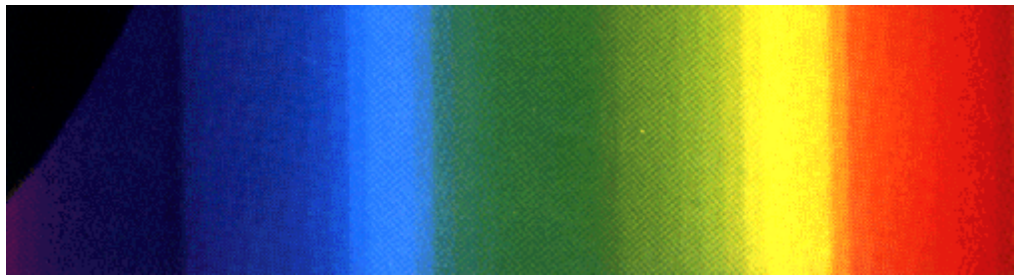
29 - COLOR

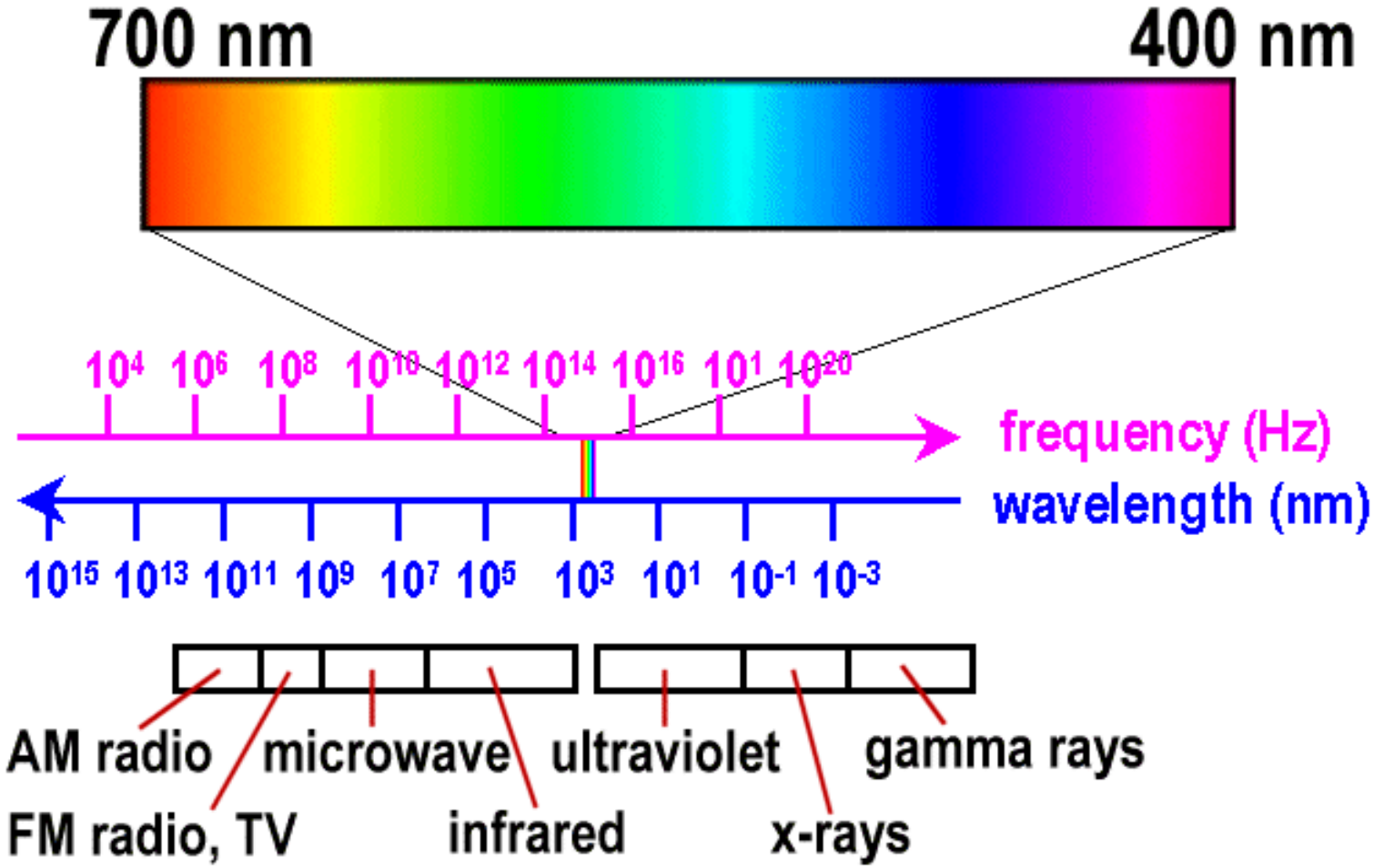


Textbook: 19

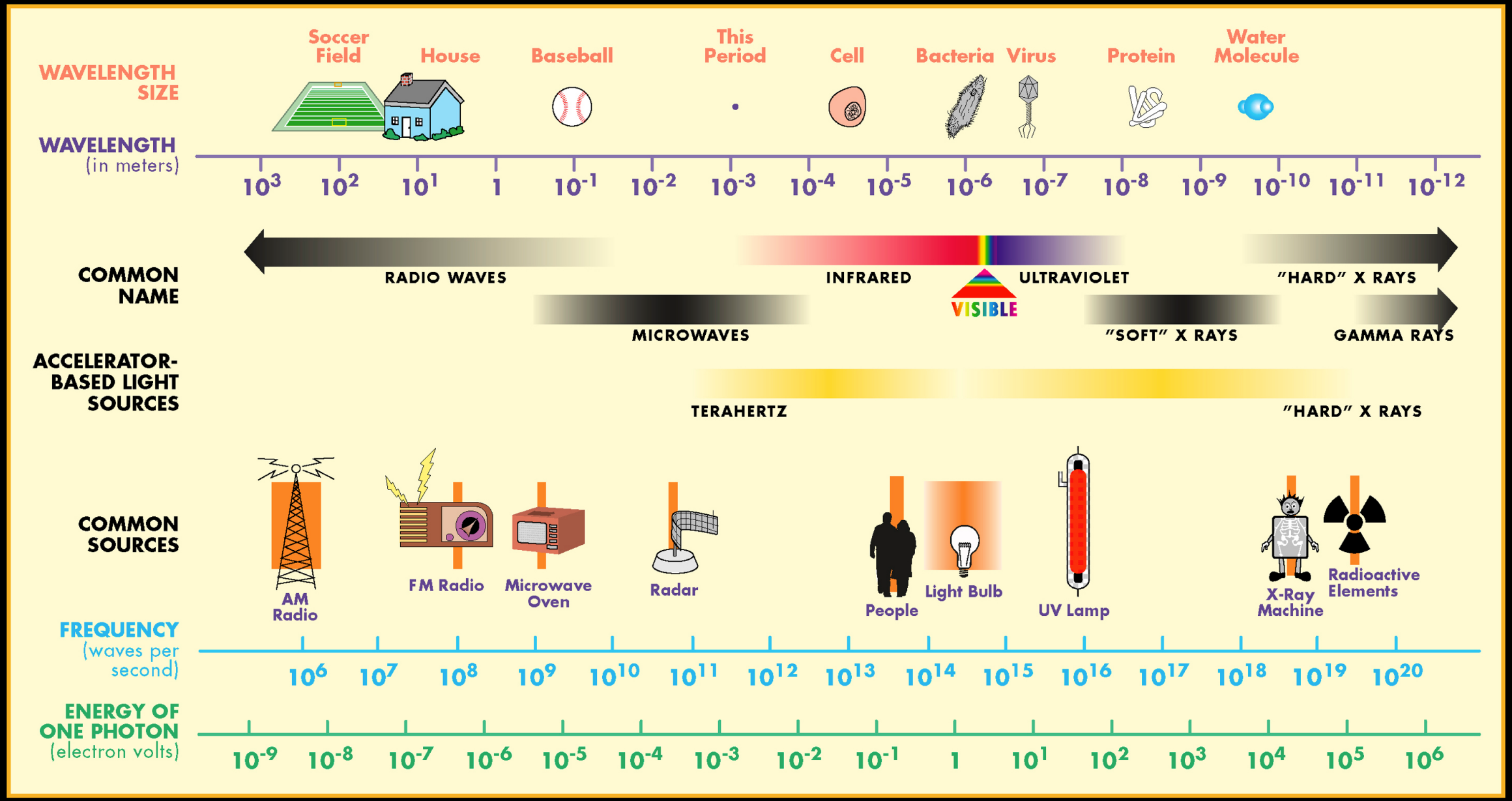
UGRAD.CS.UBC.CA/~CS314

Mikhail Bessmeltsev

ELECTROMAGNETIC SPECTRUM

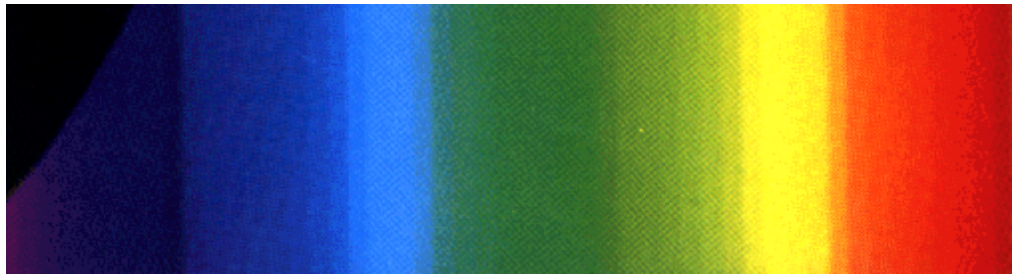


THE ELECTROMAGNETIC SPECTRUM



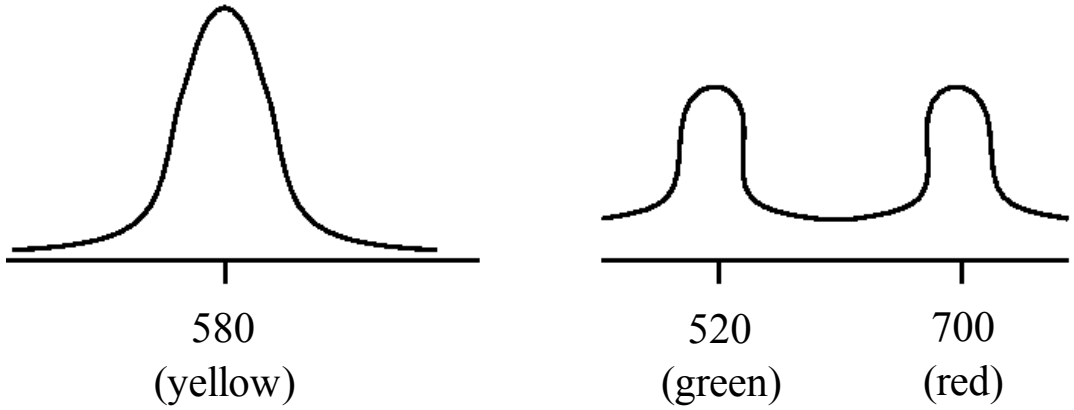
PHYSICAL COLOR

- Visible energy - small portion of the electro-magnetic spectrum
- Pure *monochromatic* colors are found at wavelengths between 380nm (violet) and 780nm (red)



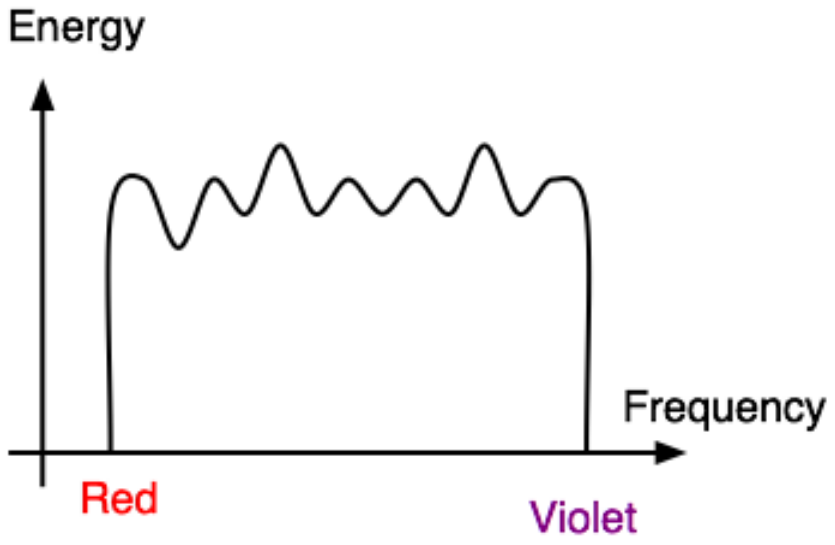
VISIBLE COLOR

- Eye can perceive other colors as combination of several pure colors
- Most colors may be obtained as combination of small number of *primaries*
- Output devices use this approach



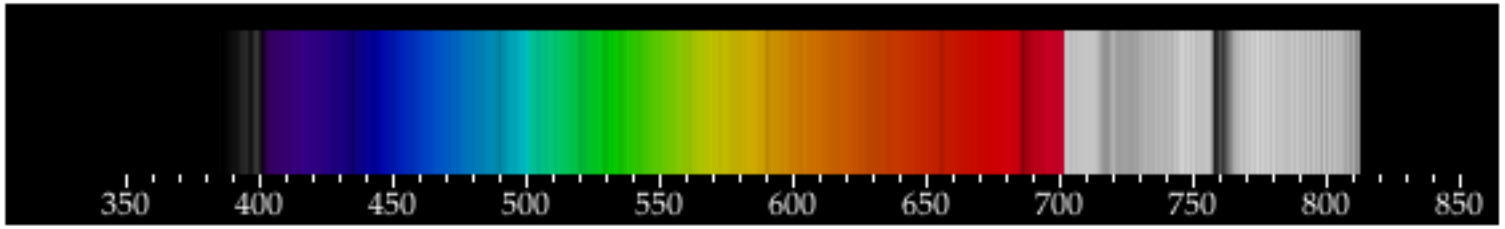
WHITE LIGHT

- sun or light bulbs emit all frequencies within visible range to produce what we perceive as "white light"

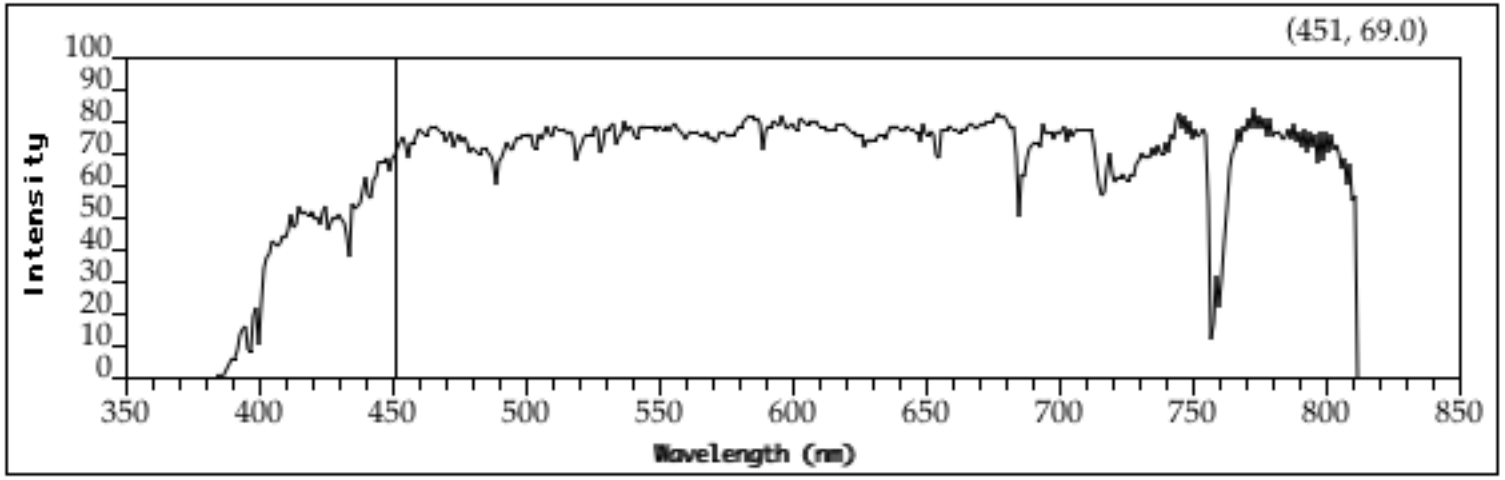


SUNLIGHT SPECTRUM

- spectral distribution: power vs. wavelength



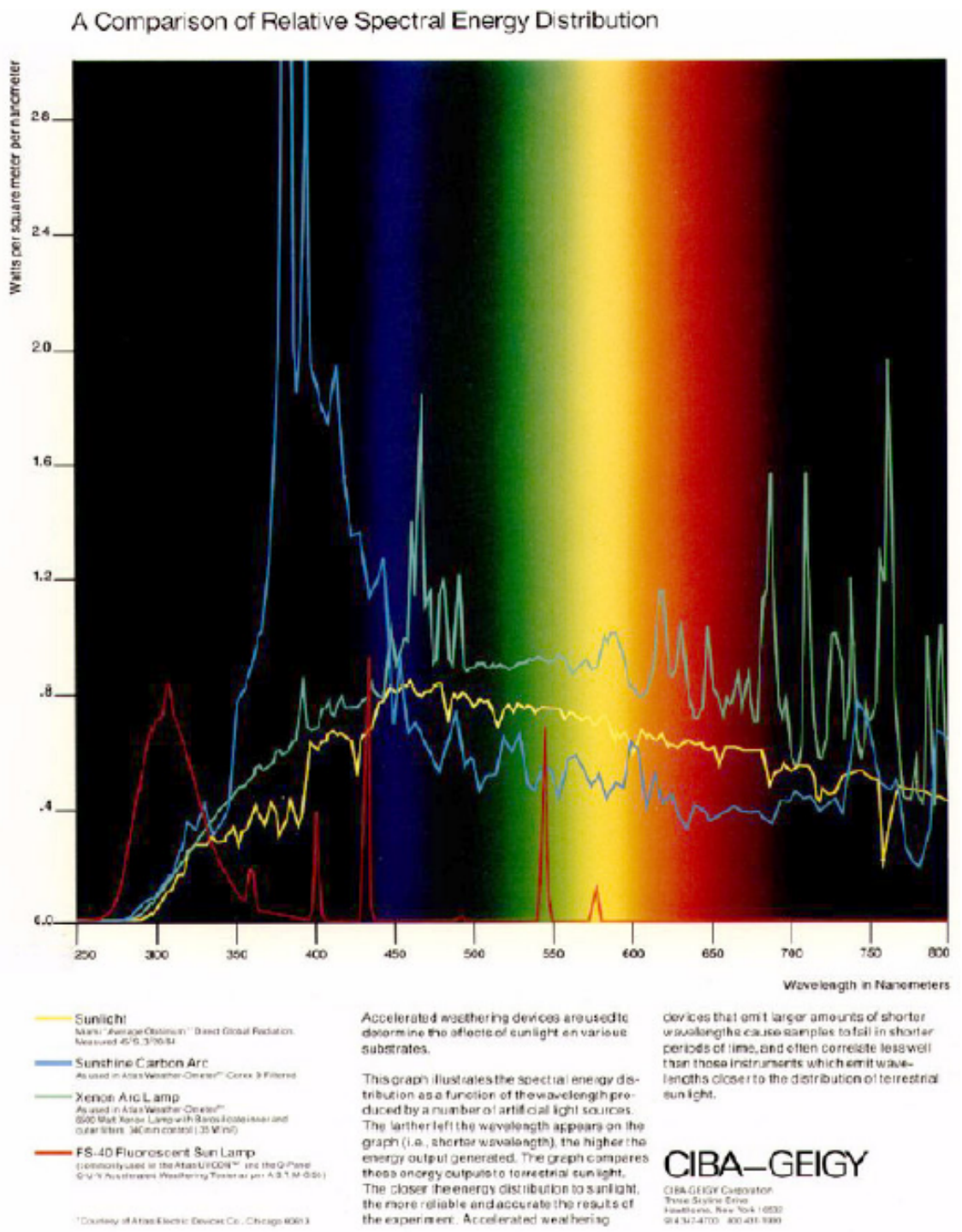
Emission Graph



Electromagnetic Spectrum

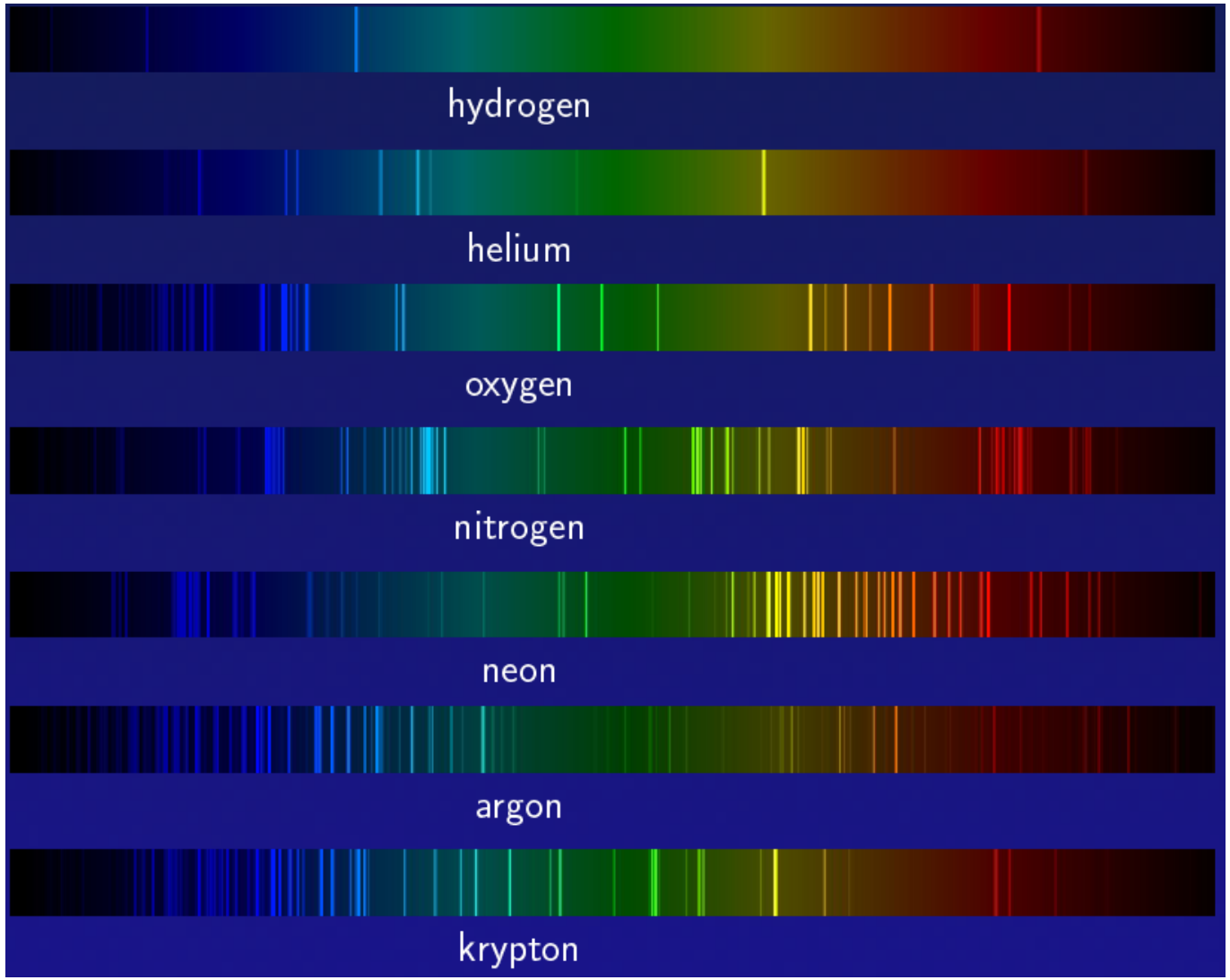
CONTINUOUS SPECTRUM

- sunlight
- various “daylight” lamps



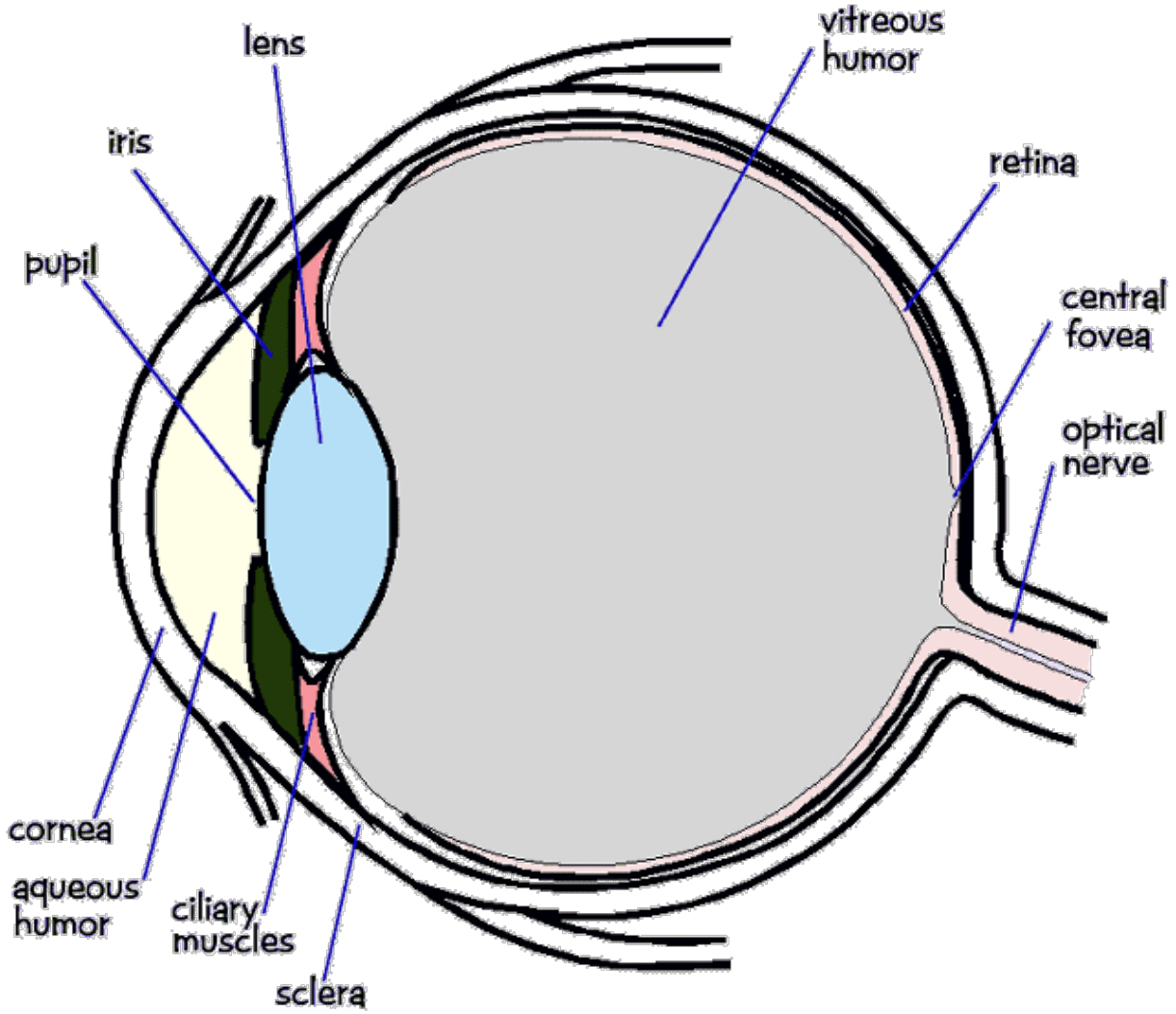
LINE SPECTRUM

- ionized gases
- lasers
- some fluorescent lamps

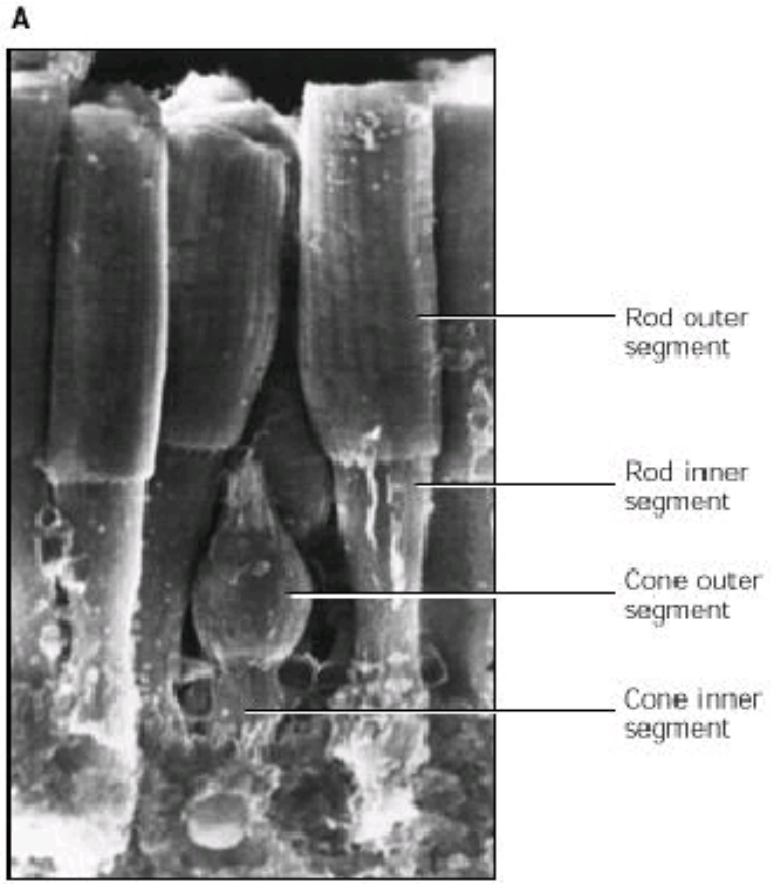


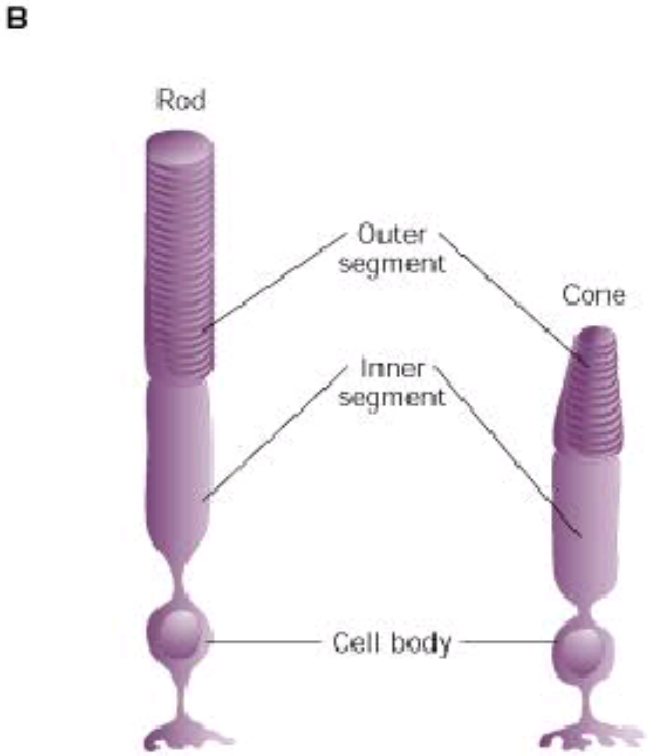
PHYSIOLOGY OF VISION

- the retina
  - rods
    - b/w, edges
  - cones
    - 3 types
    - color sensors
  - uneven distribution
    - dense fovea



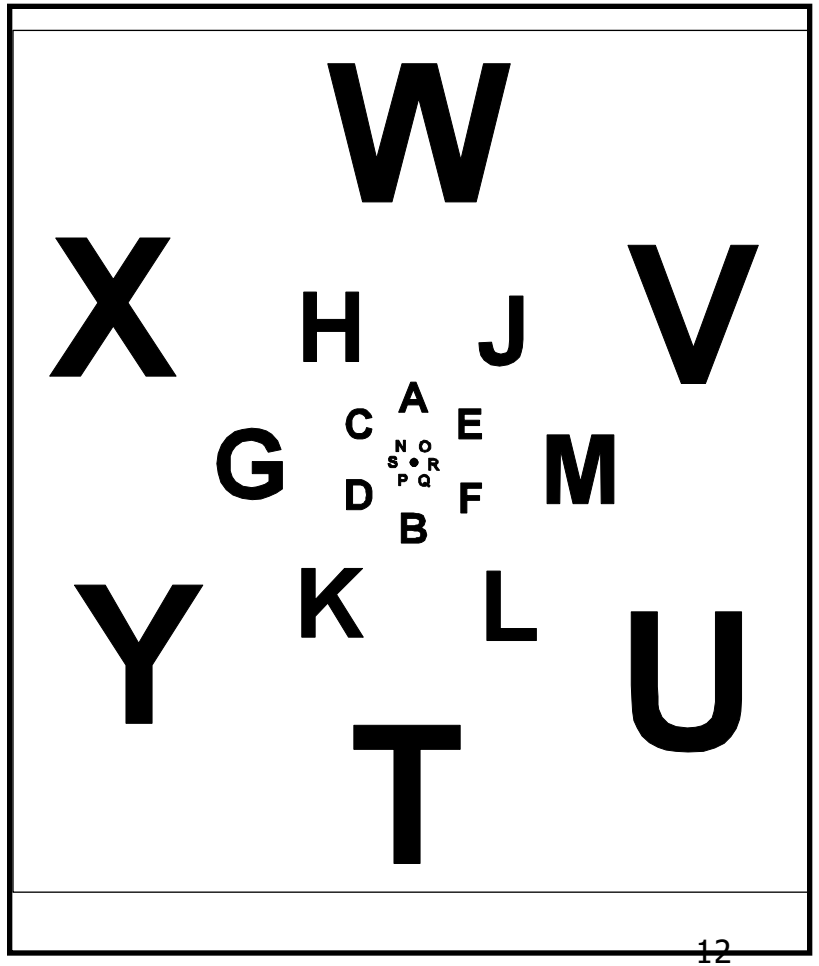
RODS AND CONES





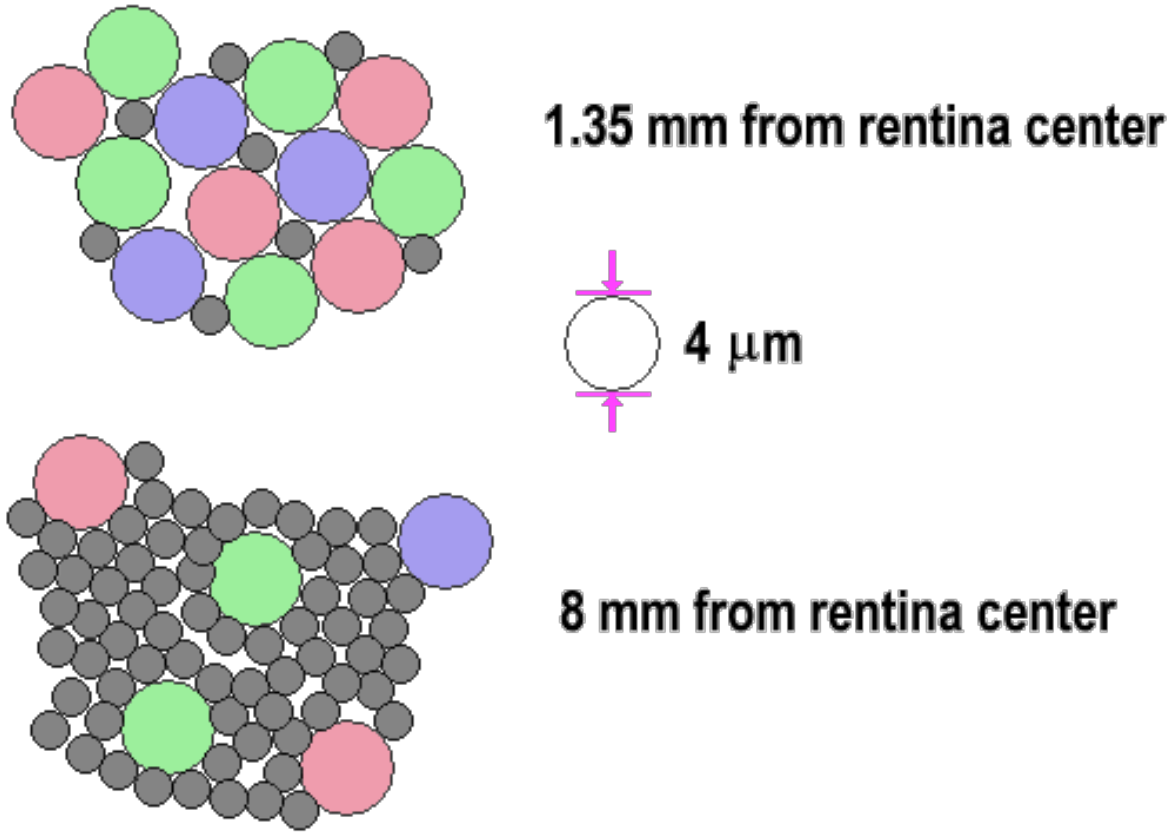
FOVEAL VISION

- hold out your thumb at arm's length



PHYSIOLOGY OF VISION

- Center of retina is densely packed region called the *fovea*.
  - Cones much denser here than the *periphery*



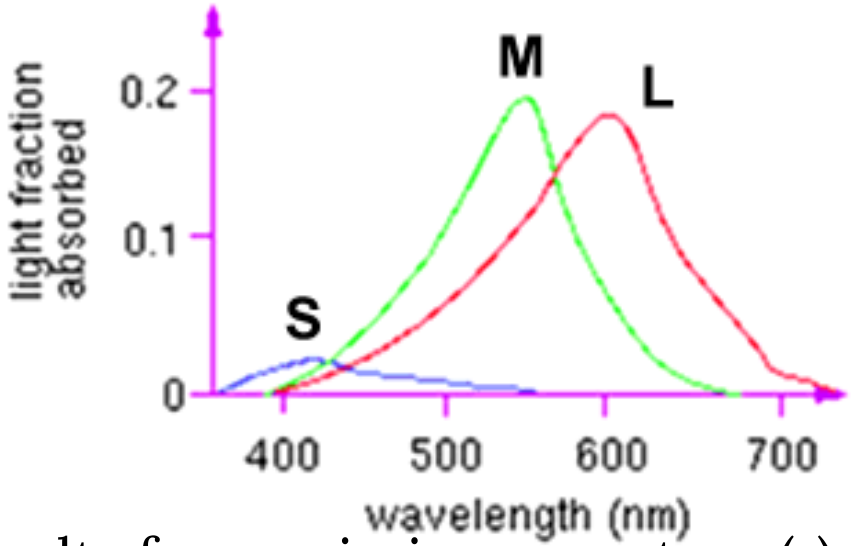
TRISTIMULUS THEORY OF COLOR VISION

- Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 primaries

- Colors that look the same but have different spectra are called metamers

TRICHROMACY

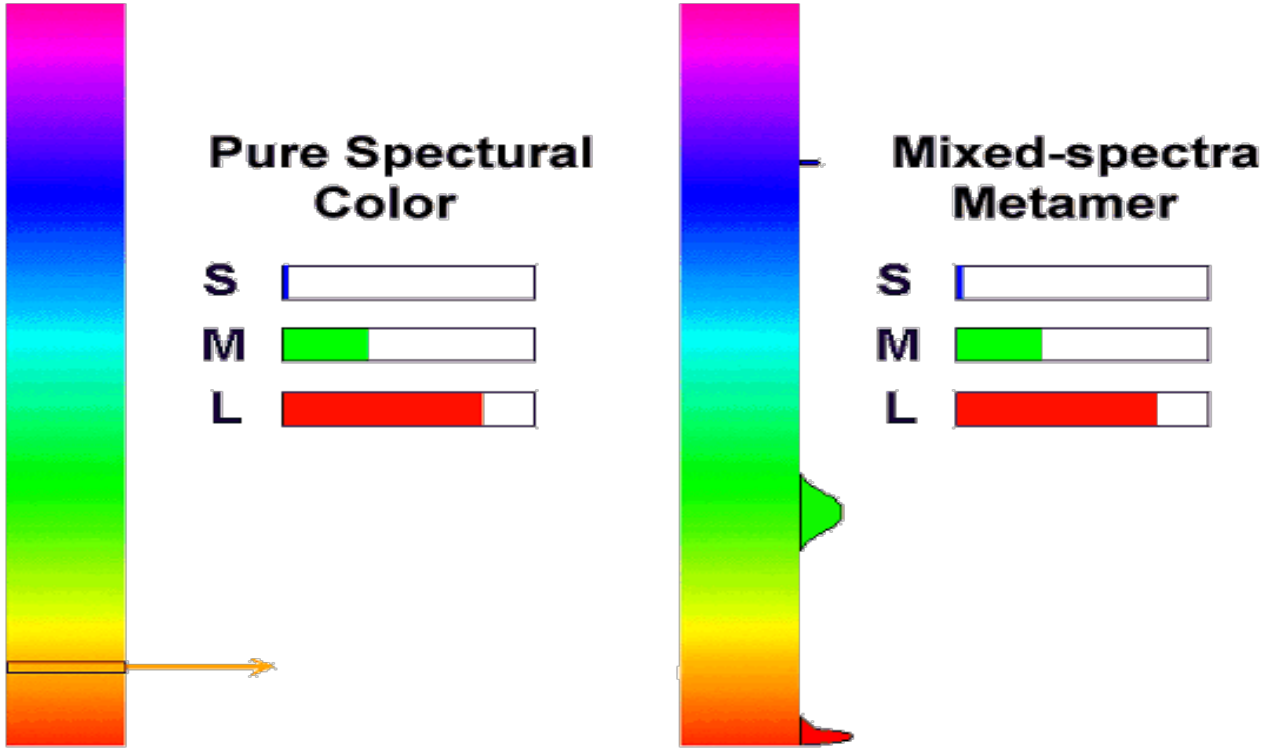
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)



  - color blindness results from missing cone type(s)

METAMERS

- a given perceptual sensation of color derives from the stimulus of all three cone types

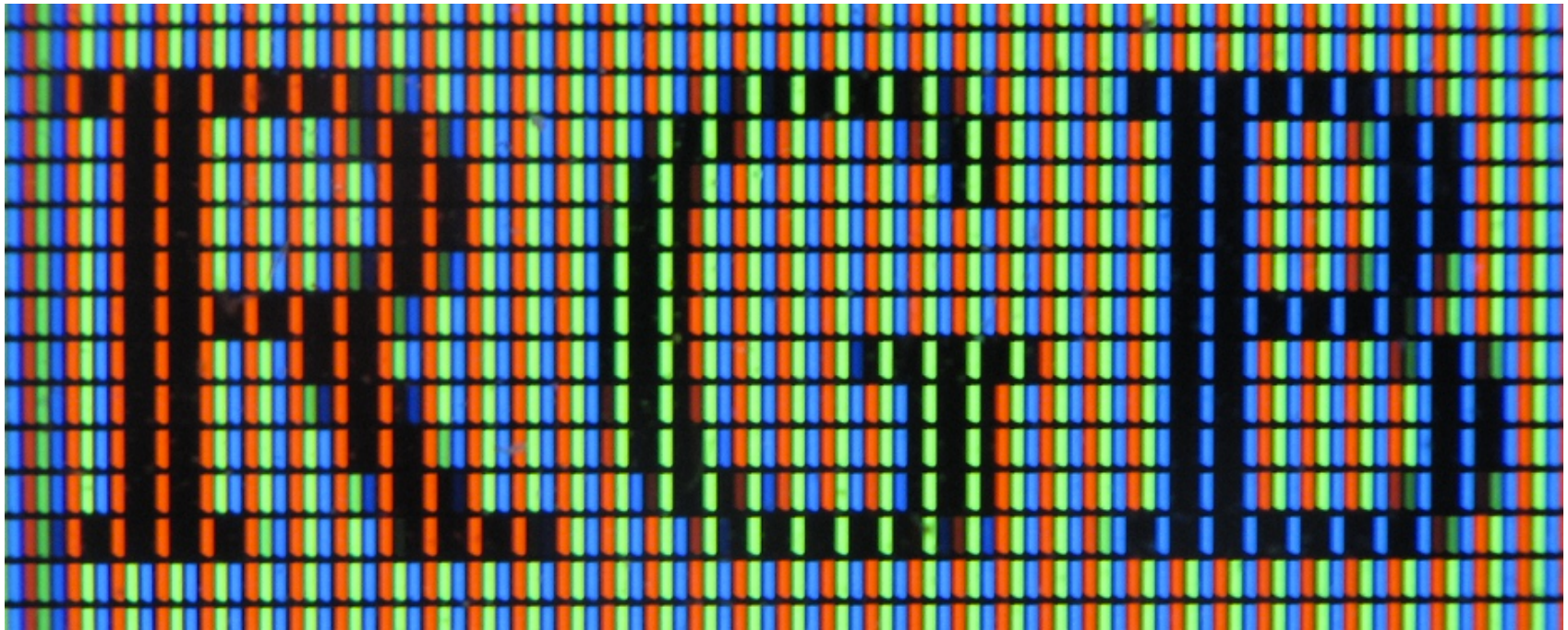


- identical perceptions of color can thus be caused by very different spectra
- demo

http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html

MANUFACTURING DISPLAYS

- This means we can only have R,G,B lights and mix them to get any color!
- Can we?
- Humans won't know the difference



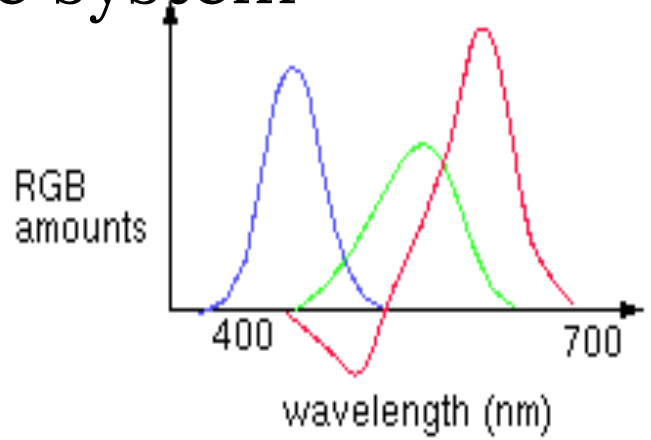
MANUFACTURING DISPLAYS

- This means we can only have R,G,B lights and mix them to get any color!
- Can we?
- Humans won't know the difference

- An experiment: show a pure color and ask a person to mix R,G,B to match it perfectly

NEGATIVE LOBES

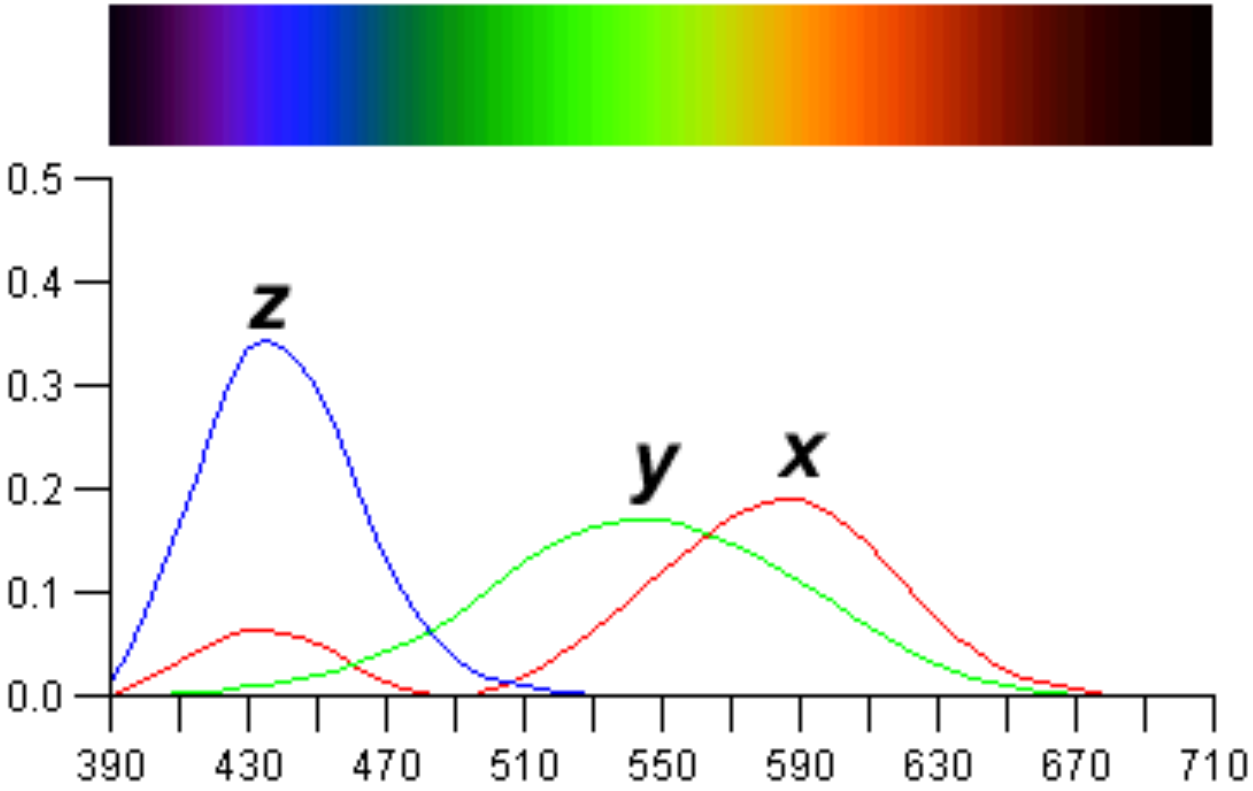
- sometimes they couldn't match the color perfectly!
  - sometimes RGB produced "too much red"
  - but physically impossible to remove red from CRT phosphors
- can't generate all other wavelenths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy



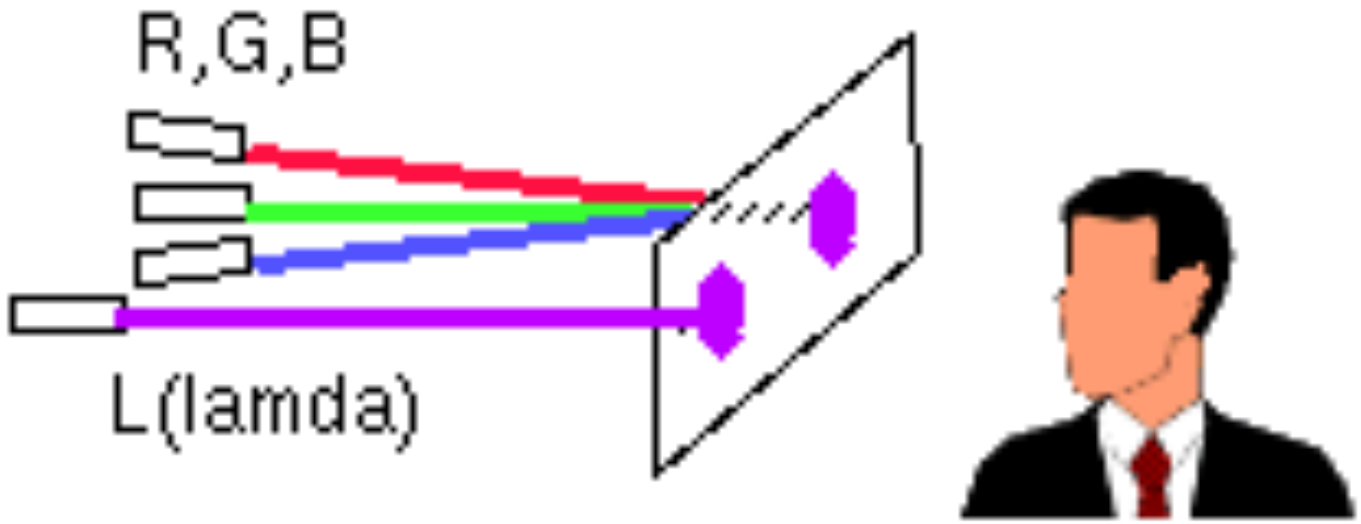
CIE COLOR SPACE

- CIE defined 3 “imaginary” lights X, Y, Z
  - any wavelength λ can be matched perceptually by positive combinations
  - basis functions!

Note that:
X ~ R
Y ~ G
Z ~ B

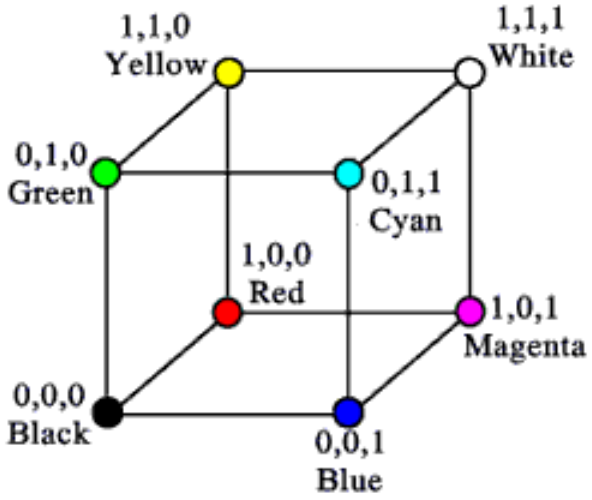


COLOR SPACES

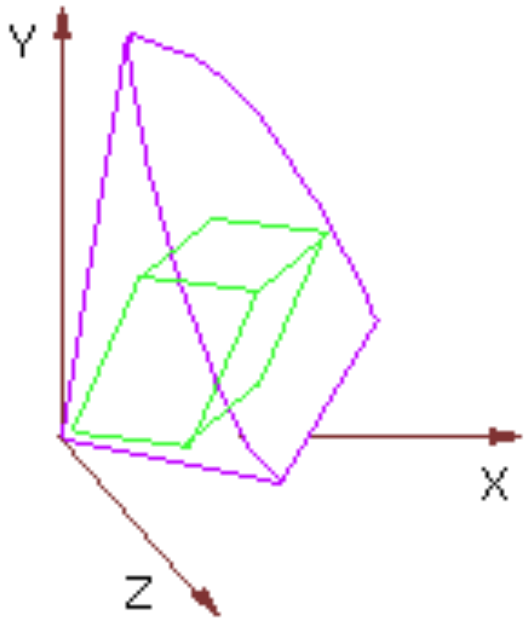


RGB COLOR SPACE (COLOR CUBE)

- define colors with (r, g, b) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric



- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube



XYZ AND RGB COLOUR SPACES

- colour transformation matrix:
  (for monochromatic R=700nm, G=546nm,B=436nm)

$$\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \\ \mathbf{Z} \end{bmatrix} = \begin{bmatrix} 2.36460 & -0.51515 & 0.00520 \\ -0.89653 & 1.42640 & -0.01441 \\ -0.46807 & 0.08875 & 1.00921 \end{bmatrix} \begin{bmatrix} \mathbf{R} \\ \mathbf{G} \\ \mathbf{B} \end{bmatrix}$$

- each monitor has its own RGB-to-XYZ transformation matrix
  - suppose we have a colour $R_A G_A B_A$ on monitor A and wish to view the same colour on monitor B:

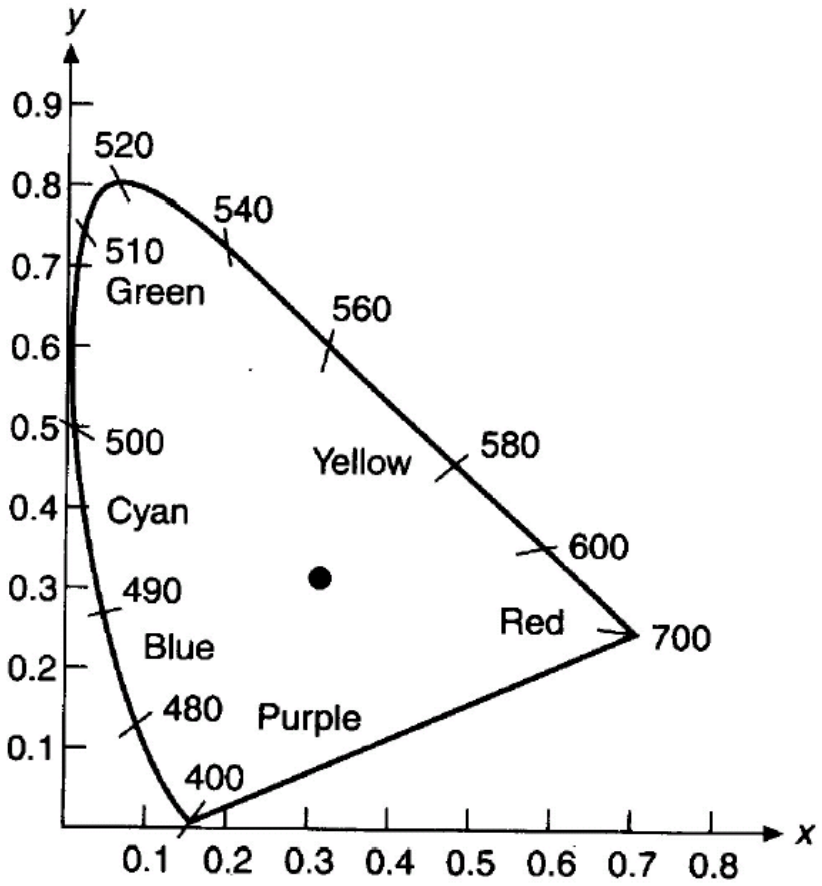
(2) $$\begin{bmatrix} R_B \\ G_B \\ B_B \end{bmatrix} = \begin{bmatrix} & M_B^{-1} & \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

(1) $$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} & M_A & \end{bmatrix} \begin{bmatrix} R_A \\ G_A \\ B_A \end{bmatrix}$$

$$C_B = M_B^{-1} M_A C_A$$

CIE CHROMATICITY DIAGRAM

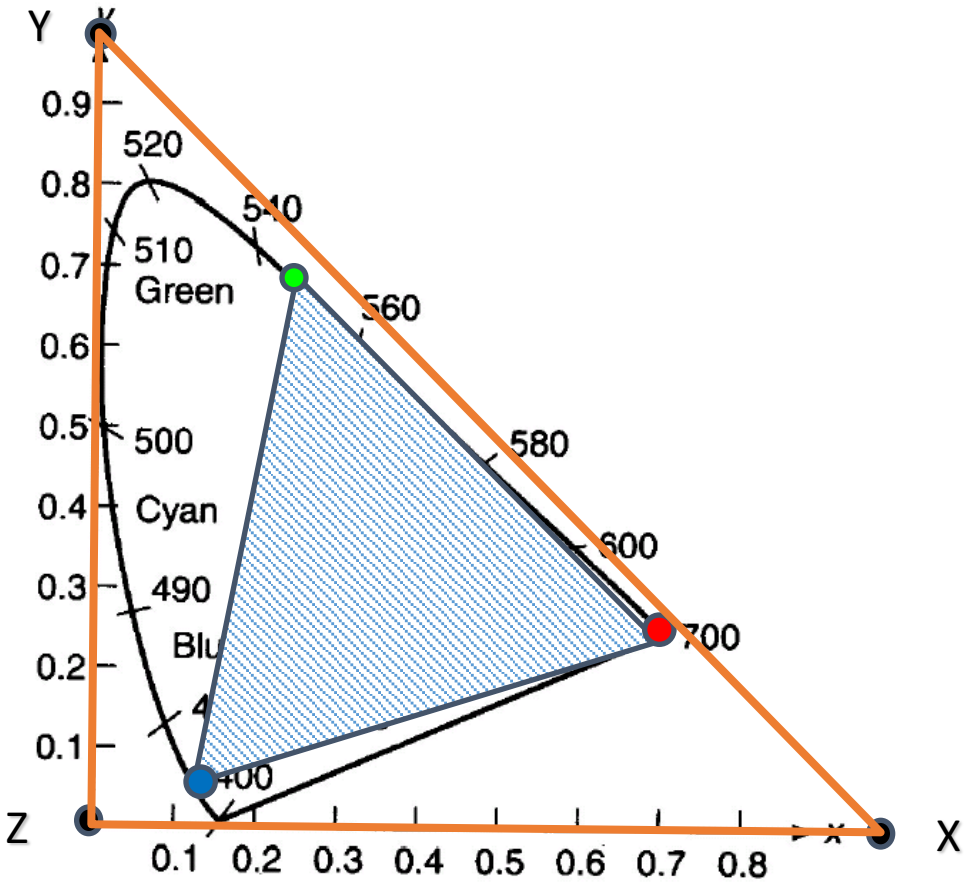
- produce a 2D colour space by projecting onto the plane given by X+Y+Z = 1



$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}$$

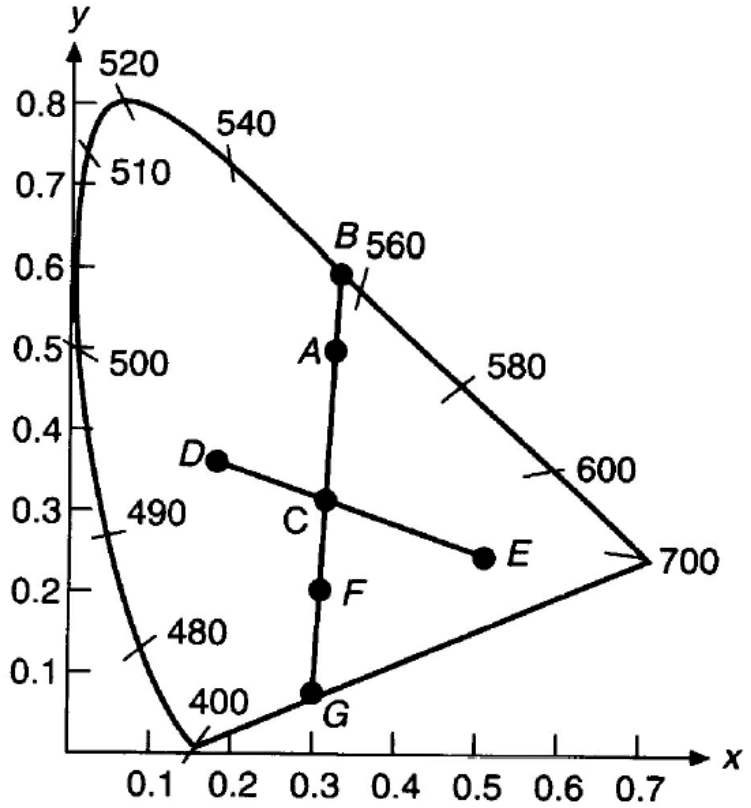
RGB VS XYZ REVISITED

- another view of why the R curve goes negative

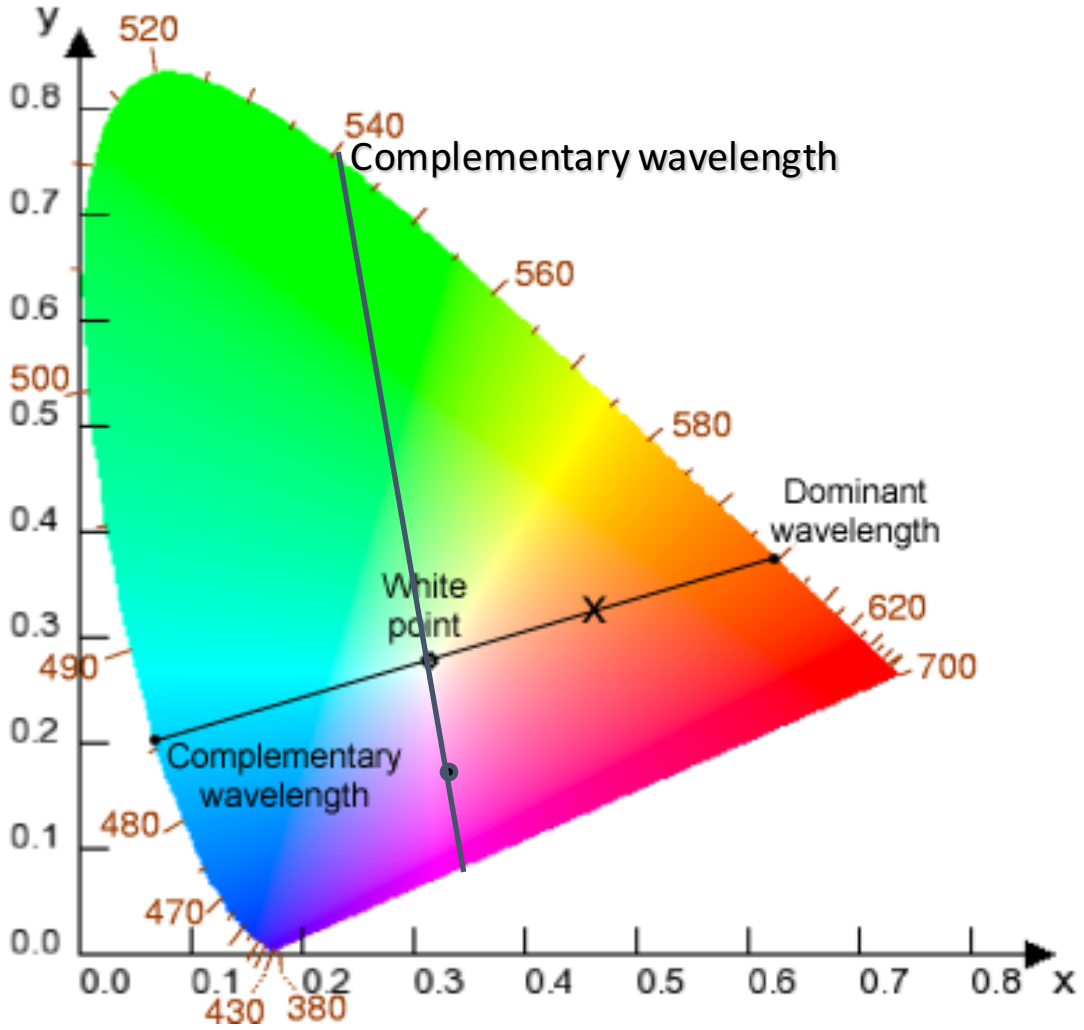


CIE CHROMATICITY DIAGRAM

- C: white point
- complementary colours
- dominant wavelength
- non-spectral colors



COLOR INTERPOLATION, DOMINANT & OPPONENT WAVELENGTH

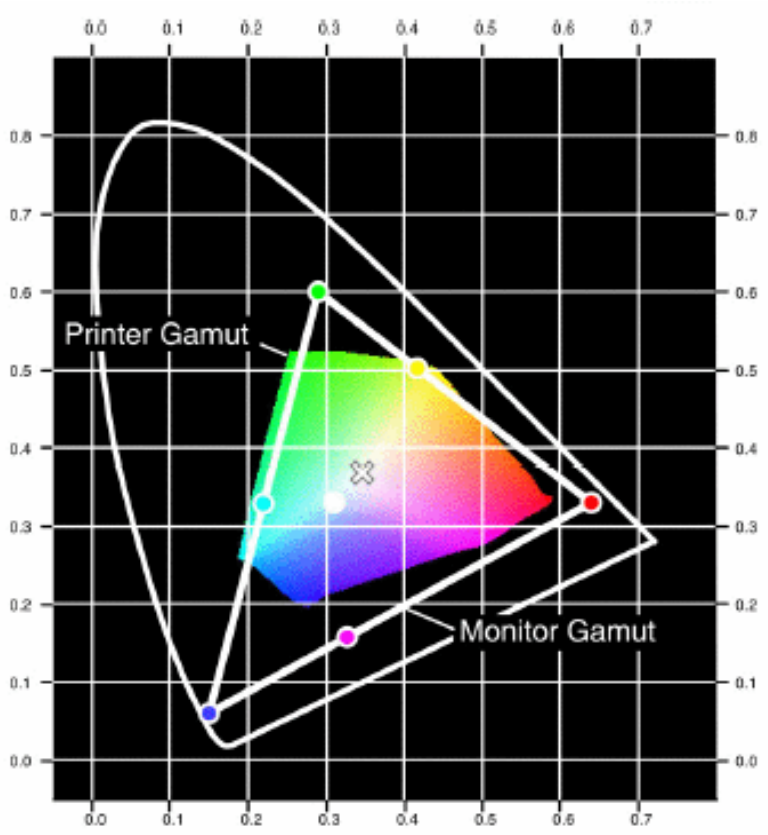


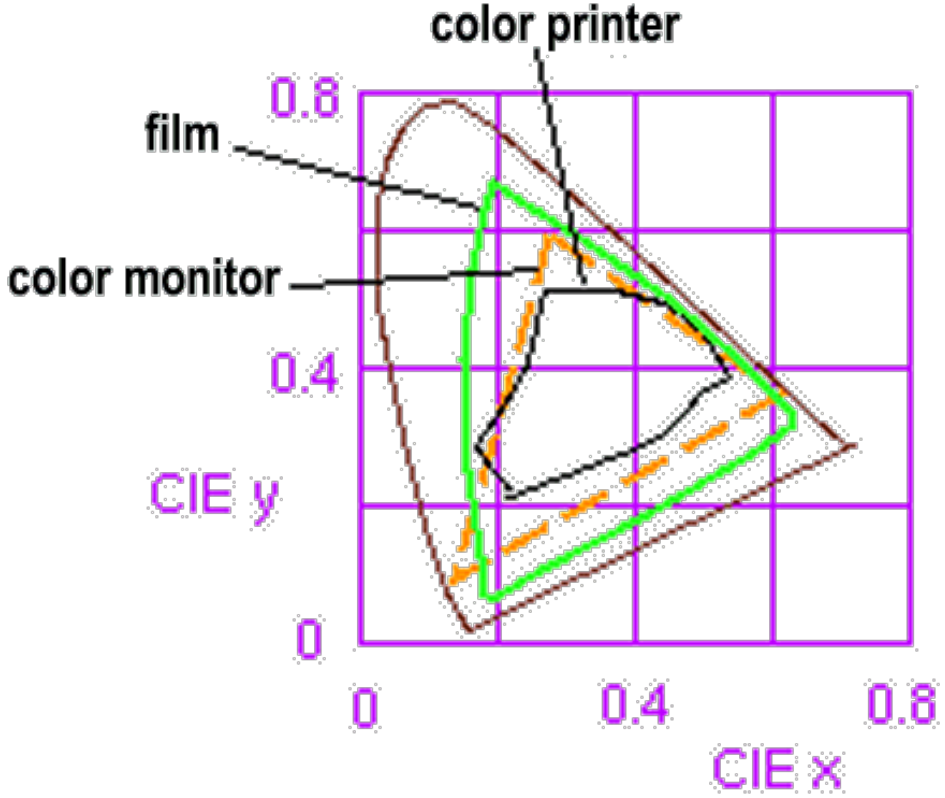
CIE “HORSESHOE” DIAGRAM FACTS

- all visible colors lie inside the horseshoe
  - result from color matching experiments
- spectral (monochromatic) colors lie around the border
  - straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

DEVICE COLOR GAMUTS

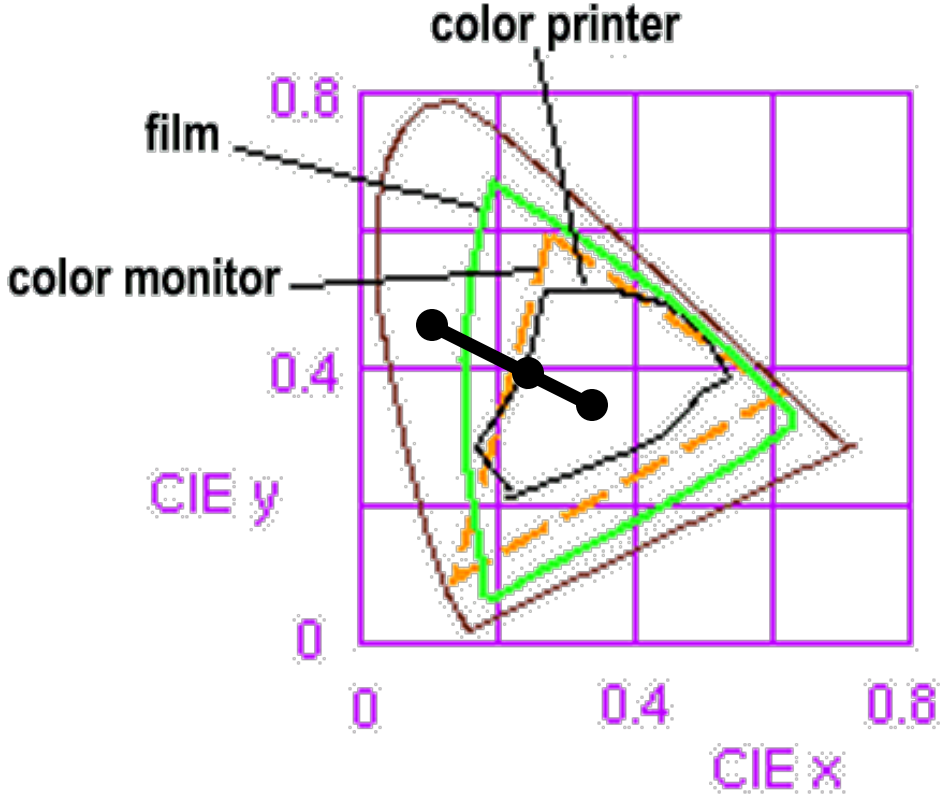
- gamut is polygon, device primaries at corners
  - defines reproducible color range
  - X, Y, and Z are hypothetical light sources, no device can produce entire gamut



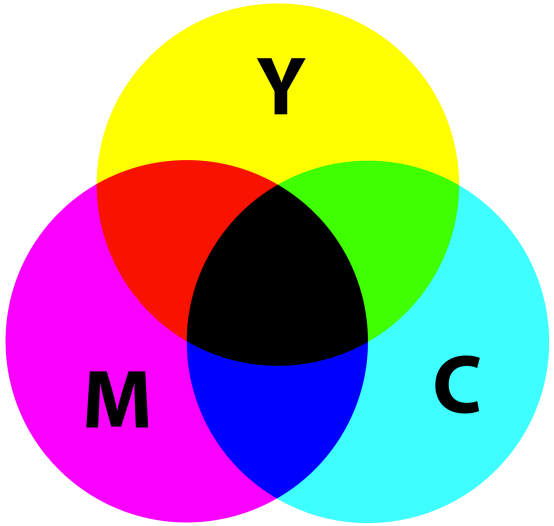


GAMUT MAPPING

- how to handle colors outside gamut?
  - one way: construct ray to white point, find closest displayable point within gamut



THE CMY COLOR MODEL

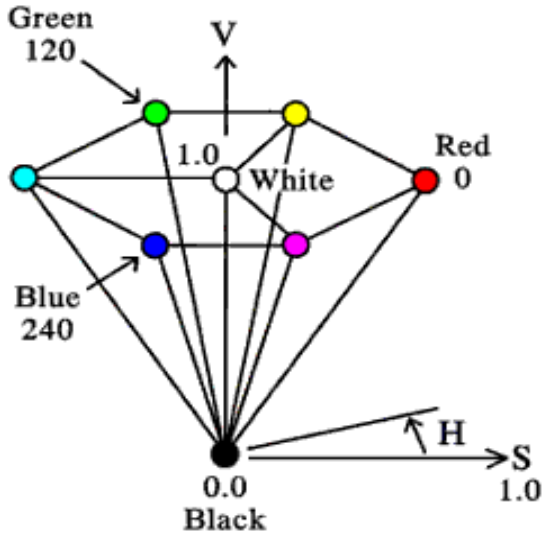


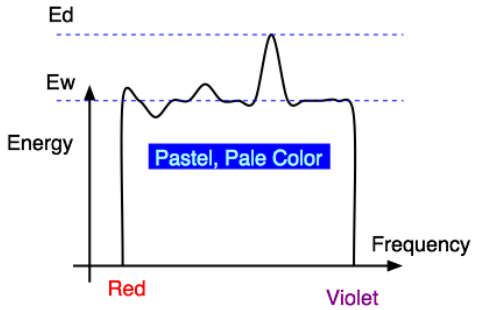
- Used in color printing
  - light is absorbed by dyes
- Cyan, Magenta and Yellow primaries are complements of Red, Blue and Green
- Primaries (dyes) subtracted from white paper
  - Red = White-Cyan = White-Green-Blue (0,1,1)
  - Green = White-Magenta = White-Red-Blue (1,0,1)
  - Blue = White-Yellow = White-Red-Green (1,1,0)
  - (r,g,b) = (1-c,1-m,1-y)

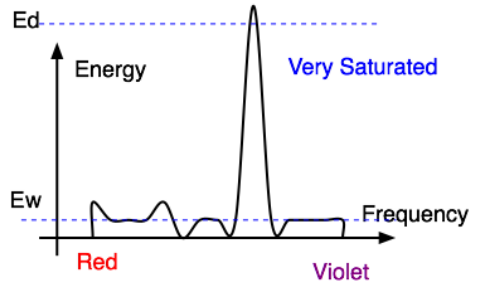
HSV COLOR SPACE

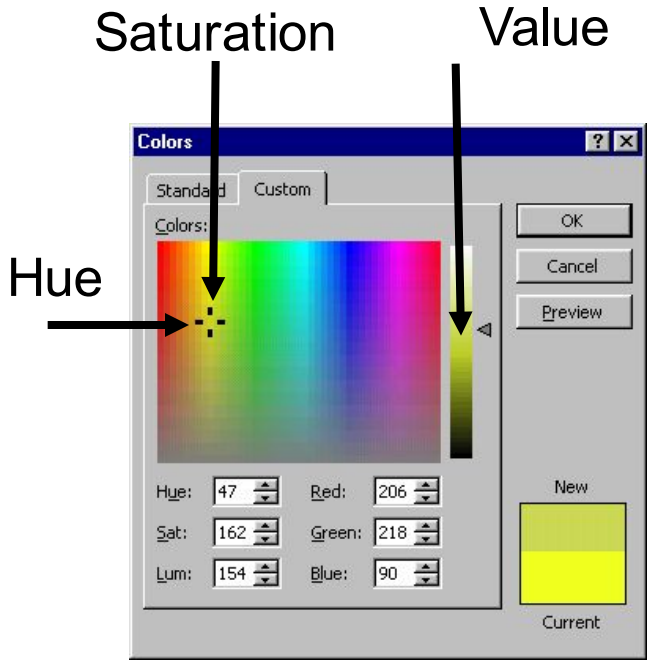
more intuitive color space for people

- H = Hue
  - dominant wavelength, “color”
- S = Saturation
  - how far from grey/white
- V = Value
  - how far from black
  - also: brightness B, intensity I, lightness L









HSI/HSV AND RGB

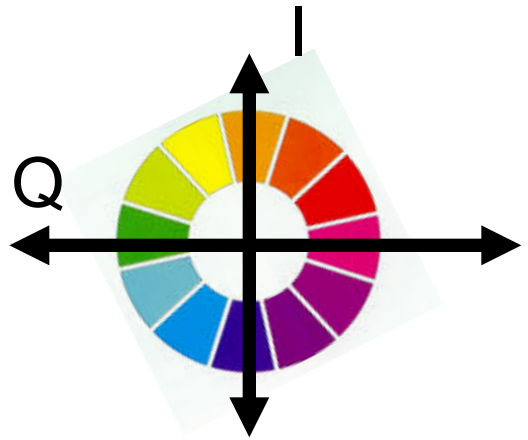
- HSV/HSI conversion from RGB is non-linear
  - H=hue same in both
  - V=value is max, I=intensity is average

$$H = \cos^{-1}\left[\frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right] \quad \text{if (B > G)},\quad H = 360 - H$$

HSI: $$S = 1 - \frac{\min(R,G,B)}{I} \qquad I = \frac{R+G+B}{3}$$

HSV: $$S = 1 - \frac{\min(R,G,B)}{V} \qquad V = \max(R,G,B)$$

YIQ COLOR SPACE



color model used for color TV

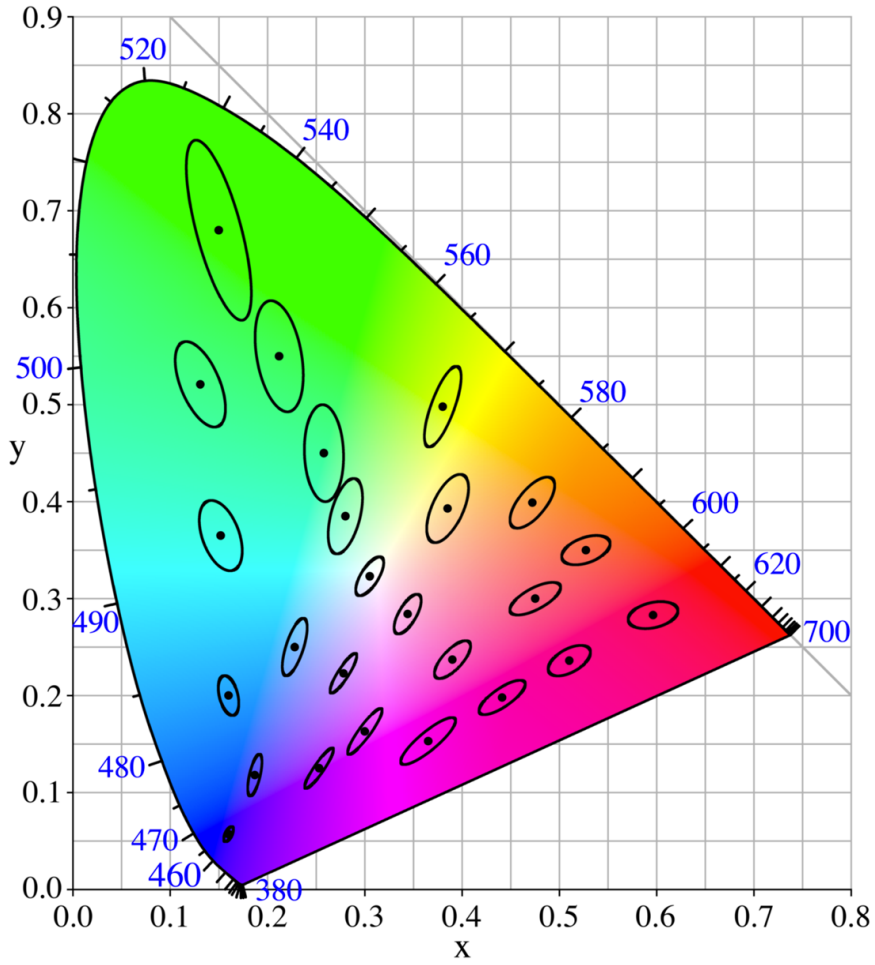
- Y is luminance (same as CIE)
- I & Q are color (not same I as HSI!)
- using Y backwards compatible for B/W TVs
- conversion from RGB is linear
  - expressible with matrix multiply

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

  - green is much lighter than red, and red lighter than blue

LUV COLOR SPACE

- Our precision in distinguishing close colors is different for different areas in CIE XYZ
  - “Tolerance”



LUV COLOR SPACE

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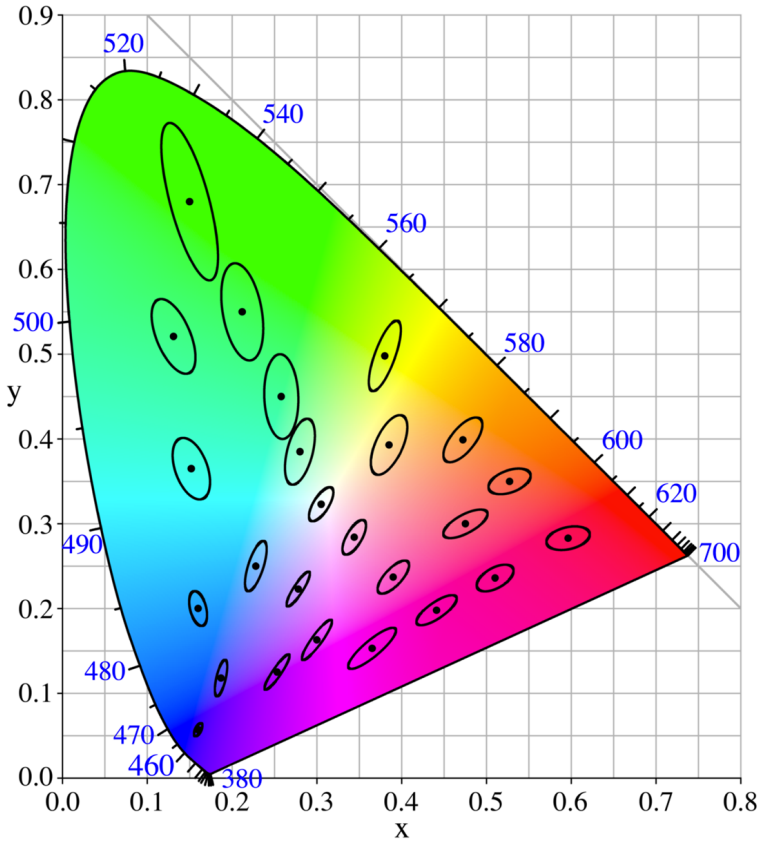
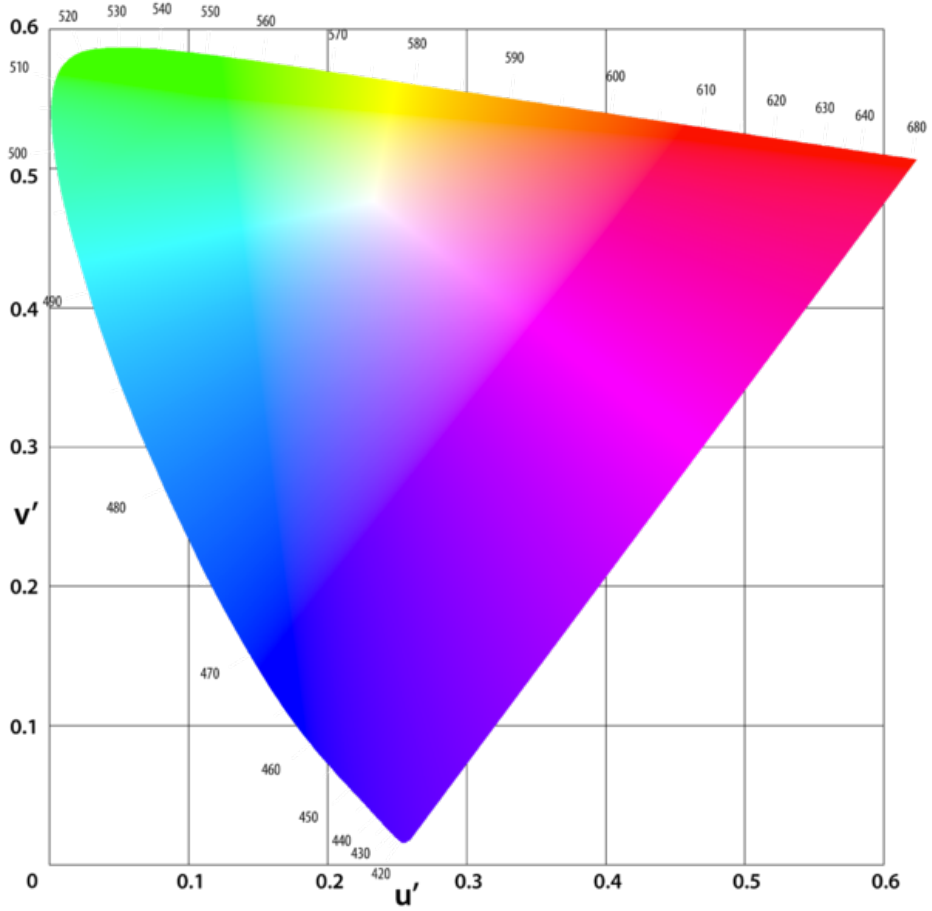
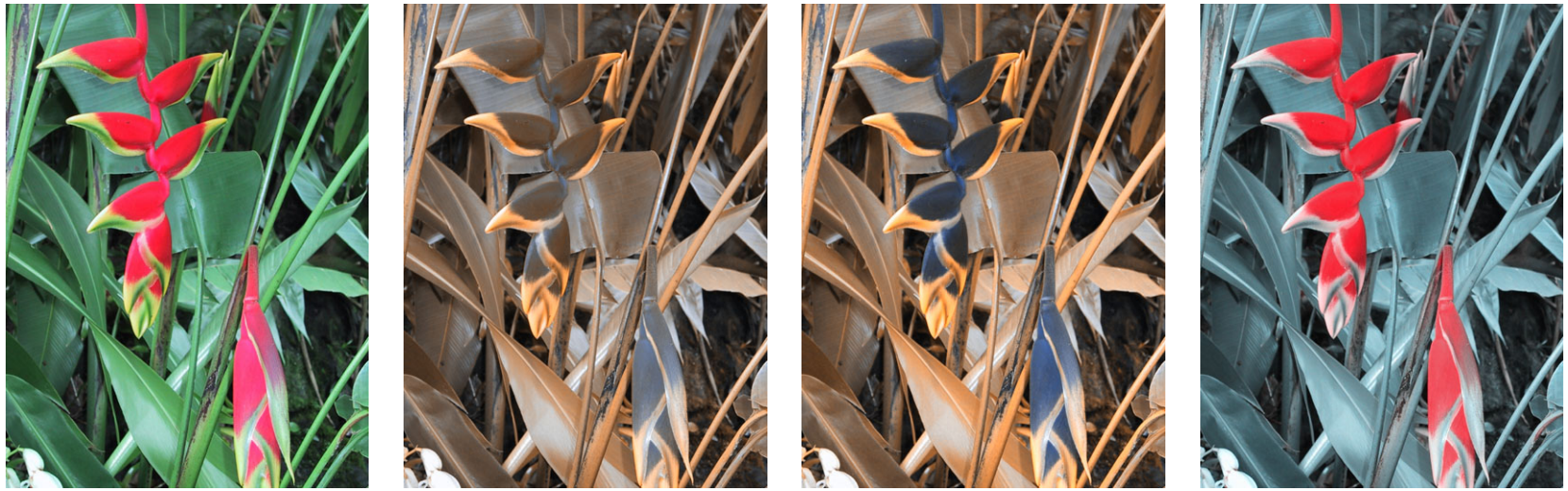




COLOUR BLINDNESS, TETRACHROMATS

- simulating color vision deficiencies

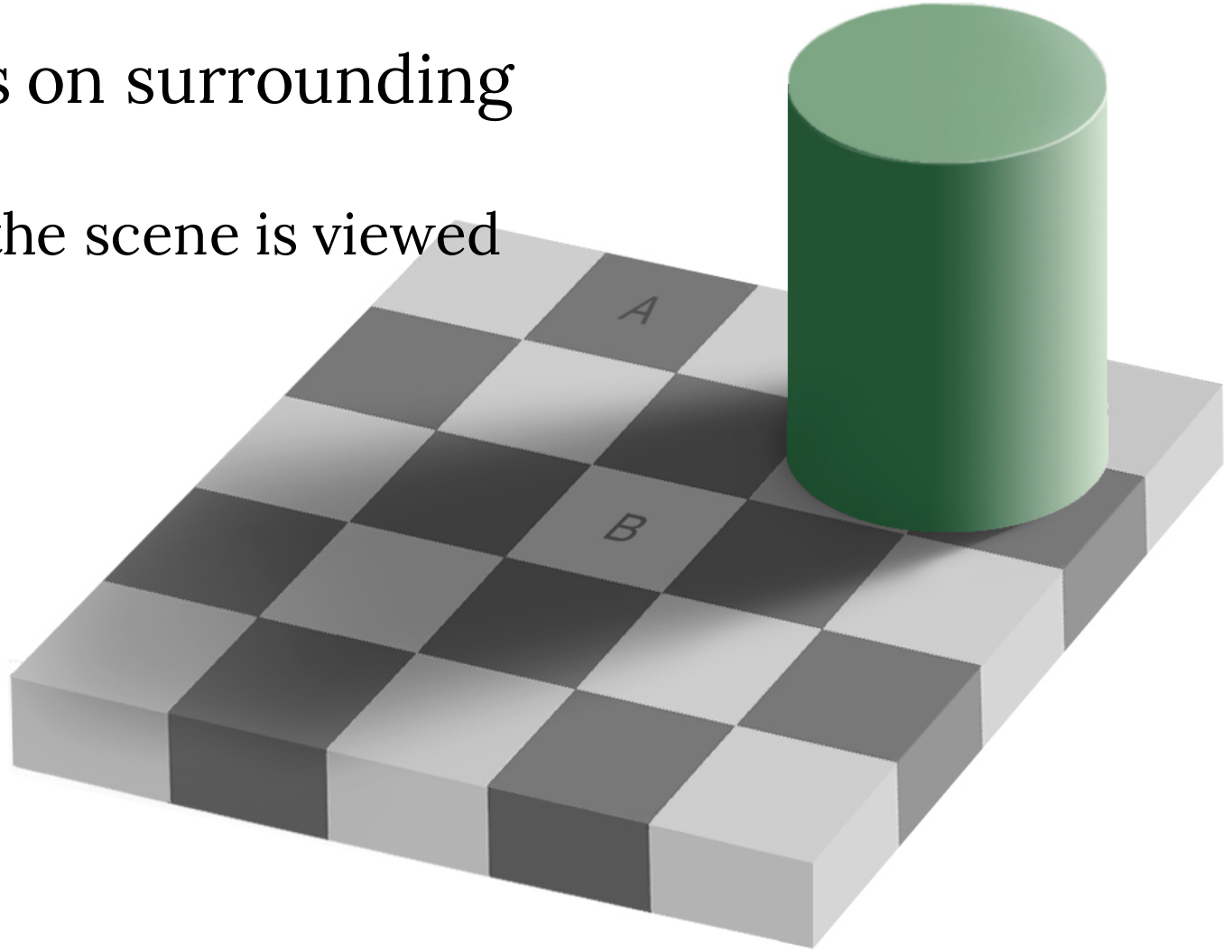


Normal vision | Deuteranope | Protanope | Tritanope

VISCHECK.COM

COLOR/LIGHTNESS CONSTANCY

- color perception depends on surrounding
  - colors in close proximity
  - illumination under which the scene is viewed



STROOP EFFECT

- **blue**
- **green**
- **purple**
- **red**
- **orange**

- interplay between cognition and perception
- used as a test (of what?)

STROOP EFFECT

- **зеленый**
- **оранжевый**
- **синий**
- **красный**
- **фиолетовый**

- interplay between cognition and perception
- used as a test (of what?)