

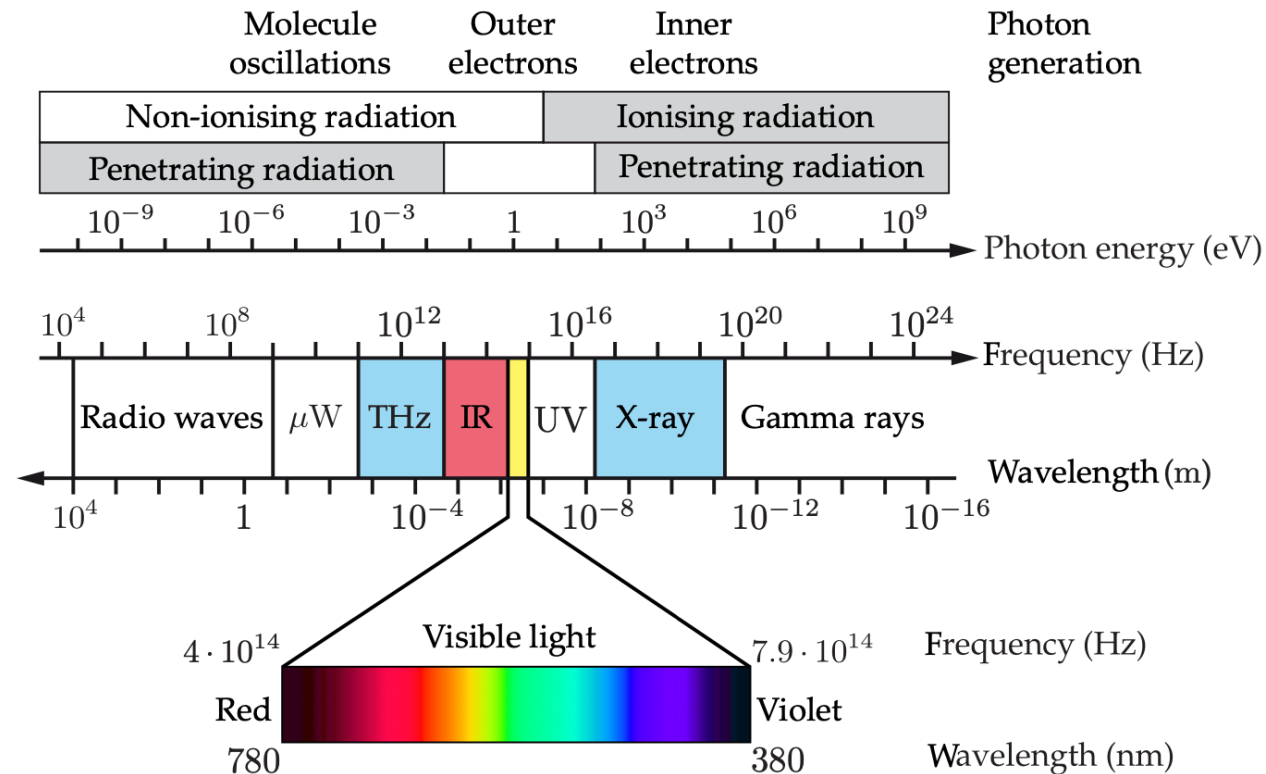


# Computer Vision

## Color

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

# Electromagnetic Spectrum

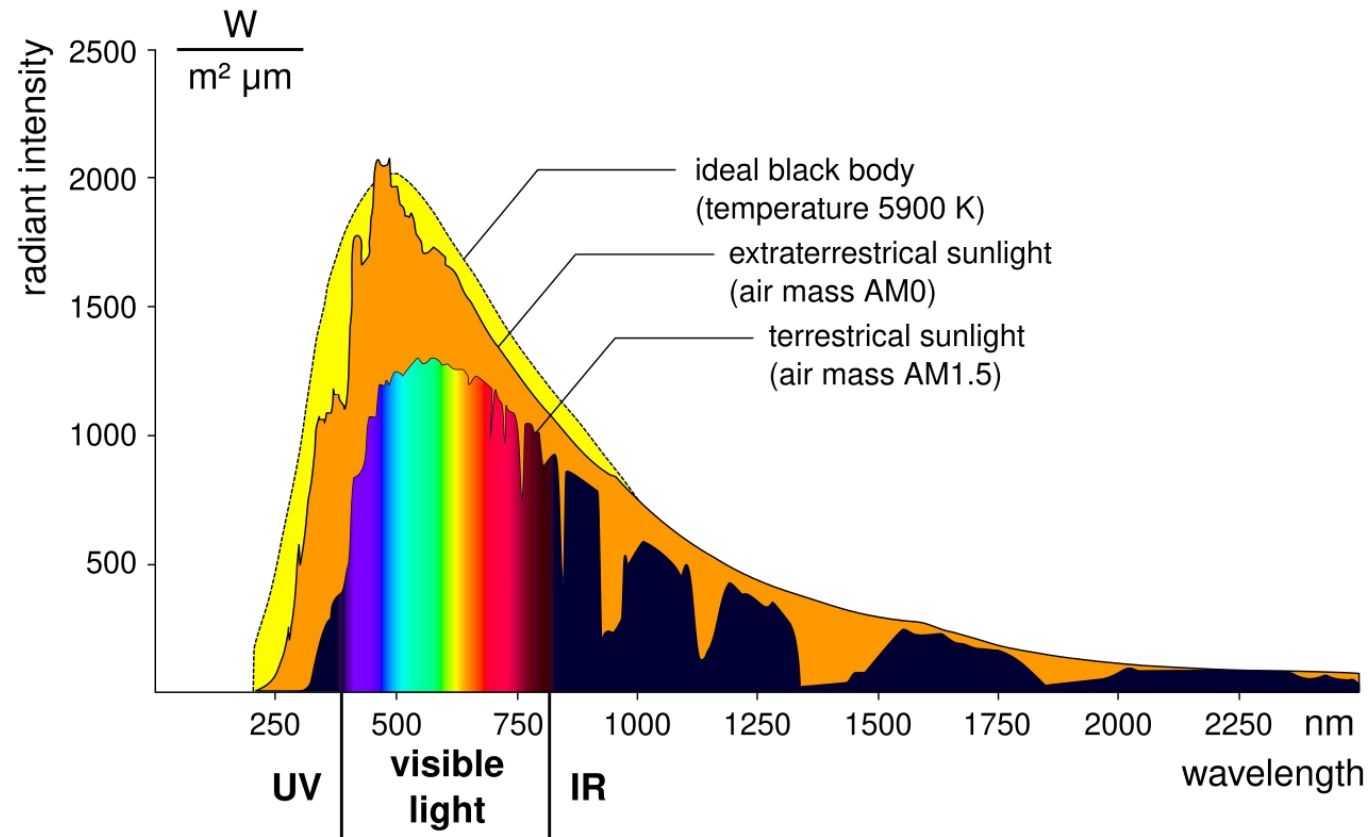
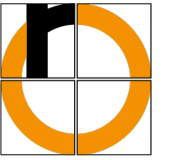


$$\lambda = c/f \quad f = \text{frequency [Hz]} \quad \lambda = \text{wavelength [m]}$$

$c$  = speed of light; in a vacuum,  $c \approx 2.9979 \cdot 10^8$  m/s

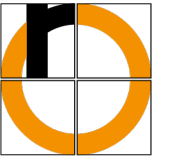
$\mu W$  = microwaves, THz = Terahertz radiation, IR = infrared, UV = ultraviolet

from: [Beyerer16]

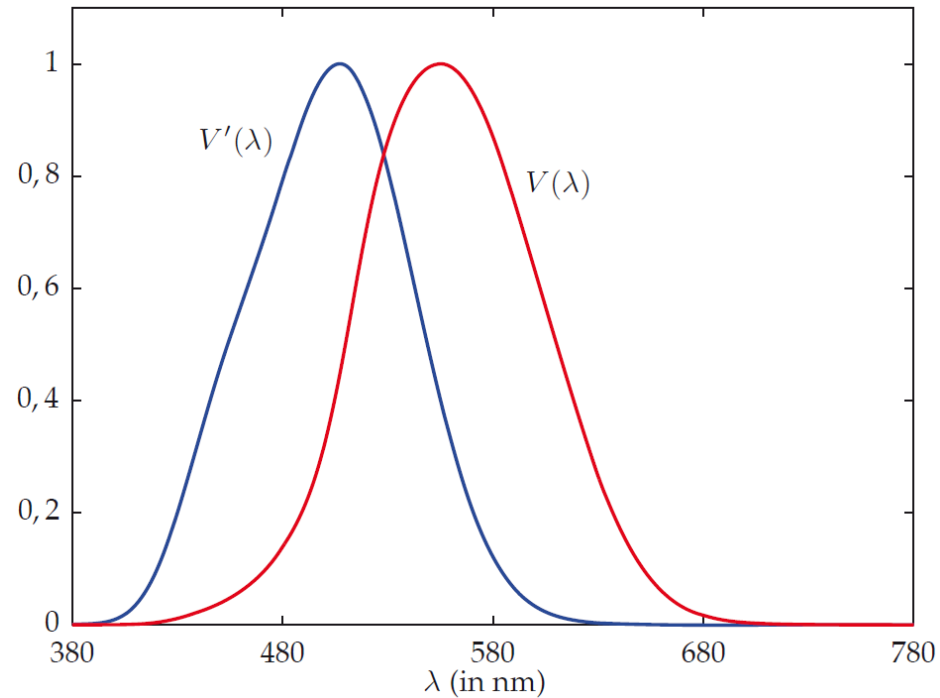


The original uploader was [Degreen](#) at [German Wikipedia](#). Improved [Baba66](#) (opt [Perhelion](#)) on request; En. translation [Locusta](#)  
Fr. translation [Eric Bajart](#) Nl. translation [BoH](#), [Sonne Strahlungsintensitaet](#), [CC BY-SA 2.0 DE](#)

# Perception of Brightness by the Human Eye



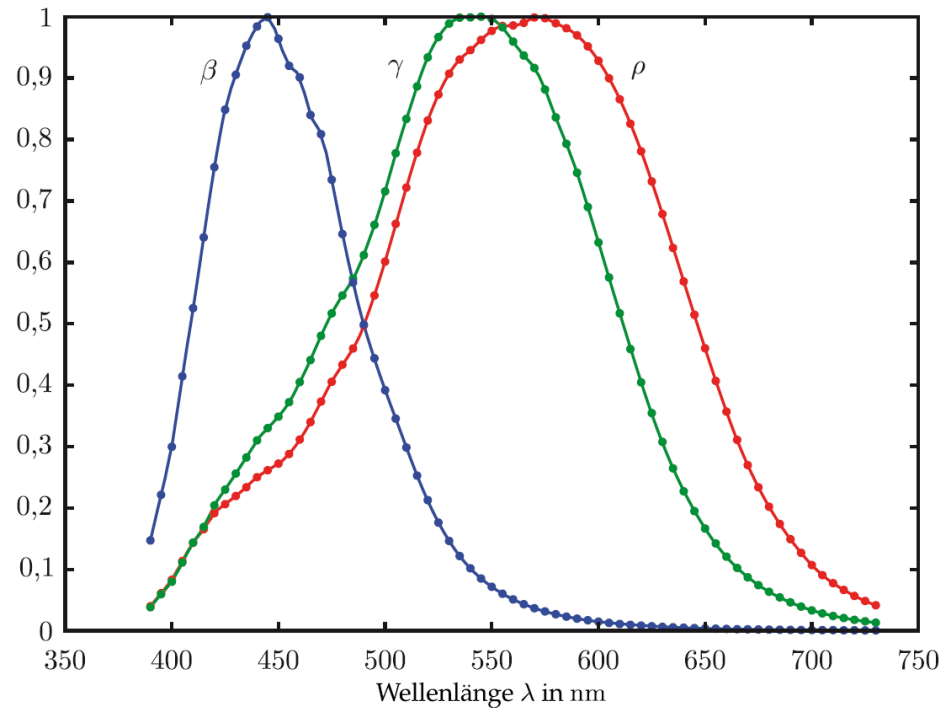
Sensitivity of the human eye to brightness



$V'$ : dark-adapted eye

$V$ : light-adapted eye

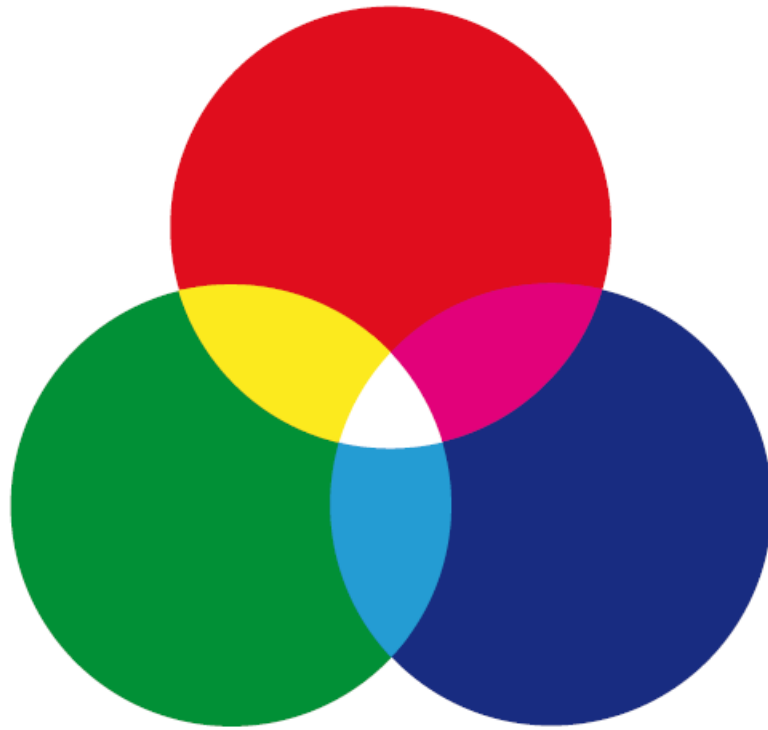
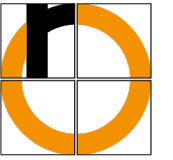
Spectral sensitivity of the cone cells



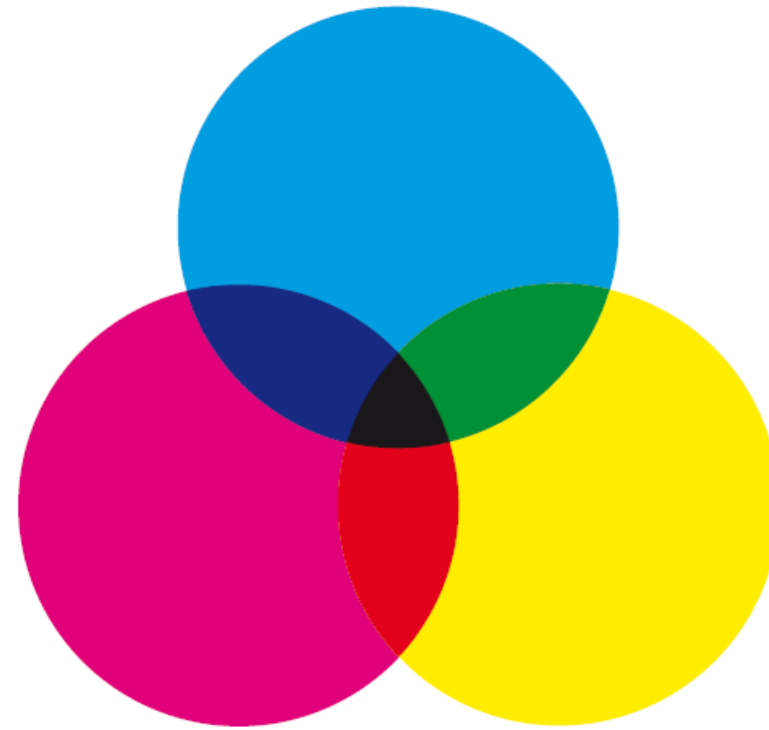
each curve normalized to maximum 1

from: [Beyerer16]

# Additive and Subtractive Color Mixing

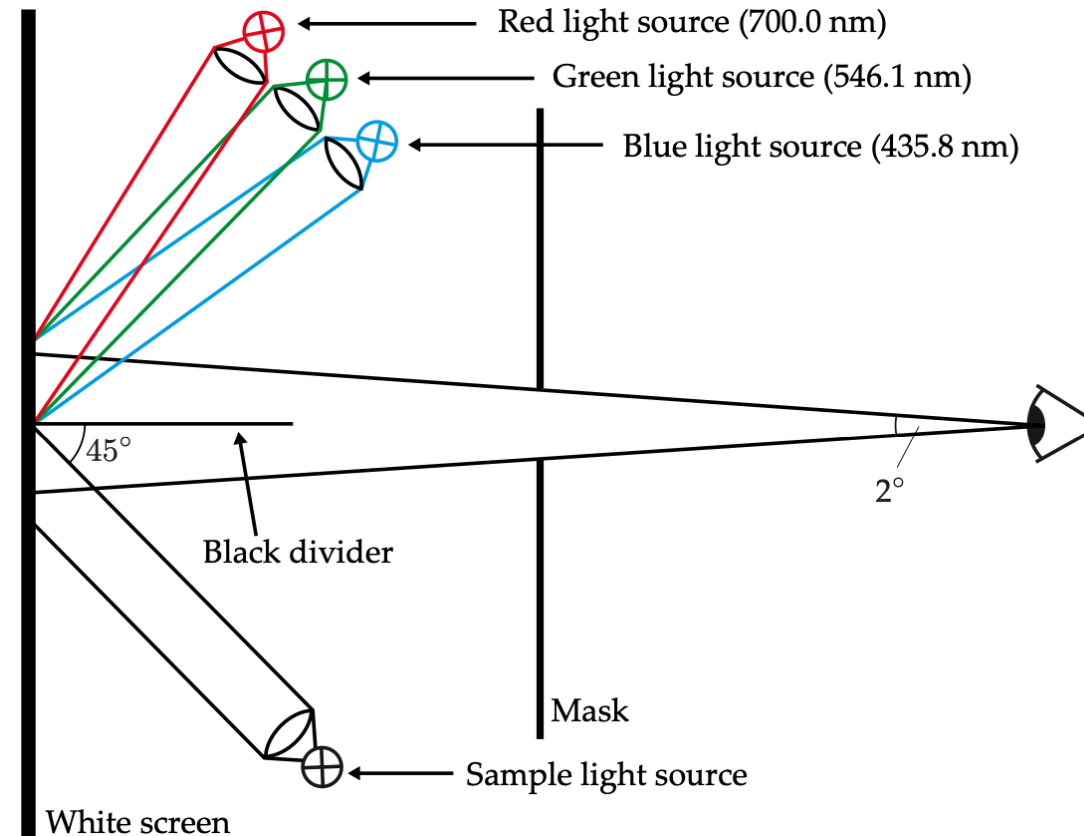


additive



subtractive

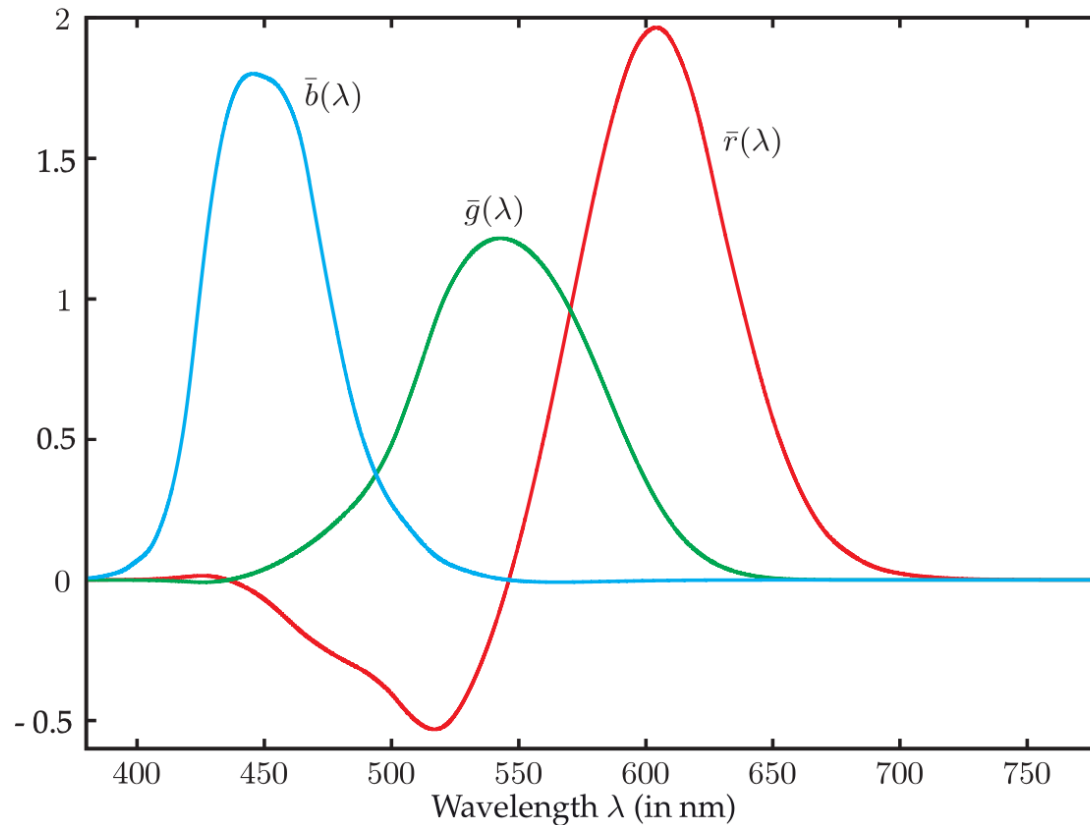
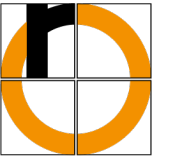
from: [Beyerer16]



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  
 $R_{\text{CIE}} = G_{\text{CIE}} = B_{\text{CIE}}$

Color value of any spectrum :

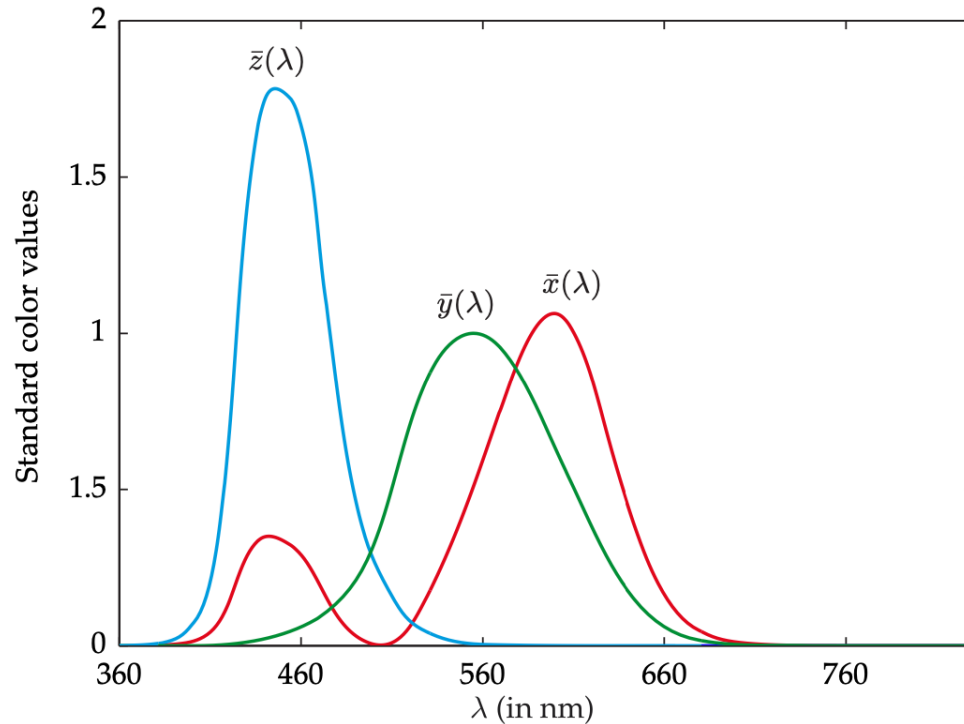
$$R_{\text{CIE}} = \int_{380\text{nm}}^{780\text{nm}} I(\lambda) \bar{r}(\lambda) d\lambda$$

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

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

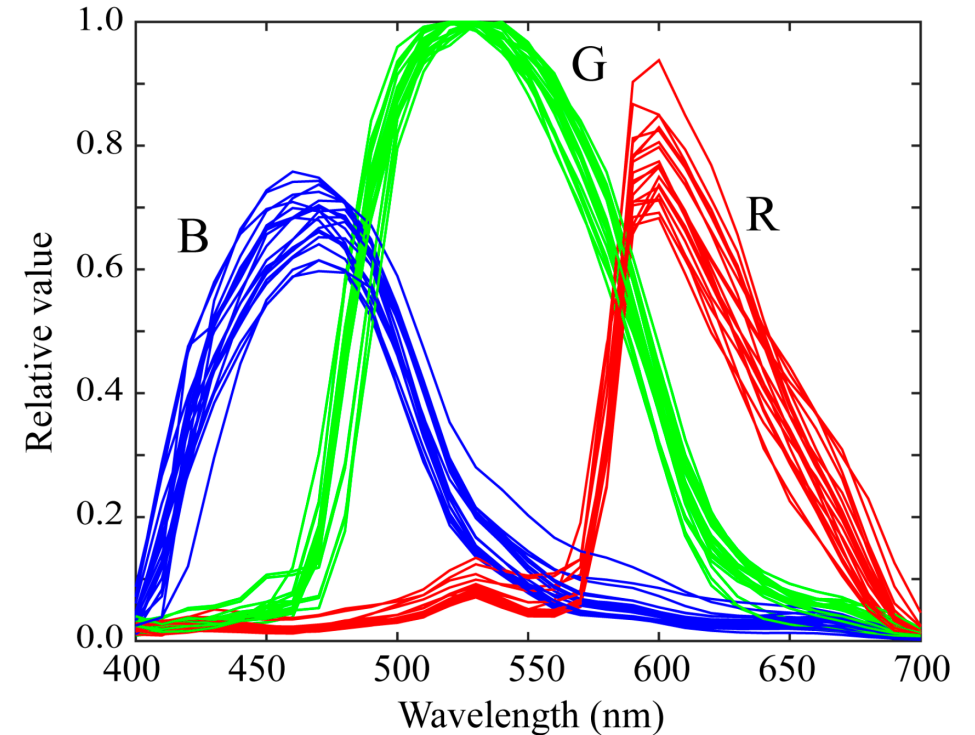
from: [Beyerer12]

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>



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  $X$ ,  $Y$ ,  $Z$ :

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

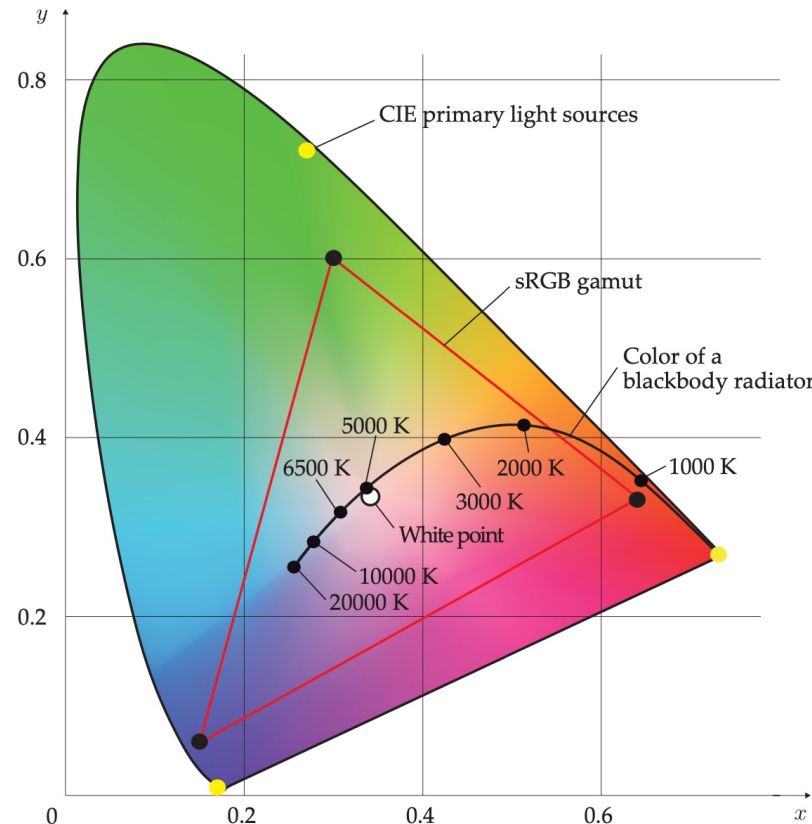
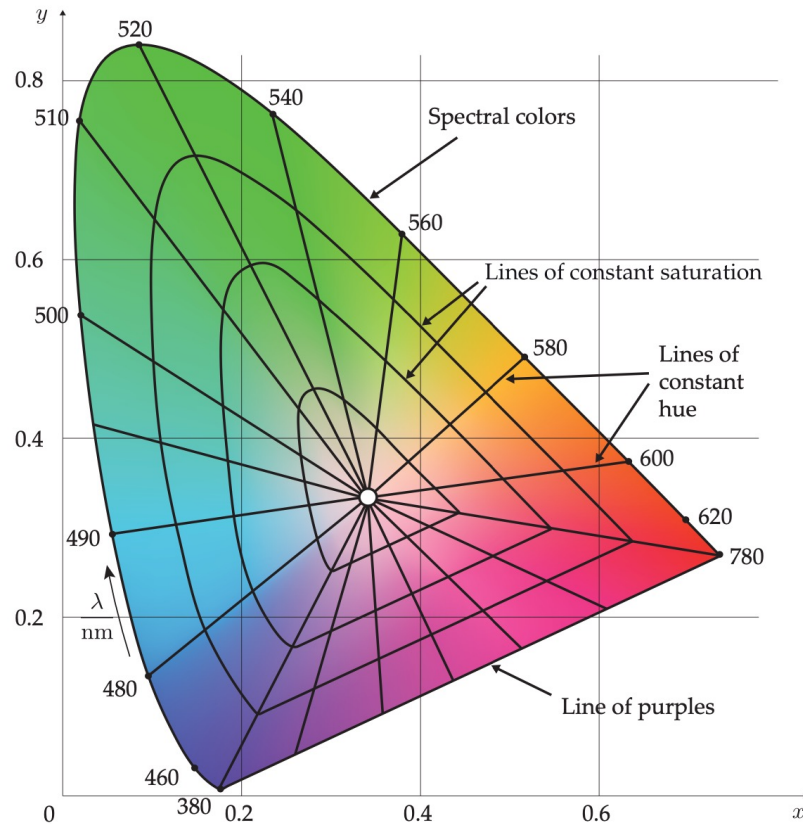
As  $x + y + z = 1$ : one color component is redundant →  $z$  discarded

$x$ ,  $y$ : 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:

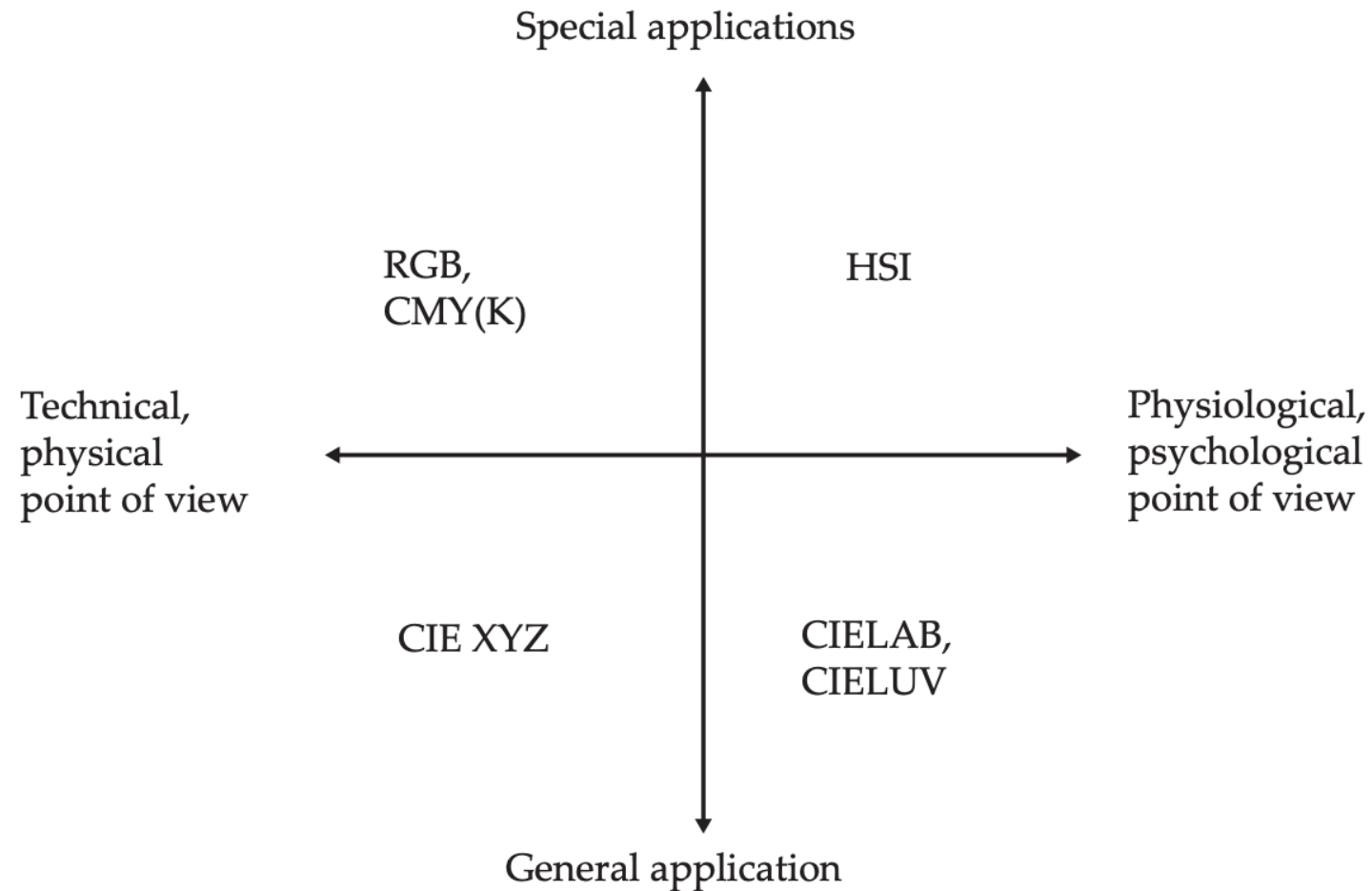
- given:  
Chromaticity coordinates  
of  $N$  colors
- by additive mixing we get  
all colors within the  
convex hull

from: [Beyerer16]

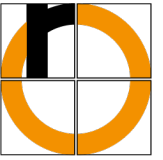
- Standard color values  $x, y$  cannot be interpreted easily (e.g. as hue or saturation)
- Distance between two points in the color chart  $\neq$  Distance (similarity) of the associated colors
  - resolution of green is very fine
  - resolution of blue is very coarse
  - a certain distance in the  $x$ -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)

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

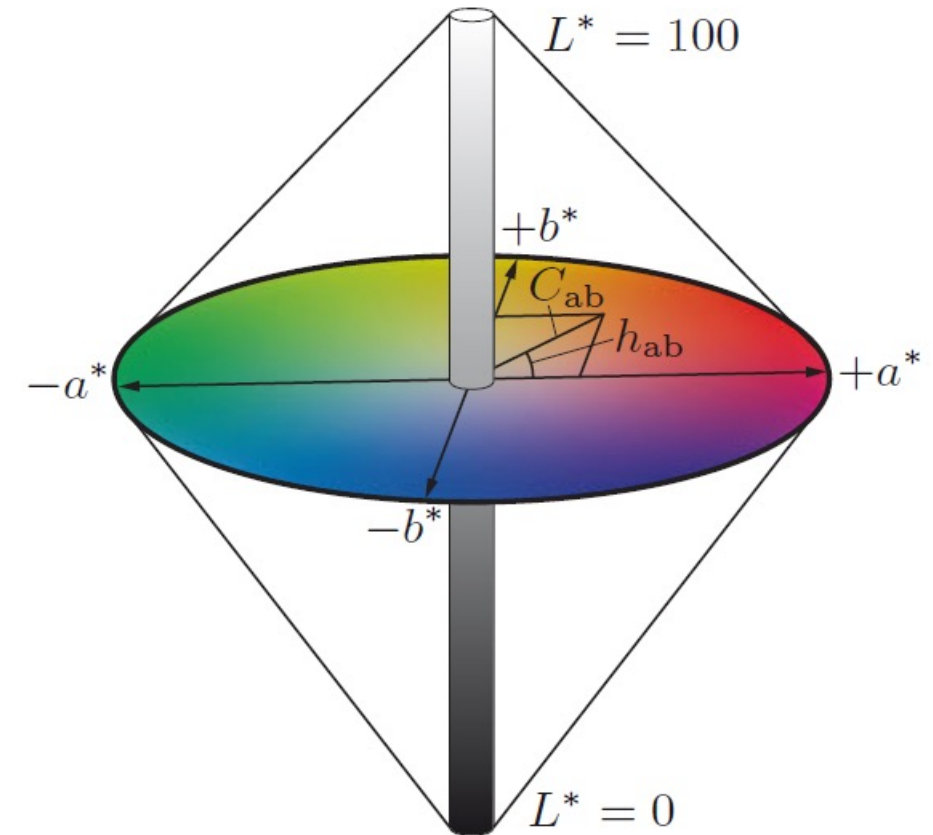
→ Depending on the application, other color spaces are more suitable



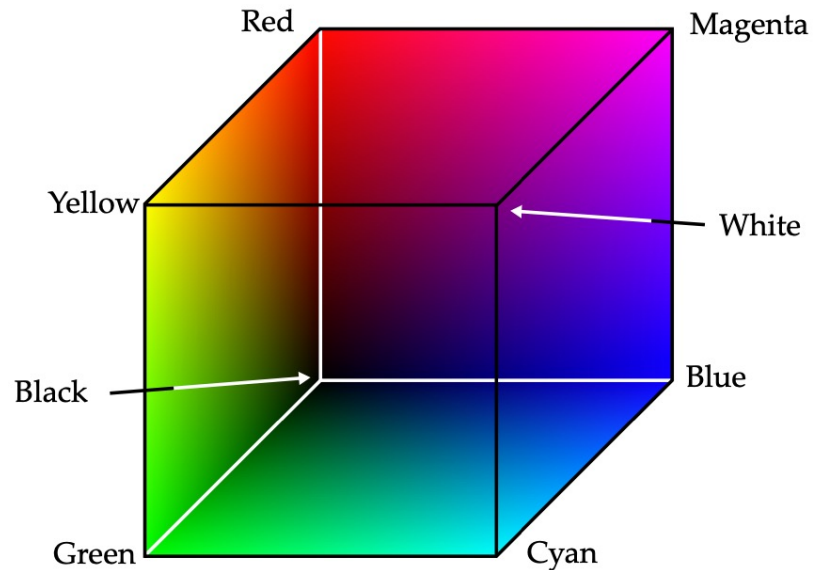
from: [Beyerer16]



- 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

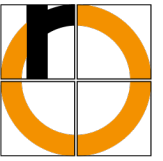


from: [Beyerer16]



- 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

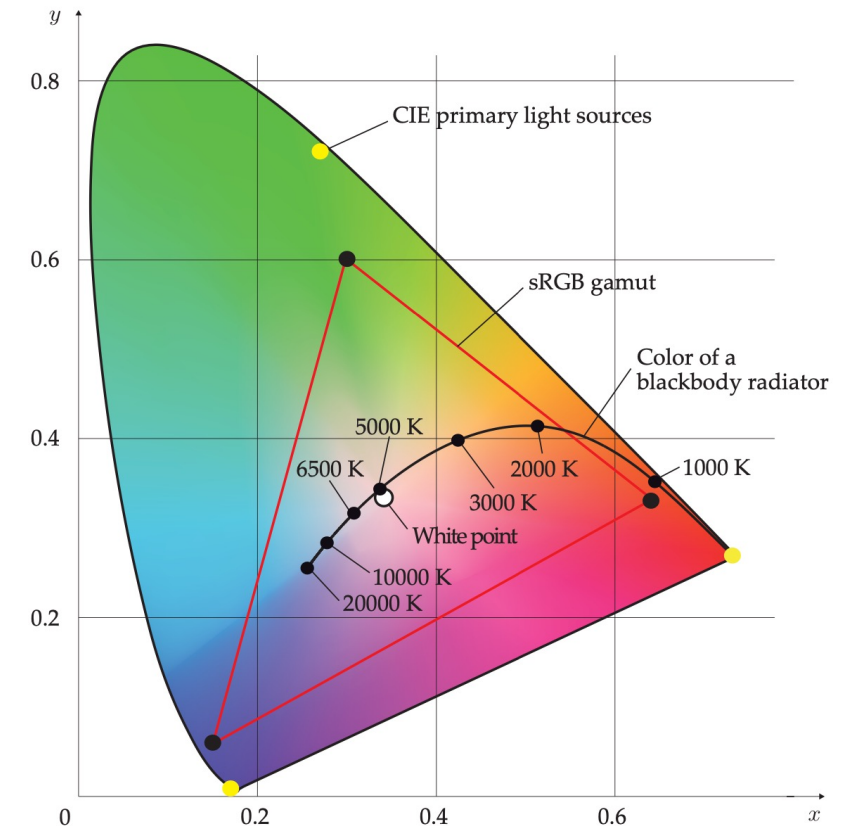
from: [Beyerer16]

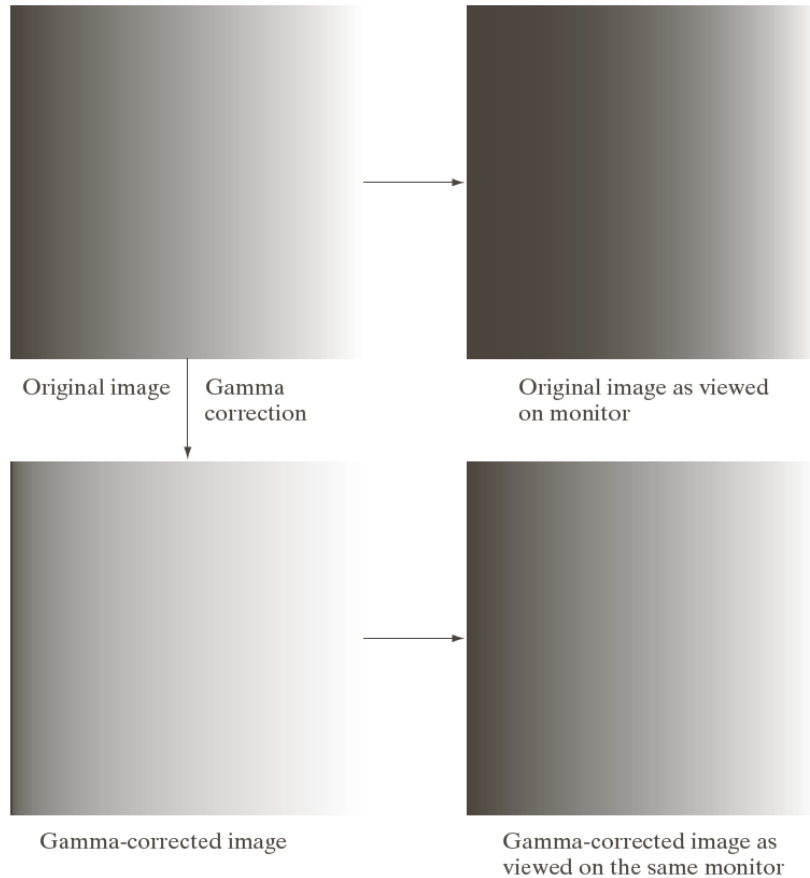
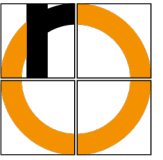


is obtained from XYZ space by

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

- if a value becomes negative  $\rightarrow$  value = 0
- if a value  $> 1 \rightarrow$  value = 1
- these colors cannot be represented in sRGB
- transformation sRGB to XYZ: invert matrix
- sRGB non-linear  $\rightarrow$  results from linear sRGB by gamma correction





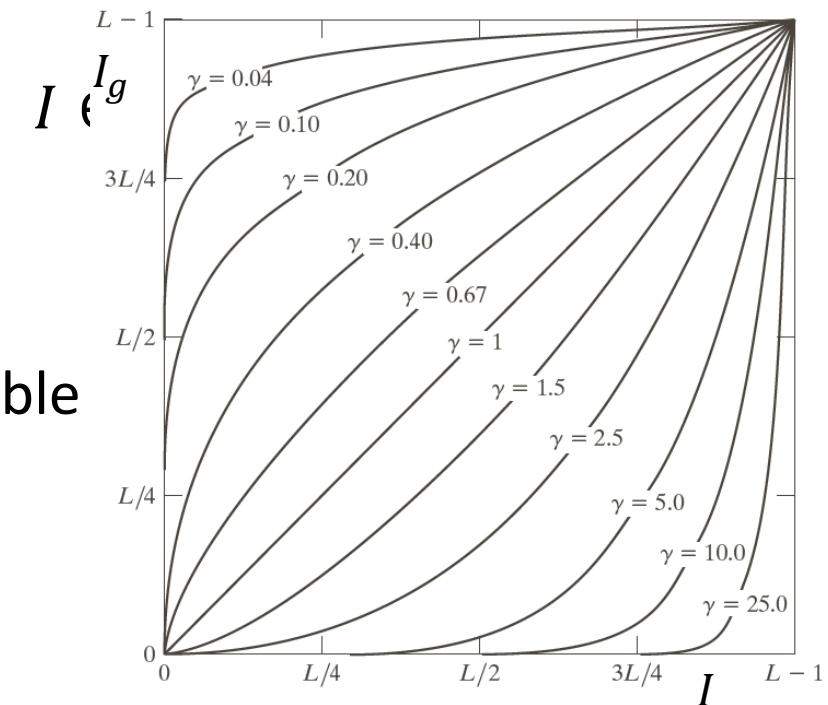
- Equalization of
  - Non-linearities in human perception
  - non-linear characteristics of devices (monitor, camera)

- Gamma correction of an intensity  $I$ :

$$I_g = cI^\gamma$$

$c, \gamma > 0$

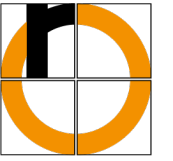
- often:  $c = 1$
- Transformation is reversible



from: [Gonzalez08]



# Gamma Correction



Original



$\gamma = 3$



$\gamma = 4$



$\gamma = 5$



$c = 1$

from: [Gonzalez08]

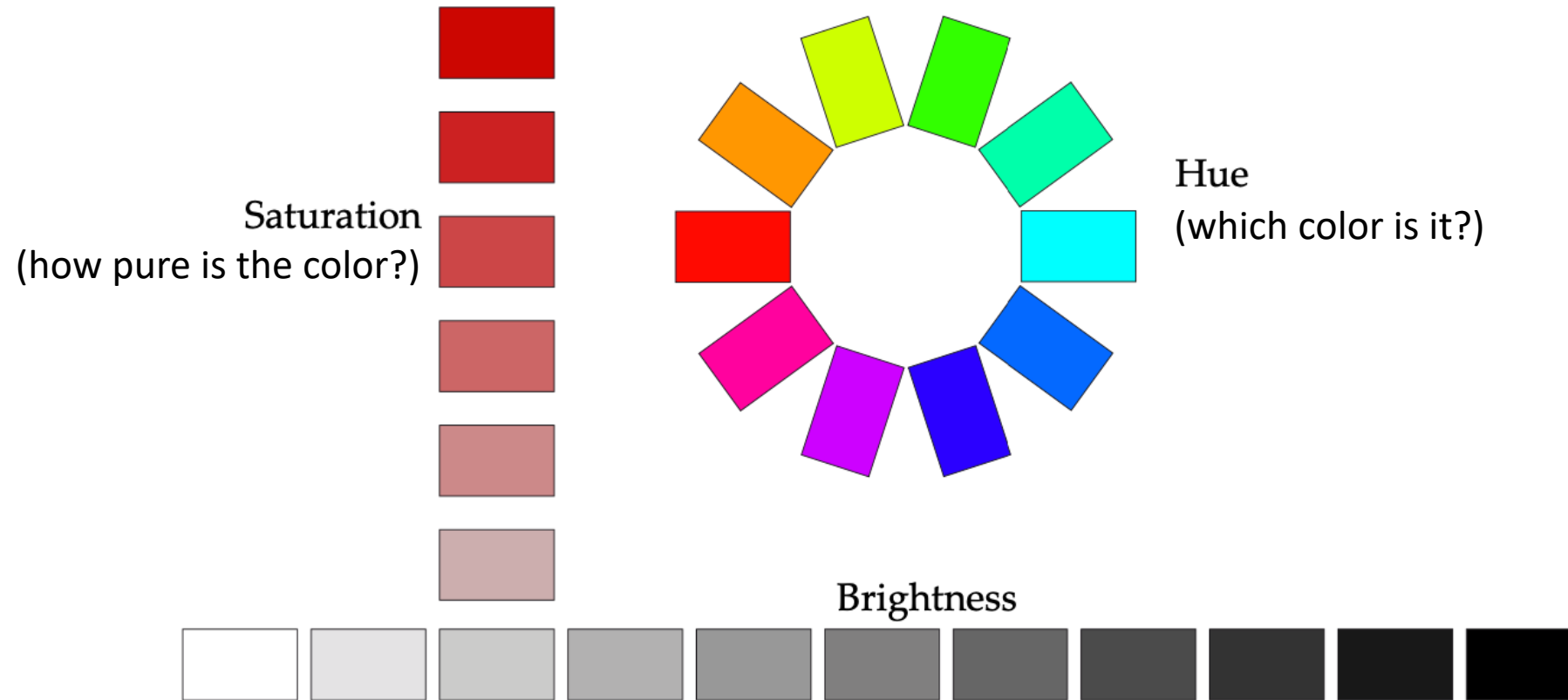
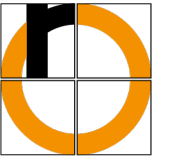
- usually: additional non-linear gamma correction on top of (linear) sRGB
- adjusts intensities to human perception
- improves display on monitors
- corrected sRGB values are still in [0; 1]

$$\begin{pmatrix} R'_S \\ G'_S \\ B'_S \end{pmatrix} = \begin{pmatrix} f_\gamma(R_S) \\ f_\gamma(G_S) \\ f_\gamma(B_S) \end{pmatrix} \quad \text{with } f_\gamma(x) = \begin{cases} 1,055x^{\frac{1}{2,4}} - 0,055 & \text{if } x > 0,00304 \\ 12,92x & \text{if } x \leq 0,00304 \end{cases}$$

- 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:

$$H = \arctan \frac{\sqrt{3}(G'_s - B'_s)}{2R'_s - G'_s - B'_s} \quad I = \frac{1}{3}(R'_s + G'_s + B'_s) \quad S = 1 - \frac{\min\{R'_s, G'_s, B'_s\}}{I}$$

# Hue, Saturation, Brightness



from: [Beyerer16]

- Brightness (Y) and color difference signals (U, V / C<sub>B</sub>, C<sub>R</sub>)
- Usage
  - YUV: PAL television standard
  - YC<sub>B</sub>C<sub>R</sub>: JPEG
- Calculation from gamma-corrected sRGB:

$$Y = 0,299R'_s + 0,587G'_s + 0,114B'_s$$

$$U = 0,493(B'_s - Y)$$

$$V = 0,877(R'_s - Y)$$

$$C_B = 0,564(B'_s - Y)$$

$$C_R = 0,713(R'_s - Y)$$

[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.