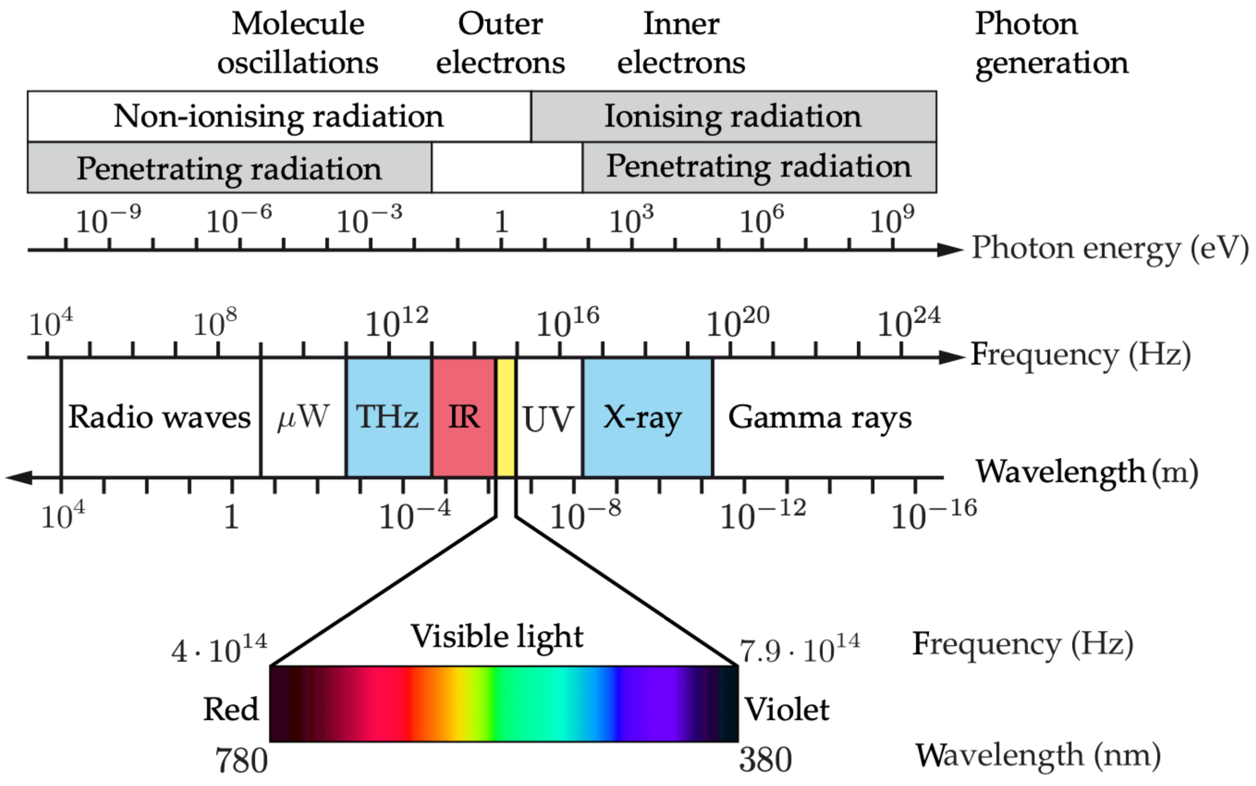
Computer Vision

Color

Technische Hochschule Rosenheim
Winter 2024/25
Prof. Dr. Jochen Schmidt

Electromagnetic Spectrum

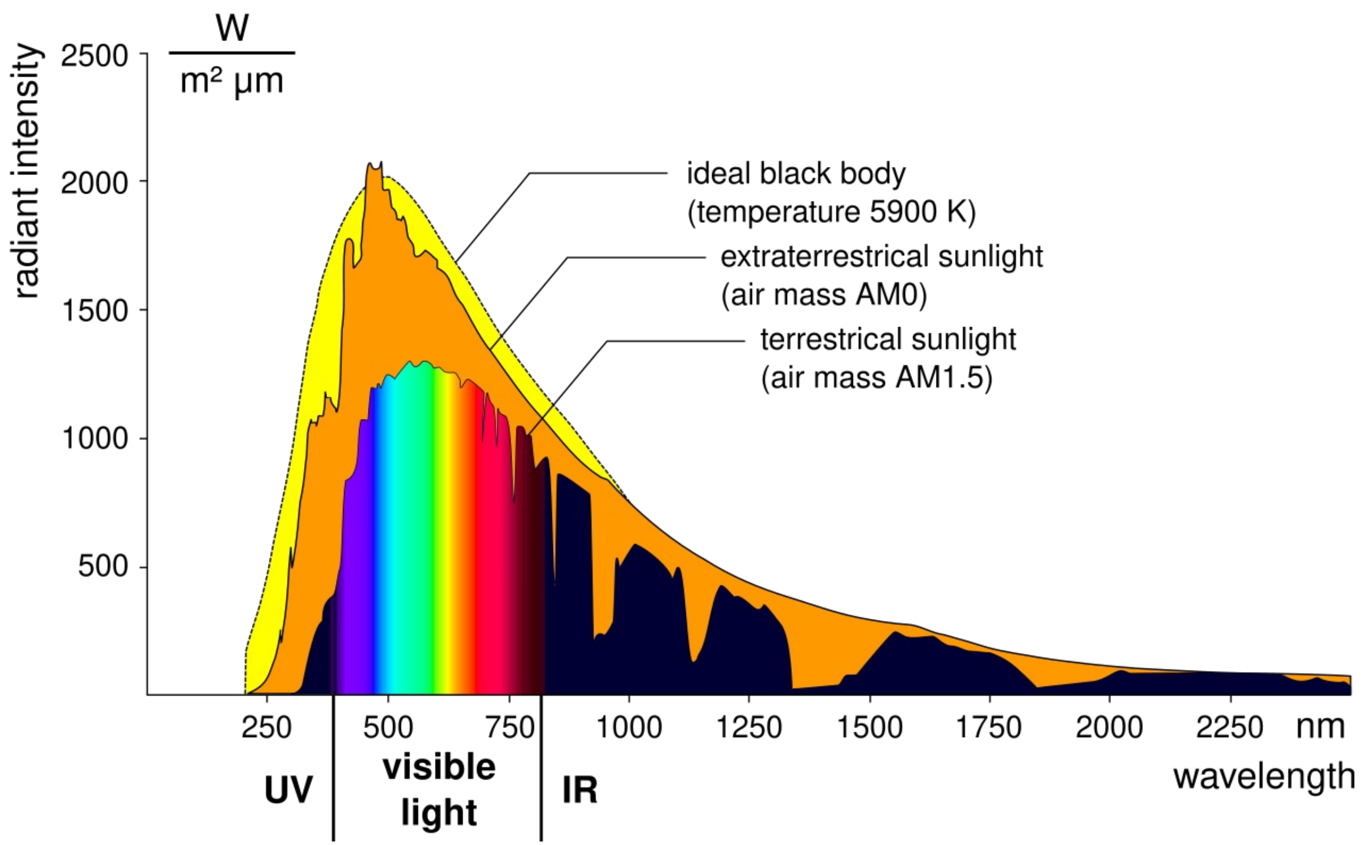


$\lambda = c/f$ f = frequency [Hz] λ = wavelength [m]
c = speed of light; in a vacuum, $c \approx 2.9979 \cdot 10^{8}$ m/s

μW = microwaves, THz = Terahertz radiation, IR = infrared, UV = ultraviolet

from: [Beyerer16]

Solar Spectrum



Perception of Brightness by the Human Eye

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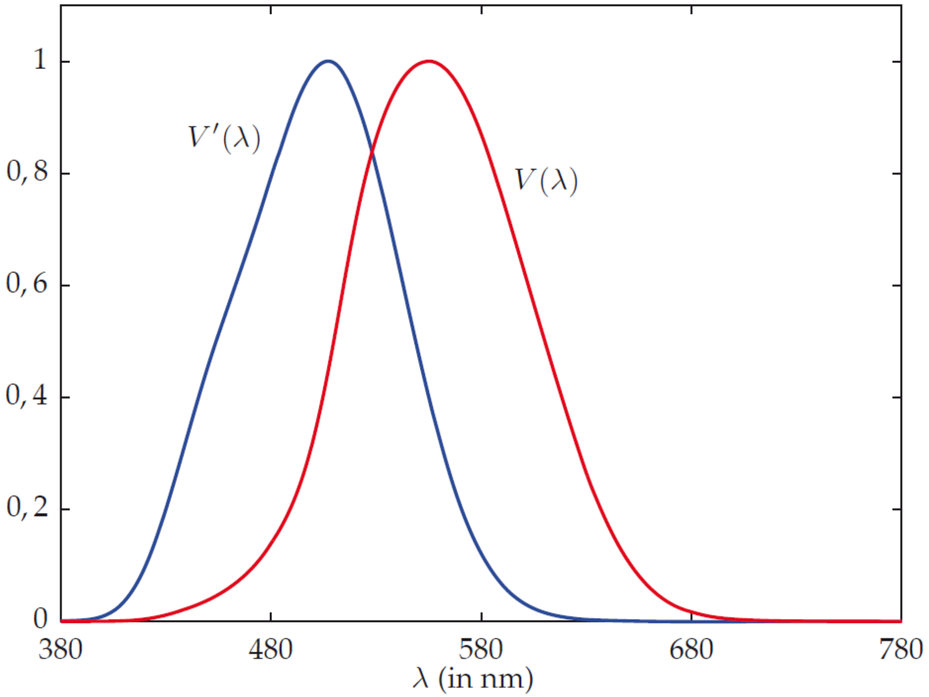
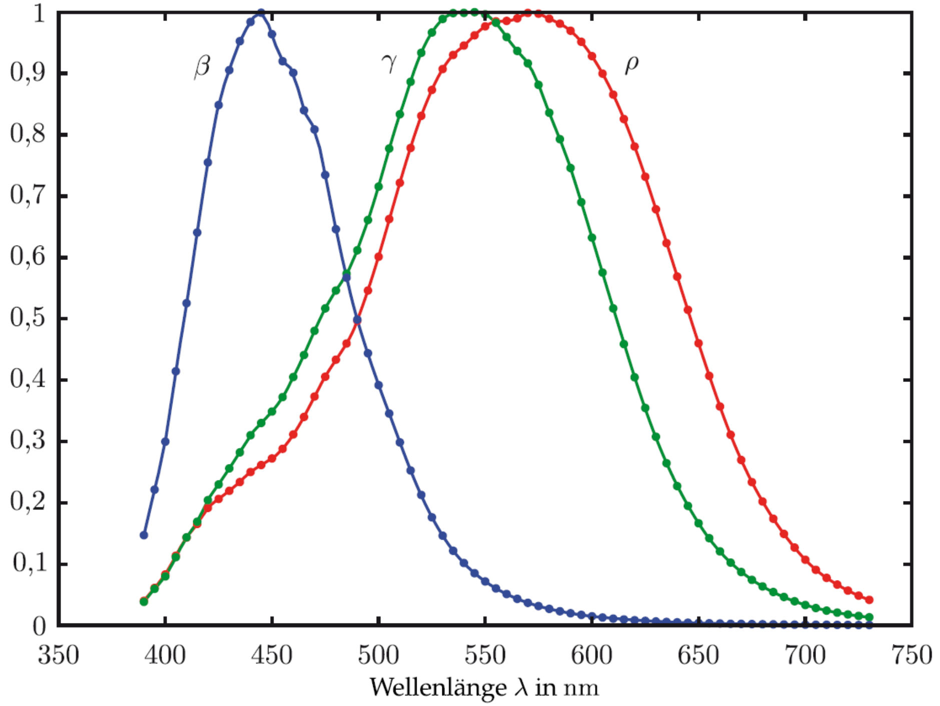
Sensitivity of the human eye to brightness



V': dark-adapted eye
V: light-adapted eye

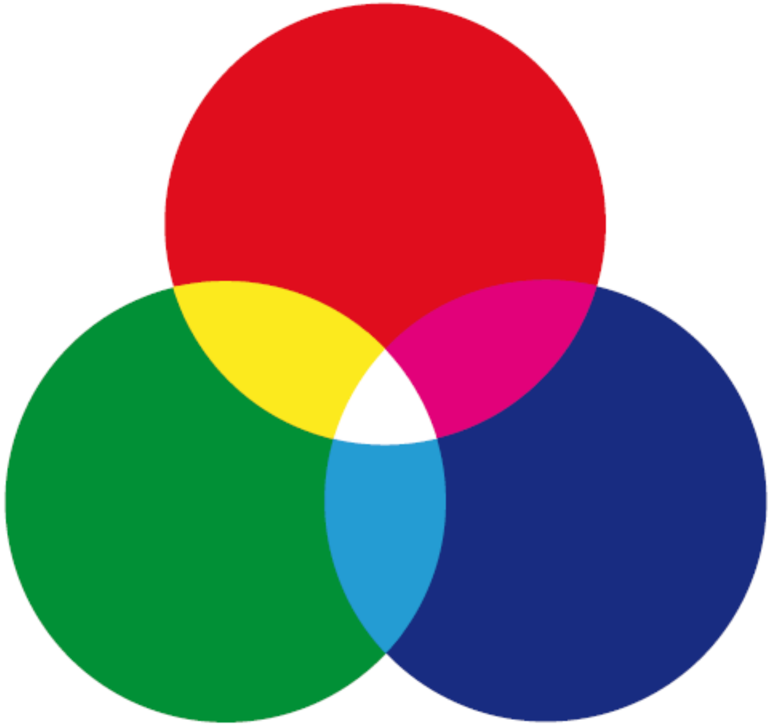
Spectral sensitivity of the cone cells



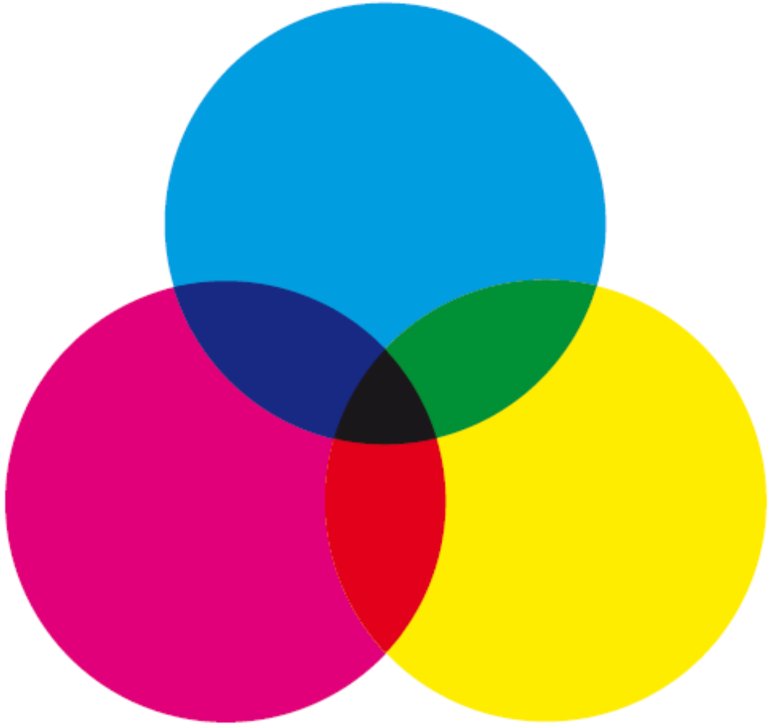
each curve normalized to maximum 1

from: [Beyerer16]

Additive and Subtractive Color Mixing



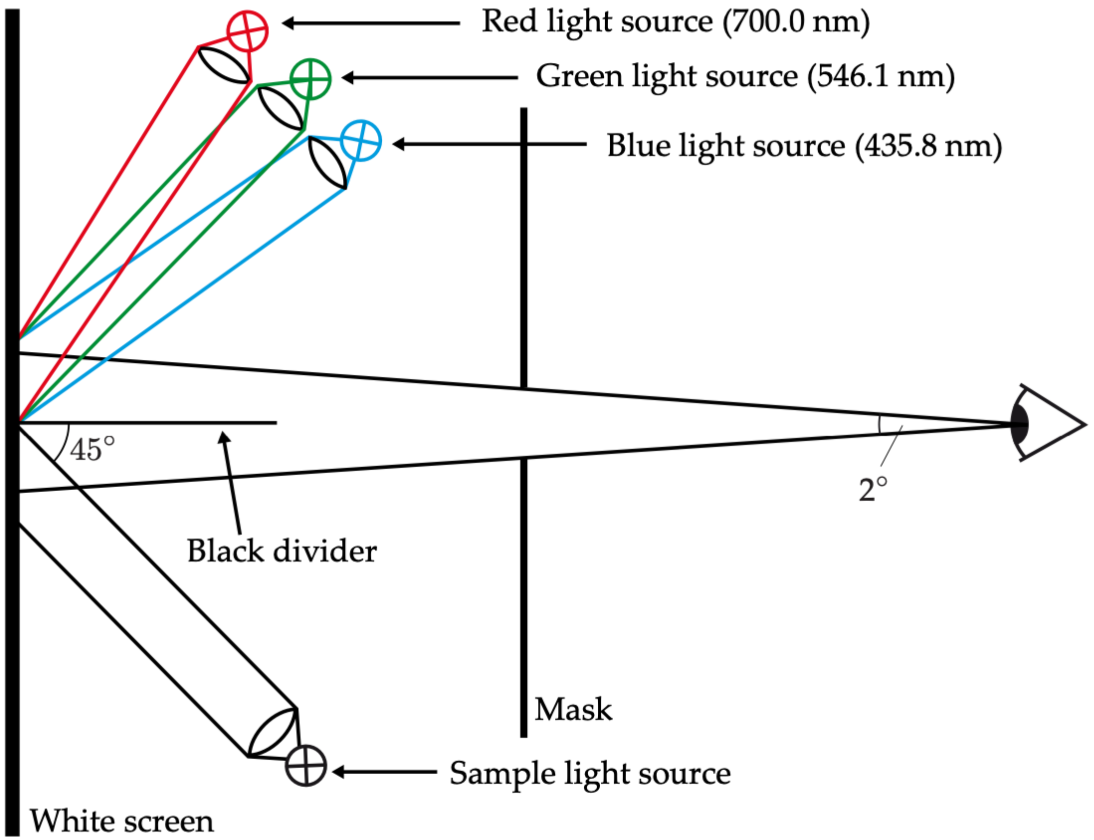
additive



subtractive

from: [Beyerer16]

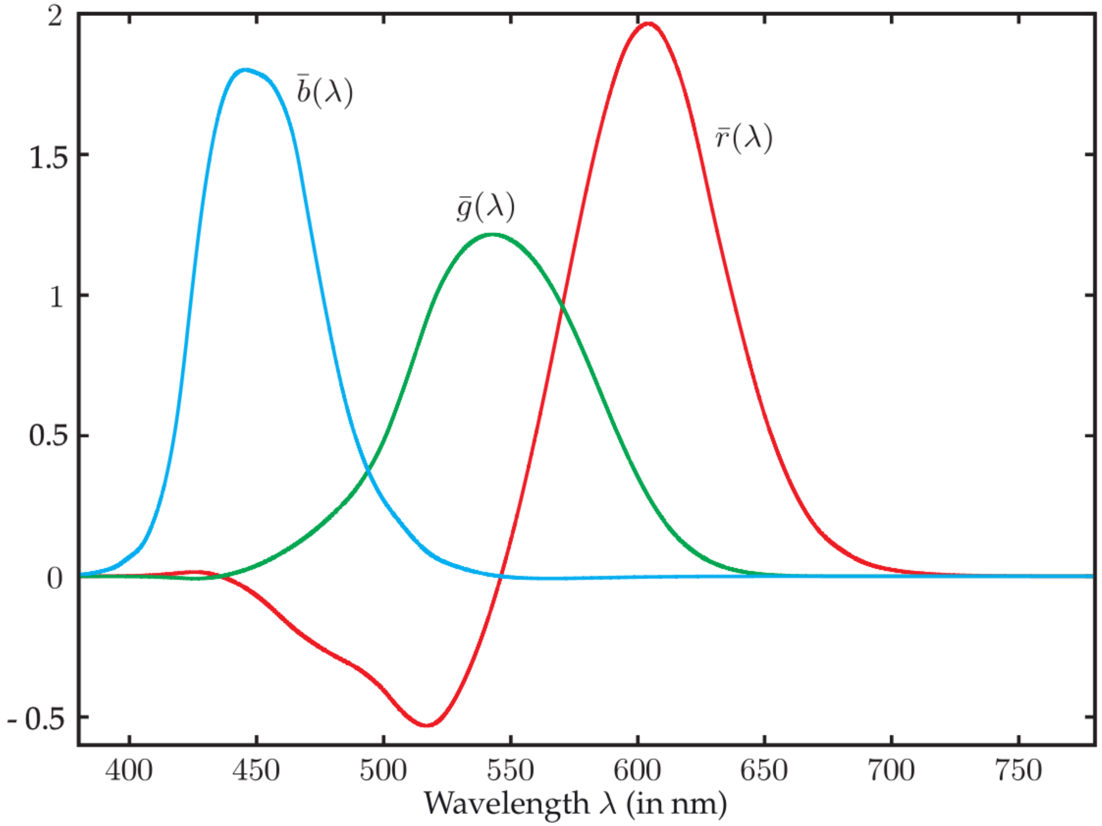
CIE Color Experiment



Color measurement experiment to empirically determine the color values with regard to the CIE primary colors

from: [Beyerer16]

Color Values of the Spectral Colors According to CIE



Scaled so that white light leads to
$R_{\mathrm{CIE}} = G_{\mathrm{CIE}} = B_{\mathrm{CIE}}$

Color value of any spectrum :

$$R_{\mathrm{CIE}} = \int_{380\mathrm{nm}}^{780\mathrm{nm}} I(\lambda)\bar{r}(\lambda)\mathrm{d}\lambda$$

$$G_{\mathrm{CIE}} = \int_{380\mathrm{nm}}^{780\mathrm{nm}} I(\lambda)\bar{g}(\lambda)\mathrm{d}\lambda$$

$$B_{\mathrm{CIE}} = \int_{380\mathrm{nm}}^{780\mathrm{nm}} I(\lambda)\bar{b}(\lambda)\mathrm{d}\lambda$$

from: [Beyerer12]

CIE Standard Color Value Functions

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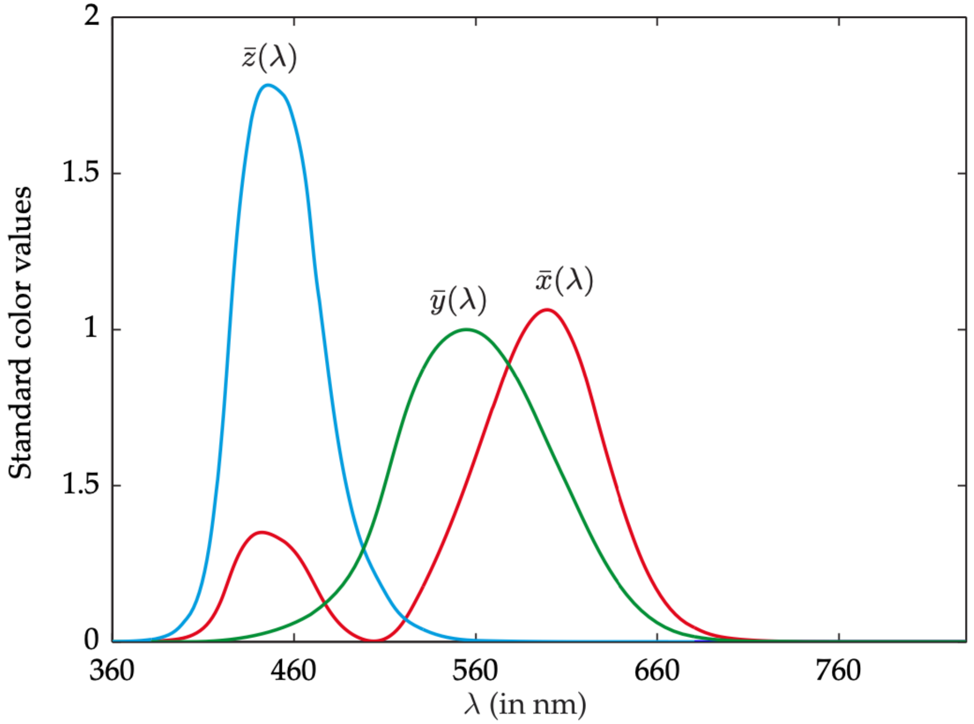
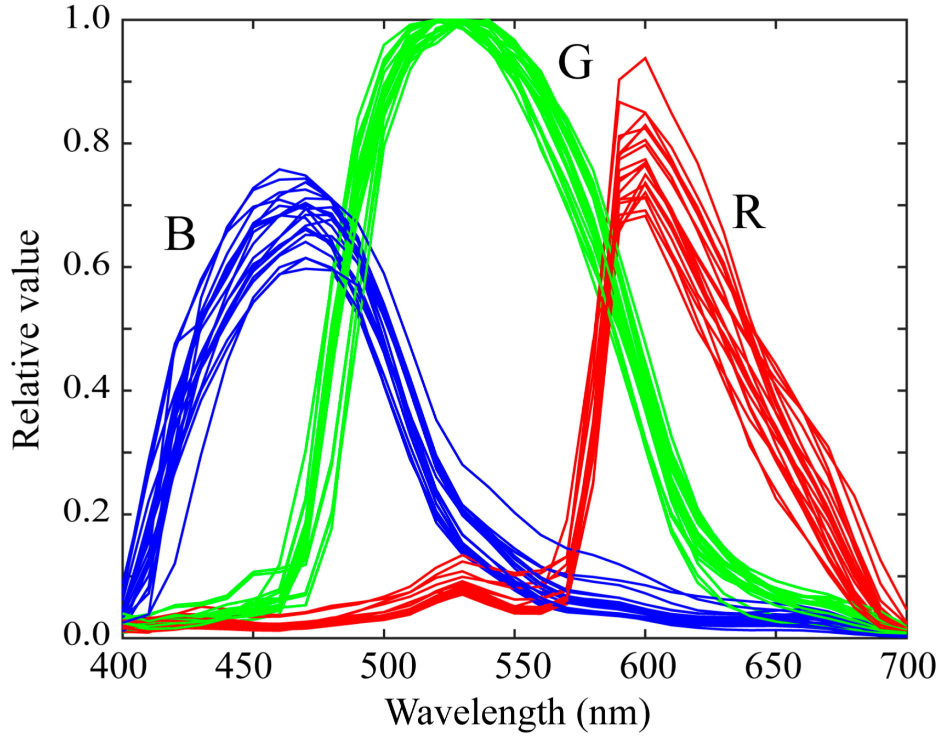
CIE standard color space

Color coordinates: X, Y, Z



$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0{,}49 & 0{,}31 & 0{,}20 \\ 0{,}17697 & 0{,}81240 & 0{,}01063 \\ 0{,}00 & 0{,}01 & 0{,}99 \end{pmatrix} \begin{pmatrix} R_{\text{CIE}} \\ G_{\text{CIE}} \\ B_{\text{CIE}} \end{pmatrix}$$

Y: Brightness = gray value image



spectral sensitivity of 20 mobile phone cameras

from: Tominaga, S.; Nishi, S.; Ohtera, R. Measurement and Estimation of Spectral Sensitivity Functions for Mobile Phone Cameras. *Sensors* **2021**, *21*, 4985. https://doi.org/10.3390/s21154985

CIE (x, y, z) Color Space

Characterization of a color independent of brightness: 2D is sufficient → Normalization

Calculation of the normalized color value components x, y, z from standard color values X, Y, Z:

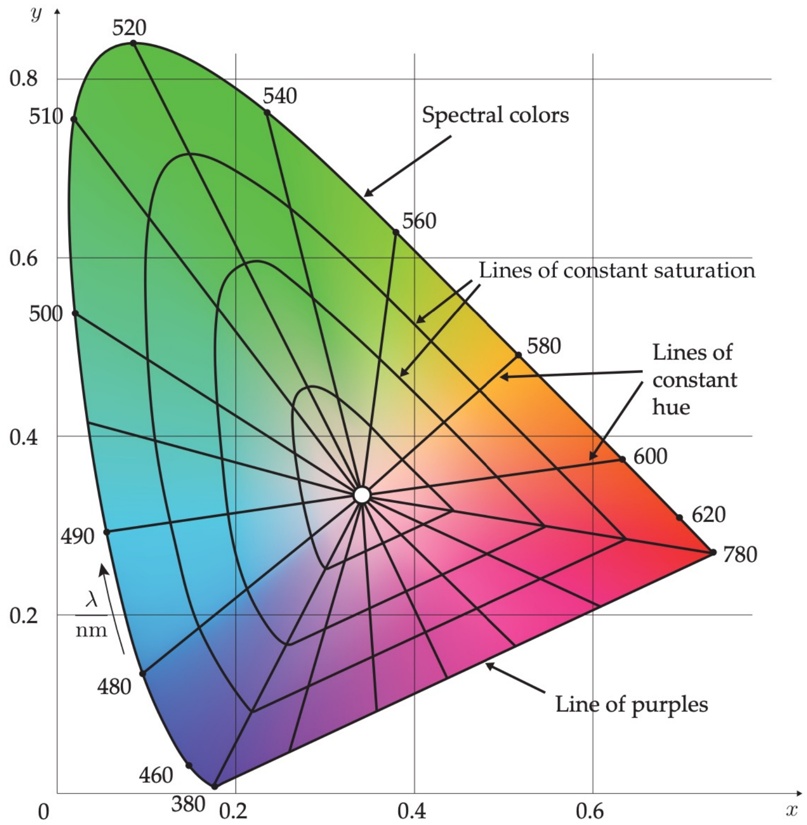
$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

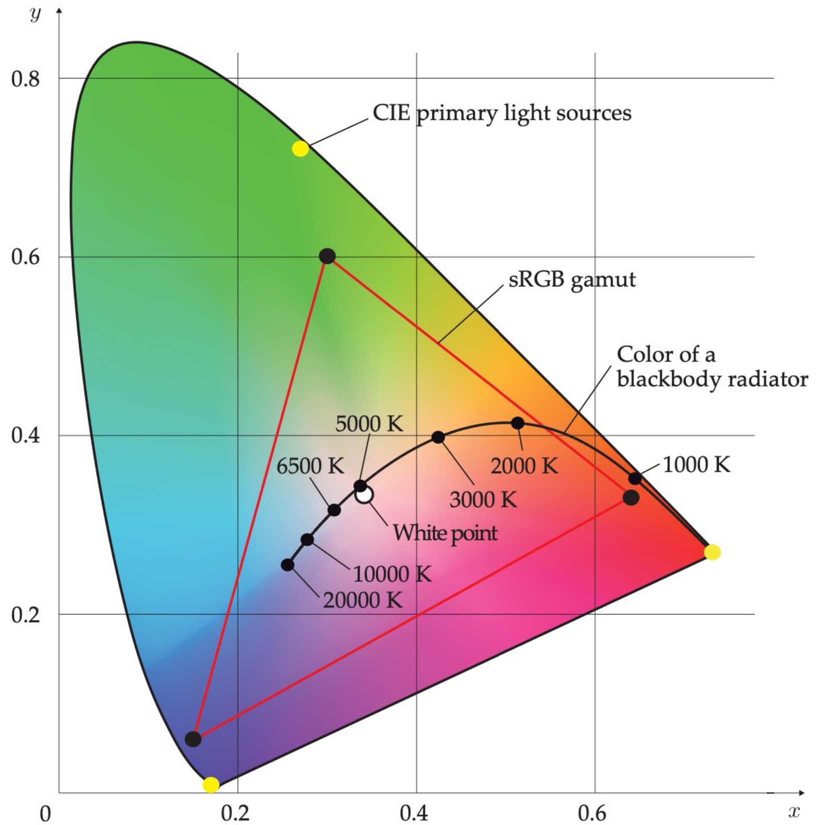
As $x + y + z = 1$: one color component is redundant → z discarded

x, y: Chromaticity coordinates: describe color independent of brightness
Y: Luminance coordinate

(x, y, Y) completely describes a color value

CIE Standard Color Chart (Chromaticity Diagram)





Additive color mixing:

- given:
  Chromaticity coordinates of N colors
- by additive mixing we get all colors within the convex hull

from: [Beyerer16]

CIE Standard Color Chart – Restrictions

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- Standard color values x, y cannot be interpreted easily (e.g. as hue or saturation)

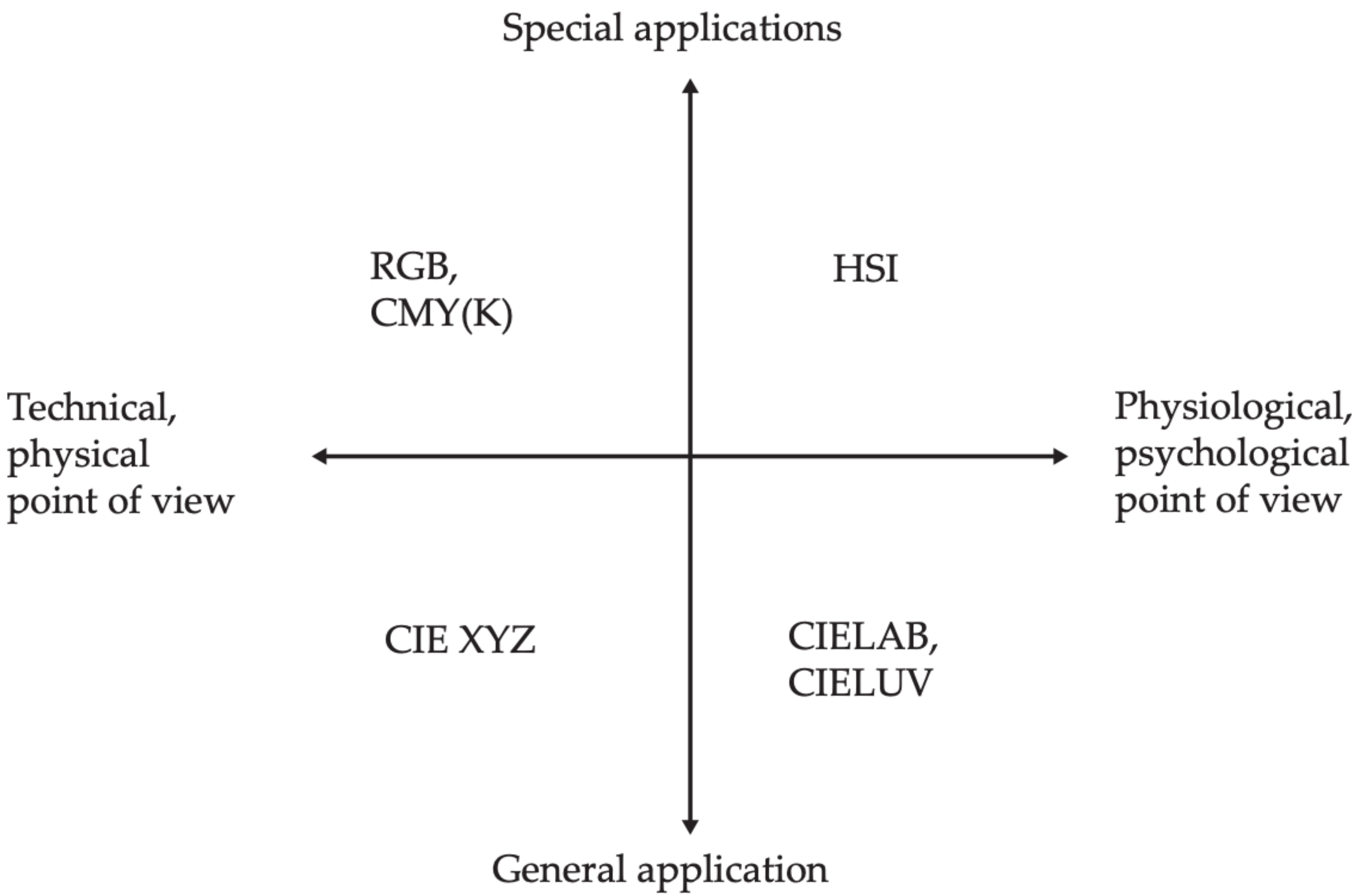
- Distance between two points in the color chart ≠ Distance (similarity) of the associated colors
  - resolution of green is very fine
  - resolution of blue is very coarse
  - a certain distance in the x-direction can appear visually significantly smaller than the same distance in the y-direction

- Position of perfect black is not well-defined (because of $X = Y = Z = 0 \rightarrow$ denominator)

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

→ Depending on the application, other color spaces are more suitable

Color Spaces – Classification



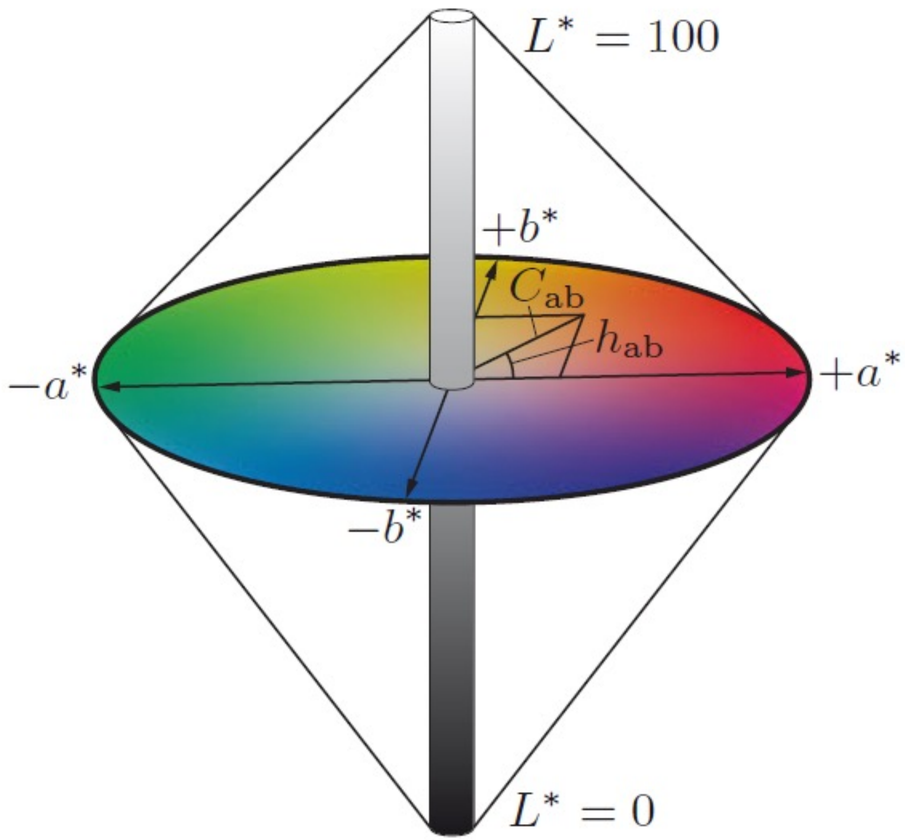
from: [Beyerer16]

CIELAB Color Space

- results from non-linear transformation
- L^*: Brightness
- a^*, b^*: Color differences to green component

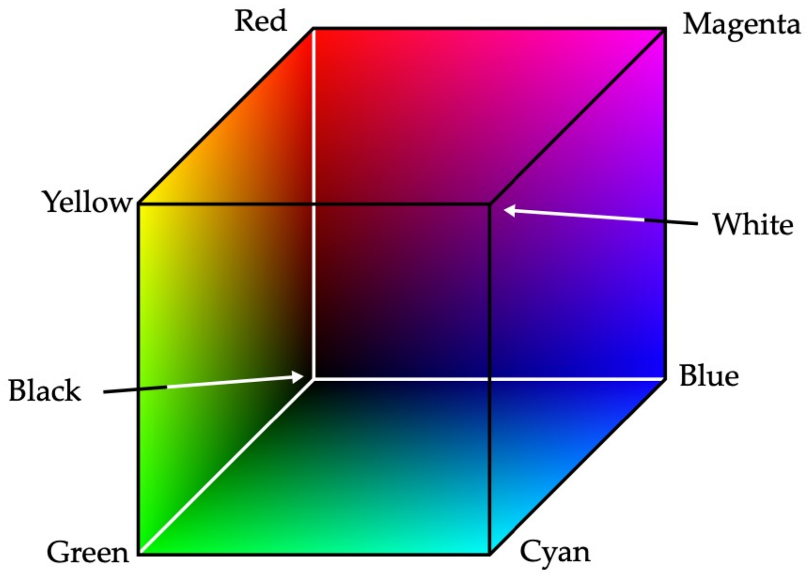
- colors arranged in a circle around the white point ($L^* = 100, a^* = b^* = 0$)
- achromatic colors: $a^* = b^* = 0$
- black: $L^* = 0, a^* = b^* = 0$

- Polar coordinates *C*, *h* illustrative:
  - h = hue angle
  - C = radius (chroma) = saturation



from: [Beyerer16]

RGB Color Space



- additive color mixing:
  Red (R), Green (G), Blue (B)
- Value range: 0 – 1

- Used for: Monitors, cameras, projectors
- RGB color spaces and color gamuts vary depending on the device
- device-independent: sRGB

from: [Beyerer16]

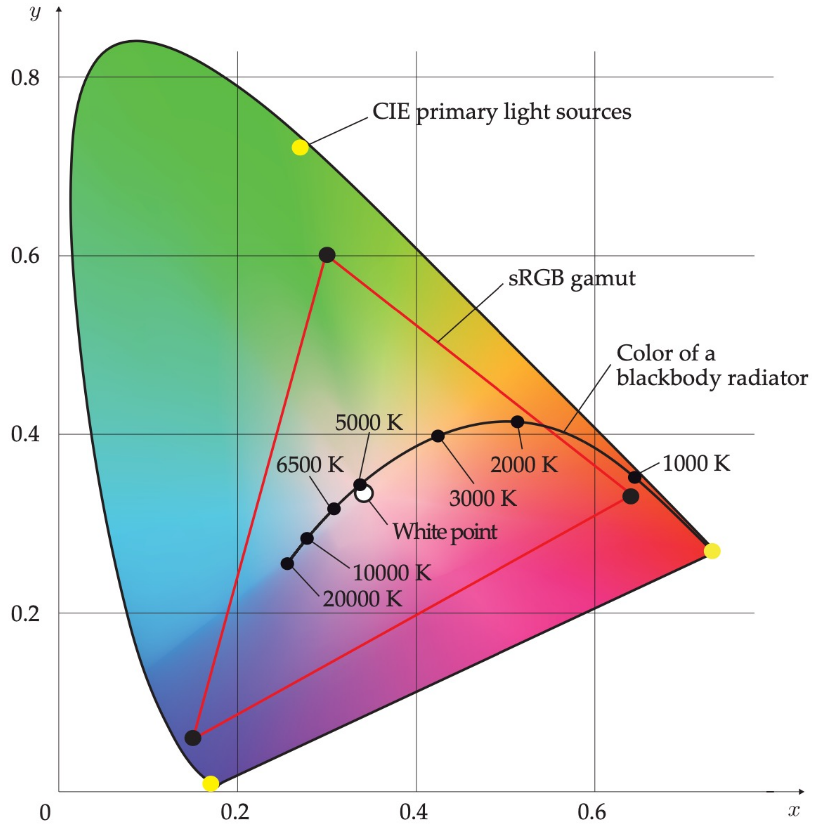
sRGB – linear

is obtained from XYZ space by

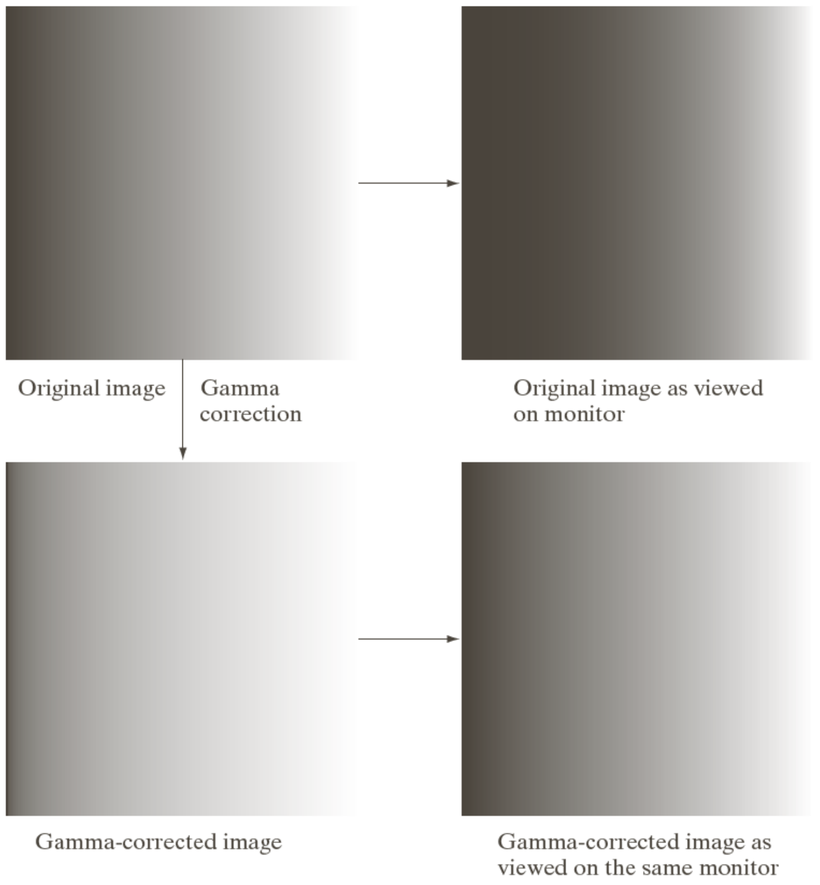
$$\begin{pmatrix} R_S \\ G_S \\ B_S \end{pmatrix} = \begin{pmatrix} 3{,}2410 & -1{,}5374 & -0{,}4986 \\ -0{,}9692 & 1{,}8760 & 0{,}0416 \\ 0{,}0556 & -0{,}2040 & 1{,}0570 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

- if a value becomes negative → value = 0
- if a value > 1 → value = 1
- these colors cannot be represented in sRGB
- transformation sRGB to XYZ: invert matrix

- sRGB non-linear → results from linear sRGB by gamma correction



Gamma Correction

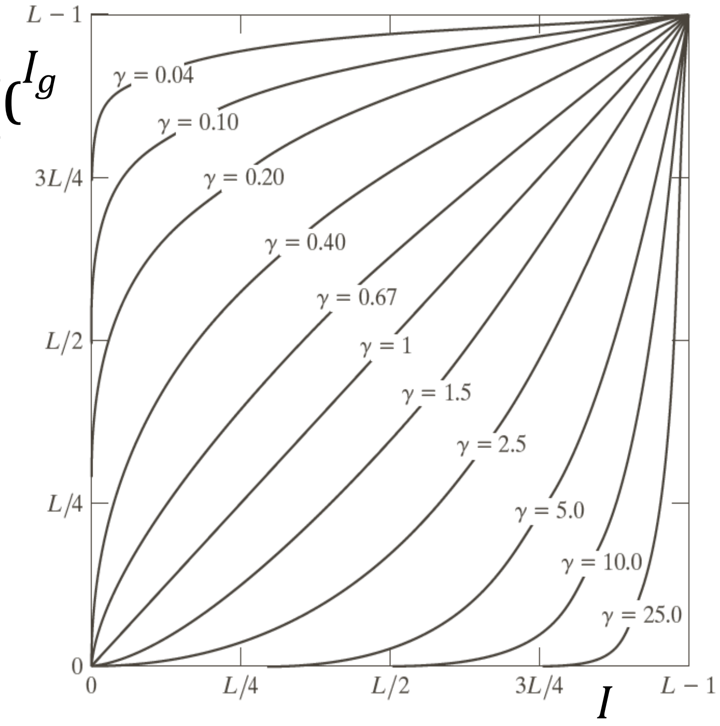


- Equalization of
  - Non-linearities in human perception
  - non-linear characteristics of devices (monitor, camera)
- Gamma correction of an intensity I:

$$I_g = cI^\gamma$$

$$c, \gamma > 0, \qquad I \in [($$

- often: $c = 1$
- Transformation is reversible



from: [Gonzalez08]

Gamma Correction

Original

$\gamma = 3$

$\gamma = 4$

$\gamma = 5$

$c = 1$

from: [Gonzalez08]

sRGB – non-linear

- usually: additional non-linear gamma correction on top of (linear) sRGB
- adjusts intensities to human perception
- improves display on monitors
- corrected sRGB values are still in [0; 1]

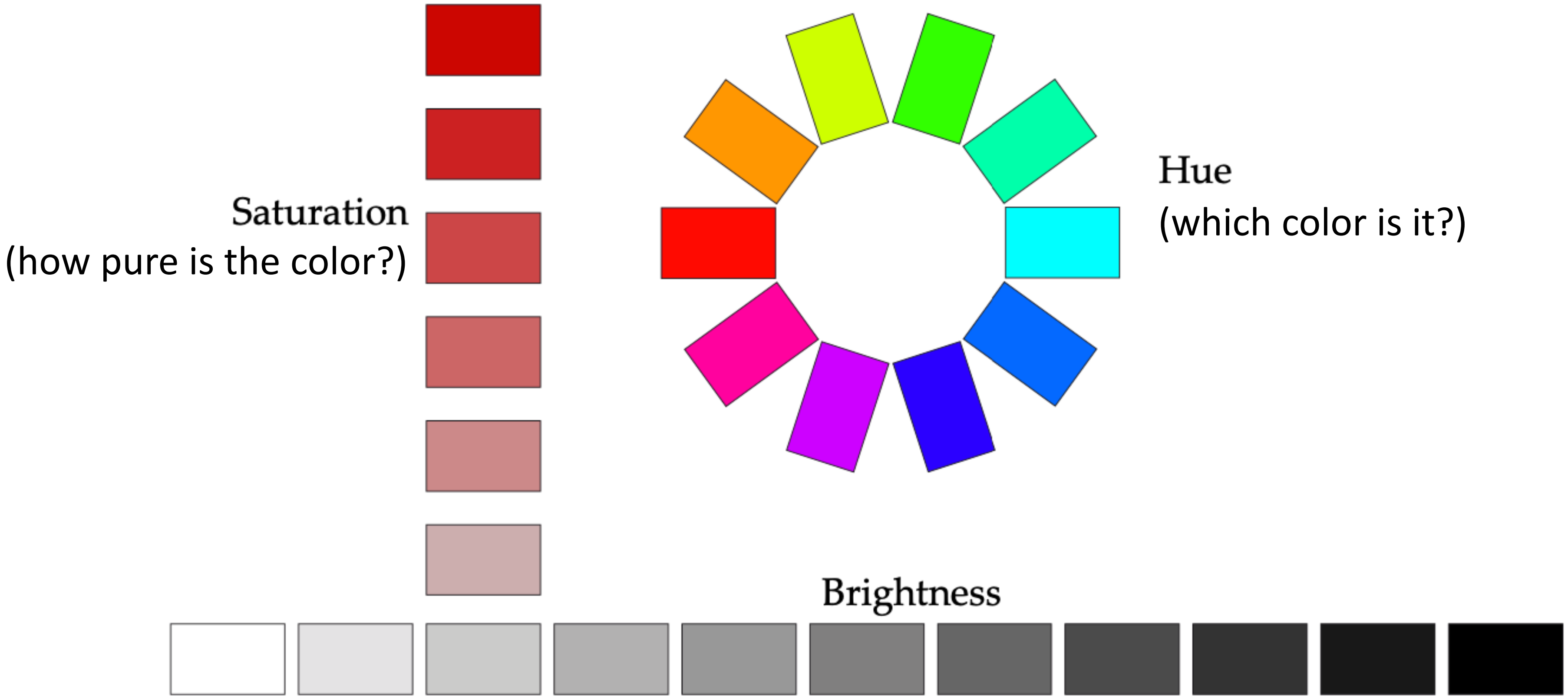
$$\begin{pmatrix} R_s' \\ G_s' \\ B_s' \end{pmatrix} = \begin{pmatrix} f_\gamma(R_s) \\ f_\gamma(G_s) \\ f_\gamma(B_s) \end{pmatrix} \qquad \text{with } f_\gamma(x) = \begin{cases} 1{,}055x^{\frac{1}{2{,}4}} - 0{,}055 & \text{if } x > 0{,}00304 \\ 12{,}92x & \text{if } x \leq 0{,}00304 \end{cases}$$

HSV/HSL/HSI

- H = Hue (*Farbton*)
  S = Saturation (*Sättigung*)
  V = Value, L = Luminance, I = Intensity (Brightness, *Helligkeit*)
  - all three color spaces are slightly different
  - values can be easily interpreted
- Intensity coordinate
  - weighs all channels equally
  - does not correspond to the human perception of brightness
- Calculation of HSI from gamma-corrected sRGB:

$$H = \arctan \frac{\sqrt{3}(G_s' - B_s')}{2R_s' - G_s' - B_s'} \qquad I = \frac{1}{3}(R_s' + G_s' + B_s') \qquad S = 1 - \frac{\min\{R_s', G_s', B_s'\}}{I}$$

Hue, Saturation, Brightness



from: [Beyerer16]

YUV/YC_BC_R

- Brightness (Y) and color difference signals (U, V / C_B, C_R)
- Usage
  - YUV: PAL television standard
  - YC_BC_R: JPEG
- Calculation from gamma-corrected sRGB:

$$Y = 0{,}299R_s' + 0{,}587G_s' + 0{,}114B_s'$$

$$U = 0{,}493(B_s' - Y) \qquad C_B = 0{,}564(B_s' - Y)$$

$$V = 0{,}877(R_s' - Y) \qquad C_R = 0{,}713(R_s' - Y)$$

Sources

[Beyerer16] Beyerer, J., Puente Leon, F., Frese, Ch.: ***Machine Vision***, Springer, 2016.

[Gonzalez08] Gonzalez, R.C., Woods, R.E.: ***Digital Image Processing***, Prentice Hall International, 3rd edition, 2008.