Color Theory summary

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Artificial Intelligence &
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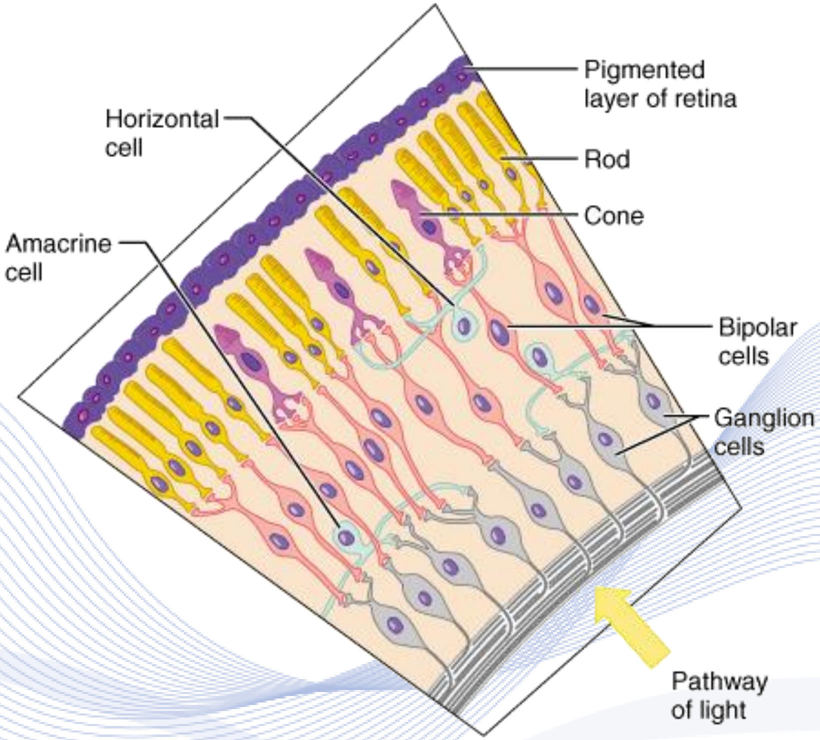
Color theory

- ***Visible light***: an electromagnetic wave with wavelength λ varying in the range $380 - 780\ nm$.
- Perceived color: depends on the spectral content of the light.
  - ***Red light***: a signal with energy concentrated around $700\ nm$.
  - ***White light***: a signal with evenly distributed energy across the wavelength spectrum.
  - **Monochromatic color**: a color with a very narrow spectral content (typically ***single-wavelength light***).

Color theory

Human Visual System (***HVS***):

- Eye ***retina*** has cones and rods.
- ***Rods*** are responsible for night vision (***scotopic vision***).
- They are plenty and have ***low-pass*** characteristics.
- ***Cones*** are responsible for day vision and for color perception.
- They are fewer and concentrate at the retina center.



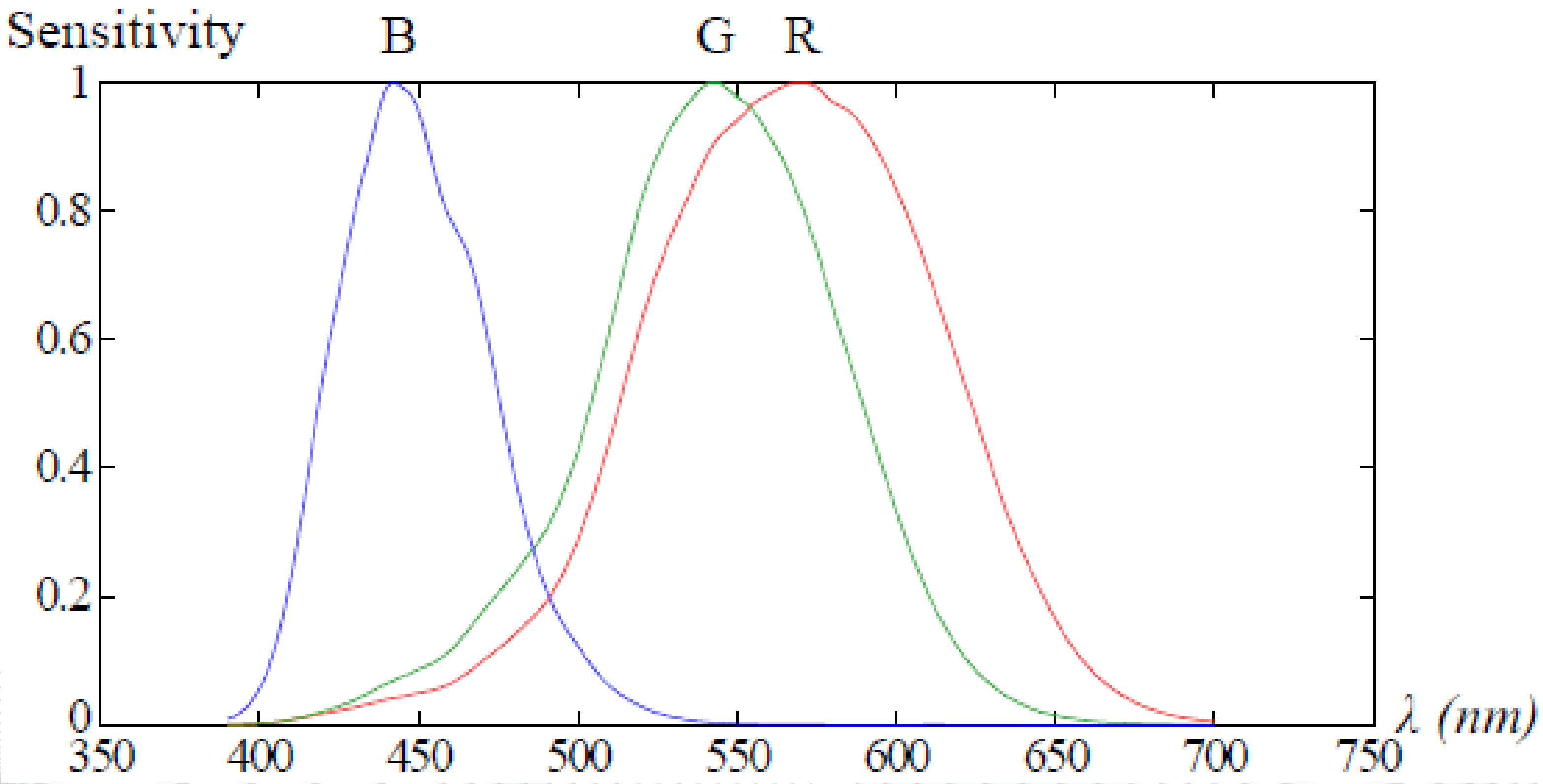
Color theory

- Cone response to an incoming signal can be described by:

$$C_i = \int f_a(\lambda) h_i(\lambda) d\lambda, \qquad i = r, g, b$$

- $h_r(\lambda), h_g(\lambda), h_b(\lambda)$: red, green and blue ***cone sensitivities***.
- The combination of these three types of sensors enables the human eye to perceive any color.
  - ***Trichromatic color vision***: the perceived color depends only on three numbers C_r, C_g, C_b, rather than $f_\alpha(\lambda)$.

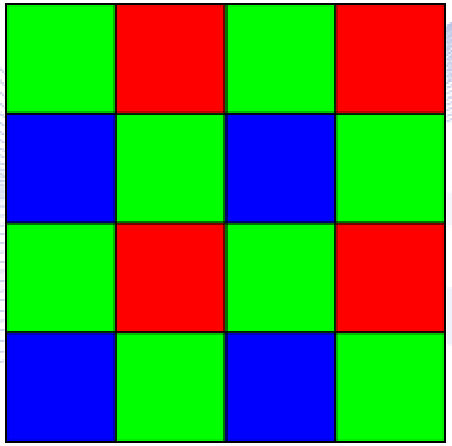
Color theory



Color cone sensitivities.

Color theory

- Similarly, artificial optical sensors (e.g., CCD-based ones) can become sensitive to red, green and blue light, respectively.
- ***Bayer filters*** are overlaid on CCD cells to enable color sensitivity.



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Color theory

Multispectral/multichannel (n -channel) images are 2D ***vectorial functions*** of the form:

$$\boldsymbol{f}(x,y)\colon \mathbb{R}^2 \rightarrow \mathbb{R}^n.$$

Special cases:

- ***Color images*** ($n = 3$):

$$\boldsymbol{f}(x,y) = [f_R(x,y), f_G(x,y), f_B(x,y)]^T\colon \quad \mathbb{R}^2 \rightarrow \mathbb{R}^3.$$

- Digital color images (assigning b bits per color channel to each voxel):

$$\boldsymbol{f}(n_1,n_2)\colon\ \mathbb{Z}^2 \rightarrow \{0,\ldots,2^b-1\}^3.$$

Color theory

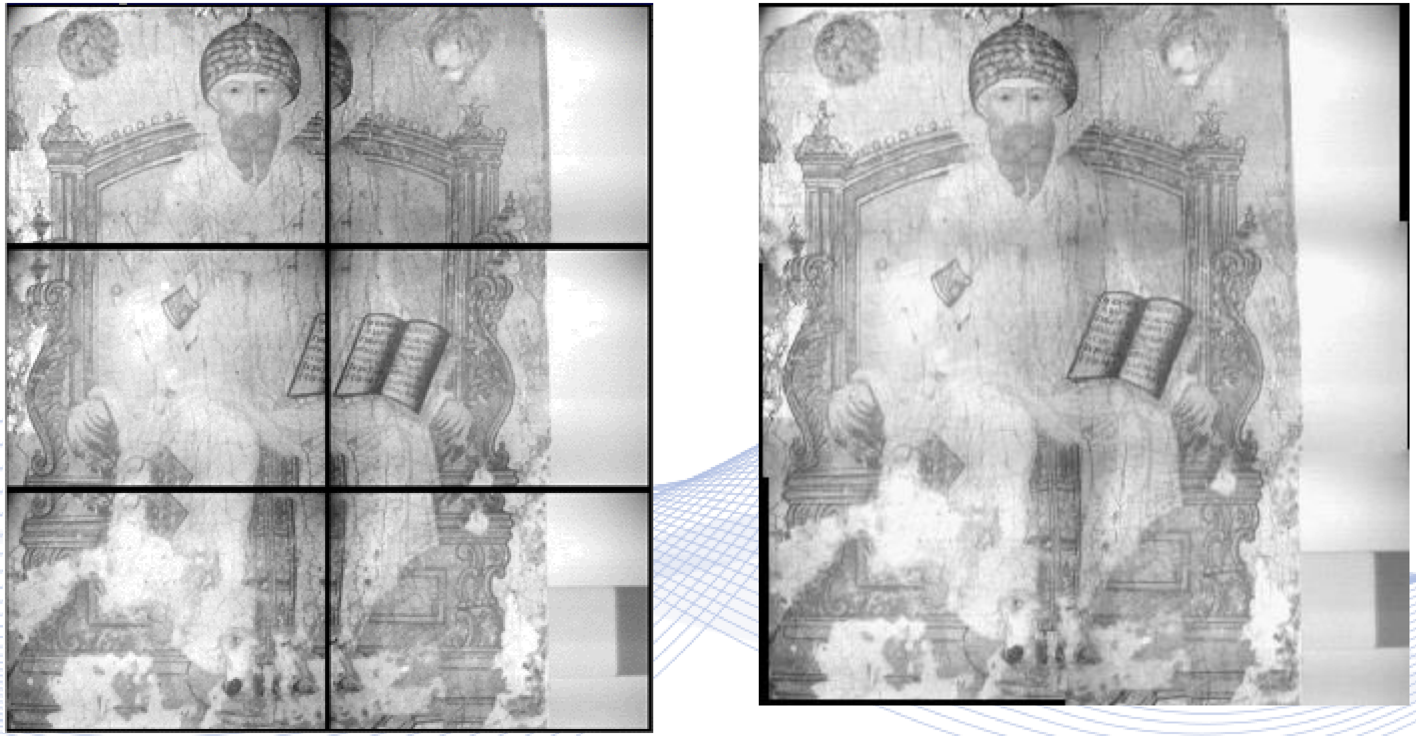
- Multichannel images can also be considered as 3D images: $f(n_1, n_2, i),\ i = 1,2,3$.

    - ***Hyperspectral images*** are 3D images of the form:

$$f(x, y, \lambda): \quad \mathbb{R}^3 \to \mathbb{R}.$$

- λ: light wavelength.
- ***Infrared images***: $f(x, y, \lambda),\ \lambda > 780\ nm$.
- ***Ultraviolet images***: $f(x, y, \lambda),\ \lambda < 380\ nm$.

Color theory



Infrared painting reflectography mosaicing.

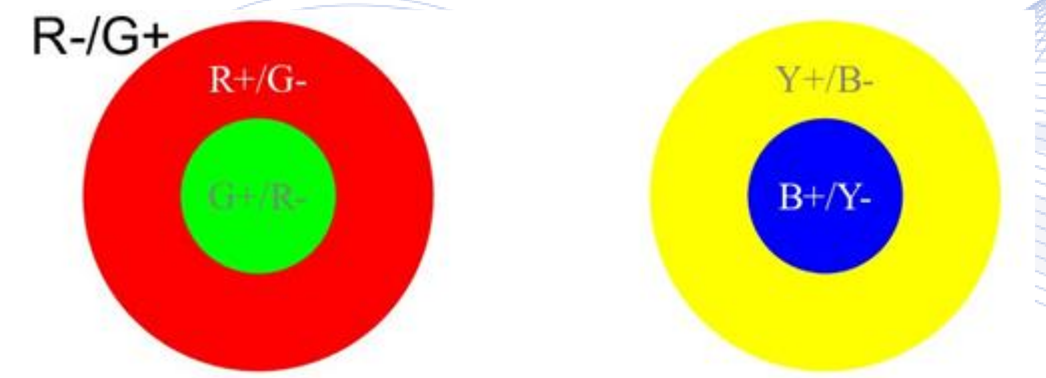
Color theory

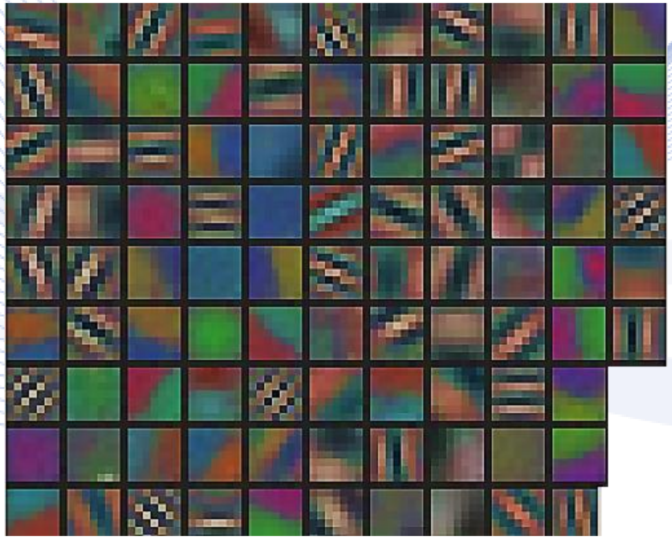
Multichannel images: visible (left), X-ray (middle) overlaid image channels(right).

Color theory

***Color opponency*.**

- In V1 and LNG there are center-surround color opponent cells.
- Trained CNN kernels support color opponency.





Color theory

T. Young color theory (1802): Any color can be produced by mixing three basic colors C_1, C_2, C_3 at appropriate proportions:

$$C = aC_1 + bC_2 + cC_3.$$

- Each color image pixel can be represented by a vector $[a, b, c]^T$ in the 3D space (C_1, C_2, C_3).

- The individual ***color chromaticities*** are defined by:

$$c_i = \frac{C_i}{C_1+C_2+C_3}, \qquad i = 1,2,3.$$

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Color coordinate systems

CIE also proposed the ***XYZ color system***:

- Hypothetical coordinates X, Y, Z.
- White reference color: $X = Y = Z = 1$.
- Linear transformation of RGB to XYZ color systems:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{bmatrix} R_{CIE} \\ G_{CIE} \\ B_{CIE} \end{bmatrix}.$$

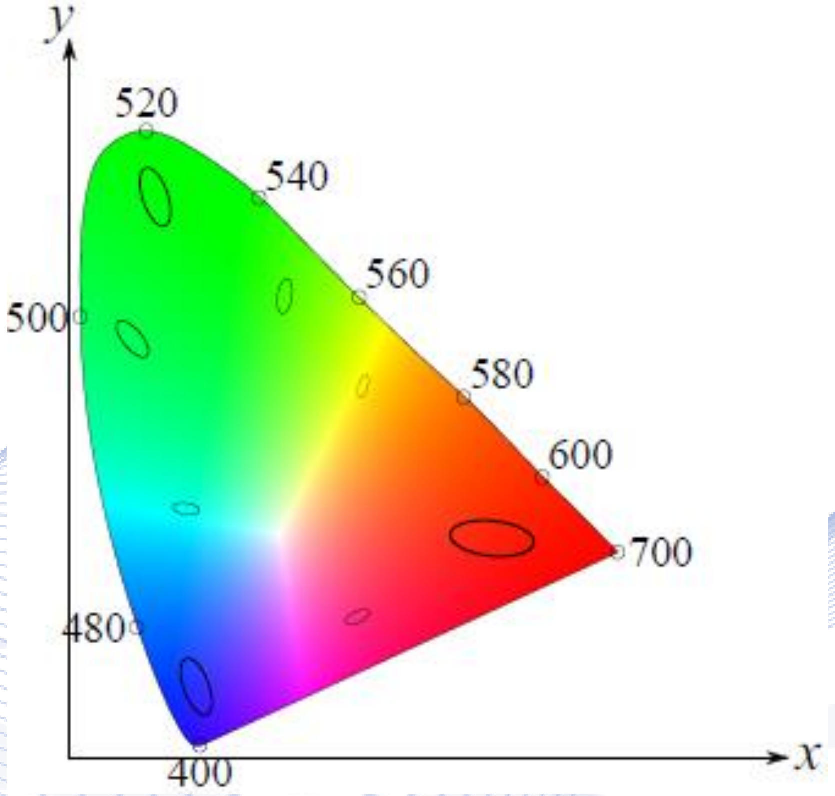
Color coordinate systems

- The color coordinates:

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

can be used to produce a ***chromaticity*** diagram.

- Ellipses correspond to colors which cannot be discerned by the human visual system.



Color coordinate systems

$L^*a^*b^*$ ***Color System*** is also used to measure color differences:

$$L^* = 25(100Y/Y_0)^{1/3} - 16, \qquad 1 \le 100Y \le 100,$$
$$a^* = 500\left[(X/X_0)^{1/3} - (Y/Y_0)^{1/3}\right],$$
$$b^* = 200\left[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}\right].$$

- (X_0, Y_0, Z_0): reference white light;

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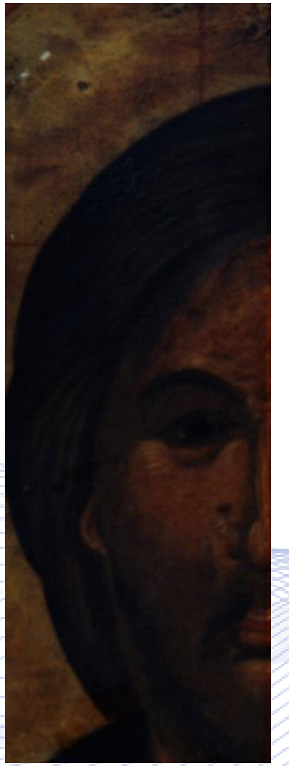
Color coordinate systems

- L^*: brightness;
- a^*b^*: chromaticity in the red-green and yellow-blue light domains.
- Color difference ΔC in $L^*a^*b^*$:

$$\Delta C^2 = (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2.$$

Color coordinate systems



Byzantine painting restoration using the $L^*a^*b^*$ Color System.

Color coordinate systems

YIQ color space used in NTSC:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.211 & -0.523 & 0.312 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}.$$

- Y: luminance component.
- I, Q: image chrominance.
- Advantages of the YIQ color space:
  - It guarantees backwards compatibility with monochrome television.

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Color coordinate systems

YC_bC_r color space is an efficient color representation in European analog and digital TV systems.

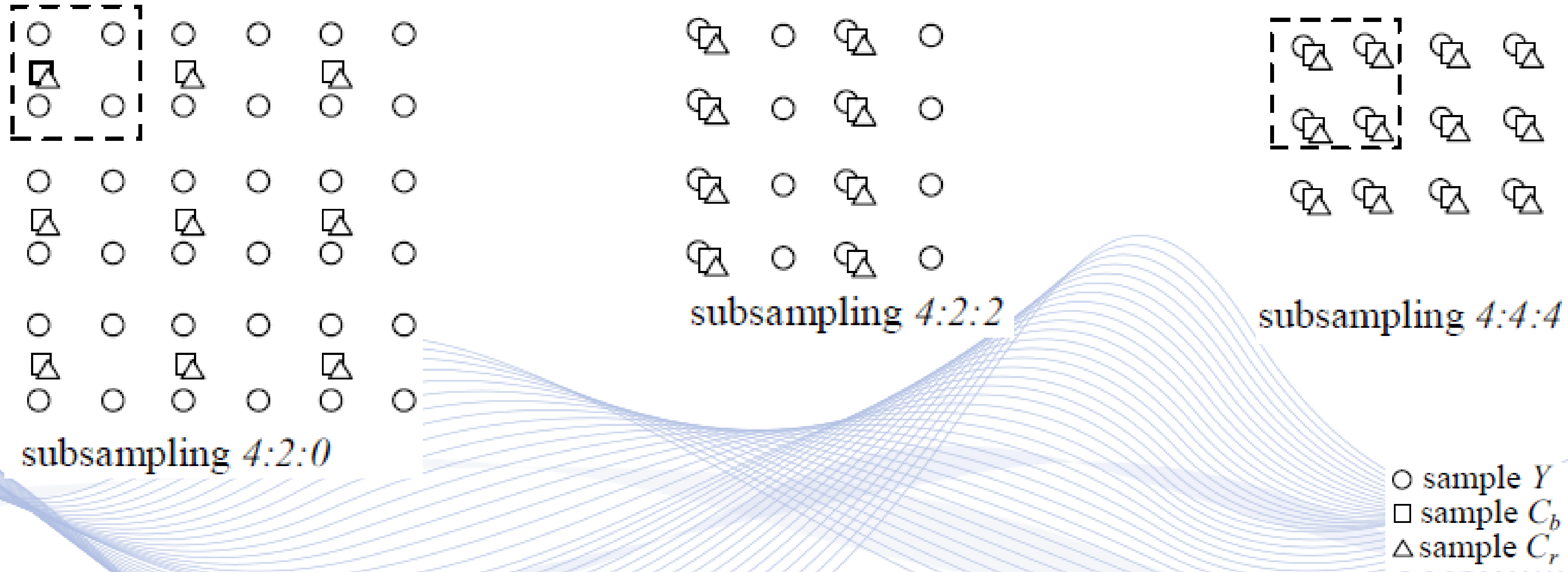
- Luminance channel Y:

$$Y = k_r R + k_g G + k_b B.$$

- Typical k coefficients: $k_r = 0.299$, $k_g = 0.587$, $k_b = 0.114$.
  - Small weight on the B channel.
- Chrominance information can be represented as:

$$C_b = B - Y, \qquad C_r = R - Y.$$

Color coordinate systems



$4:2:0$, $4:2:2$, $4:4:4$ C_b, C_r chrominance subsampling systems.

Color coordinate systems

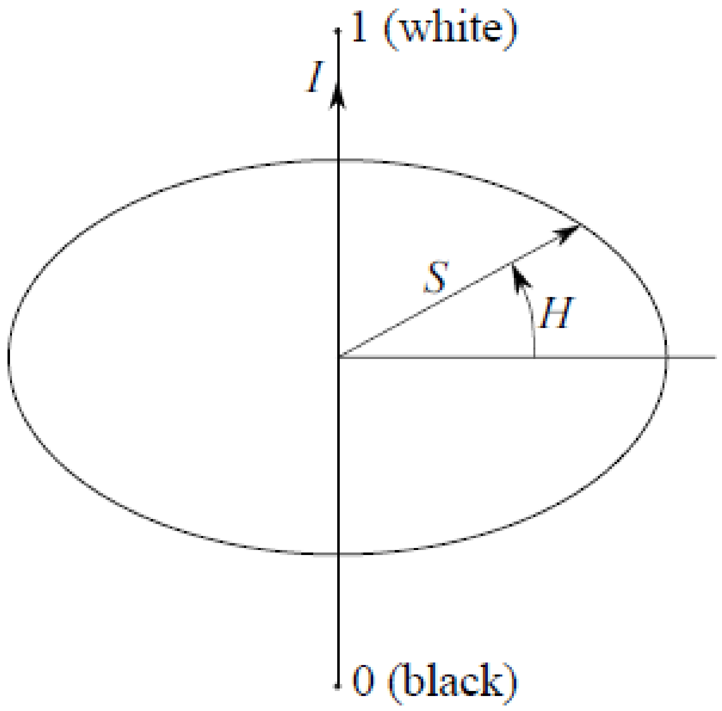
Human visual perception of the following three color properties:

- ***Hue*** determines color redness, greenness, blueness.
- ***Saturation*** defines the percentage of white light added to a pure color.
  - For example, red is a highly saturated color, whereas pink is less saturated.
- ***Brightness*** indicates the perceived light luminance.

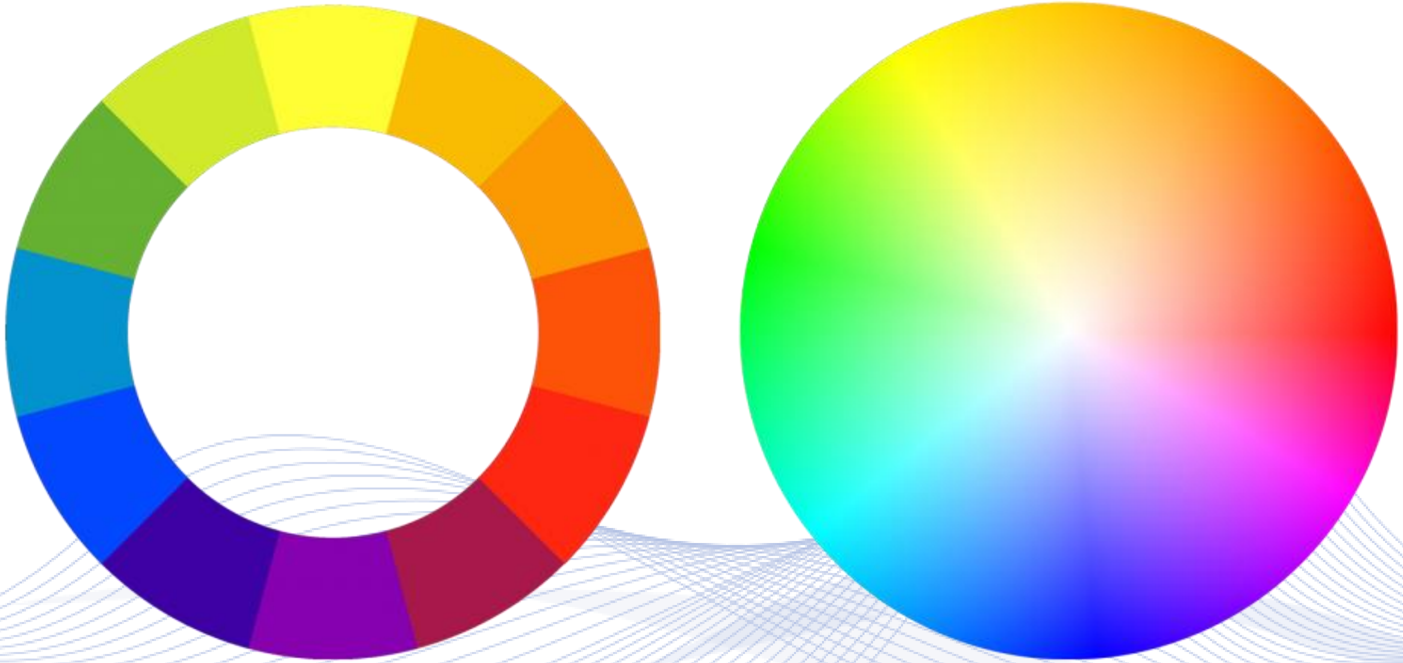
Color coordinate systems

Hue, saturation and brightness define a cylindrical color coordinate system:

- Brightness I varies from pure black ($I = 0$) to pure white color ($I = 1$).
- Saturation S ranges from pure gray ($S = 0$) to highly saturated colors ($S = 1$).
- Hue H is measured by the angle between the actual color vector and a reference pure color vector.



Color coordinate systems

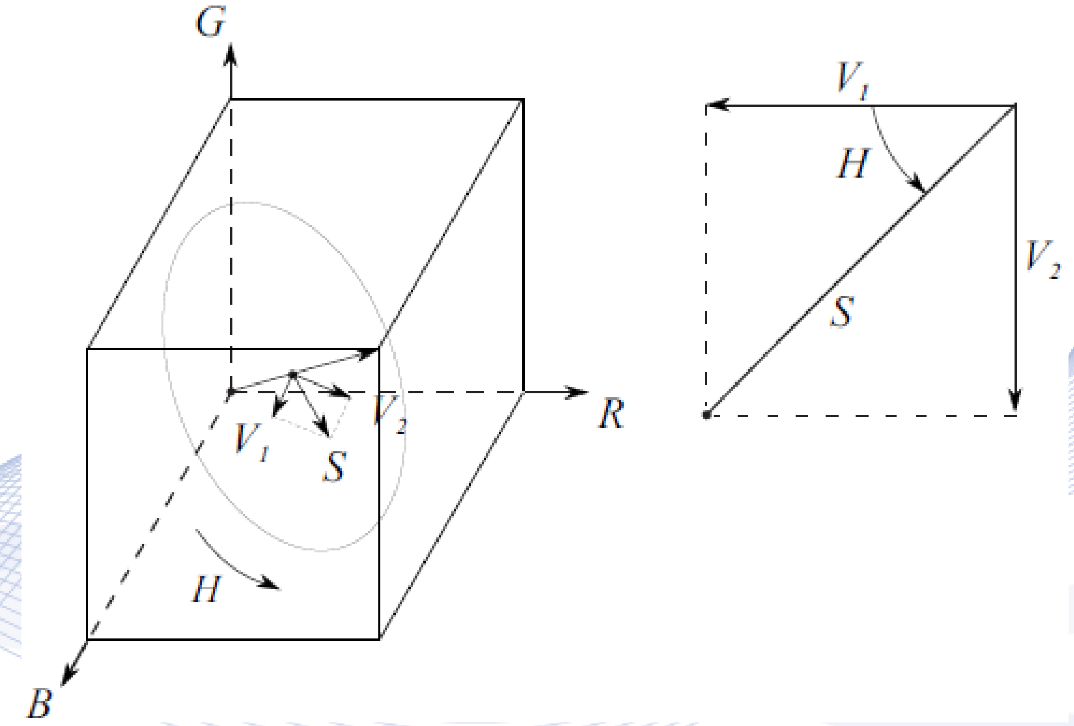


Color hue and saturation [HUE].

Color coordinate systems

HSI color system (Hue, Saturation, Intensity):

- It is a cylindrical coordinate system whose axis is the diagonal line $R = G = B$ in the RGB space.
- Only the HIS colors that are inside the RGB cube can be displayed.



Color coordinate systems

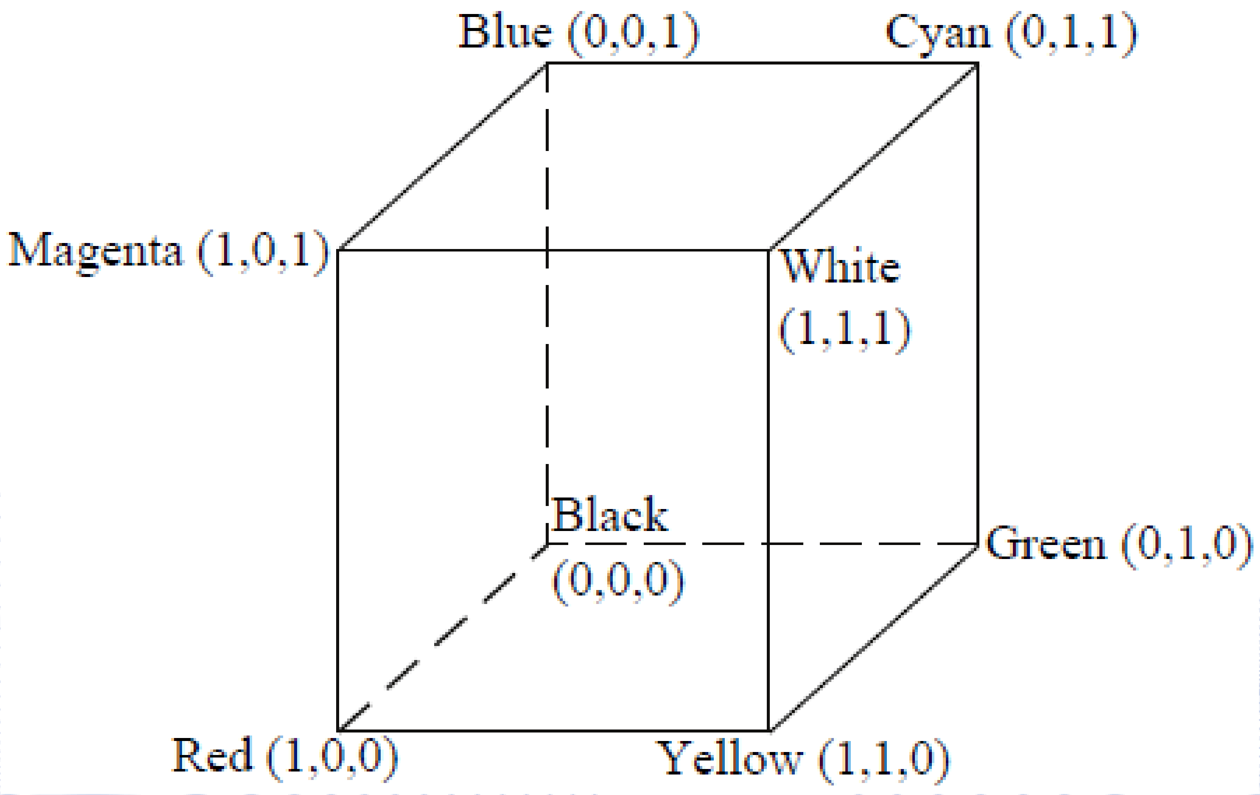
Subtractive colors:

- cyan, magenta, yellow = subtractive primaries
- red, green, blue = additive primaries
- cyan, magenta, yellow (complementary of red, green, blue primary colors).

CMYK color system: subtractive color model complemented with black color.

  - It is mainly used in color image printing (4 inks).

Color coordinate systems

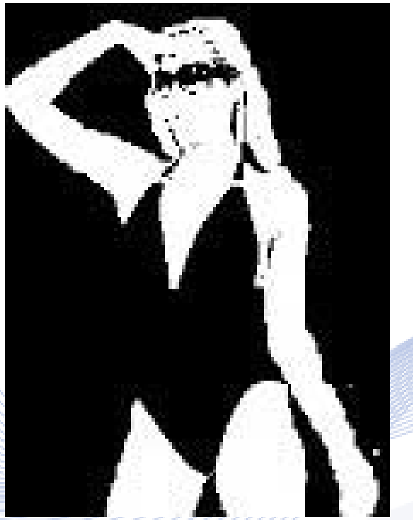


Additive and subtractive primary colors.

Color coordinate systems

Color image CMYK dithering.

Color coordinate systems

Face, body skin detection.

Color coordinate systems

Face, hand detection:

- They can be used for human eating/drinking activity recognition.
- Drinking activity recognition is very important for elderly care (to prevent dehydration).

Bibliography

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Q & A

Thank you very much for your attention!

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