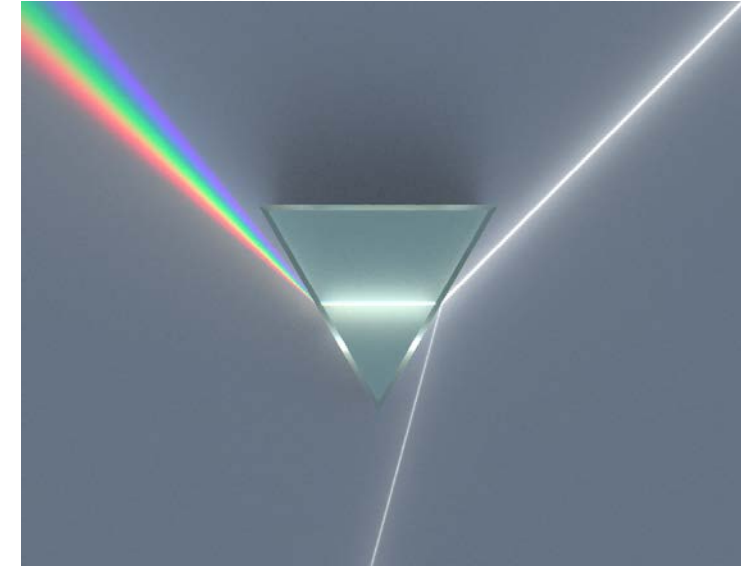
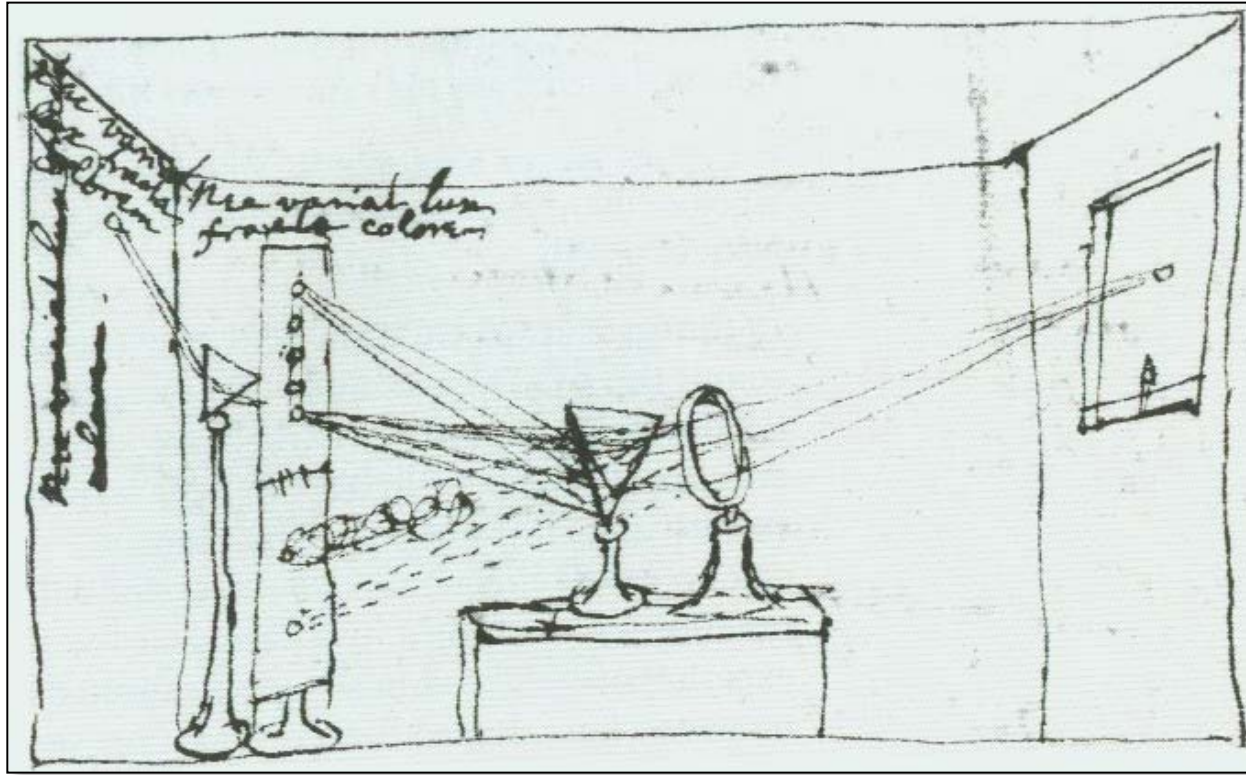


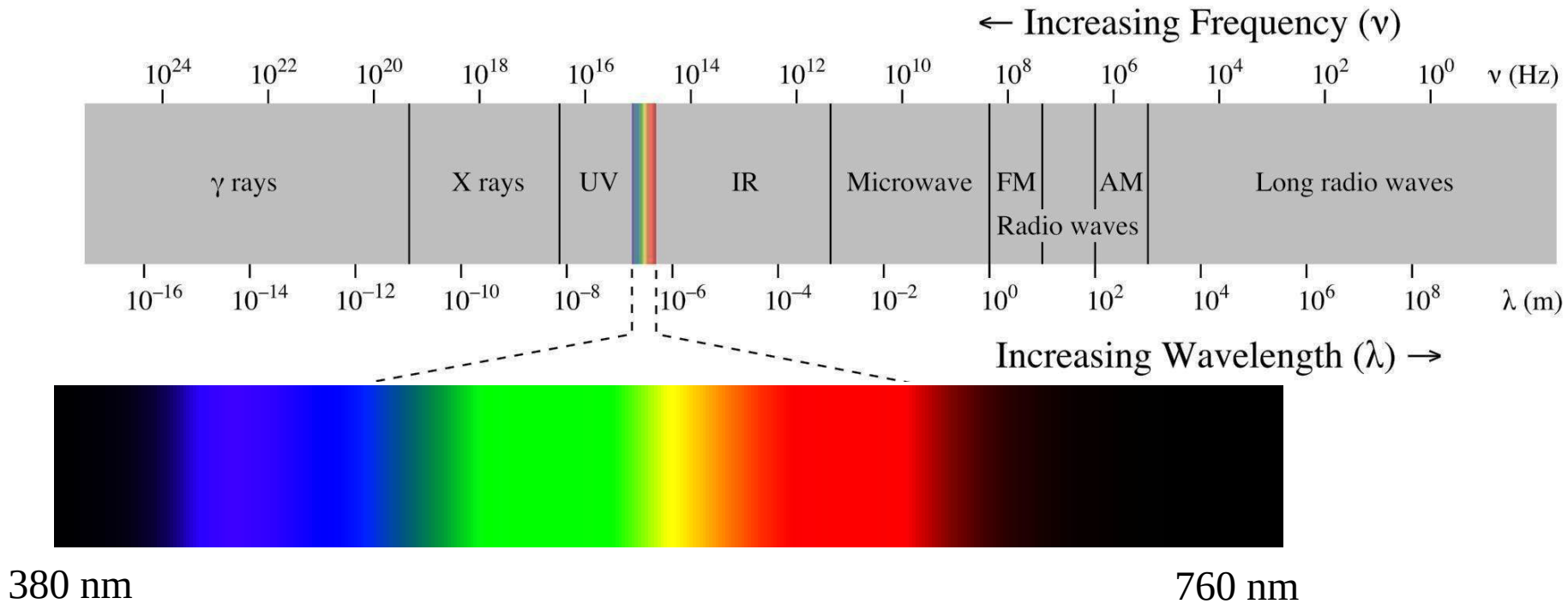
Introduction to color science

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

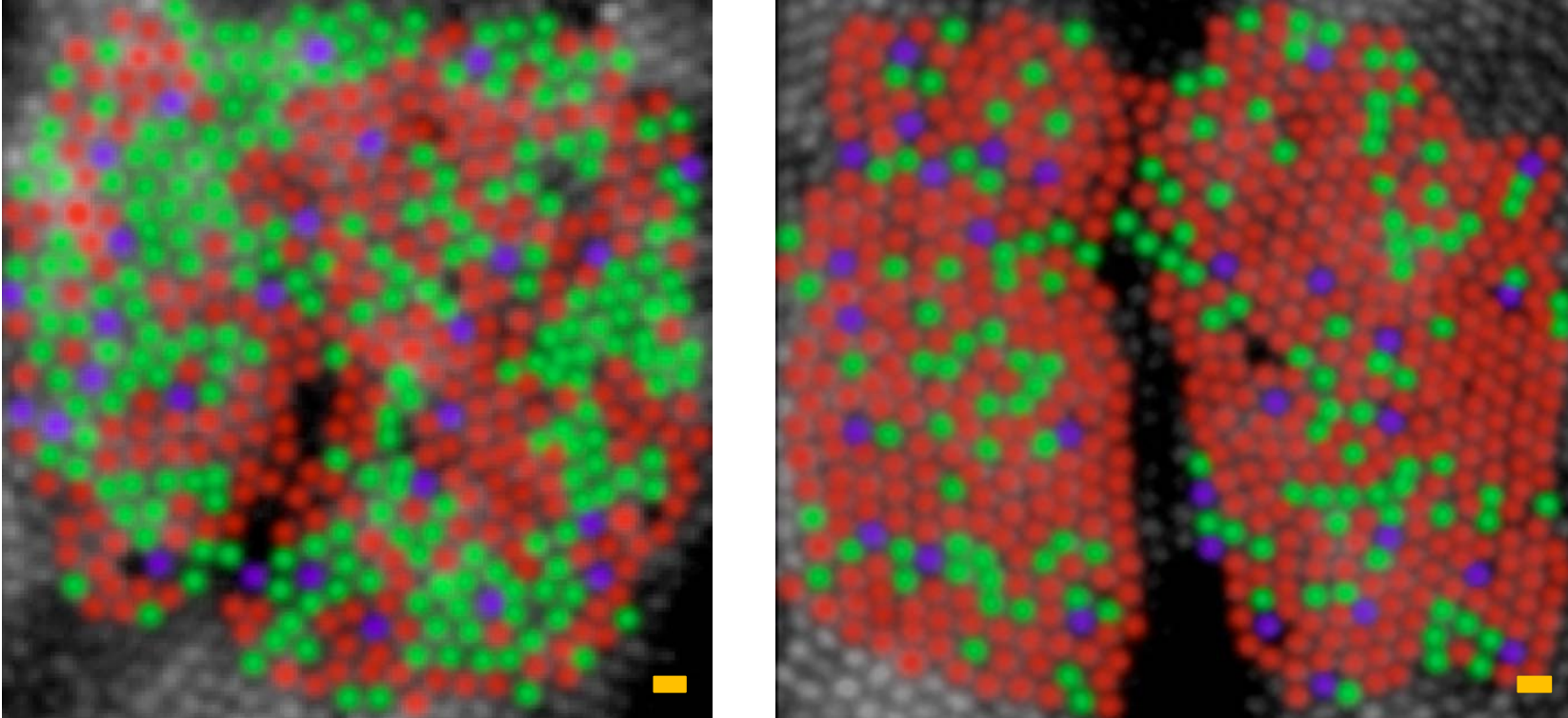
Newton's Prism Experiment - 1666



Color: visible range of the electromagnetic spectrum



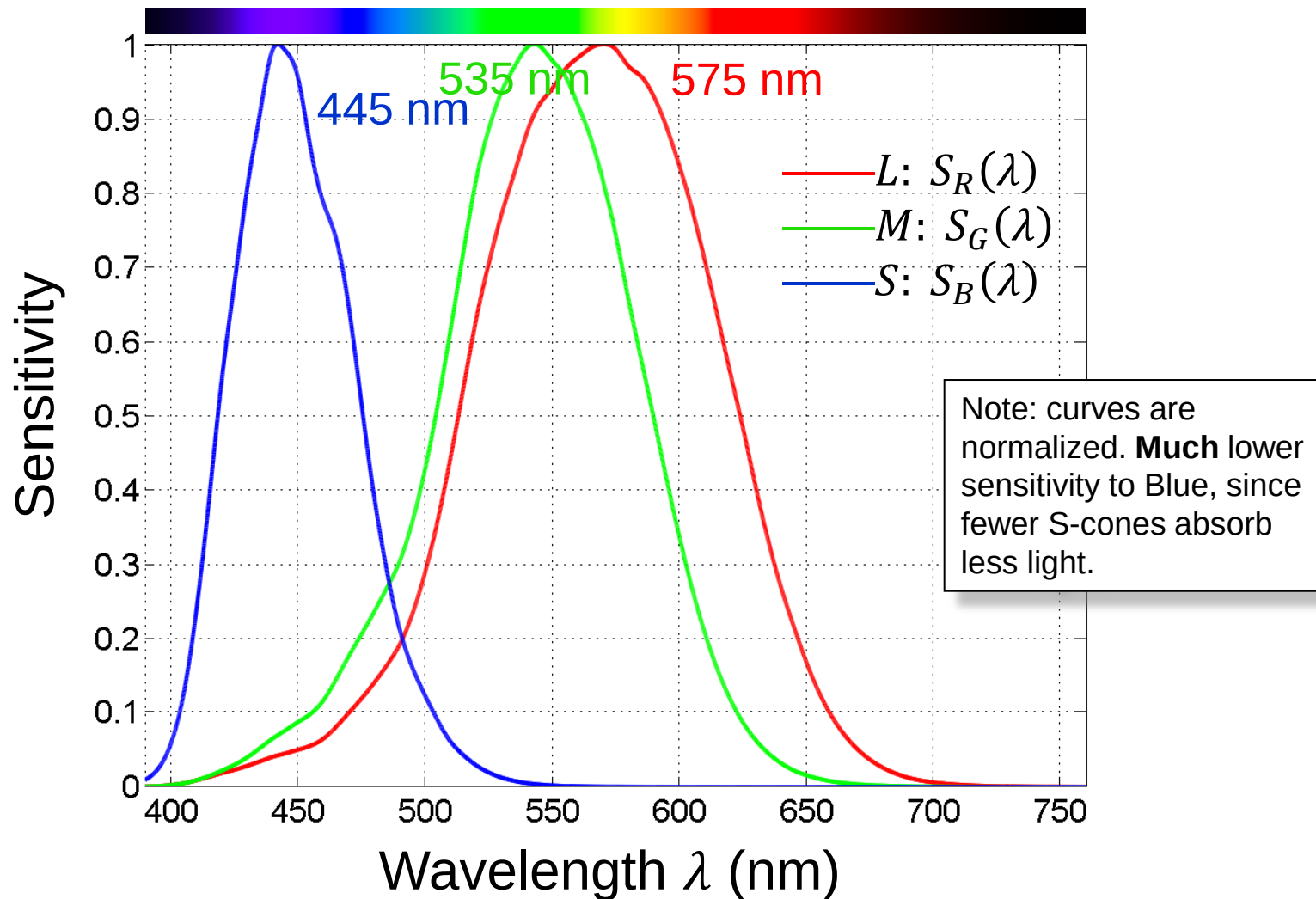
Human retina



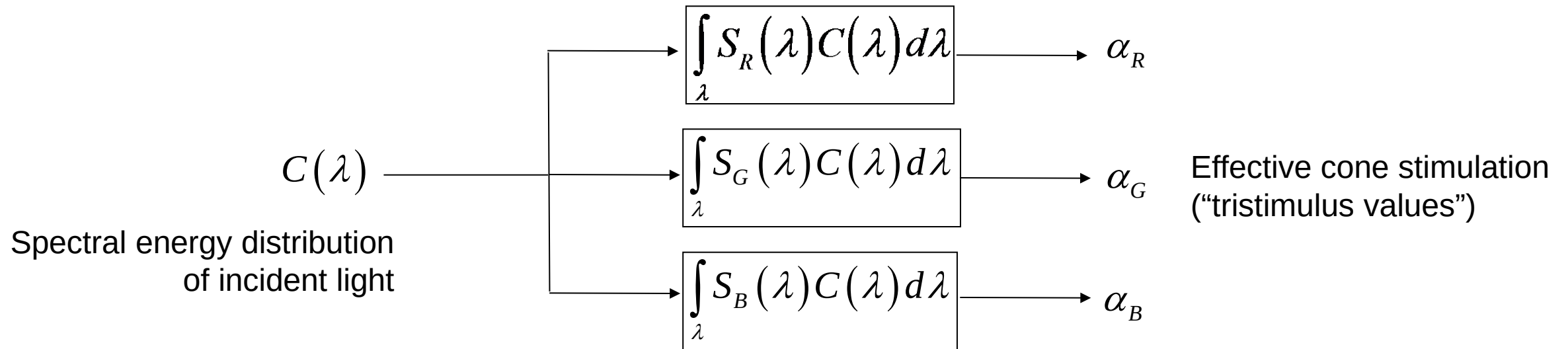
[Roorda, Williams, 1999]

Pseudo-color image of nasal retina,
1 degree eccentricity, in two male subjects, scale bar 5 micron

Absorption of light in the cones of the human retina



Three-receptor model of color perception

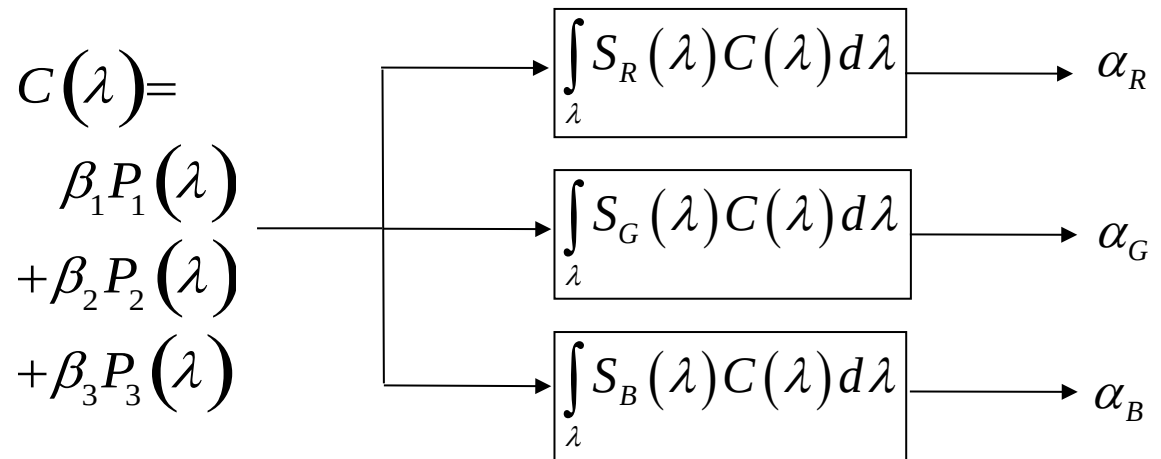


[T. Young, 1802] [J.C. Maxwell, 1890]

- 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 $P_k(\lambda)$, $k = 1, 2, 3$
- Intensity of each light source can be adjusted by factor β_k
- How to choose β_k , $k = 1, 2, 3$, such that desired tristimulus values $(\alpha_R, \alpha_G, \alpha_B)$ result ?

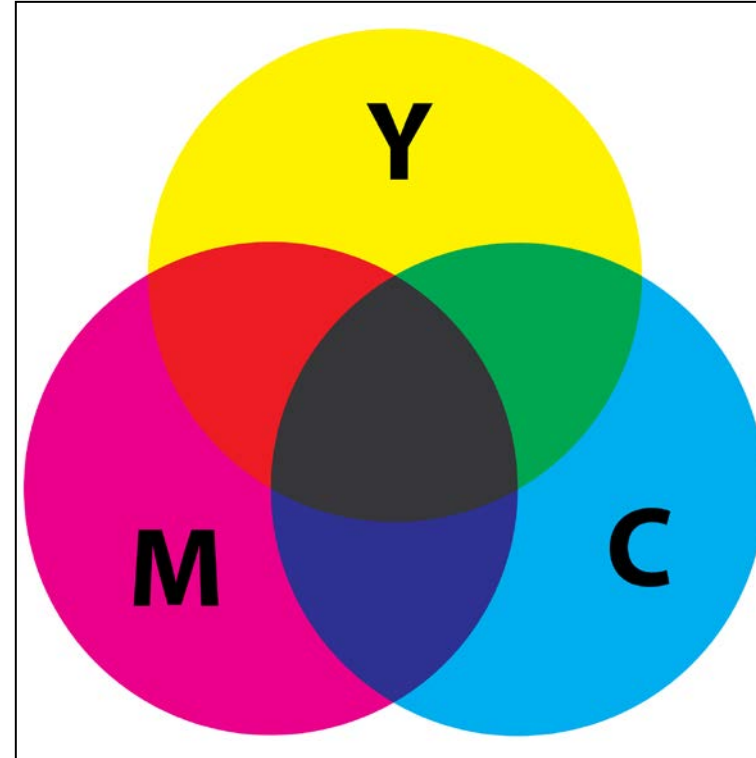
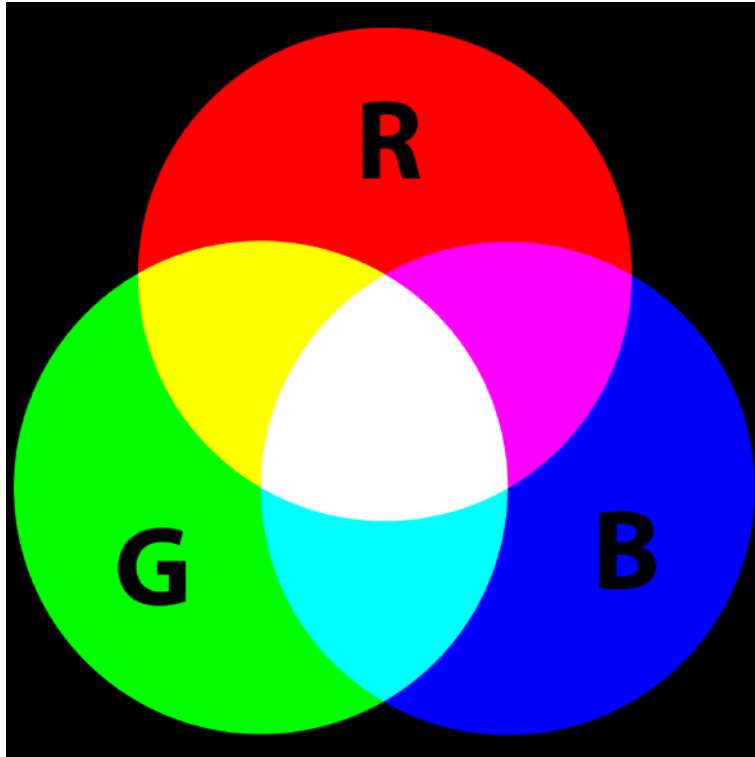


$$\begin{aligned}\alpha_i &= \int_{\lambda} S_i(\lambda) [\beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda)] d\lambda \\ &= \beta_1 \cdot K_{i,1} + \beta_2 \cdot K_{i,2} + \beta_3 \cdot K_{i,3}\end{aligned}$$

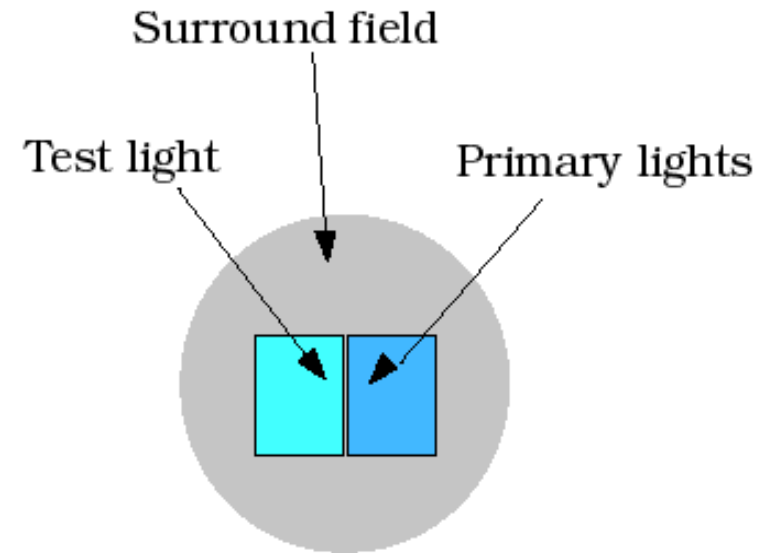
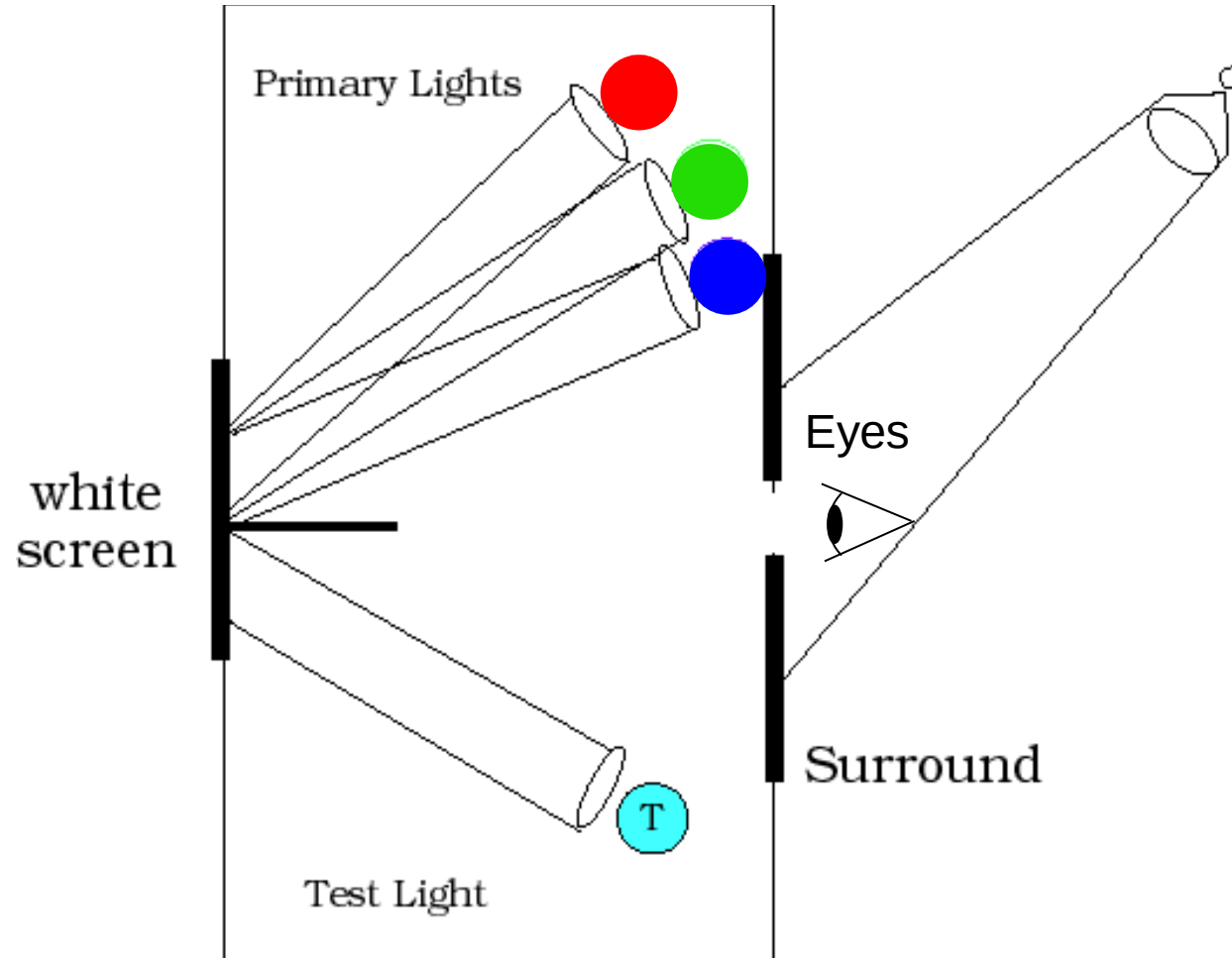
$$\text{with } K_{i,j} = \int_{\lambda} S_i(\lambda) P_j(\lambda) d\lambda$$

Color matching is linear!

Additive vs. subtractive color mixing

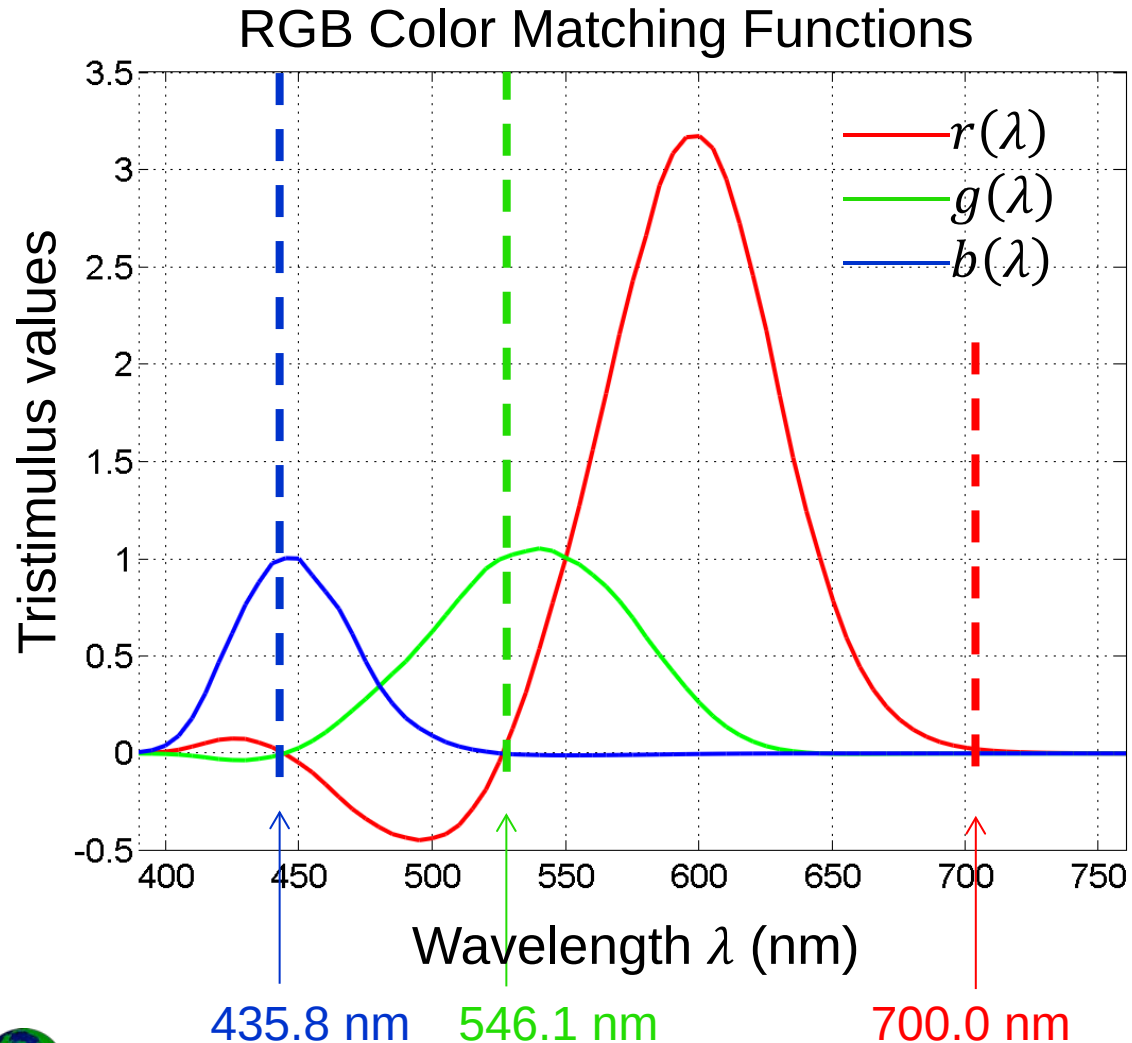


Color matching experiment



Courtesy B. Wandell, from [Foundations of Vision, 1996]

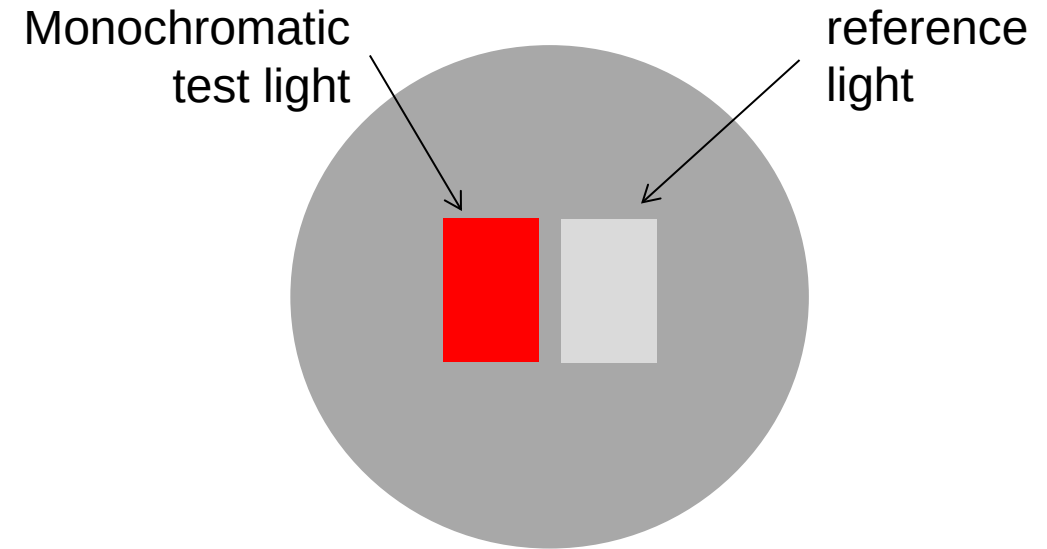
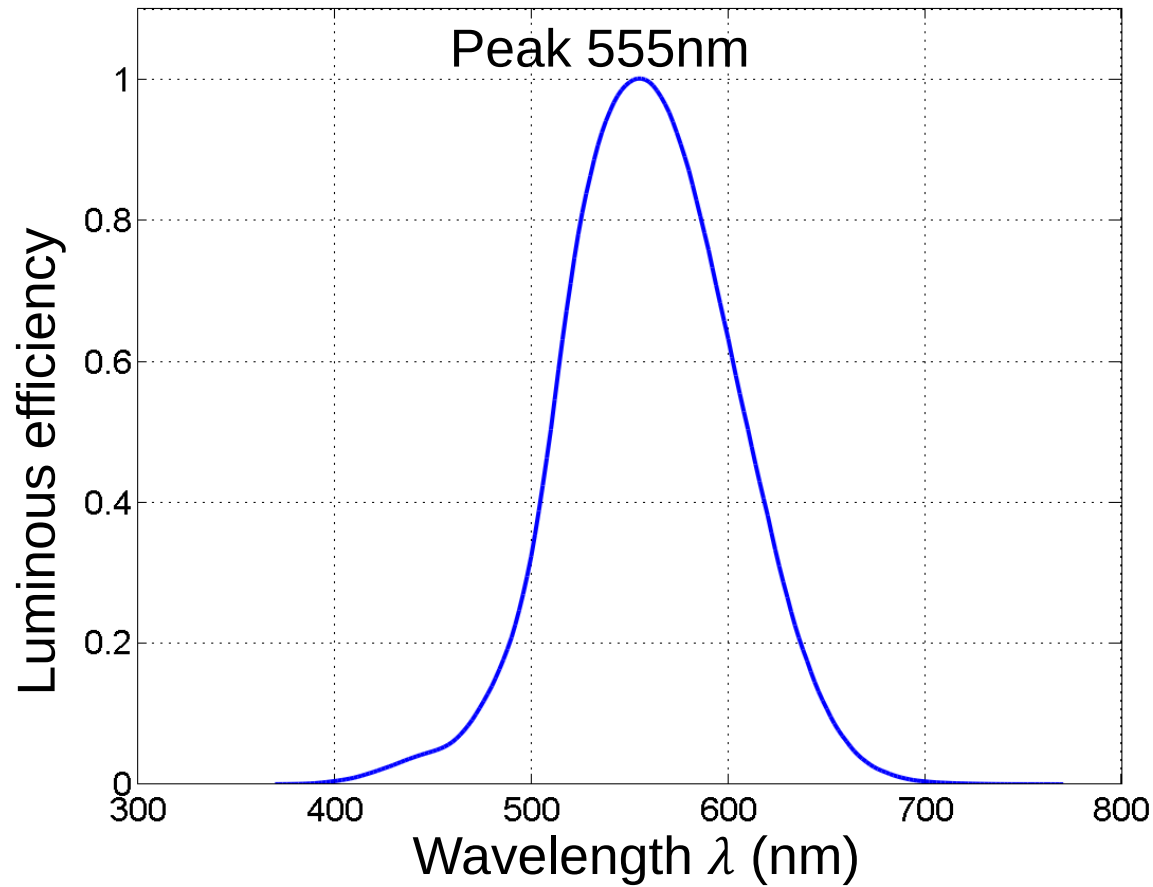
Spectral matching functions



- Color matching experiment: Monochromatic test light and monochromatic primary lights
- Spectral RGB primaries (scaled, such that $R_\lambda = G_\lambda = B_\lambda$ matches spectrally flat white).
- “Negative intensity”: color is added to test color
- Standard human observer: CIE (Commission Internationale de L’Eclairage), 1931.



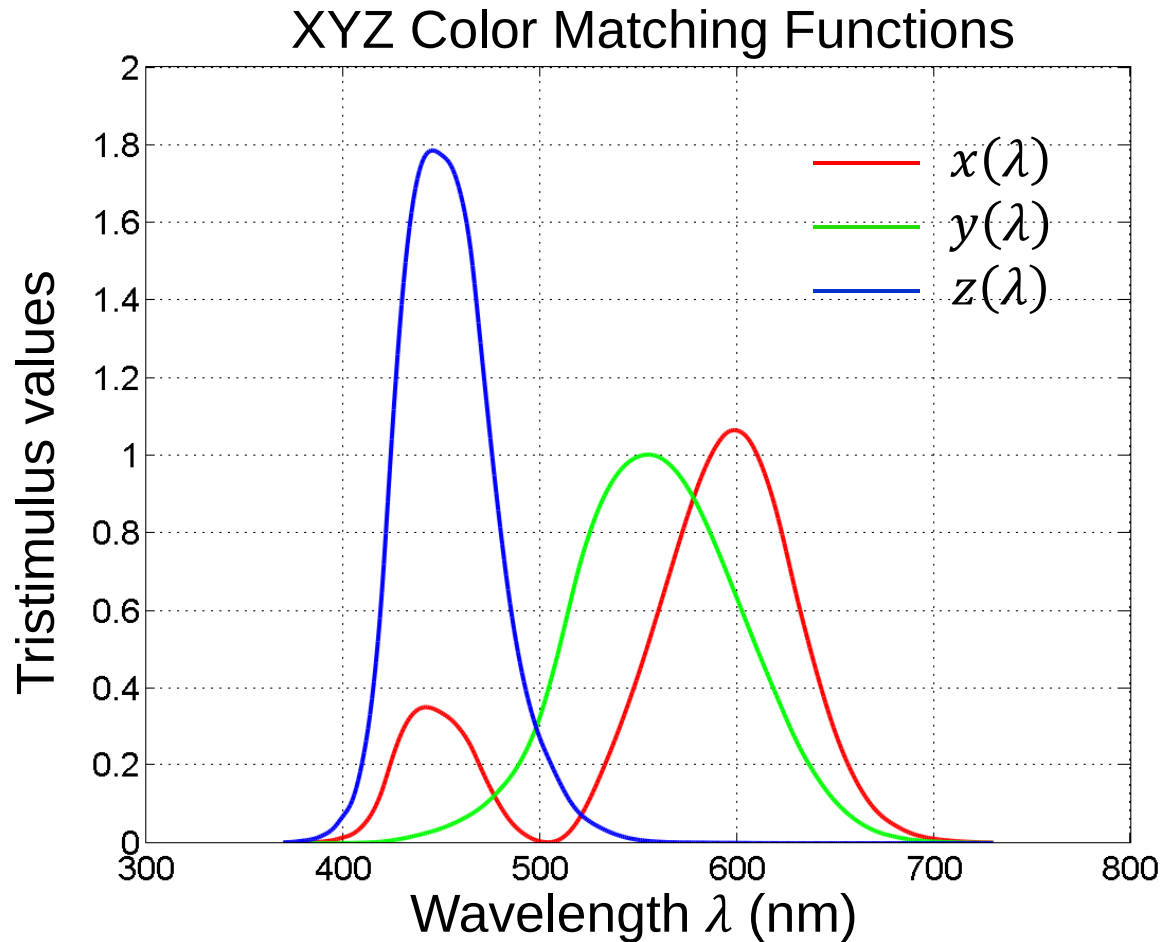
Luminosity function



- Experiment:
Match the brightness of a white reference light and a monochromatic test light of wavelength λ
- Links photometric to radiometric quantities



CIE 1931 XYZ color system



Properties:

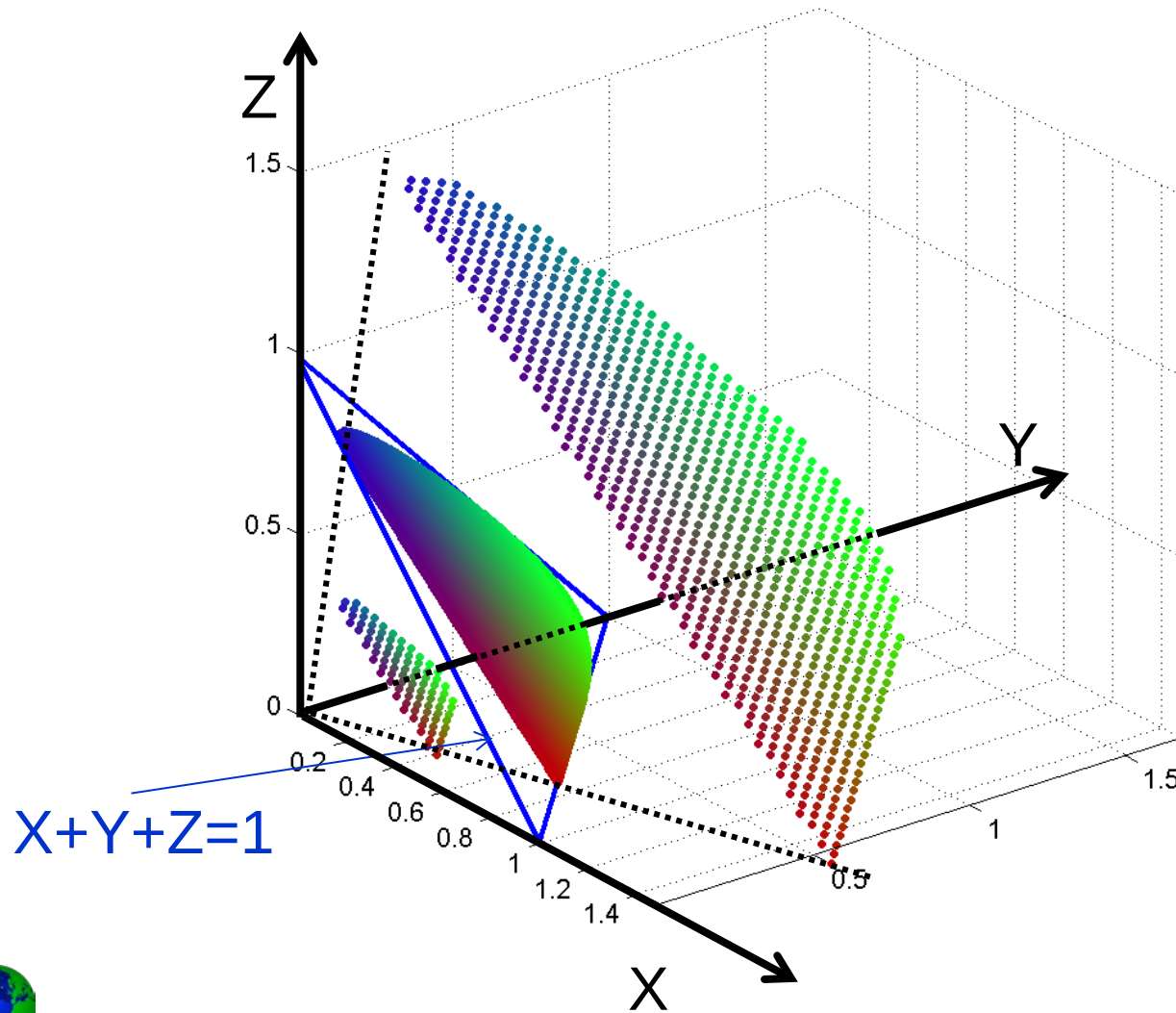
- All positive spectral matching functions

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

- Y corresponds to luminance
- Equal energy white: $X=Y=Z$
- Virtual primaries



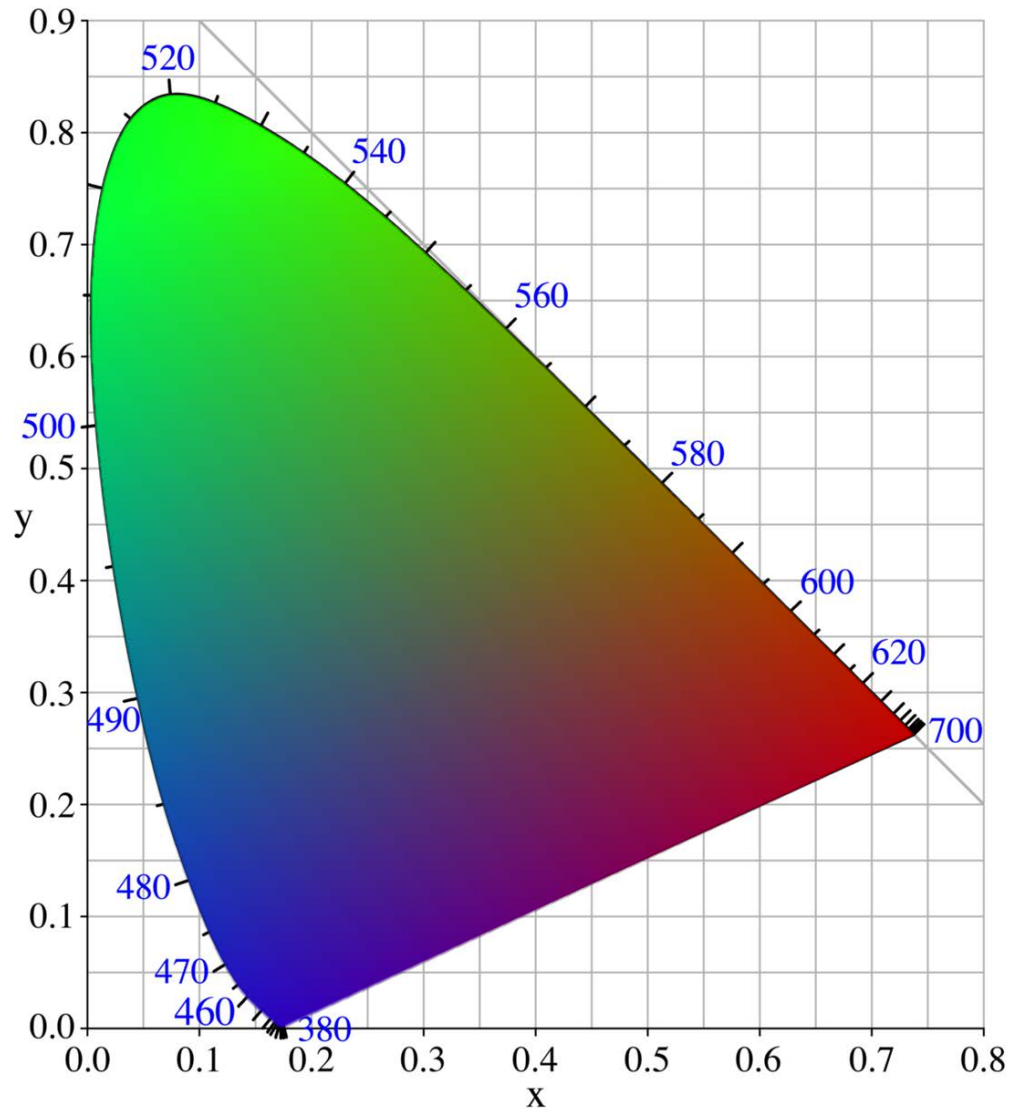
Color gamut and chromaticity



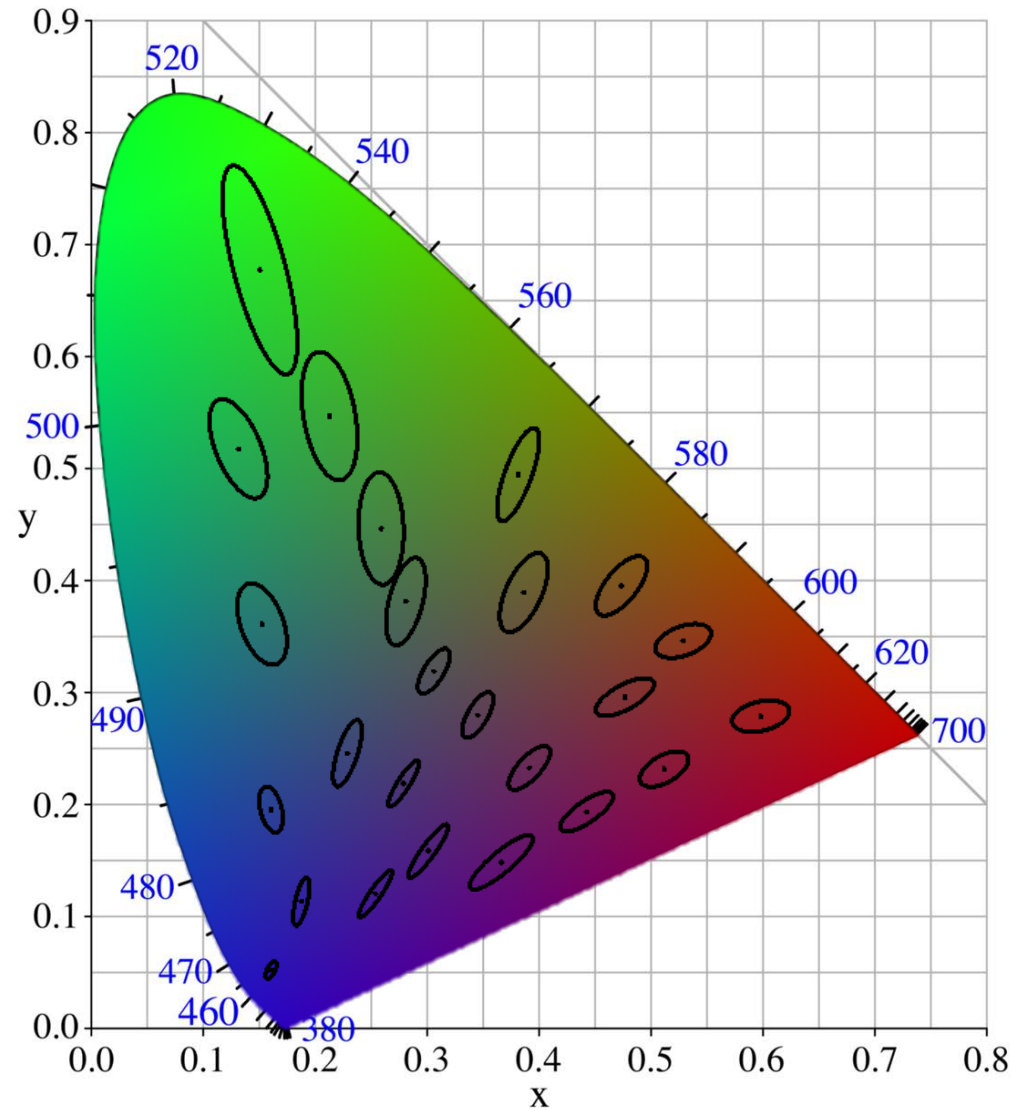
$$x = \frac{X}{X + Y + Z}$$
$$y = \frac{Y}{X + Y + Z}$$



CIE chromaticity diagram



Perceptual non-uniformity of xy chromaticity

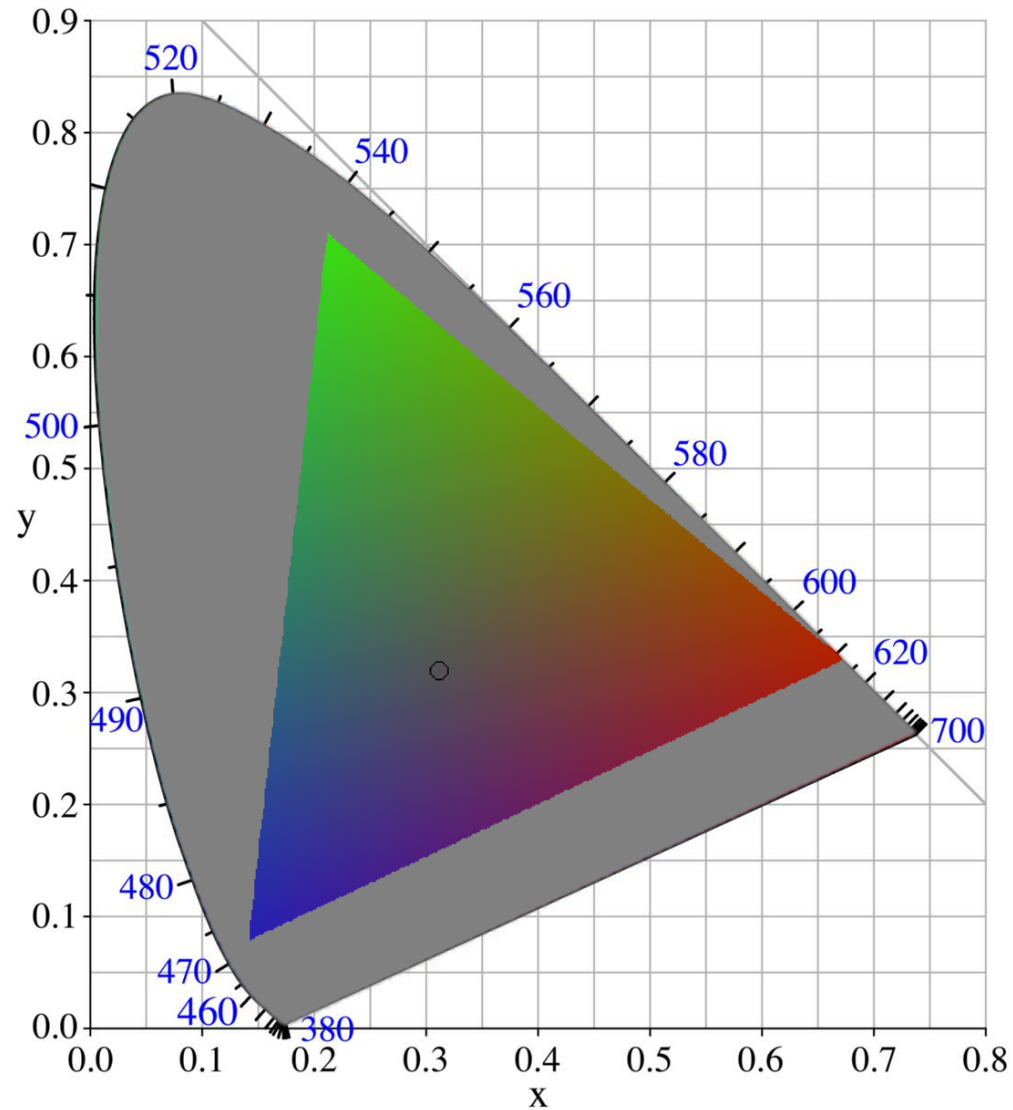


Just noticeable chromaticity differences (10X enlarged)

[MacAdam, 1942]



Color gamut



NTSC phosphors

R: $x=0.67$, $y=0.33$

G: $x=0.21$, $y=0.71$

B: $x=0.14$, $y=0.08$

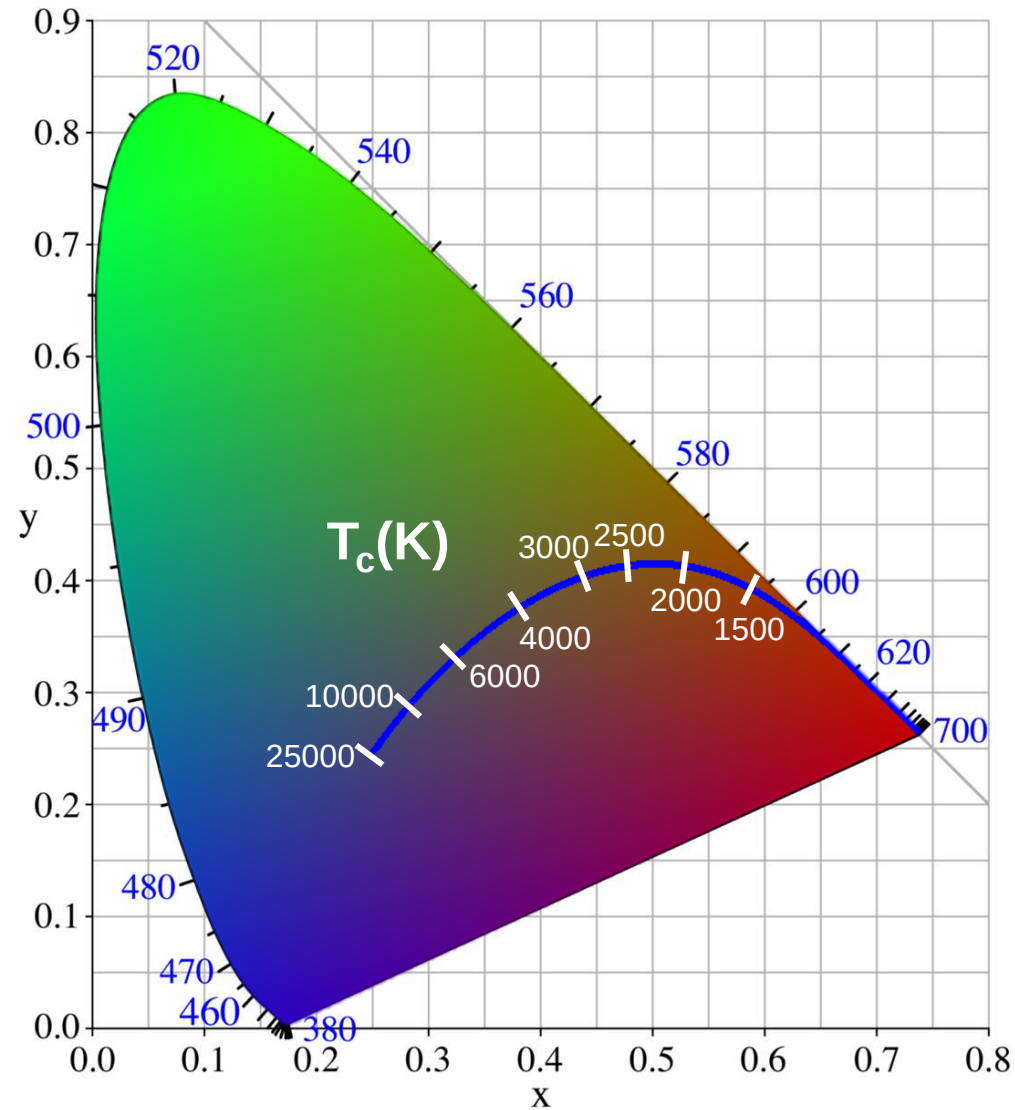
Reference white:

$x=0.31$, $y=0.32$

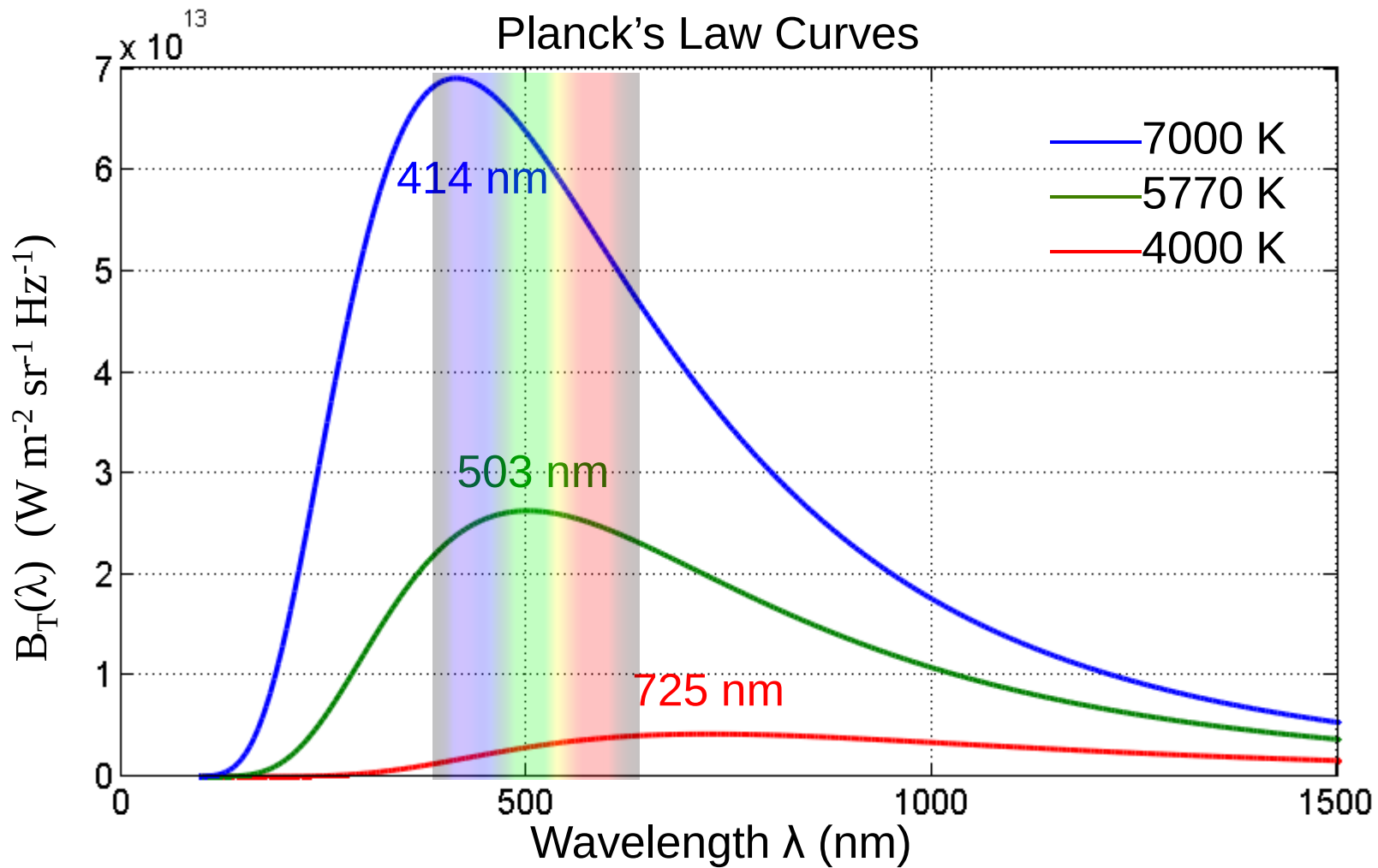
Illuminant C



White at different color temperatures



Blackbody radiation



Planck's Law, 1900

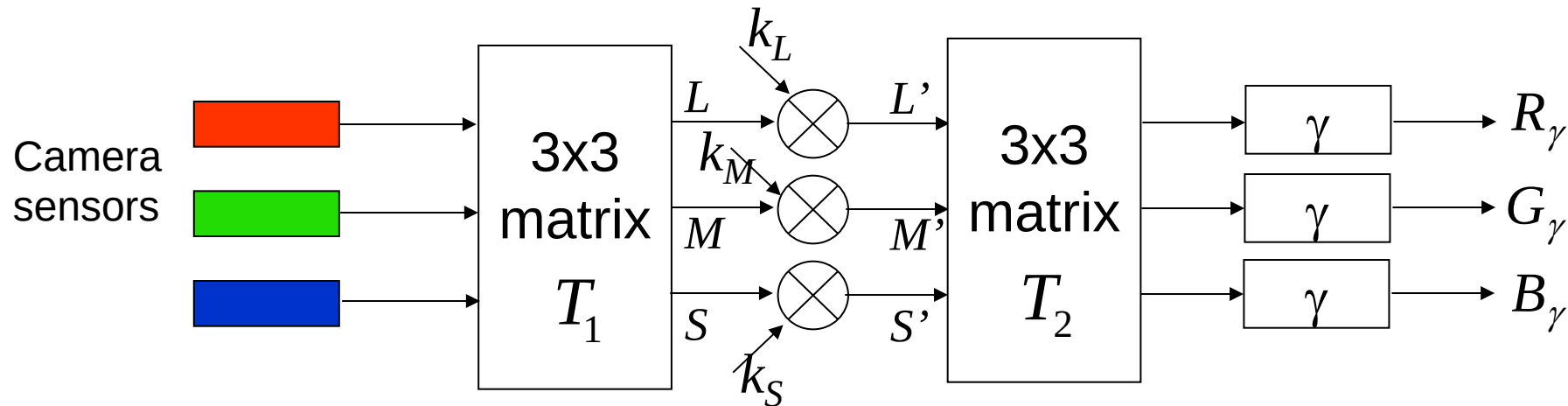
$$B_T(\lambda) = \frac{2hc^2 / \lambda^5}{e^{hc/\lambda kT} - 1}$$

Wien's Law

$$\lambda_{peak} [nm] = \frac{2,900,000}{T[K]}$$

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)



- 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

$$k_L \sum_{x,y} L[x,y] = k_M \sum_{x,y} M[x,y] = k_S \sum_{x,y} S[x,y]$$

- Scale-by-max

$$k_L \max_{x,y} L[x,y] = k_M \max_{x,y} M[x,y] = k_S \max_{x,y} S[x,y]$$

- Shades-of-gray
[Finlayson, Trezzi, 2004]

$$k_L \left(\sum_{x,y} L^p[x,y] \right)^{\frac{1}{p}} = k_M \left(\sum_{x,y} M^p[x,y] \right)^{\frac{1}{p}} = k_S \left(\sum_{x,y} S^p[x,y] \right)^{\frac{1}{p}}$$

- » Special cases: gray-world ($p = 1$), scale-by-max ($p = \infty$)
- » Best performance for $p \approx 6$

- Refinements:
smooth image, exclude saturated color/dark pixels,
use spatial derivatives instead (“gray-edge,” “max-edge”)
[van de Weijer, 2007]

Color balancing example



Original



Gray-world



Scale-by-max



Gray-edge



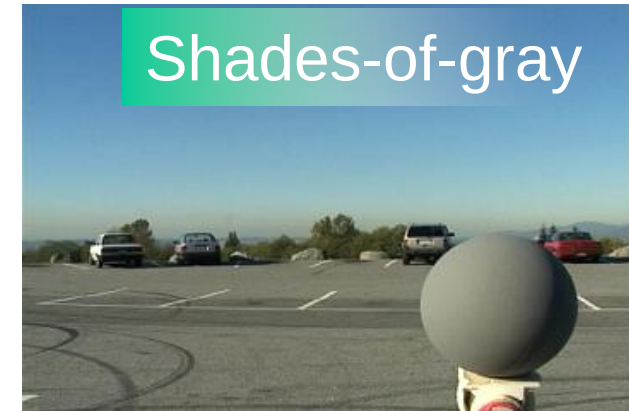
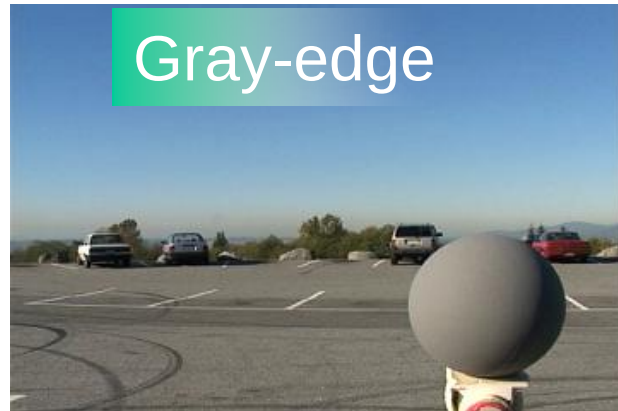
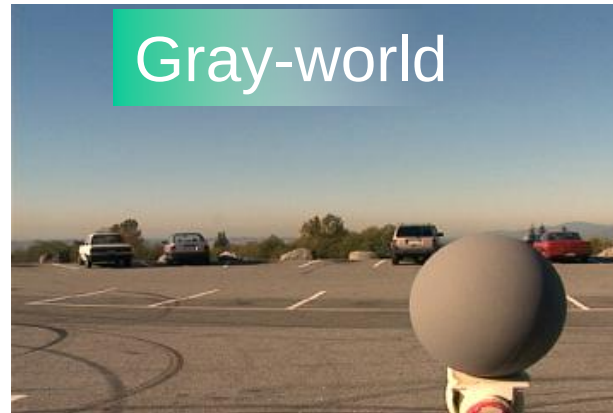
Max-edge



Shades-of-gray

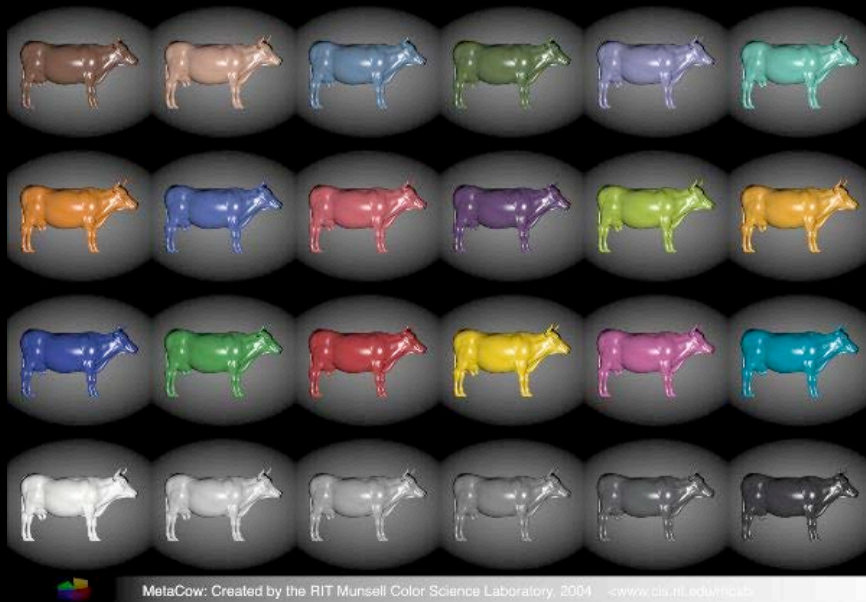


Color balancing example



Original image courtesy Ciurea and Funt

Daylight D65
CIE observer



Daylight D65
cheap camera



Illuminant A
CIE observer

