Color Theory summary

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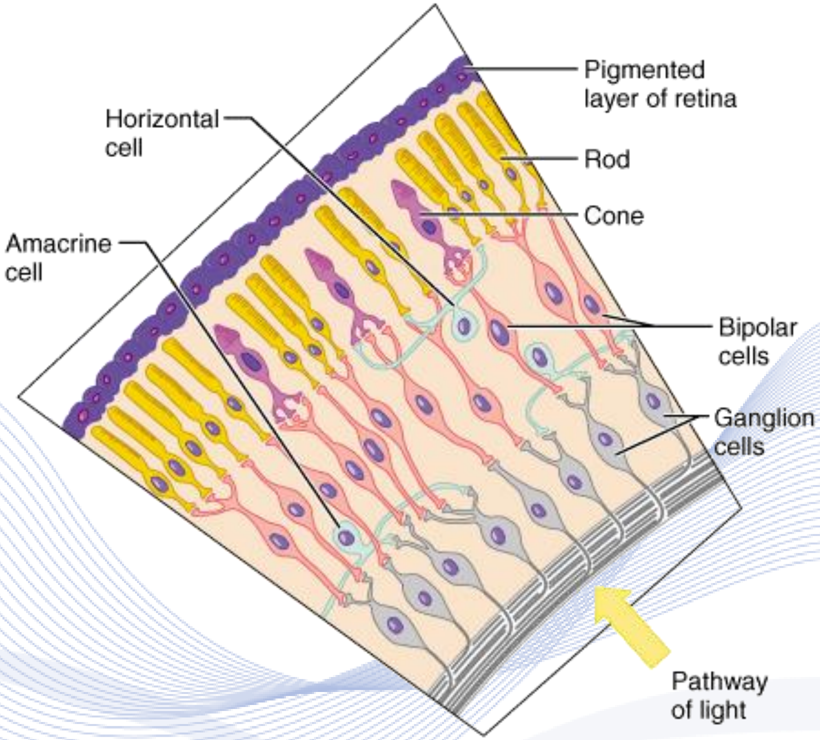
Color theory

- ***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.



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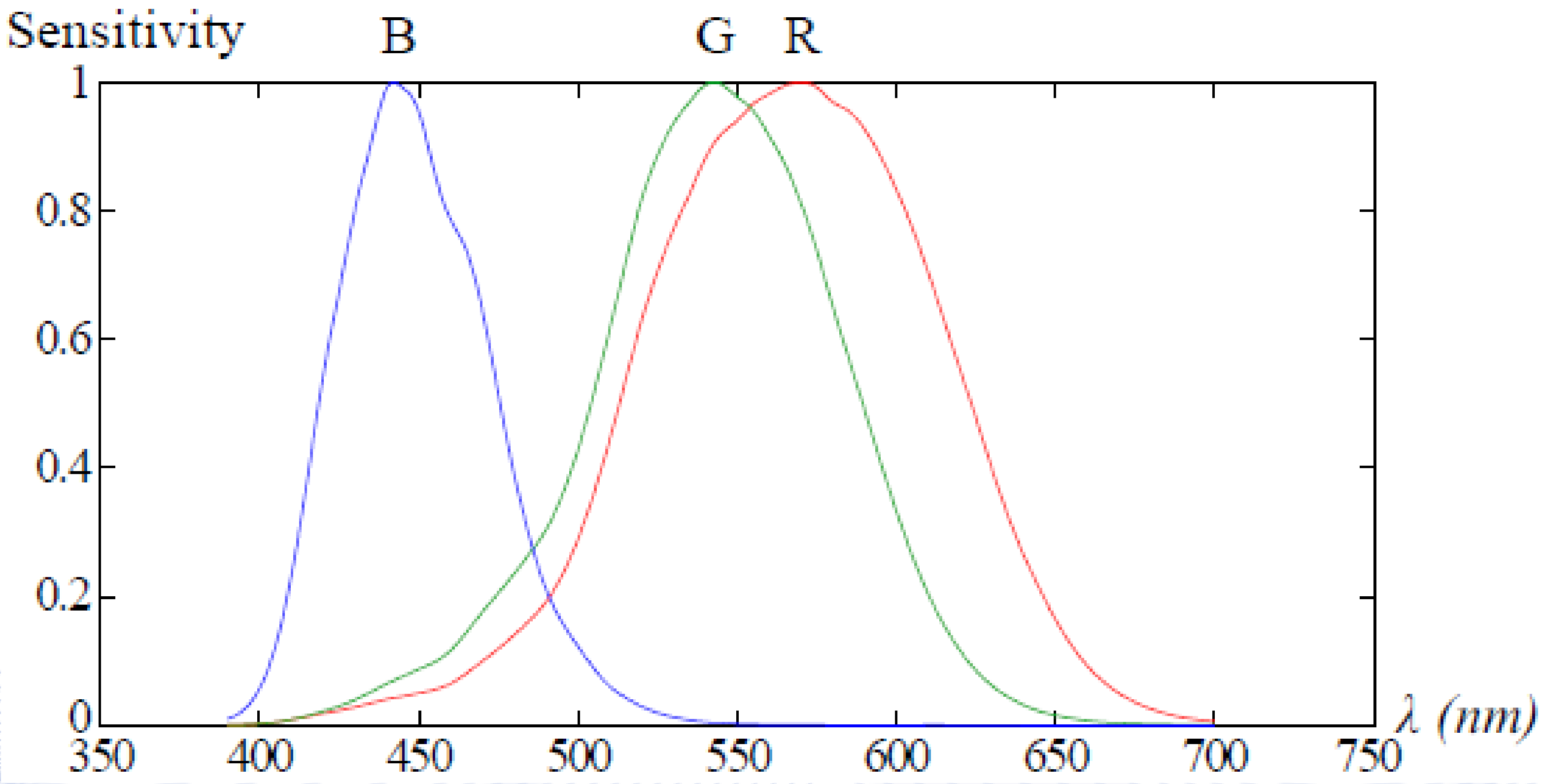
Color theory

- 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.

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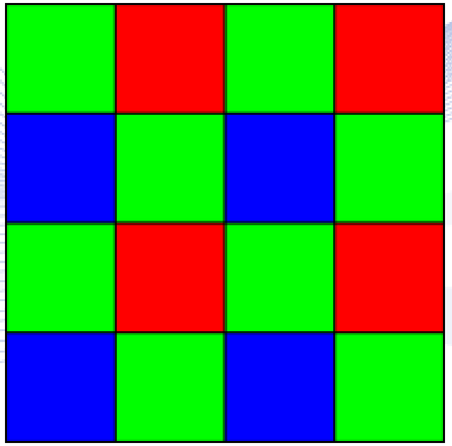
Color theory

- 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:

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

Special cases:

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

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

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

$$\mathbf{f}(n_1,n_2): \mathbb{Z}^2 \rightarrow \{0, \dots, 2^b - 1\}^3.$$

Color theory

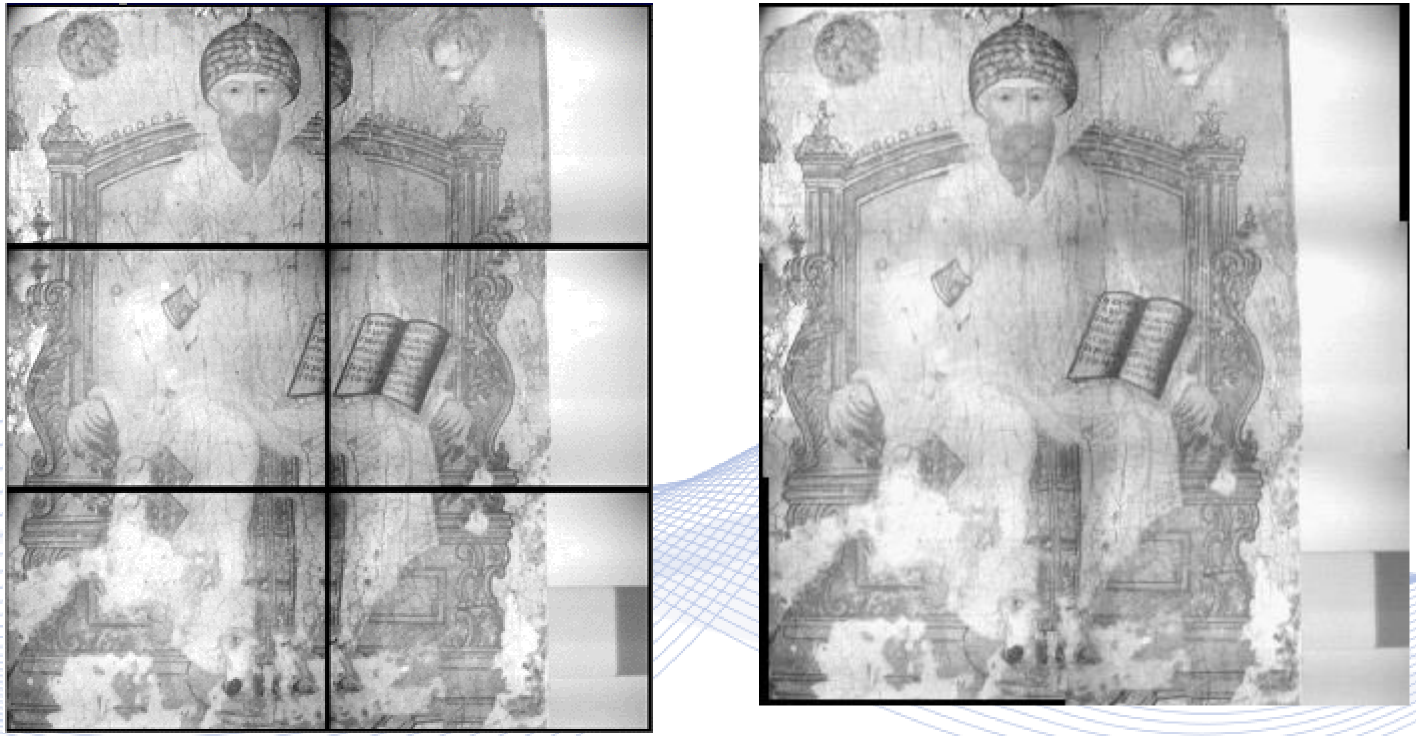
- Multichannel images can also be considered as 3D images: $f(n_1, n_2, i),\ i = 1,2,3$.

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

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

- 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

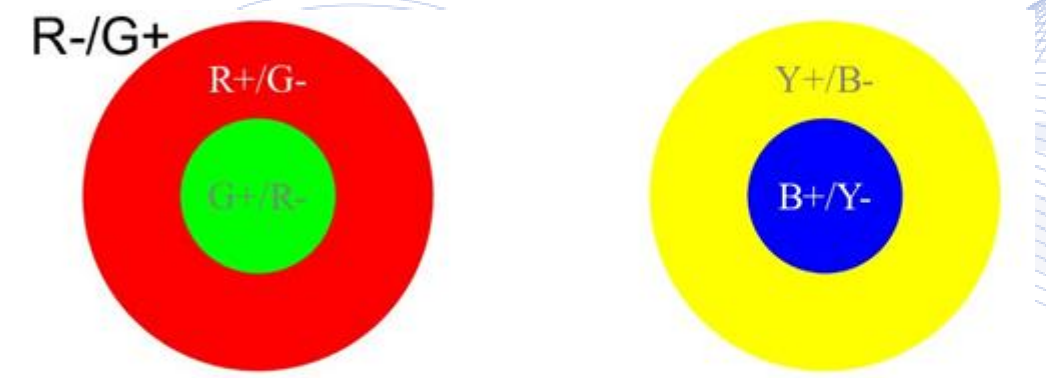


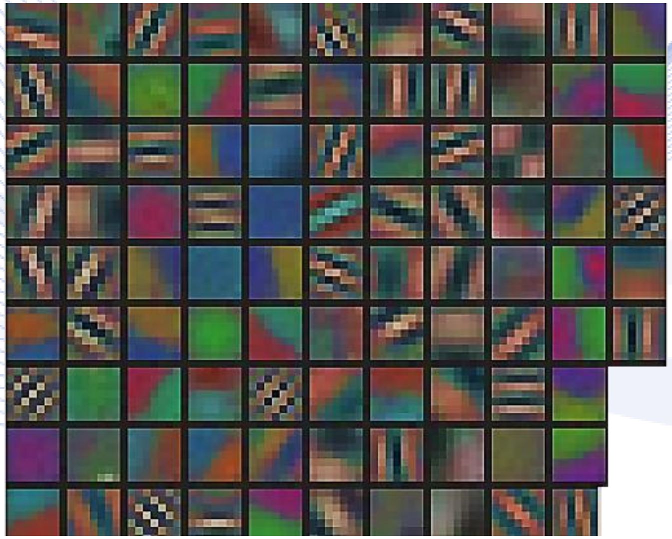
Multichannel images: visible (left), X-ray (middle) overlaid image channels(right).

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:

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

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:

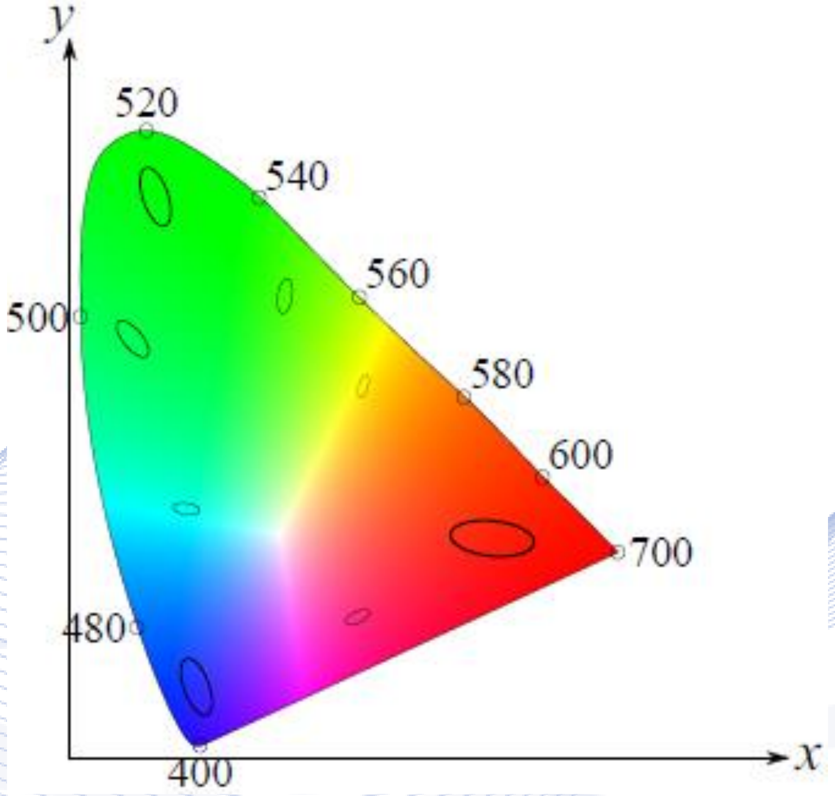
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{bmatrix} R_{CIE} \\ G_{CIE} \\ B_{CIE} \end{bmatrix}.$$

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

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

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

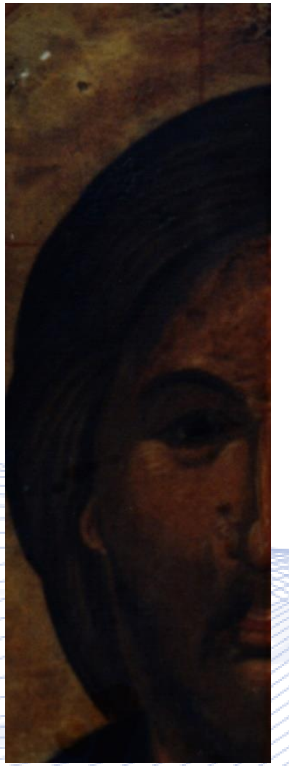
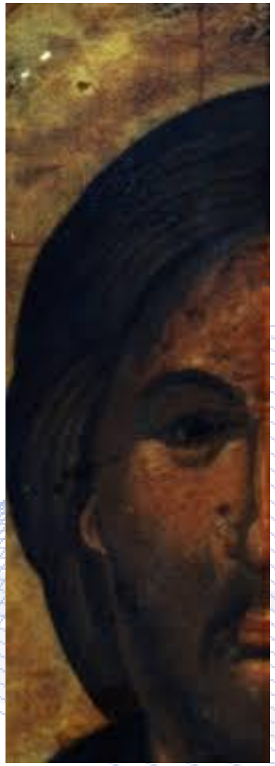
- (X_0, Y_0, Z_0): reference white light;

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.

Color coordinate systems

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

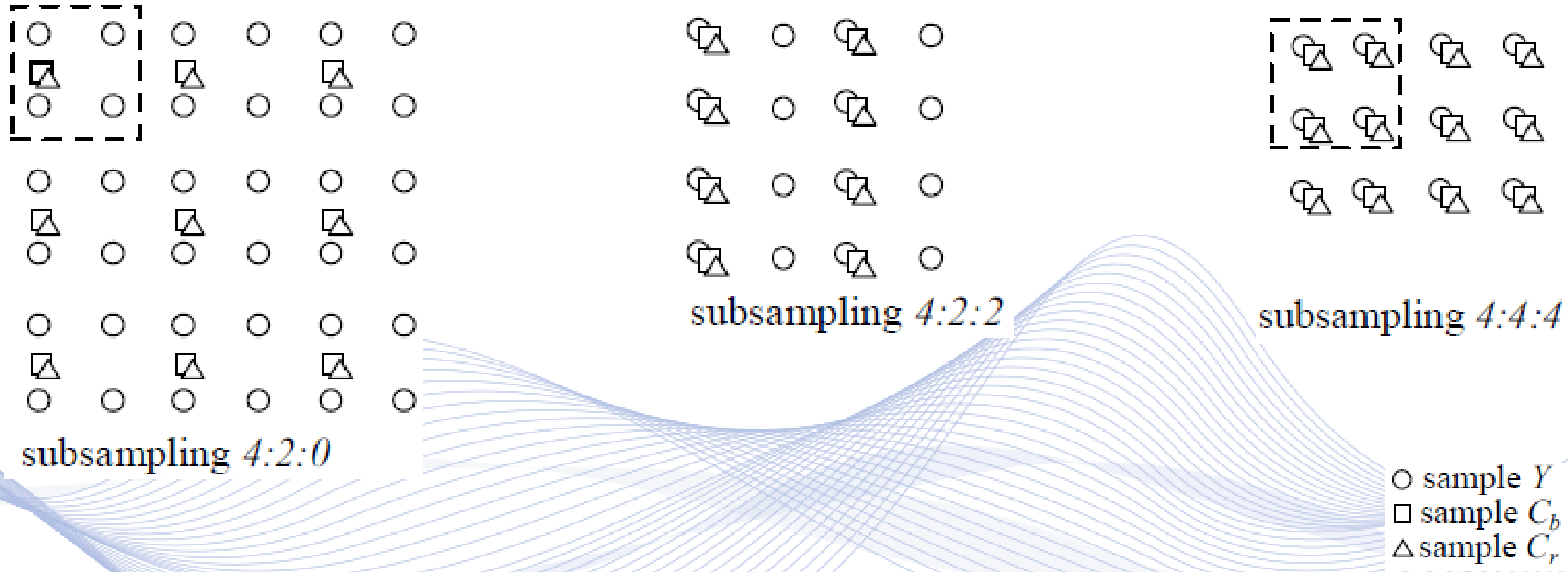
- Luminance channel Y:

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

- 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

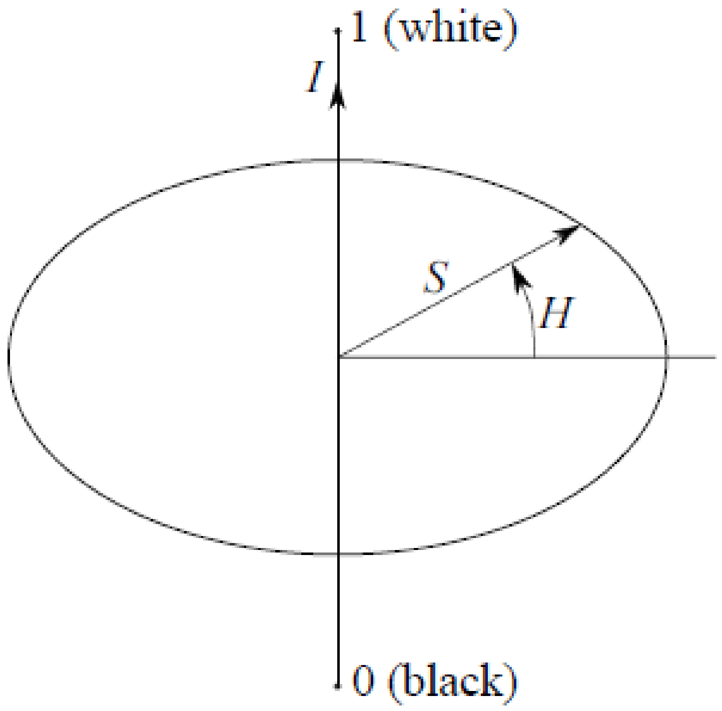
Human visual perception of the following three color properties:

- ***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.



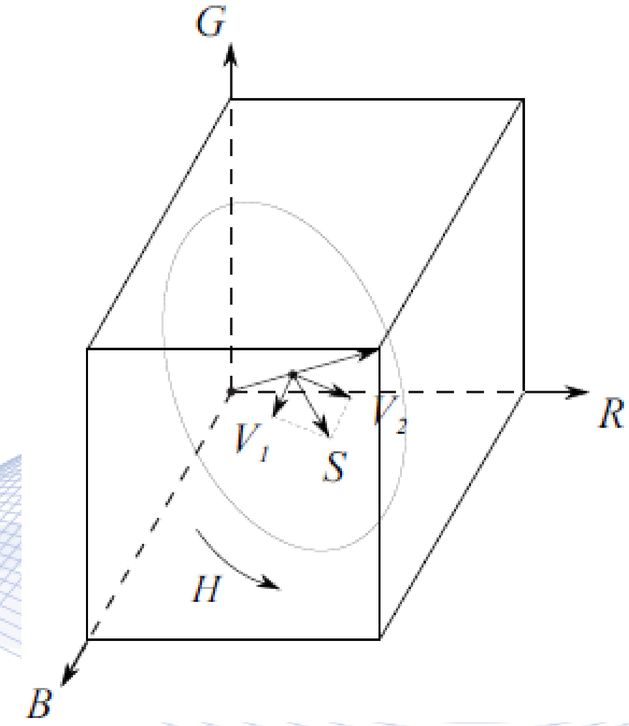
Color coordinate systems

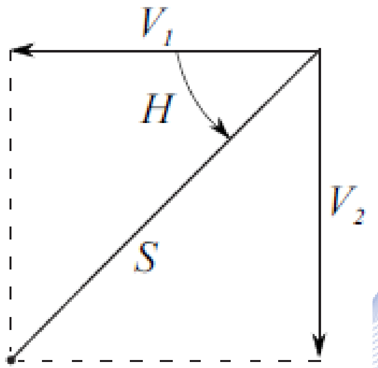
Color hue and saturation [HUE].

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

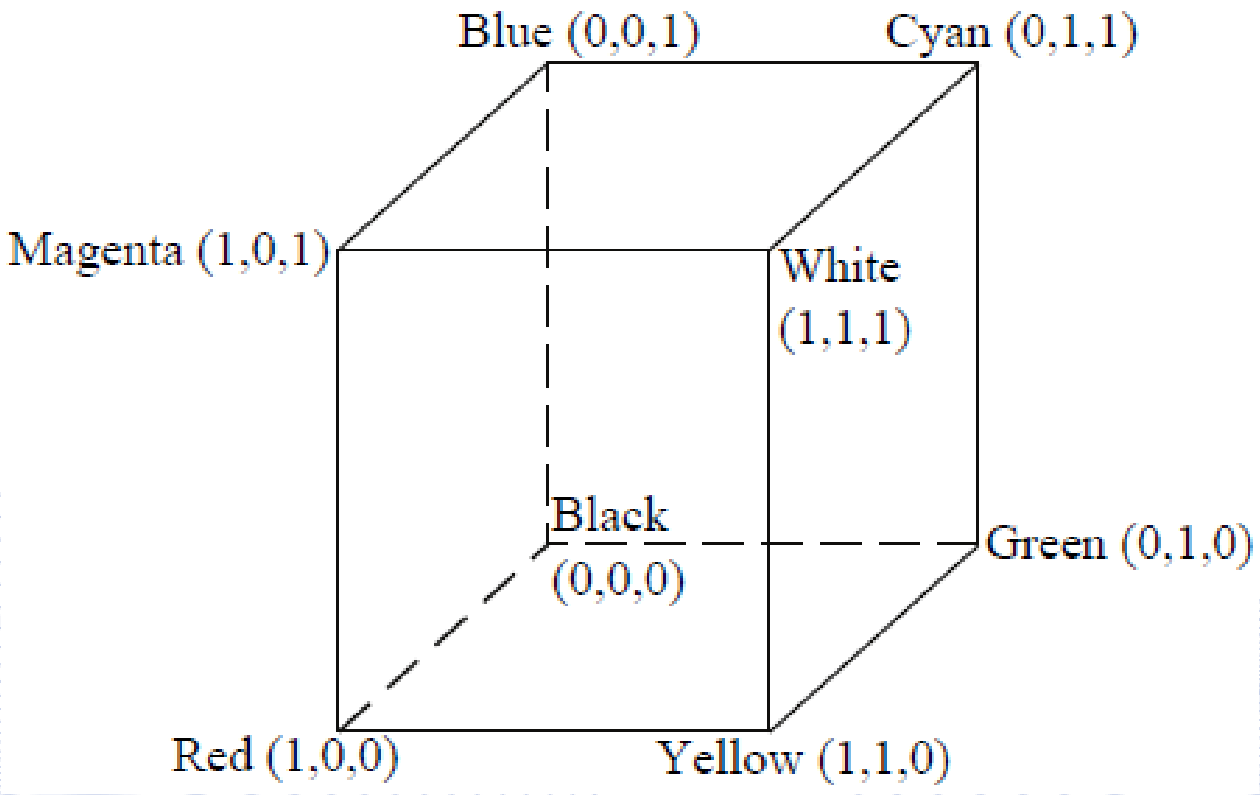
Subtractive colors:

- 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.

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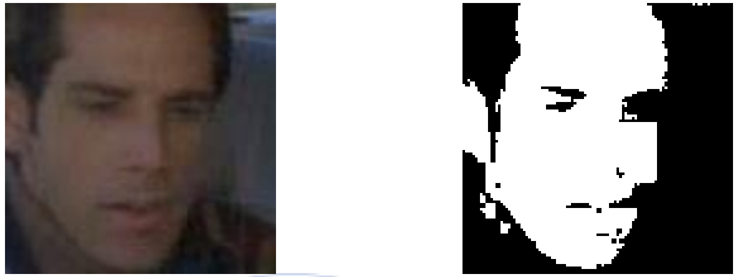
Color coordinate systems

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).

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Q & A

Thank you very much for your attention!

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