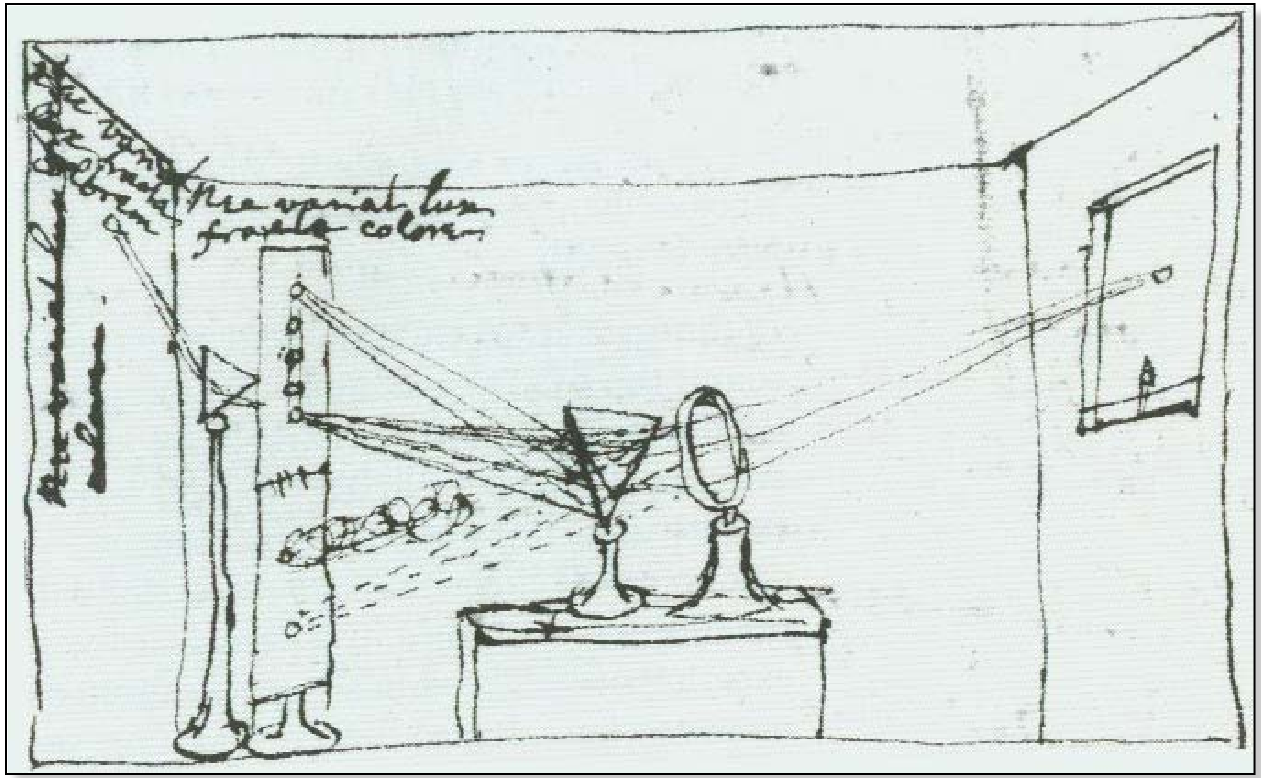
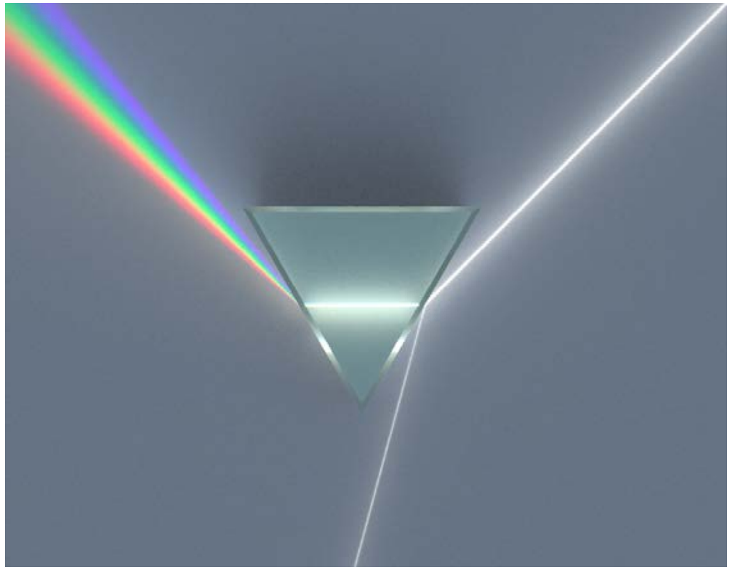
Introduction to color science

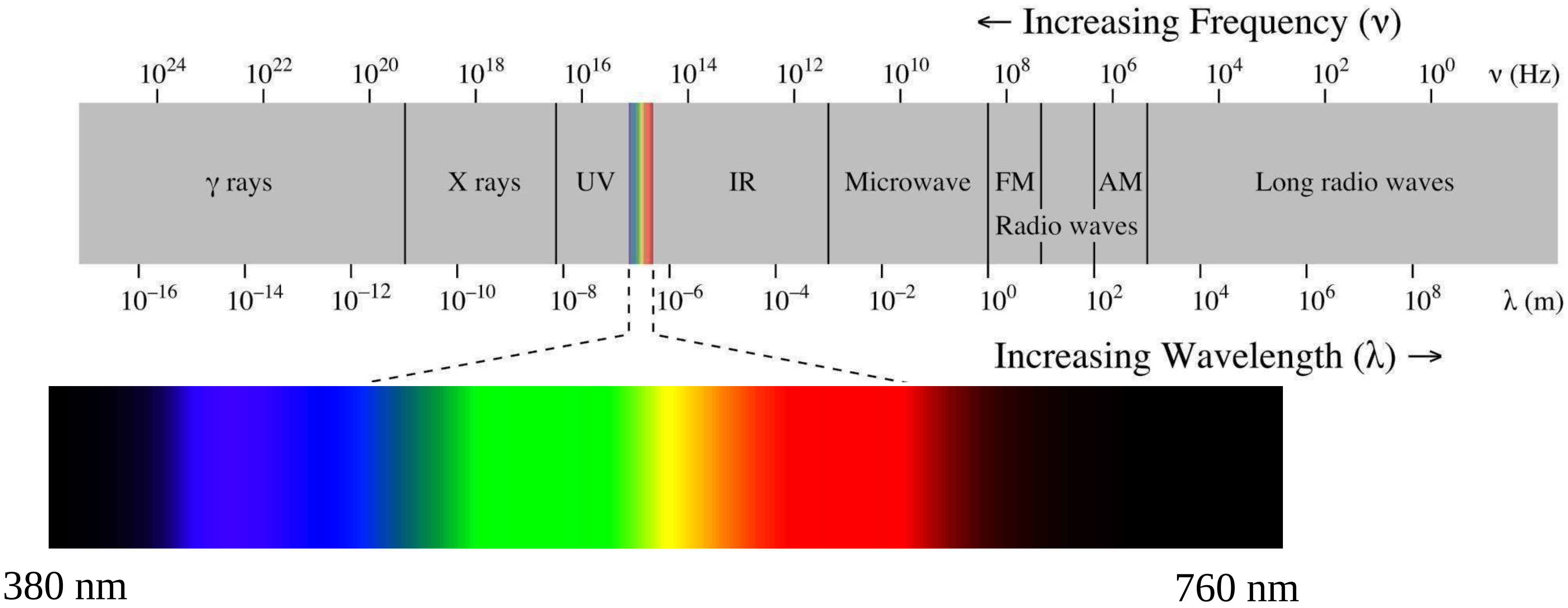
- Trichromacy
- Spectral matching functions
- CIE XYZ color system
- xy-chromaticity diagram
- Color gamut
- Color temperature
- Color balancing algorithms

Newton's Prism Experiment - 1666

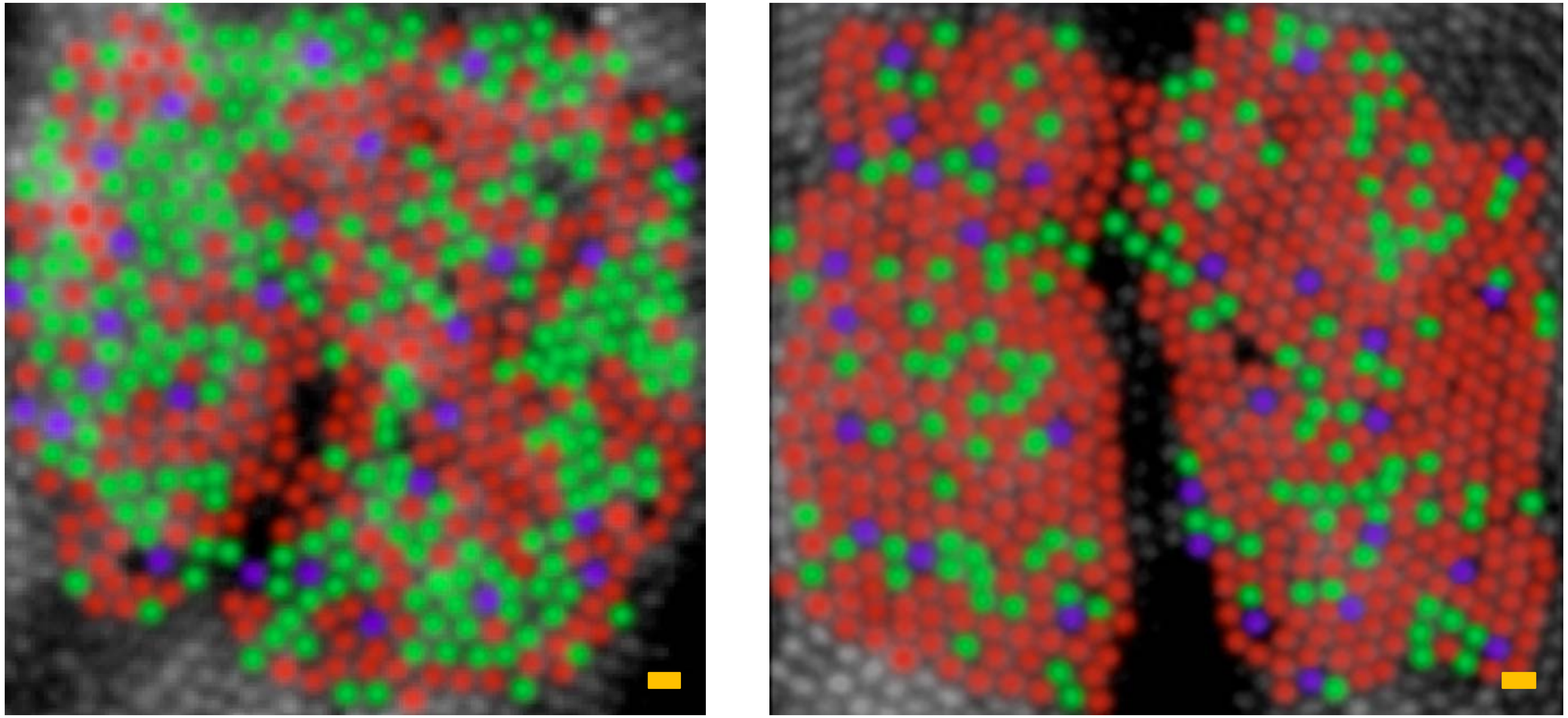




Color: visible range of the electromagnetic spectrum



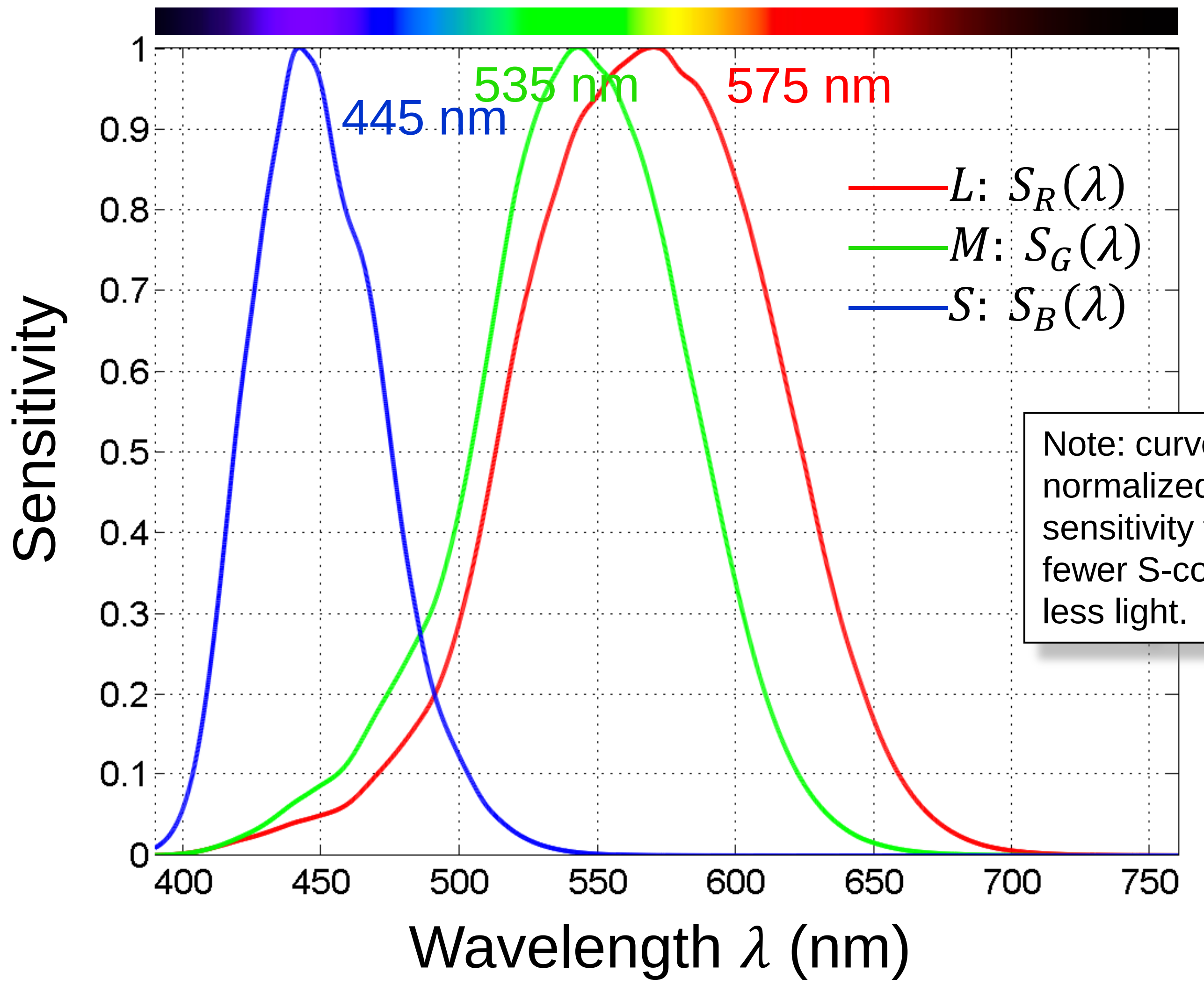
Human retina



[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



Note: curves are normalized. **Much** lower sensitivity to Blue, since fewer S-cones absorb less light.

Three-receptor model of color perception

$C(\lambda)$

Spectral energy distribution of incident light

$$\int_{\lambda} S_R(\lambda)C(\lambda)\,d\lambda \rightarrow \alpha_R$$

$$\int_{\lambda} S_G(\lambda)C(\lambda)\,d\lambda \rightarrow \alpha_G$$

$$\int_{\lambda} S_B(\lambda)C(\lambda)\,d\lambda \rightarrow \alpha_B$$

Effective cone stimulation (“tristimulus values”)

[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

What is the smallest number of monochromatic components that the spectral energy distribution of light that appears white to a human observer must contain?

(a) 1 (b) 2 (c) 3 (d) infinitely many

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 (α_R, α_G, α_B) result ?

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

$$\int_\lambda S_R(\lambda) C(\lambda) d\lambda \rightarrow \alpha_R$$

$$\int_\lambda S_G(\lambda) C(\lambda) d\lambda \rightarrow \alpha_G$$

$$\int_\lambda S_B(\lambda) C(\lambda) d\lambda \rightarrow \alpha_B$$

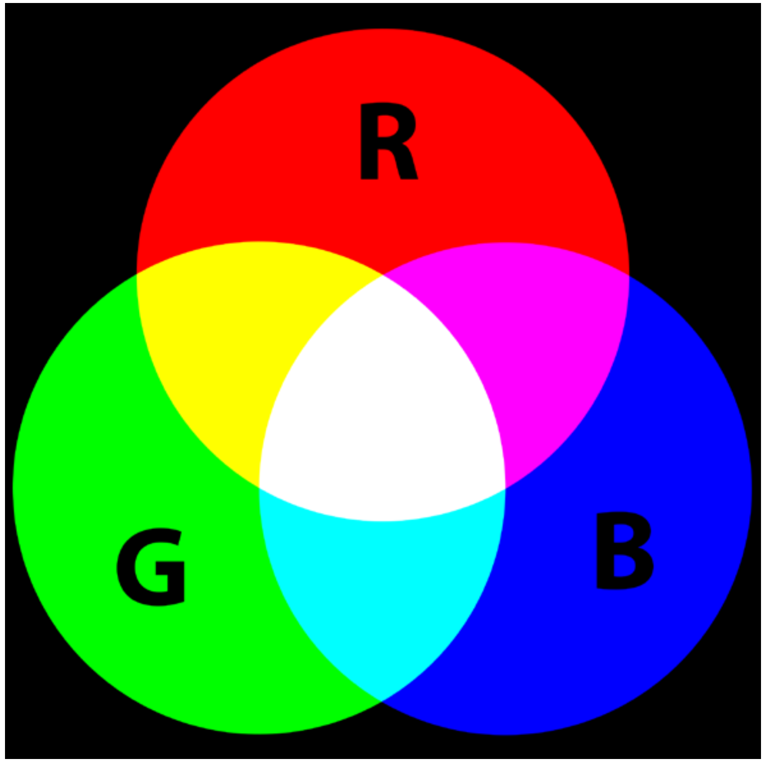
$$\alpha_i = \int_\lambda S_i(\lambda) \left[\beta_1 P_1(\lambda) + \beta_2 P_2(\lambda) + \beta_3 P_3(\lambda) \right] d\lambda$$

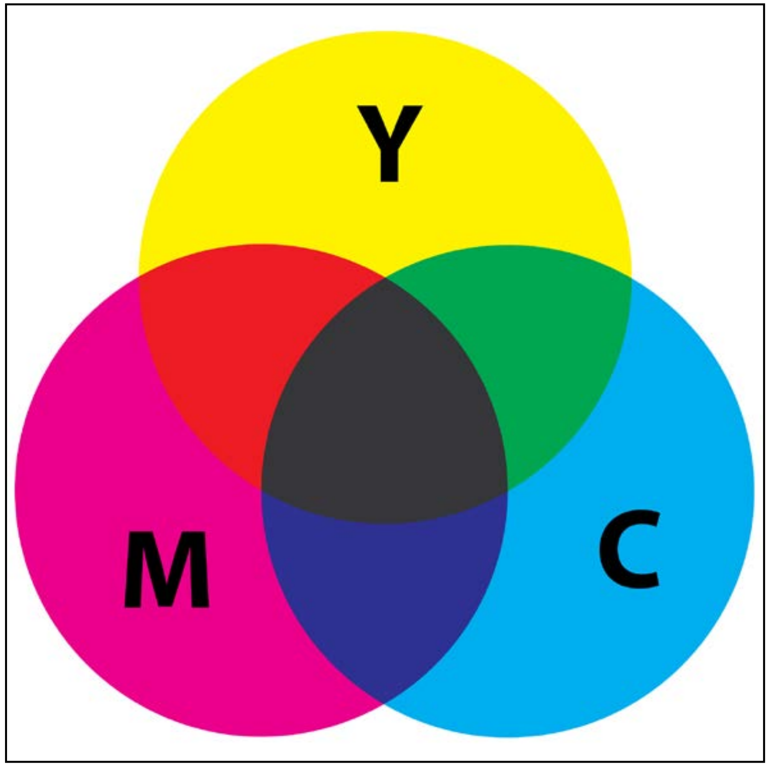
$$= \beta_1 \cdot K_{i,1} + \beta_2 \cdot K_{i,2} + \beta_3 \cdot K_{i,3}$$

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

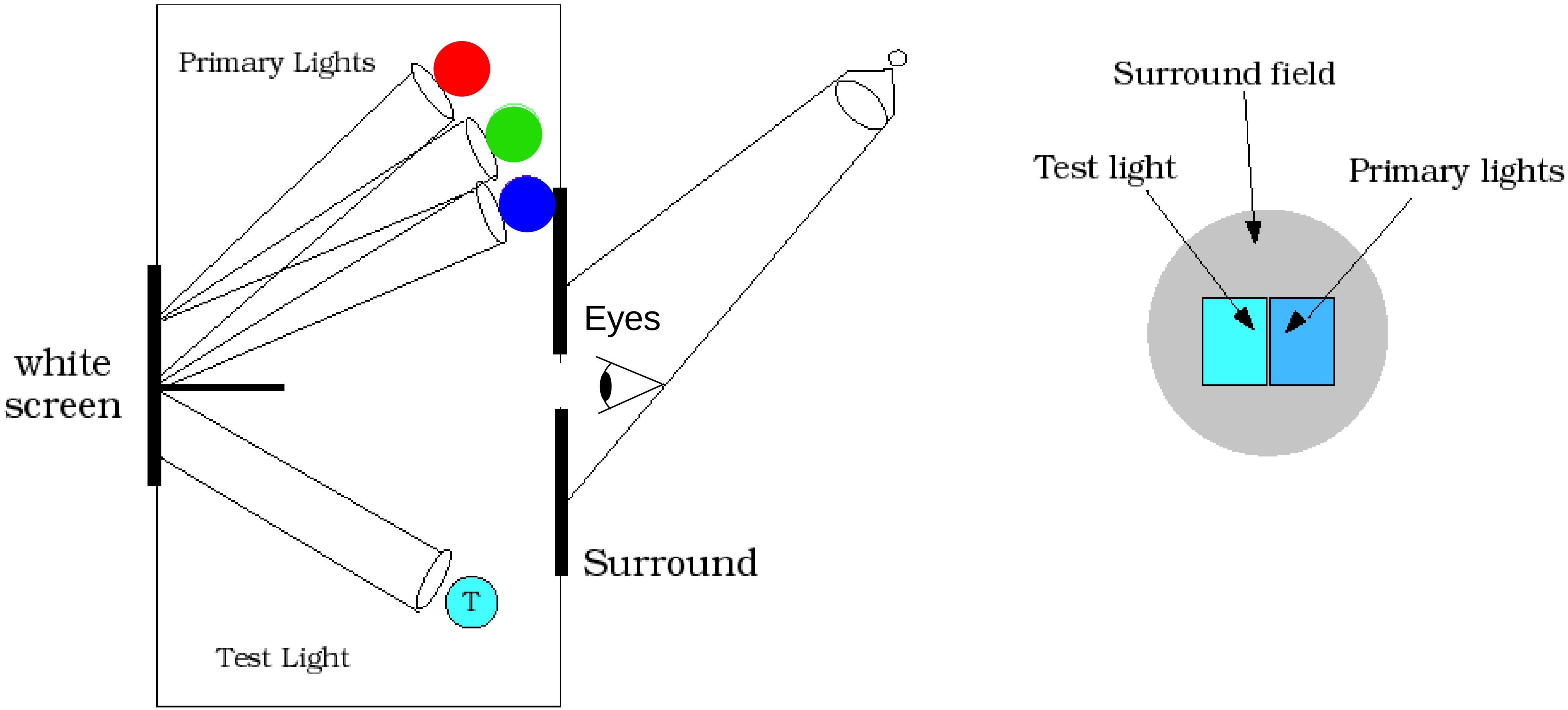
Color matching is linear!

Additive vs. subtractive color mixing



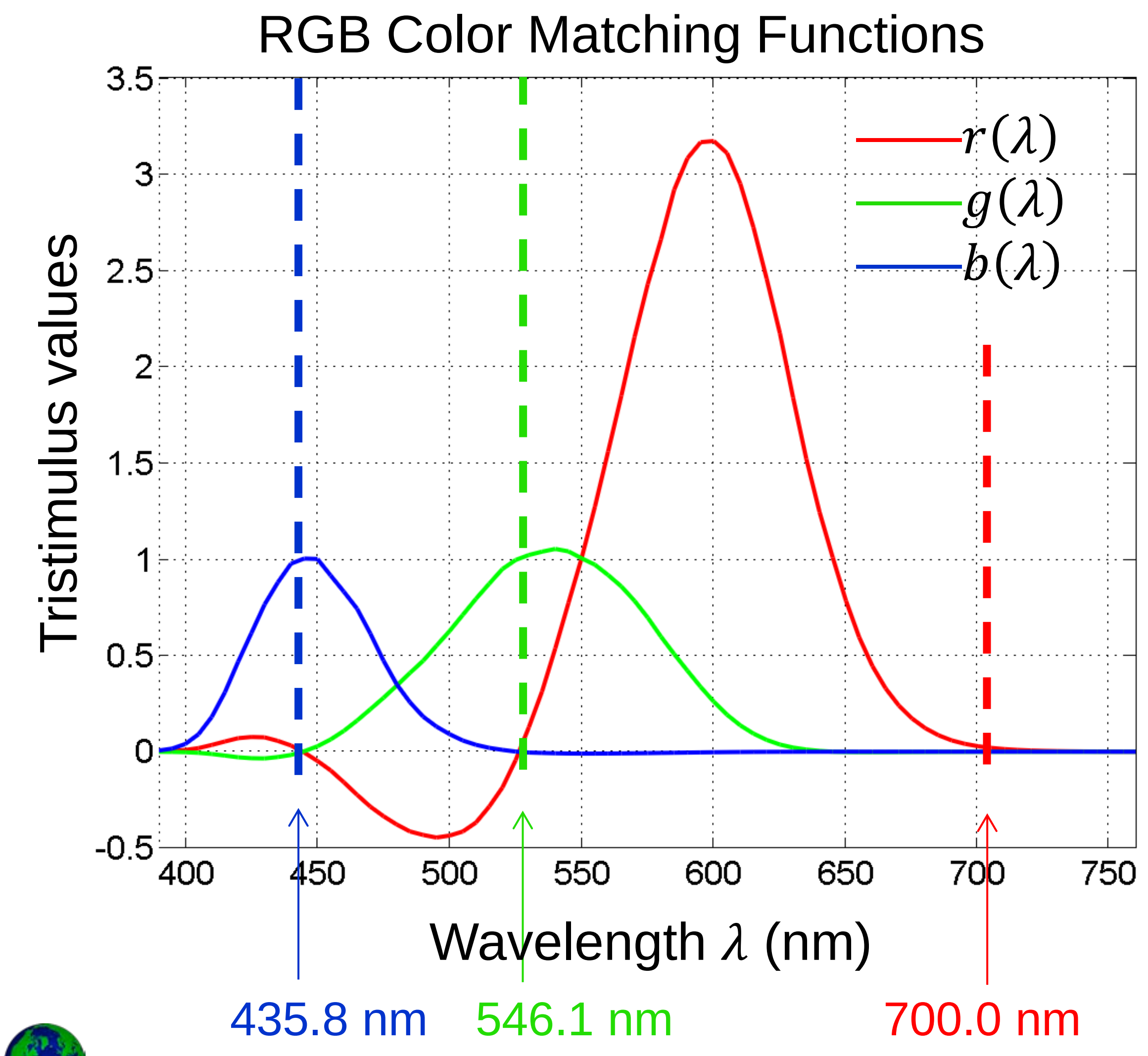


Color matching experiment



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 (Commision Internationale de L’Eclairage), 1931.

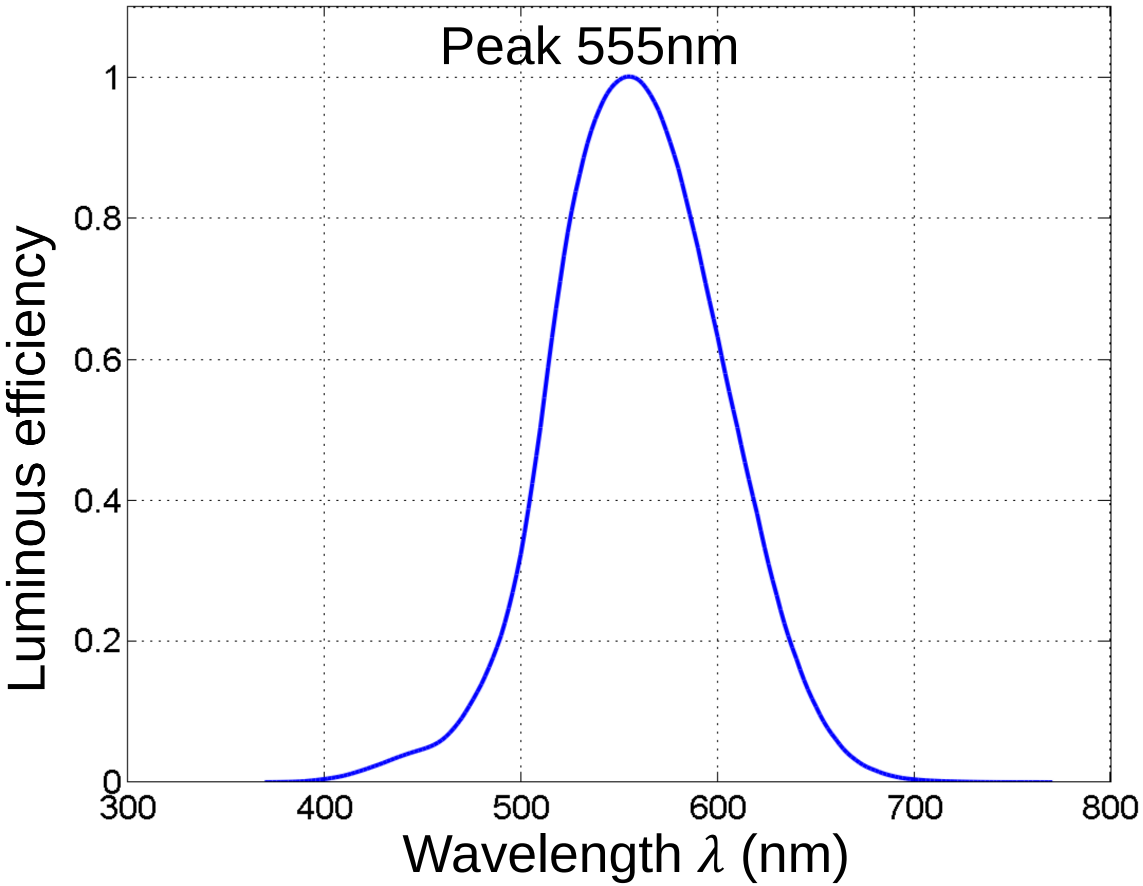
The human eye can distinguish monochromatic light between 650 and 700 nm only based on intensity, but not based on color.

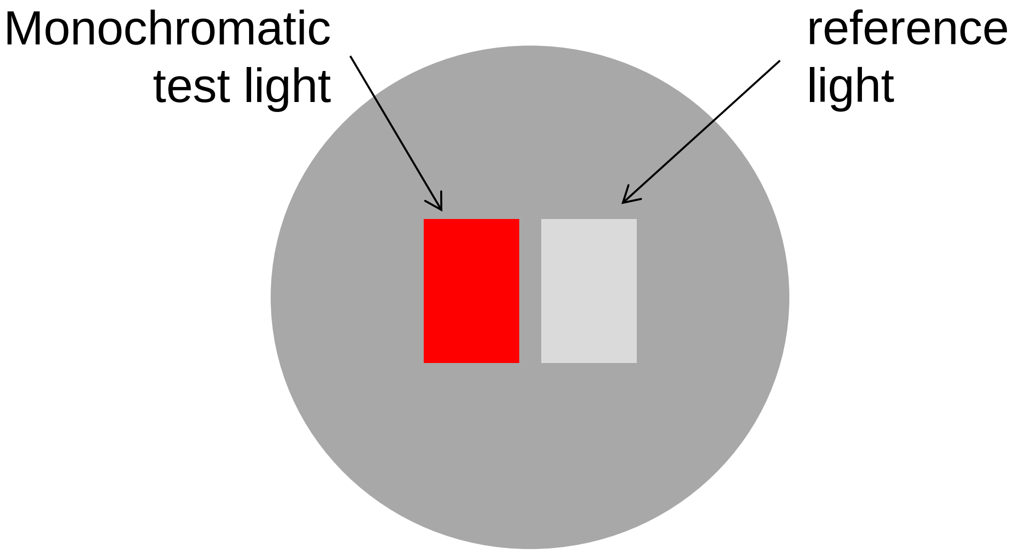
(a) True   (b) False

Spectral matching curves for any set of three primary lights are a linear combination of the 1931 CIE RGB color matching functions

(a) False
(b) True, but only if the primaries are monochromatic lights
(c) True, but only if the tristimulus values of the primaries are linearly independent
(d) True in general

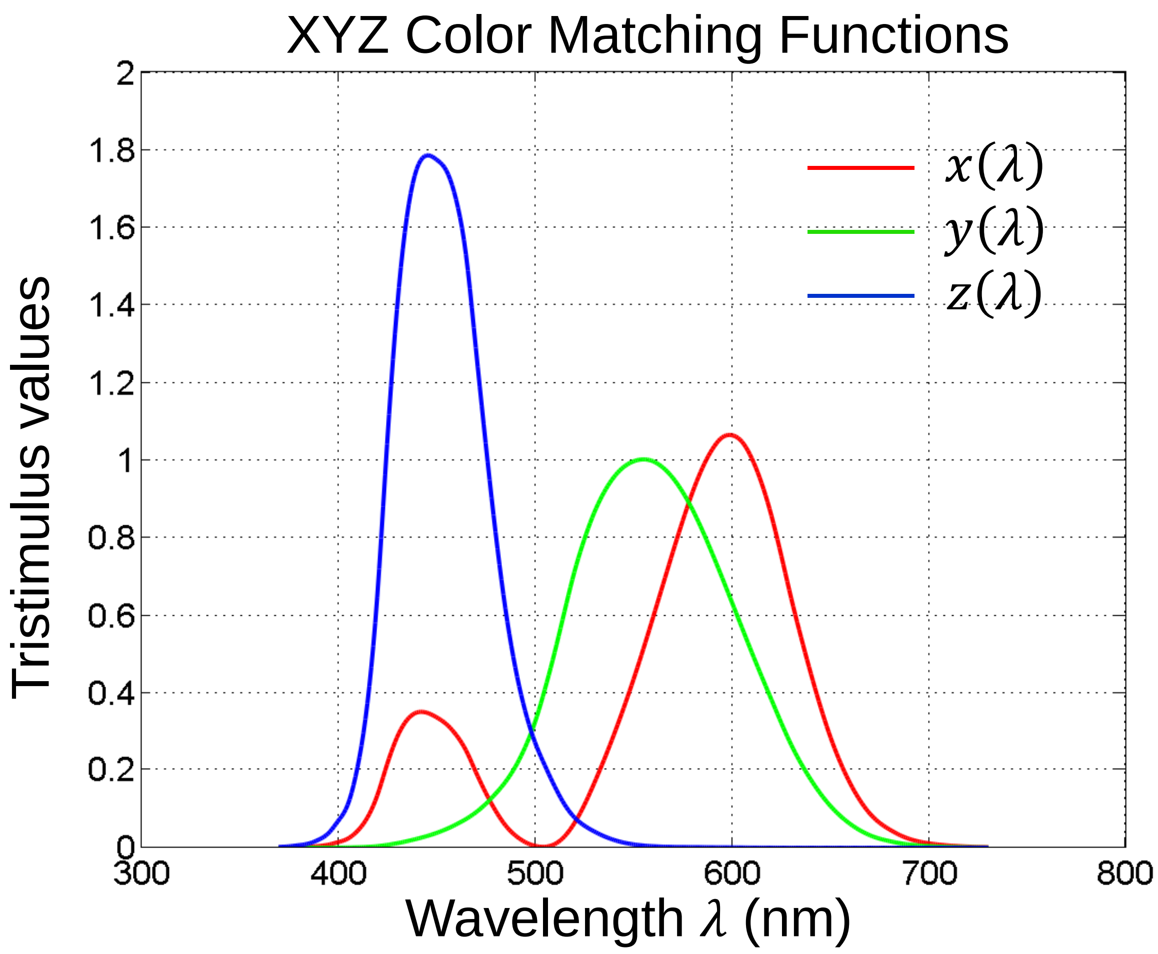
Luminosity function





- 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



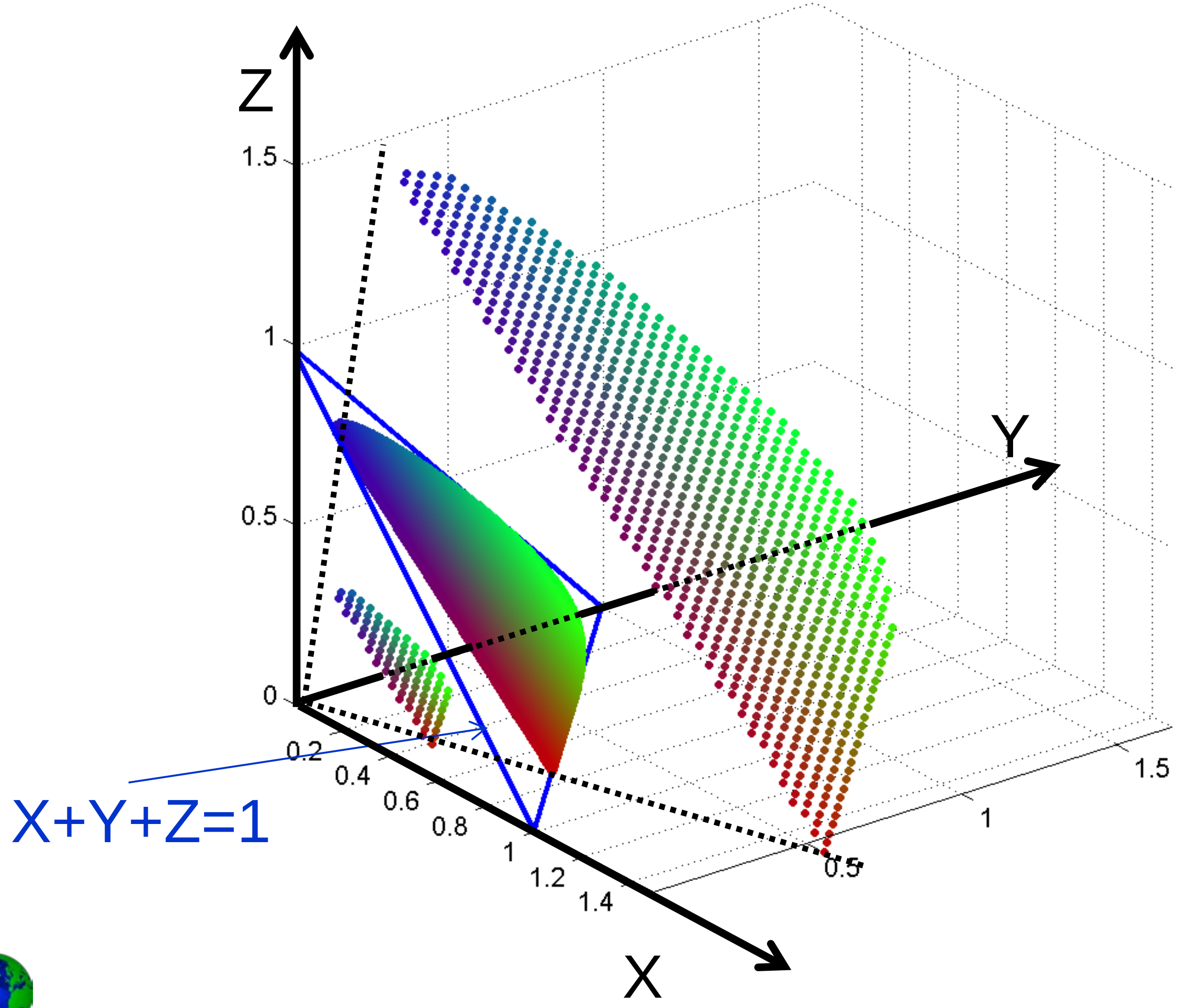
Properties:

- 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

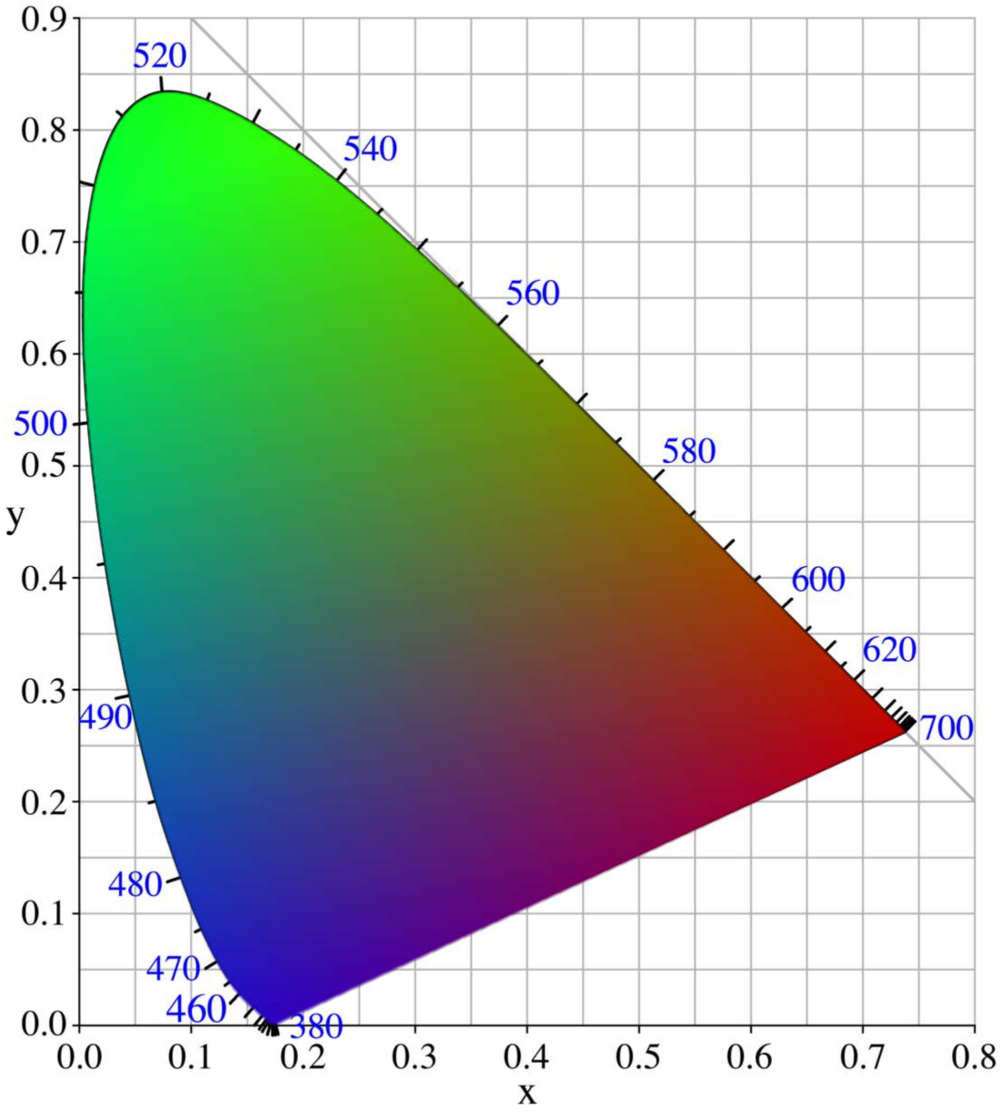
Color gamut and chromaticity



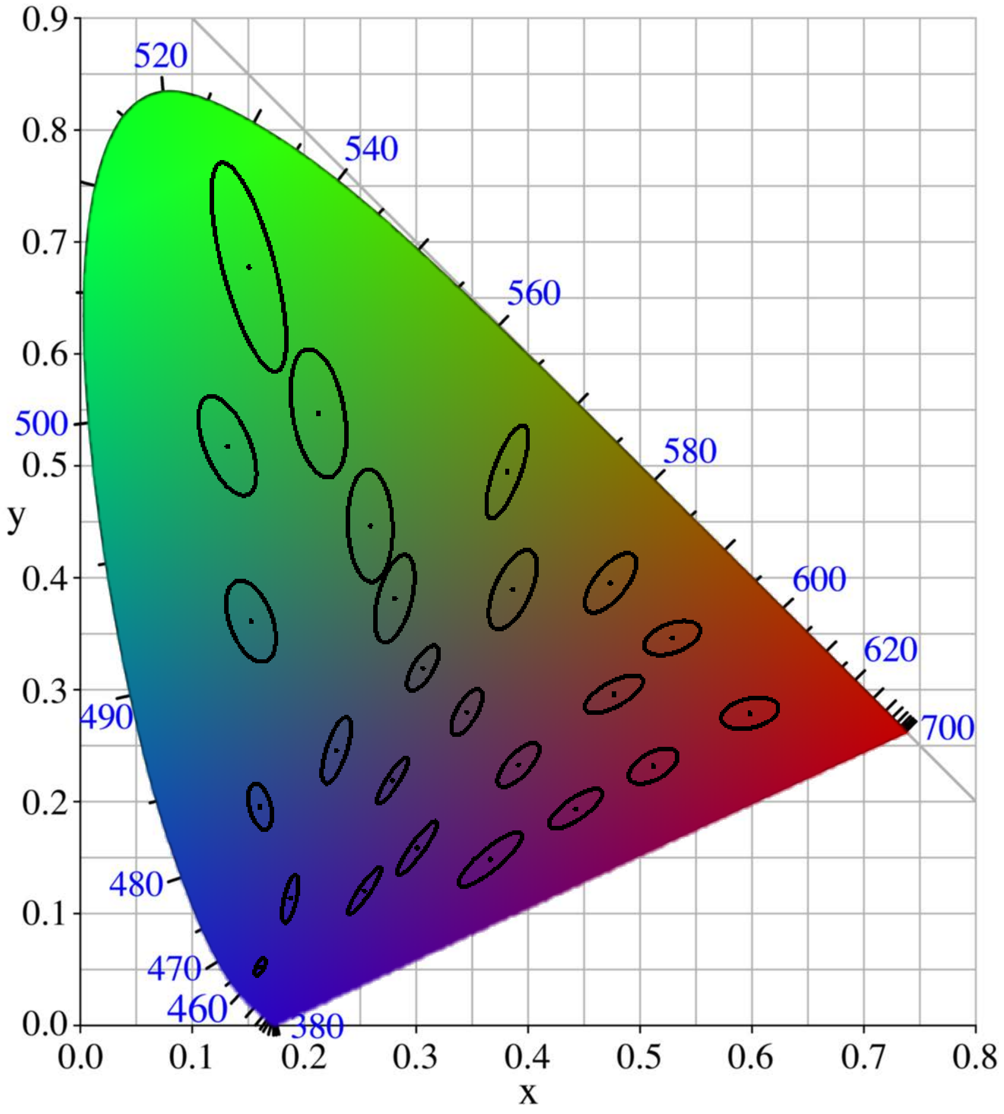
$$x = \frac{X}{X + Y + Z}$$

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

CIE chromaticity diagram



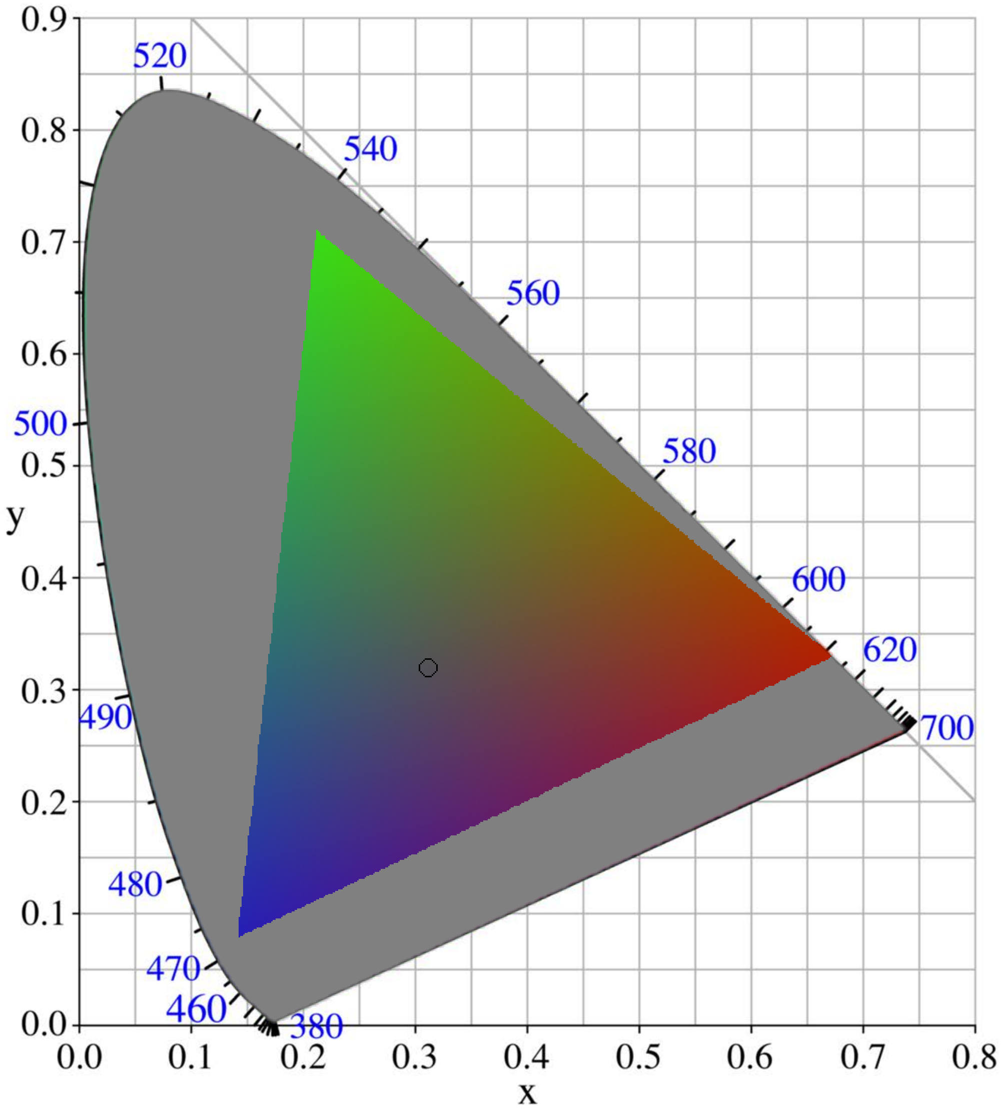
Perceptual non-uniformity of xy chromaticity



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

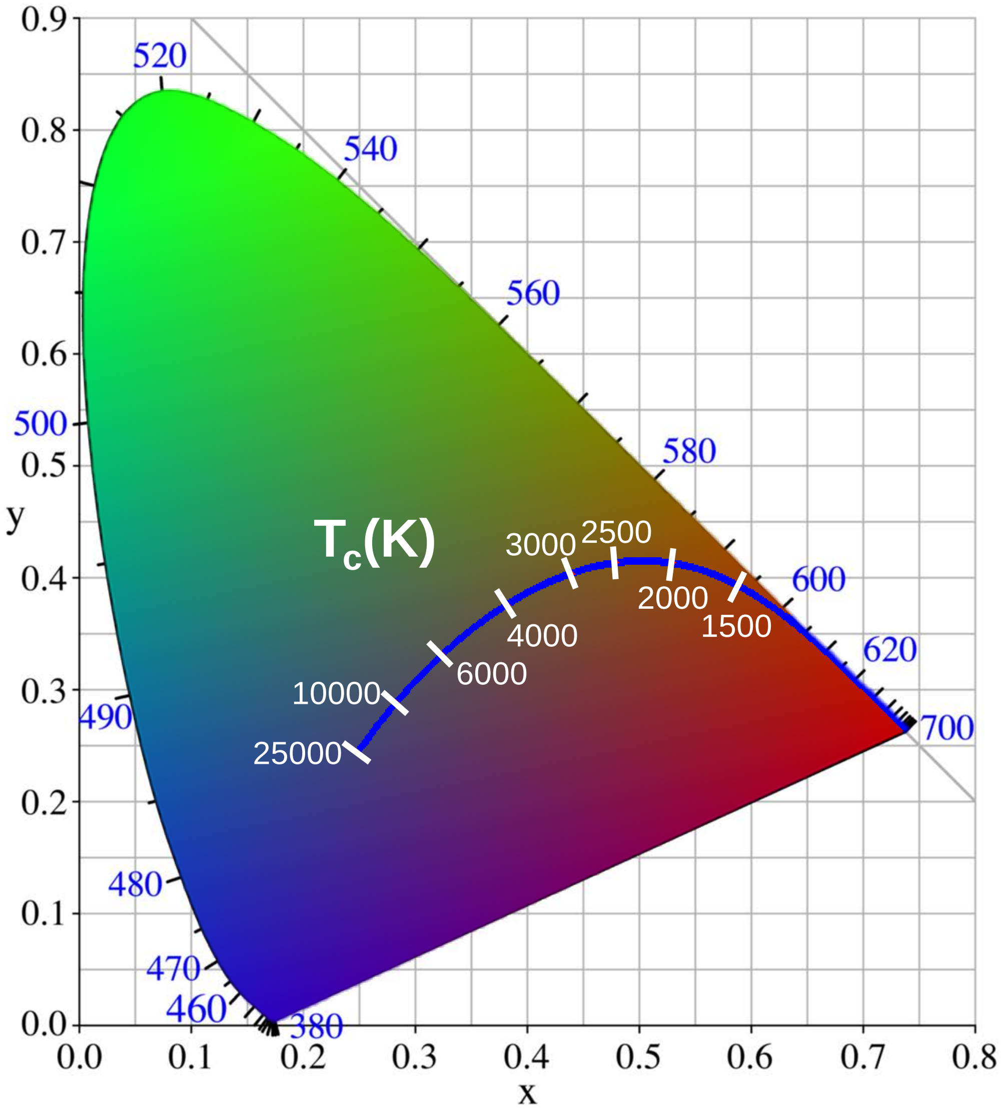
It is not possible to build a display that directly uses X, Y, Z as primary light sources.

(a) True (b) False

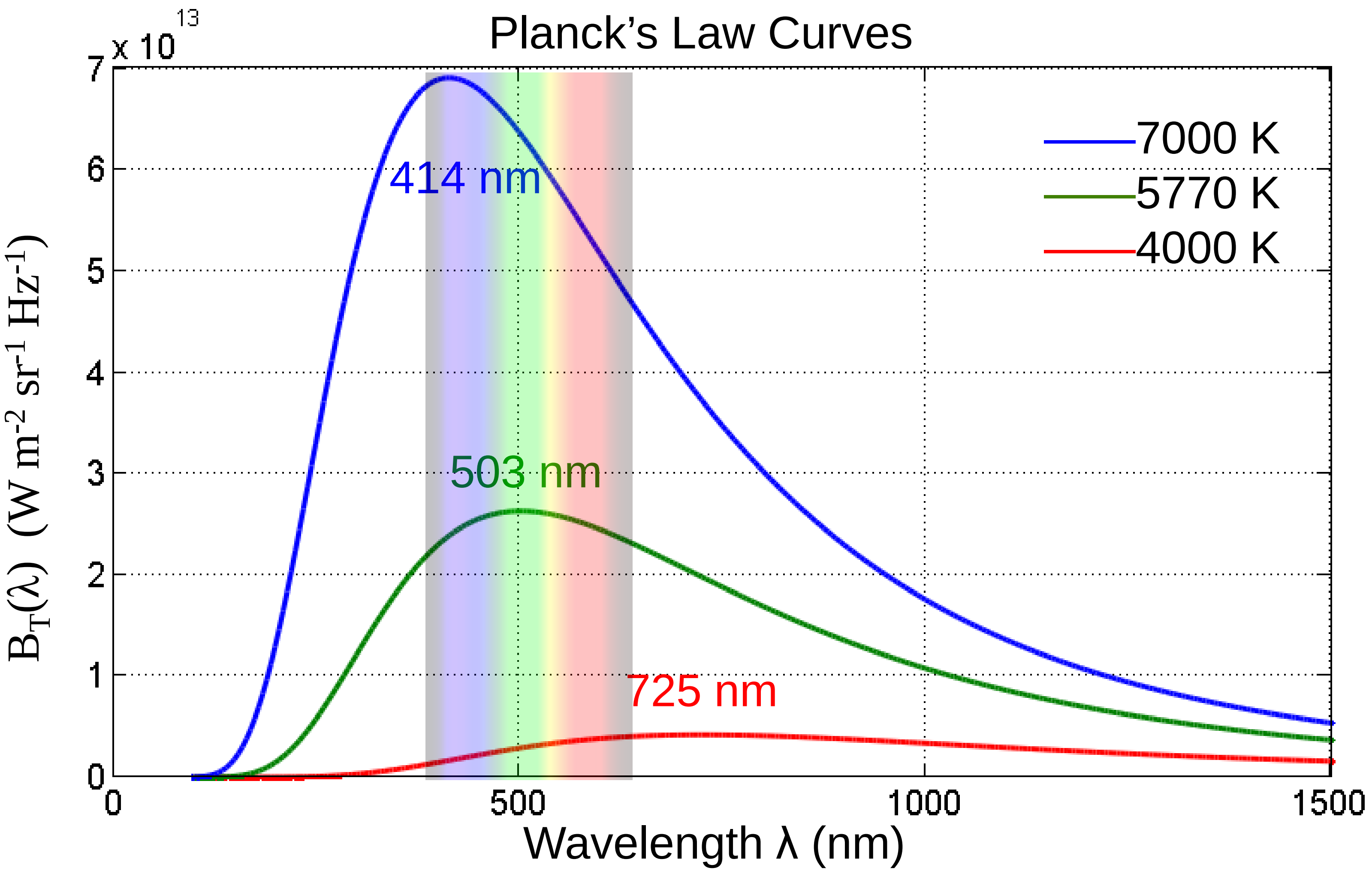
With additive color mixing, how many primaries are required to perfectly reproduce every possible color?

(a) 2 (b) 3 (c) 4 (d) 256 (e) infinitely many

White at different color temperatures



Blackbody radiation



Planck's Law, 1900

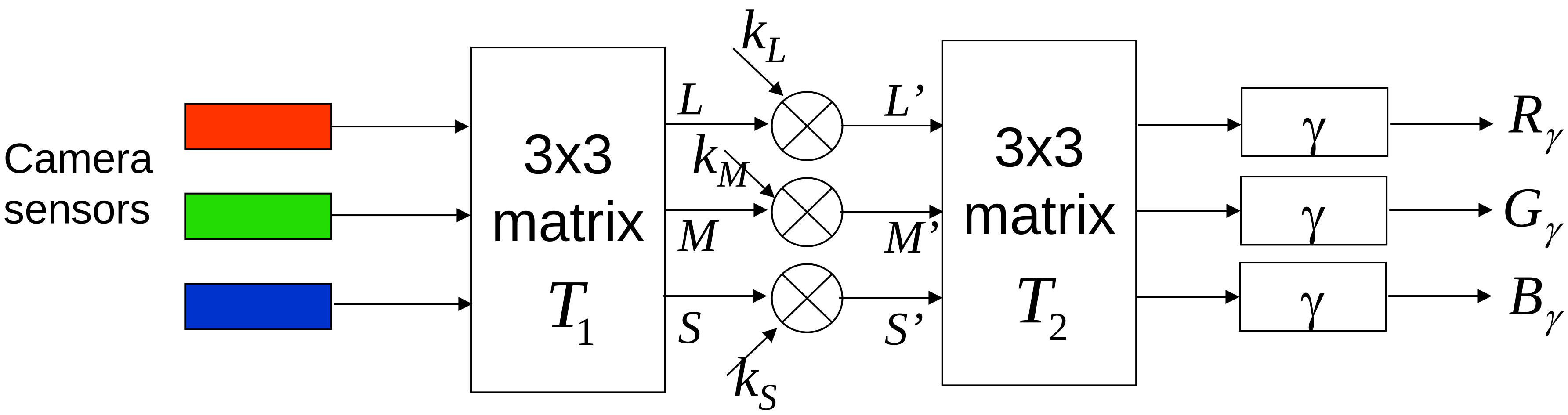
$$B_T(\lambda) = \frac{2hc^2 / \lambda^5}{e^{hc/\lambda kT} - 1}$$

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

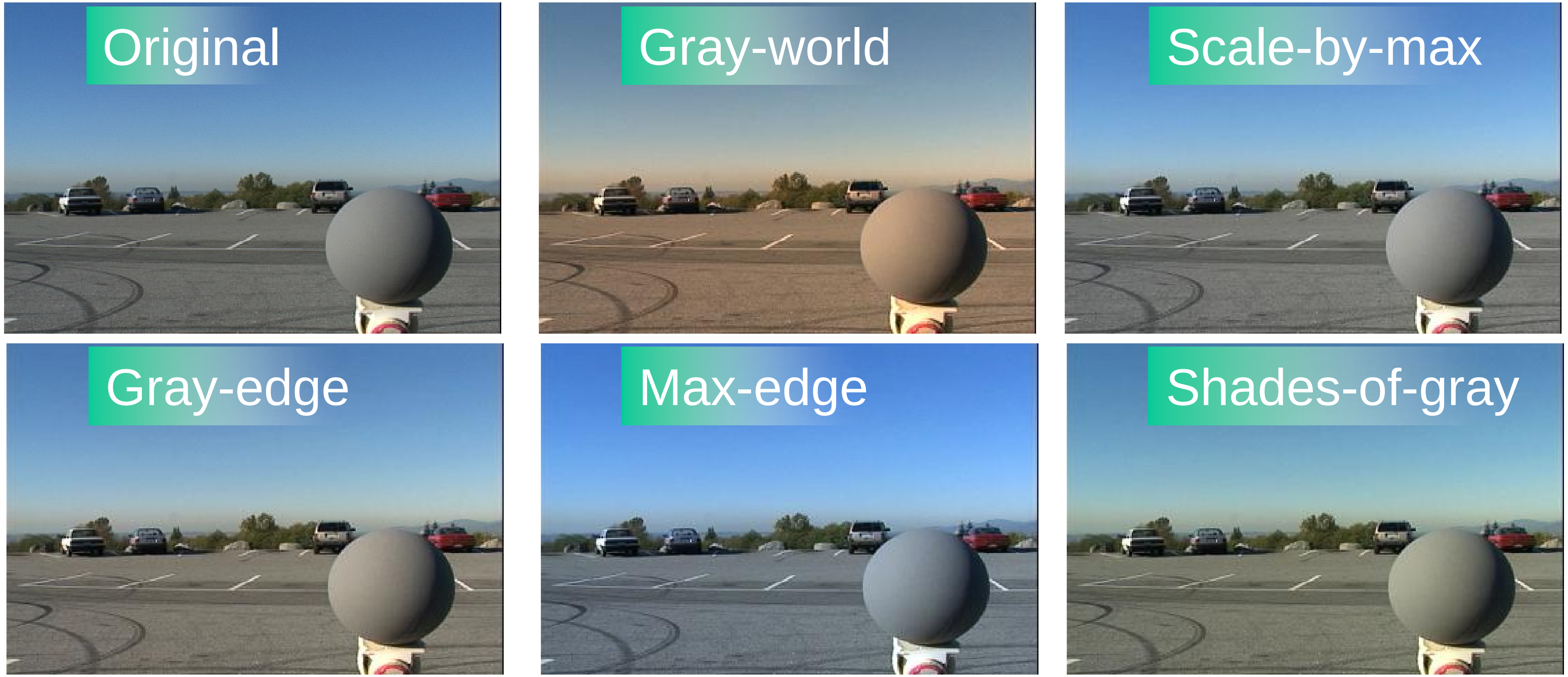

Scale-by-max


Gray-edge


Max-edge


Shades-of-gray

Color balancing example



Original image courtesy Ciurea and Funt

Even if the spectrum of the illuminant is known exactly, perfect color correction is generally not possible in a 3-dimensional color space.

(a) True (b) False

For accurate color reproduction, the absorption spectra of an R,G,B image sensor

(a) Must exactly match the absorption spectra of the L,M,S cones in the human retina.
(b) Must be a linear combination of the absorption spectra of the L,M,S cones.
(c) Can be any set of 3 functions that are not linearly dependent and cover the entire visible spectrum.

Daylight D65
CIE observer

Daylight D65
cheap camera

Illuminant A
CIE observer