Light and Color

CS475 / 675, Fall 2016

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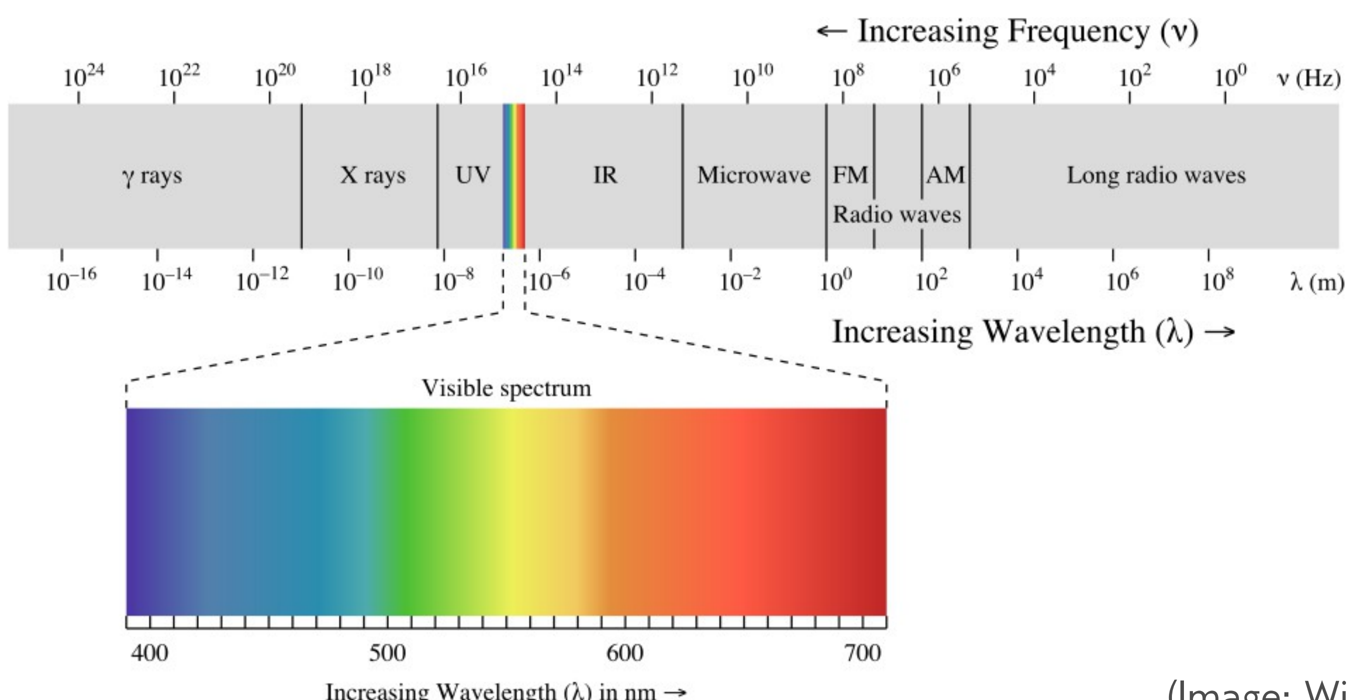
Rainbow over the Potala Palace, Lhasa, Tibet (Galen Rowell, 1981)

What is Light?

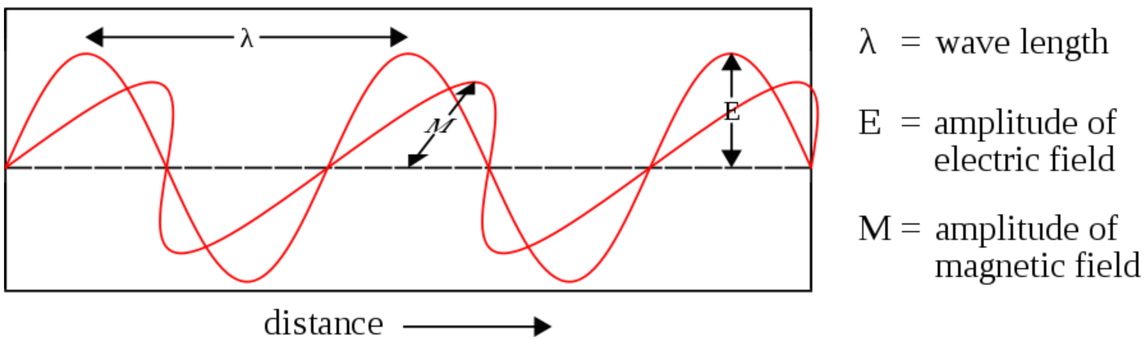
- Electromagnetic radiation
  - "Light" usually refers to radiation visible to human eye
- Travels through vacuum at c = 299,792,458 m/s
  - Travels through other media at lower speeds



(Image: Wikimedia Commons)

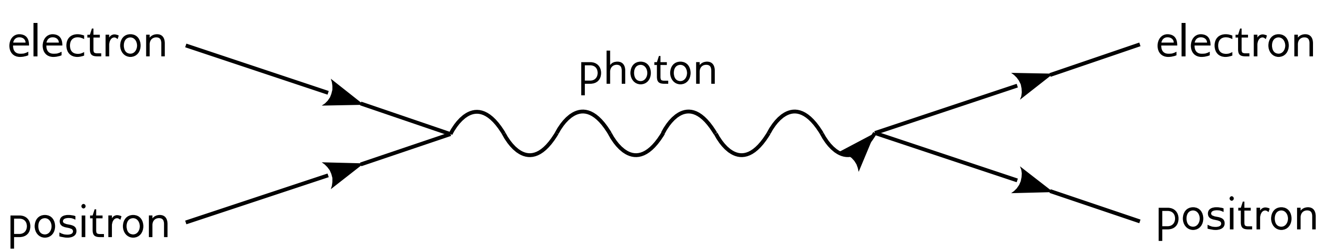
Characteristics of Light

- Exhibits both wave and particle-like characteristics
  - Has wavelength (λ), frequency (ν), amplitude etc.



(Wikimedia Commons)

  - Emitted in discrete quanta, called *photons*

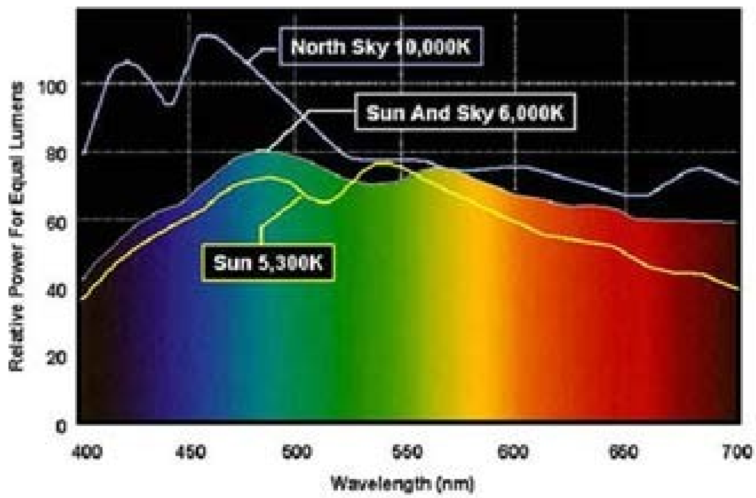


  - Reconciled by quantum electrodynamics

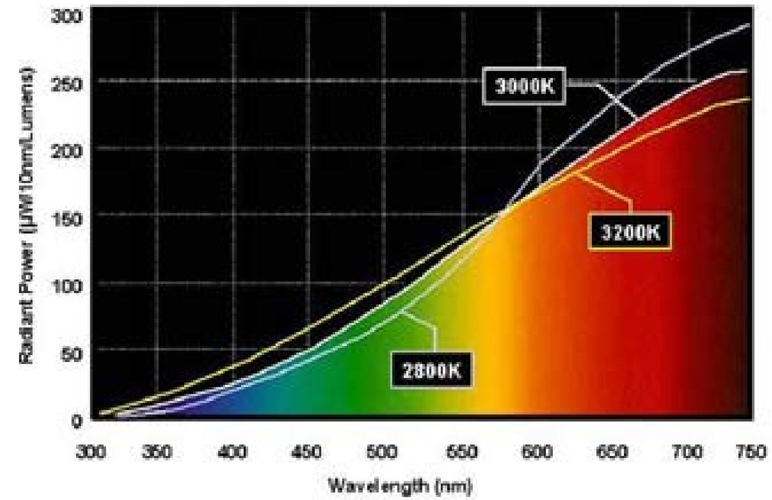
Radiometry

- Light carries *radiant energy*
    - Energy of a single photon = $h\nu = \dfrac{hc}{\lambda}$
- A light source emits photons over time. Its power (energy per unit time) is called the *radiant flux* Φ.
- Let radiant flux of photons with wavelengths in range $[\lambda, \lambda + \Delta\lambda)$ be $\Delta\Phi$
- The *spectral radiant flux* at wavelength λ is $\dfrac{\Delta\Phi}{\Delta\lambda}$
    - Modeling radiant flux as a continuous function, this becomes the derivative $\dfrac{d\Phi}{d\lambda}$

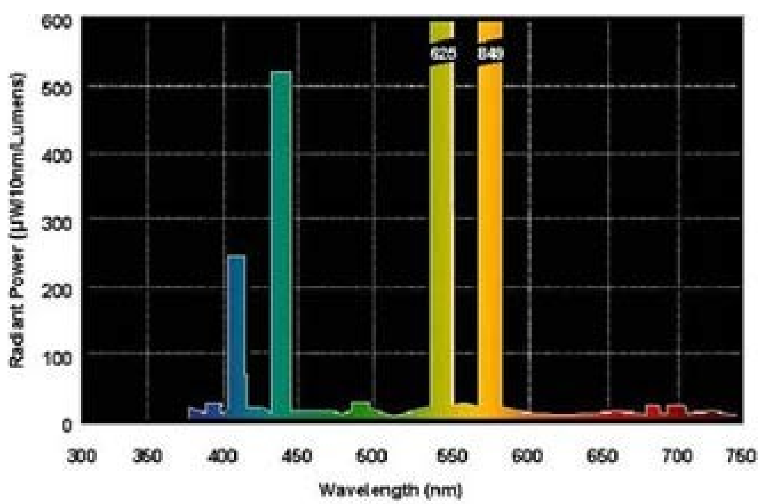
Some Spectral Radiant Flux Curves



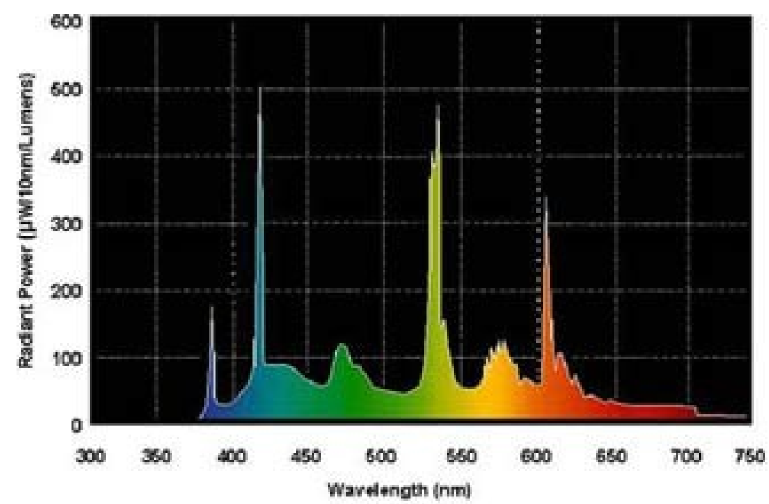
Outdoor daylight



Incandescent bulb



Mercury lamp

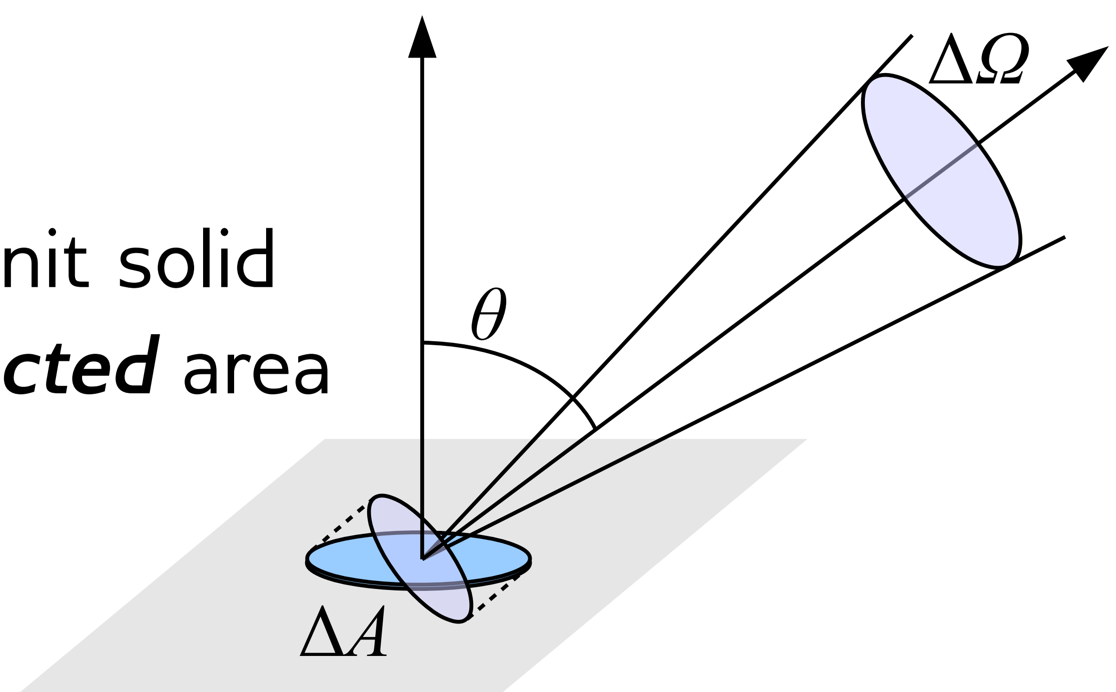


SP65 triphosphor fluorescent

A Few More Radiometric Terms

- *Irradiance*: Incident flux per unit area of surface
  - Called *radiant exitance* when surface emits light
- *Radiant intensity*: Flux per unit solid angle
  - Directional quantity
- *Radiance*: Flux per unit solid angle per unit ***projected*** area

$$\frac{\Delta \Phi}{\Delta \Omega \, \Delta A \cos \theta}$$



Why do I need to know all this?

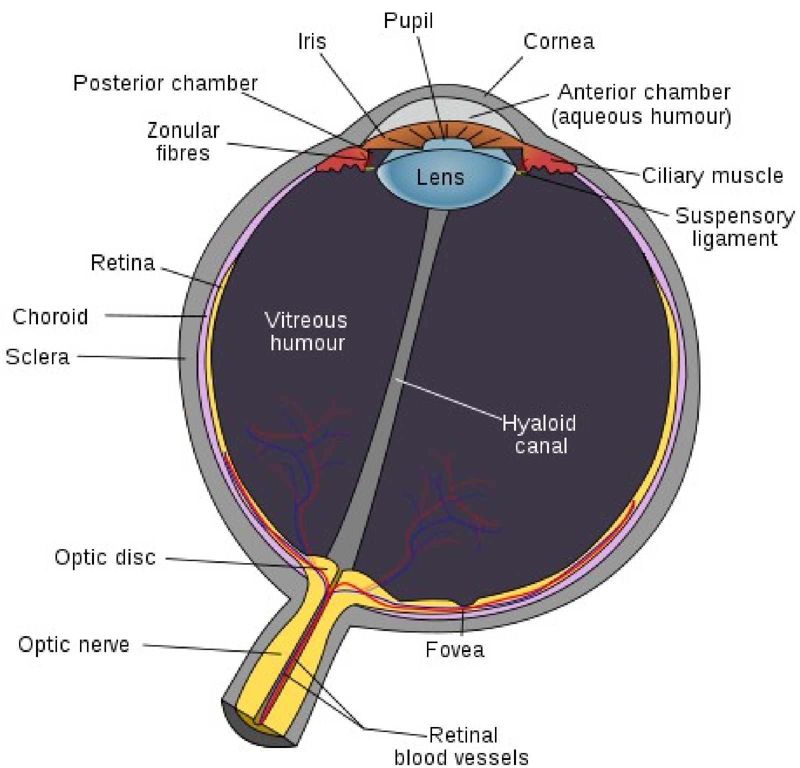
To produce photorealistic images of virtual 3D scenes, by simulating actual light transport

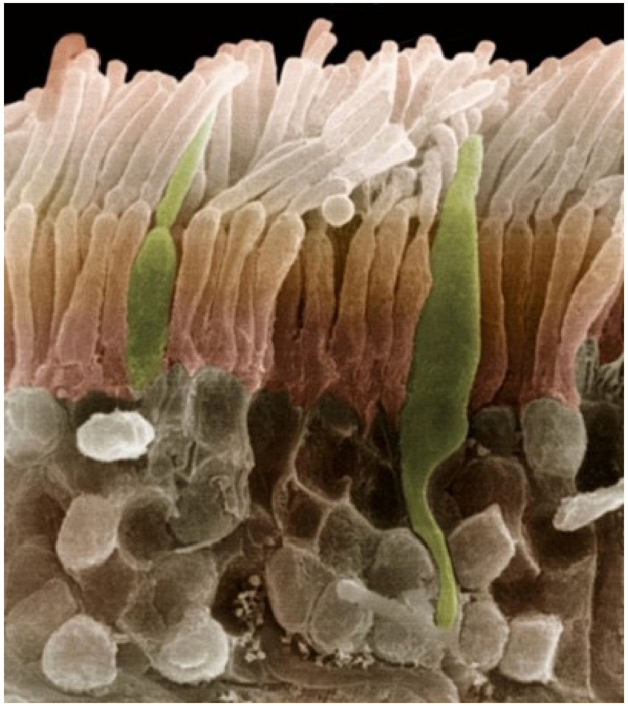
(we won't study this too much in this course, take CS775 if you want an in-depth treatment)

Just to convince you...

Photometry

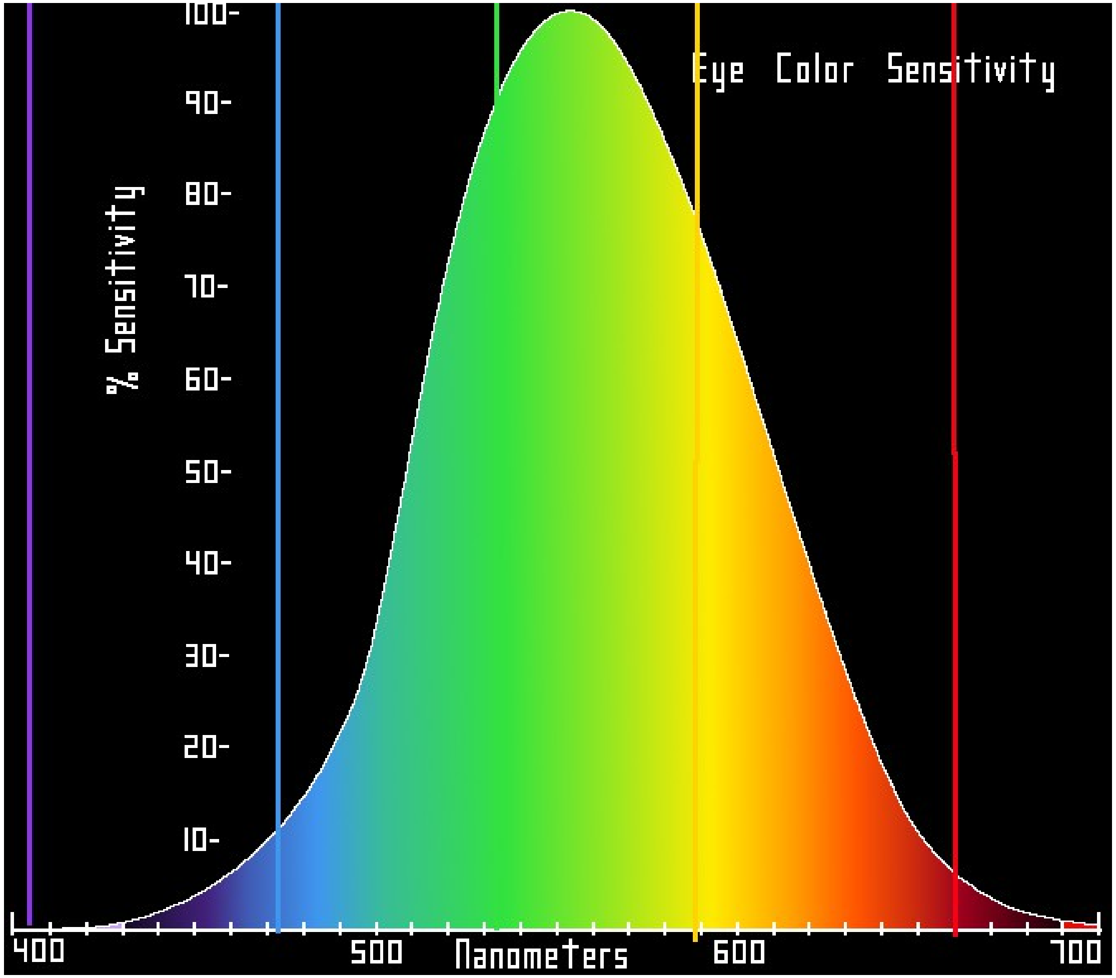
- *Perceptual* study of light
- Brightness, color etc. depend on the interaction of our eyes with light





Rod (brown) and cone (green) cells
(© Visuals Unlimited, 2009)

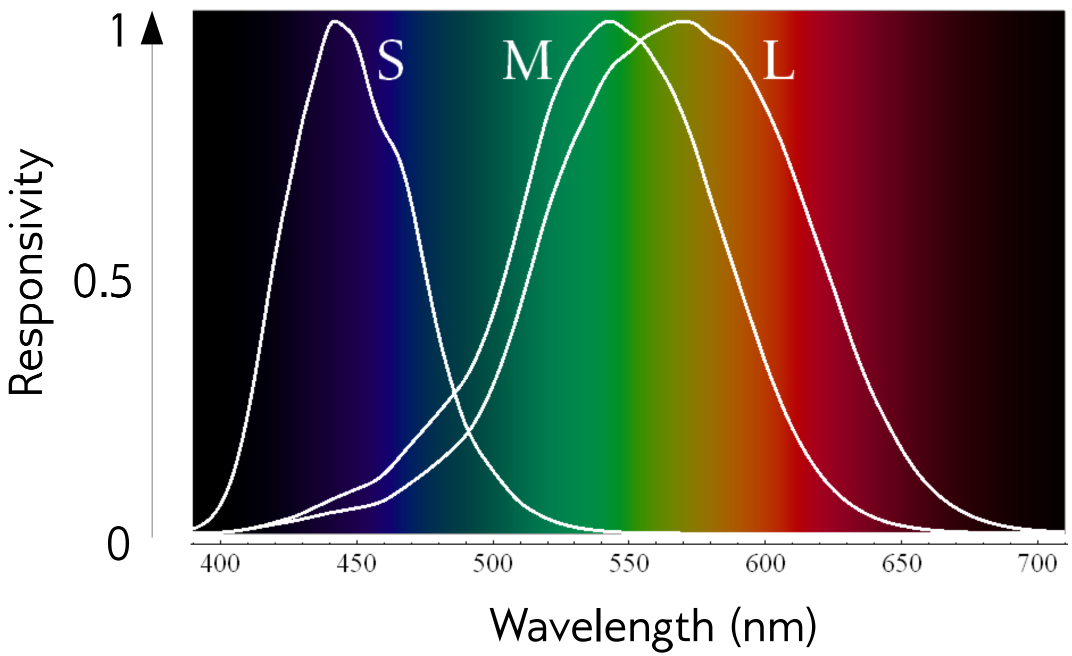
Photopic Luminous Efficiency



Overall sensitivity of human eye to different parts of the spectrum
(in bright lighting conditions)

Tristimulus Theory

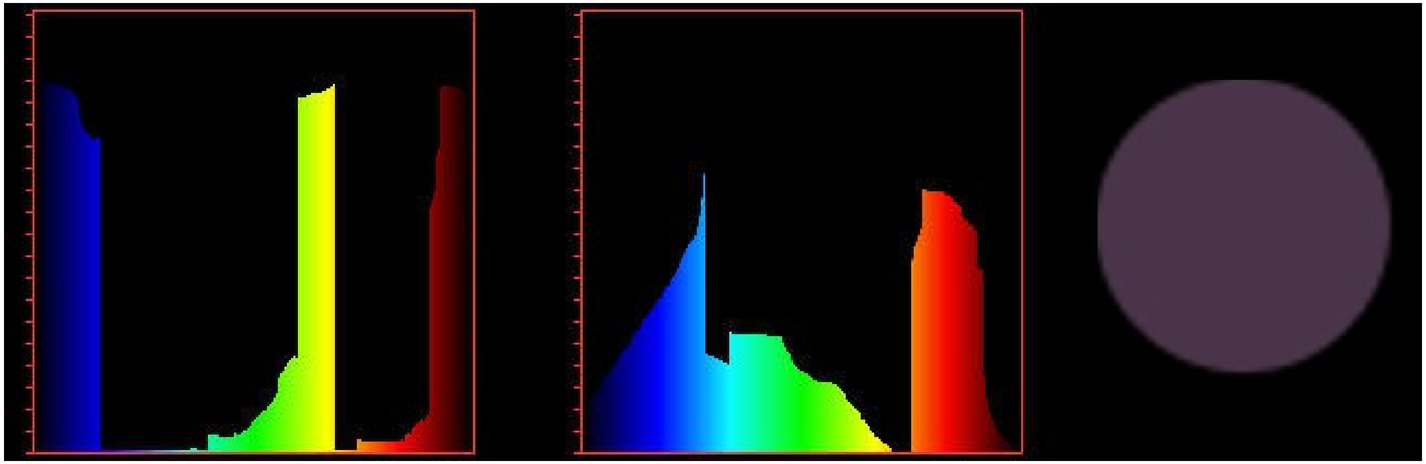
- Cone cells perceive color (less sensitive than rods)
- Three types of cone cells: (L)ong, (M)edium and (S)hort



Normalized response curves of human cone cells

Tristimulus Theory

- Presence of 3 cone types suggests: 3 parameters describe all colors
- Two light sources with different spectral distributions can appear to be the same color. Such pairs are called *metamers*.

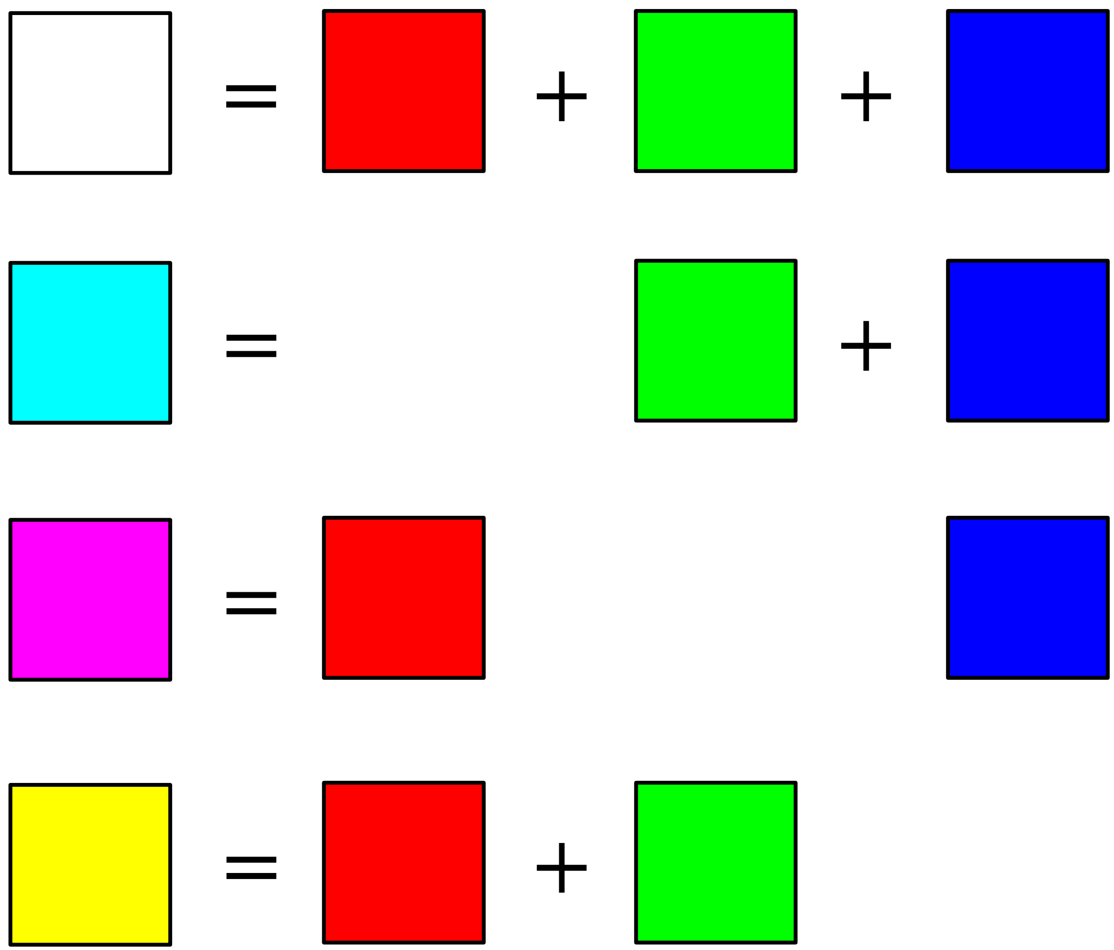


Different spectra can appear the same color (Hughes, Bell and Doppelt)

Color Matching Experiments

- Wright and Guild (1920s)
  - Choose lights of 3 different *primary colors*
  - Show a user single-wavelength light
  - Ask her/him to match it with a weighted combination of the primaries
- Primaries standardized by the CIE in 1931
  - Red (**R**): 700 nm
  - Green (**G**): 546.1 nm
  - Blue (**B**): 435.8 nm

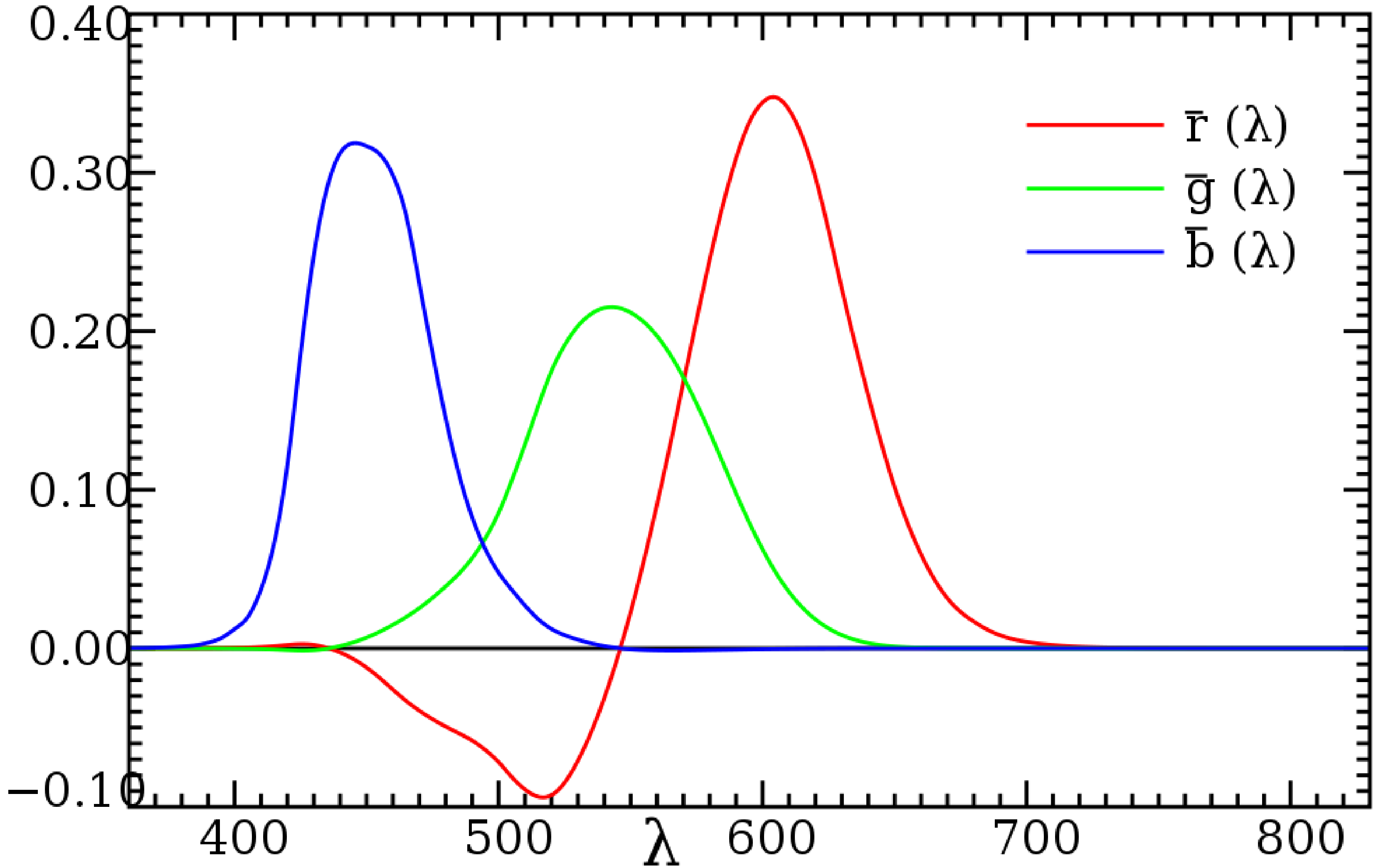
Examples



Grassmann's "Law"

- Chromatic sensation is *linear*
- Let:
  - Beam 1 color-match (R_1, G_1, B_1)
  - Beam 2 color-match (R_2, G_2, B_2)
- Then:
  - $\alpha \cdot$ Beam 1 + $\beta \cdot$ Beam 2 matches $(\alpha R_1 + \beta R_2, \alpha G_1 + \beta G_2, \alpha B_1 + \beta B_2)$
- Holds for any set of primaries of any size, defines *additive color model*

Color Matching Functions for CIE RGB



Amounts of the red, green and blue primaries needed to match any color

What's a negative amount of color???

- Mathematical convenience, doesn't really exist
- Implies that experimenters had to add the corresponding amount of primary to the *source* beam to get the colors to match
- It turns out there is no small set of *physically realizable* primaries such that any visible color is formed by combining them with positive weights
- And computing with negative numbers was tricky in 1931

Oops.

Enter **CIE XYZ**...

- Luckily, the CIE has a solution...

  ... Let's have imaginary primaries (oh great...)

- Construct linear, *possibly non-realizable*, combinations of RGB primaries s.t. color matching functions are positive throughout visible range

- We have a great deal of flexibility in this choice
  - We want one color matching function to approximate photopic luminous efficiency as closely as possible
  - Used to separate *relative luminance* (loosely, brightness) from *chromaticity* (loosely, hue)

The CIE XYZ Primaries, 1931

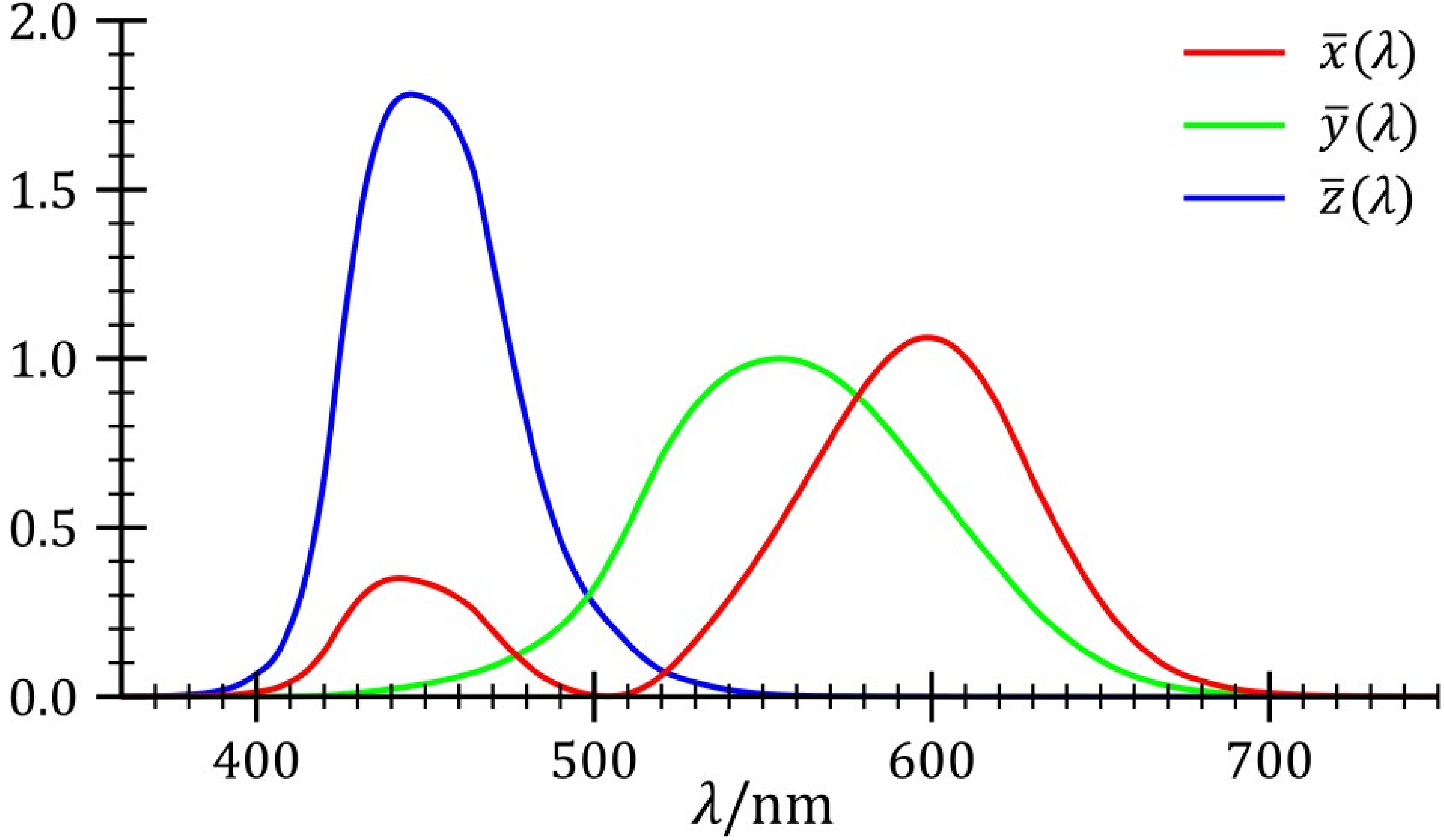
- Map $R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$ to $X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$
- Conversion between XYZ and RGB coordinates

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = M^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$M = \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix}$$

- Note that M^{-1} has negative elements – XYZ basis is not physically realizable

Color Matching Functions for CIE XYZ



Amounts of the XYZ primaries needed to match any color
($\bar{y}$ function is precisely CIE-standardized photopic luminous efficiency, 1931)

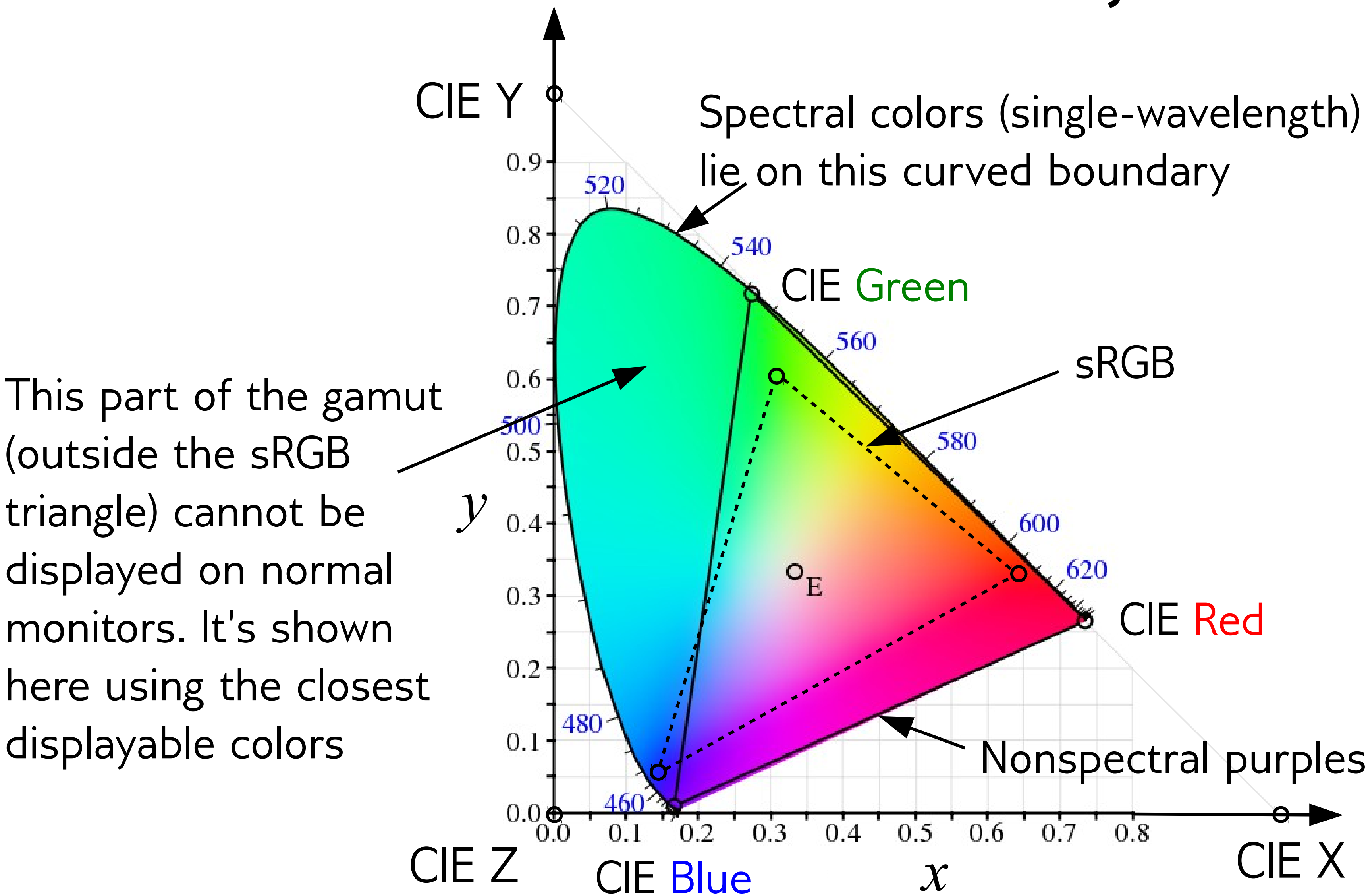
xyY: Separate Chrom from Lum

- Formed nonlinearly from X, Y and Z

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

- x and y are chromaticity coordinates, Y is relative luminance coordinate
- *Gamut*: Set of colors that can be physically realized in a color space (without negative coefficients etc.)

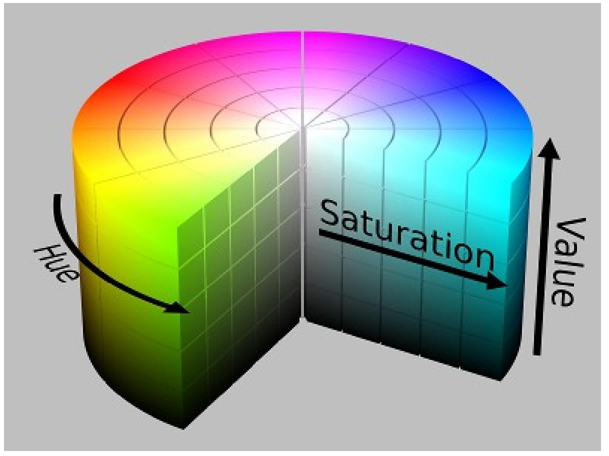
CIE XYZ and RGB Chromaticity Gamuts



All visible chromaticities mapped to xy plane

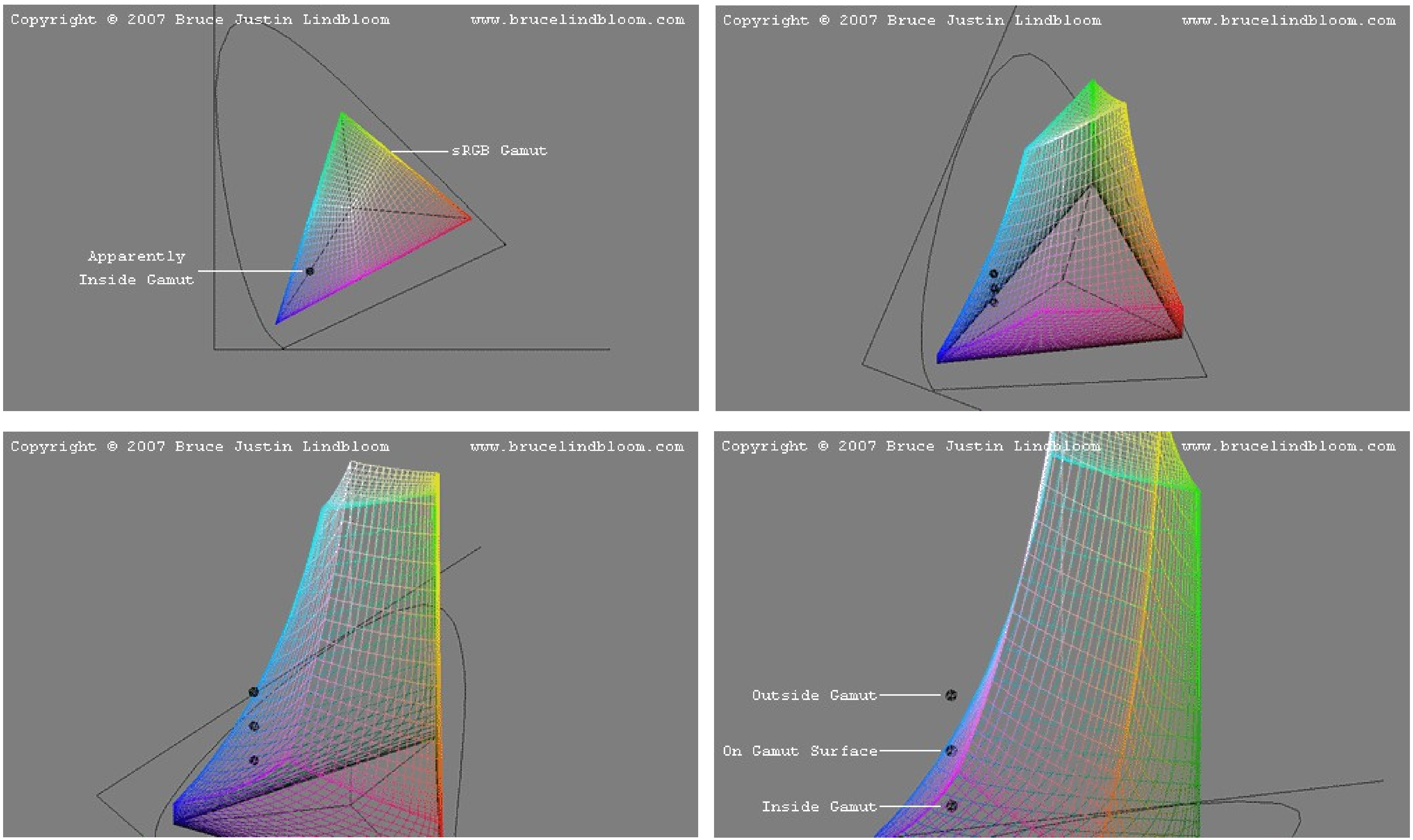
Some More Color Representations

- **sRGB**: HDTV/monitor/digicam standard color space, similar to but smaller gamut than CIE RGB
- *Perceptually uniform representations*: Distance between two colors in color model reflects ability of humans to discriminate between them
  - **HSL** color model
  - **HSV** color model
  - **L*a*b*** color space



(SharkD@Wikimedia Commons)

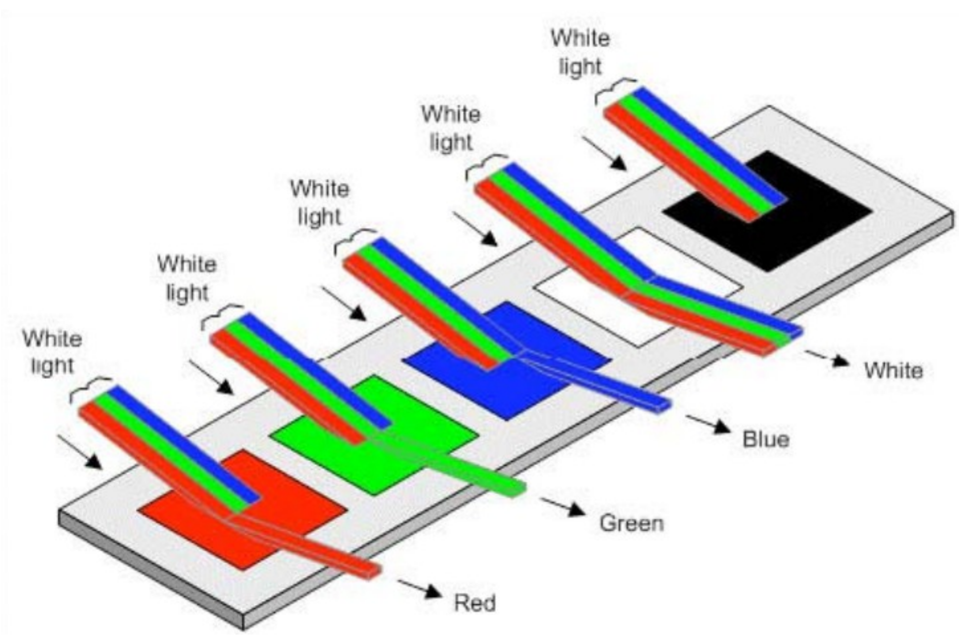
Remember: Gamuts are actually 3D!



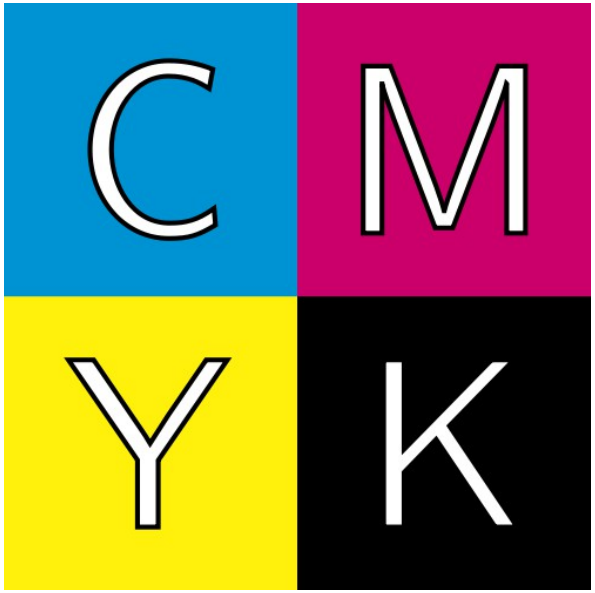
Colors projecting inside 2D sRGB chromaticity gamut may not be within true 3D gamut
(Lindbloom, 2007)

Reflected Light (Pigments)

- *Subtractive color model*: color of pigment is defined by light it does *not* absorb

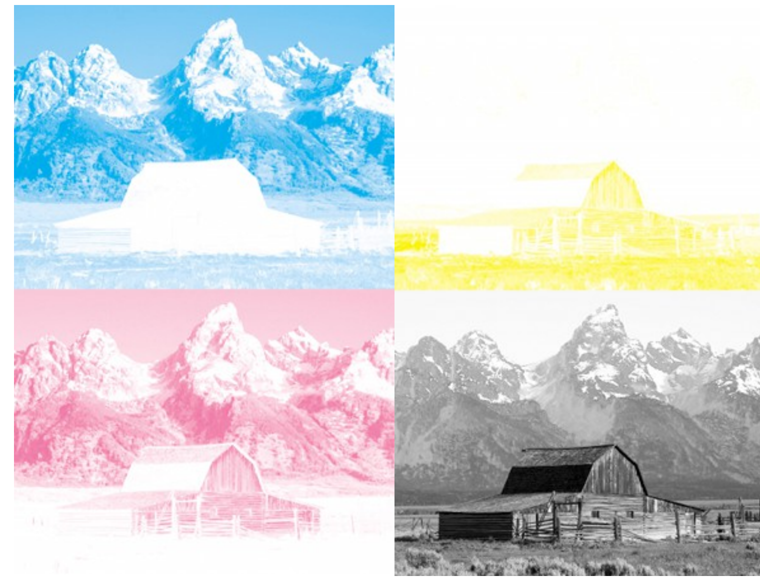


Different components of white light are absorbed by pigments



(C)yan, (M)agenta, (Y)ellow, (K)ey black: typical printer primaries

CMYK Separation is Not Unique



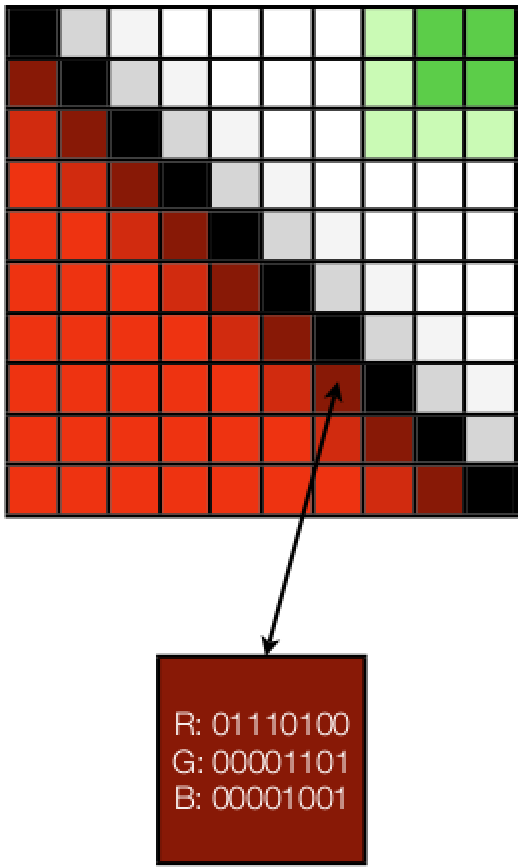
Full black

No black

(Images: Wikimedia Commons)

Raster Images

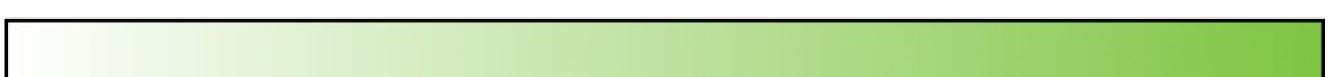
- Array of *pixels* (**pic**ture **el**ements)
  - We'll consider only 2D arrays
- Types of images
  - *Binary*: 0 / 1 per pixel
  - *Greyscale*: Single value (channel) per pixel, usually floating point number in [0, 1] or byte in [0, 255]
    - 0: black, 1: white, intermediate value: grey
  - *Color*: Multiple channels per pixel, usually RGB triplet
    - Interpretation depends on color space
    - Value of channel = weight of component



Raster Images

- *Resolution*: Number of pixels
  - 640x480, 1024x768 etc.
- *Color/Bit Depth*: Number of bits per pixel
  - 24-bit color image has 8 bits (1 byte) per channel
- *Transparency*
  - *Alpha channel* added to pixel (e.g. RGBA)
  - $\alpha = 0 \Rightarrow$ pixel is fully transparent
  - $\alpha = 1 \Rightarrow$ pixel is fully opaque

$\alpha = 0$



$\alpha = 1$