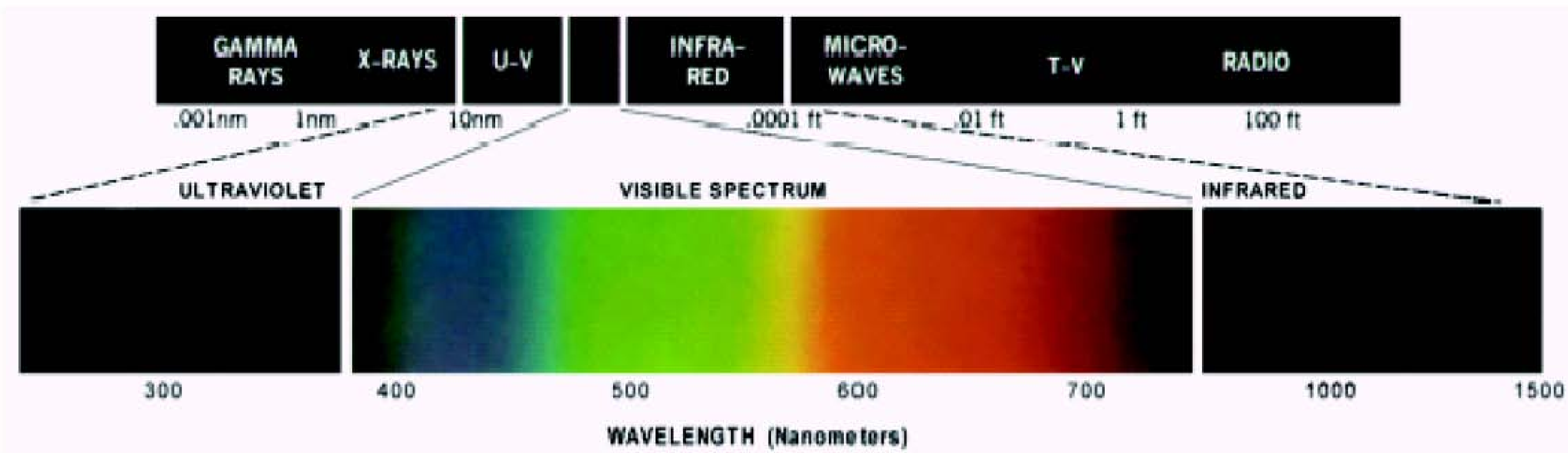
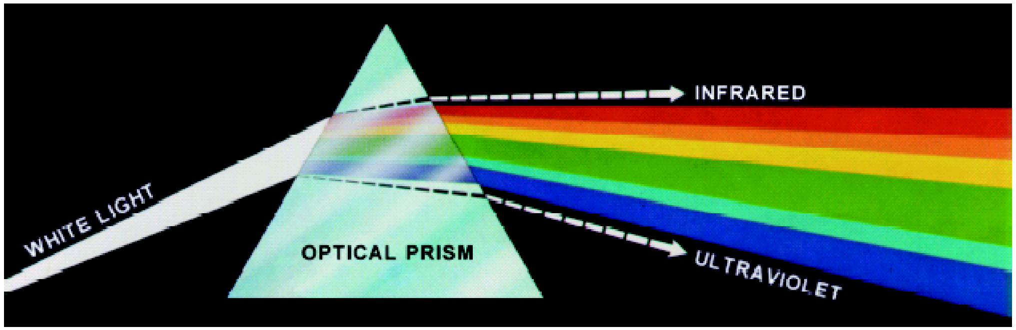
Color

- Trichromacy
- Spectral matching curves
- CIE XYZ color system
- xy-chromaticity diagram
- Color gamut
- Color temperature
- Color balancing algorithms

Visible Range of the Electromagnetic Spectrum

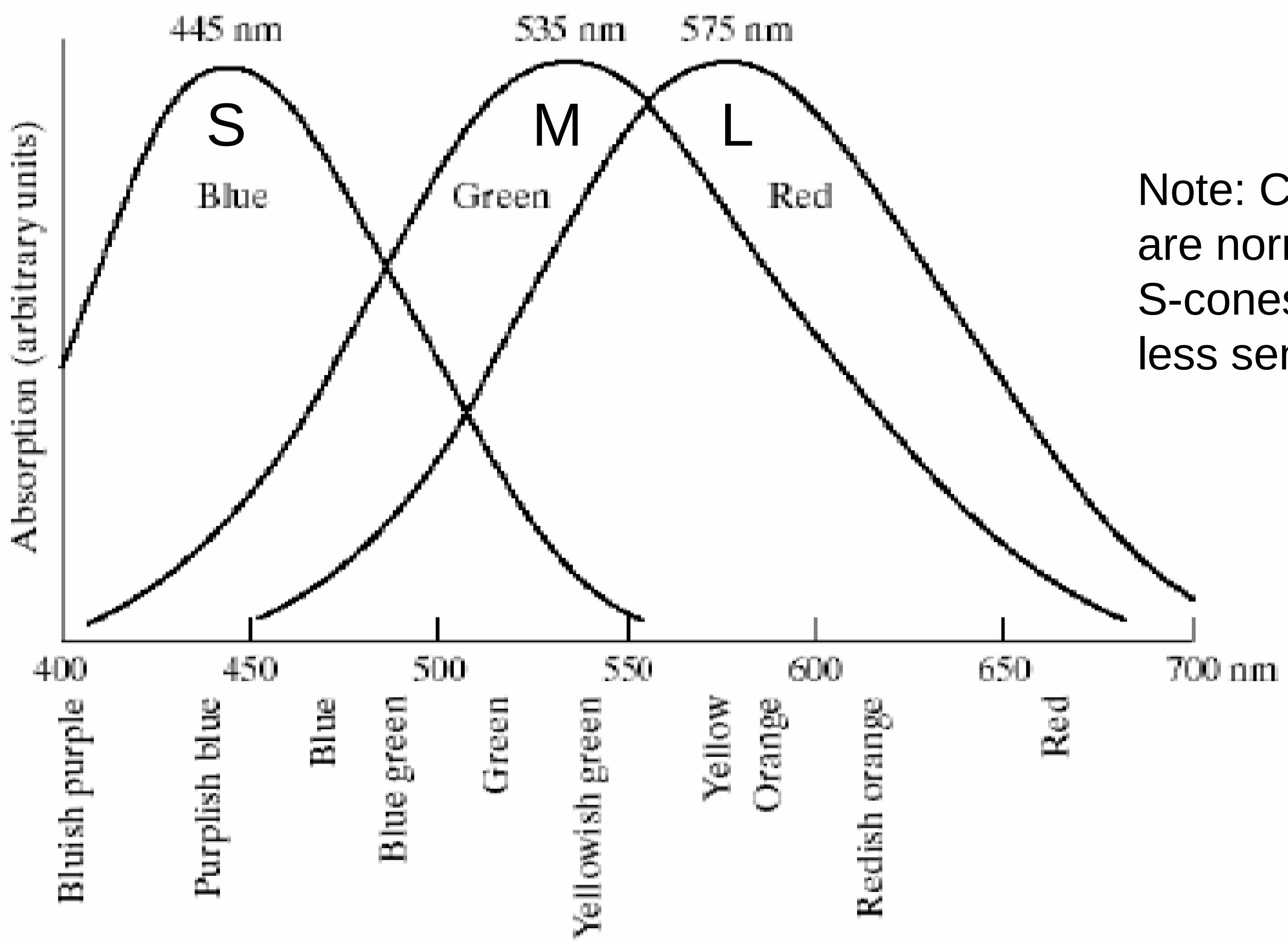




[Newton, 1666]

Source: Gonzalez, Woods, Figs. 6.1, 6.2

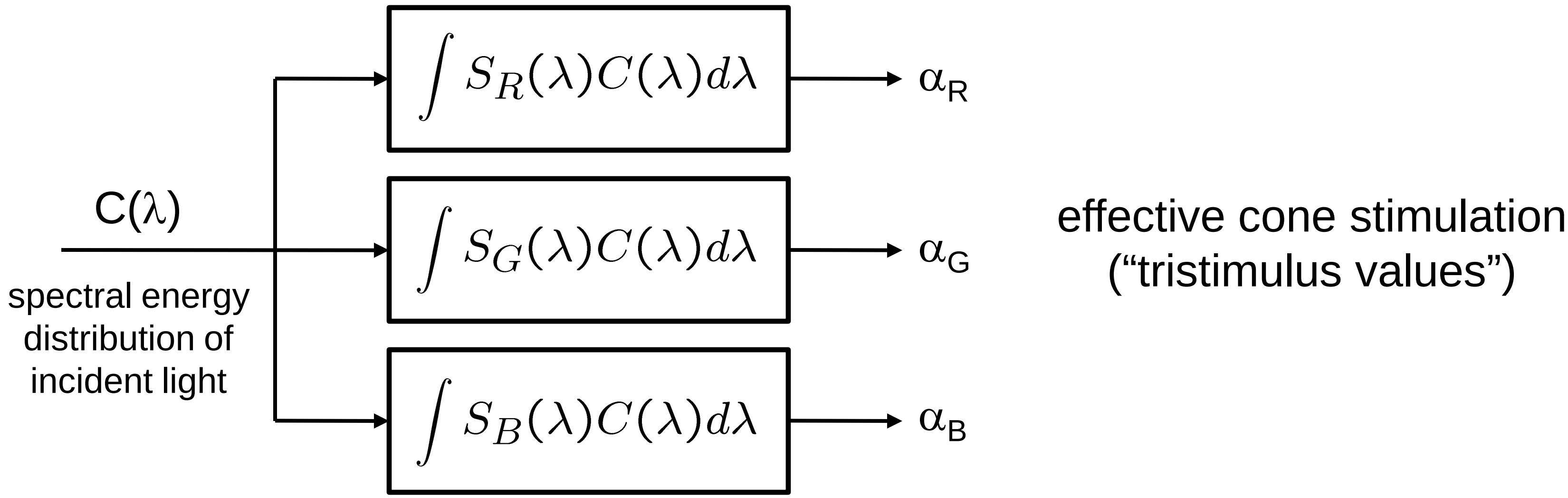
Absorption of Light in the Cones of the Human Retina



Note: Curves are normalized. S-cones are much less sensitive.

Source: Gonzalez, Woods, Fig. 6.3

Three-Receptor Model of Color Perception



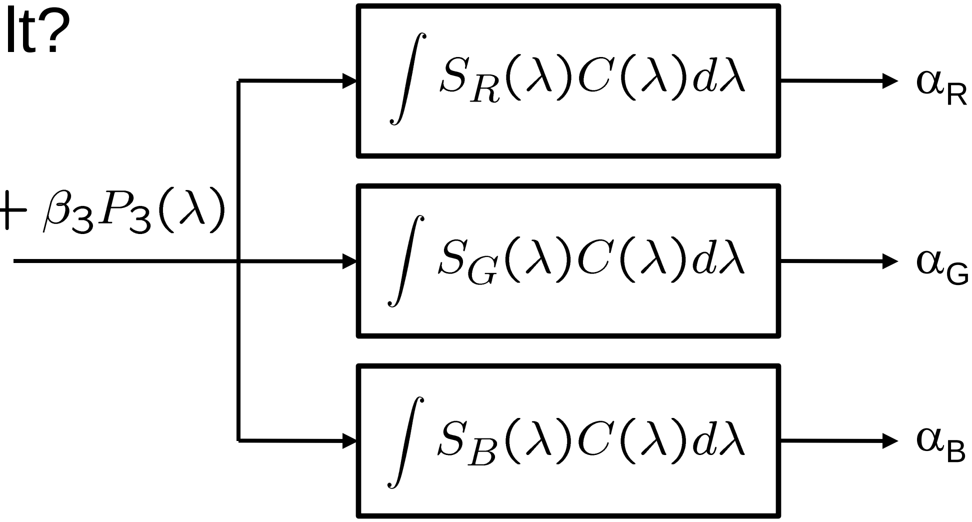
[T. Young, 1802], [J.C. Maxwell, 1890]

- Different spectra can map into the same tristimulus values and hence look identical (“metamers”)
- Three numbers suffice to represent any color

Color Matching

- Suppose 3 primary light sources with spectra $P_k(\lambda)$, k=1,2,3
- How to choose β_k, k=1,2,3, such that desired tristimulus values (α_R, α_G, α_B) result?

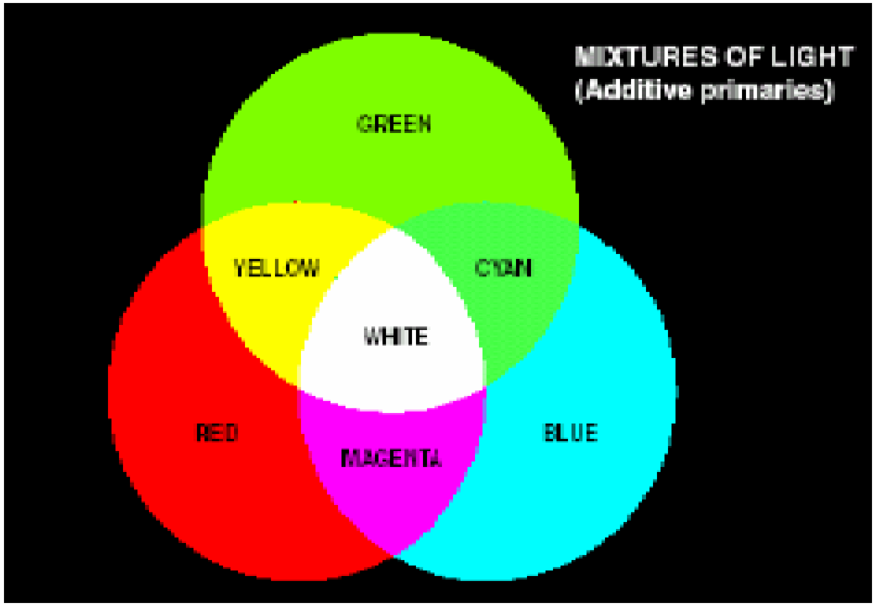
$$C(\lambda) = \beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda)$$

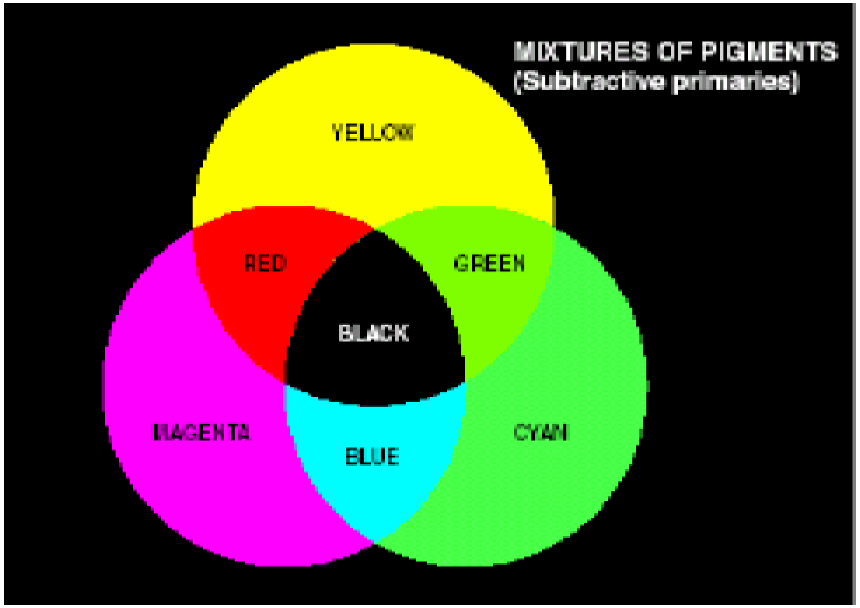


$$\begin{aligned} \alpha_i &= \int S_i(\lambda) \left[\beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda)\right] d\lambda \\ &= \beta_1 K_{i,1} + \beta_2 K_{i,2} + \beta_3 K_{i,3} \quad \text{with} \quad K_{i,j} = \int S_i(\lambda) P_j(\lambda) d\lambda \end{aligned}$$

- Color matching is **linear** (“Grassman’s Laws”)

Additive vs. Subtractive Color Mixing

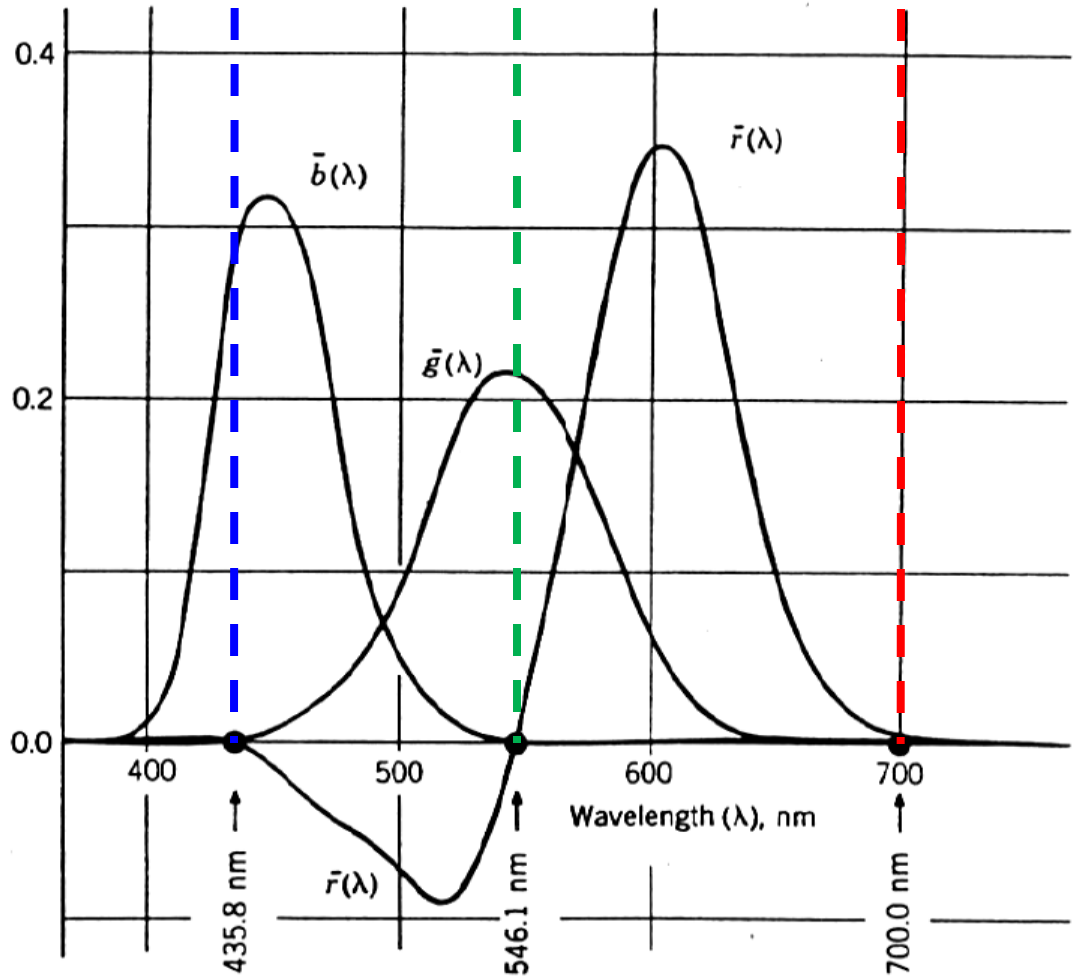




Source: Gonzalez, Woods, Fig. 6.4

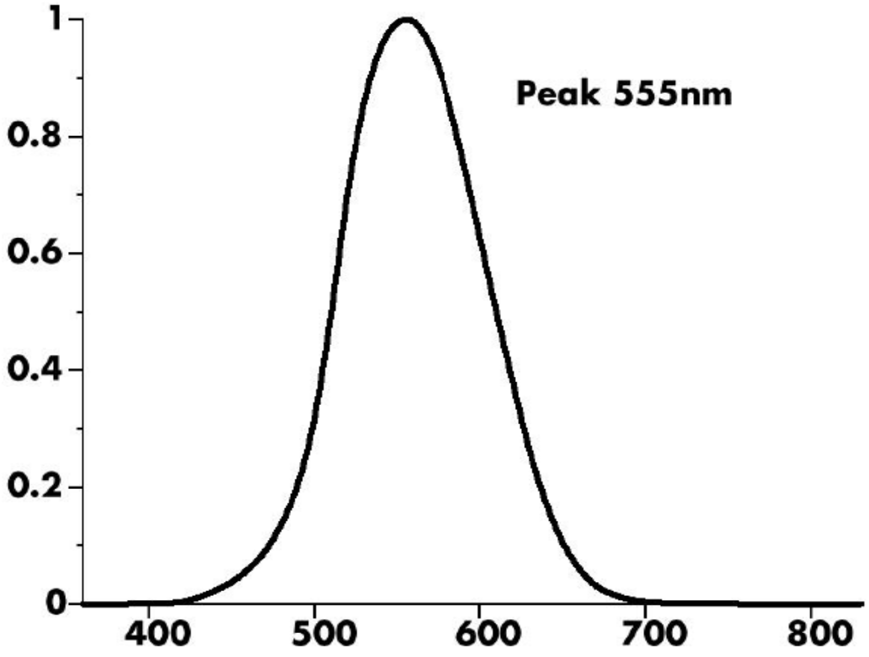
Spectral Matching Curves

- **Experiment:**
  Match monochromatic light with 3 monochromatic primaries
- "Negative intensity":
  Color is added to test color
- **CIE** (*Commission Internationale de L'Eclairage*), **1931:** Spectral RGB primaries (scaled such that $R_\lambda = G_\lambda = B_\lambda$ matches spectrally flat white)



Luminous Efficiency Curve

- **Experiment:**
  Match the brightness of a monochromatic light with a white reference light
- Links photometric and radiometric quantities

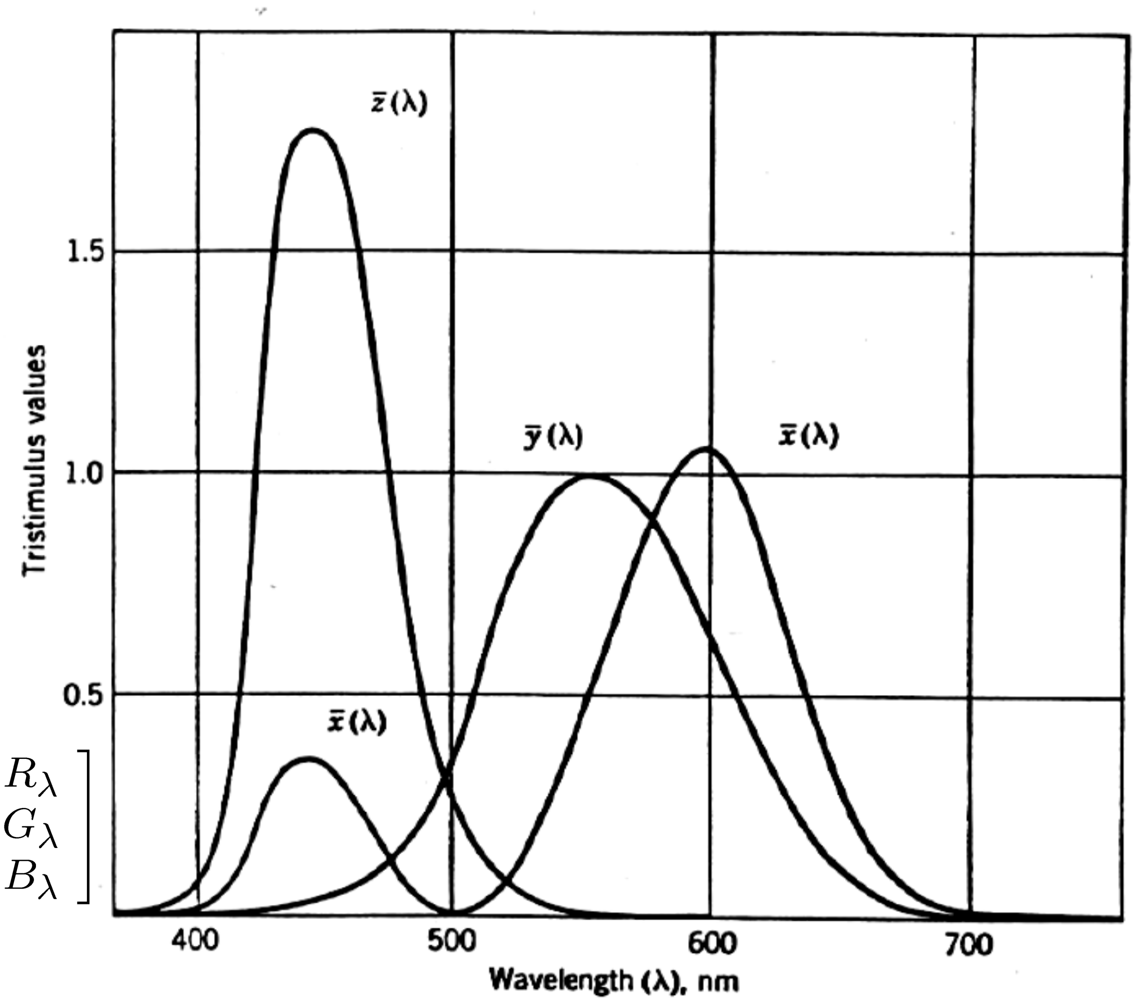


CIE 1931 XYZ Color System

Properties:

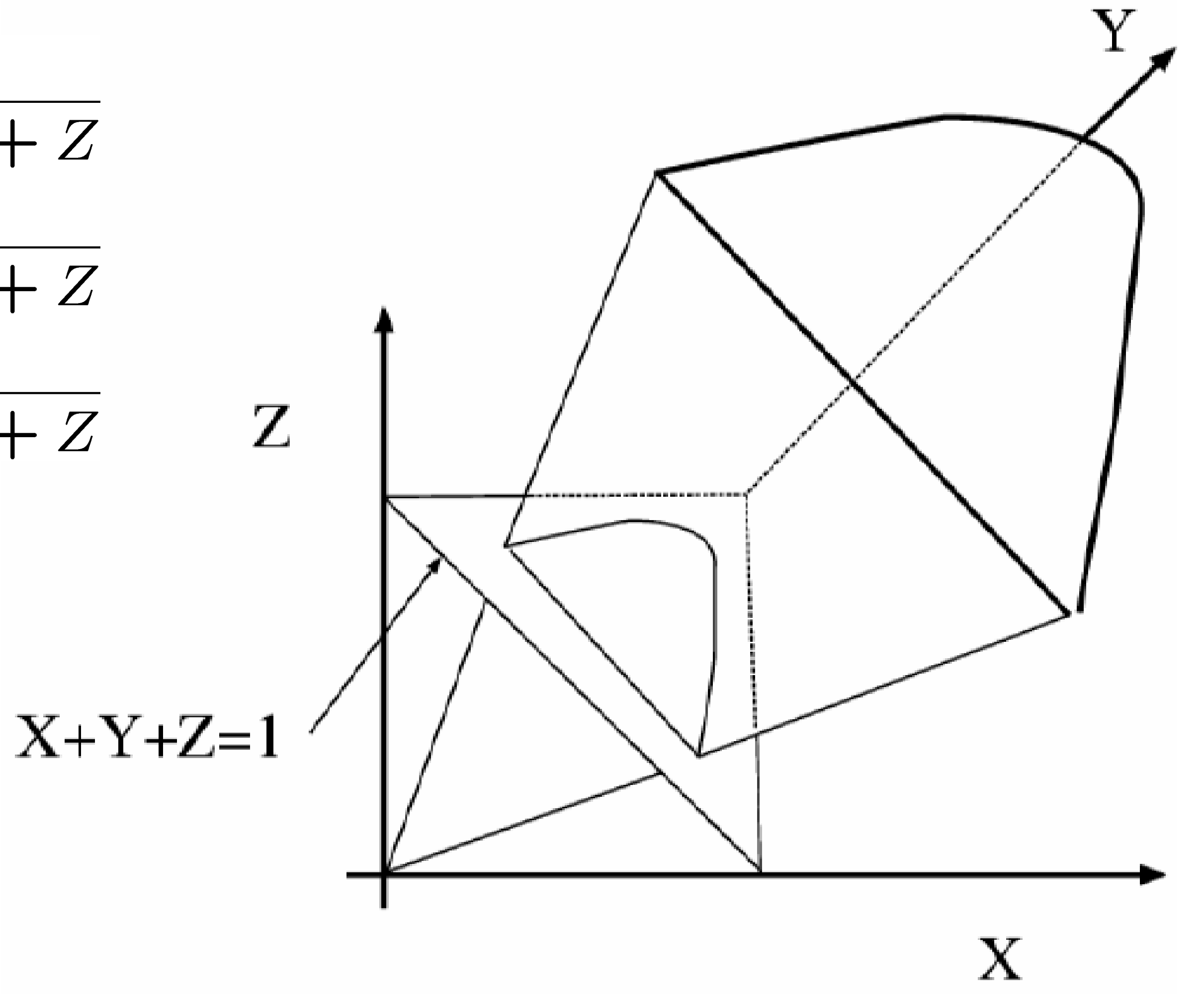
- All positive spectral matching curves
- Y corresponds to luminance
- Equal energy white: X=Y=Z
- Virtual primaries

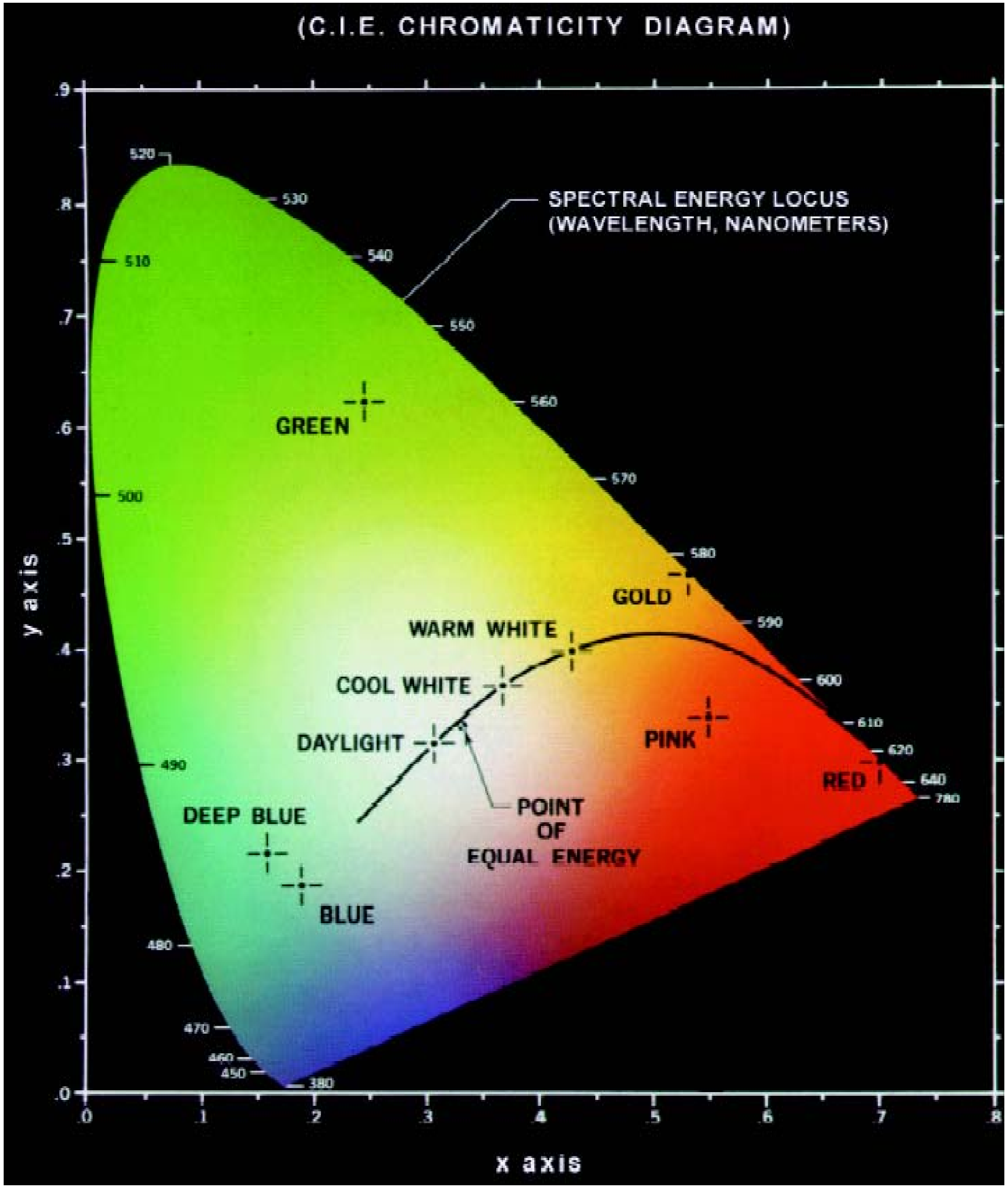
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} .490 & .310 & .200 \\ .177 & .812 & .011 \\ .000 & .010 & .990 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$



Chromaticity Diagram

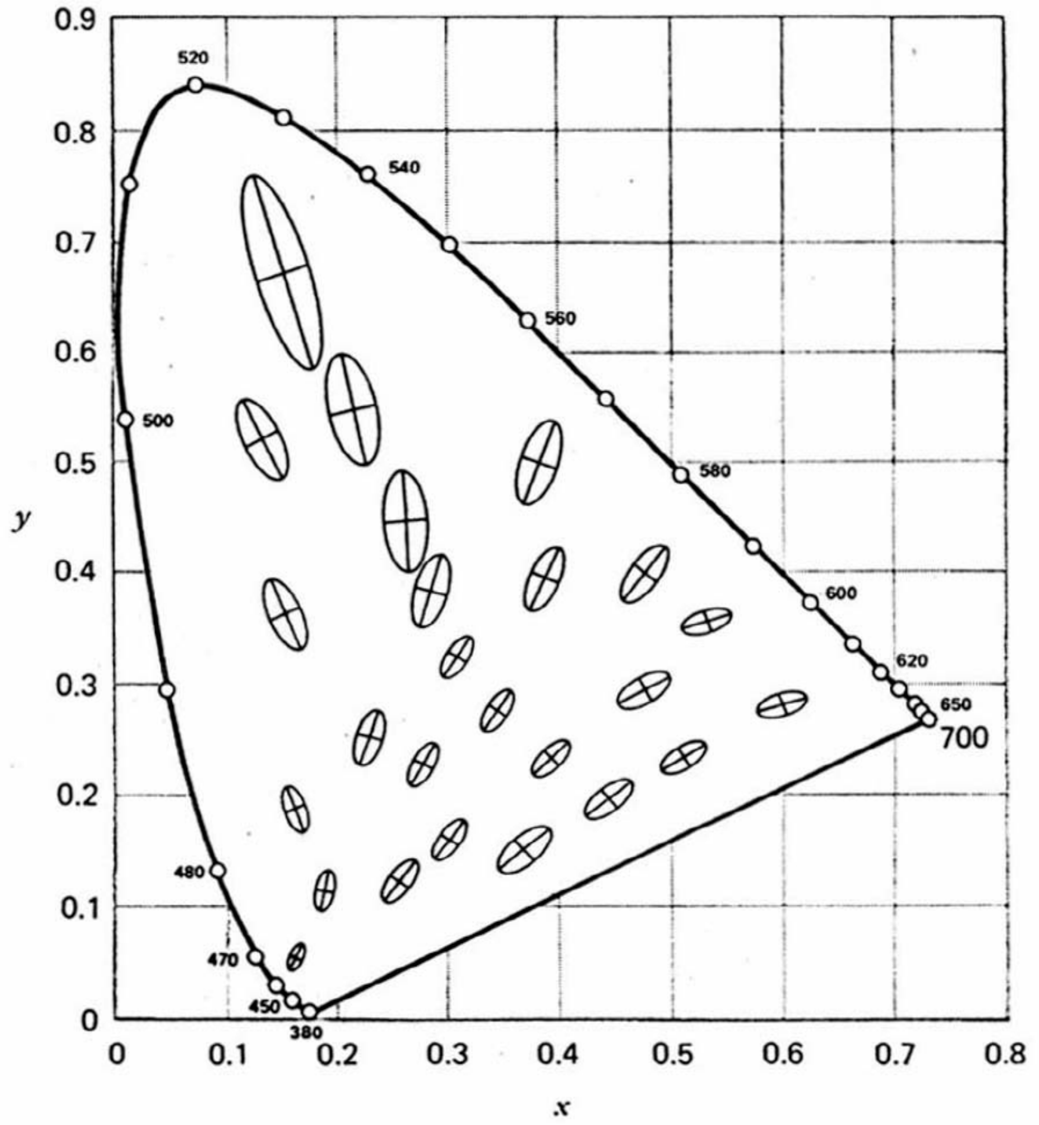
$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z}$$





Source:
Gonzalez, Woods, Fig. 6.5

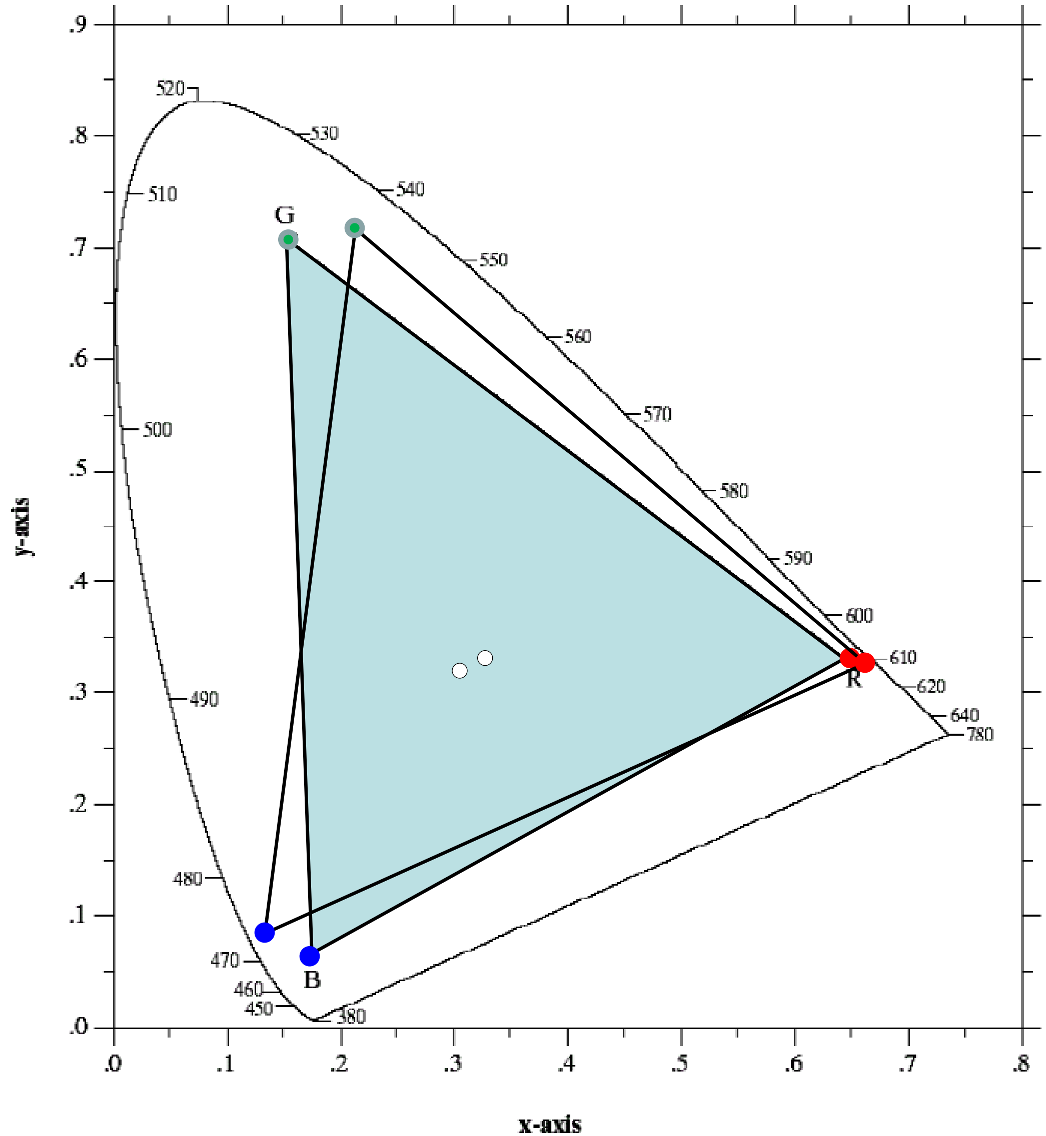
Inaccuracy for Color Matches



Just noticeable chromaticity differences (10x enlarged)

[MacAdam, 1942]

Color Gamut

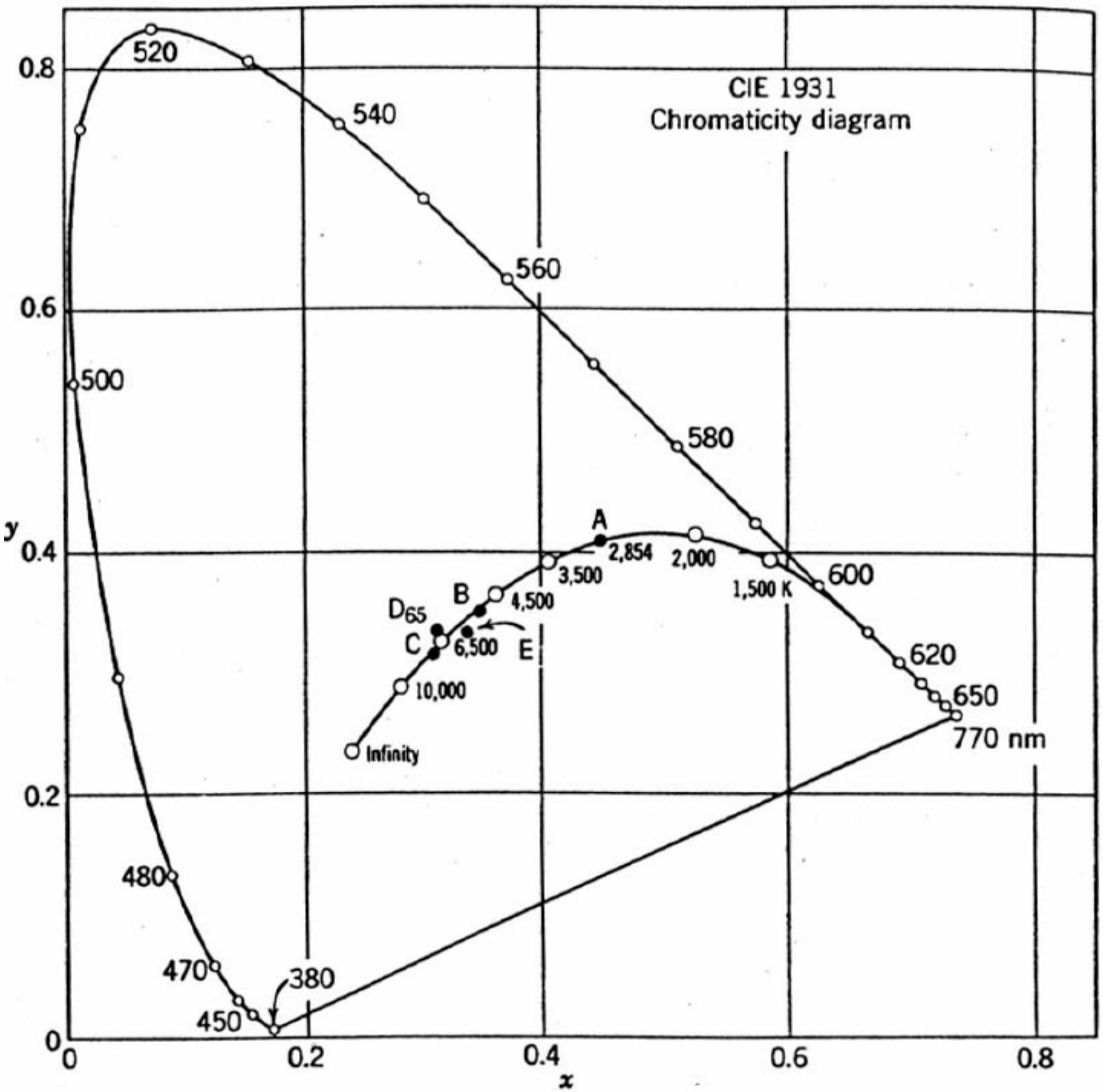


NTSC phosphors:

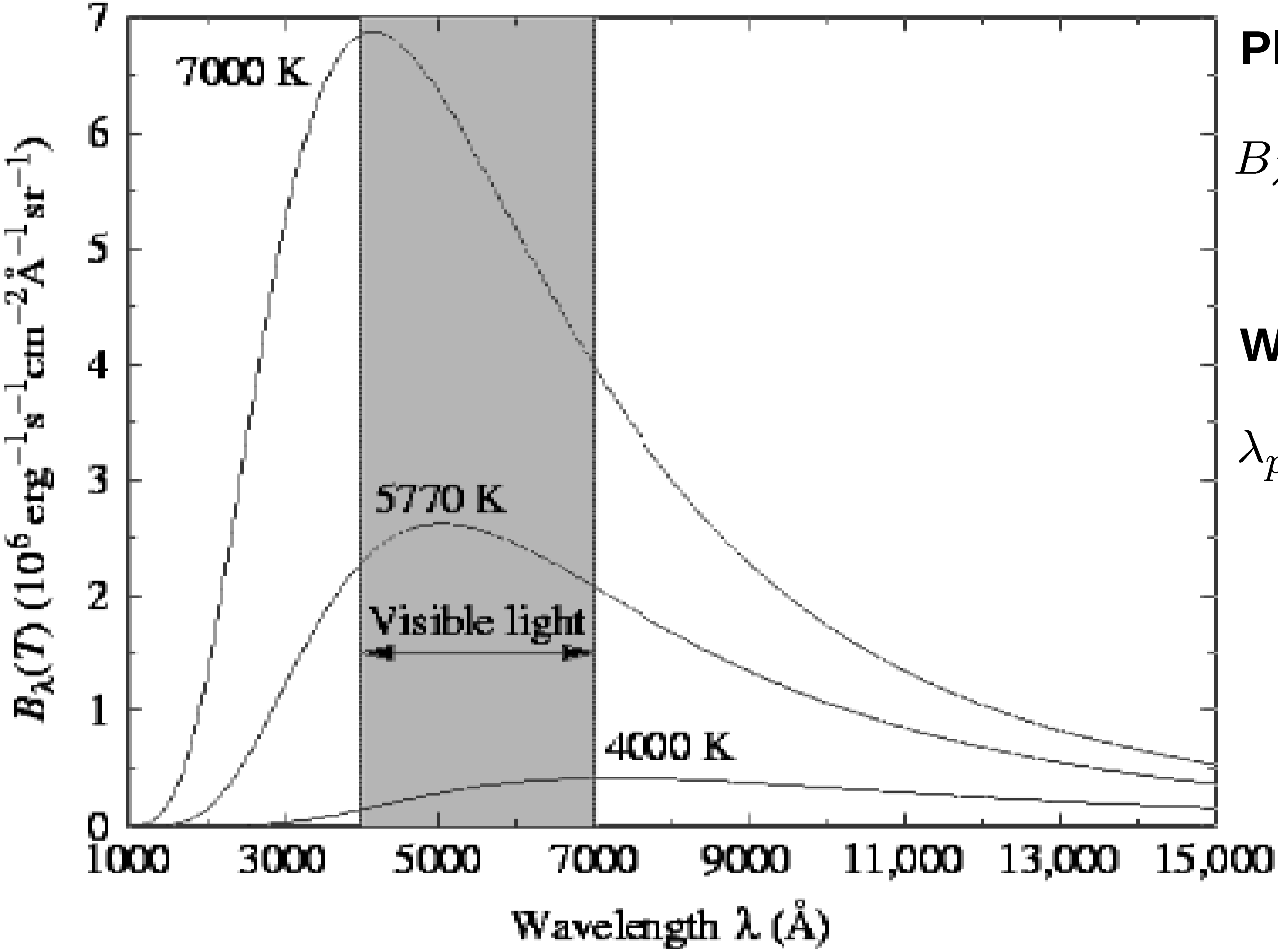
R: x=0.67, y=0.33
G: x=0.21, y=0.71
B: x=0.14, y=0.08

Reference white:
x=0.31, y=0.32
Illuminant C

White at Different Color Temperatures



Blackbody Radiation



Planck's Law

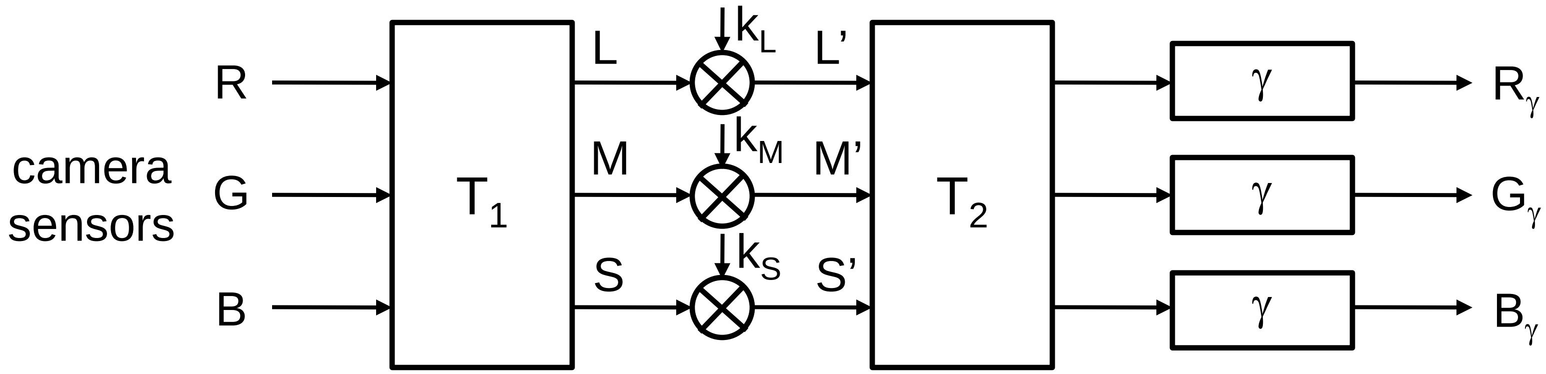
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\left(\frac{hc}{\lambda k T}\right)} - 1}$$

Wien's Law

$$\lambda_{peak} = \frac{2900 \mu m K}{T}$$

Color Balancing

- Effect of different illuminants can be cancelled only in the spectral domain (impractical)
- Color balancing in 3-d color space is a practical approximation
- Color constancy in human visual system: Gain control in LMS cone space [von Kries, 1902]
- Von Kries hypothesis applied to image acquisition devices (cameras, scanners)



- Which color space is best?
- How to determine k_L, k_M, k_S automatically?

Color Balancing

- Von Kries hypothesis

$$\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} = \begin{bmatrix} k_L & 0 & 0 \\ 0 & k_M & 0 \\ 0 & 0 & k_S \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

- If illumination (or a patch of white in the scene) is known, calculate

$$k_L = \frac{L_{desired}}{L_{actual}} \qquad k_M = \frac{M_{desired}}{M_{actual}} \qquad k_S = \frac{S_{desired}}{S_{actual}}$$

Color Balancing with Unknown Illumination

- Gray-world

$$\sum_{image} k_L L = \sum_{image} k_M M = \sum_{image} k_S S$$

- Apply gray-world algorithm to a subset of pixels
  - Exclude saturated colors
  - Bright pixels only
- Scale-by-max algorithm
  - Determine max(L), max(M), max(S) separately in each channel
  - Scale each channel by its max
  - Sensitive to saturation

Color Balancing Example

original

scale-by-max
color balancing

Color Balancing Example

original

scale-by-max
color balancing