University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2016

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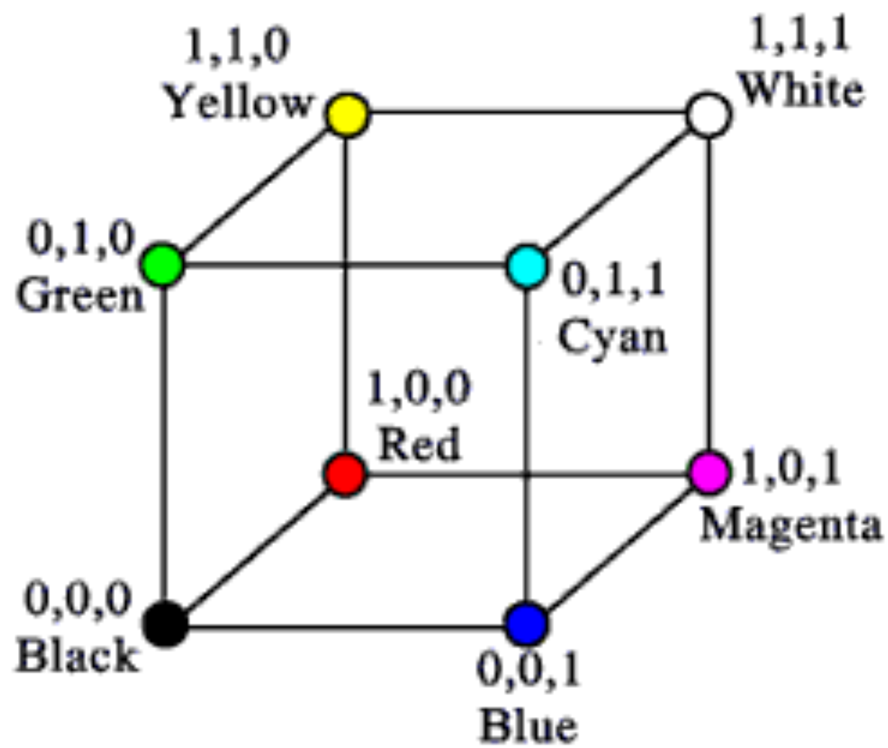
Color

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2016

Vision/Color

RGB Color

- triple (r, g, b) represents colors with amount of red, green, and blue
  - hardware-centric
  - used by OpenGL



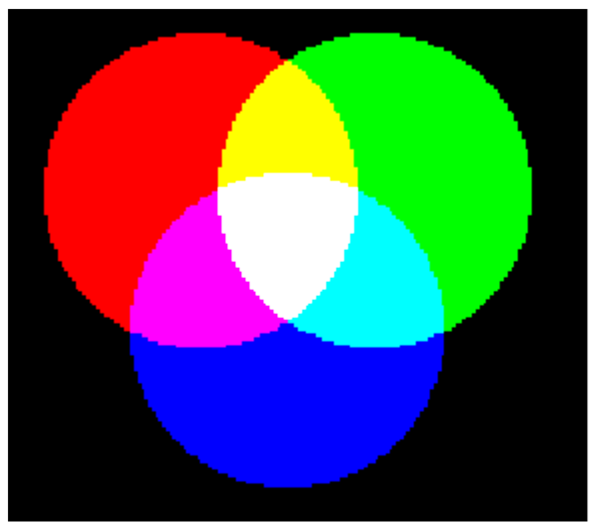
Alpha

- fourth component for transparency
  - (r,g,b,α)
- fraction we can see through
  - $c = \alpha c_f + (1-\alpha)c_b$
- as we saw in blending/compositing already

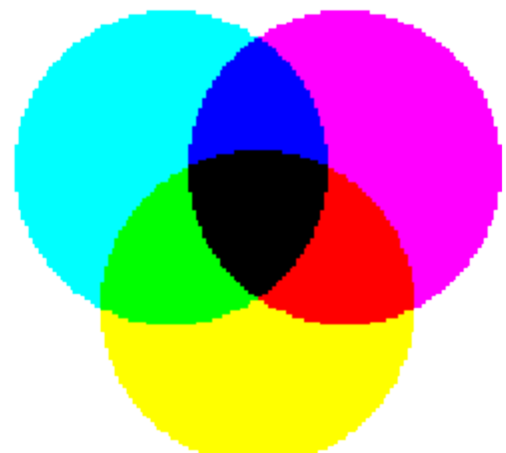
Additive vs. Subtractive Colors

- additive: light
  - monitors, LCDs
  - RGB model
- subtractive: pigment
  - printers
  - CMY model
  - dyes absorb light

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



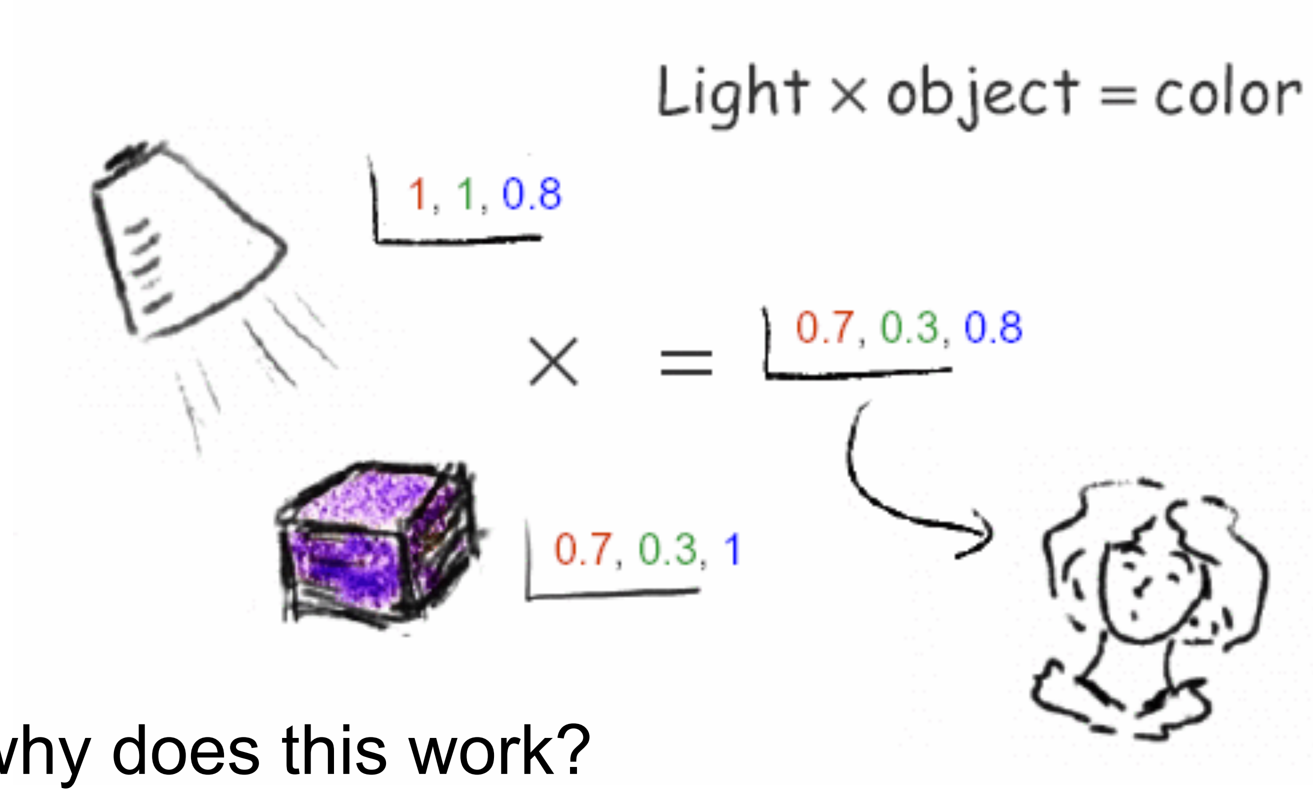
additive



subtractive

Component Color

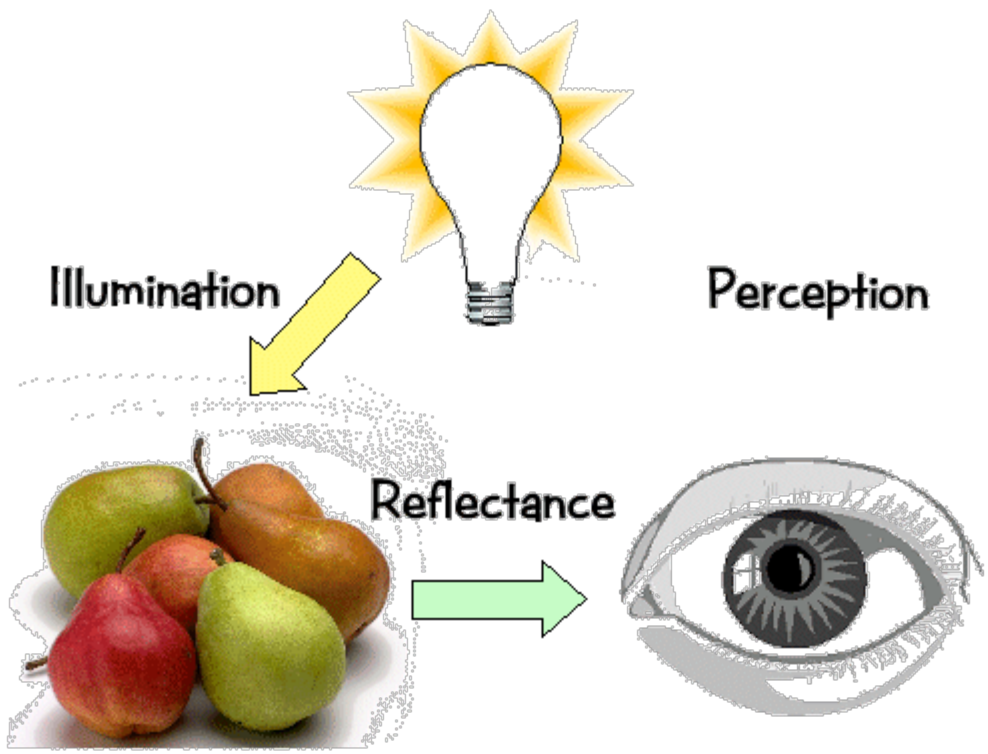
- component-wise multiplication of colors
  - (a0,a1,a2) * (b0,b1,b2) = (a0*b0, a1*b1, a2*b2)



  - why does this work?
    - must dive into light, human vision, color spaces

Basics Of Color

- elements of color:



Basics of Color

- physics
  - illumination
    - electromagnetic spectra
  - reflection
    - material properties
    - surface geometry and microgeometry
      - polished versus matte versus brushed
- perception
  - physiology and neurophysiology
  - perceptual psychology

Light Sources

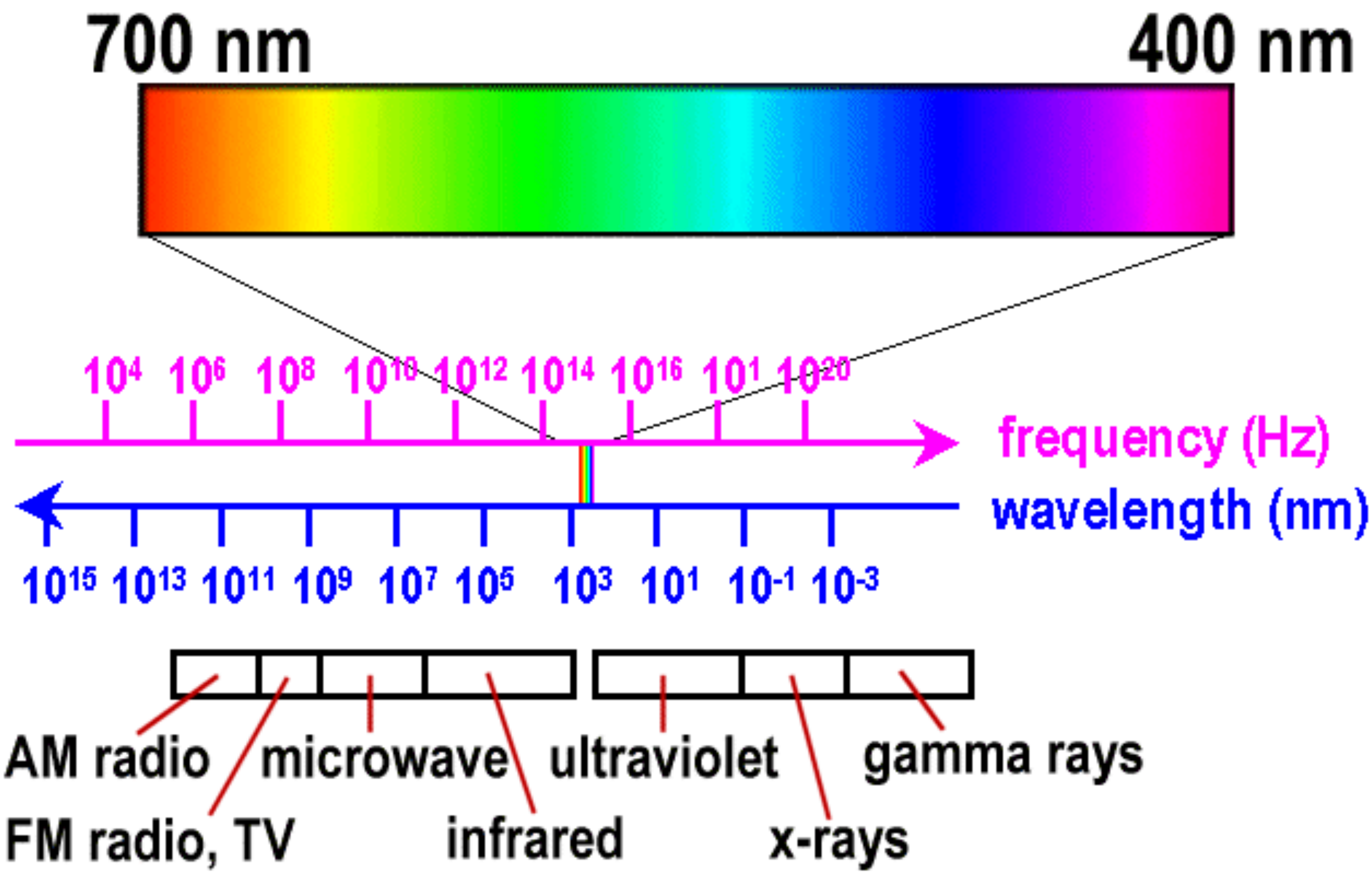
- common light sources differ in kind of spectrum they emit:
  - continuous spectrum
    - energy is emitted at all wavelengths
      - blackbody radiation
      - tungsten light bulbs
      - certain fluorescent lights
      - sunlight
      - electrical arcs
  - line spectrum
    - energy is emitted at certain discrete frequencies

Blackbody Radiation

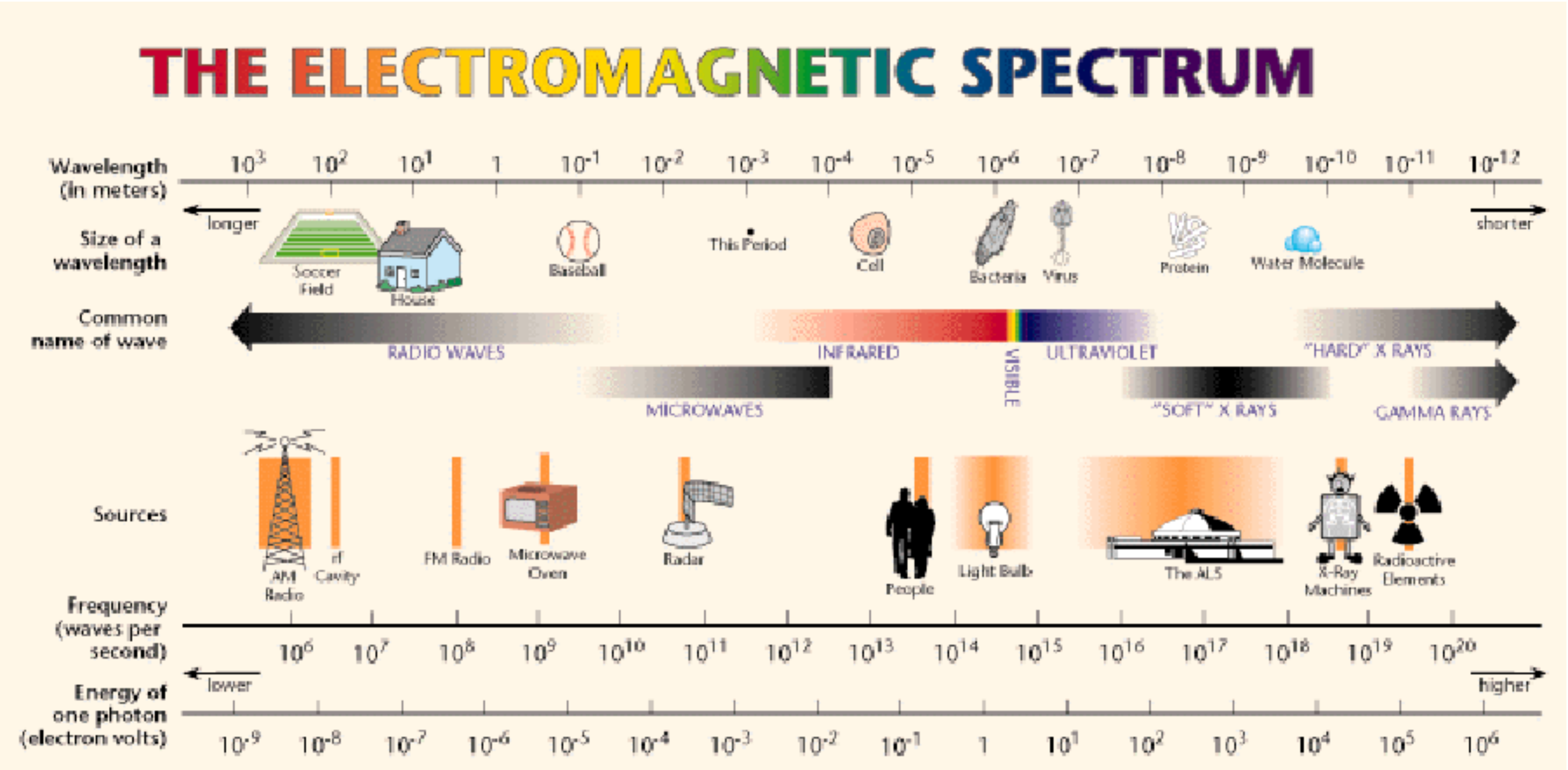
- black body
  - dark material, so that reflection can be neglected
  - spectrum of emitted light changes with temperature
    - this is the origin of the term “color temperature”
      - e.g. when setting a white point for your monitor
    - cold: mostly infrared
    - hot: reddish
    - very hot: bluish
  - demo:

http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html

Electromagnetic Spectrum

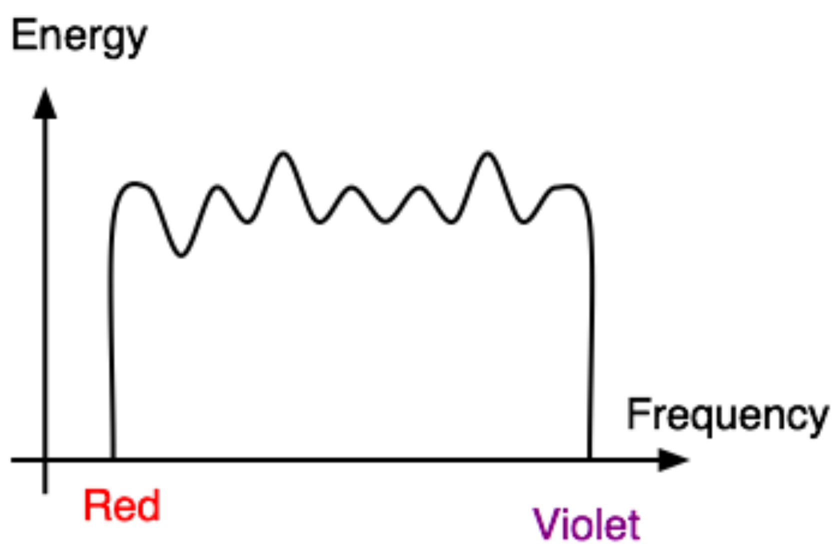


Electromagnetic Spectrum



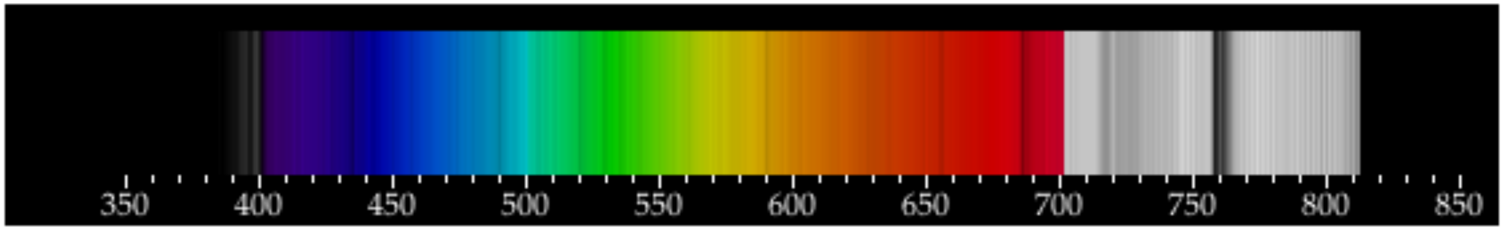
White Light

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

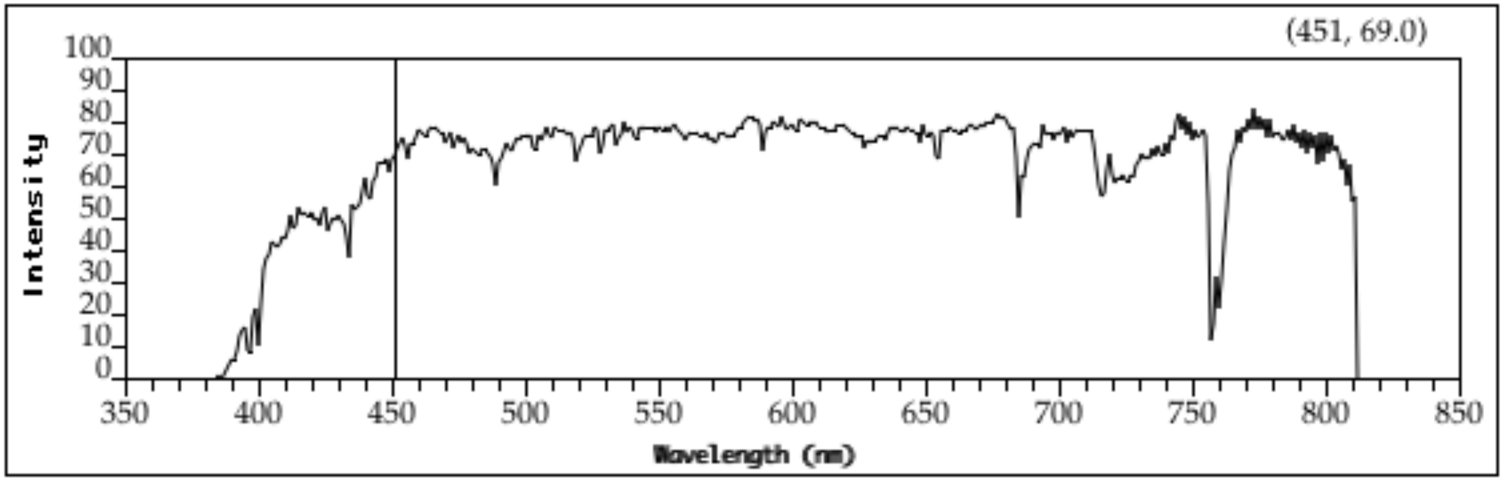


Sunlight Spectrum

- spectral distribution: power vs. wavelength



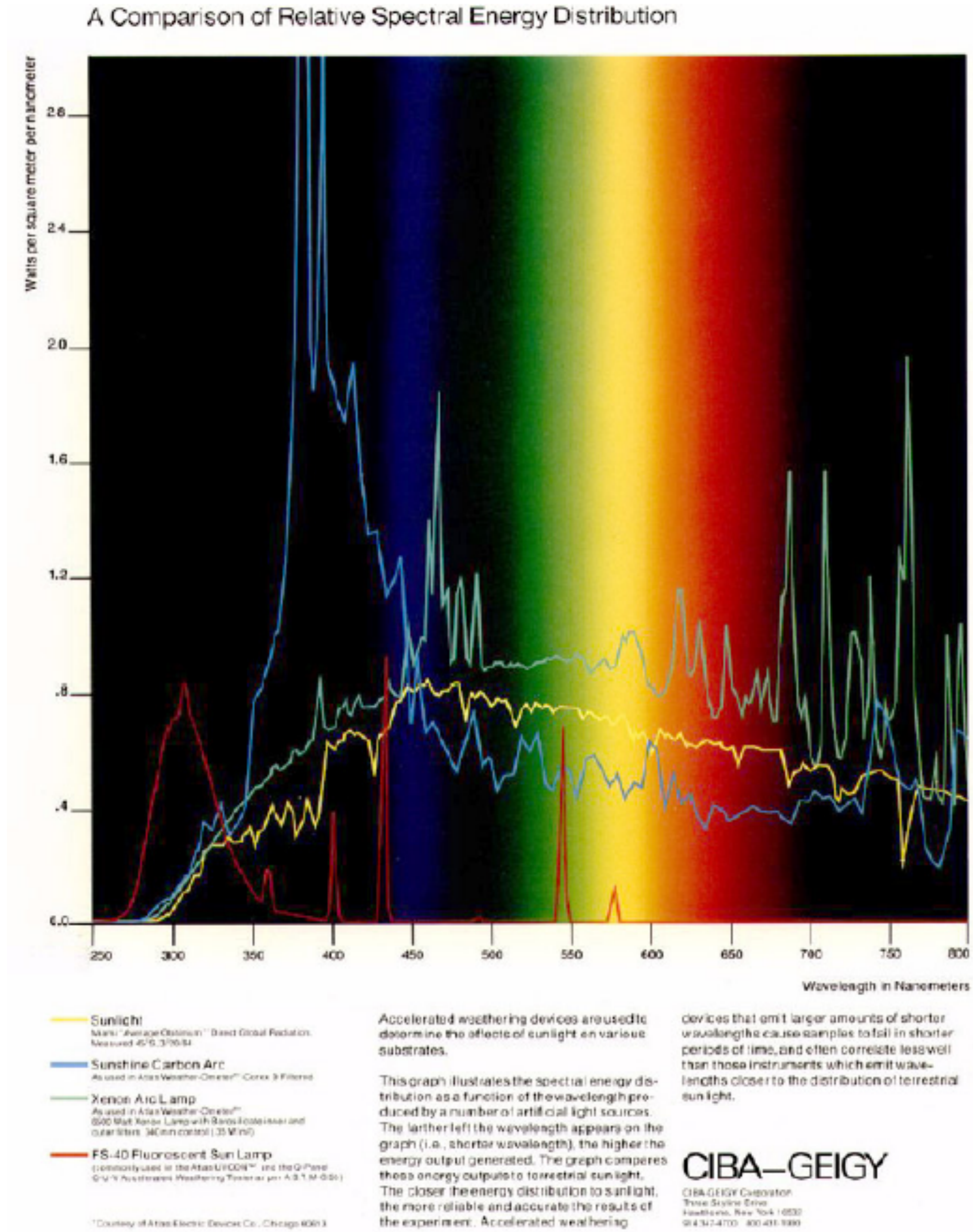
Emission Graph



Electromagnetic Spectrum

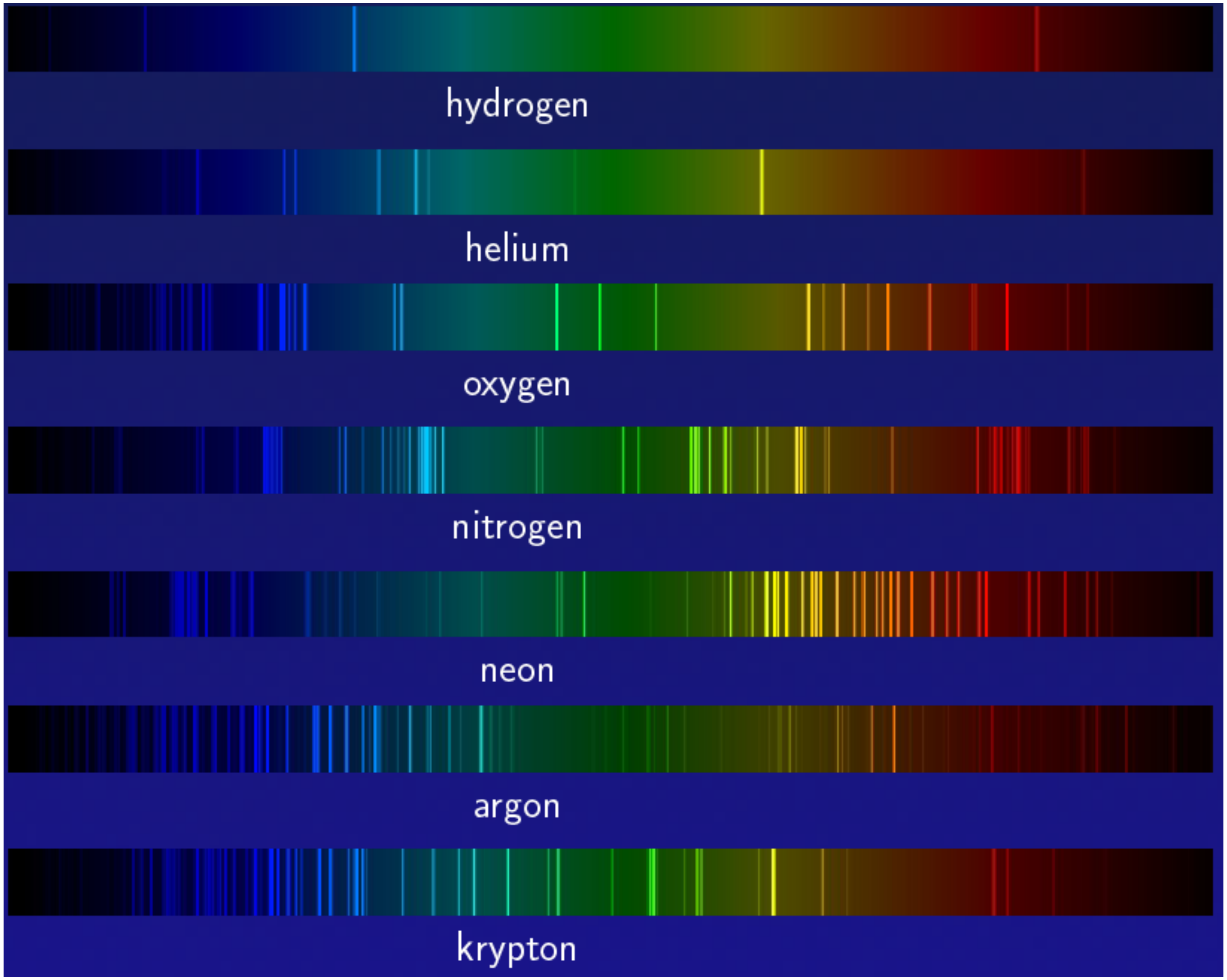
Continuous Spectrum

- sunlight
- various "daylight" lamps



Line Spectrum

- ionized gases
- lasers
- some fluorescent lamps

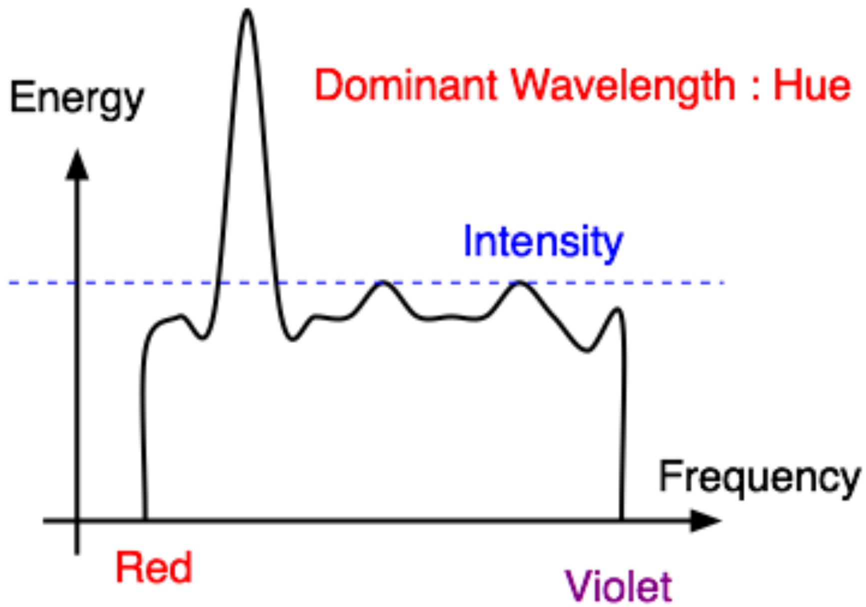


White Light and Color

- when white light is incident upon an object, some frequencies are reflected and some are absorbed by the object
- combination of frequencies present in the reflected light that determines what we perceive as the color of the object

Hue

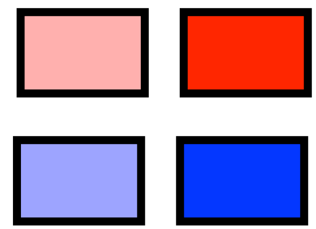
- hue (or simply, "color") is dominant wavelength/ frequency

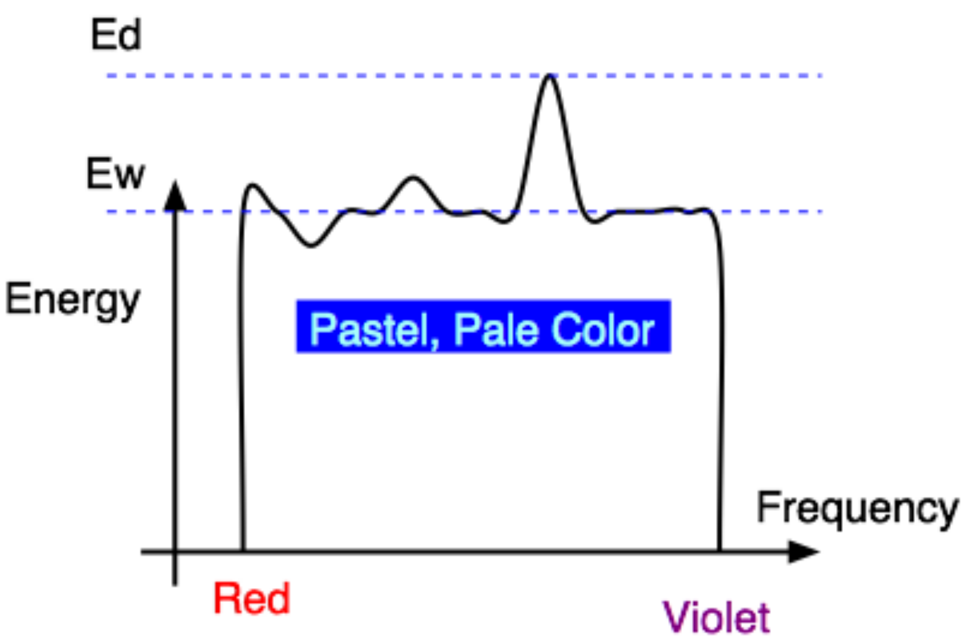


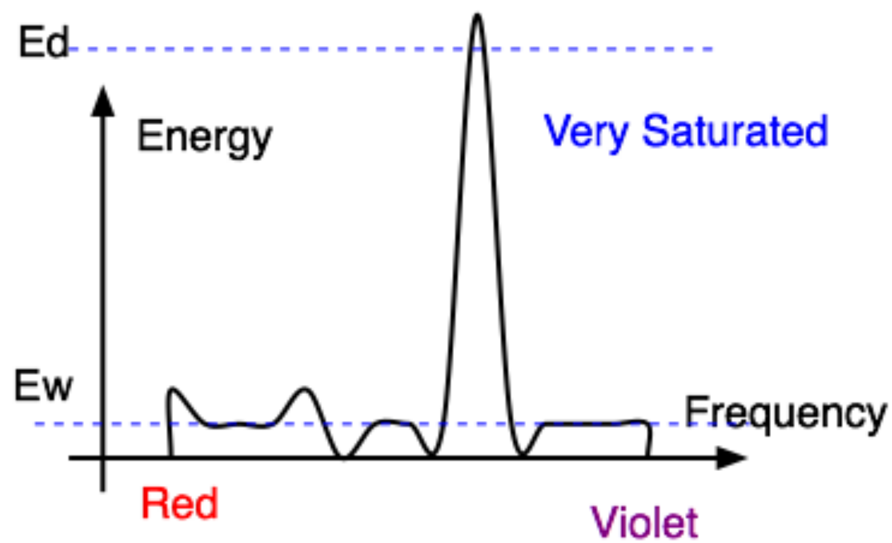
  - integration of energy for all visible wavelengths is proportional to intensity of color

Saturation or Purity of Light

- how washed out or how pure the color of the light appears
  - contribution of dominant light vs. other frequencies producing white light
  - saturation: how far is color from grey
    - pink is less saturated than red
    - sky blue is less saturated than royal blue







Intensity vs. Brightness

- intensity : physical term
  - measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)
- lightness/brightness: perceived intensity of light
  - nonlinear

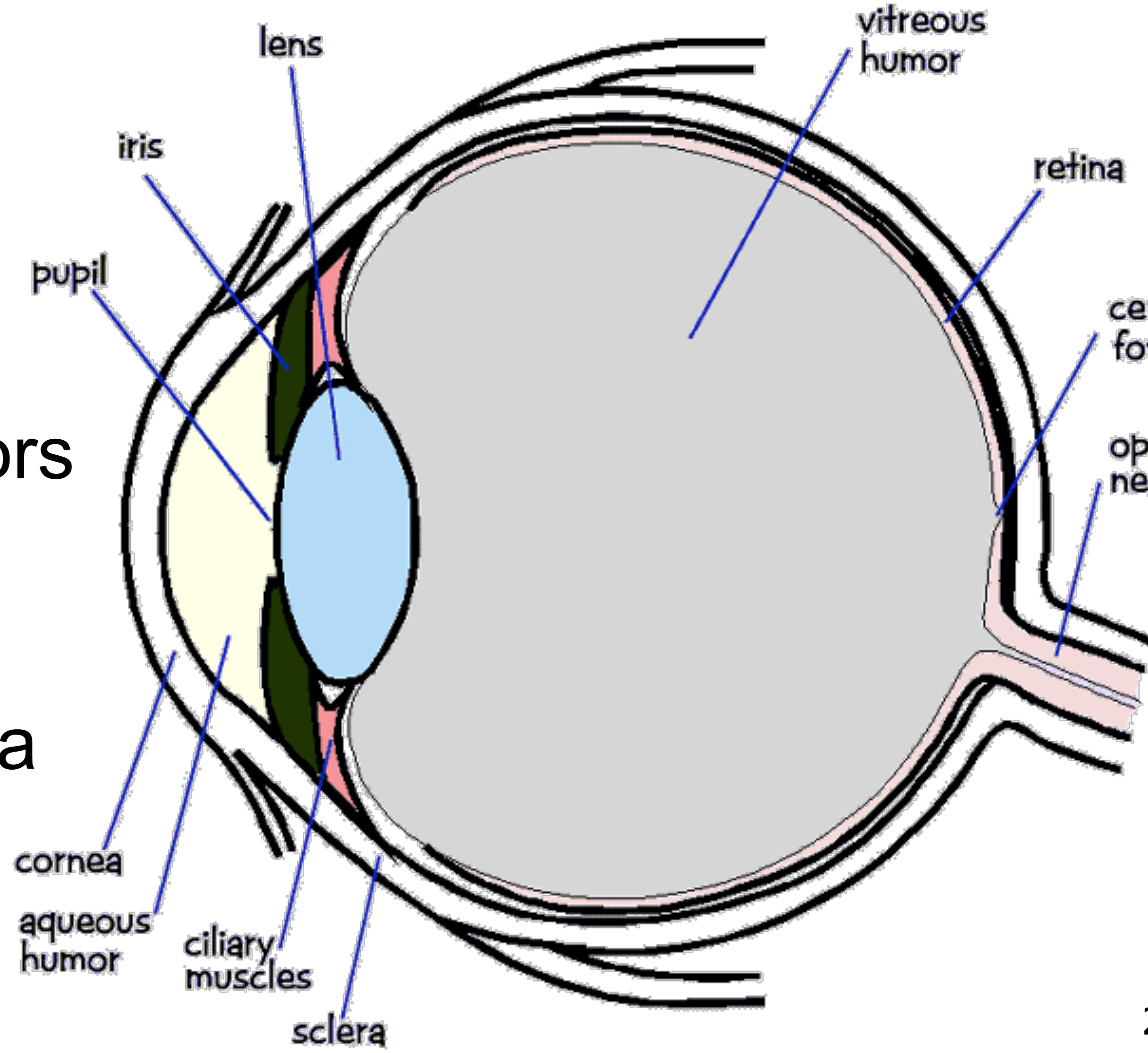
Perceptual vs. Colorimetric Terms

- Perceptual
  - Hue
  - Saturation
  - Lightness
    - *reflecting objects*
  - Brightness
    - *light sources*

- Colorimetric
  - Dominant wavelength
  - Excitation purity
  - Luminance
  - Luminance

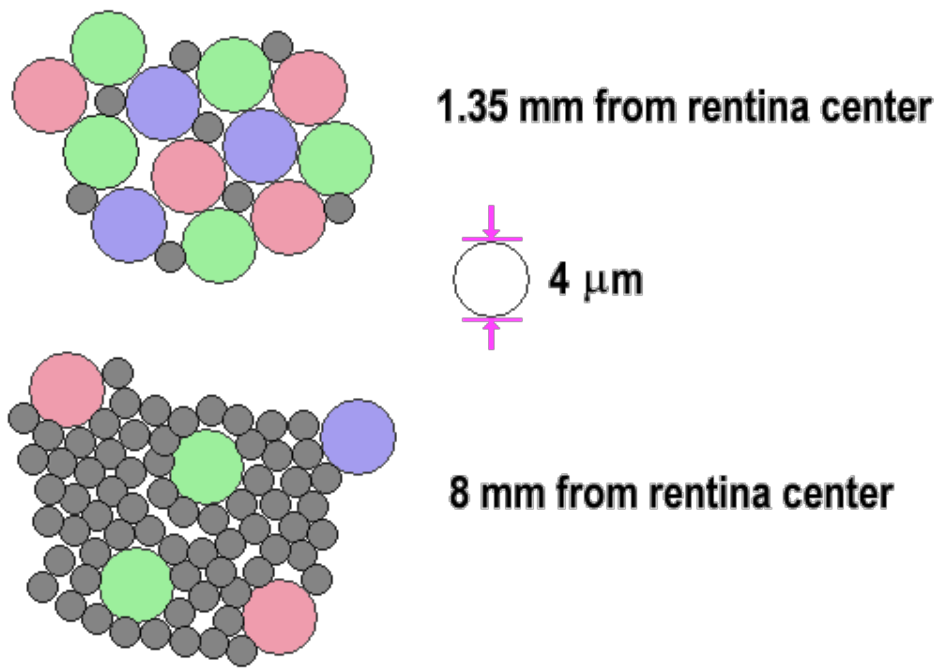
Physiology of Vision

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



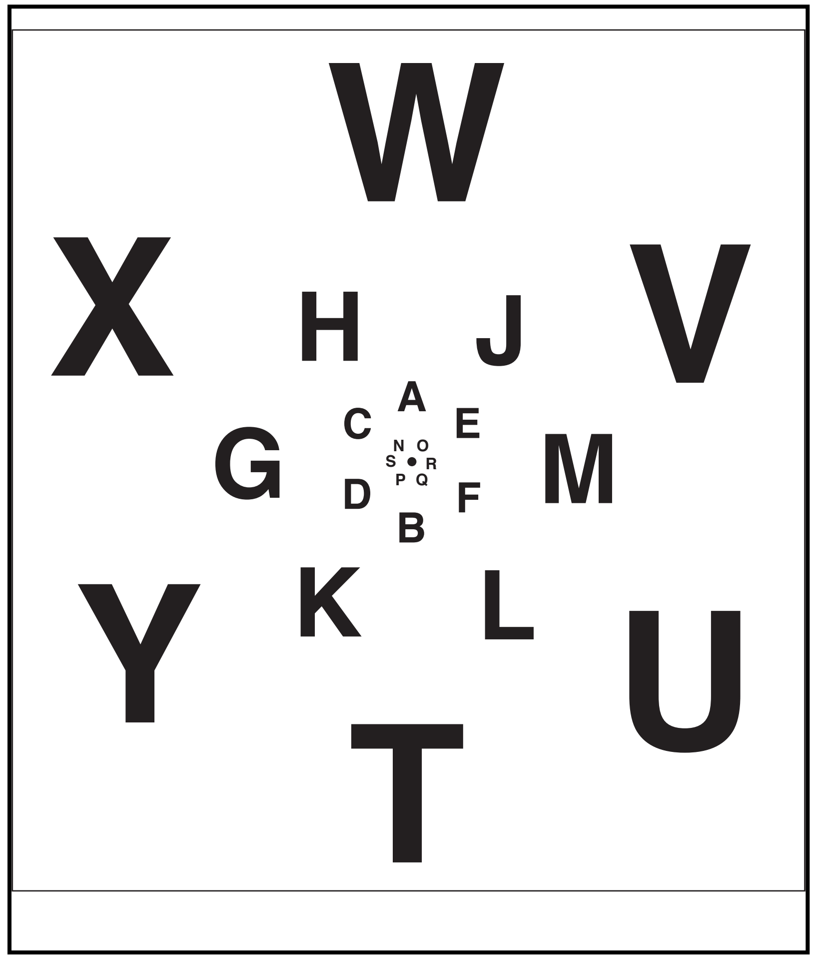
Physiology of Vision

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



Foveal Vision

- hold out your thumb at arm’s length



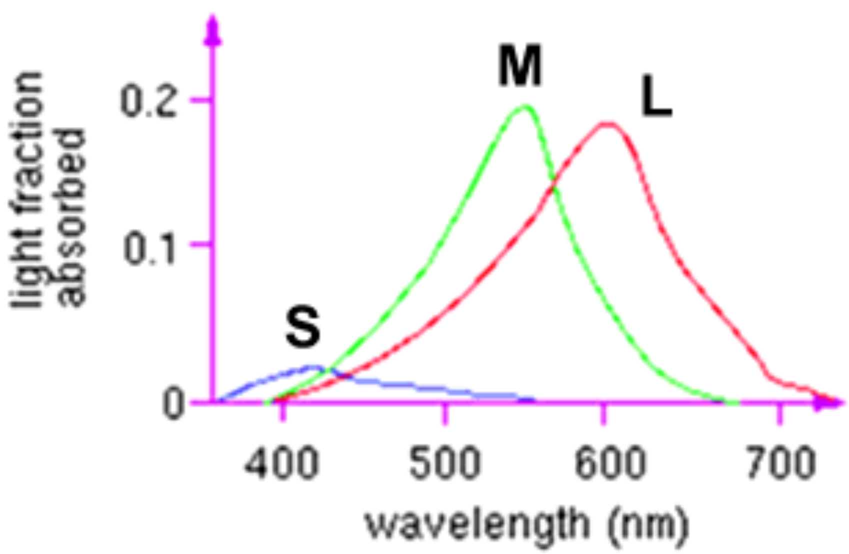
Tristimulus Theory of Color Vision

- 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

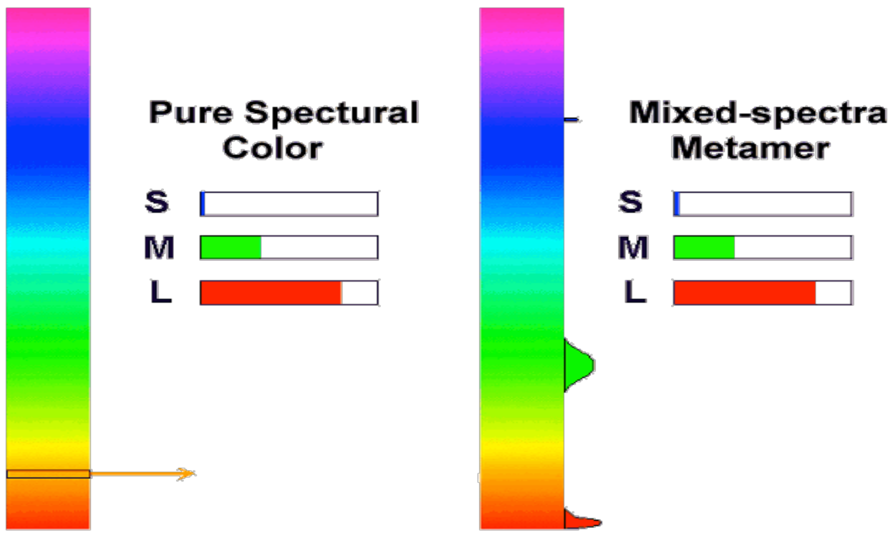
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)



  - color blindness results from missing cone type(s)

Metamers

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

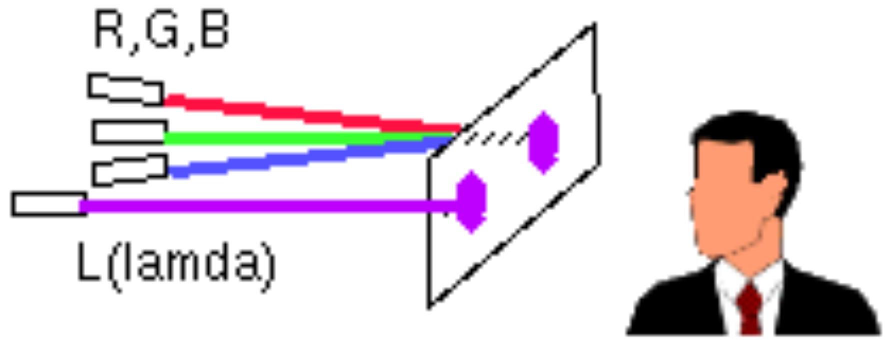


- identical perceptions of color can thus be caused by very different spectra
- demo

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

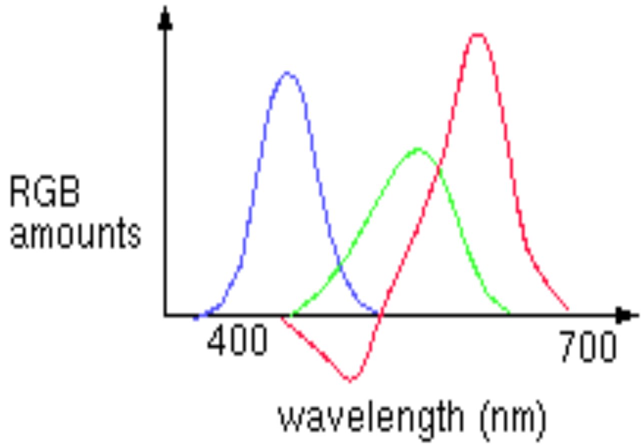
Color Spaces

- three types of cones suggests color is a 3D quantity. how to define 3D color space?



- idea: perceptually based measurement
  - shine given wavelength (λ) on a screen
  - user must control three pure lights producing three other wavelengths
    - used R=700nm, G=546nm, and B=436nm
  - adjust intensity of RGB until colors are identical
    - this works because of metamers!
    - experiments performed in 1930s

Negative Lobes

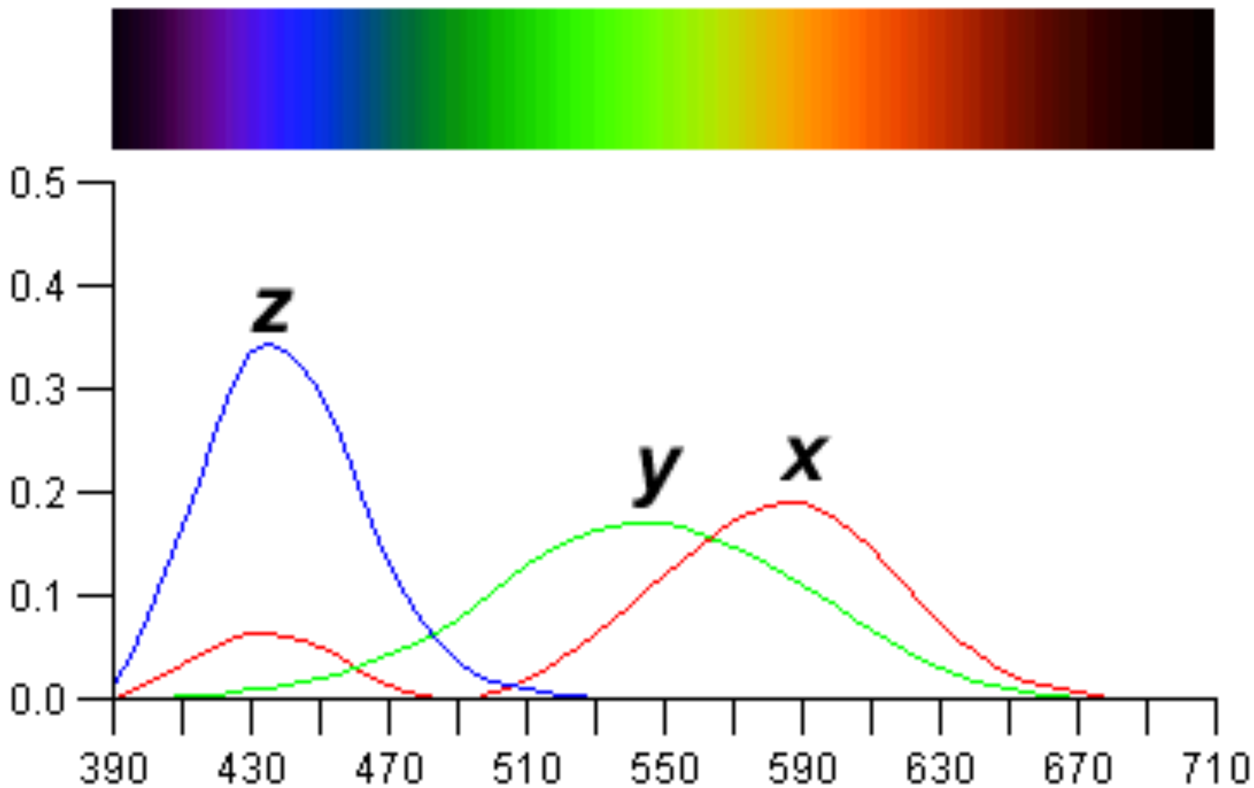


- sometimes need to point red light to shine on target in order to match colors
  - equivalent mathematically to "removing red"
    - but physically impossible to remove red from CRT phosphors
- can't generate all other wavelenths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy

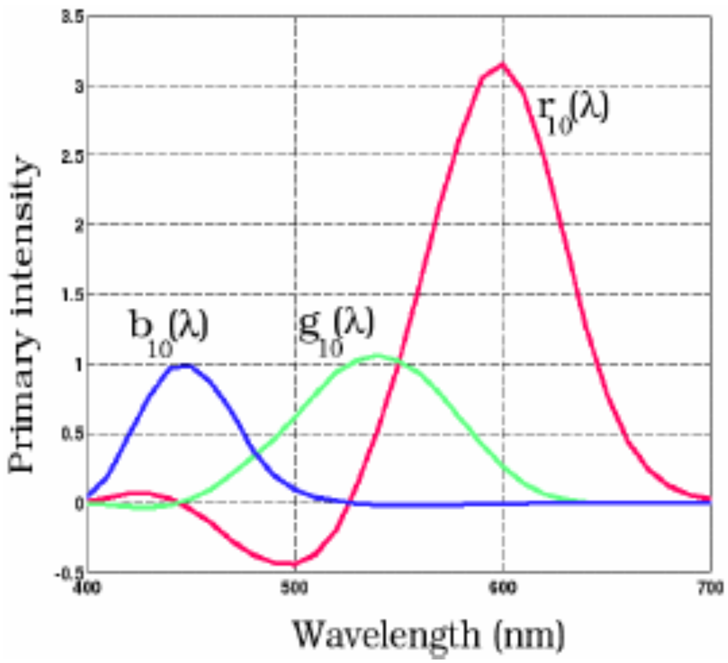
CIE Color Space

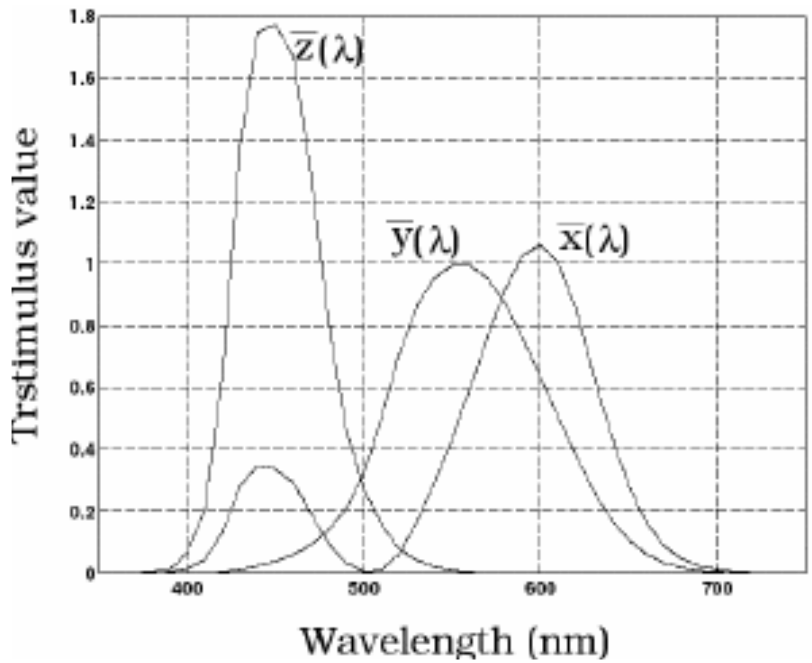
- CIE defined 3 “imaginary” lights X, Y, Z
  - any wavelength λ can be matched perceptually by positive combinations

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



Measured vs. CIE Color Spaces



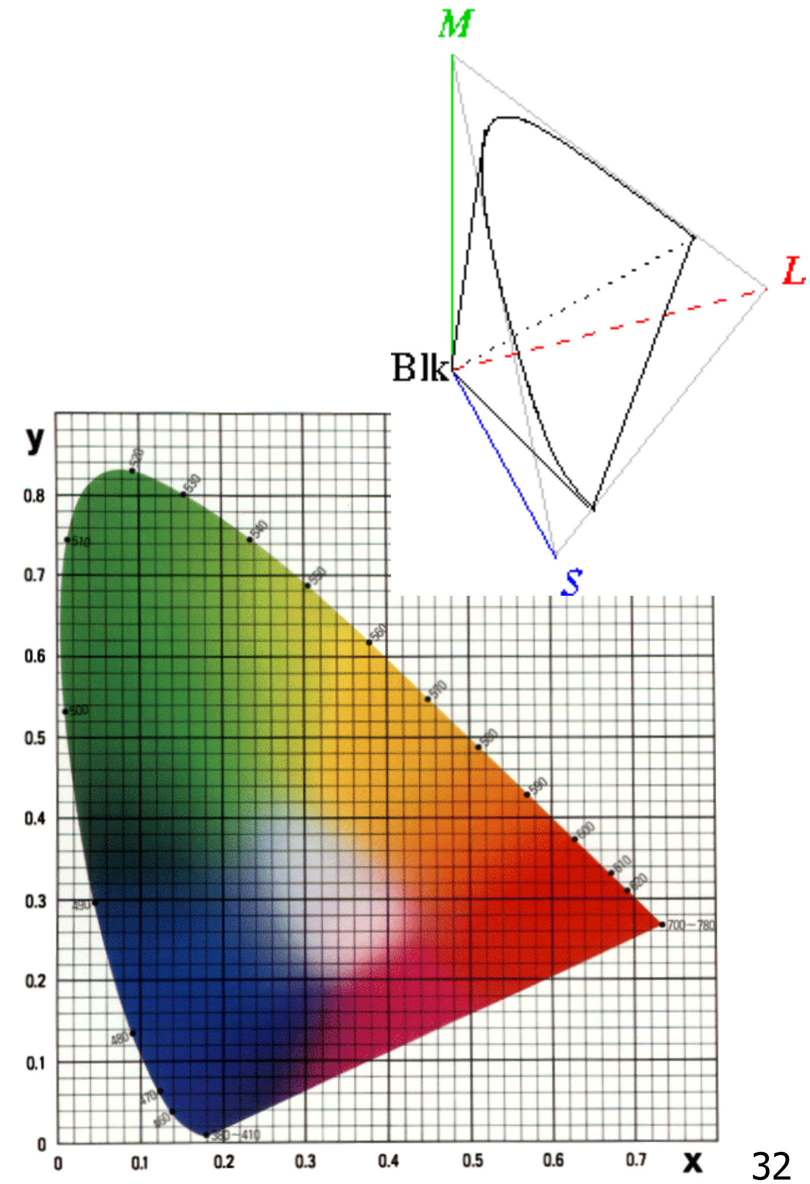


- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes

- transformed basis
  - “imaginary” lights
  - all positive, unit area
  - Y is luminance, no hue
  - X,Z no luminance

CIE and Chromaticity Diagram

- X, Y, Z form 3D shape
- project X, Y, Z on X+Y+Z=1 plane for 2D color space
  - chromaticity diagram
    - separate color from brightness
    - x = X / (X+Y+Z)
    - y = Y / (X+Y+Z)



CIE “Horseshoe” Diagram Facts

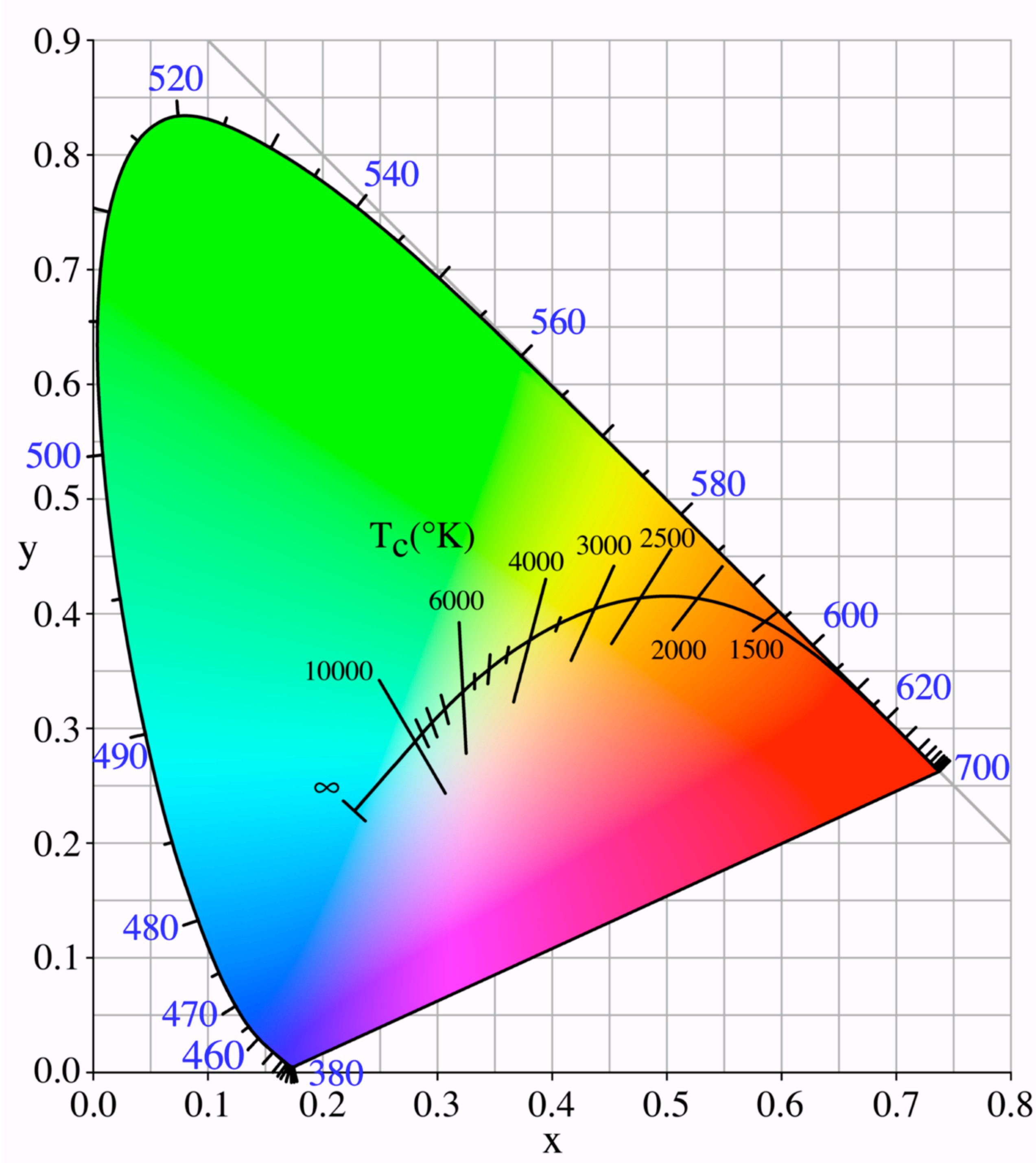
- all visible colors lie inside the horseshoe
  - result from color matching experiments
- spectral (monochromatic) colors lie around the border
  - straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

CIE "Horseshoe" Diagram Facts

- can choose a point C for a white point
  - corresponds to an illuminant
  - usually on curve swept out by black body radiation spectra for different temperatures

Blackbody Curve

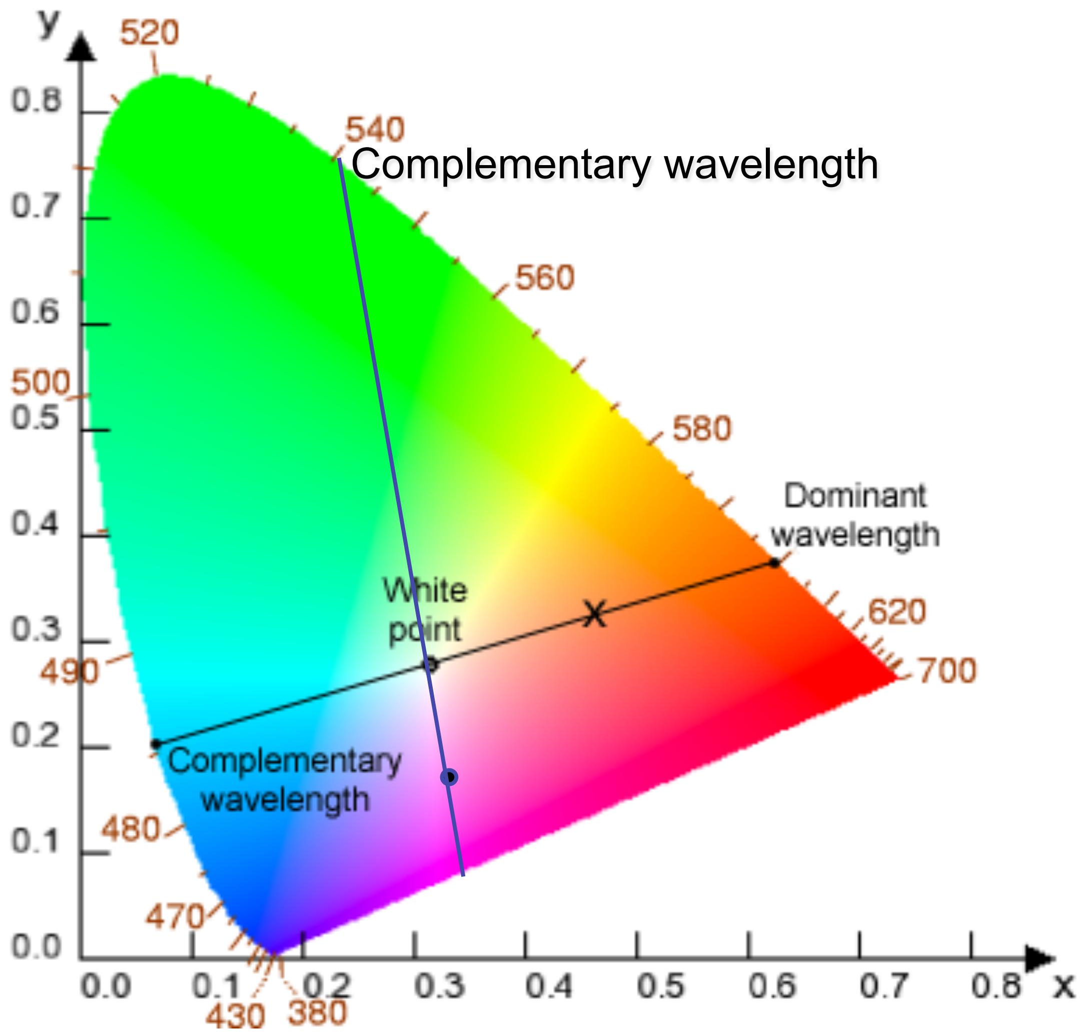
- illumination:
  - candle 2000K
  - A: Light bulb 3000K
  - sunset/ sunrise 3200K
  - D: daylight 6500K
  - overcast day 7000K
  - lightning >20,000K



CIE "Horseshoe" Diagram Facts

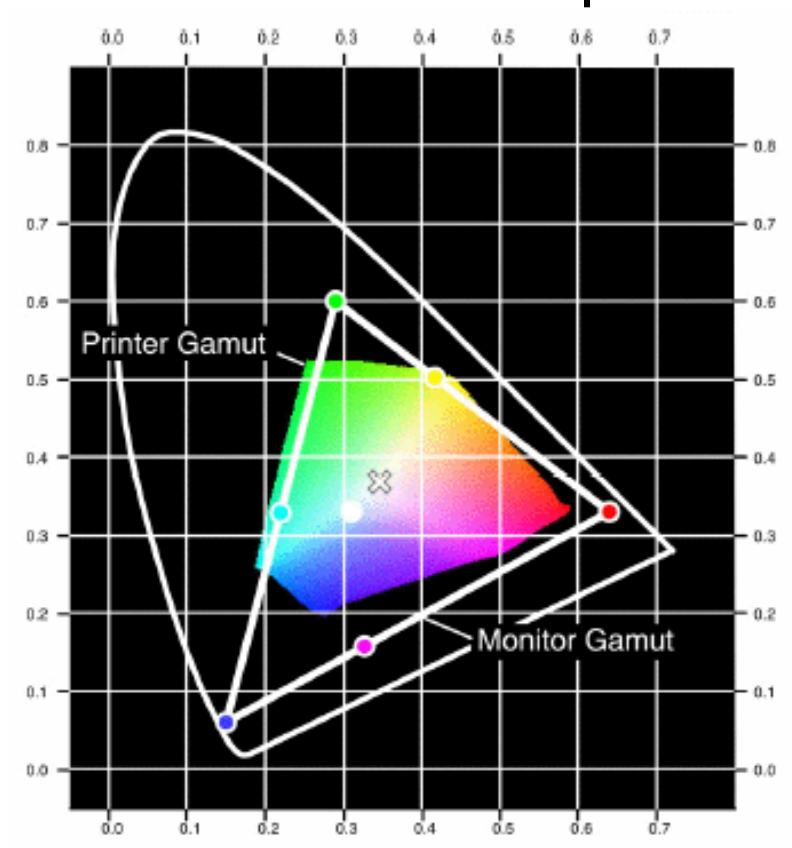
- can choose a point C for a white point
  - corresponds to an illuminant
  - usually on curve swept out by black body radiation spectra for different temperatures
  - two colors are complementary relative to C when are
    - located on opposite sides of line segment through C
      - so C is an affine combination of the two colors
  - find dominant wavelength of a color:
    - extend line from C through color to edge of diagram
    - some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does

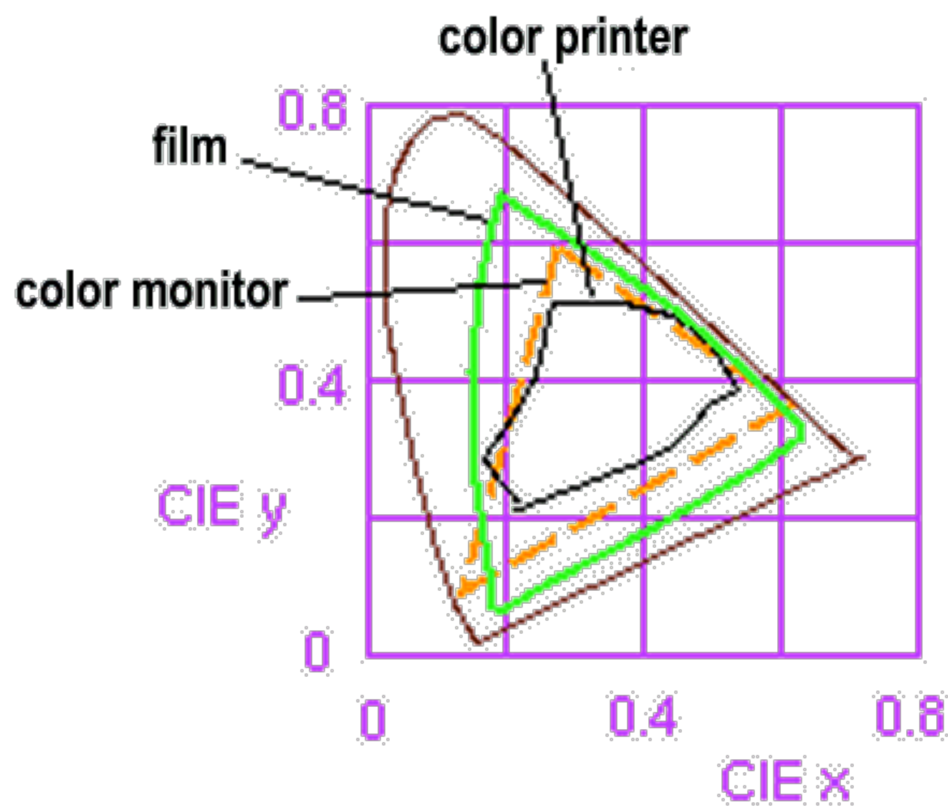
Color Interpolation, Dominant & Opponent Wavelength



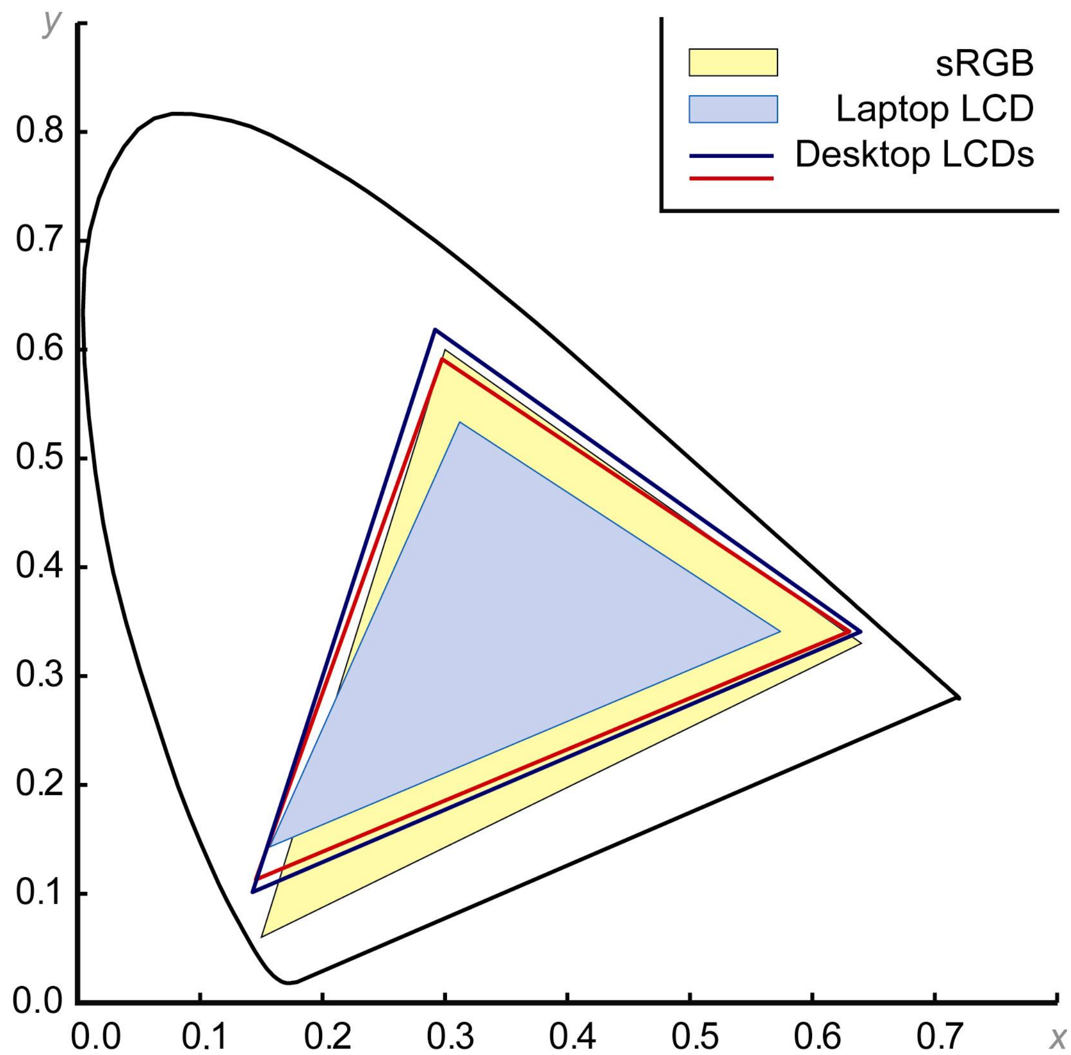
Device Color Gamuts

- 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



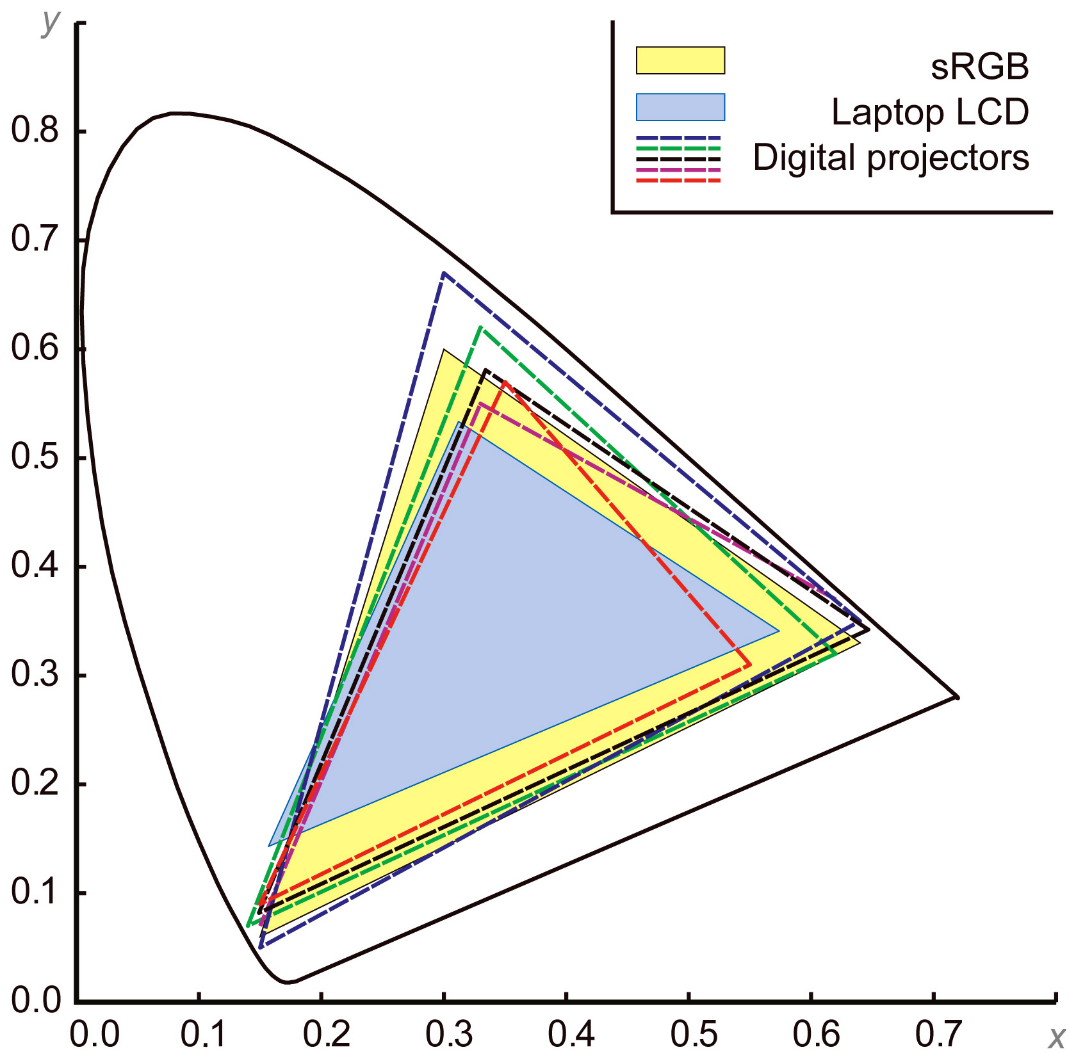


Display Gamuts



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

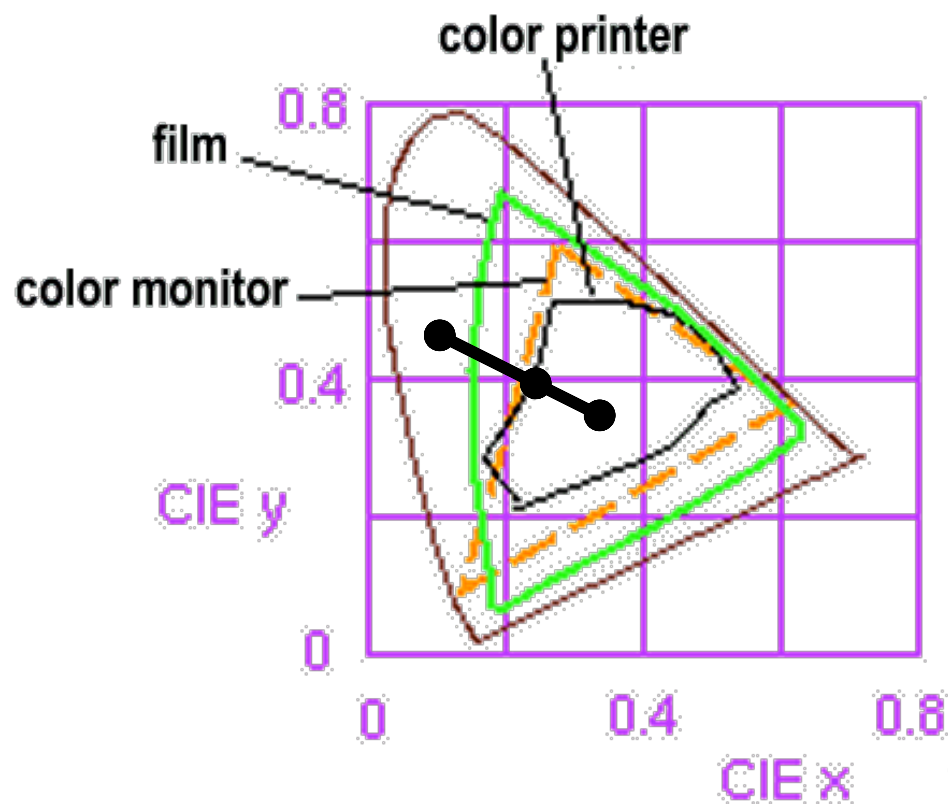
Projector Gamuts



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

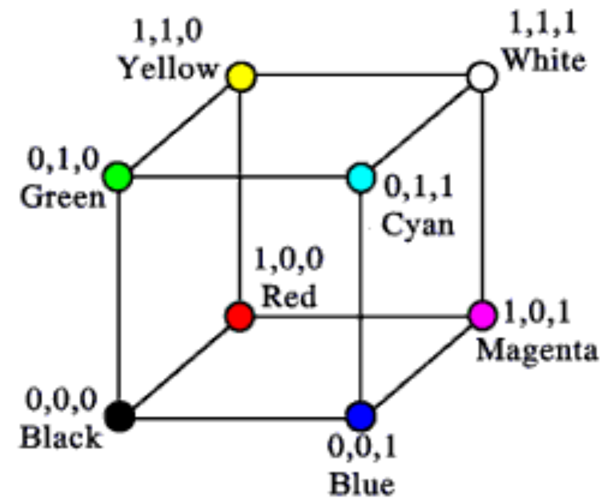
Gamut Mapping

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

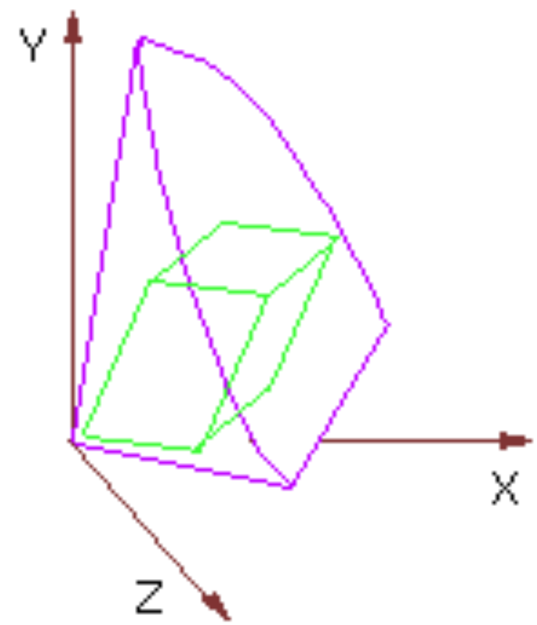


RGB Color Space (Color Cube)

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

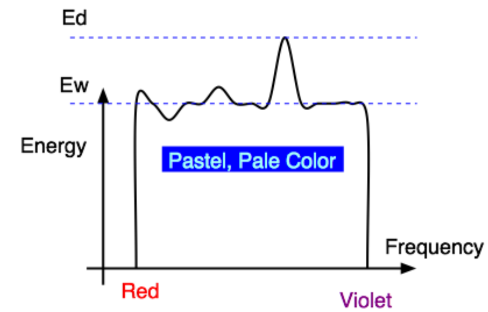


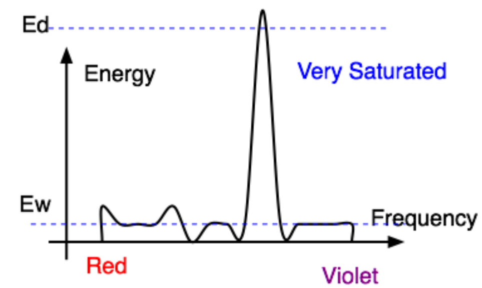
- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube

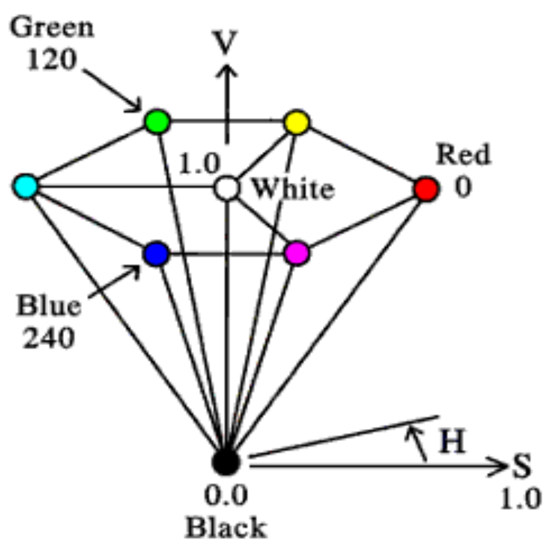


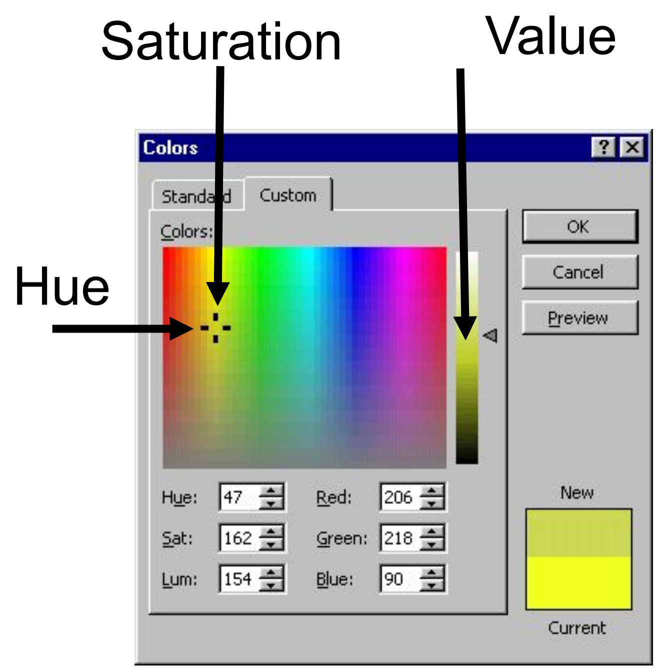
HSV Color Space

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









HSI/HSV and RGB

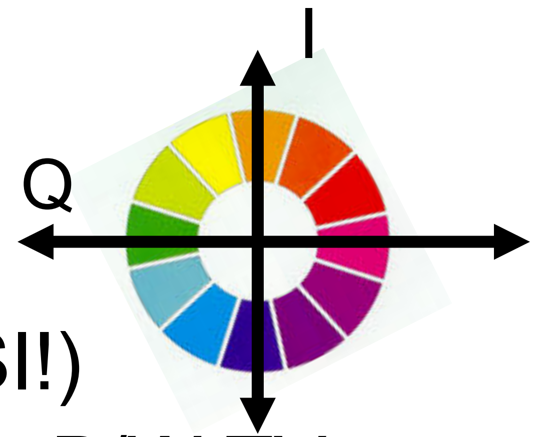
- HSV/HSI conversion from RGB not expressible in matrix
  - H=hue same in both
  - V=value is max, I=intensity is average

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

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

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

YIQ Color Space



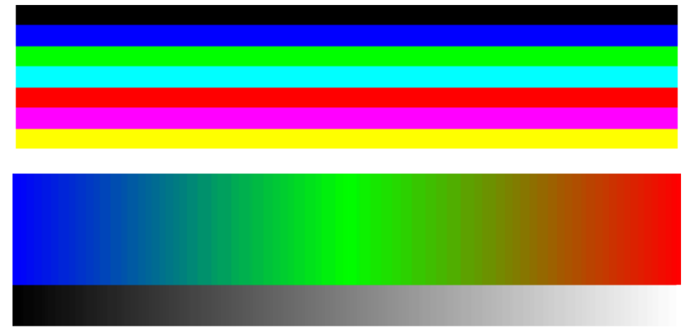
- color model used for color TV
  - Y is luminance (same as CIE)
  - I & Q are color (not same I as HSI!)
  - using Y backwards compatible for B/W TVs
  - conversion from RGB is linear
    - expressible with matrix multiply

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

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

Luminance vs. Intensity

- luminance
  - Y of YIQ
  - 0.299R + 0.587G + 0.114B
  - captures important factor
- intensity/brightness
  - I/V/B of HSI/HSV/HSB
  - 0.333R + 0.333G + 0.333B
  - not perceptually based



(a) Colour Image

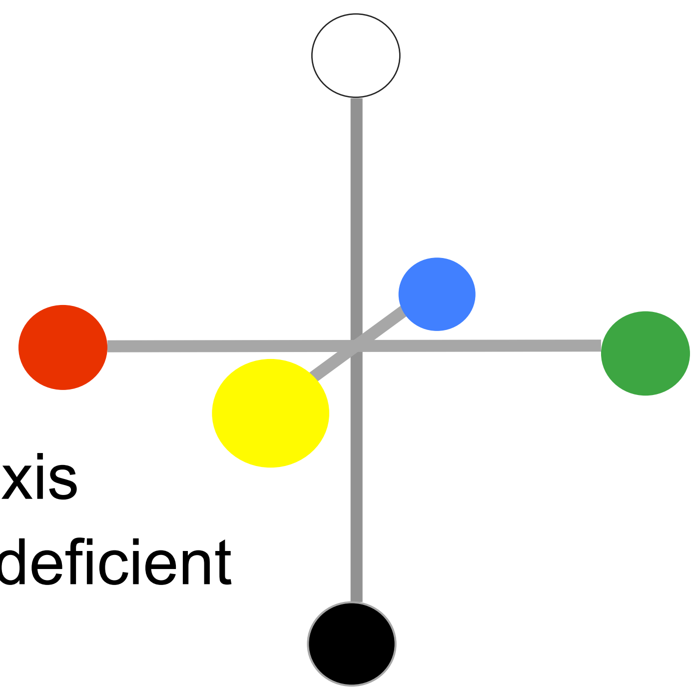
(b) Intensity Image

(c) Luminance Image

www.csse.uwa.edu.au/~robyn/Visioncourse/colour/lecture/node5.html

Opponent Color

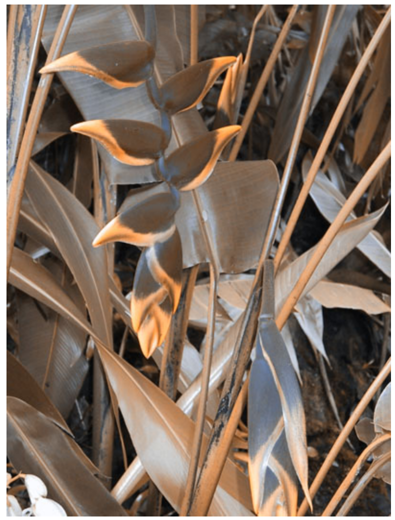
- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
- first level encoding
  - linear combination of LMS
  - before optic nerve
  - basis for perception
  - "color blind" = color deficient
    - degraded/no acuity on one axis
    - 8%-10% men are red/green deficient



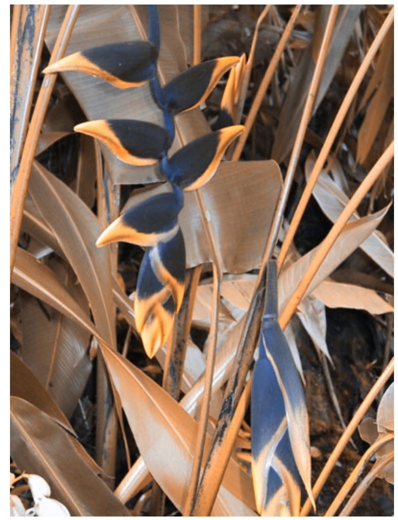
rehue.net

- simulates color vision deficiencies

Normal vision

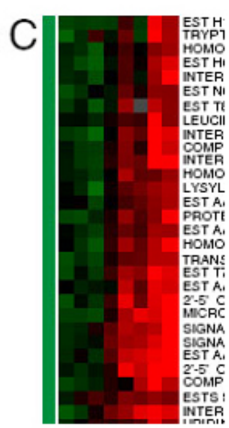


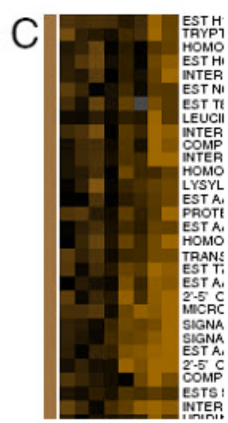
Deuteranope

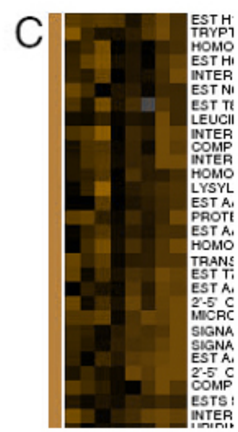


Protanope

Tritanope

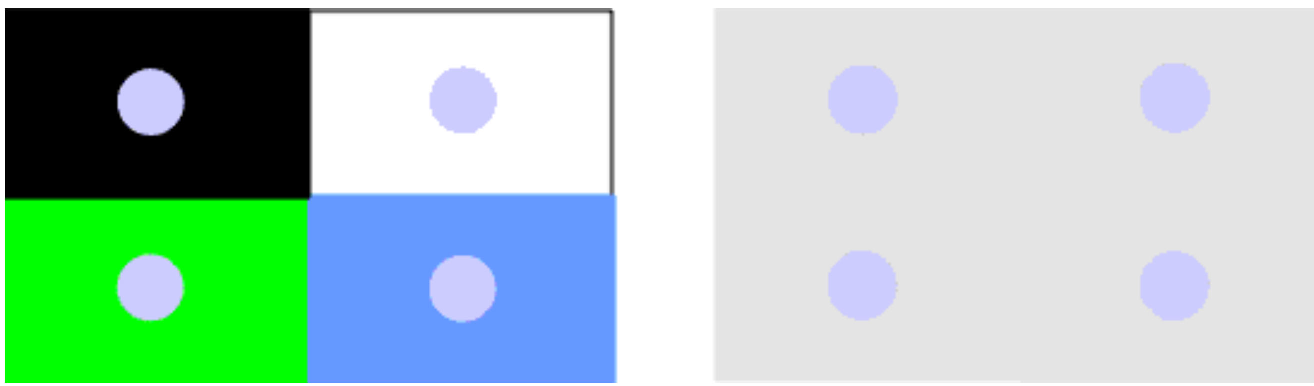






Color/Lightness Constancy

- color perception depends on surrounding
  - colors in close proximity
    - simultaneous contrast effect



  - illumination under which the scene is viewed

Color/Lightness Constancy

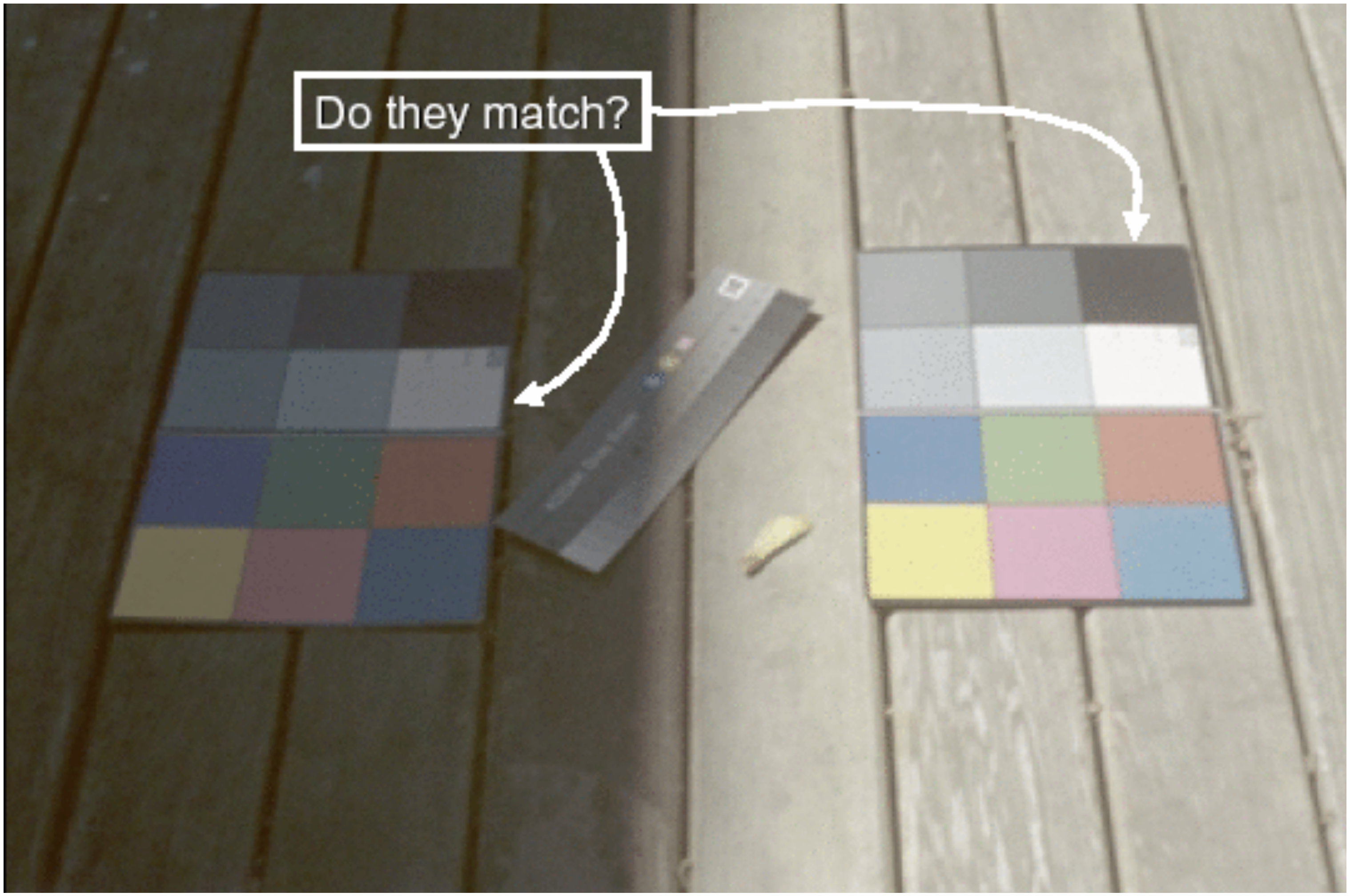


Image courtesy of John McCann

Color/Lightness Constancy

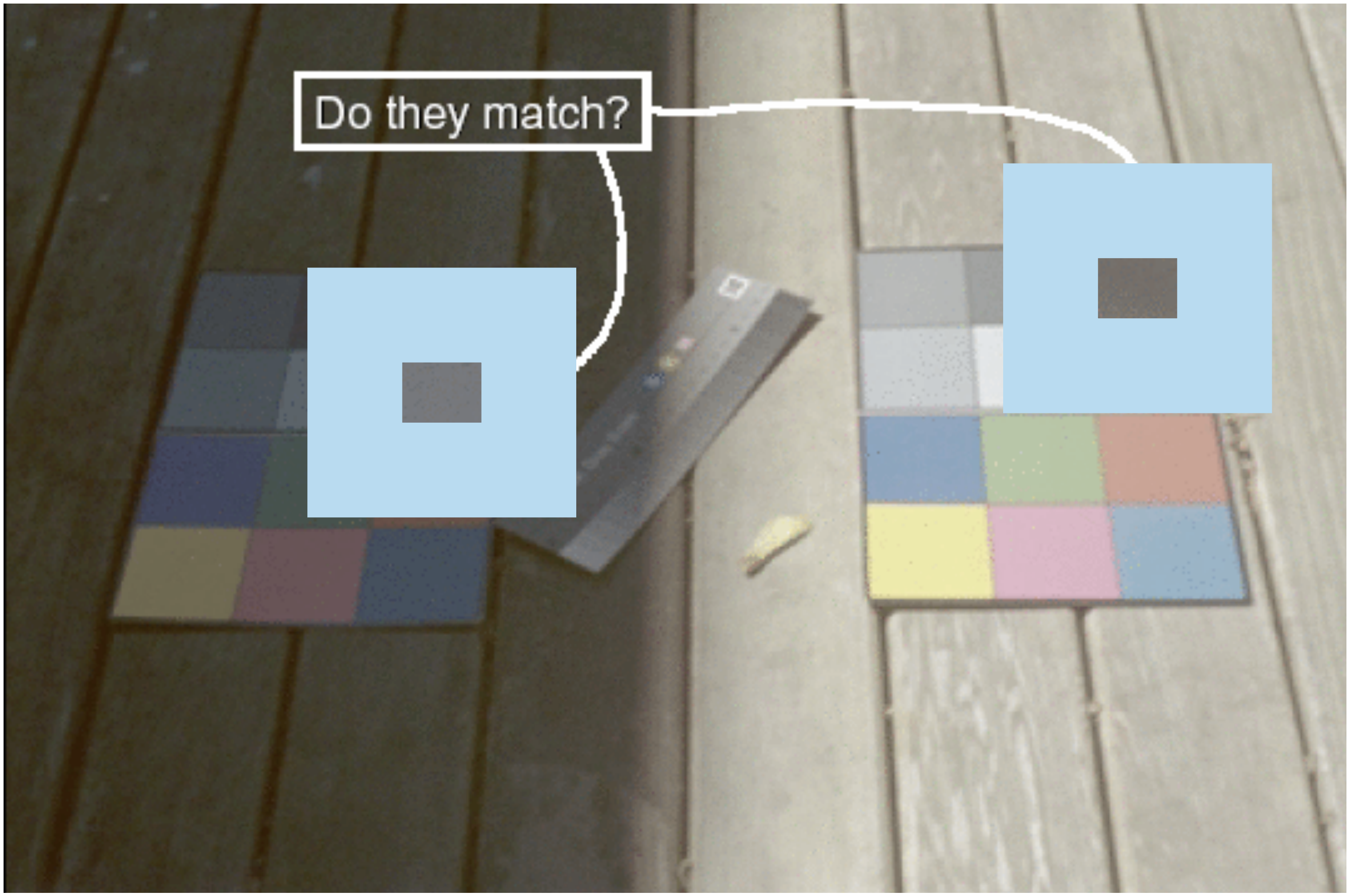


Image courtesy of John McCann

Color Constancy

- automatic “white balance” from change in illumination
- vast amount of processing behind the scenes!
- colorimetry vs. perception

From Color Appearance Models, fig 8-1

Stroop Effect

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

Stroop Effect

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

- interplay between cognition and perception