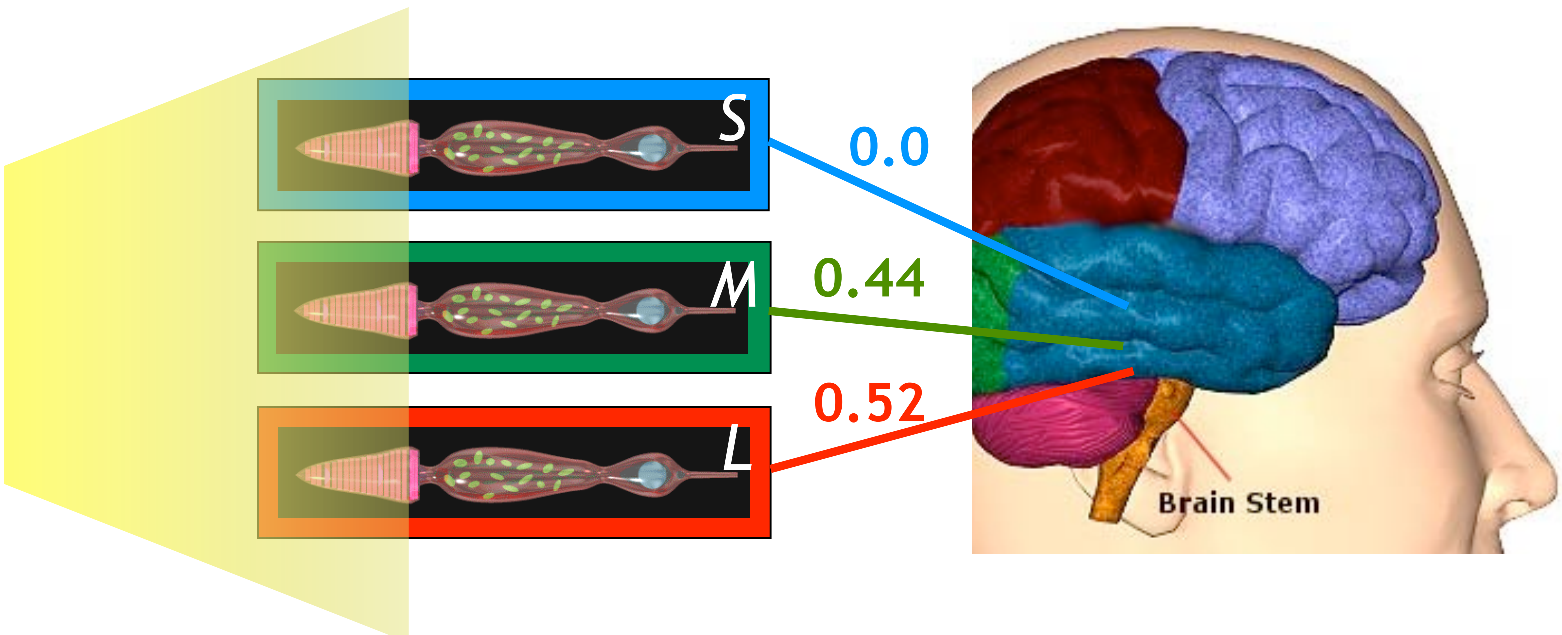
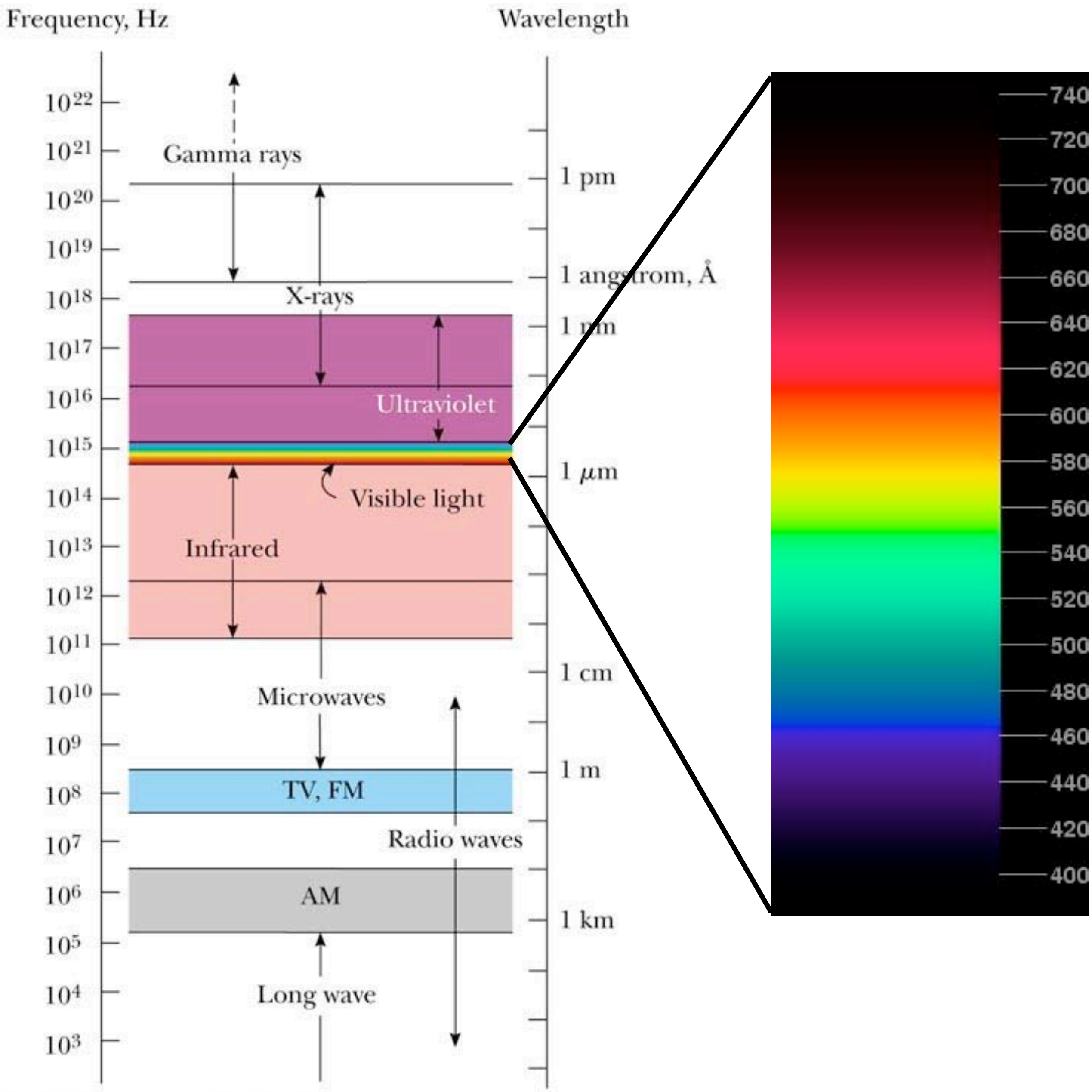
Color vision and representation



Mark Rzchowski

Physics Department



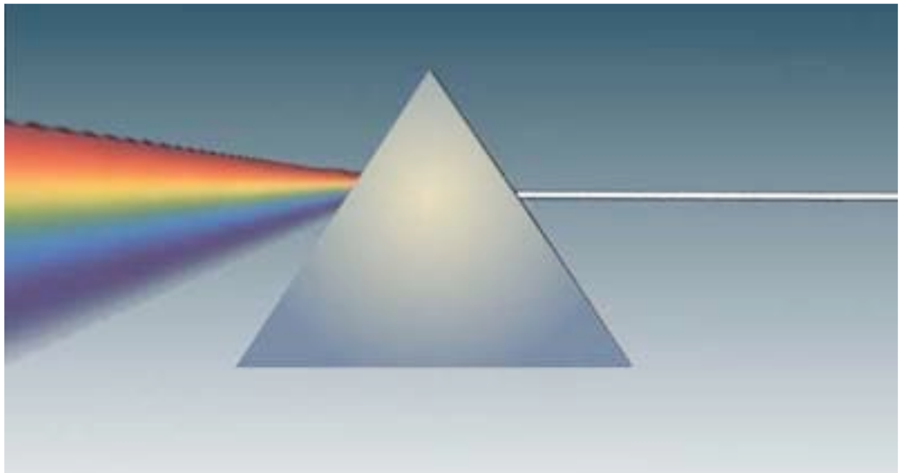
- Eye perceives different wavelengths as different colors.
- Sensitive only to 400nm - 700 nm range
- Narrow piece of the entire electromagnetic spectrum.

Comparing Sound and Light

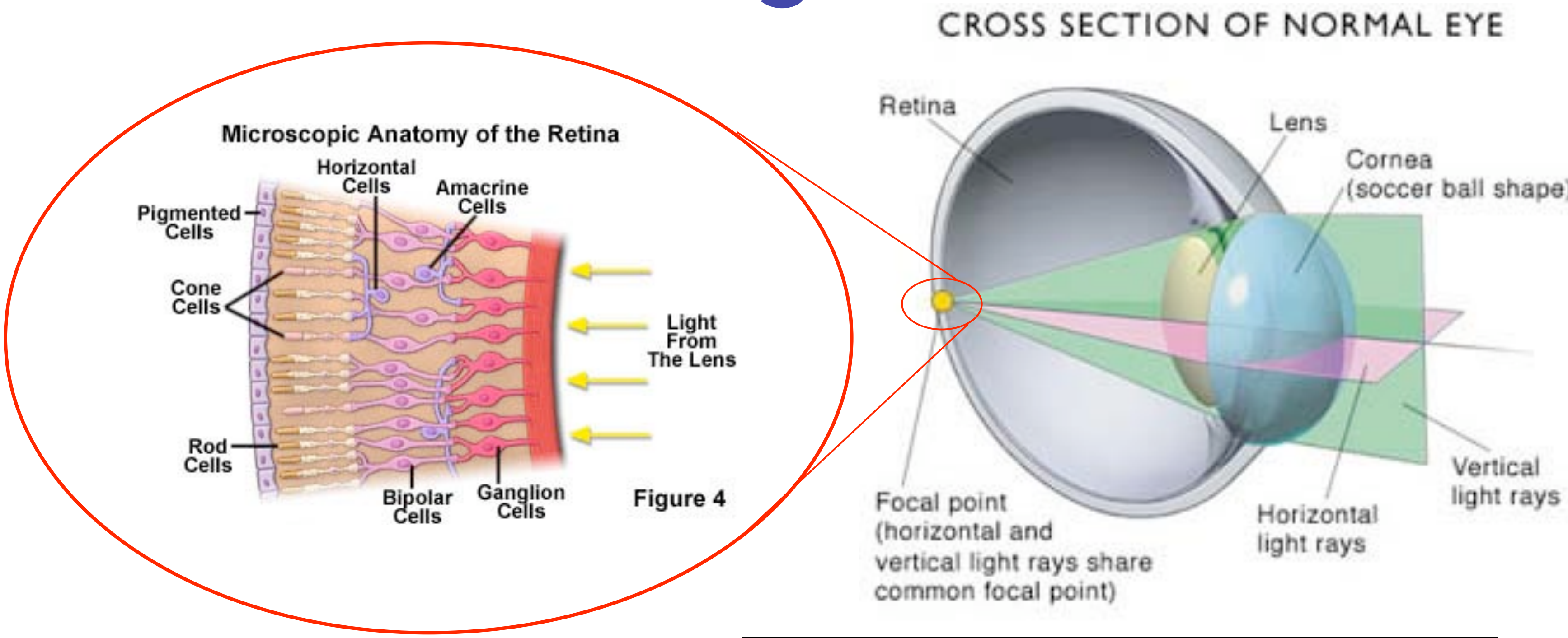
- Eye sensitive to 400 nm to 700 nm.
  - Not even a factor of 2
  - In terms of sound, less than one octave
  - If our ears had only this range, variety of sounds, instrumental, etc, would be almost nothing.
  - Ear response to sound covers factor of 1000
    - 20 Hz to 20,000 Hz
- Ear characterizes sound in a variety of ways
  - Pitch, timbre, dynamics, duration
- Eye characterizes light only as
  - Color
  - Intensity
- Partially due to eye's narrow range of wavelength sensitivity.

White light is a superposition

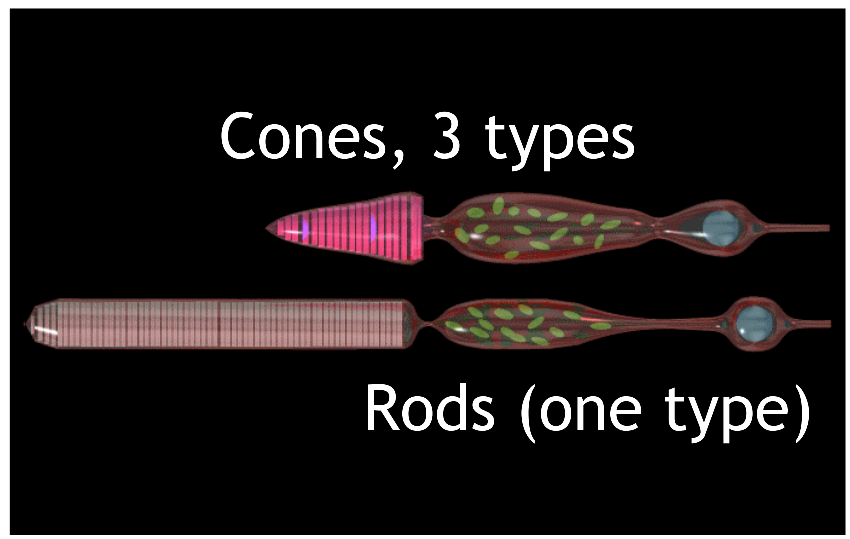
- Prism can separate the superposition into it's constituents.
- For example, 'white' light is an almost equal superposition of all visible wavelengths (as well a invisible ones!)
- This is a simple analyzer to 'deconstruct' a superposition of light waves (how much of each wavelength is present in the light).



Seeing colors

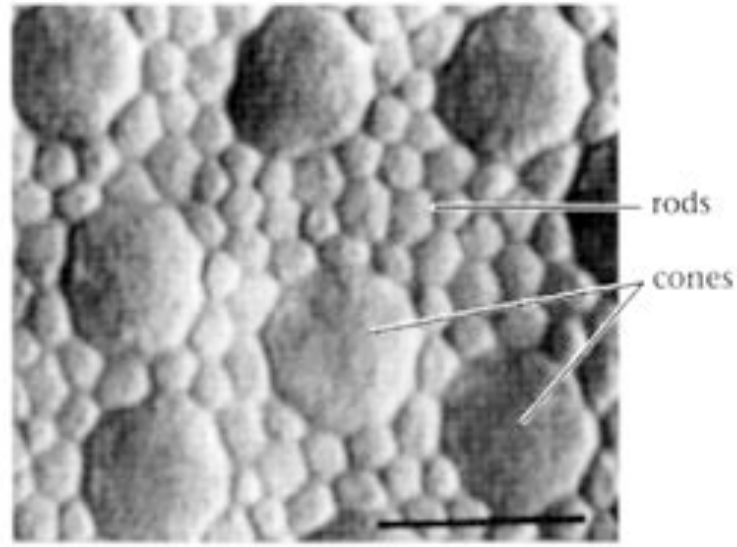


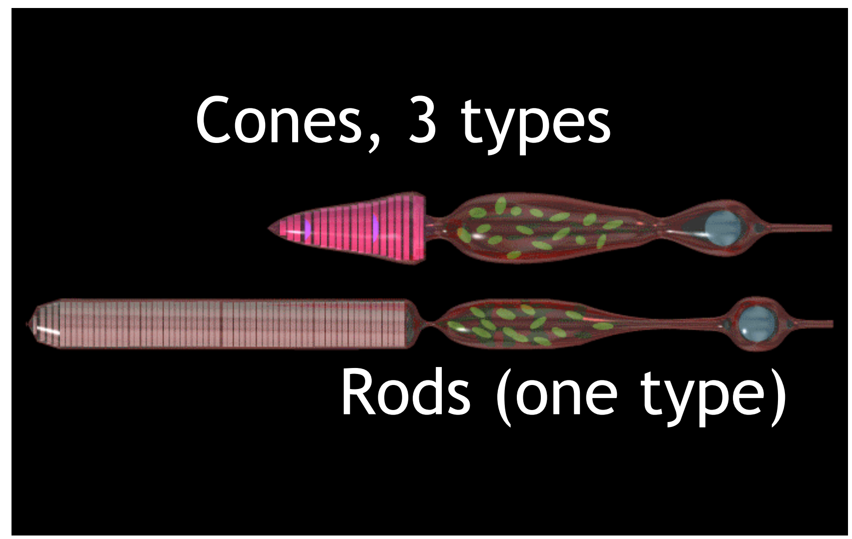
- Rods and cones send impulses to brain when they absorb light.
- Brain processes into color information.



Rods and cones

- Rods are responsible for vision at low light levels. No color sensitivity
- Cones are active at higher light levels
- The central fovea is populated only by cones.
- 3 types of cones
  - short-wavelength sensitive cones (S)
  - middle-wavelength sensitive cones (M)
  - long-wavelength sensitive cones (L)





Eye sensitivity

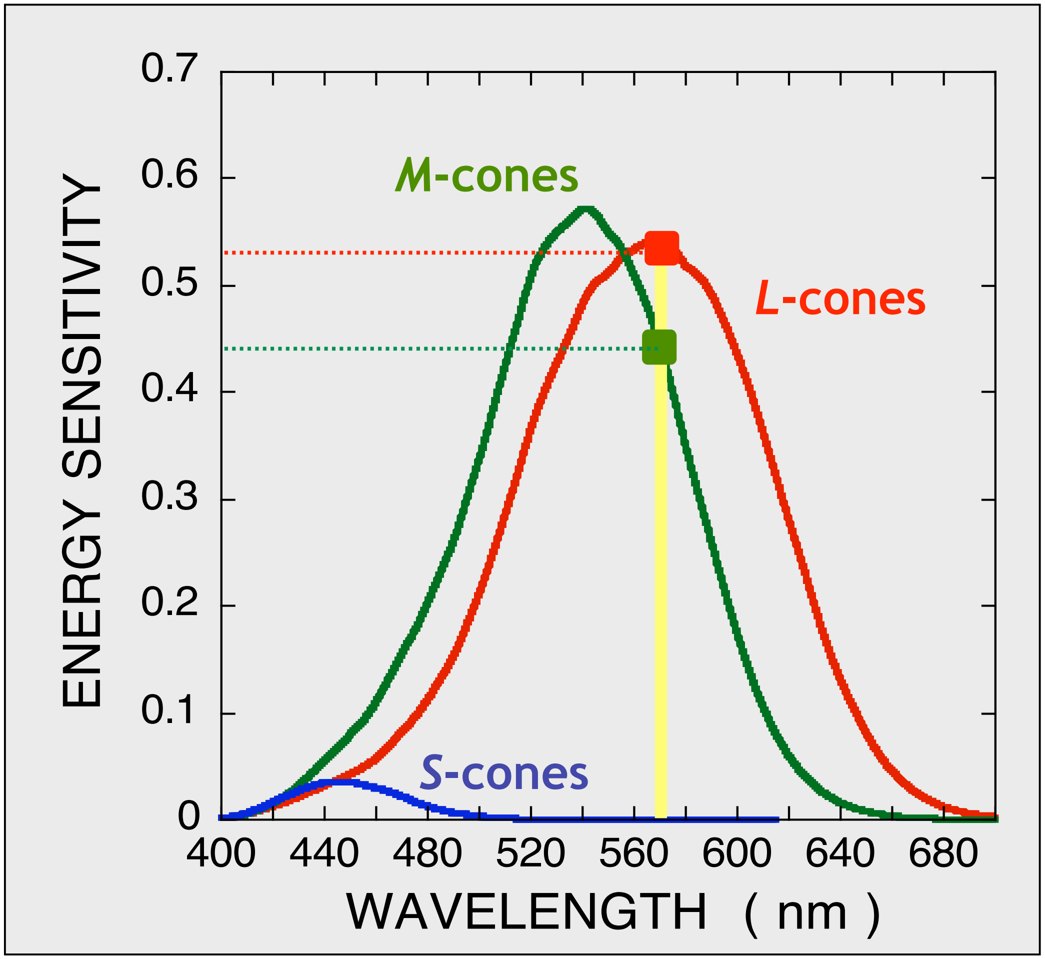
- Eye's wavelength sensitivity by cone type.
- Sensitivities overlap.

For instance, pure yellow (single wavelength of 570 nm) stimulates both *M* and *L* cones.

M-cone: 0.44

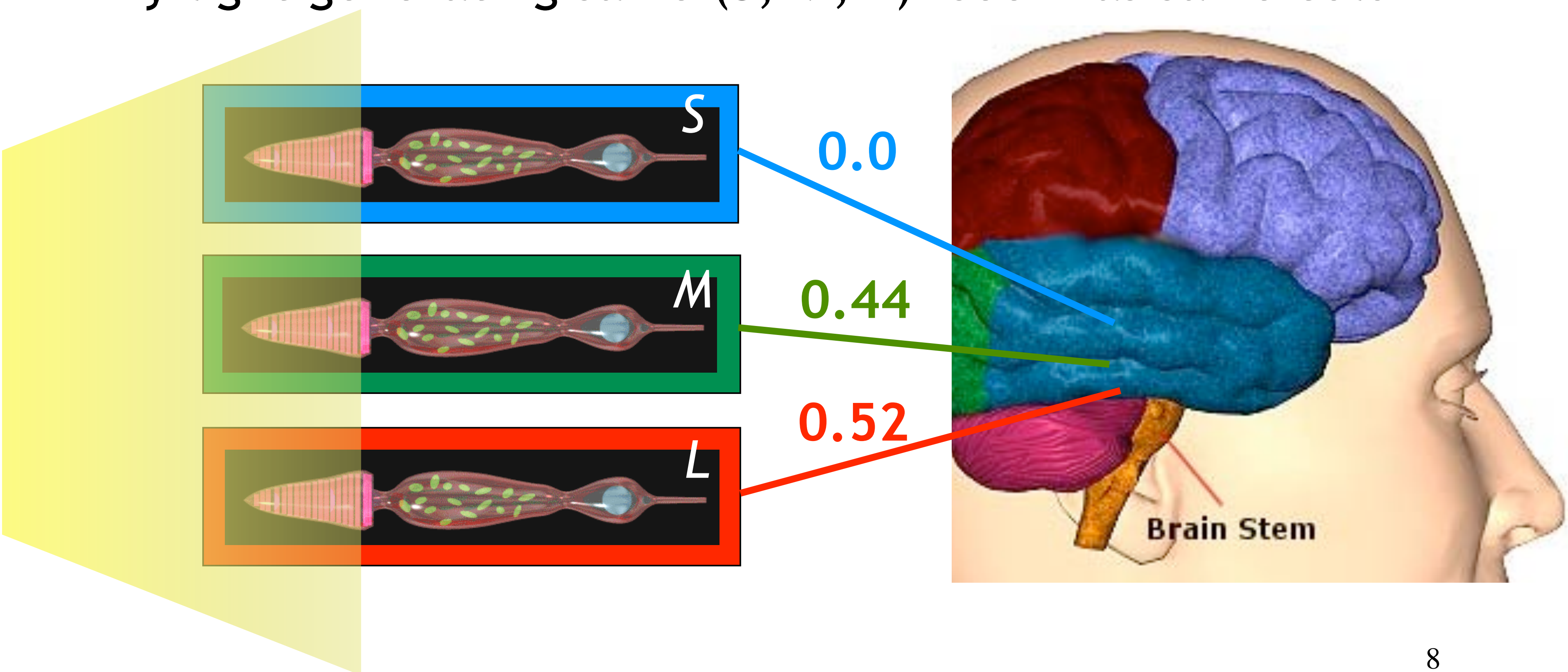
L-cone: 0.52

S-cone: 0



Interpreting colors

- Each cone sends a signal
  in relation to its degree of stimulation
- A triplet of information (*S*, *M*, *L*) is conveyed.
- Brain uses this information to assign a color
- Any light generating same (*S*, *M*, *L*) 'seen' as same color



Red + Green = ?

- Combined Green + Red

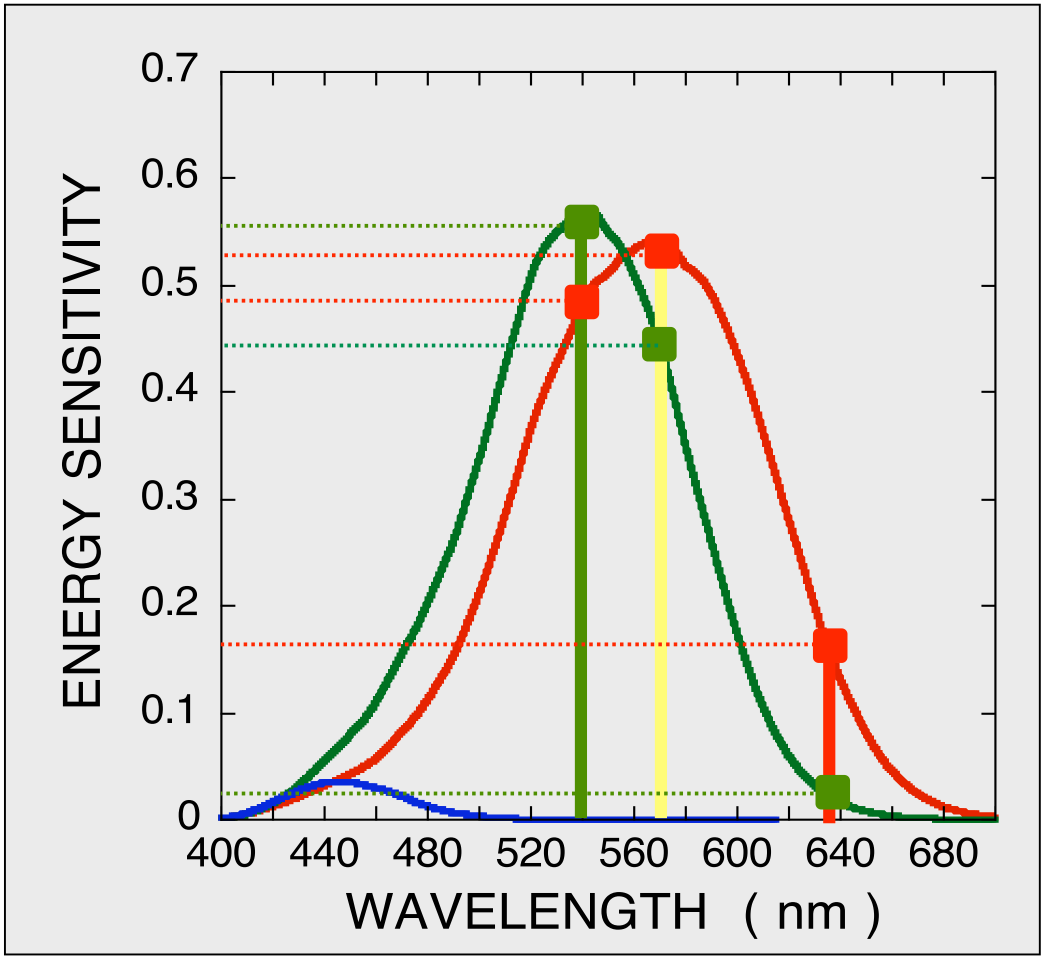
Total *M*-cone stimulus
= 0.55+0.02 = 0.57

Total *L*-cone stimulus
= 0.49+0.17=0.66

Reducing the intensity slightly (by 1.25) gives

(S, M, L)=(0,0.45,0.52)

Compare to spectrally pure yellow
(S, M, L)=(0,0.44,0.52)



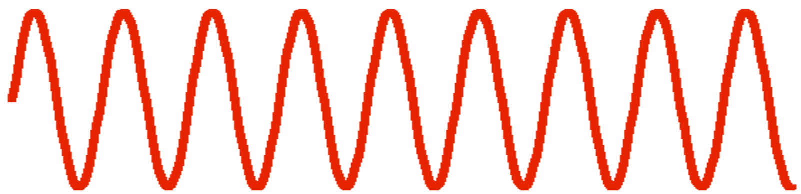
Color metamers

- Eye-brain machine does not discriminate particularly well.
- Spectrally pure yellow is exactly same color as **combination** of spectrally pure red and green.
- Such pairs of different waveforms that appear as the same color are called color metamers.

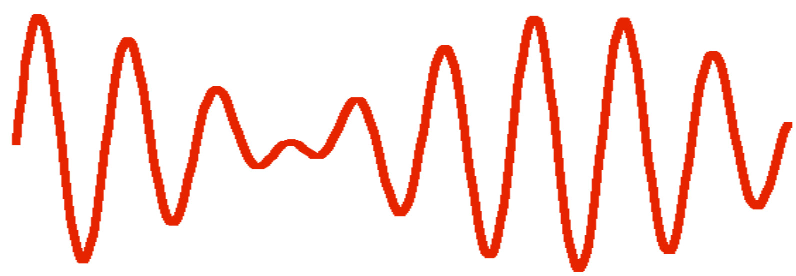
Compare waveforms

- Just said that the eye-brain system interprets some combinations identically.
- Spectral yellow is a pure color with a wavelength of 570 nm.
- But mixture red+green is indistinguishable

570 nm (yellow)



540 nm (green) +
635 nm (red)



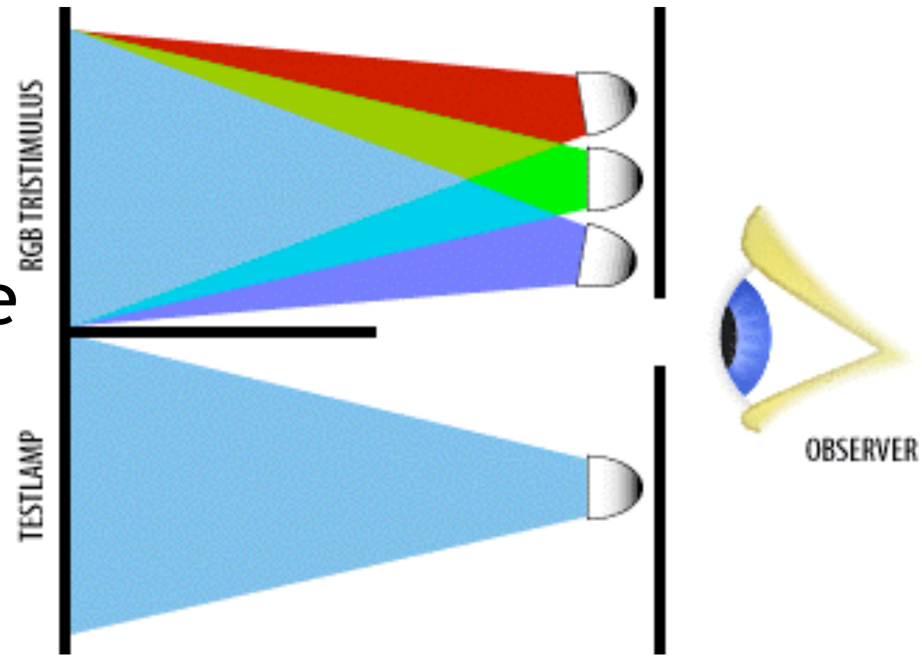
Mixing colors

- Suggests that as far as brain is concerned, entire range of colors can be represented as a mixture of small number of **primary** colors.
- Which primaries should we mix?
- How many primary colors do we need?

Trichromacy

Pioneered by Maxwell, who developed theory of electromagnetism.

- Color interpretation of almost any waveform reproduced with a mixture (addition) of three ***primary*** waveforms (colors).
- Most people make the same matches.



Color matching experiment

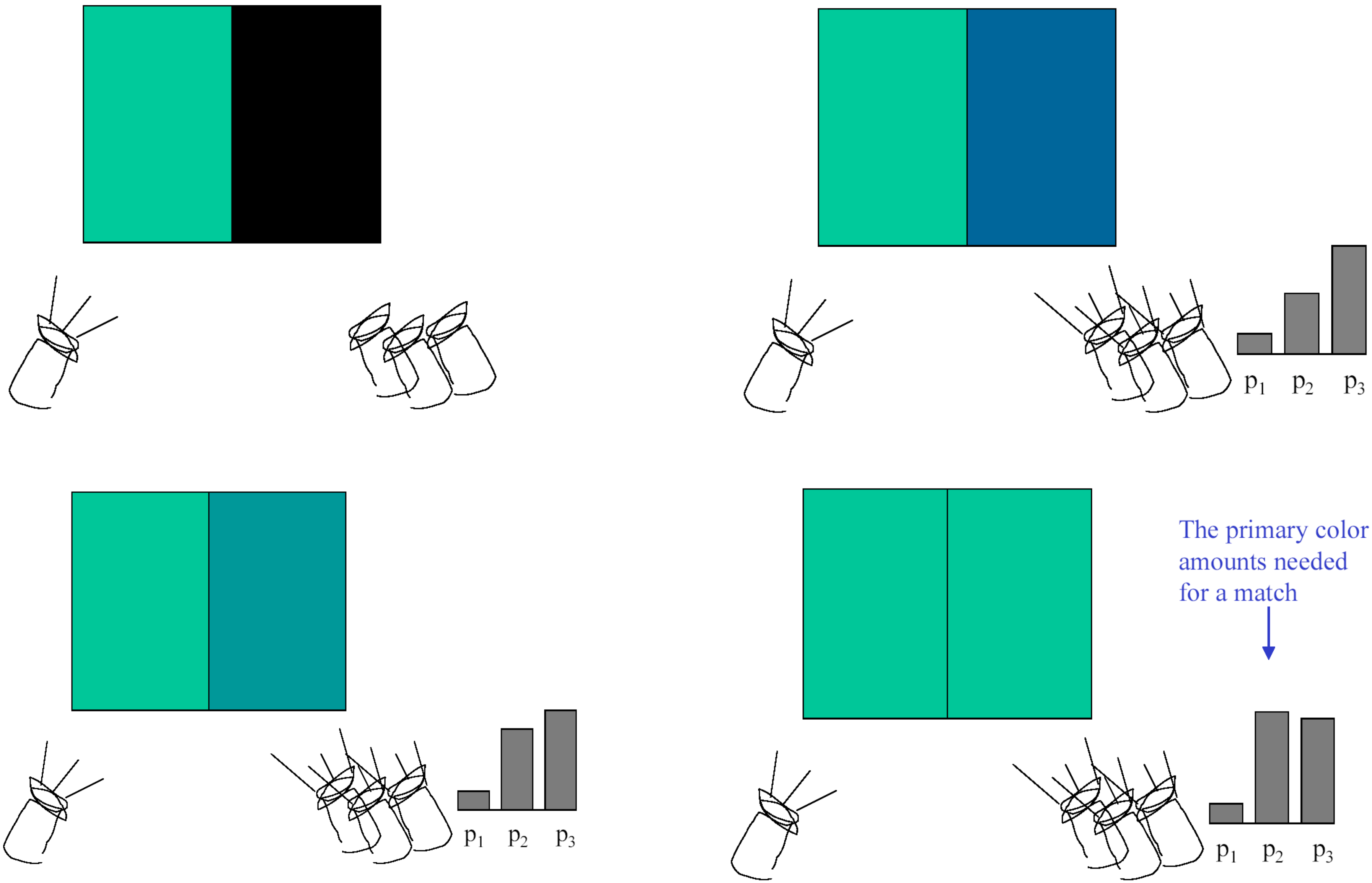


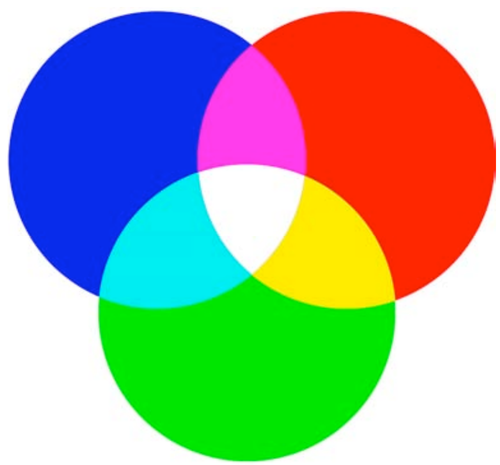
Image courtesy Bill Freeman

Additive color mixing

Almost all colors can be produced
by a mixture of **three primary colors**

Primary colors:
1) One primary cannot be matched
by a mixture of the other two
2) Often chosen to produce white
when all three combined in equal amounts

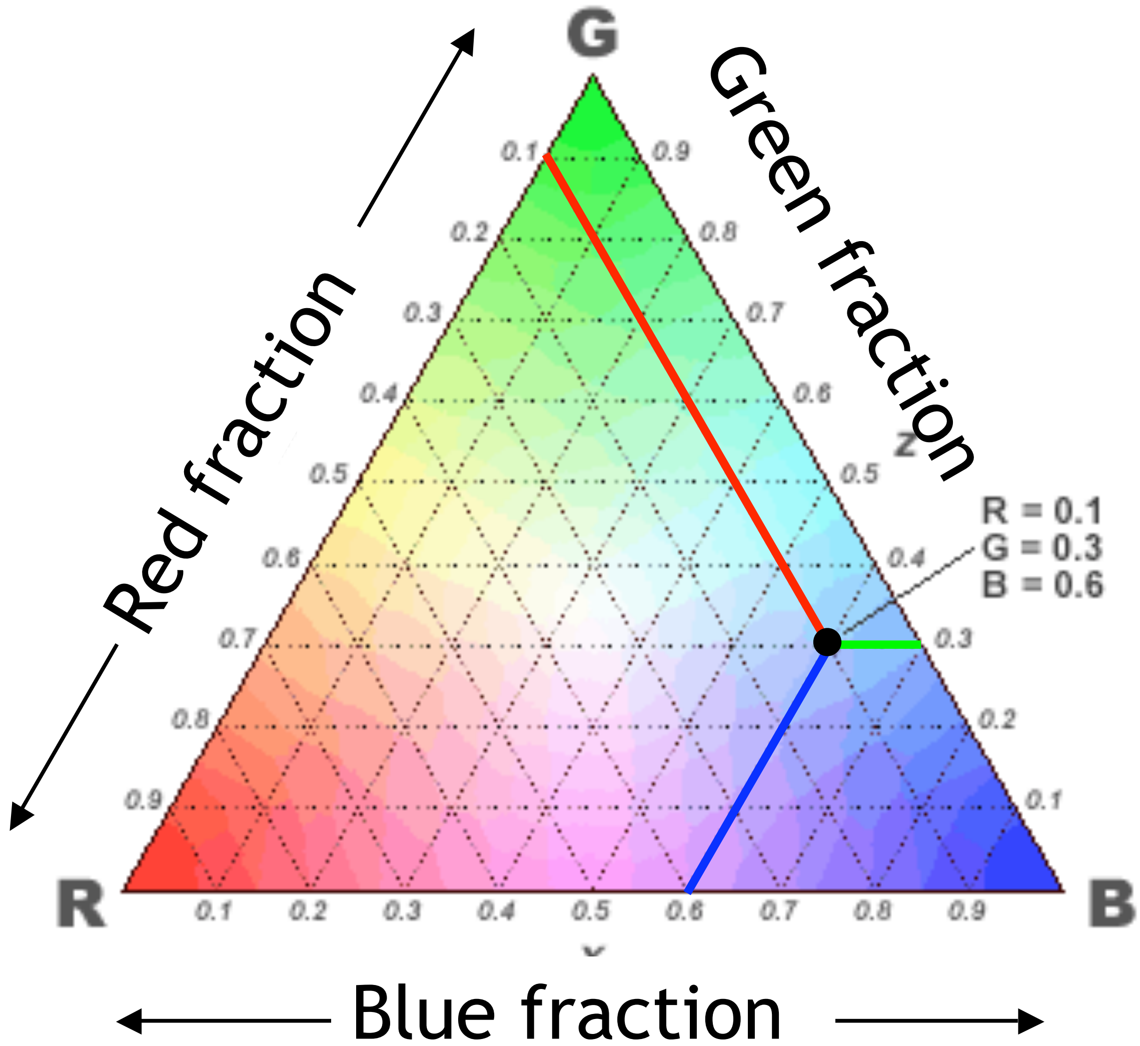
Common primaries:
red green blue



although others could be used

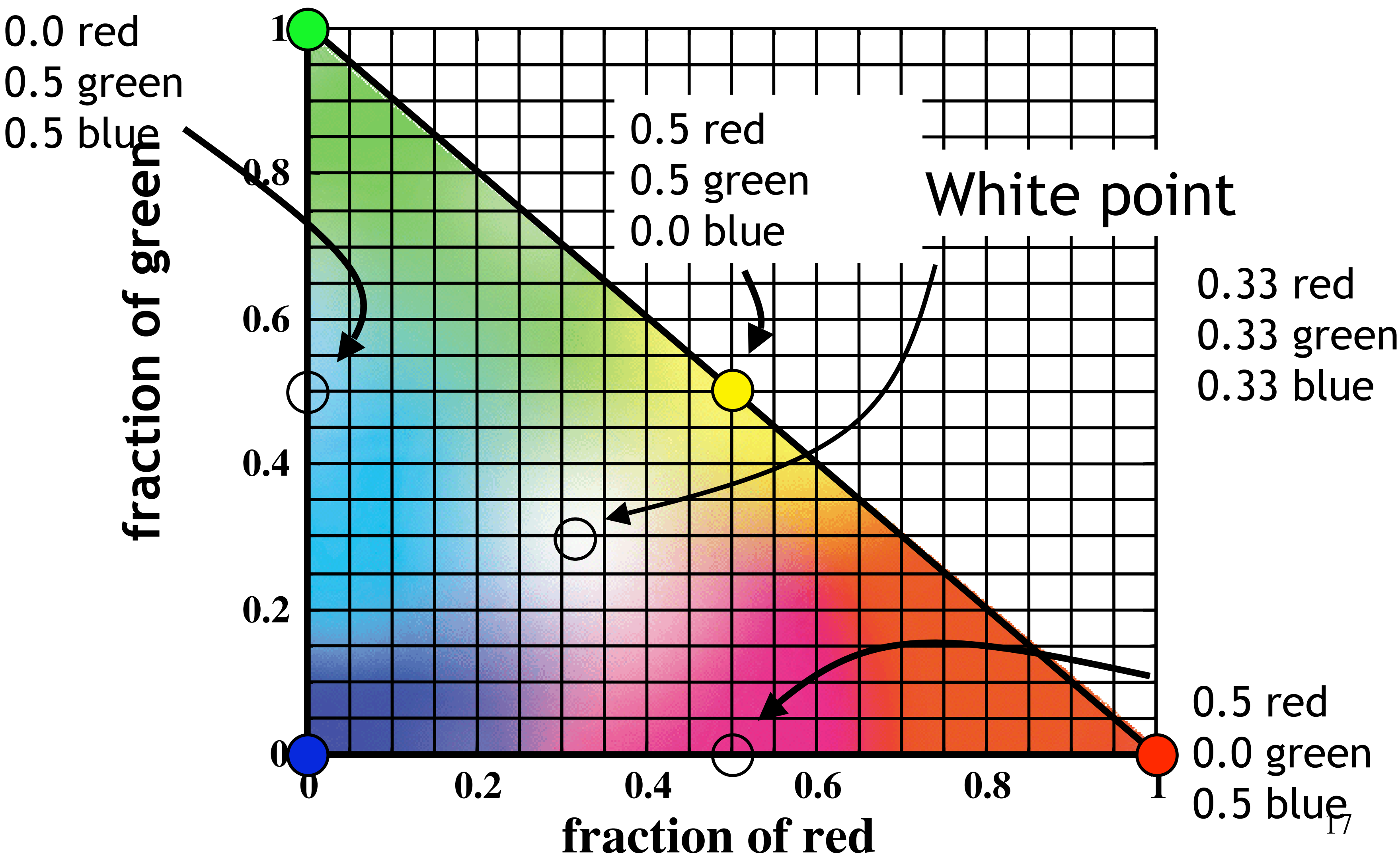
Maxwell color triangle

- Arrange colors so that they correctly represent fractional mixing along edges of triangle.
- Interior points are colors obtained by mixing appropriate fractions.
- $R+G+B=1$, so only color is indicated, not brightness.

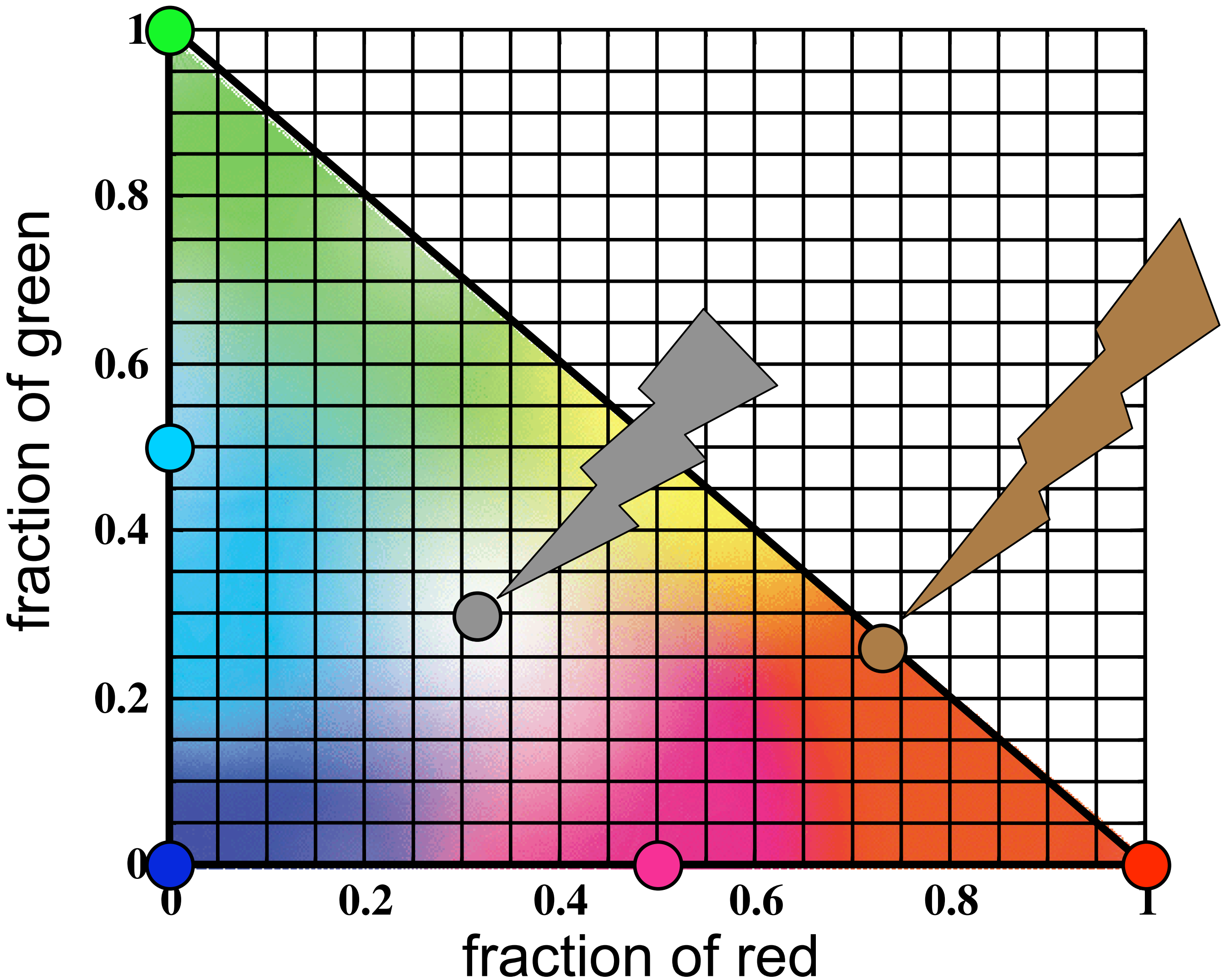


Another version of the color triangle

Since B = 1 - R - G, don't explicitly plot it



Where are the browns, grays?



Gray: low-intensity white

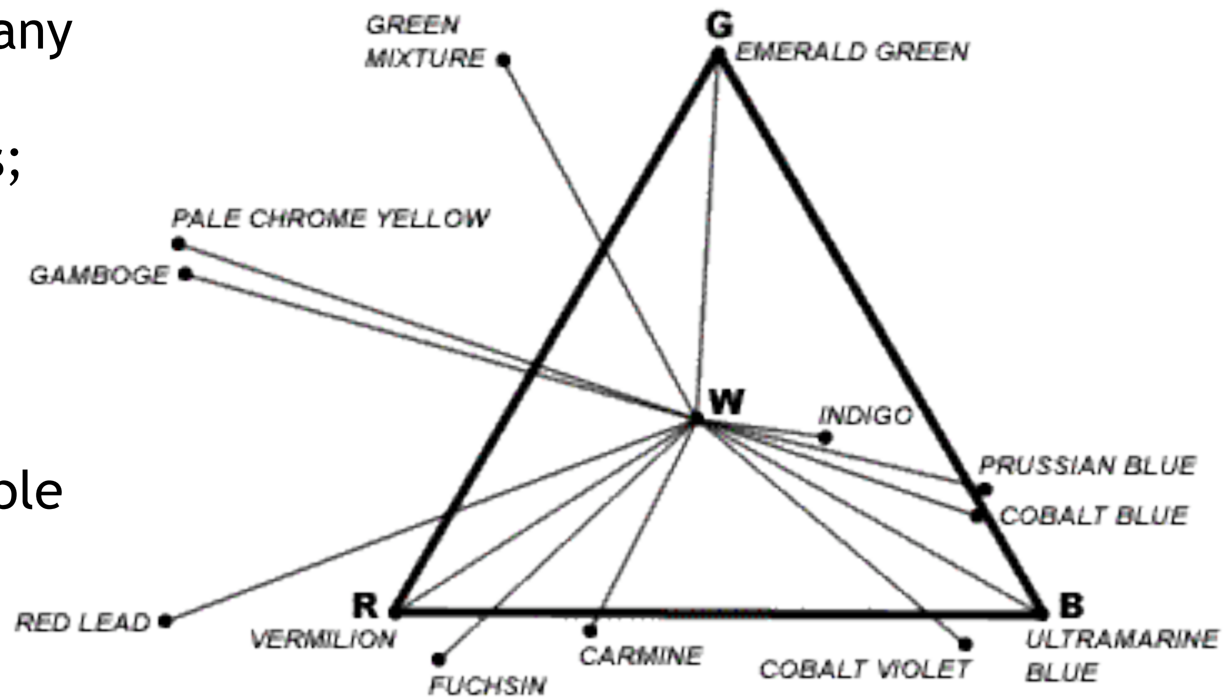
Brown: low-intensity orange

Not all colors inside a color triangle

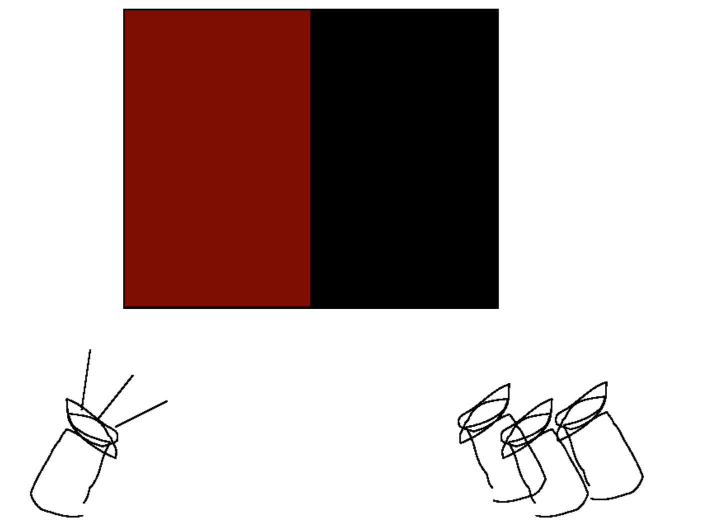
Physicist Ogden Rood's analysis of pigment chroma

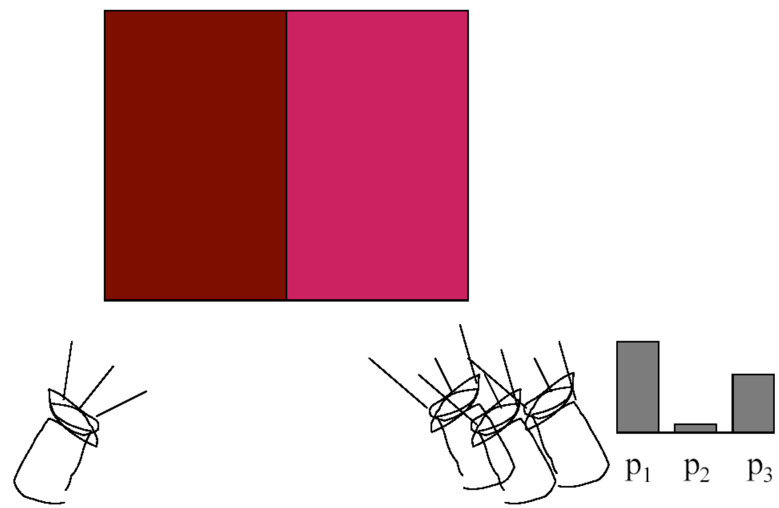
Shows location of pigments more saturated than any visual mixture of the three "primary" colors; adapted from Modern Chromatics (1879)

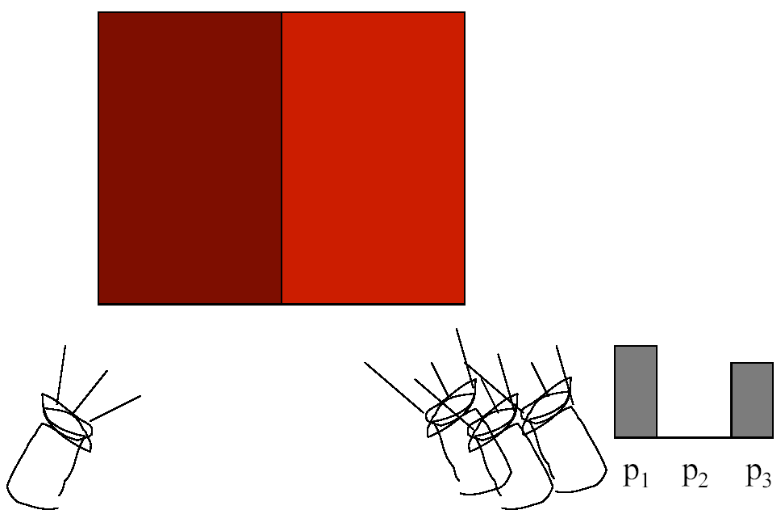
This means that not all colors obtainable by adding easily obtainable primaries



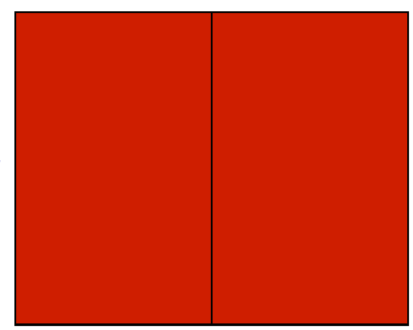
Subtractive Matching



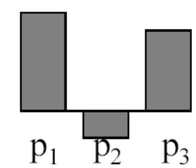


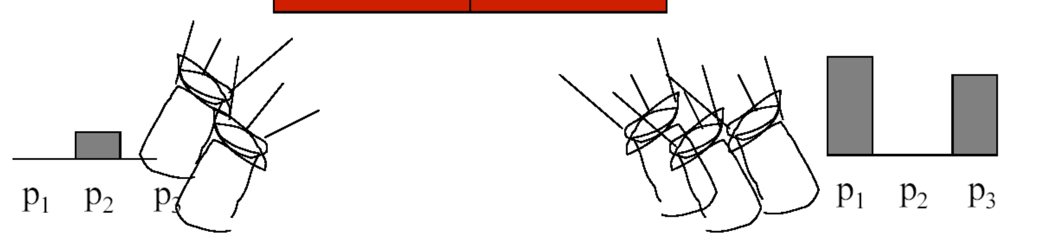


We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

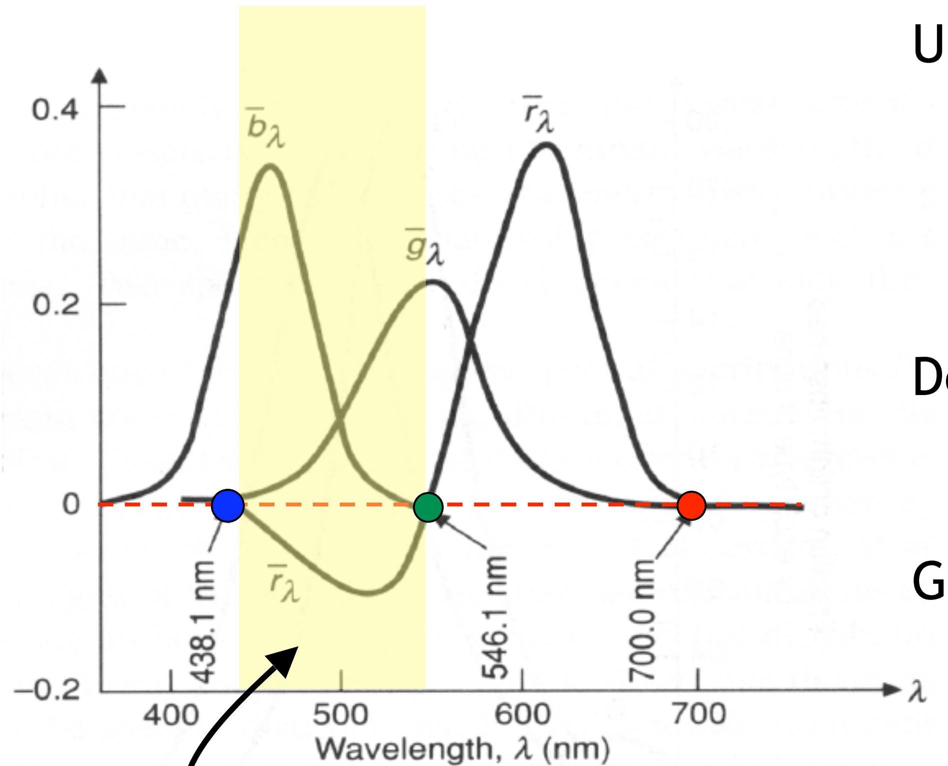


The primary color amounts needed for a match:





Human color-matching results



Subtractive color matching required
in this wavelength range.

Use spectrally pure primaries

red	(700 nm)
green	(546.1 nm)
blue	(438.1 nm)

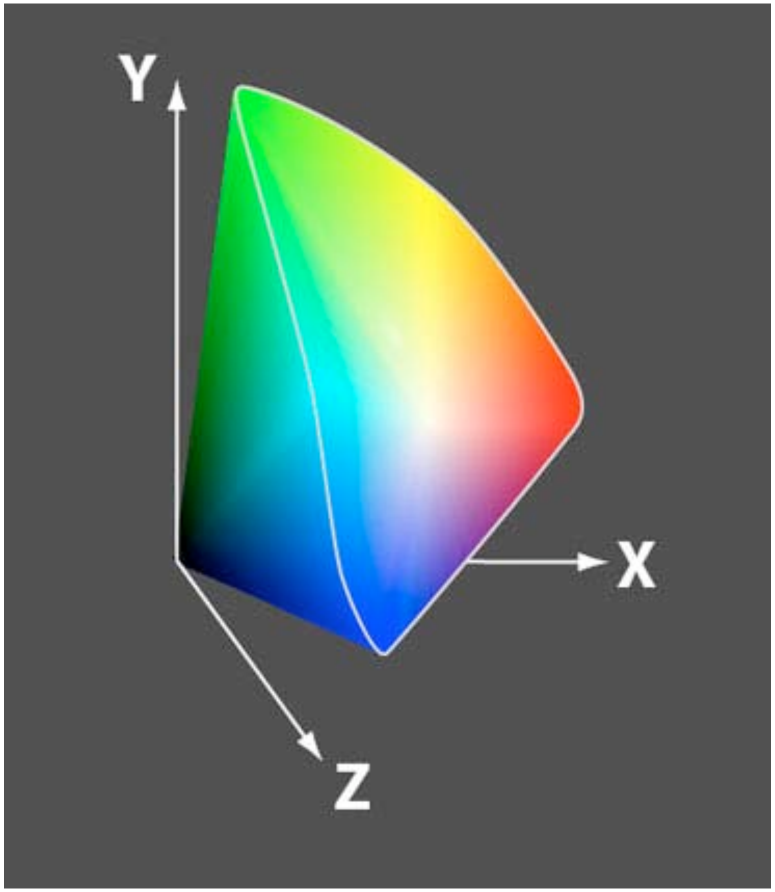
Determine red, green, blue required to match pure spectral test color.

Graph shows relative fractions of three primaries required to make a match.

Entire spectrum of pure colors produced by mixing three primaries *if* subtractive matching allowed.

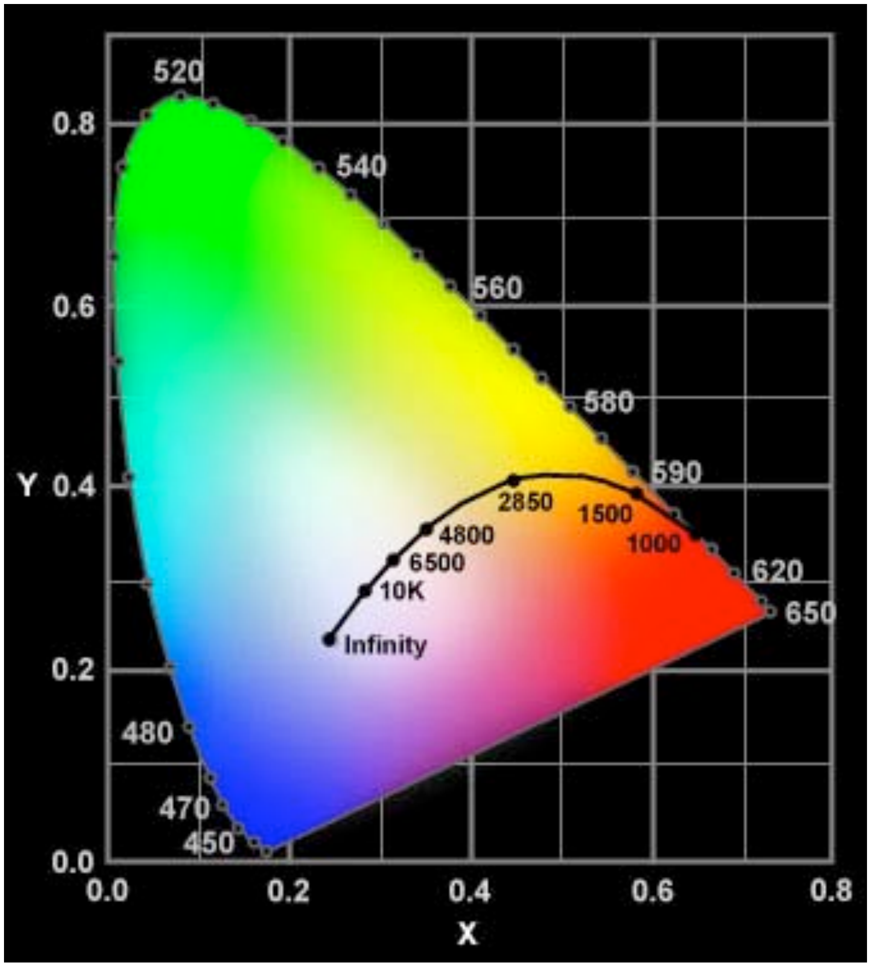
The CIE *XYZ* color space

- CIE primaries: combinations of spectrally pure RGB primaries.
- Unphysical ‘lights’. Some require *negative* amounts of the RGB primaries.
- Each color *and* intensity represented by a point (X,Y,Z).
- Some combinations of X, Y, Z are not physical lights (gray).
- Spectrally pure colors on boundary with unphysical region.



Commision Internationale de L'Eclairage, 1931

xy plane of *Yxy* color space



- Color specified by *xy* coords.
- Boundary is pure spectral colors (labeled by wavelength.
- The *Y* axis (out of page) determines brightness (luminosity).
- Colors shown here only representative.

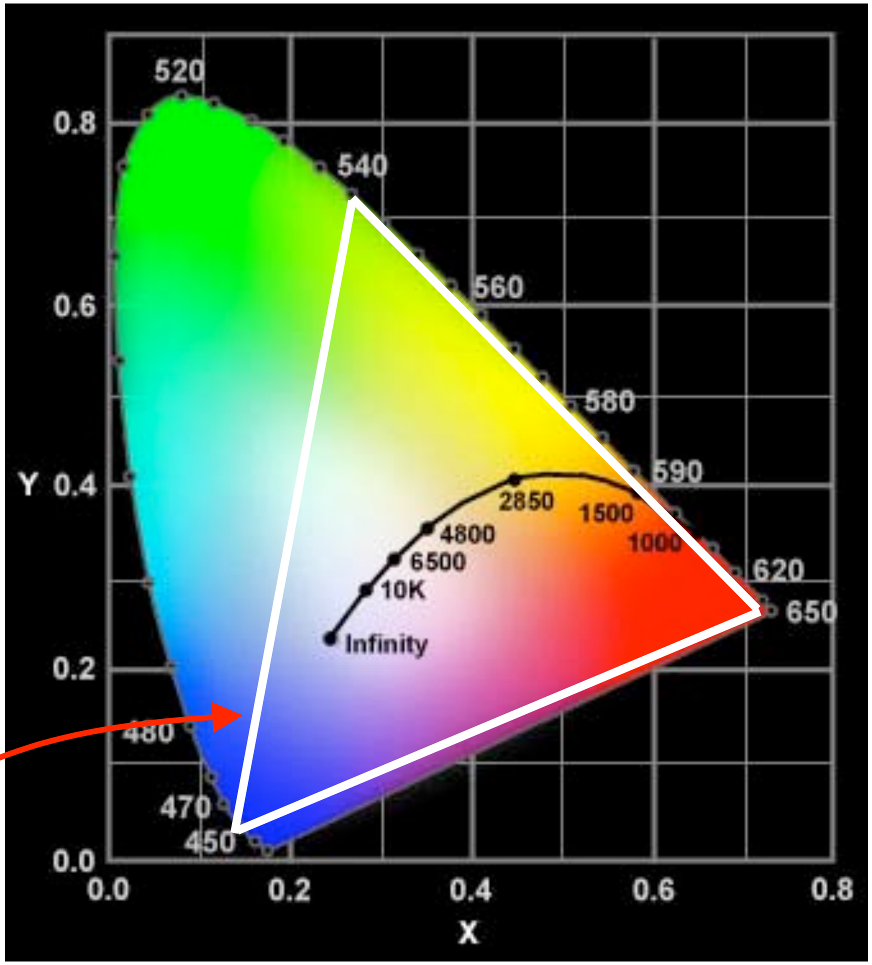
Gamut: the range of colors

Many of the physical colors can be obtained by mixing three primary colors.

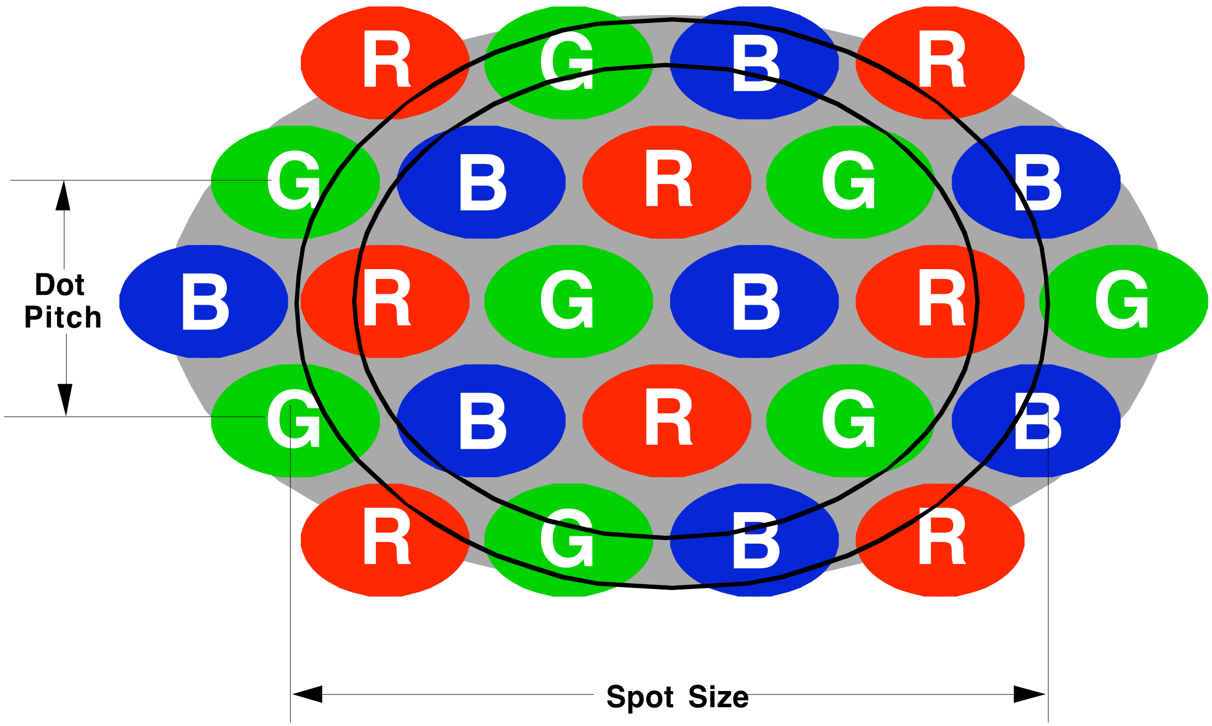
Since result of mixing two colors lies on line joining them, total range of possible colors lie inside triangle formed by three primaries.

This is the gamut projected to the *xy* plane.

Colors obtainable by additive mixing of spectrally pure primaries of 650nm, 540nm, and 450nm lie within this triangle.



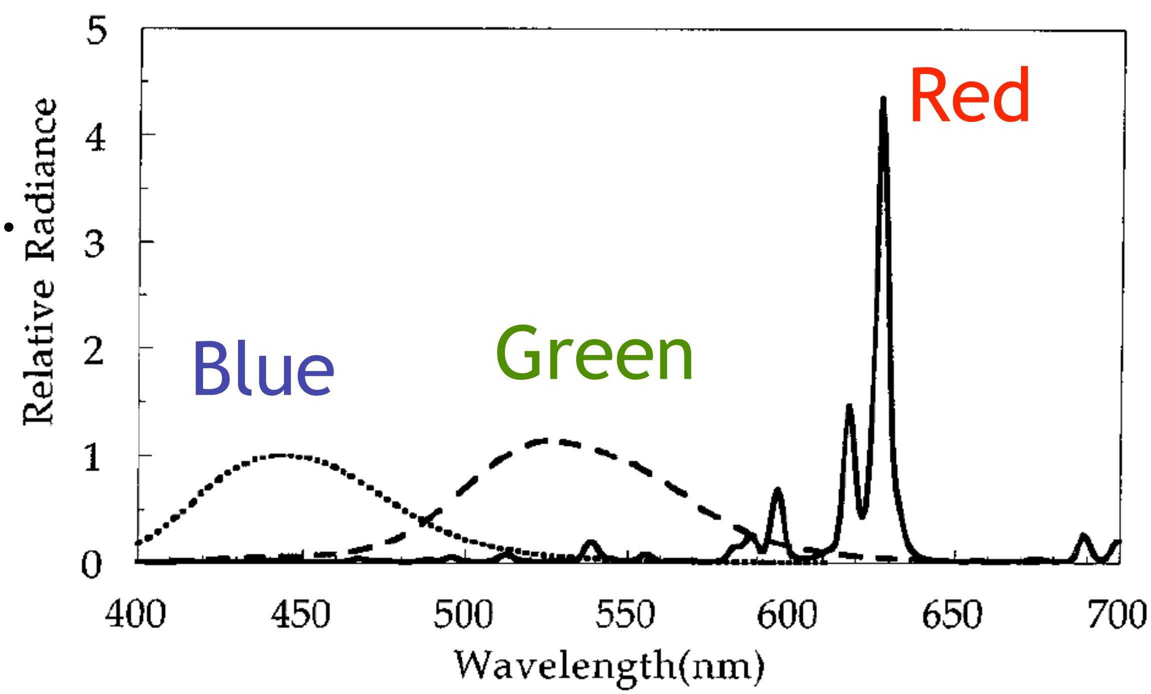
Color CRT Phosphor Pattern



- R, G, B phosphors emit R, G, B light after absorbing electrons from beam.
- Light from R, G, B phosphors combine to produce a color *r*R+*g*G+*b*B
- But the emitted light is not exactly red, blue, green.

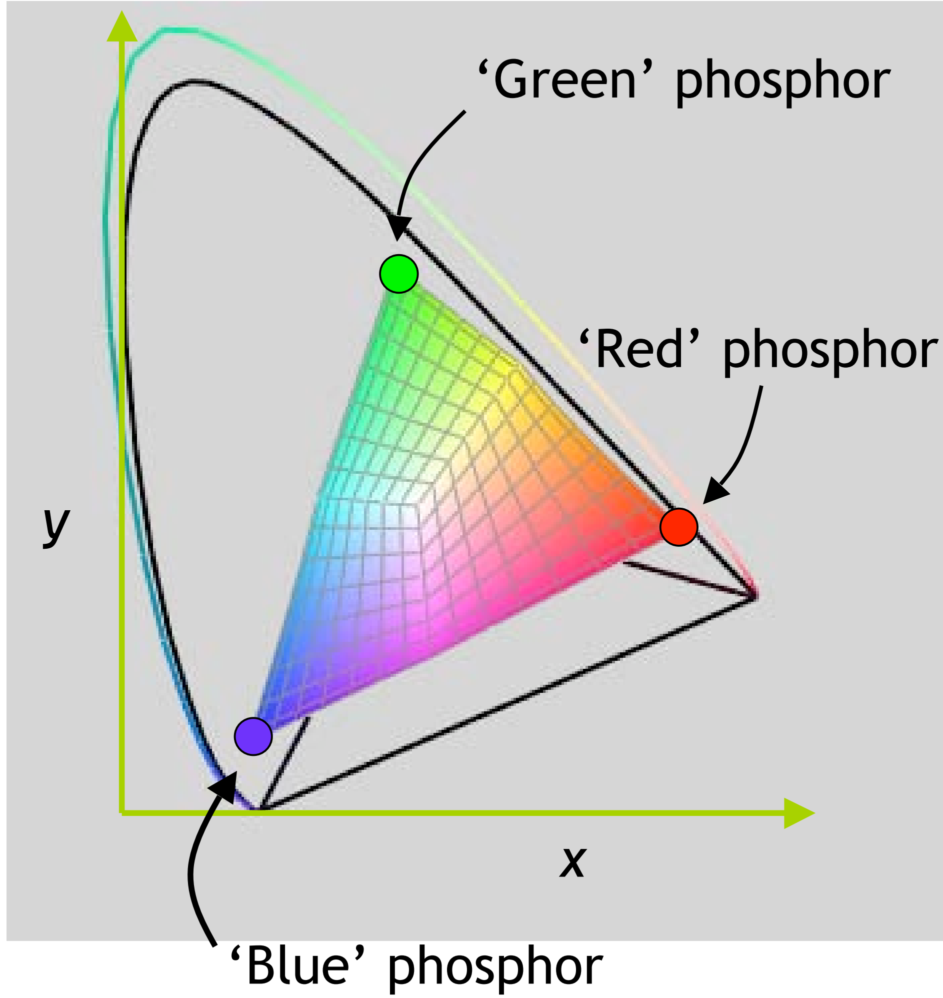
What are the R, G, B primaries?

- Light emitted by phosphors not spectrally pure colors.
- Can still make colors by combining these, but which ones?
- Or, what is the 'color gamut' of a particular computer monitor



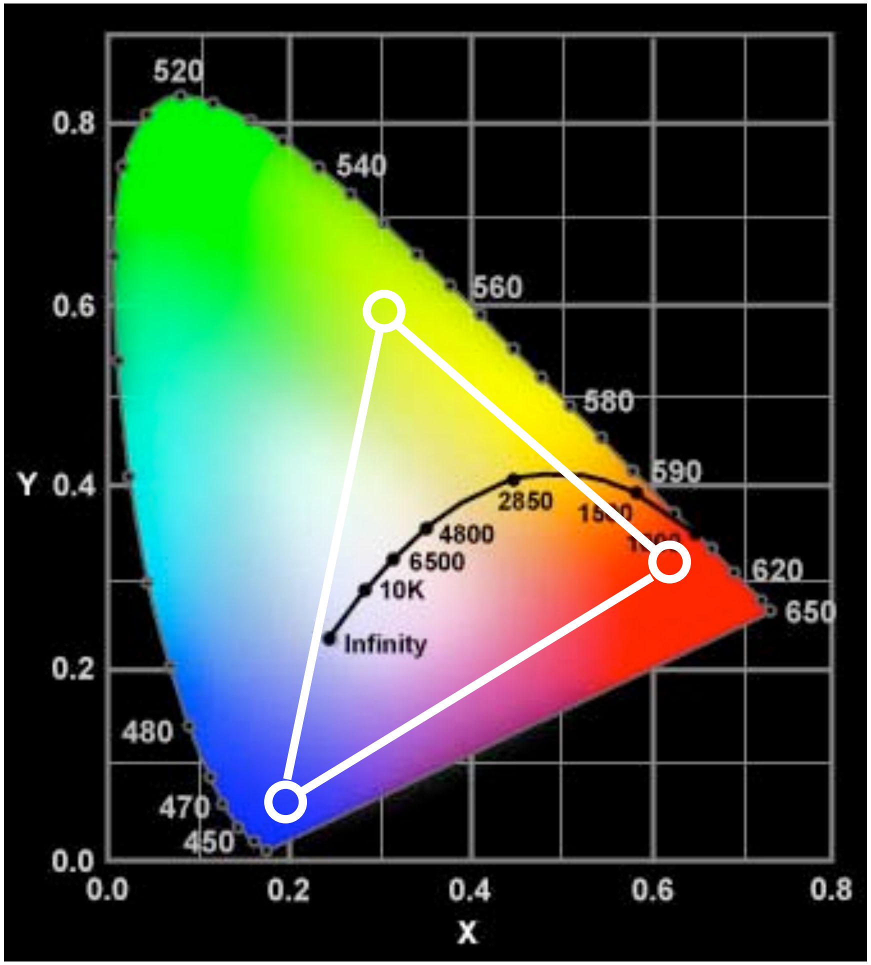
Computer monitor gamut in the *Yxy* color space

- Top view of *Yxy* color space, showing *xy* plane.
- Each phosphor described by a pair (*x*,*y*).
- Three primaries are vertices of gamut triangle.
- Colors outside triangle cannot be produced
- Pure spectral colors (on the horshoe arc) not produced.



Reproducing colors

- Most of the spectral colors are out of gamut.
- So what color is on the screen?



"Perceptual", "Absolute", but no completely satisfactory procedure