
- Triangle connecting R, G, and B points is the Gamut Boundary, indicating the range of colors that may be synthesized.
- Additive colors found at the center of mass of primaries.
- White (R=G=B=1) means rg (0.333, 0.333)



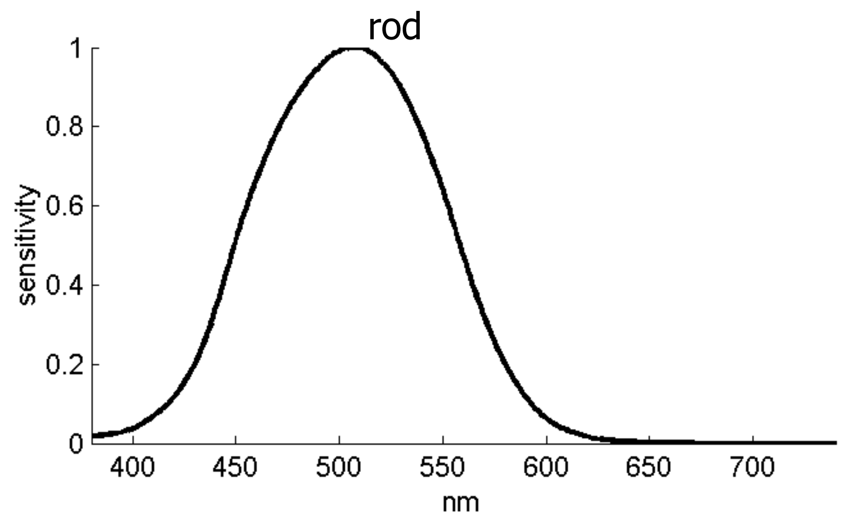
Additive Spectral Power

- Light may be described in terms of Spectral Power Distribution.
- Relative (or absolute) amount of power (i.e., photons, Watts/sr/m^2/nm) in each of a number of wavelength bands
- Discrete spectra may be thought of has unit vectors.
- Example: CRT monitor R, G, and B emission

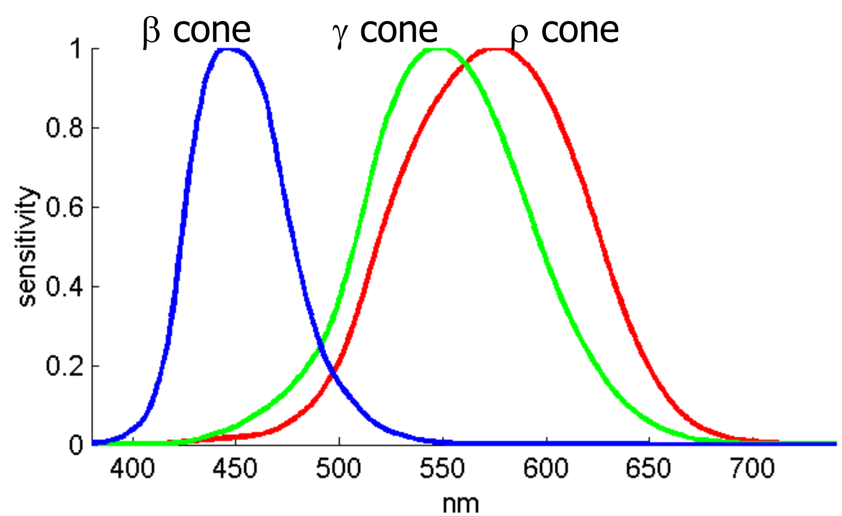


Human Eye Response

- Eyes have light-sensitive cells
- **Rods** (scotopic vision) work in low light levels, and see one band of the spectrum.
  (plot is approximate)
- Colors are not seen in low light.

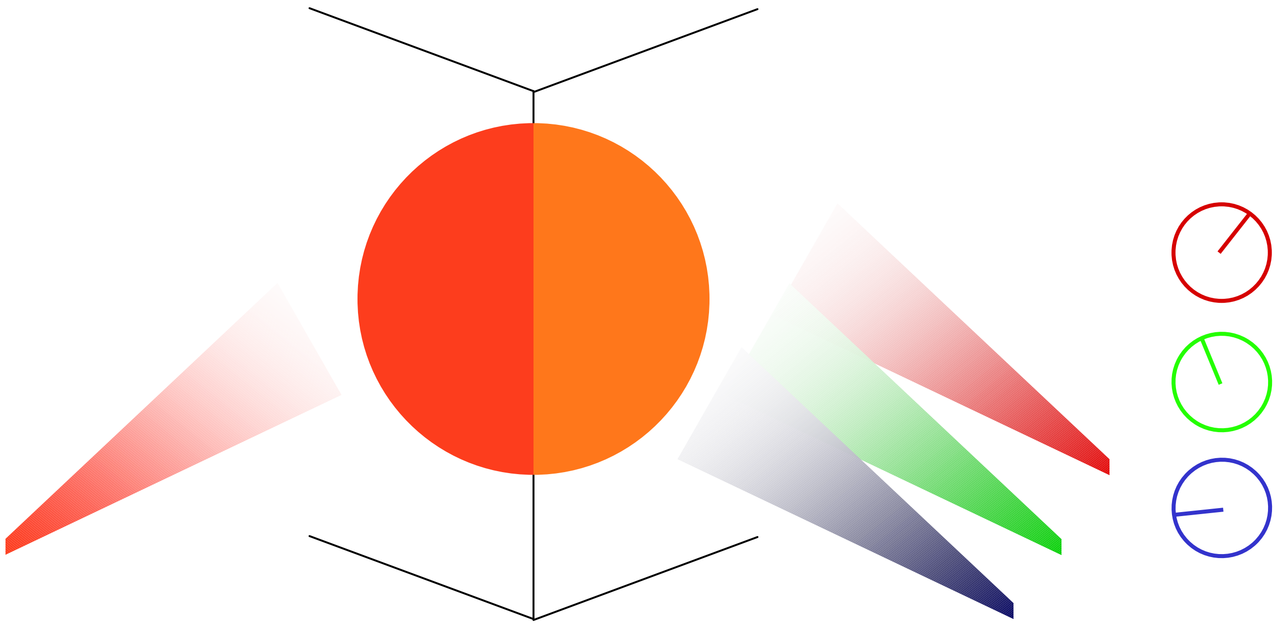


- **Cones** (photopic vision) work in high light levels.
- There are three types of cones (ρ, γ, β); each sees a different band of the spectrum.
- Colors are discerned by their relative power in each band.



1931 Color Matching Experiment

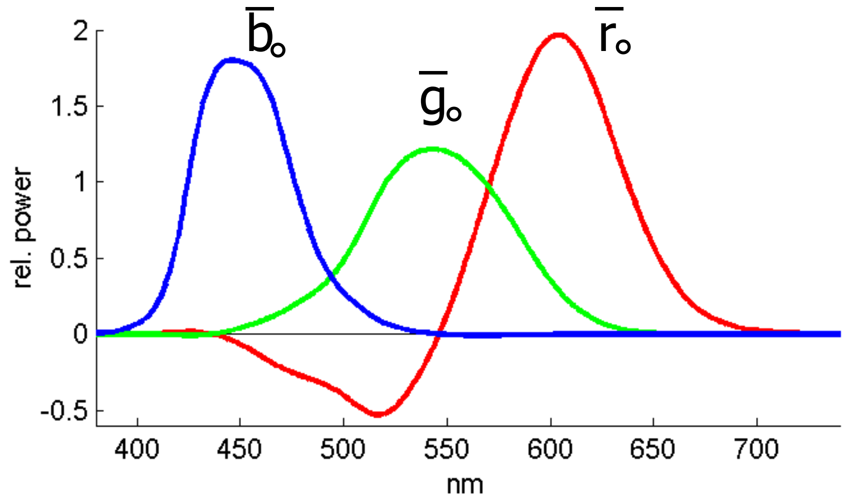
- Observers looked at monochromatic colors.
- They were asked to dial in additive mixtures of primary colors that appeared to match each monochromatic color. **Metamers!**



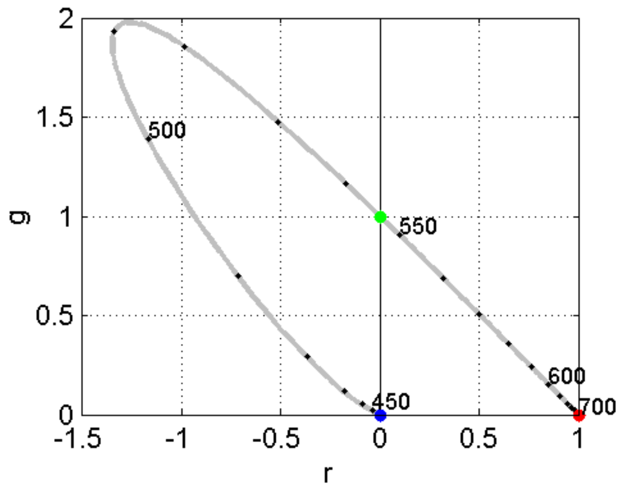
- Sometimes, the observer wanted a dial to go below zero! In this case, the primary was moved to the other side, like adding “negative light” to the monochrome color.

Color Matching Functions

- The plot shows the results of the 1931 color matching experiment: the relative amounts of R, G, and B to match each monochrome spectral color.



- The set of monochrome spectral colors (aka spectrum locus) is shown on an r,g chromaticity diagram.

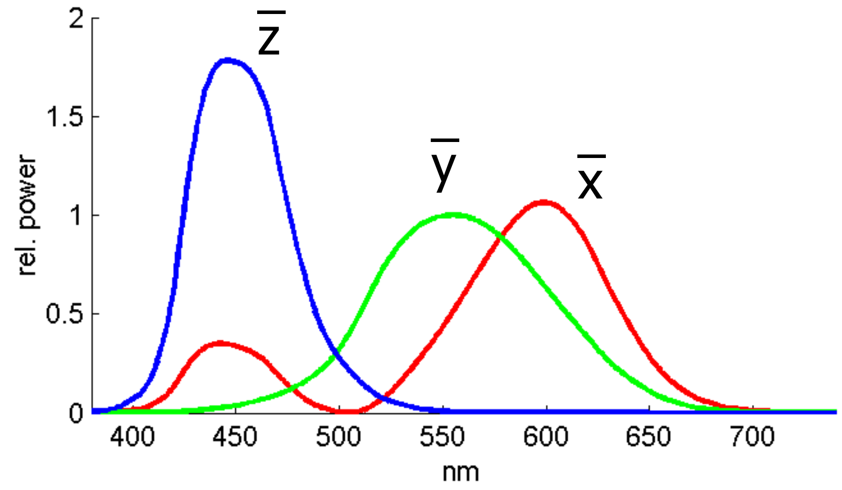


- Note how many colors have r < 0

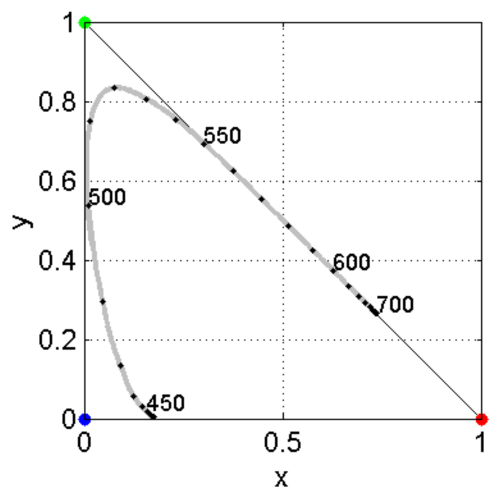
CIE (Commission Internationale de l'Eclairage) 1931 Color Matching Functions

- 1931 Standard Observer:

  The experimental color matching functions were transformed to this set of all-positive curves, called $\bar{x}$, $\bar{y}$, $\bar{z}$.
- $\bar{y}$ used to compute Luminance, Y.
- The "primaries," called X, Y, Z, corresponding to these curves are imaginary! Meaning they can't physically be made.



- The CIE 1931 xy Chromaticity Diagram
- Note that the spectrum locus fits inside the XYZ triangle.



CIE Colorimetry: $\bar{x}\ \bar{y}\ \bar{z}$, XYZ , xyz

- XYZ tristimulus values are computed from a spectral power distribution $\Phi(\lambda)$ and the three color matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$.

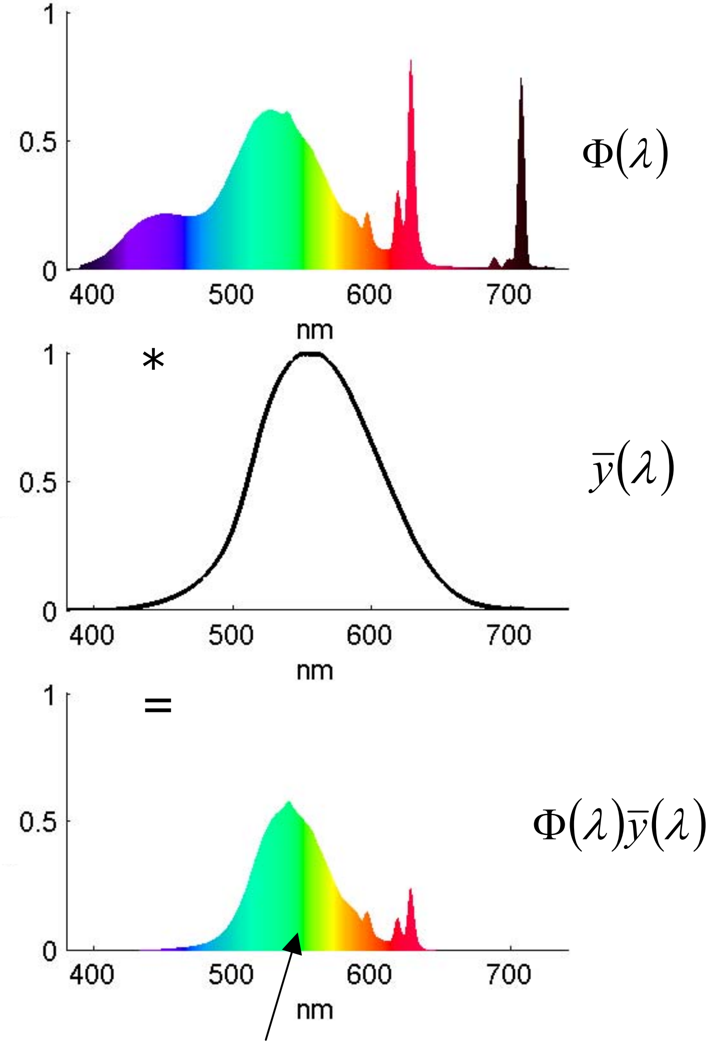
$$X = k\sum \Phi(\lambda)\bar{x}(\lambda)\Delta\lambda$$
$$Y = k\sum \Phi(\lambda)\bar{y}(\lambda)\Delta\lambda$$
$$Z = k\sum \Phi(\lambda)\bar{z}(\lambda)\Delta\lambda$$

- Two colors with same XYZ are Metamers.
- k often chosen so white Y = 100.
- xyz chromaticity values are computed from XYZ tristimulus values.

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = 1 - x - y$$

- xyY often used, because z is redundant.

Example: Y, using $\bar{y}$



Y is area under this curve

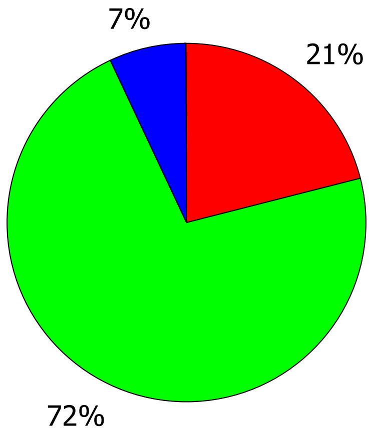
Balancing RGB to Synthesize White

- White is a sum of 3 primaries.
- Example, sRGB, a standard set of RGB primaries

	X	Y	Z
R	41	21	2
G	36	72	12
B	18	7	95
Sum	95	100	109

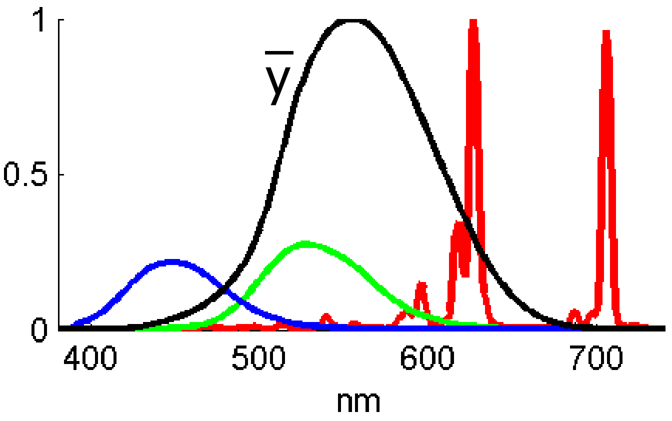
D65 Standard White

Luminance Contribution:

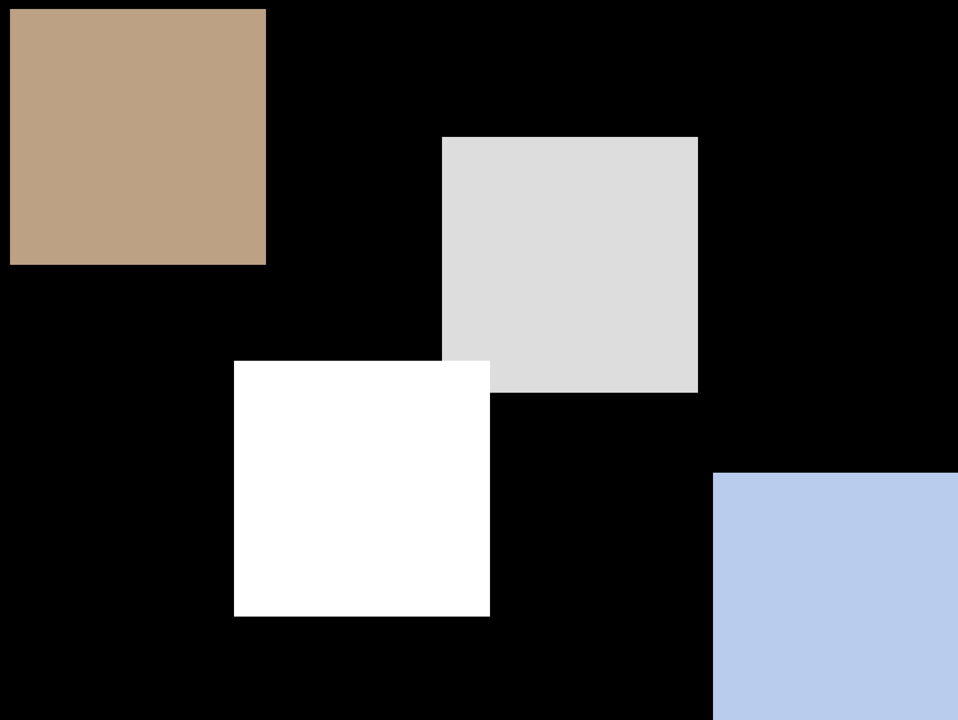


- White is a perceptual label.
  - Must be “achromatic”
  - Must be “bright”
  - Depends on surroundings

RGB Power Spectra Scaled to Add to D65 White



What is White?



Primary Matrix (RGB to XYZ)

- Need to mathematically predict XYZ tristimulus values resulting from a set of RGB values
- Enter the Primary Matrix, aka Pmat, aka Phosphor Matrix
- Example for sRGB primaries & D65 white

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 41.2 & 35.8 & 18.0 \\ 21.3 & 71.5 & 7.22 \\ 1.93 & 11.9 & 95.0 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

← Note the relationship

	X	Y	Z
R	41	21	2
G	36	72	12
B	18	7	95

- Invert the 3×3 Pmat to compute RGBs required to attain desired XYZ.
- Think of RGB and XYZ as different Primary sets.
- An inverse and forward Pmat from different RGB Primary sets may be combined to transform from one set of RGB to another.

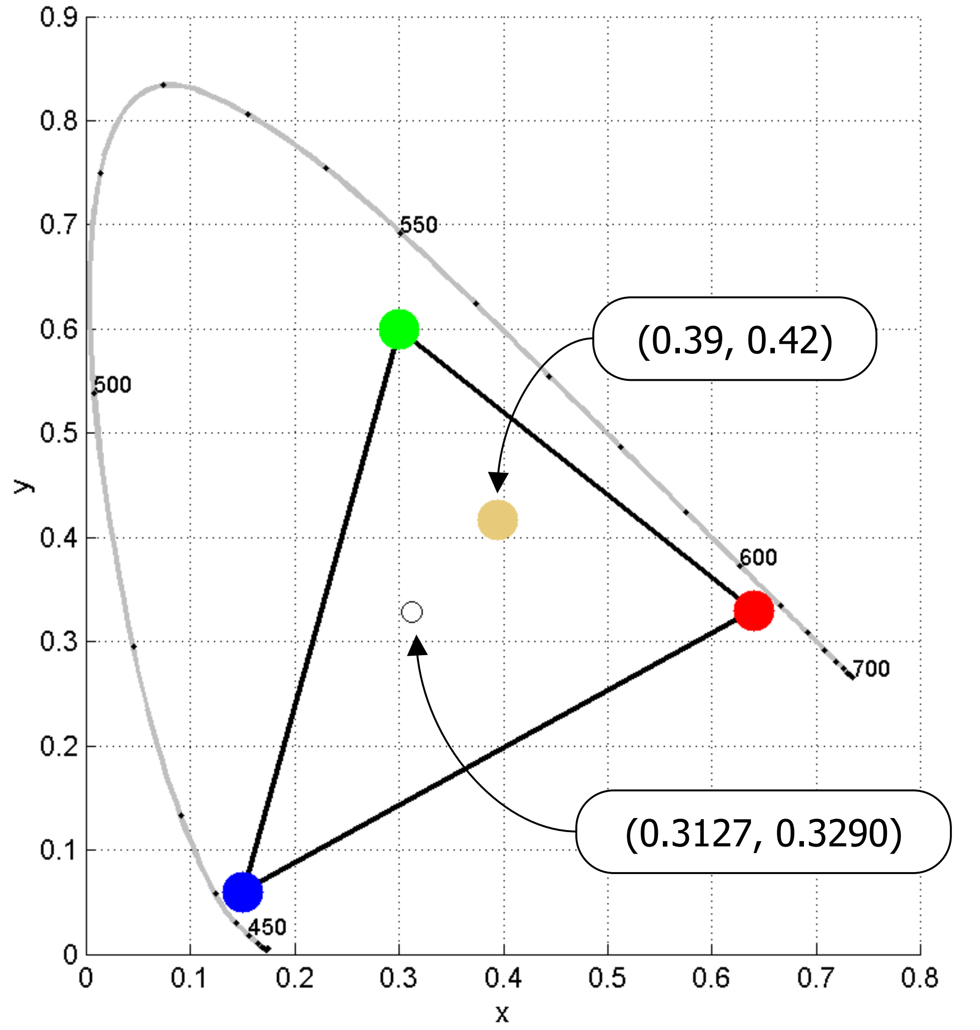
$$\begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} = \mathbf{P}_2 \mathbf{P}_1^{-1} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

CIE 1931 xy Chromaticity Diagram

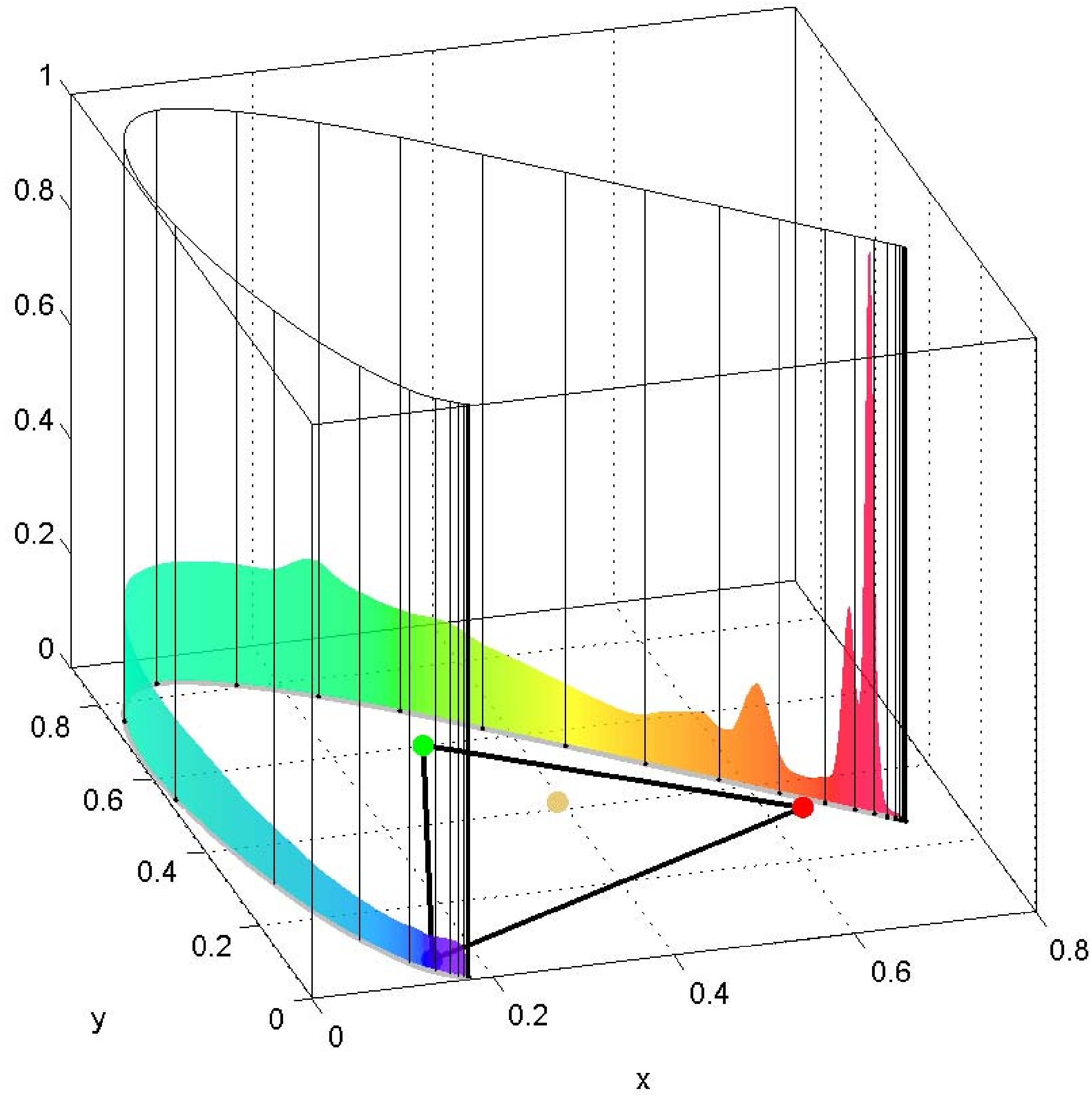
- sRGB primaries' xy chromaticities

	x	y
R	0.6400	0.3300
G	0.3000	0.6000
B	0.1500	0.0600
White	0.3127	0.3290

- Triangle is sRGB gamut boundary.
- sRGB standard white point has chromaticities equal to CIE Standard Illuminant D65.
- Addition via Center of Mass



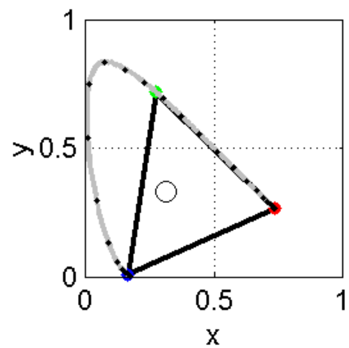
Chromaticity Diagram: Conceptualizing a Spectrum

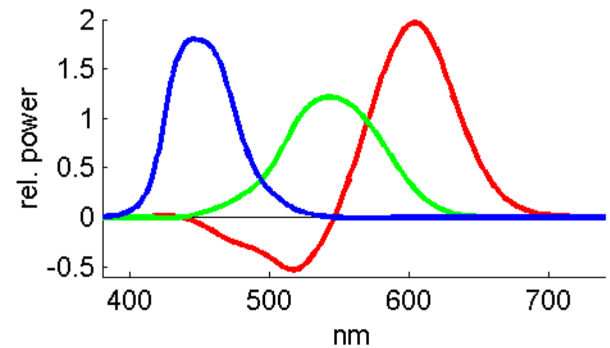


Primaries and Color Matching Functions

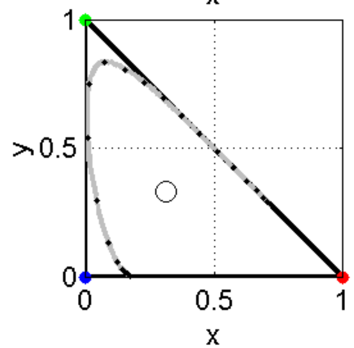
- Each set of primaries has a corresponding set of color matching functions

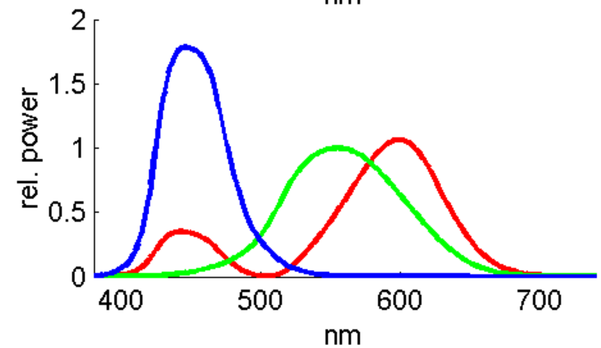
- 1931 Color-Matching Primaries



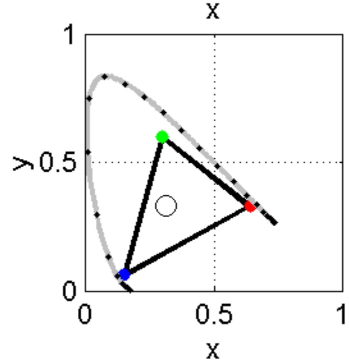


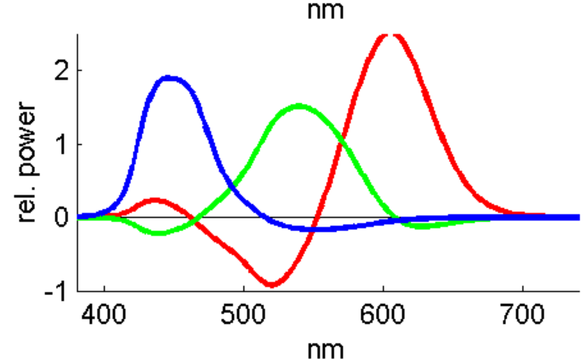
- XYZ





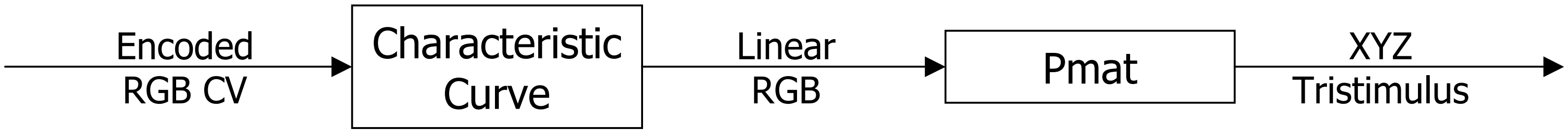
- sRGB

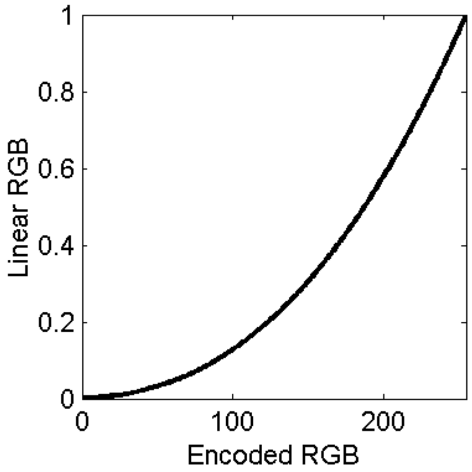




RGB Implies a System Model: Example sRGB

- Pmat is only half the story. A real system has a Characteristic Curve, recalling the nonlinearity between Code Value and Luminance.
- sRGB is an encoding standard based on an idealized monitor/TV.
  - sRGB (ITU-R Rec 709) Primaries (same as HDTV)
  - Gamma 2.2-like Characteristic Curve
- The model is simple.





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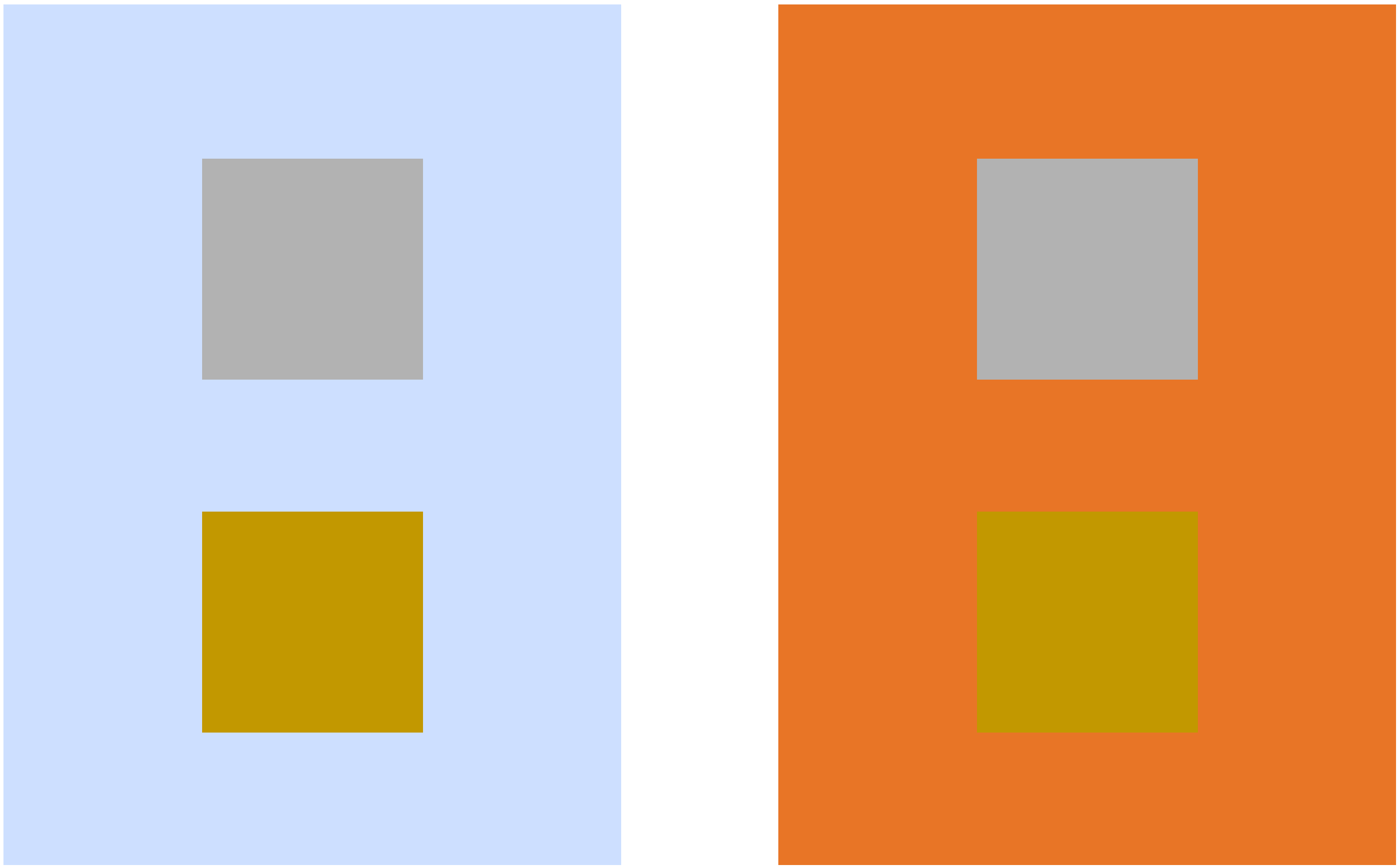
Color Appearance

- Color is perceived, not measured.
- XYZ is useful for quantifying color stimuli and measuring how well they match one another.
- BUT, the appearance of a stimulus as a color depends on (among other things)
  - Absolute luminance of the stimulus
  - Surrounding color(s)
  - State of adaptation of the observer
- Predicting color appearance is difficult, especially in images.

Example: Surround Effects

- The appearance of colors can be influenced by their surroundings.



References & Further Reading

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- Giorgianni, E., and Madden, T., *Digital Color Management: Encoding Solutions*. Addison-Wesley, 1998. (out of print!)
- Berns, R.S., *Billmeyer and Saltzman's Principles of Color Technology, 3ed*. Wiley-Interscience, 2000.