Lecture #02

Color

Computer Graphics

Winter term 2016/17

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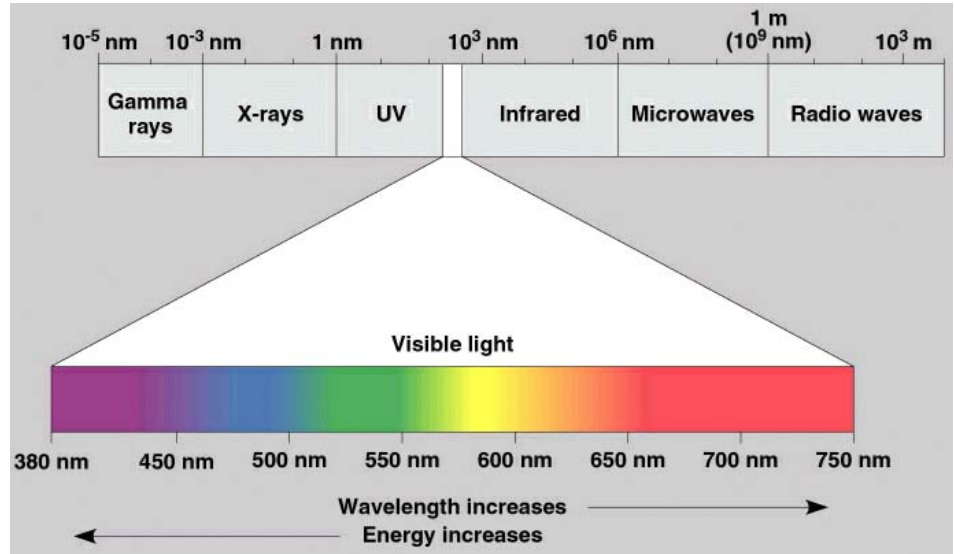
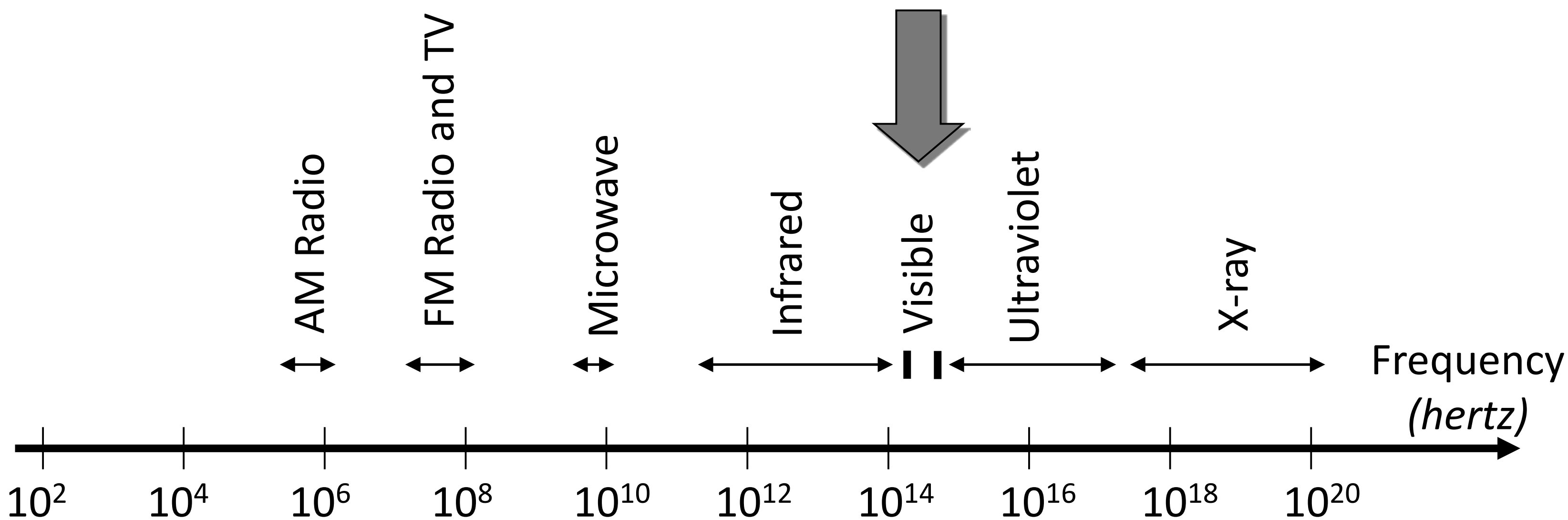
What is light?

- What is light?
  - visible light = narrow frequency band of electromagnetic spectrum
  - Red color: $4.3 \cdot 10^{14}$ hz
  - Violet color: $7.5 \cdot 10^{14}$ hz





What is light?

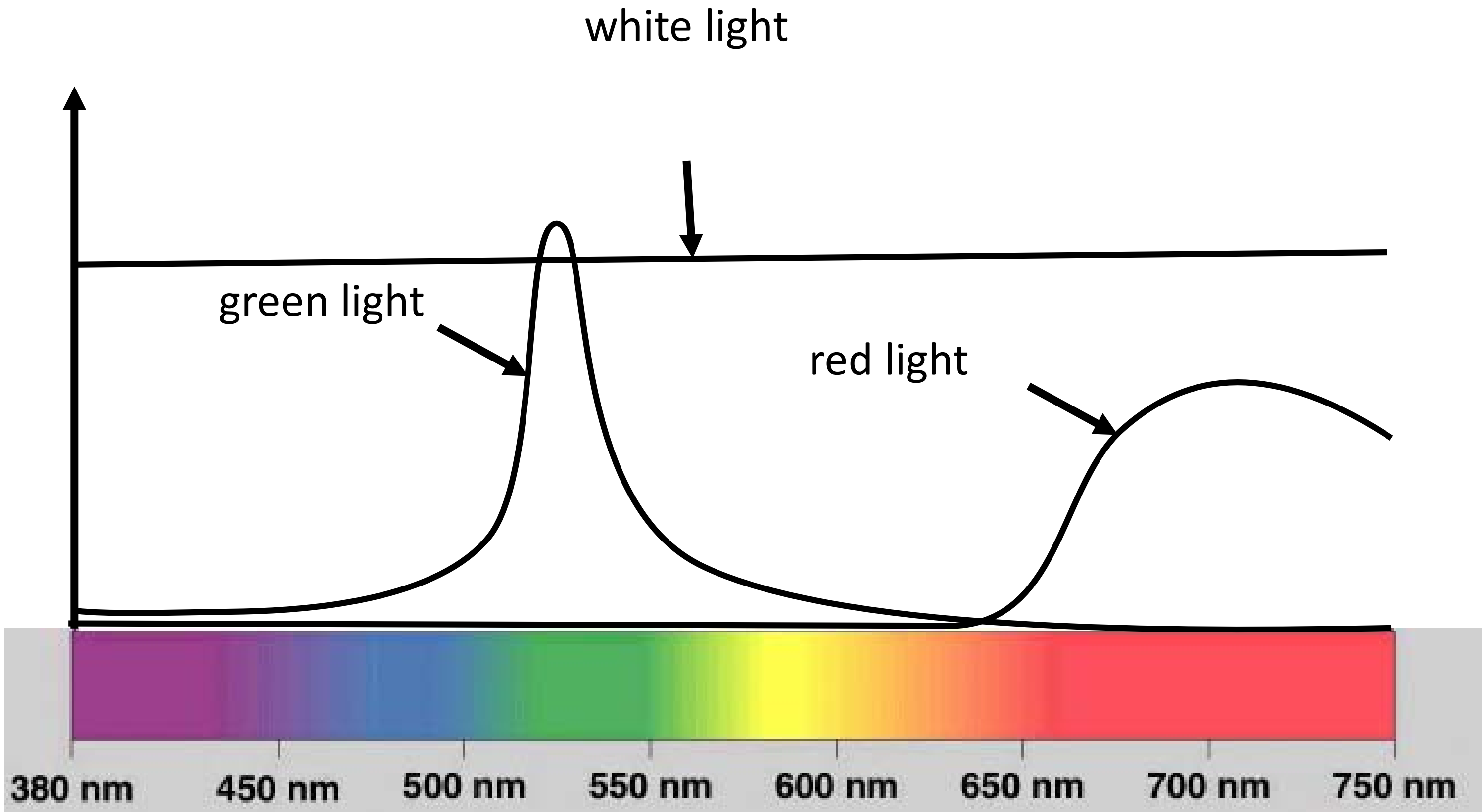
- Alternative model: photons = light particles
- Relationship: wave and particle picture
  - Frequency: f
  - Wavelength: $\lambda = c / f$ where c = speed of light
  - Photon Energy: $E = hf$ where h = Planck's quantum of action

What is color ?

- Physical description
  - A spectra of wavelengths
- Psychological perception
  - A stimulus sent from the optic system to the brain.
  - Sensors on the retina of the eye: rods and cones
- Computer graphics
  - Different sets of bases and coordinates,
    depending on the type of display and application

Spectrum

- Spectrum: how much energy is emitted per wave length?

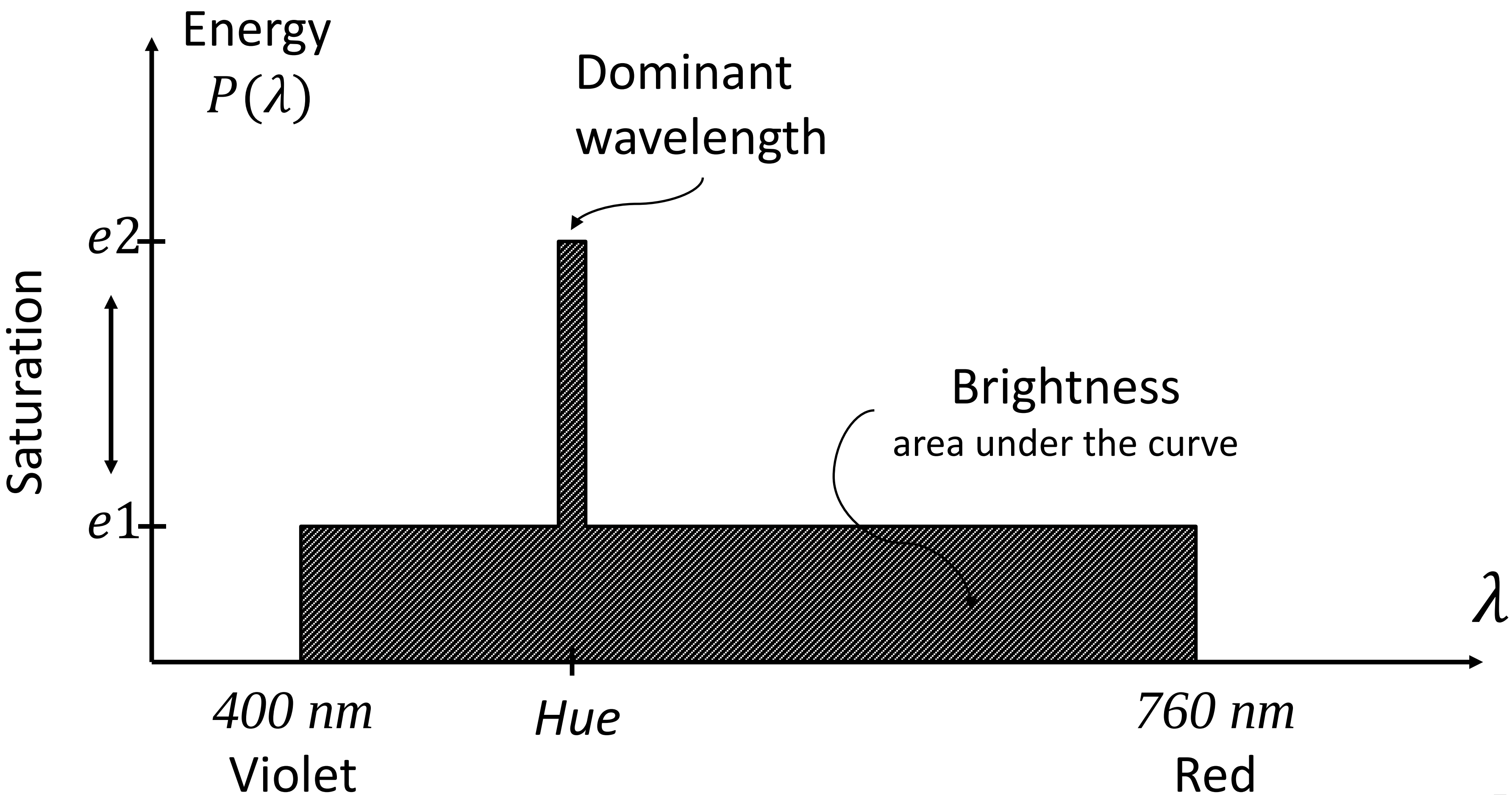


Color perception

- Perceptual Terms
  - **Hue**: The color seen (e.g. red, green, …) – dominant wavelength
  - **Saturation** (purity): Refers to how far a color is from a grey of equal intensity (How intense is the hue? – expressed objectively)
  - **Brightness:** Total light energy – quantified as luminance

Color perception

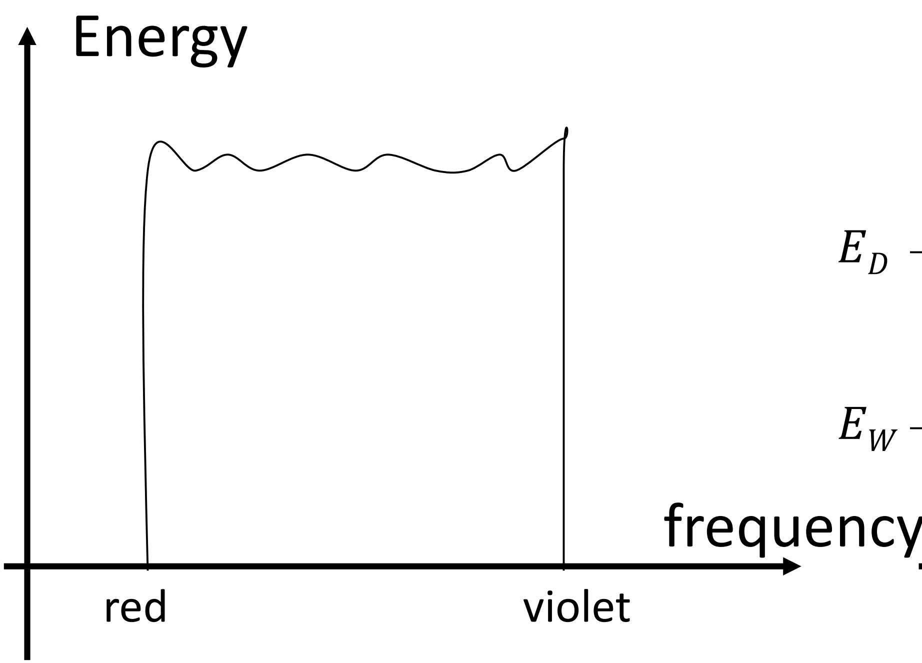
- Hue, Saturation and Brightness



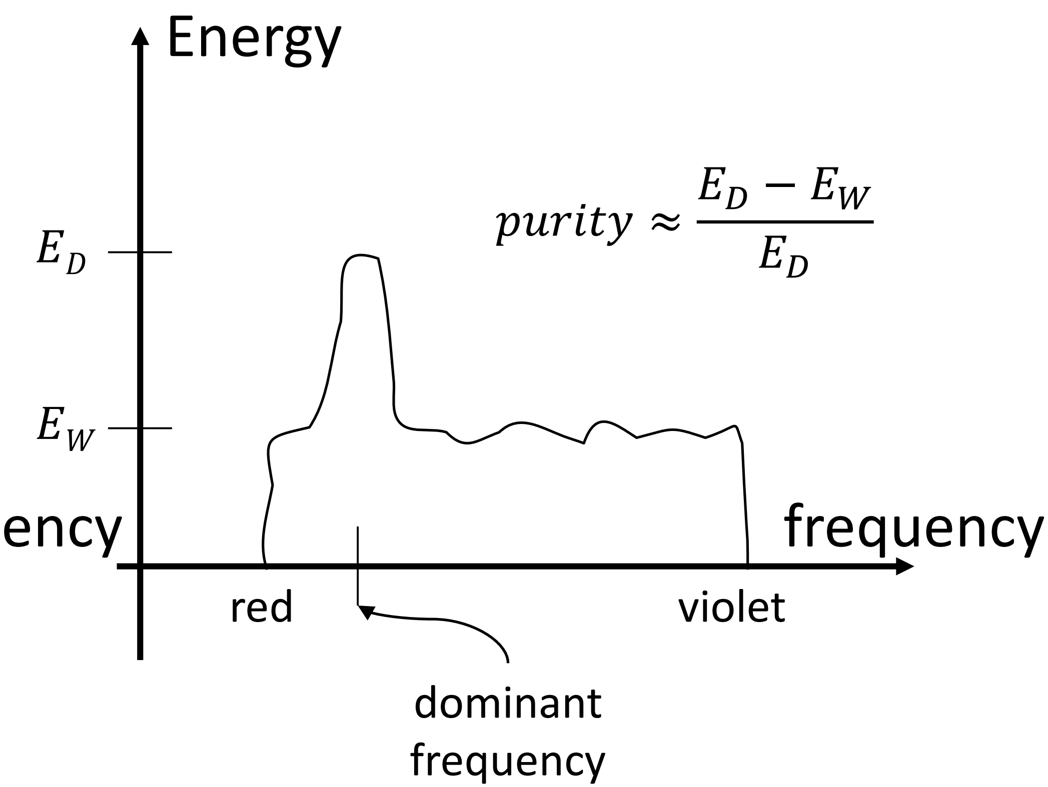
Color perception

- Dominant frequency

white light

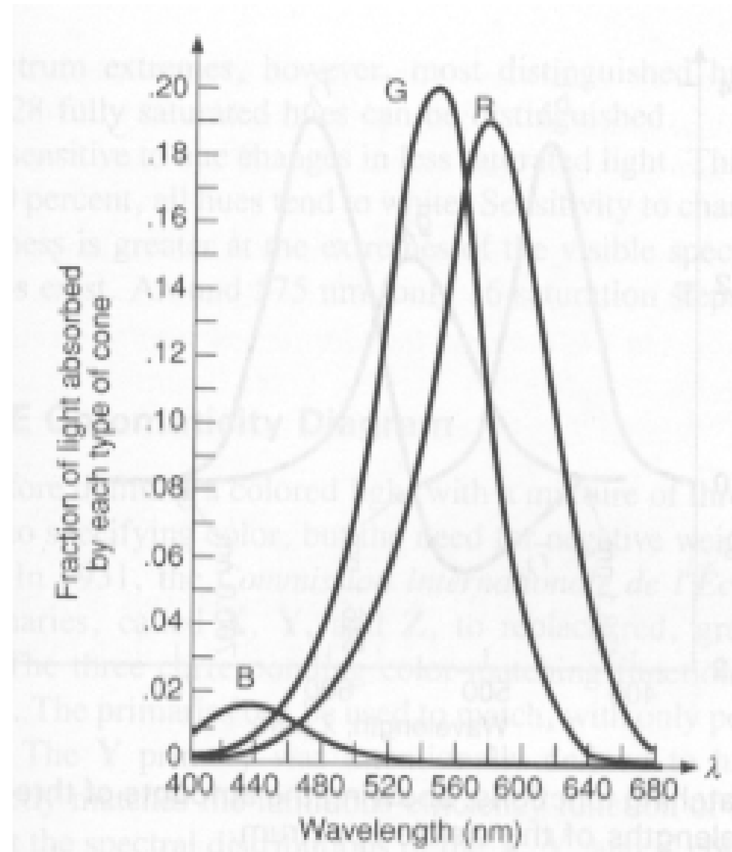


reddish light



Tristimulus Theory:

- the human eye has tiny light-sensitive sensors in the retina: rods and three different cones.
- Rods are sensors that detect brightness and darkness,
- Cones are sensors that detect colors.
- The cones in the human retina have peak sensitivity to red, green, and blue frequencies
- All other colors visible to the human eye can be represented as combinations of these three primary colors.

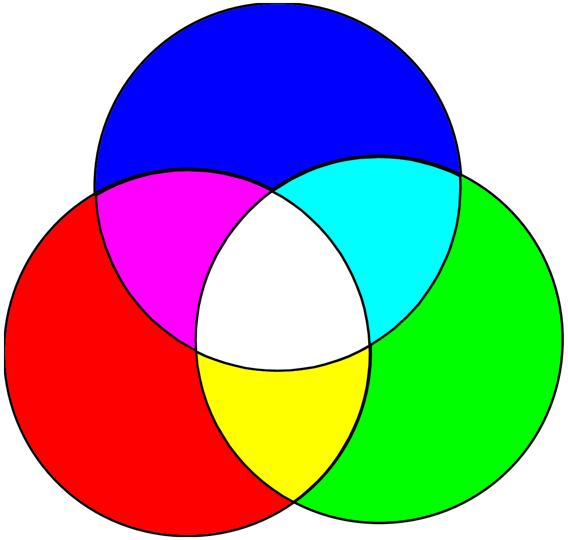


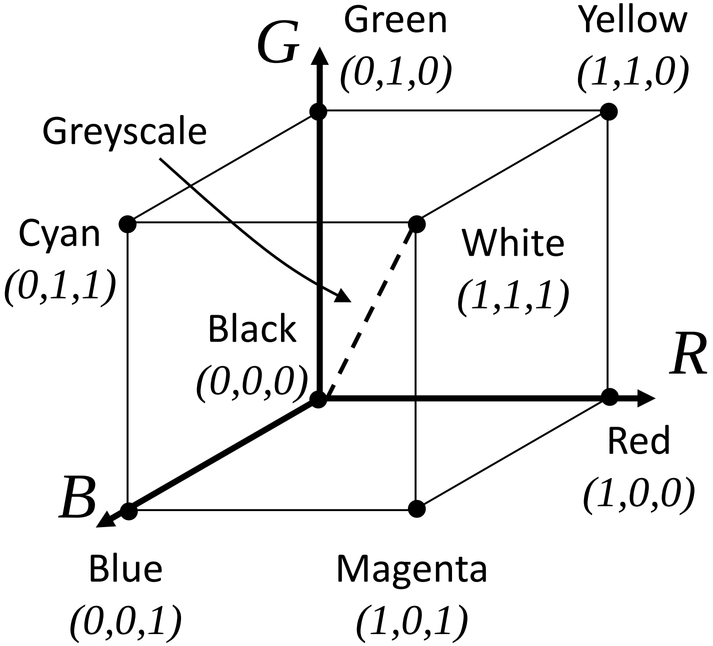
Color perception

- Complementary colors
  - Mixing produces white light.
- Primary colors
  - Base colors of color model (3 colors sufficient)
  - Other colors mixed out of primary colors
  - No finite set can produce all possible visible colors
- Color gamut
  - Set of all colors produced from primary colors

Color models

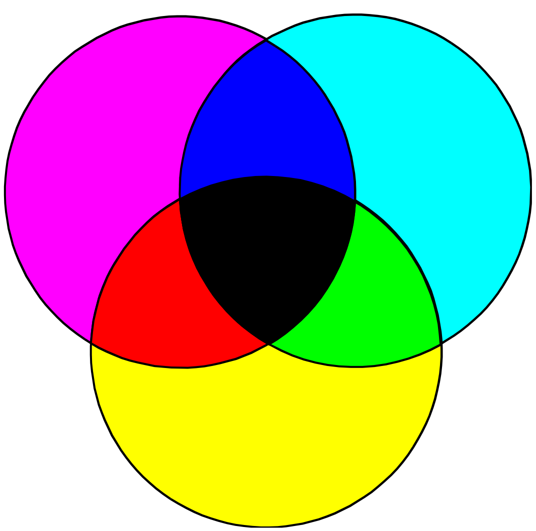
- RGB color model
  - Red, Green and Blue primaries
  - Used (internally) in every monitor
  - **Additive**: adding primitive colors produces white.
  - Black = (0,0,0), White = (1,1,1) (=Red+Green+Blue)

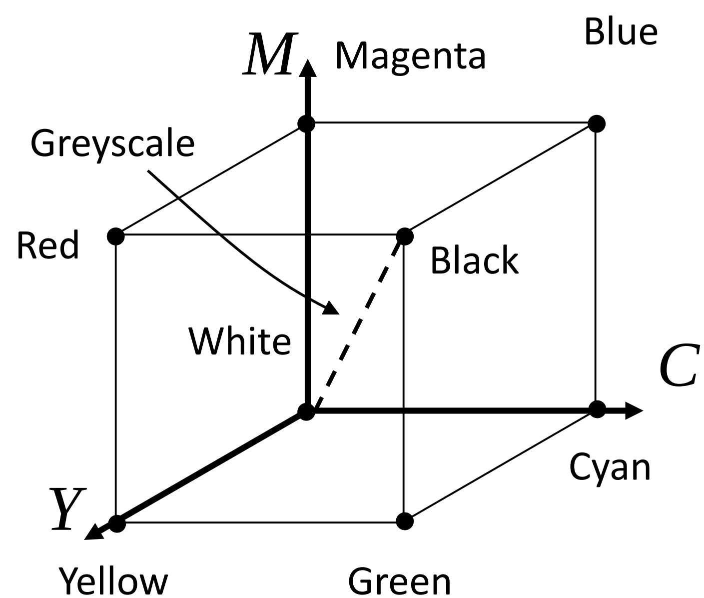




Color models

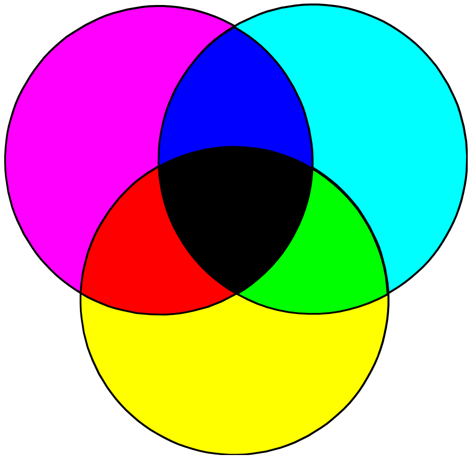
- CMY color model
  - Cyan, Magenta and Yellow primaries
  - Used (internally) in hardcopy devices (printers)
  - **Subtractive** (colors subtracted from white background)
    → Adding primary colors produces black.
  - Black = (1,1,1), White = (0,0,0)
  - Complementary to RGB : C = 1-R, M = 1- G, Y = 1-B





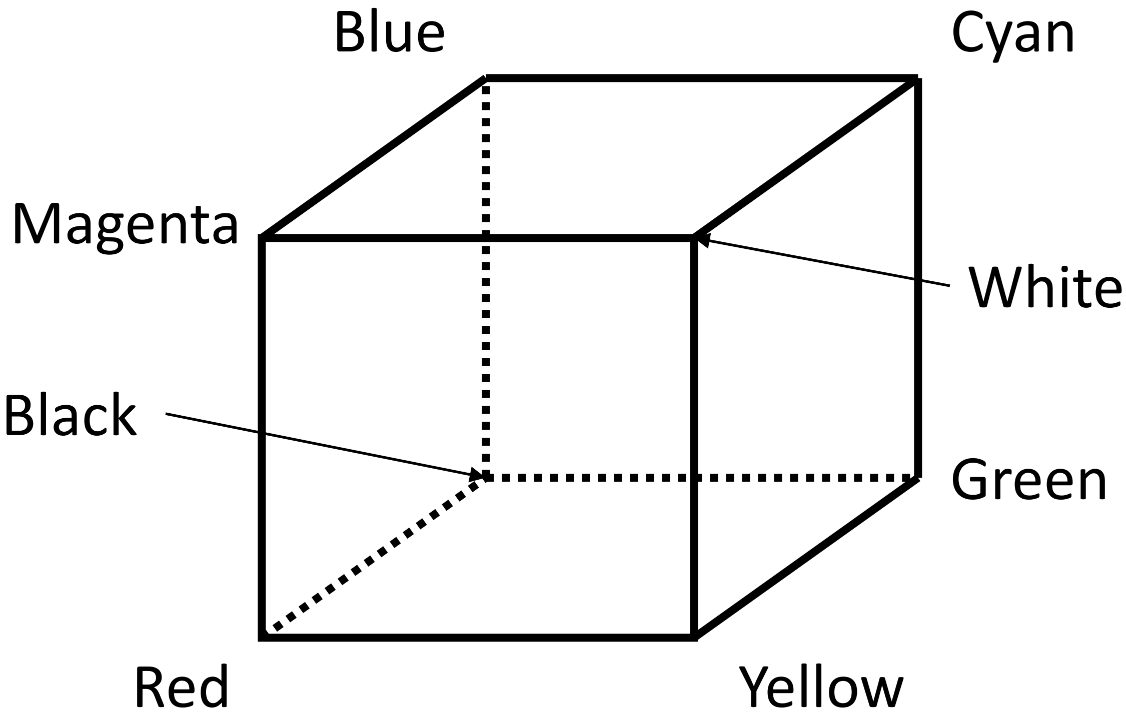
Color models

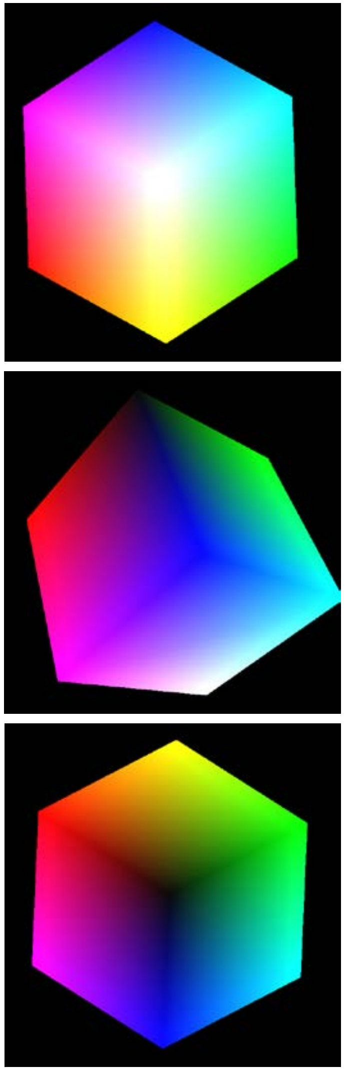
- CMYK color model
  - Modification of CMY-model
  - K for black, additional ‘color’ channel (for saving ink)
  - No unique presentation: e.g. (1,1,1,0) and (0,0,0,1)
  - Standard conversion CMY -> CMYK
    K = min(C,M,Y) , C = C-K ,
    M = M-K , Y = Y-K



Color models

- The RGB/CMY cube



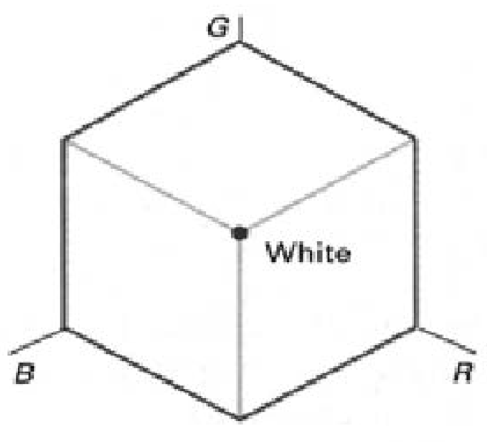


Color models

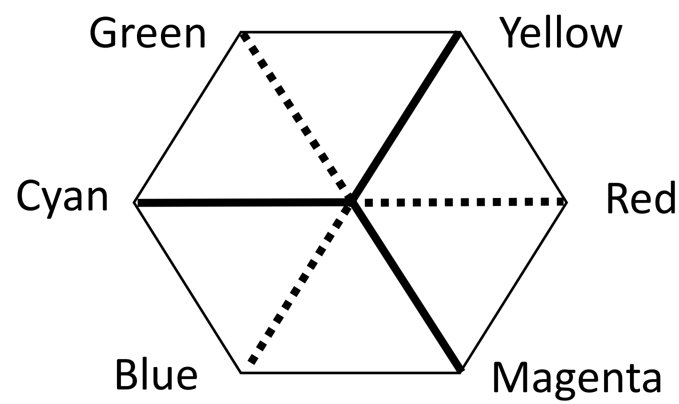
- HSV color model (sometimes HSB or HSL)
  - More intuitive color specification
  - Derived from RGB color model
    - Flatten RGB color cube along the diagonal from white to black
  - Hue, Saturation and Value Primaries
    - User oriented and based on the intuitive appeal of artist’s colors (hue, tint, shade).

Color models

- HSV color model (sometimes HSB or HSL)



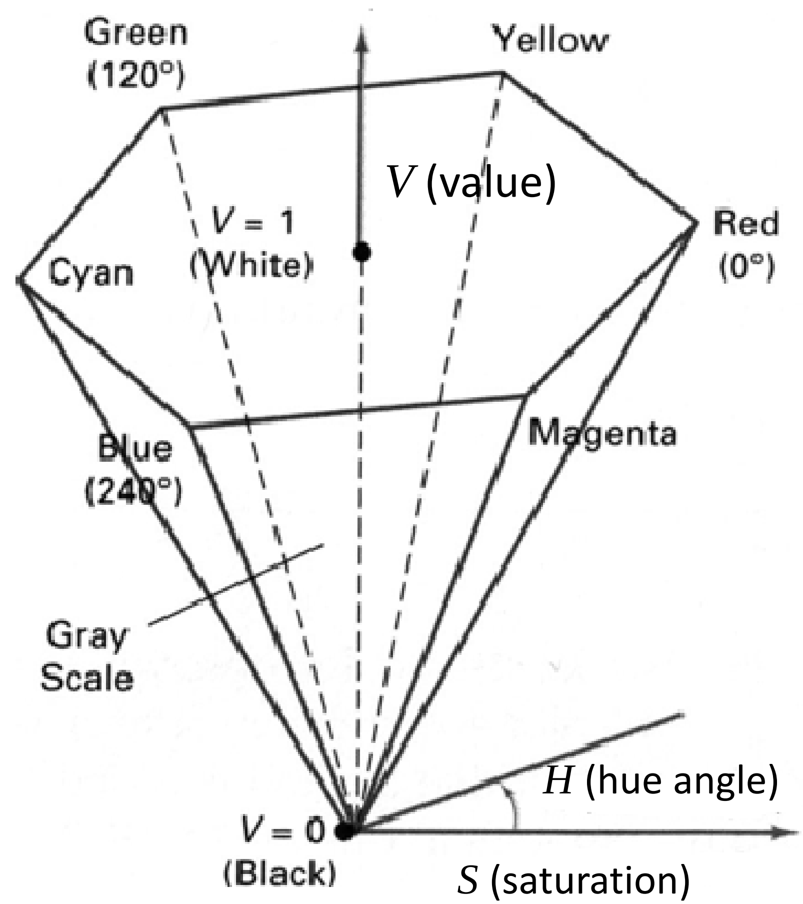
RGB color cube



Color hexagone

Color models

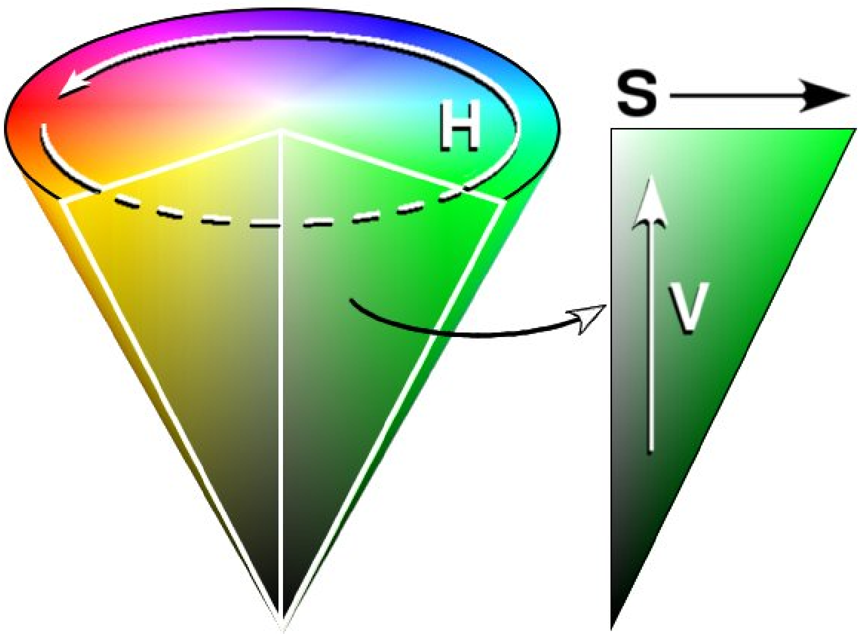
- HSV color model
  - Color components
    - Hue (H) range [0, 360]
    - Saturation (S) range [0, 1]
    - Value (V) range [0, 1]

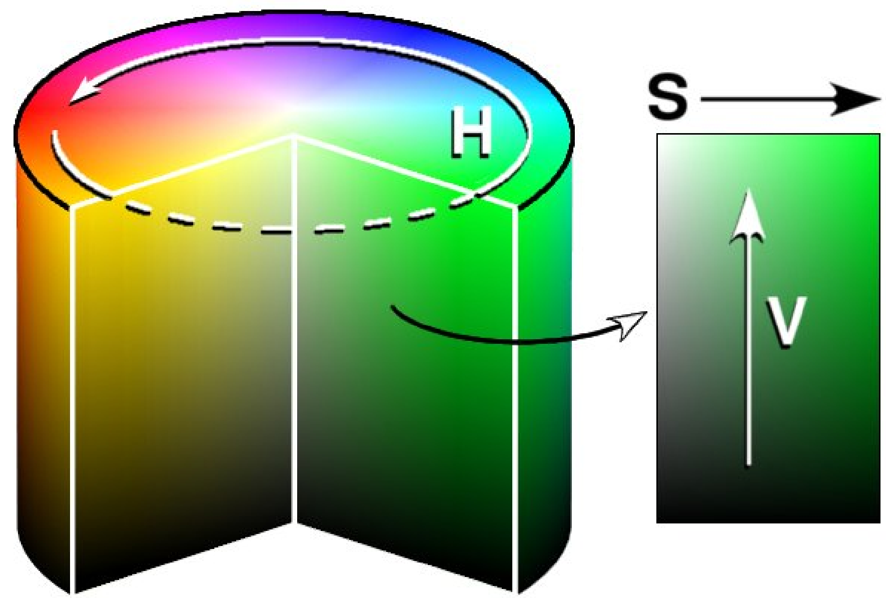


HSV hexcone

Color models

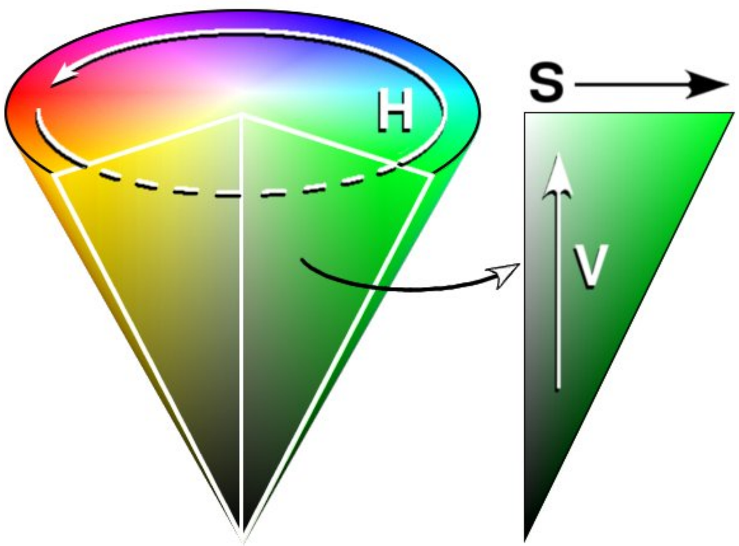
- Geometric model for HSV
  - circular cone or cylinder





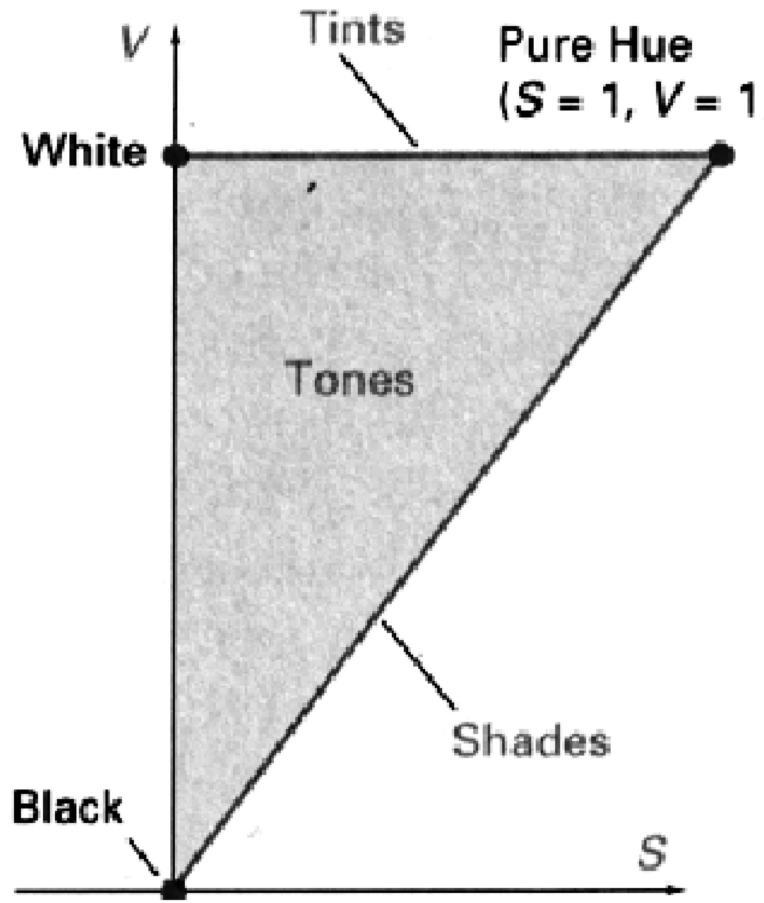
Color models

- RGB → HSV (cone model)
  - $V = \max(R, G, B) = max$
  - $S = \frac{max-min}{max}$
  - $H = \begin{cases} 60\,\frac{G-B}{max-min} & if\ \max\{R,G,B\} = R \\ 60\,\frac{(B-R)}{max-min} + 120 & if\ \max\{R,G,B\} = G \\ 60\,\frac{R-G}{max-min} + 240 & if\ \max\{R,G,B\} = B \end{cases}$



Color models

- HSV color definition
  - Select hue, S=1, V=1
  - Add black pigments i.e. decrease V
  - Add white pigments i.e. decrease S
    - Cross section of the HSV hexcone showing regions for shades, tints, and tones



Color models

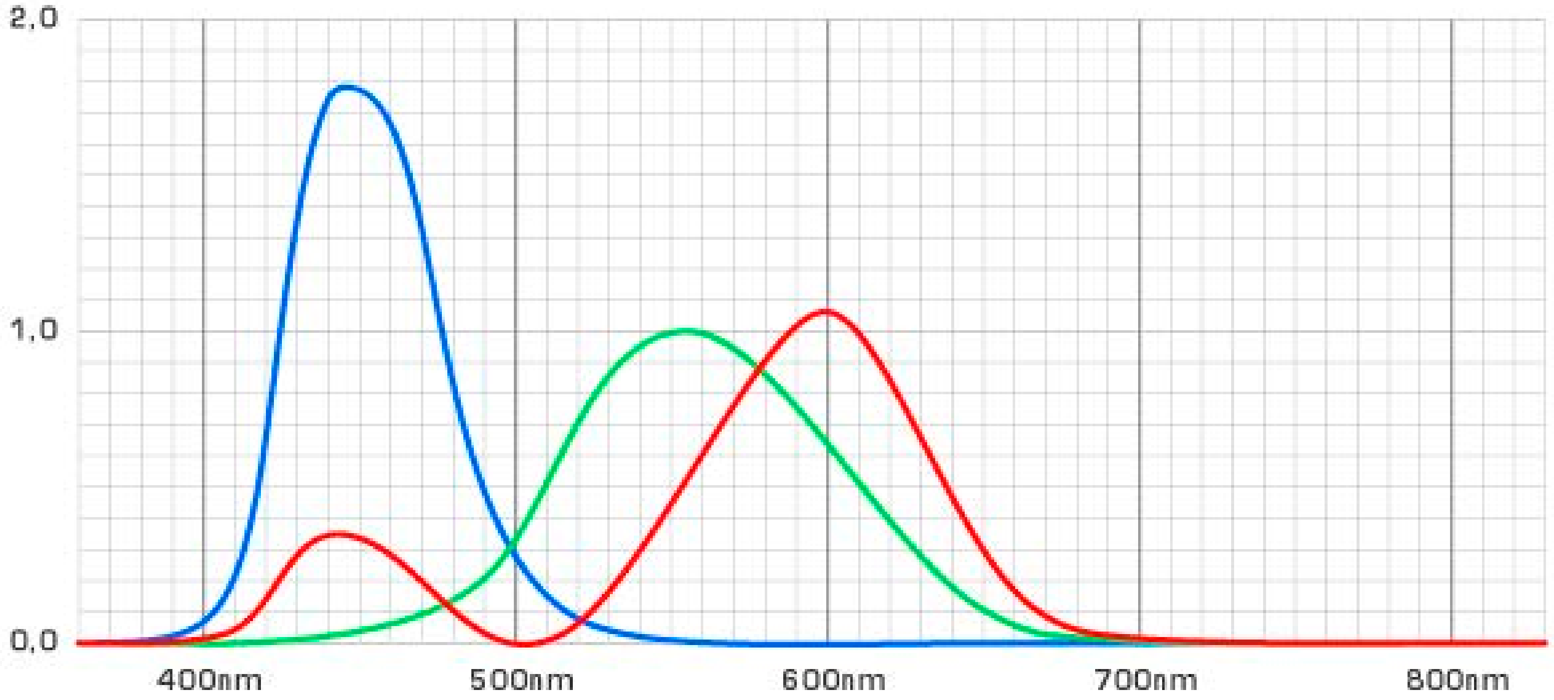
- All models mentioned so far, i.e. RGB, CMY, CMYK, HSV, are device dependent
- Universal model : CIE-XYZ
  CIE = Commission Internationale de l'Eclairage
- Absolute model - not device dependent
- Used for calibration and data exchange
- Based on tristimulus theory

Color models

- Universal model : CIE-XYZ
  - Measuring its spectral power distribution at each wavelength
  - Multiply by universal three color matching functions (defined 1940 by CIE)
  - Integrate to get the three values X, Y, Z
  - Normalize the tristimulus values $x = X/(X + Y + Z), y = \cdots$
  - x and y are the chromaticity coordinates.
  - Y is the brightness and $x + y + z = 1$.

Color models

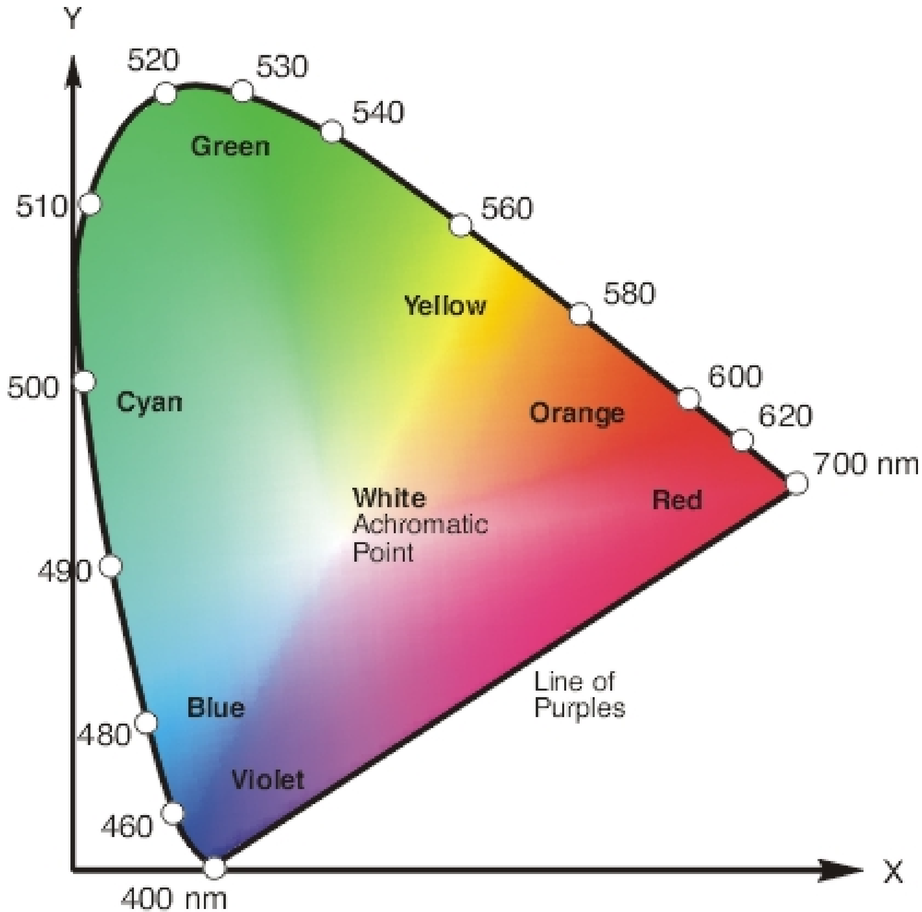
CIE normalized sensitivity curves for the three colors x(red), y(green)
And z(blue). Tristimulus curves.

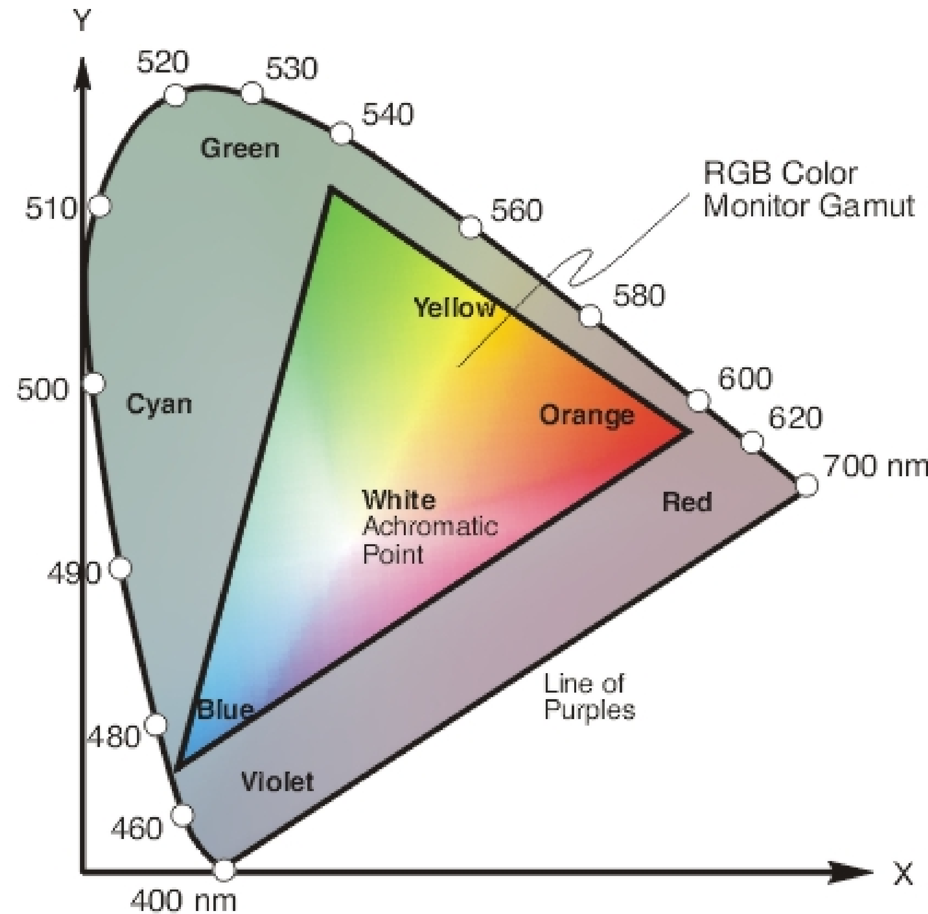


http://de.wikipedia.org/wiki/CIE-Normvalenzsystem

Color models

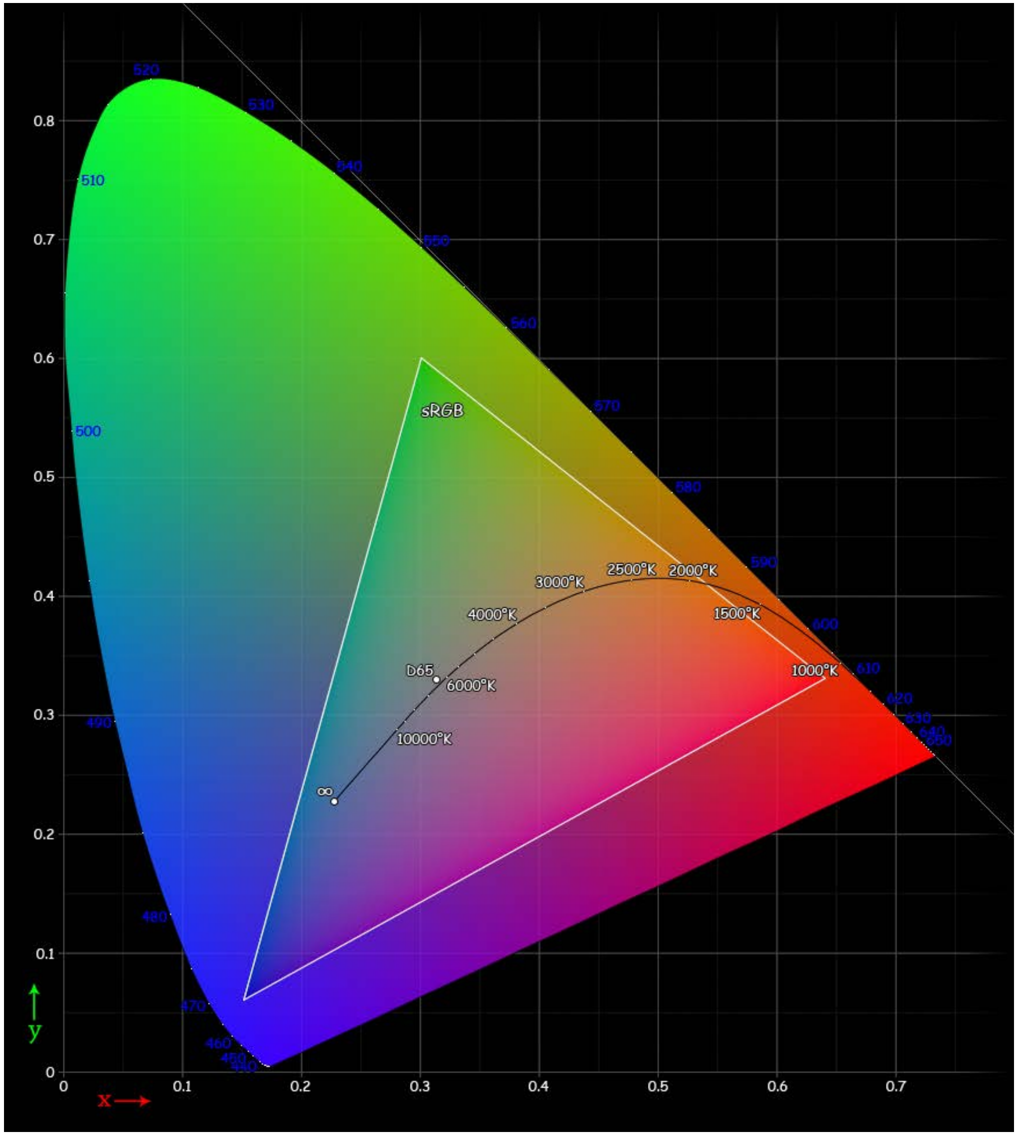
- CIE-XYZ color model





Color Models

CIE XYZ compared to sRGB.



http://upload.wikimedia.org/wikipedia/commons/6/60/Cie_Chart_with_sRGB_gamut_by_spigget.png

Color Models

- Remark:
  - The CIE system was created in 1931.
  - The accuracy of the measurements at that time and the experimental protocols used for the standard curves are not conform to the experimental accuracy today.

Color Models

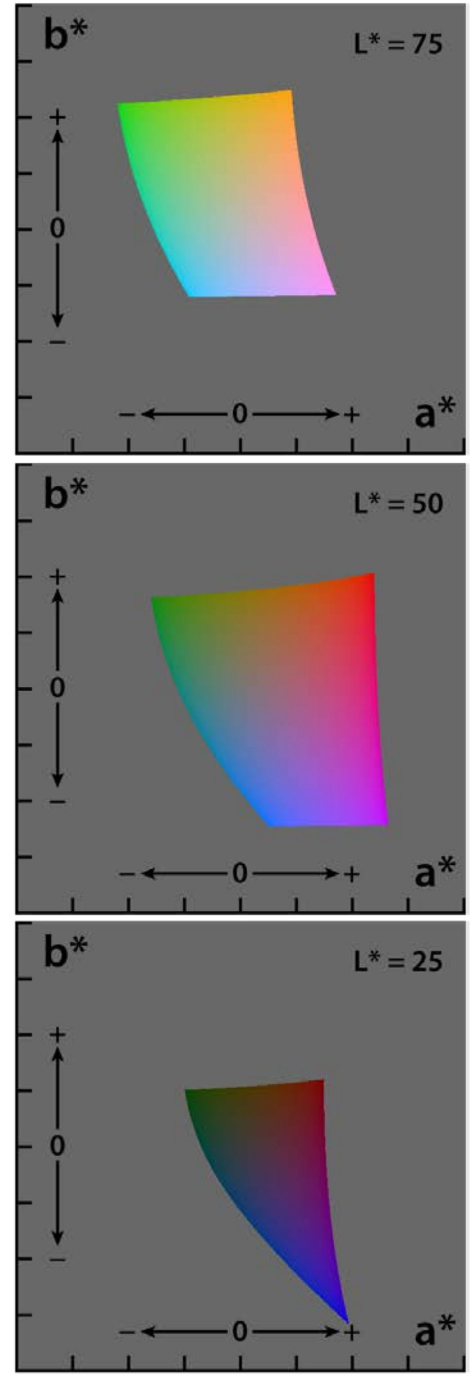
- sRGB = well-defined „standard“ RGB model
- Conversion sRGB -> XYZ
  - $X = 0{,}4124564\ R + 0{,}3575761\ G + 0{,}1804375\ B$
  - $Y = 0{,}2126729\ R + 0{,}7151522\ G + 0{,}0721750\ B$
  - $Z = 0{,}0193339\ R + 0{,}1191920\ G + 0{,}9503041\ B$

Color Models

- RGB, XYZ and CMY do not allow us to measure **perceived color distance**
- Alternative CIELAB or L*a*b*
  - $L^* = 116 \cdot \sqrt[3]{\frac{Y}{Y_n}} - 16$ perceived brightness
  - $a^* = 500\left(\sqrt[3]{\frac{X}{X_n}} - \sqrt[3]{\frac{Y}{Y_n}}\right)$ green-red
  - $b^* = 200\left(\sqrt[3]{\frac{Y}{Y_N}} - \sqrt[3]{\frac{Z}{Z_N}}\right)$ yellow-blue

  (formulae from Wikipedia)

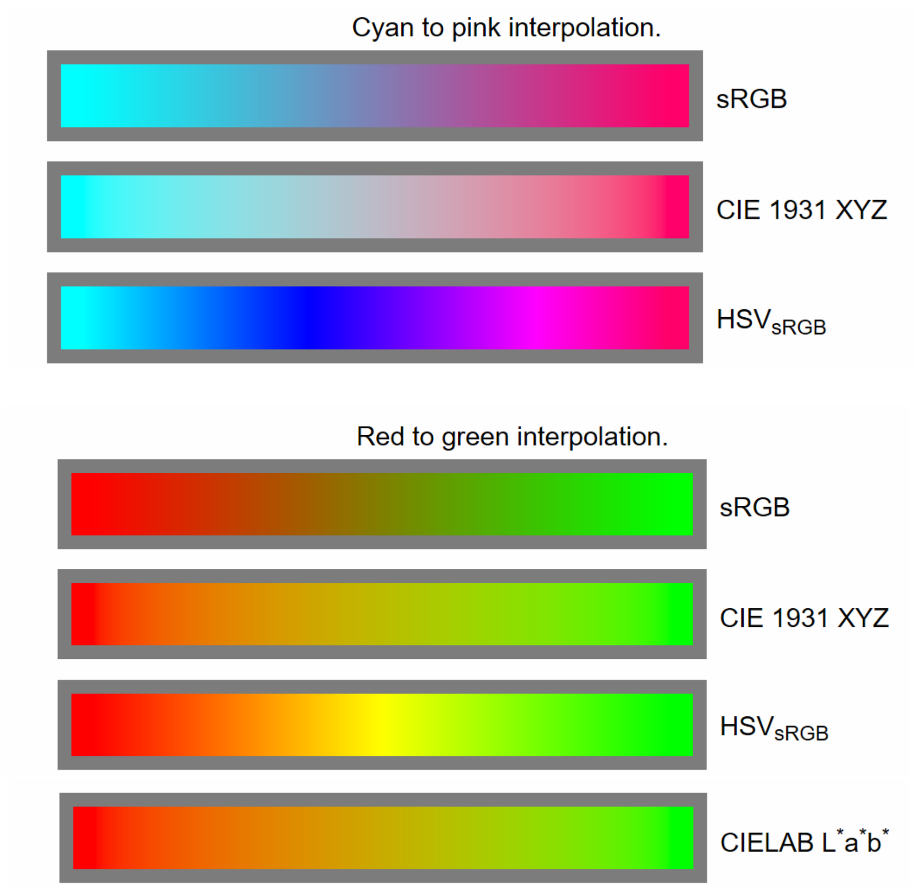
- Euclidean Distance in L*a*b*-coordinates proportional to perceived color difference



Color Models

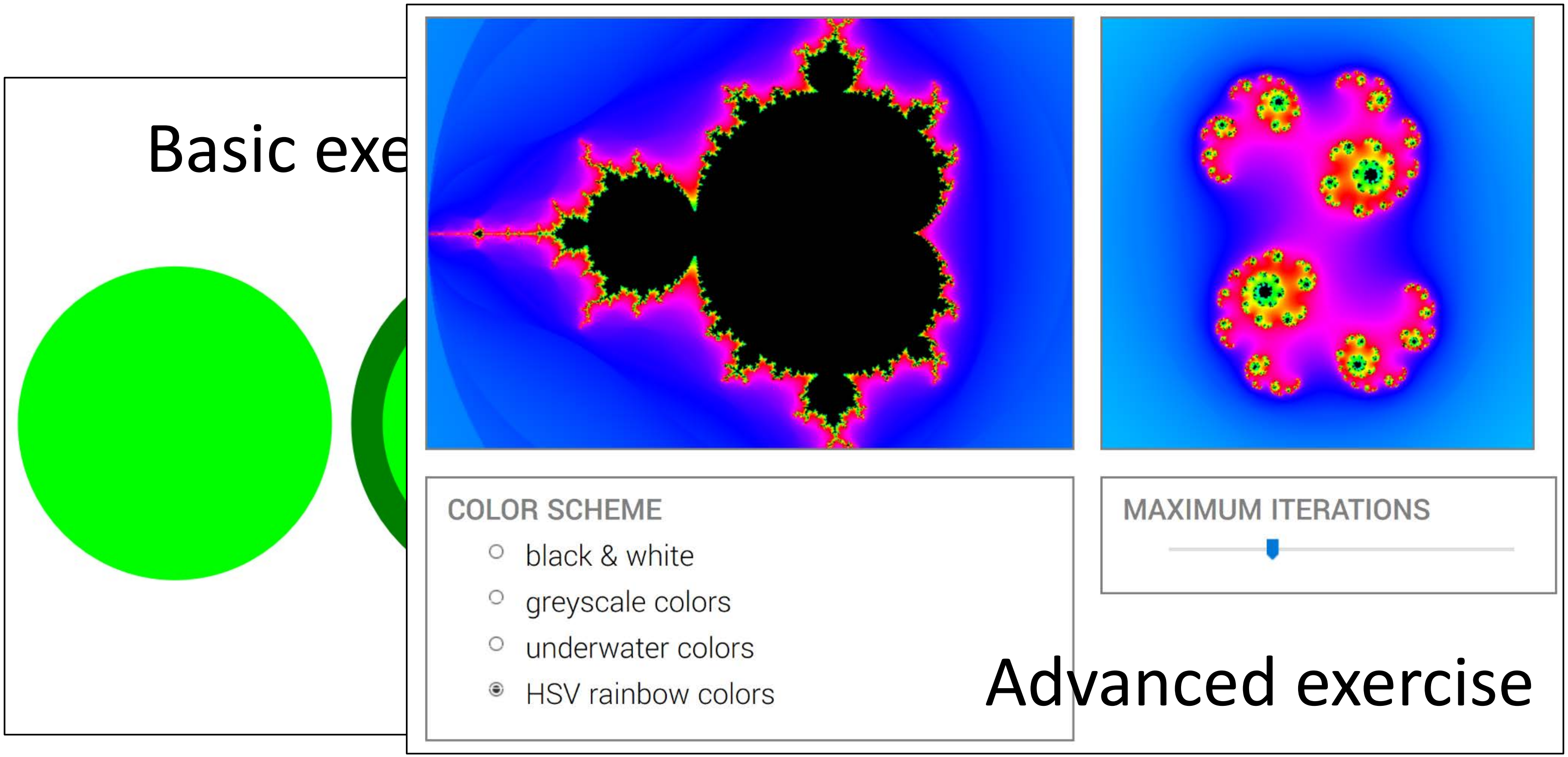
- Color Interpolation:
  Interpolation in different color spaces generates different results
- Half way between
  red and blue is

  → in RGB: 50% magenta
  → in HSV: 100% magenta



howaboutanorange.com

Current Exercise Sheet



Next Lecture

- #03: Rasterization of lines and polygons