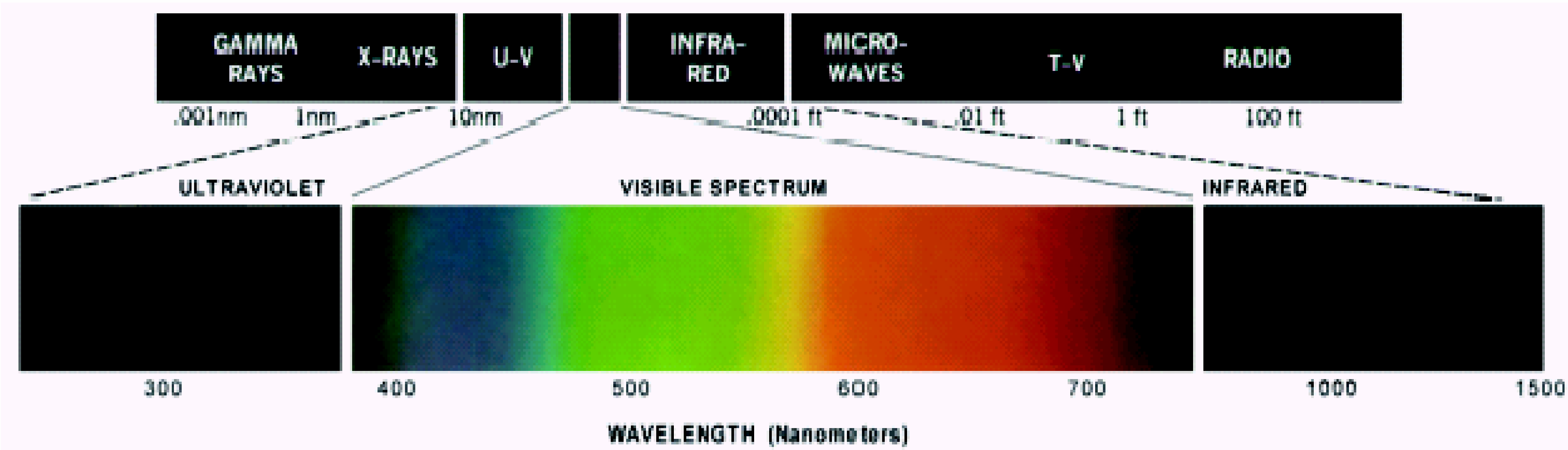
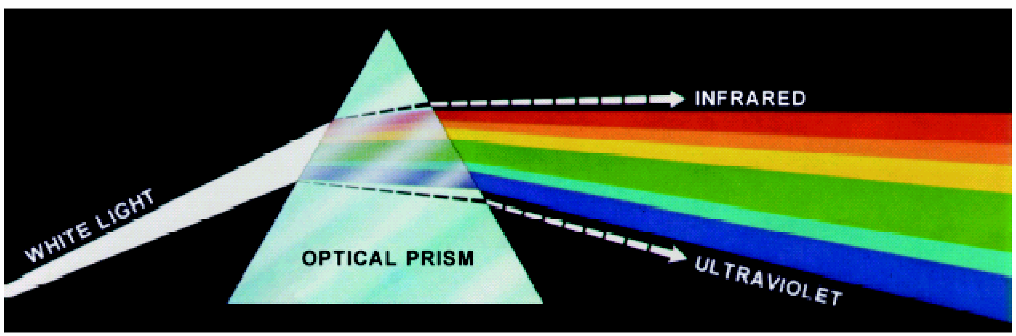
Color

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

Color: visible range of the electromagnetic spectrum

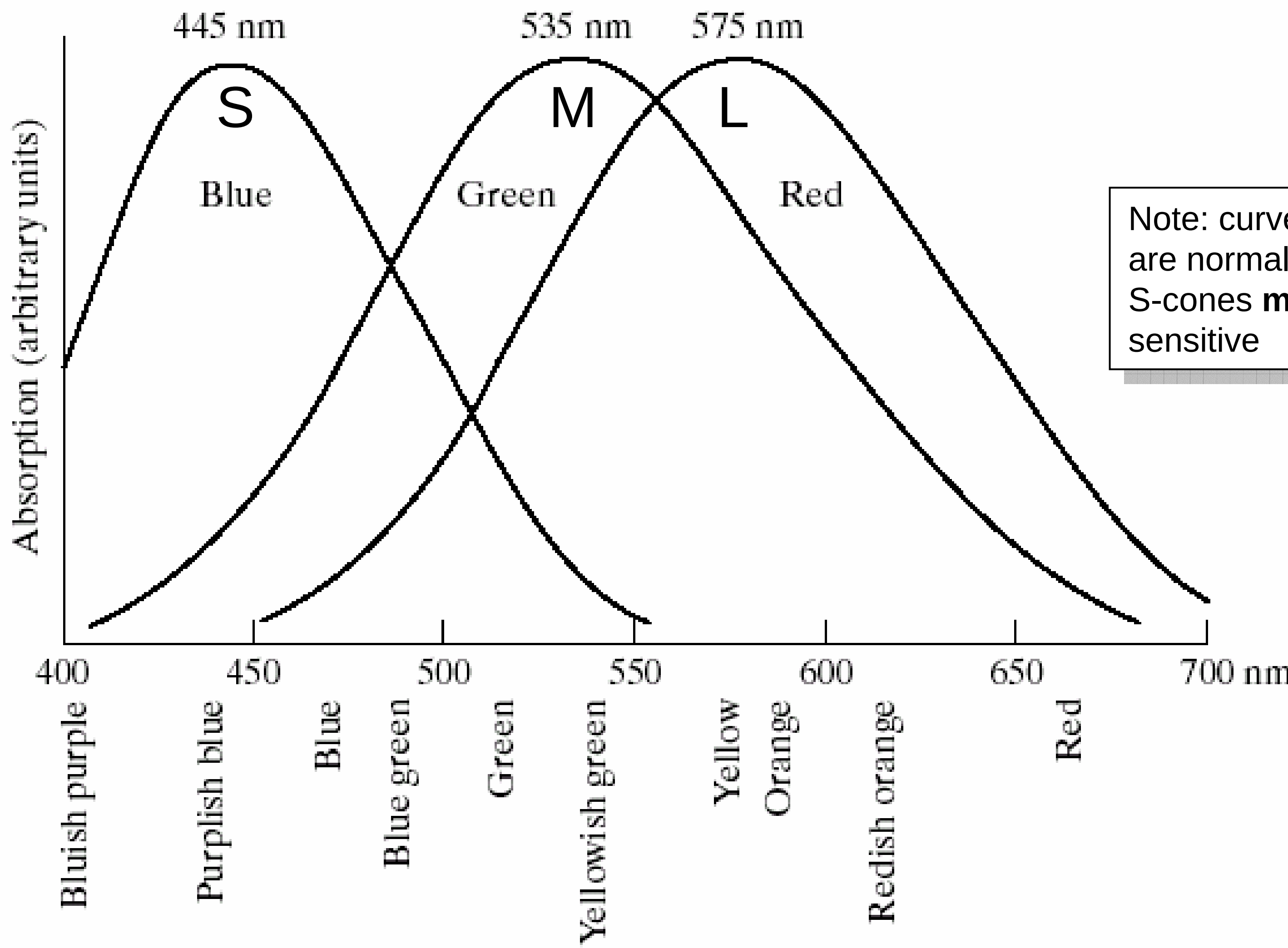




[Newton, 1666]

Source: Gonzalez+Woods, Figs. 6.1, 6.2

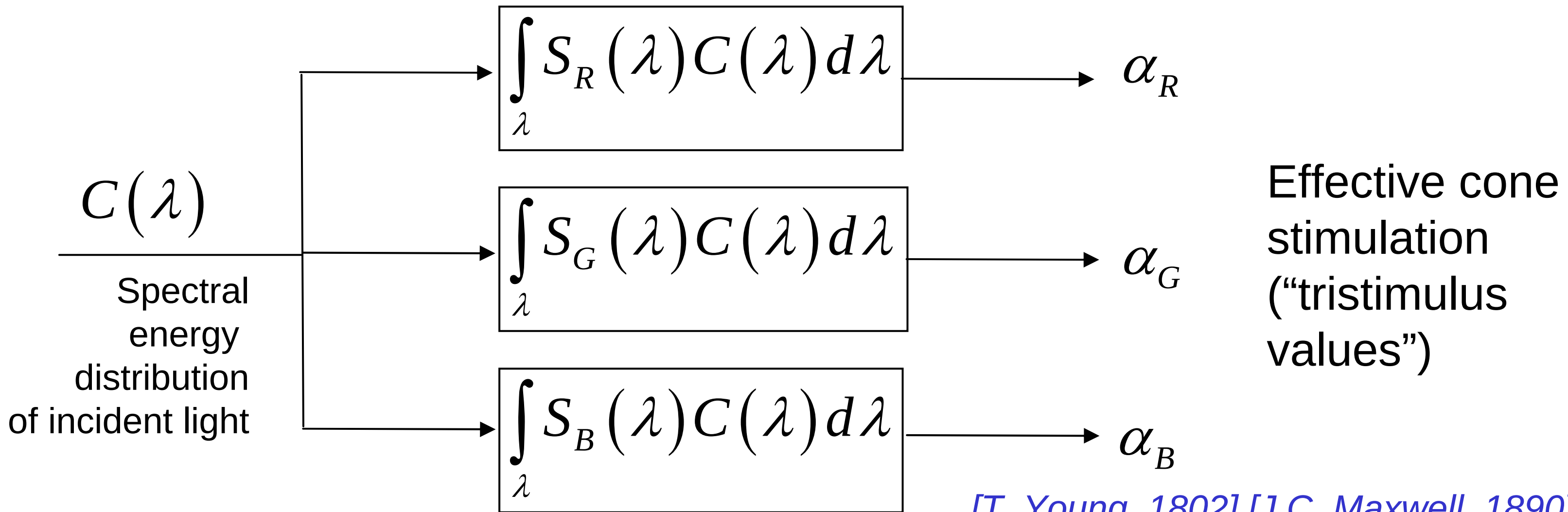
Absorption of light in the cones of the human retina



Note: curves are normalized. S-cones **much** less sensitive

Source: Gonzalez+Woods, Fig. 6.3

Three-receptor model of color perception

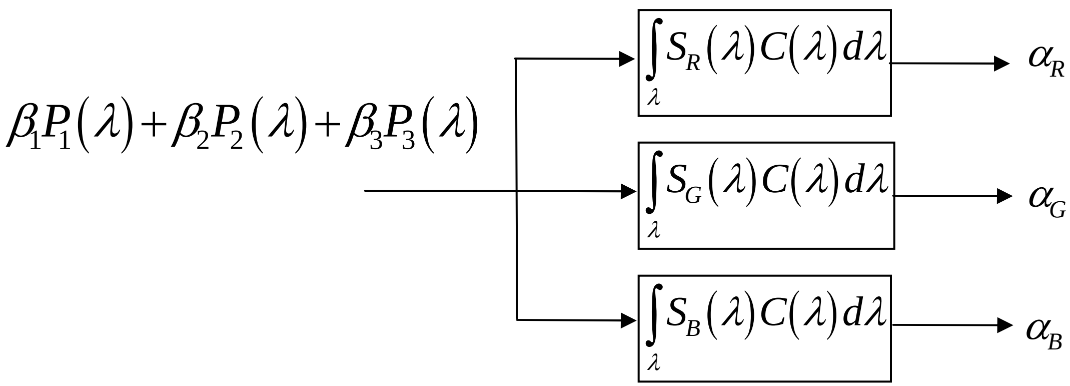


[T. Young, 1802] [J.C. Maxwell, 1890]

- 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 $(\alpha_R, \alpha_G, \alpha_B)$ result ?

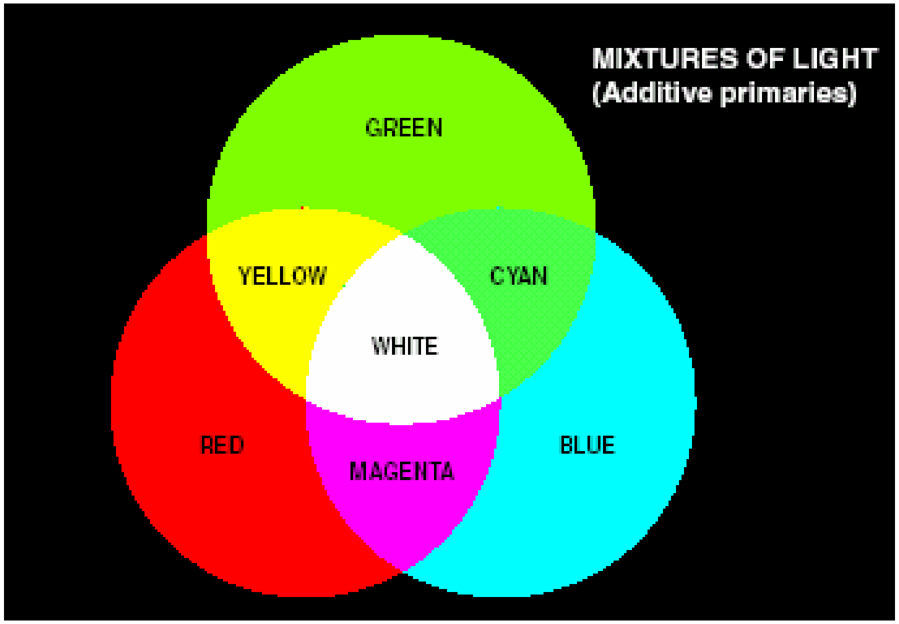


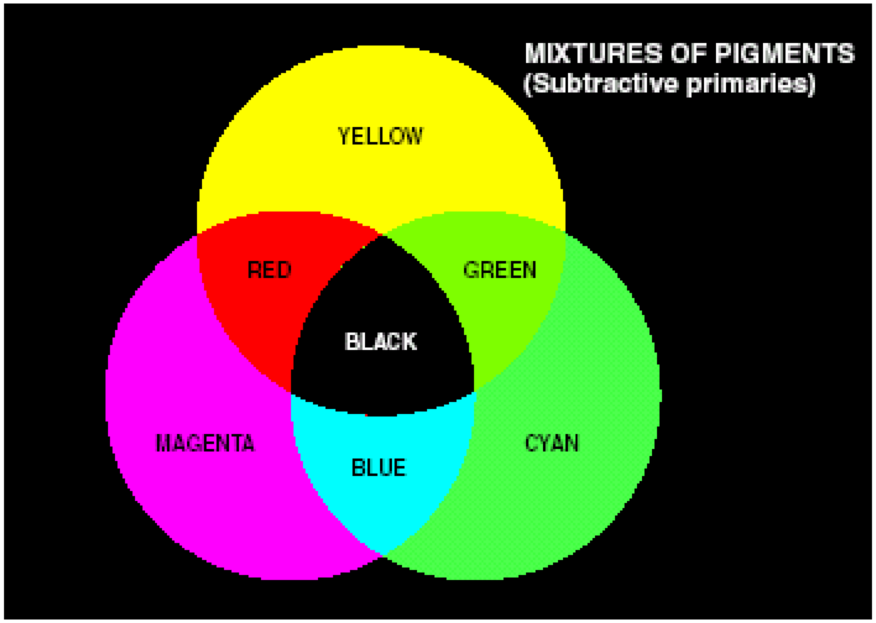
$$\alpha_i = \int_\lambda S_i(\lambda)\left[\beta_1 P_1(\lambda)+\beta_2 P_2(\lambda)+\beta_3 P_3(\lambda)\right]$$

$$= \beta_1 \cdot K_{i,1} + \beta_2 \cdot K_{i,2} + \beta_3 \cdot K_{i,3} \qquad \text{with } K_{i,j} = \int_\lambda S_i(\lambda)P_j(\lambda)d\lambda$$

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

Additive vs.subtractive color mixing

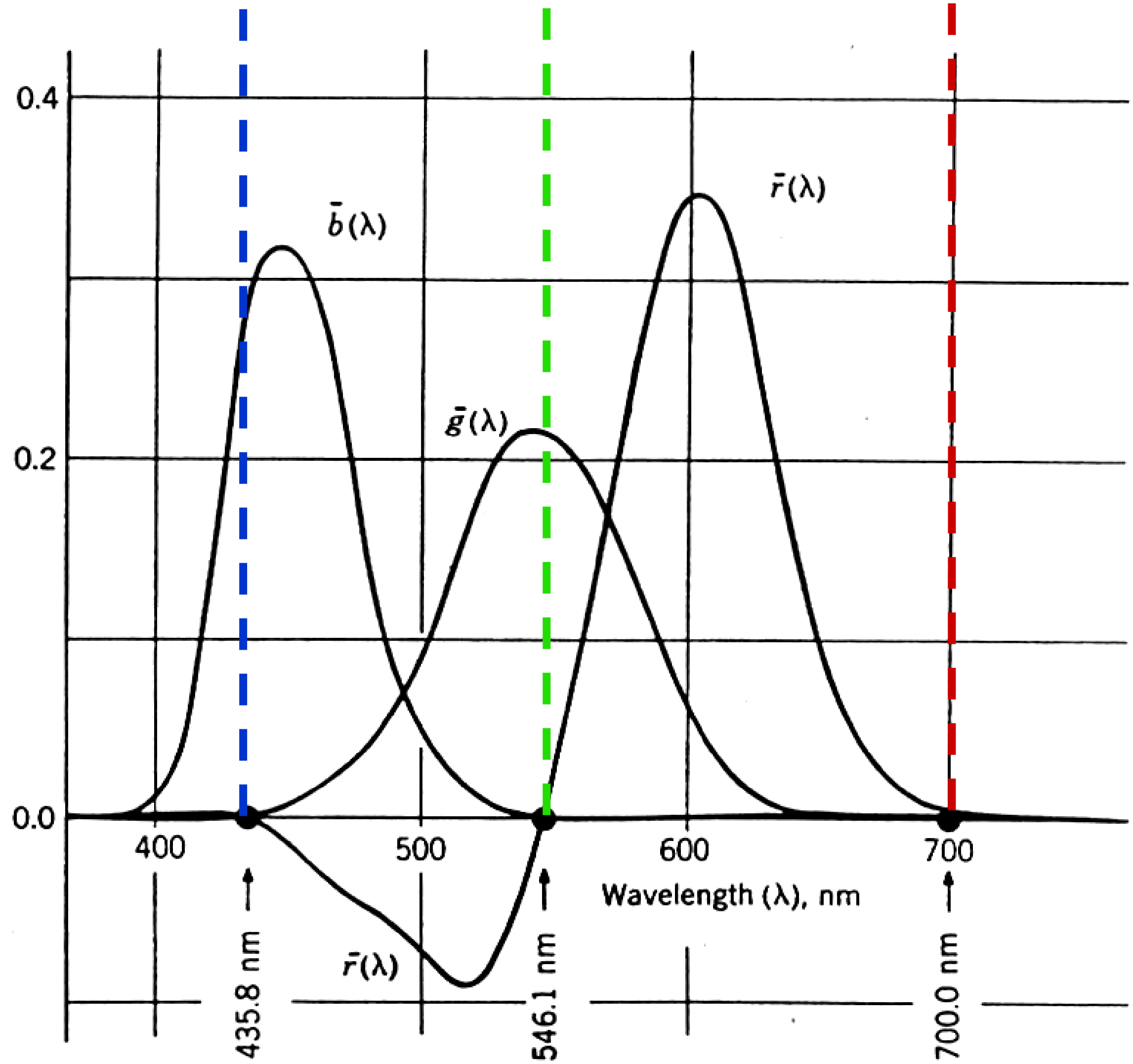




Source: Gonzalez+Woods, Fig. 6.4

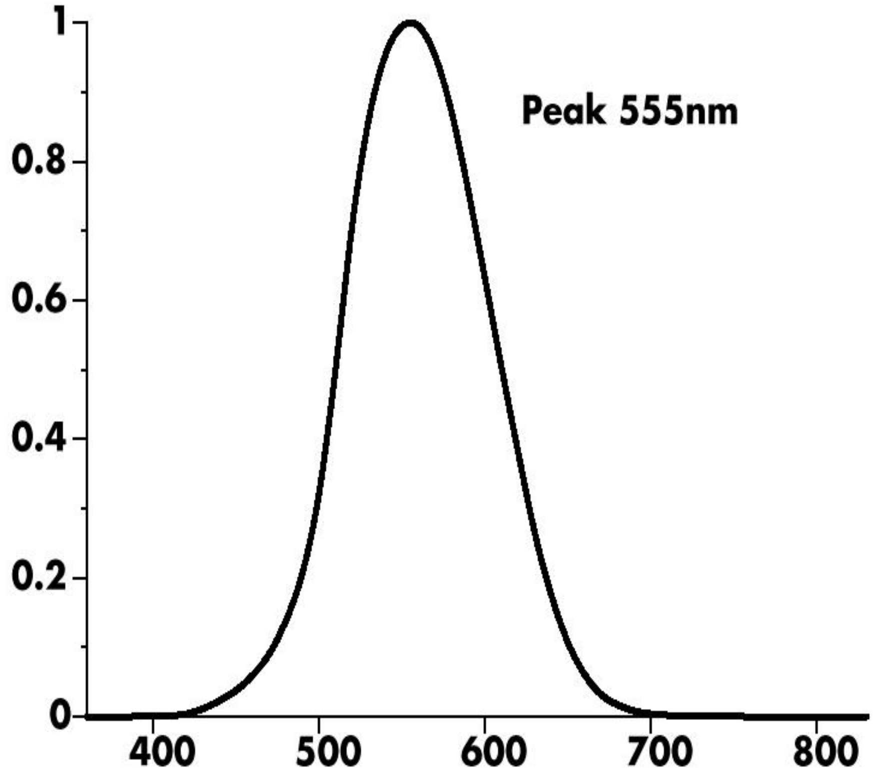
Spectral matching curves

- <u>Experiment:</u> Match monochromatic light with 3 monochromatic primaries
- "Negative intensity": color is added to test color
- CIE (Commision 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 to radiometric quantities

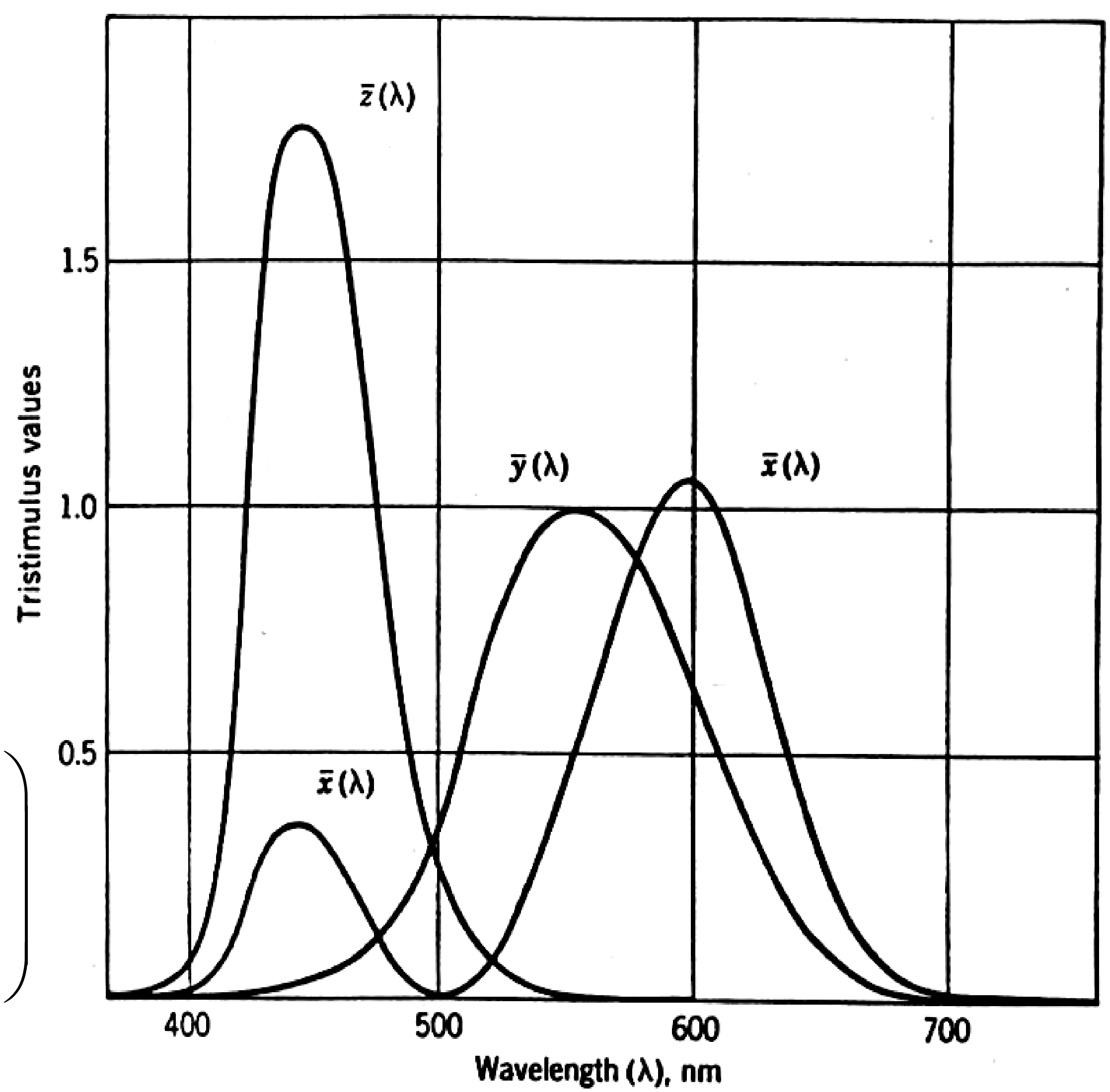


CIE 1931 XYZ color system

<u>Properties:</u>

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

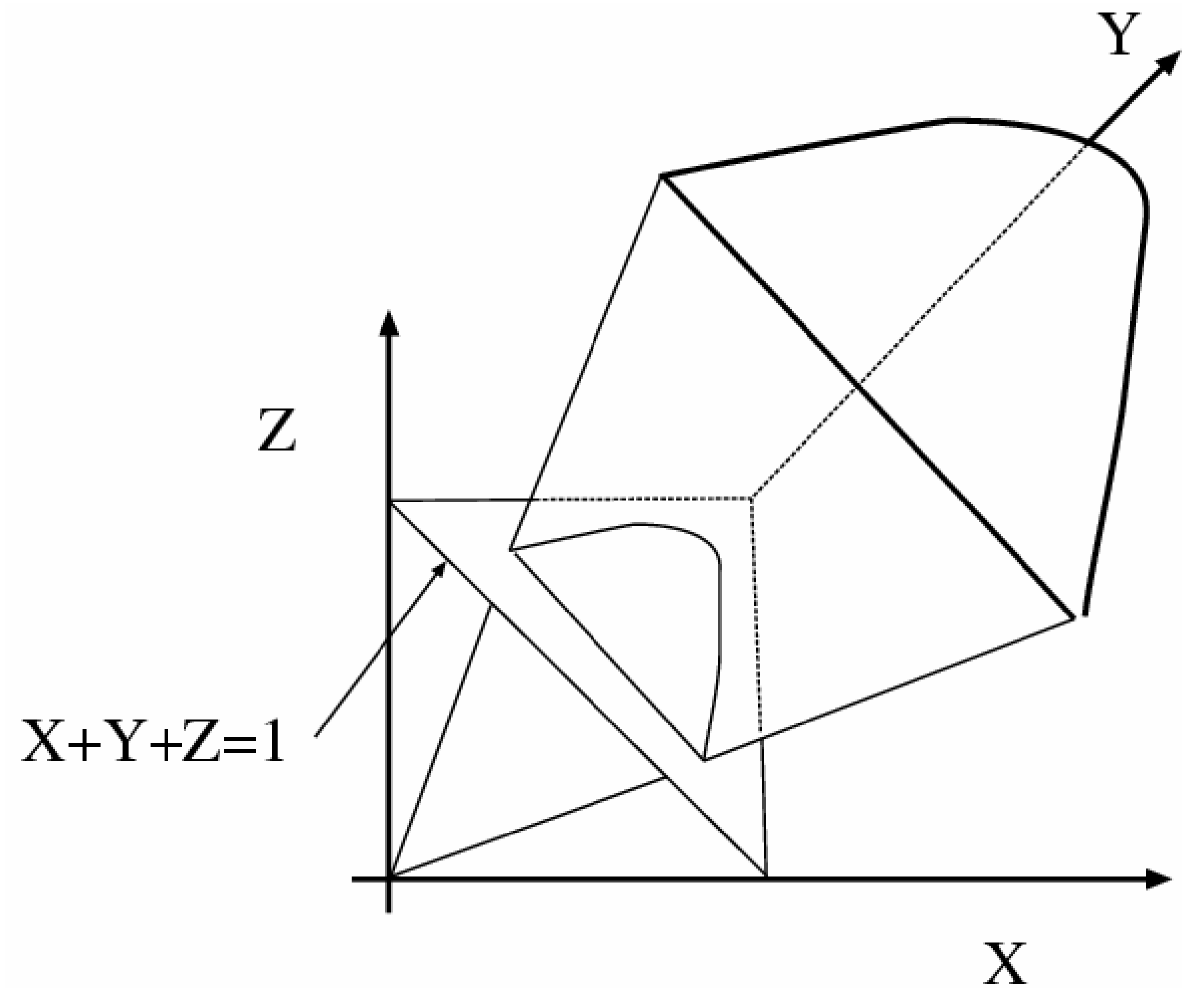
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} .490 & .310 & .200 \\ .177 & .813 & .011 \\ .000 & .010 & .990 \end{pmatrix} \begin{pmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{pmatrix}$$

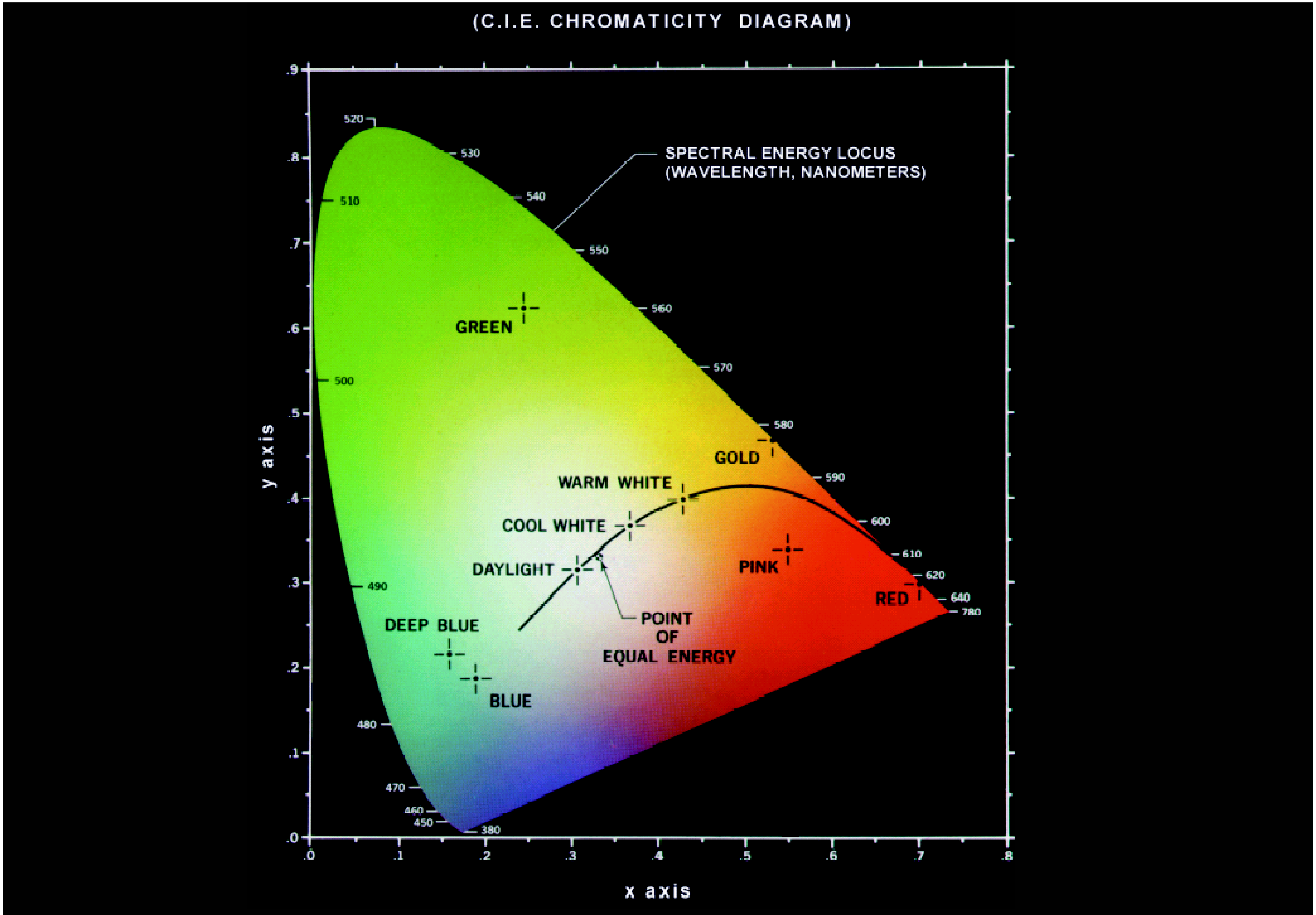


Color gamut and chromaticity

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

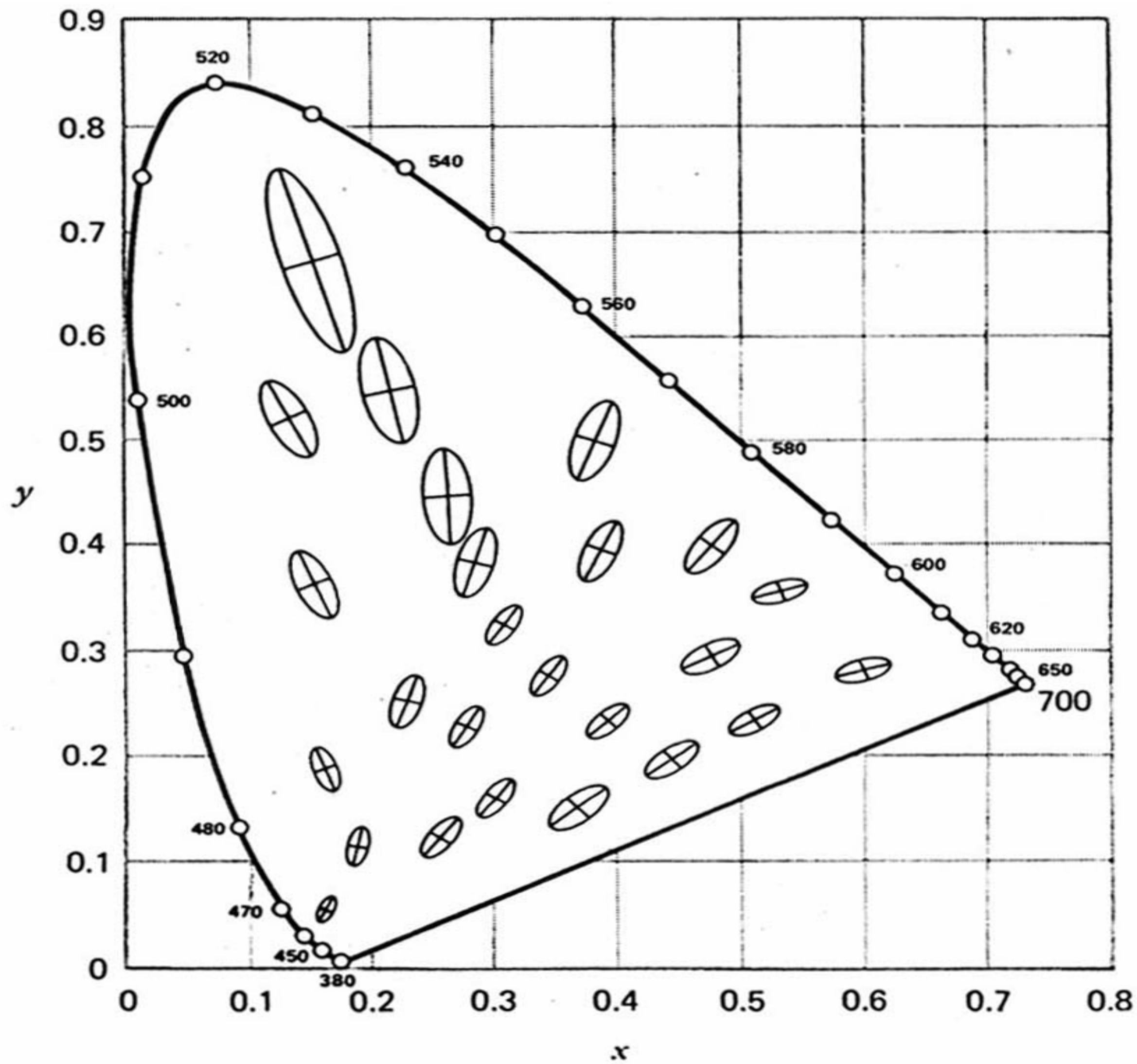
$$y = \frac{Y}{X+Y+Z}$$





Source: Gonzalez+Woods, Fig. 6.4

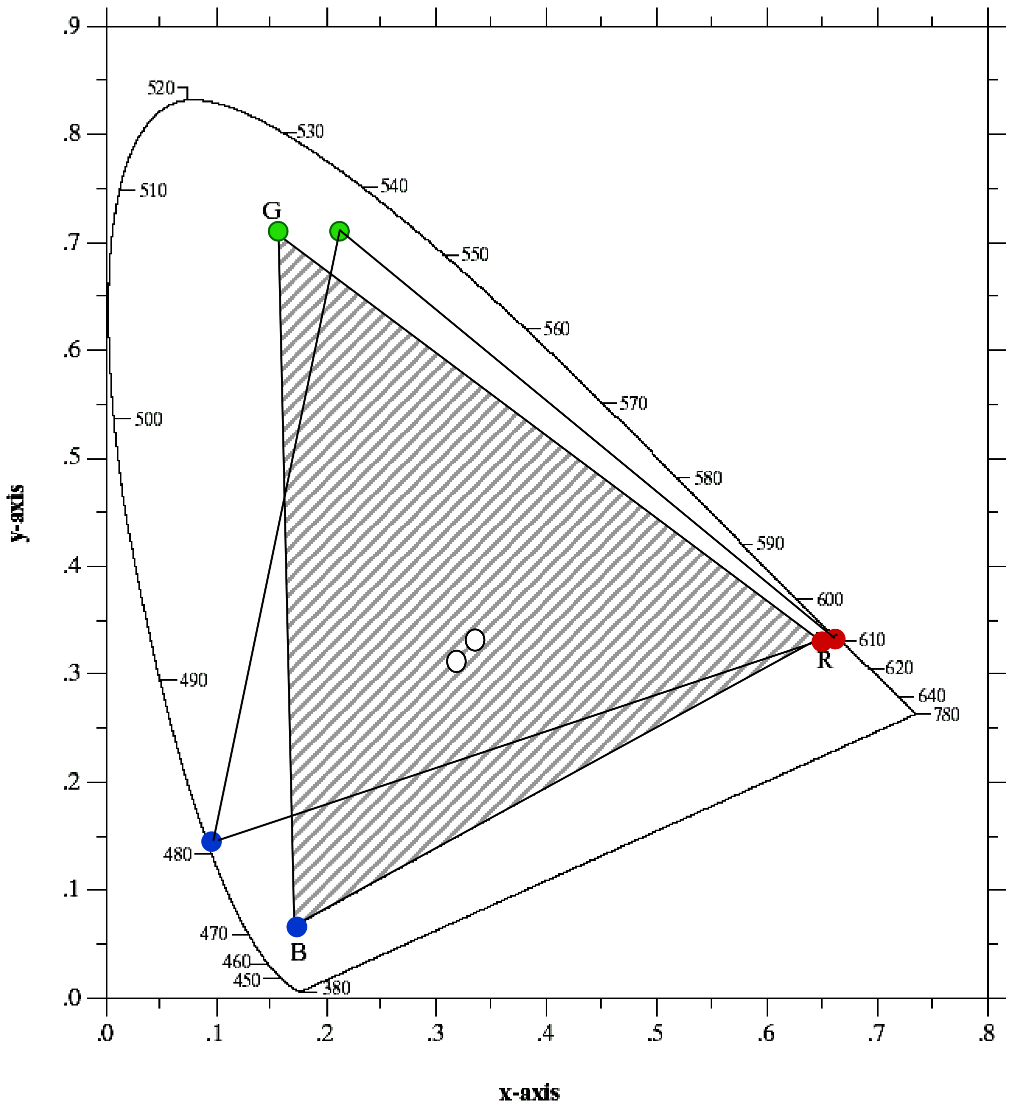
Inaccuracy for color matches



Just noticable chromaticity differences (10X enlarged)

[MacAdam, 1942]

Color gamut

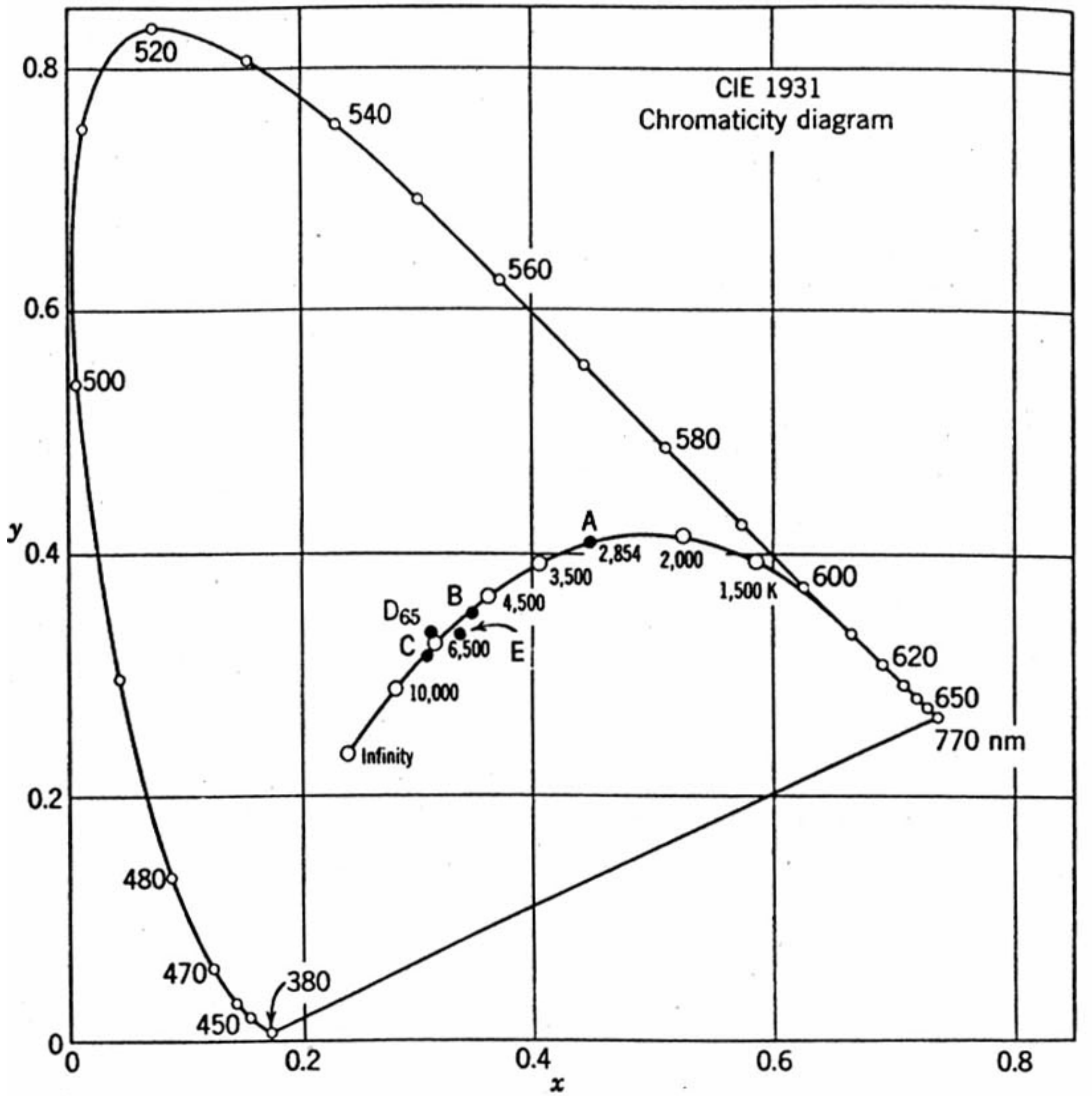


NTSC phosphors

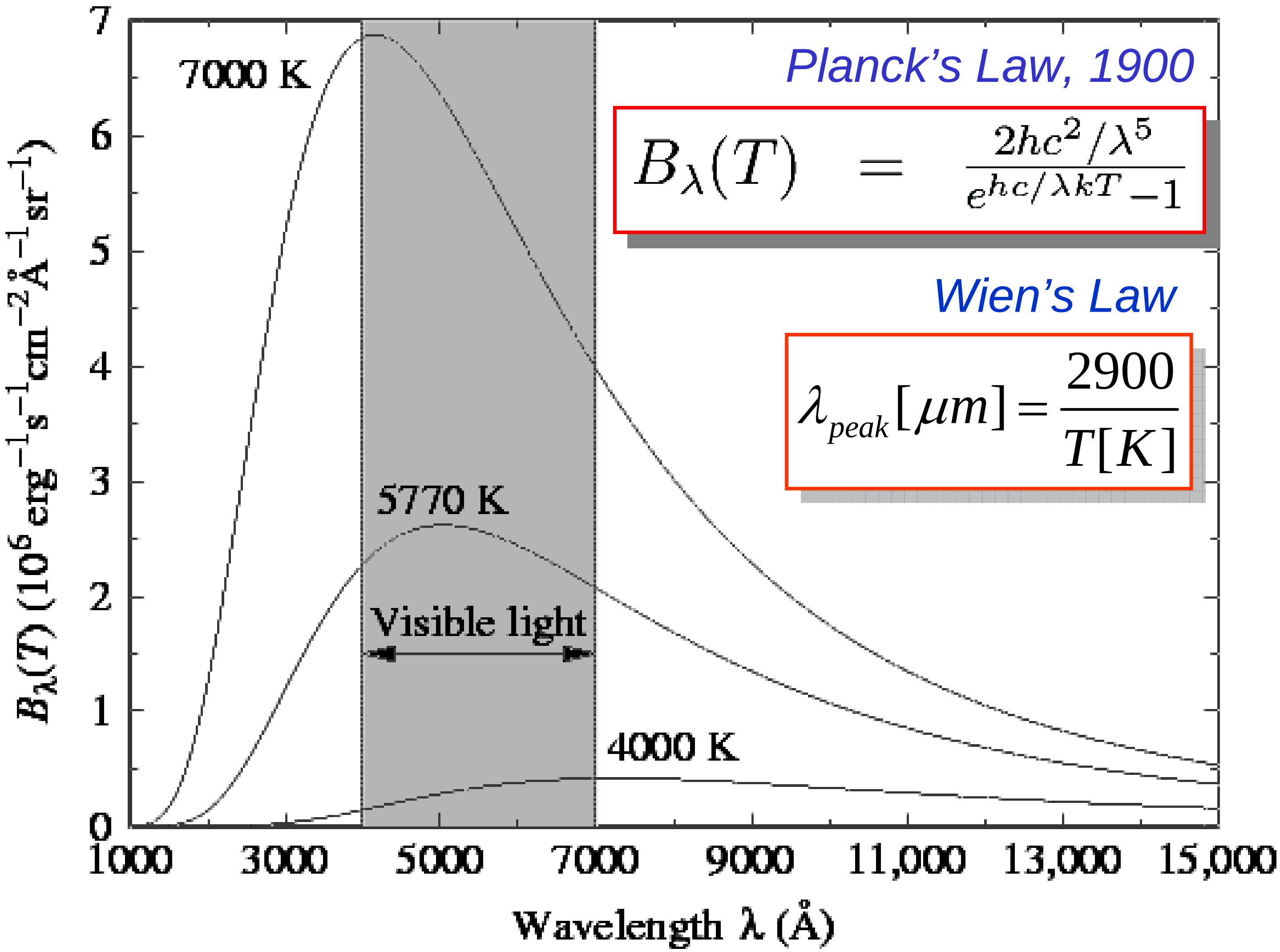
R: x=0.67, y=0.33
G: x=0.21, y=0.71
B: x=0.14, y=0.08

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

White at different color temperatures

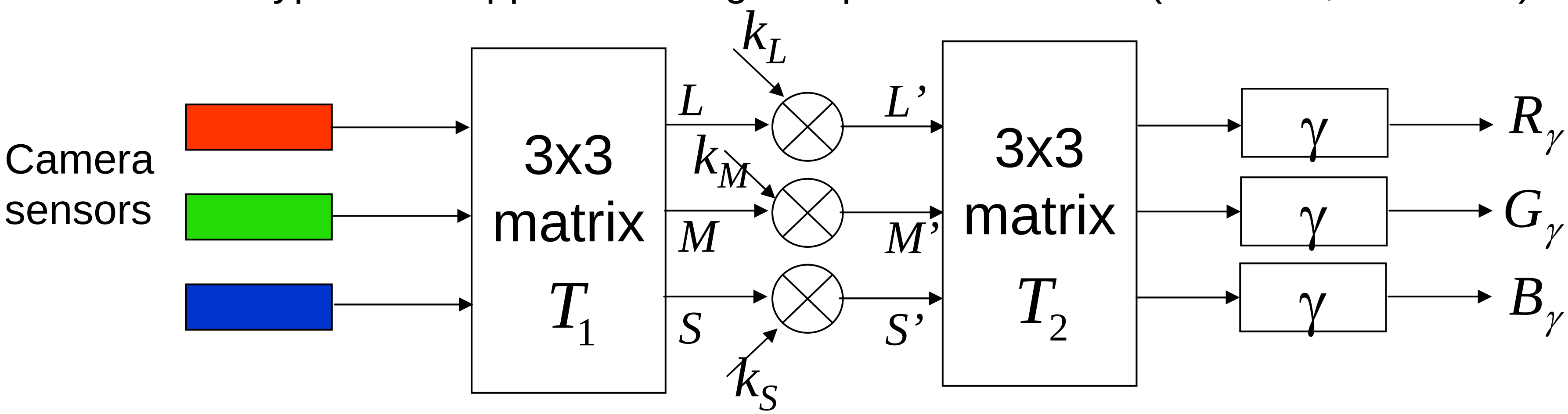


Blackbody radiation



Color balancing

- Effect of different illuminants can be cancelled only in the spectral domain (impractical)
- Color balancing in 3-d color space is practical approximation
- Color constancy in human visual system: gain control in cone space LMS *[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 (cont.)

- Von Kries hypothesis

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

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

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

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 Lena

Scale-by-max
color balancing