DCGI

KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

APG – Color

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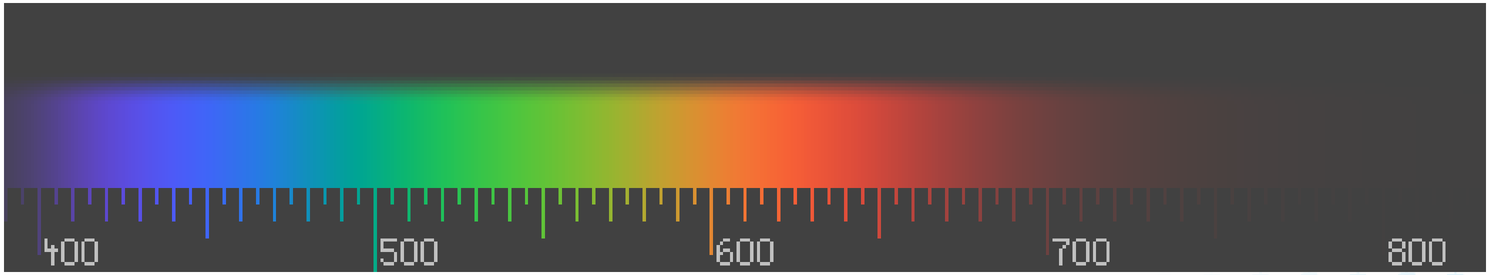
Contents

- 1) Principles of color perception, colorimetry
  - Light, color, perception
  - Colorimetry, comparison of colors
- 2) Color models in technical applications
  - RGB, CMY(K), HSV, HLS, YUV, YC_bC_r
  - CIE L*a*b, CIE Luv

Visible light

- EM (electro-magnetic) radiation cca 380nm – 720nm
- Retina (human eye) is sensitive to



- Light is a *physical phenomenon*
- Physics can describe light properties and behavior [Physics <= ☺ => Computer Graphics]

Color

- Perception (individual)
- No (direct) relation with physics
- Color description relates to psychology

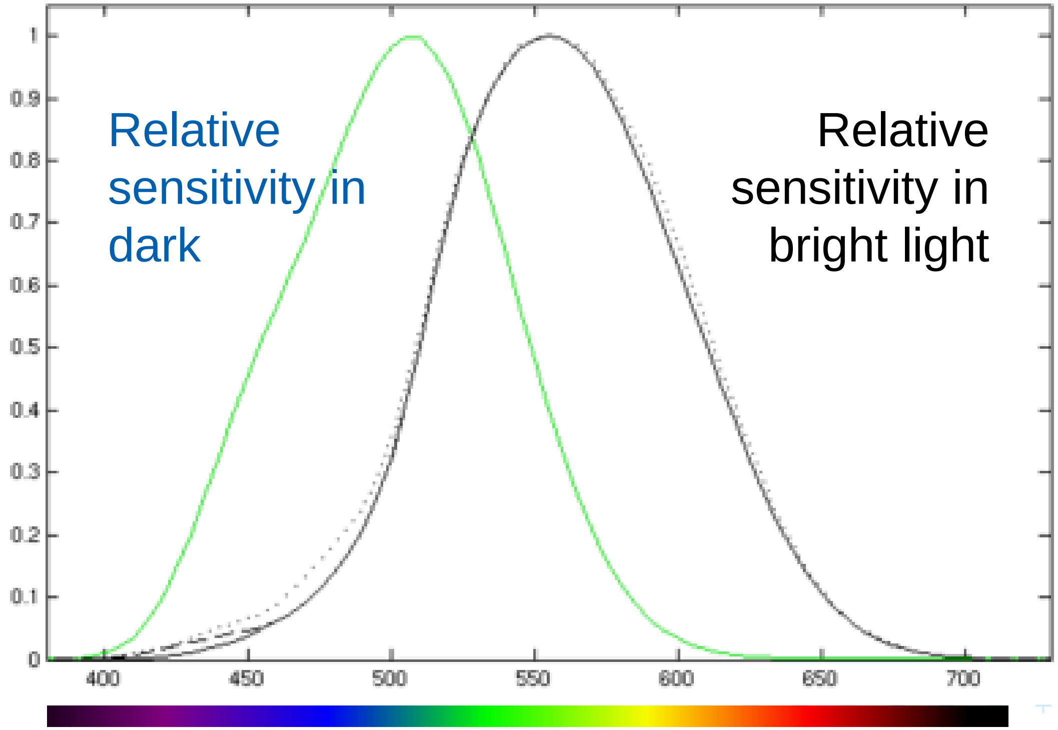
- *What is “dark blue”? “army green”? “rosy”?*

Human Eye

- Light passes through lens and falls to **retina** (array of photoreceptor **cells**):
  - Cone cells [*čípky*]
    - 3 kinds responsive to three different wavelengths - L / M / S (long / medium / short wavelength) – approx. Red/ Green / Blue
    - Essential for **color perception**
    - Bright light is required
  - Rod cells [*tyčinky*]
    - Activated in low intensity of light – *scotopic* (night) vision
    - Saturated during the day light (*photopic* intensity) – no signal produced
    - 1 kind only – monochrome, black & white vison => impossible to distinguish colors in dark

Luminance curve

- How we perceive intensity according to wavelength



- *Purkyně shift*:
  - Change in the brightness of red and blue colors as light intensity decreases
  - Example: Red paper looks brighter than the blue one during the day, while reversely in the dark.

Jan Evangelista Purkyně

* 1787, Libochovice

† 1869, Praha

- Medicine, poetry, philosophy, …
- Idea: „*Cell is the most important entity for a life*“ [1837, Prague]

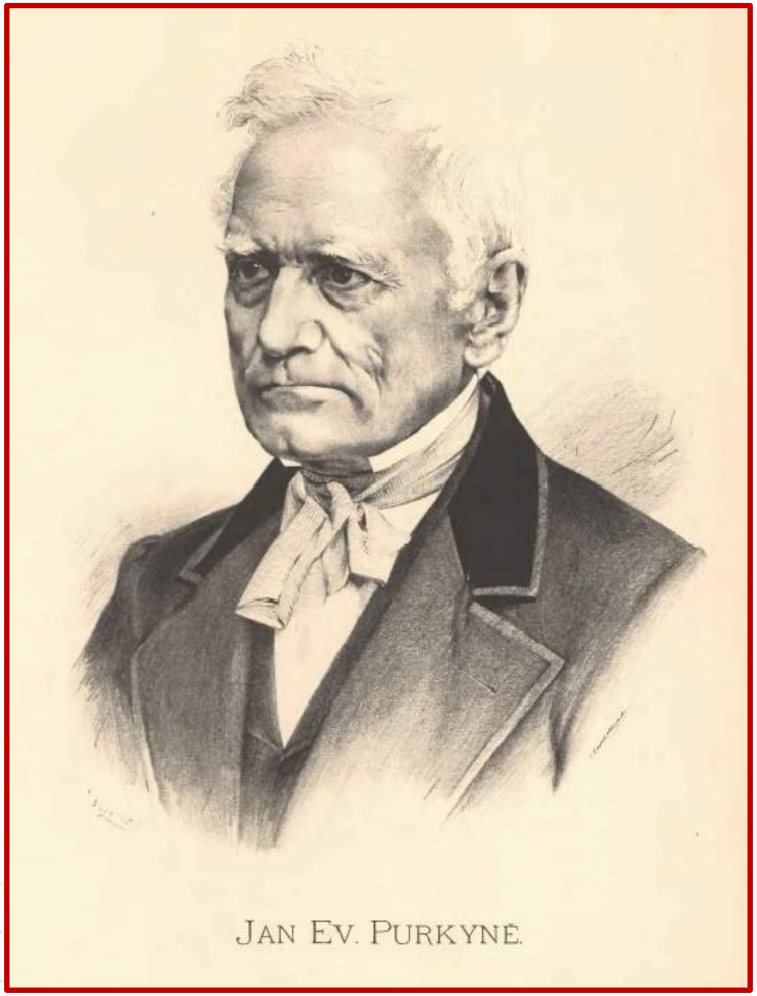


Image source: Wikipedia

What influences the color perception?

- A. Light Source
  - ***Spectral radiance***, ***L*(λ)**: quantity of (emitted) radiation of specific wavelength λ within a given angle in a given direction. [W sr^{-1} m^{-2} Hz^{-1}] [W sr^{-1} m^{-2} nm^{-1}] [*záře*]
    - **Radiance**: total emission (non-spectral), [W sr^{-1} m^{-2}]
  - Influences human eye adaptation
    - People tend to consider light as white, even if it is not
- B. Material properties of lighted object(s)
- C. Perceptual processes in an eye and a brain

What influences the color perception?

- A. Light source
- B. Material properties of lighted object(s)
  - Spectral reflectivity, reflectance $\rho(\lambda)$ [*odrazivost*]

$$\boldsymbol{L_{\text{reflected}}(\lambda) = L_{\text{incoming}}(\lambda)\, \rho(\lambda)}$$

- C. Perceptual processes in an eye and a brain
  - Radiance $L(\lambda)$ falling in the eye (i.e. function of wavelengths) is „decoded“ by brain as something like:
    - **Hue** – dominant color [*odstín*]
    - **Saturation** – how far is the color from gray of equal intensity [*sytost*]
    - **Lightness** – perceived intensity of reflecting object [*jas*]

Note: **Brightness** – when object is emitter

Colorimetry

- Studies human perception of colors – how spectral radiance is interpreted by humans
- (Historical) questions:
  a) Are 2 different spectral radiances perceived as 2 colors?
     - No! Human eye is not a perfect spectrophotometer.

  b) Under which conditions 2 spectral radiances are perceived as the same color?
  c) Is it possible to find „clear“, basic colors (**primaries**) and make all visible colors by mixing these primaries?
  d) If yes, how to define the intensities of primaries for a given spectral radiance, which make the same color perception?

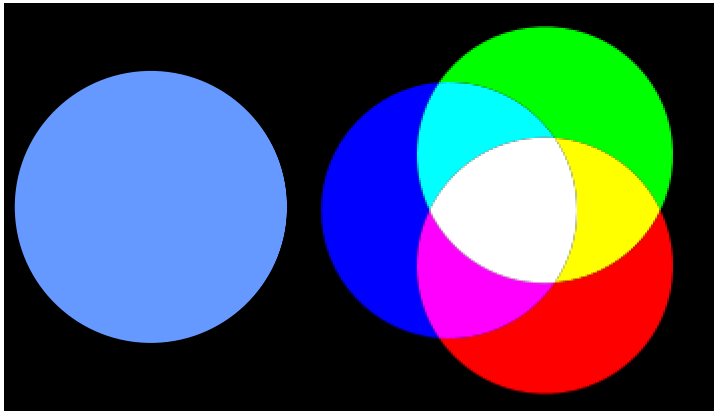
Colorimetry

- The key is the characteristics of cones in retina:
  - What are responses of S, M, L cones for a given radiance?
- Answers to previous questions:
  - Ad b)
    - If responses of S, M, L cones to different spectral radiances are equal then the same color is perceived.
  - Ad c) + d)
    - **GOOD NEWS**: Since we have 3 types of cones, human perception is 3-dimensional (only!), thus we can use/mix 3 primaries to define all visible colors.
    - **BAD NEWS**: Those primaries need to have also negative coefficients/intensities! (physically impossible)

Color matching experiment

- Colorimetry tool used in the 19th and 20th century:

Left:
Real color projected from projector



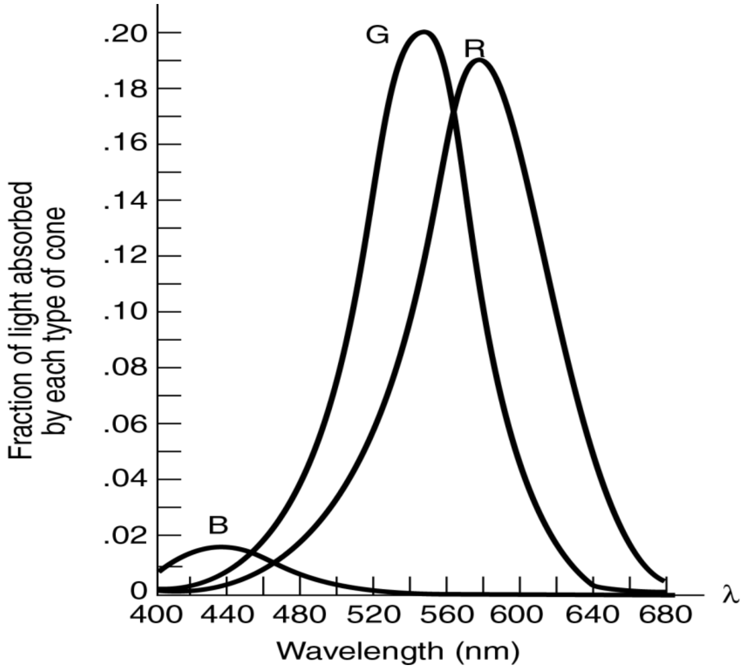
Right:
Three primaries (monochromatic colors) projected and overlaid (additive composition)

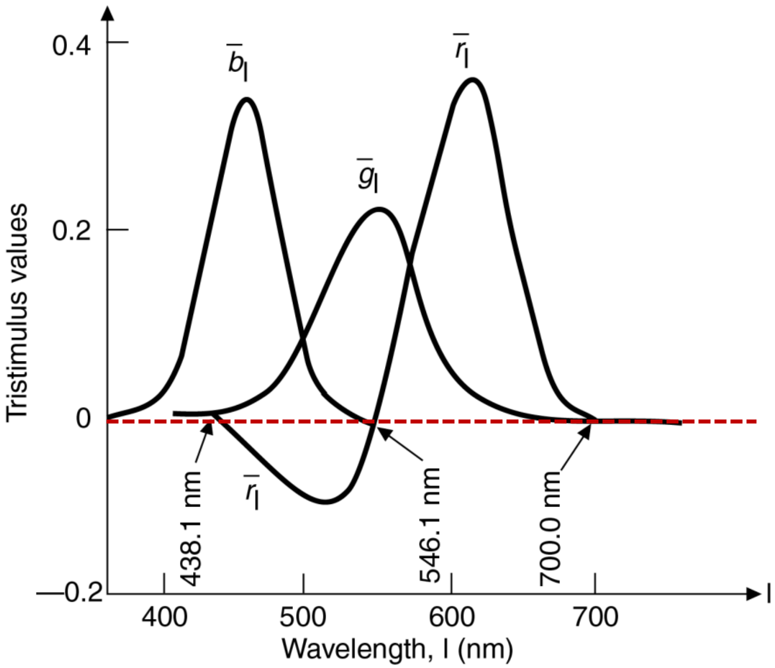
- Task for a human: Set the intensities of primaries on the right to reach the came color as on the left.
- Solve the “visual equation”: $c_{real} = c_R + c_G + c_B$

Color matching experiment results

- Two primaries are not enough (as expected…)
- Three primaries are enough, but in same cases the mixed color has a lower saturation than the real color on the right:
  - If red primary is added to **left** color, the same perception is reached.
  - Instead of **adding** red to the left, we could **subtract** red from the **right** => mathematically we add red with negative intensity (negative coefficient $\mathbf{c_R}$) to the right.
  - This stands for all possible three primaries ☹.

Cones and Primaries





- Cone responses
- Required tri-stimulus values

Images from [Foley, van Dam,1990]

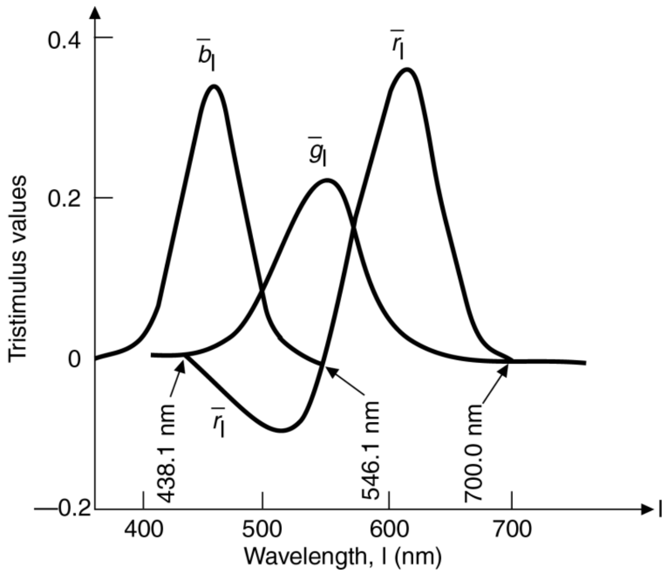
Conclusions

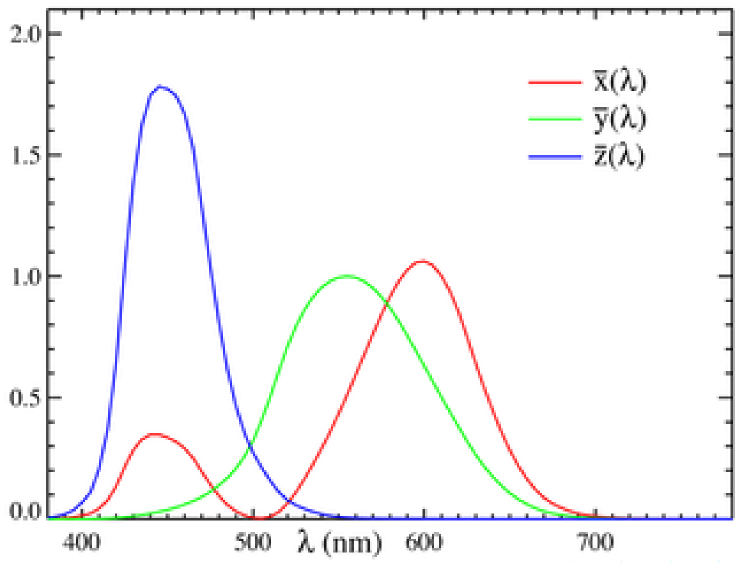
- No triple of primaries (with positive coeffs.) can be found to make **all** visible colors.
- Each triple of primaries defines limited range/amount **(gamut)** of colors.
- Theoretically, having negative coeffs., it would be possible to make **all** colors from only three primaries.

CIE XYZ Color Model

- CIE: **C**ommission **I**nternationale de l'**E**clairage (1931)
  - Defines international standards
- Disadvantage of RGB primaries
  - Composition with positive coeffs. does not make all colors
- Artificial color space CIE XYZ
  - Newly designed X, Y, Z color primaries (non-real)
  - All X, Y, Z functions positive
  - The idea: Make all colors by composing X, Y, Z only

CIE XYZ Color Model





- Theoretical RGB primaries
- XYZ primaries

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

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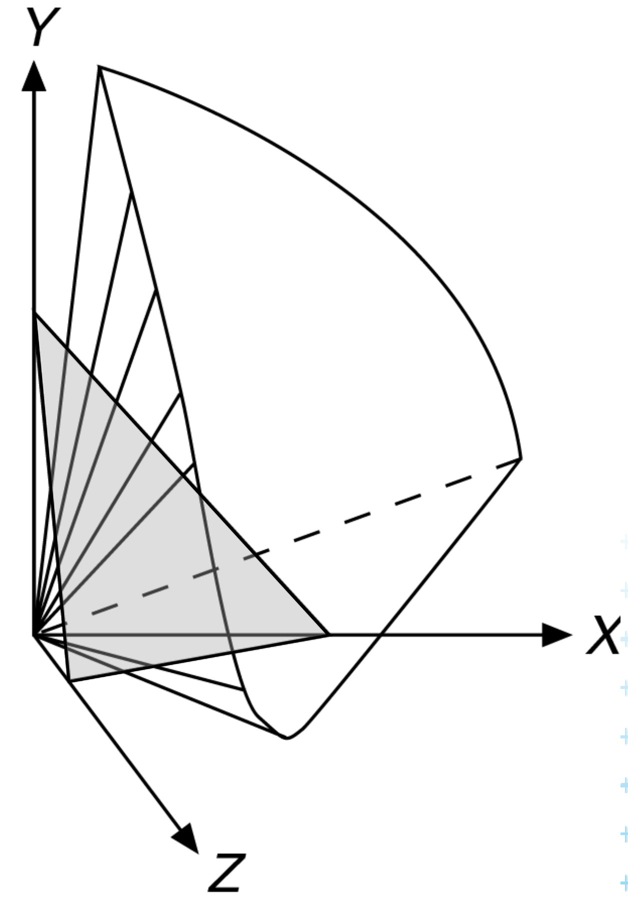
CIE XYZ Color Model

- Cone of visible colors in CIE XYZ space
- X+Y+Z=1 plane is shown:
  - Constant luminance
  - Only depends on dominant wavelength and saturation

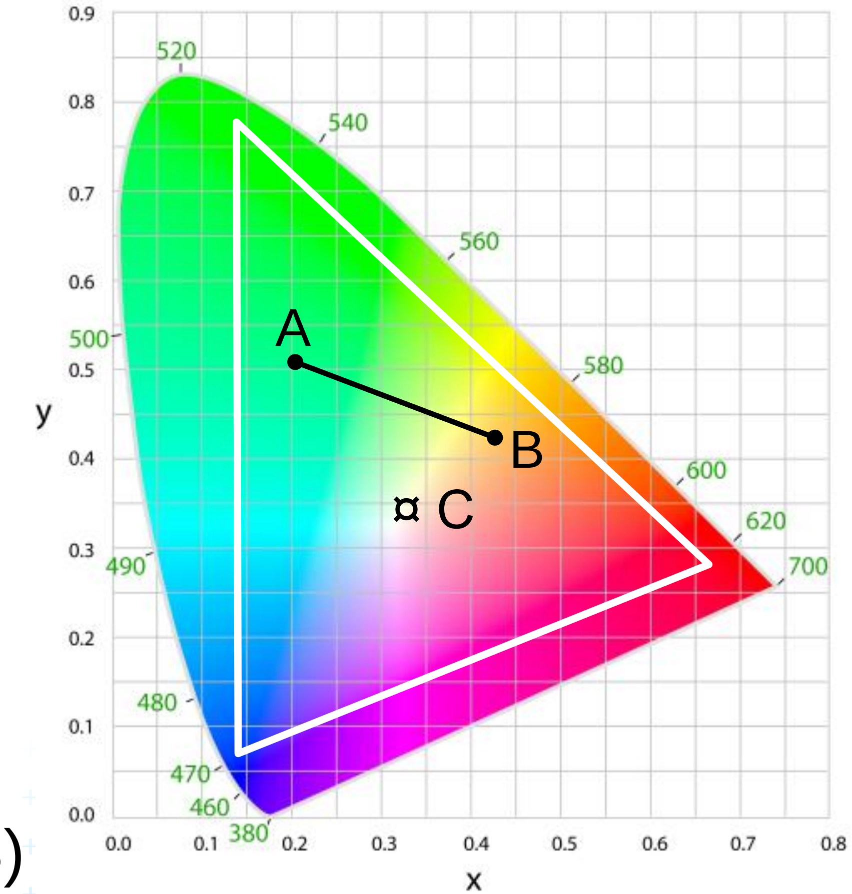


CIE Chromaticity Diagram

- Colors on X+Y+Z=1 plane
- Normalization => 2D space:

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

- Colors on the right are symbolical only:
  - No chance to show them all on RGB devices.
  - C … white (grey)
  - Triangle = gamut
  - Linear combination (gamut, AB)
  - Outline = discrete spectral colors



[http://www.rp-photonics.com/rgb_sources.html]

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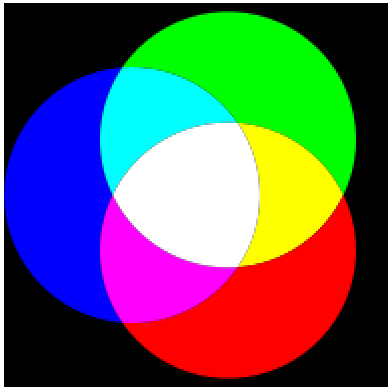
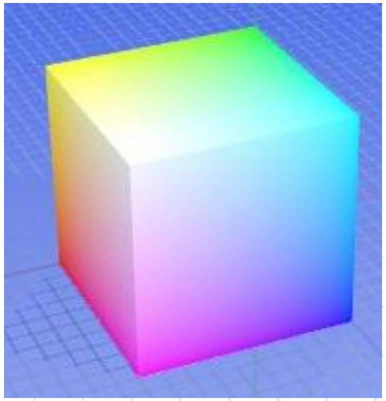
RGB = Red Green Blue

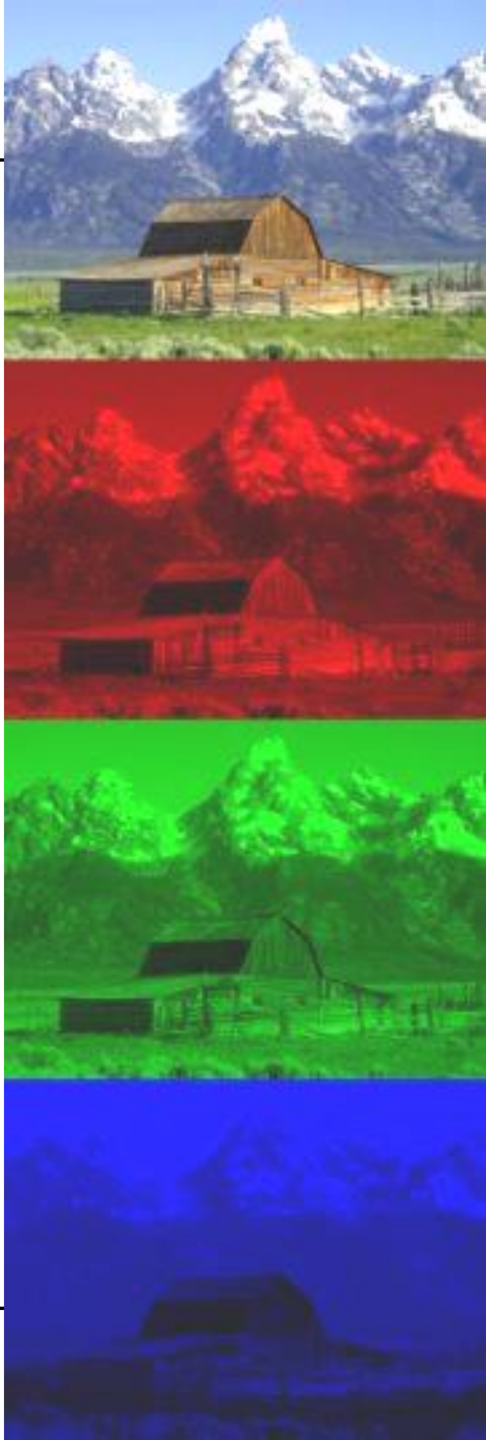
- For TVs, monitors, projectors
- Additive color composition
  - Corresponds to adding light (e.g. emitted by LED)
  - [0,0,0] = black
  - [1,1,1] = white



- RGB cube
  - Visualization of RGB space

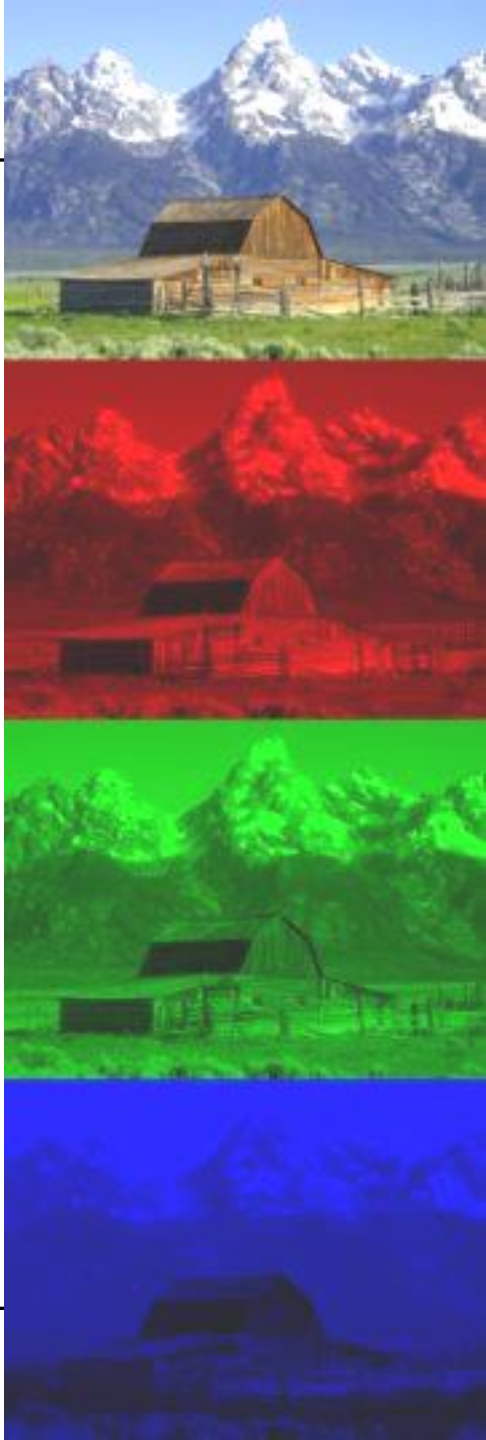


- Luminance of RGB color:
  - 0.299 r + 0.587 g + 0.114 b
  - Various formulas in various apps



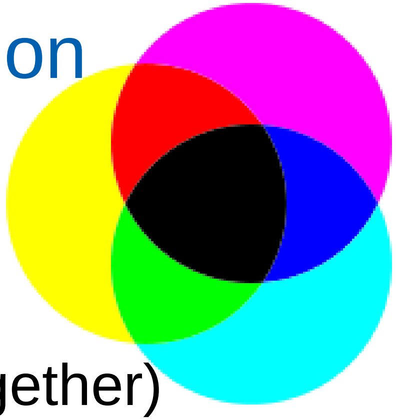
RGB = Red Green Blue

- Many different RGB spaces:
  - Standards
    - CIE RGB 1931
    - sRGB (for web)
  - Every output device has its „own“ RGB space
  - RGB image without calibration information is useless (in professional applications).



CMY = Cyan Magenta Yellow

- For printing devices
- Subtractive color composition
  - Corresponds to mixing color pigments in paintings
  - [0,0,0] = white (paper color)
  - [1,1,1] = black (all pigments together)



- Conversion RGB => CMY

$$[C, M, Y] = [1 - R, 1 - G, 1 - B]$$

CMYK = CMY + blacK

- Low quality of black when mixed from several color pigments
  - Add black pigment among primary colors
  - Save other pigments
- Conversion CMY => CMYK

$$K = \min\{C', M', Y'\}$$

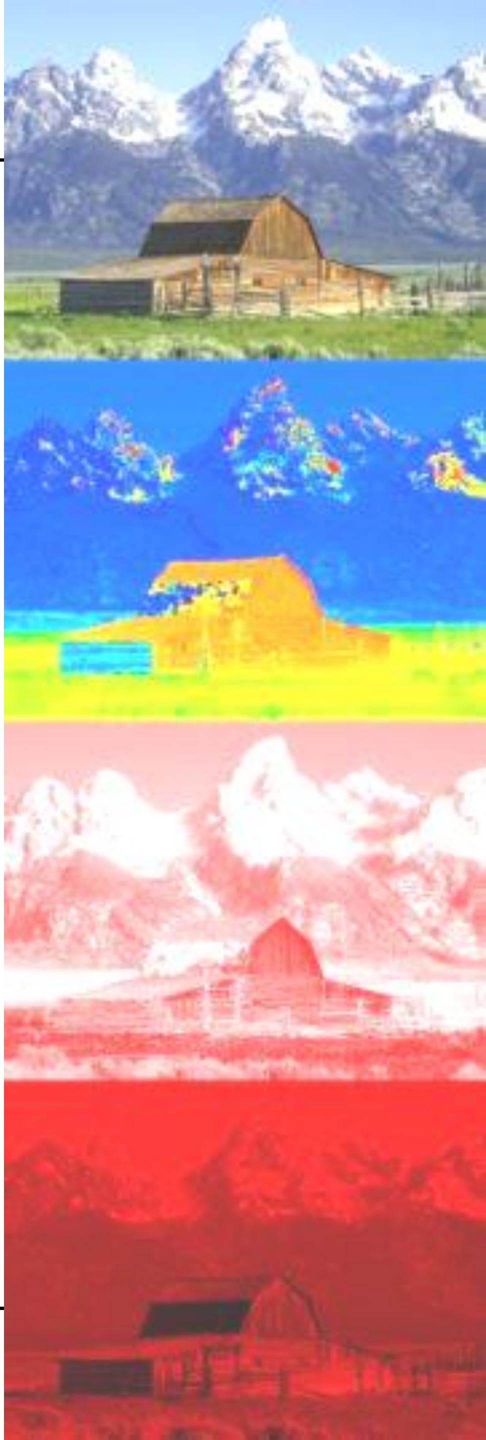
$$t_{CMYK} = \left\{ \frac{C' - K}{1 - K}, \frac{M' - K}{1 - K}, \frac{Y' - K}{1 - K}, K \right\}$$

CMYK

CMY

HSV = Hue Saturation Value

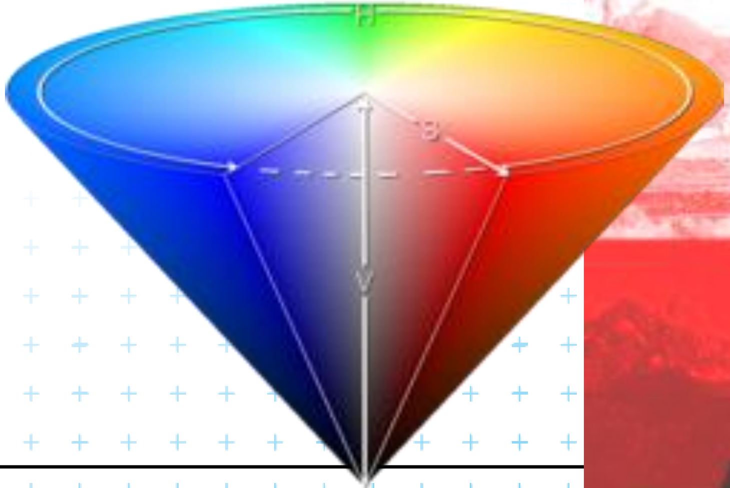
- Human-Computer interface for color selection
- Corresponds to human perception terms:
  - H (Hue)
  - S (Saturation)
  - V (Value)

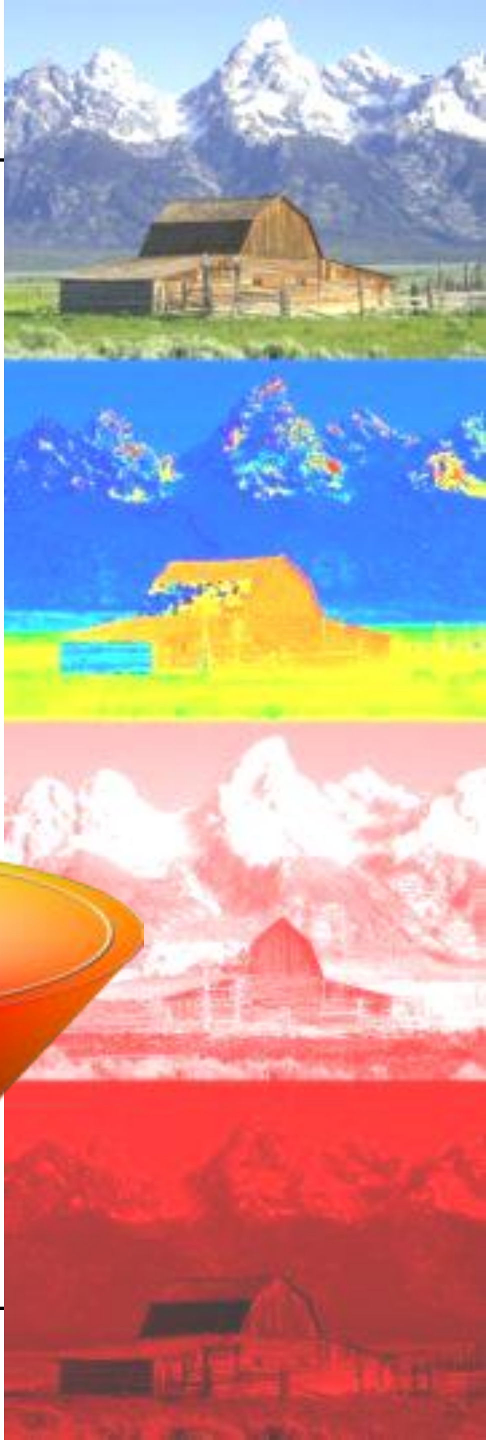


HSV = Hue Saturation Value

- H … angle
  - Color tones order:
    R Y G C B M

- S … distance from central axis
  - Saturated colors on a surface
  - Grey(s) in axis (where H is undefined!)
- V … distance from the cone top
  - Top – black
  - Base – the highest lightness





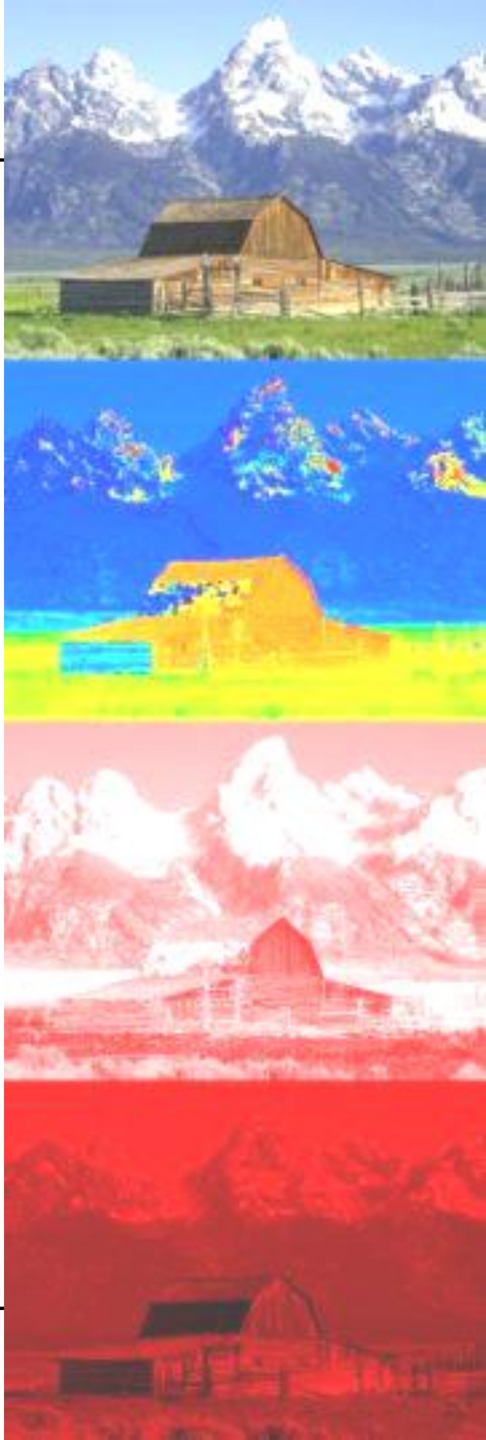
HSV: Conversion

- RGB => HSV

$$H = \begin{cases} undefined, & if\ MAX = MIN \\ 60 \times \frac{G-B}{MAX-MIN} + 0, & if\ MAX = R\ and\ G \geq B \\ 60 \times \frac{G-B}{MAX-MIN} + 360, & if\ MAX = R\ and\ G < B \\ 60 \times \frac{B-R}{MAX-MIN} + 120, & if\ MAX = G \\ 60 \times \frac{R-G}{MAX-MIN} + 240, & if\ MAX = B \end{cases}$$

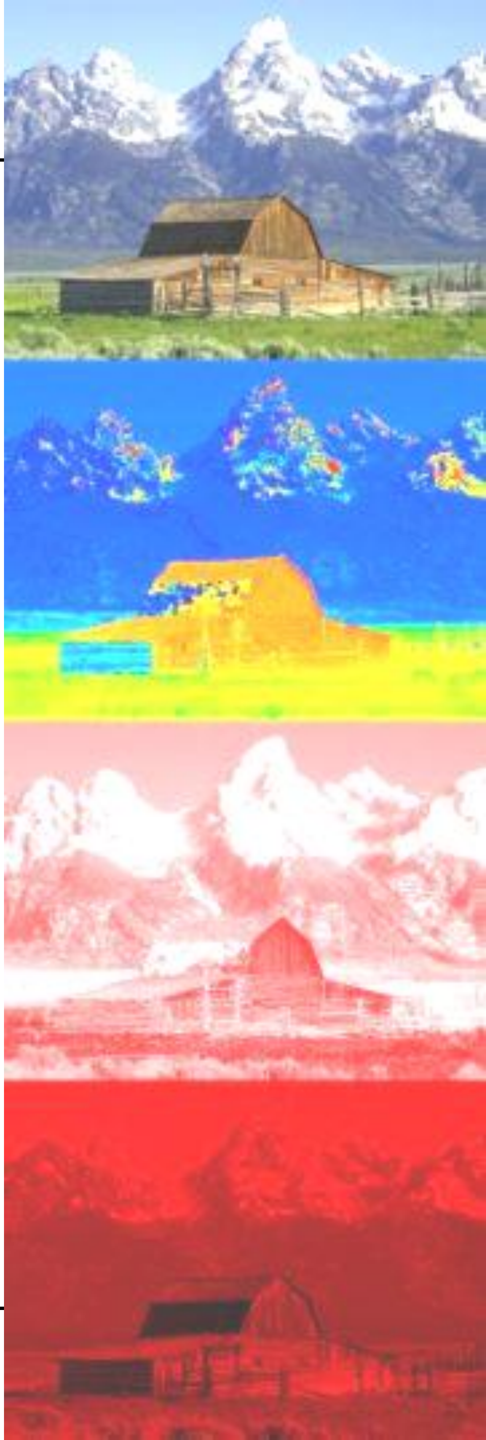
$$S = \begin{cases} 0, & if\ MAX = 0 \\ 1 - \frac{MIN}{MAX}, & otherwise \end{cases}$$

$$V = MAX$$



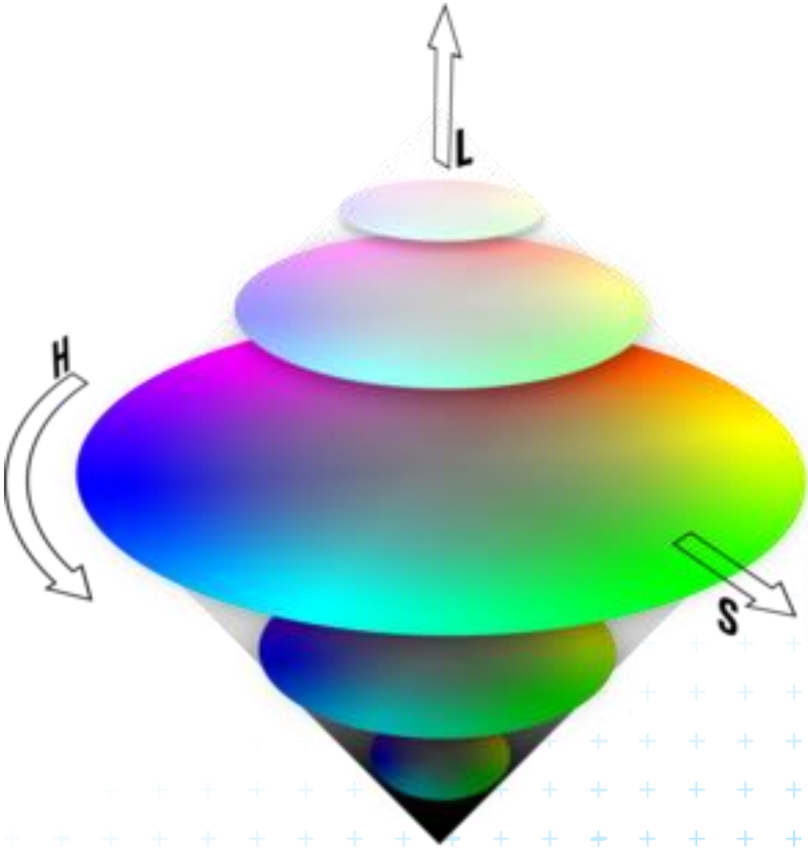
HSV in user interfaces

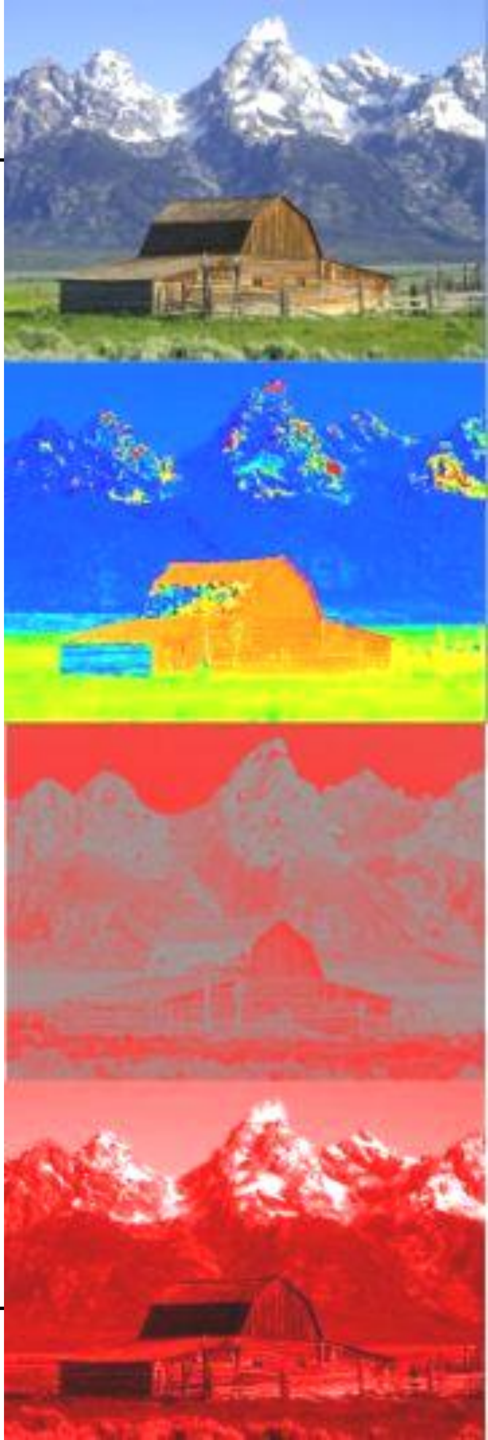
- Orientation of a triangle – H
- Inside a triangle – S, V



HLS = Hue Lightness Saturation

- Similar to HSV, but symmetrical

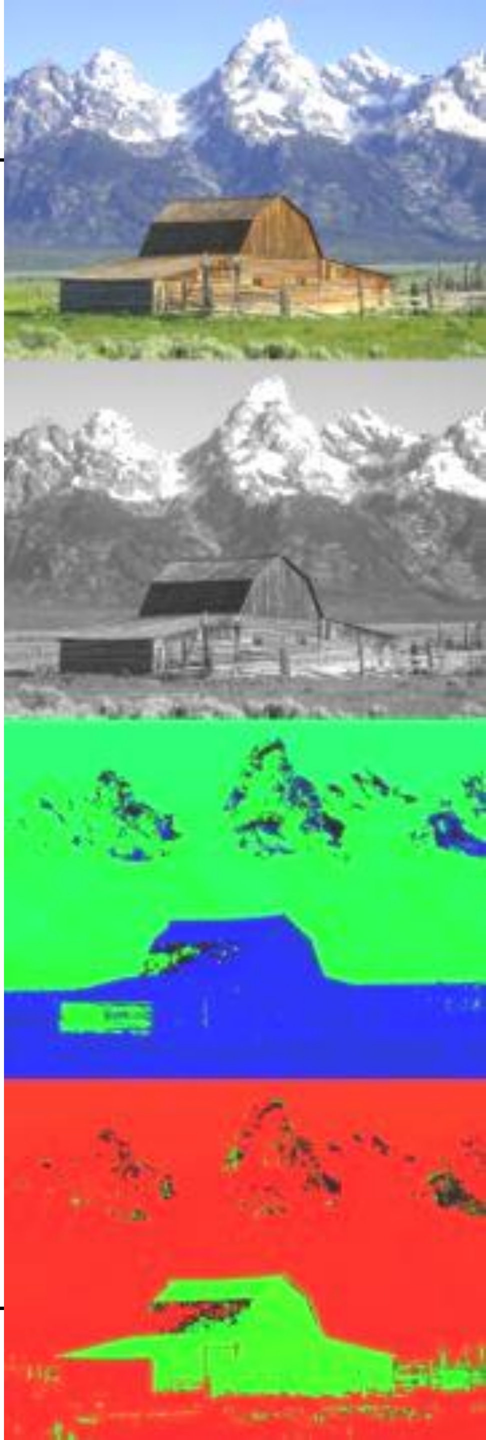




YUV

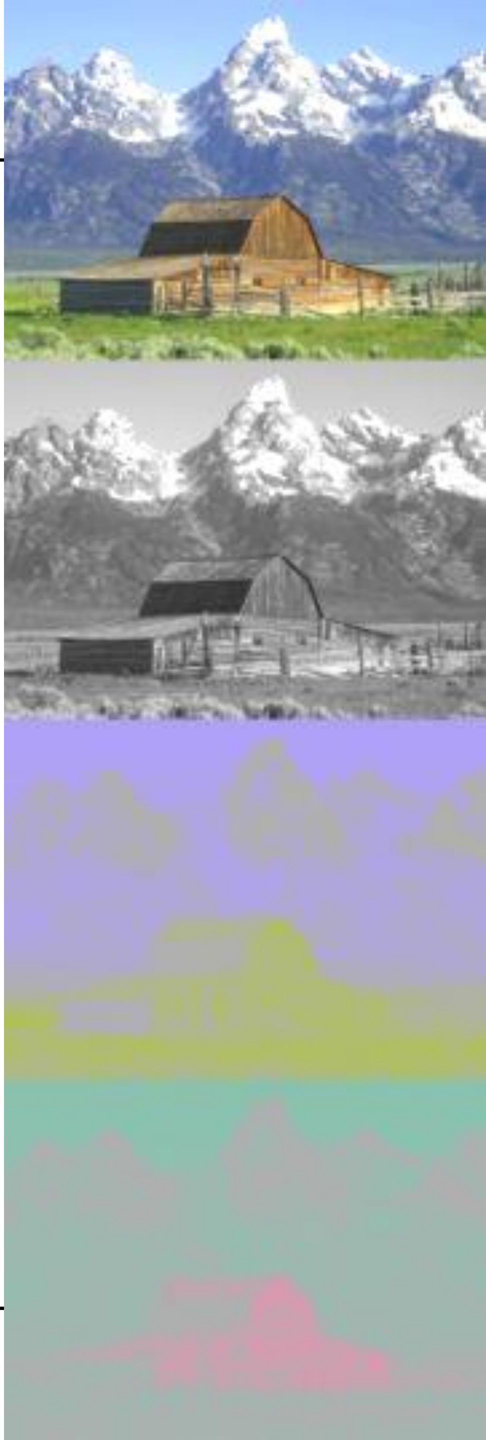
- TV signal transmission in PAL standard
- **Y** … brightness
- **UV** … color/hue components (chroma)
- Conversion RGB => YUV:

$$Y = +0.299\,\mathbf{R} + 0.587\,\mathbf{G} + 0.114\,\mathbf{B}$$
$$U = -0.1471\,\mathbf{R} - 0.288\,\mathbf{G} + 0.436\,\mathbf{B}$$
$$V = +0.615\,\mathbf{R} - 0.514\,\mathbf{G} - 0.100\,\mathbf{B}$$



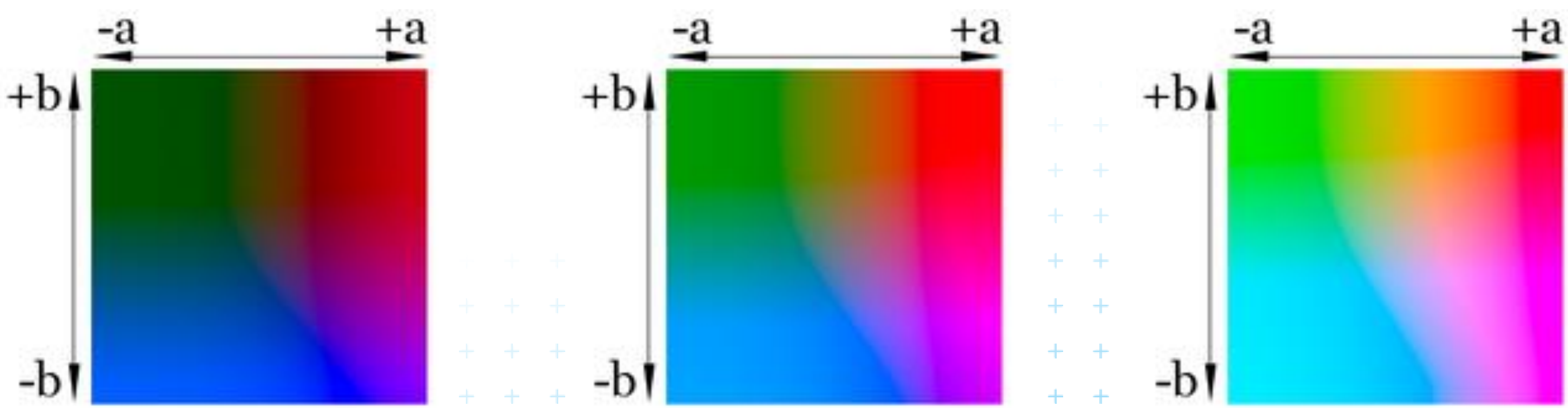
Y Cb Cr

- For digital video
- in JPEG compression algorithm



CIE L*a*b (CIELAB)

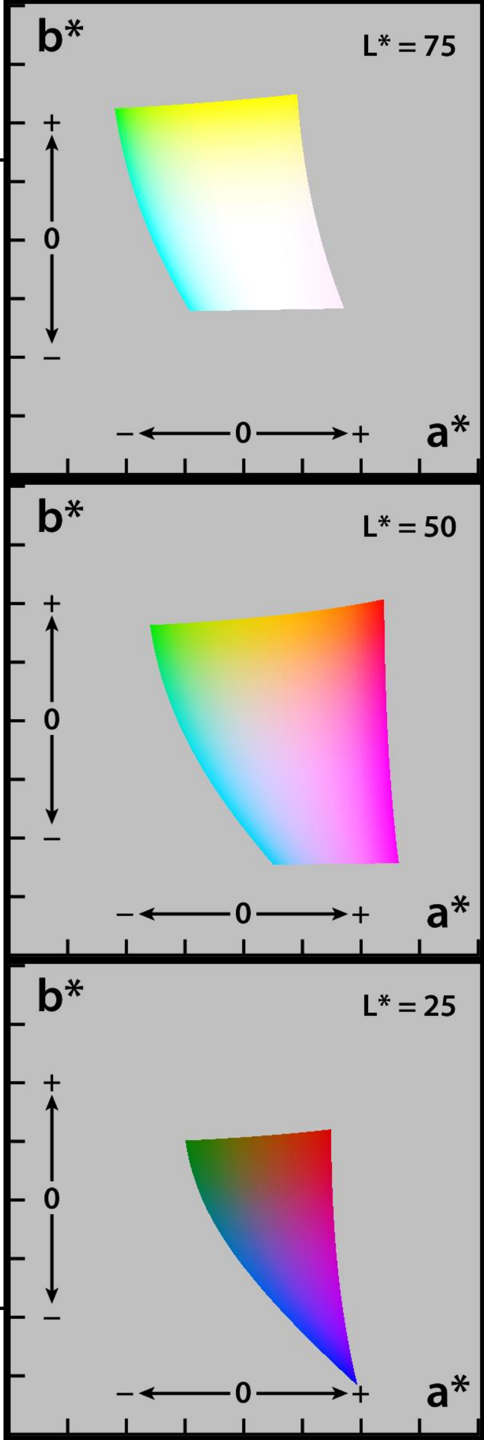
- Absolute color space (device independent)
- Non-linear compression of CIE XYZ colors
- Perceptually uniform (almost)
  - Euclidian distance in CIELAB corresponds to perceived color differences



CIE L*a*b (CIELAB)

- Impossible to display all CIELAB colors in specific device(s) – due to limited device gamut(s)

- L* … brightness
- a*, b* … color opponent dimensions:
  - a* … red <=> green
  - b* … yellow <=> blue



CIE Luv

- Similar to CIE L*a*b*
- L*a*b* is considered to be better than Luv
- Luv used in historical reasons now (backward compatibility)

Thank you for your attention

Jiří Žára, 25.11.2015