Computação Gráfica

Computer Graphics

Engenharia Informática (11569) – 3º ano, 2º semestre

Chap. 6 – Color and Perception

Outline

Based on:
https://cs.brown.edu/courses/cs123/lectures/CS123_26_Color_I_11.27.18.pdf
and
http://www.prip.tuwien.ac.at/~hanbury

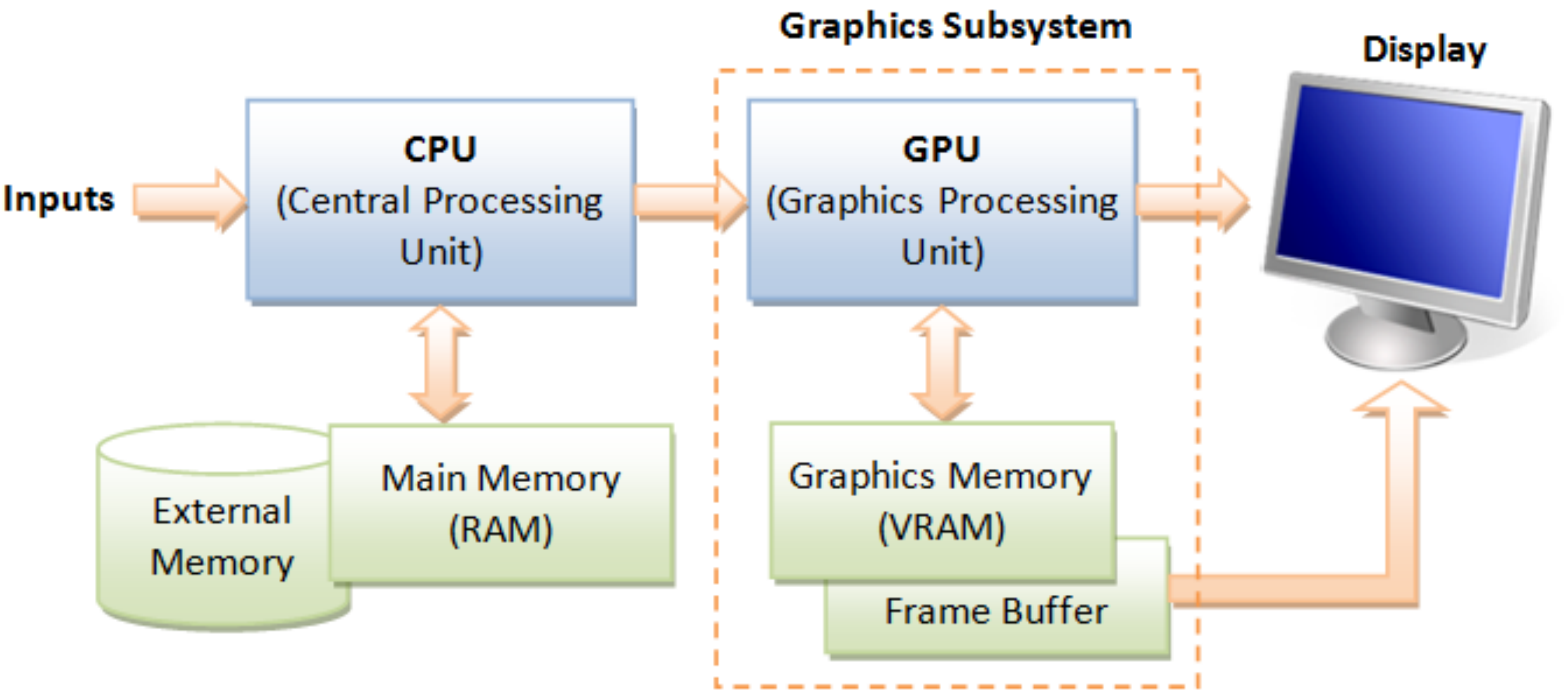
…:

- Color is about perception
- Color in nature
- Color and culture
- Why study color?
- Why is color difficult?
- Achromatic and colored light
- Chromatic light
- Psycophysics of color
- Three layers of human color perception
- Recpetors in retina
- Opponent channels
- Double opponent cells
- Color models

Raster graphics subsystem: revisited

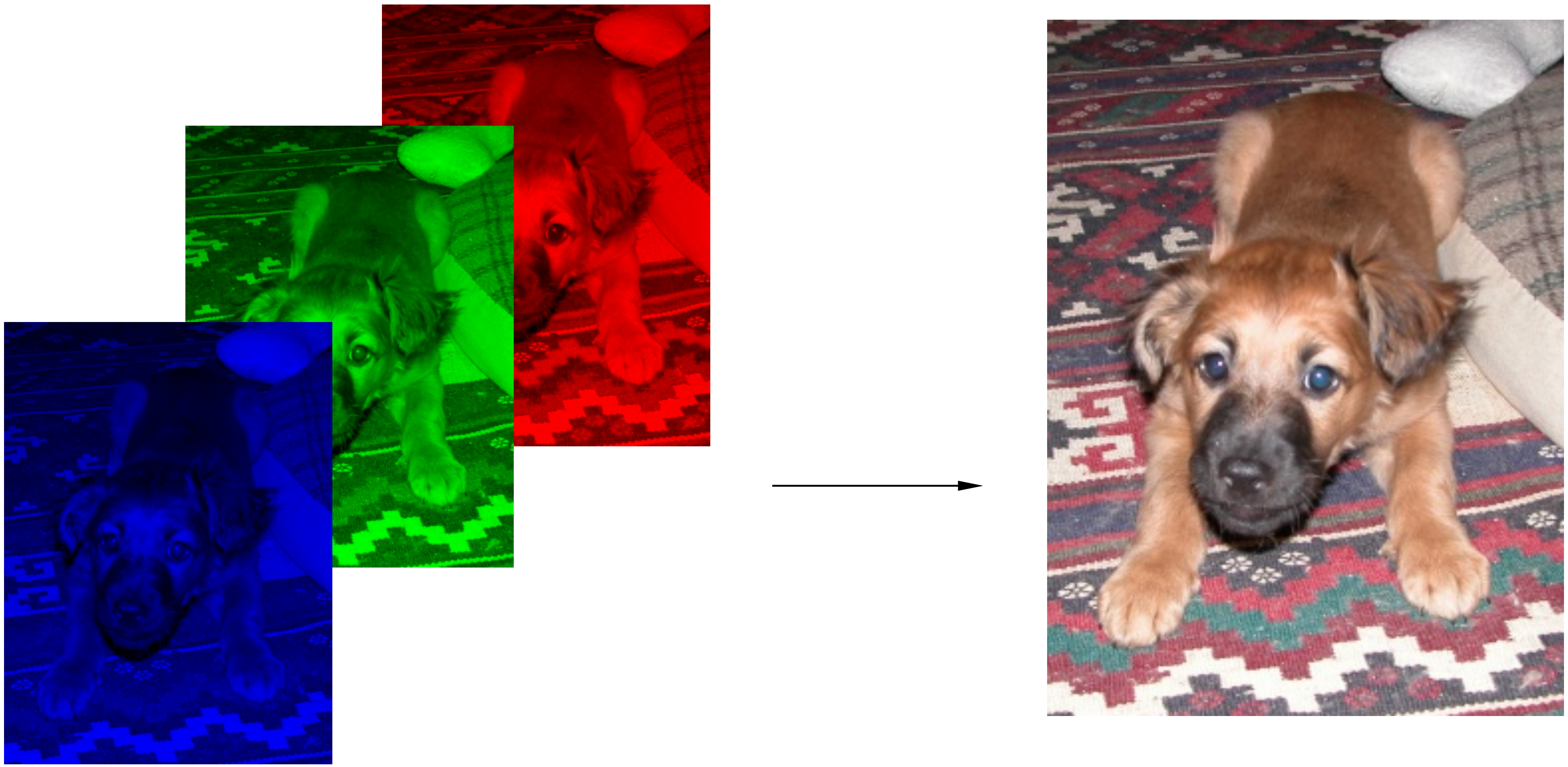
– *A frame buffer is a large, contiguous piece of computer memory. At a minimum there is one memory bit for each pixel in the raster; this amount of memory is called a bit plane. The picture is built up in the frame buffer one bit at a time.*

http://ecomputernotes.com/computer-graphics/basic-of-computer-graphics/what-is-frame-buffer



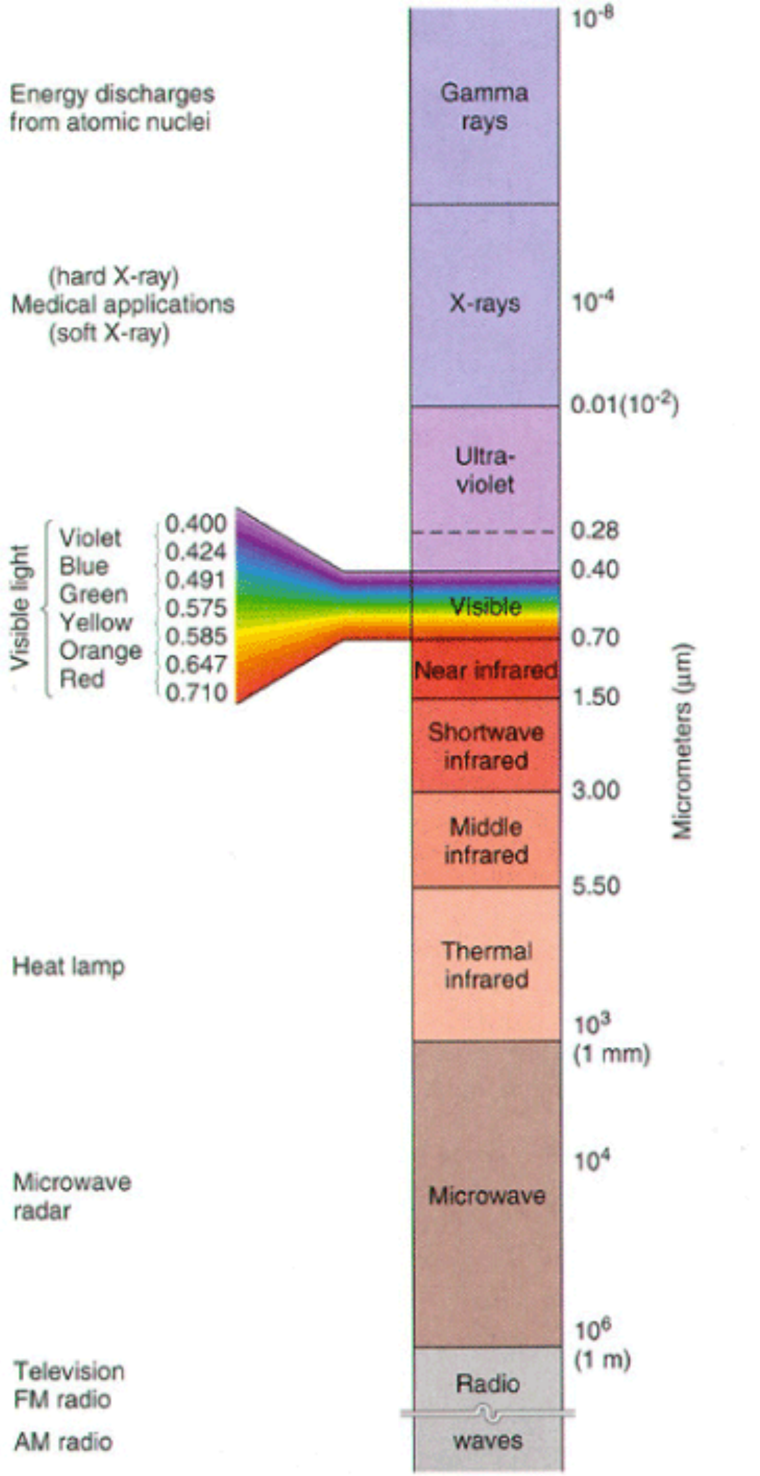
Direct color framebuffer: revisited

- *Store the actual intensities of R, G, and B individually in the framebuffer*
- *<u>Framebuffer depth</u> = 24 bits per pixel = 8 bits red, 8 bits green, 8 bits blue*
- *Store indices (usually 8 bits) in framebuffer*
- *Display controller looks up the R,G,B values before triggering the electron guns.*



Color is about perception

- Color is about perception (light waves are not colored).
- Visible light: we only see wavelengths in a narrow band of the EM spectrum: 380nm (blue) - 780nm (red).
- Wavelength: Each distinct color corresponds to at least one wavelength in this band.
- Pure Colors: Pure or monochromatic colors do not exist in nature.
- In contrast, some creatures see in other bands of the EM spectrum; e.g., bees can sense UV wavelengths.



source: Christopherson (2000) *Geosystems*

Color in nature

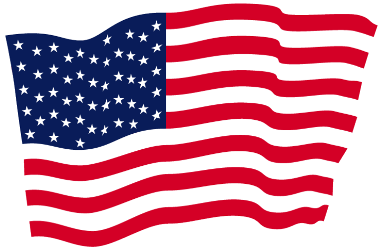
- **Warning**: e.g., poisonous berries

- **Attraction**: e.g., mating plumage

- **State shift**: e.g., changing seasons

Color and culture

- **Symbolic Coding**: e.g., the "red, white and blue"



- **Signalling**: e.g., traffic signals

- **Identity**: e.g., yellow banana is ready to eat

Why study color?

- As a user
  - awareness of influence of color (and good and bad use by others)
  - able to specify colors using appropriate systems
- As a designer
  - graphic design (make a Web page that doesn't cause headaches)
  - UI (create UIs that are effective, fun to use)
- As a programmer and software designer
  - make better tools for others (e.g., color pickers, graphics software)
  - translate between different "color spaces" (e.g., RGB to HSV, CIE)
  - manage color fidelity between input, display and output devices (color management)
  - control interpolation between colors (gradients)
  - also, provides an introduction to some signal processing issues that are important in rendering and image processing

Why is color difficult?

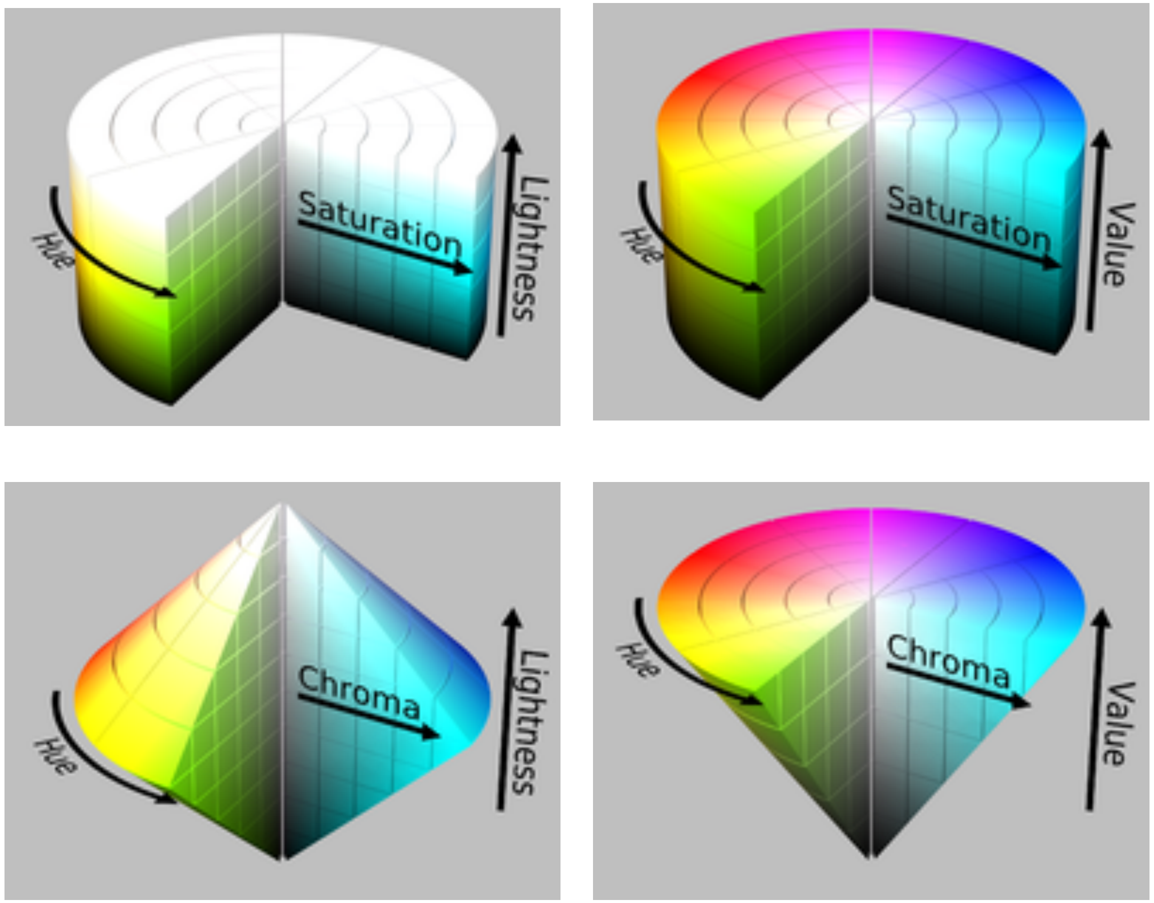
- Color is an immensely complex subject, drawing on physics, physiology, psychology, art, and graphic design
- Many theories, measurement techniques, and standards for colors, yet no one theory of human color perception is universally accepted
- Perceived color of object depends not only on object material but also on light source, color of surrounding area, and human visual system (the eye/brain mechanism)
- Some objects **reflect** *light* (wall, desk, paper), while others also **transmit** *light* (cellophane, glass)
  - surface that reflects only pure blue light illuminated with pure red light appears black
  - pure green light viewed through glass that transmits only pure red also appears black

Achromatic and colored light

- ***Achromatic light***: intensity (quantity of light) only (grayscale)
  - called intensity or luminance if measure of light's energy or brightness
    - the psychophysical sense of perceived intensity
  - gray levels (e.g., from 0.0 to 1.0)
  - seen on black and white TV or display monitors
- ***Chromatic light***:
  - produces visual color sensations
    - brightness/intensity
    - chromaticity/color
      - hue/position in spectrum (red, green, yellow . . .)
      - saturation/vividness
  - generally need 64 to 256 gray levels for continuous-tone images without contouring

Chromatic light

- **Hue** distinguishes among colors such as red, green, purple, and yellow
- **Saturation** refers to how pure the color is, how much white/gray is mixed with it
  - red saturated; pink unsaturated
  - royal blue saturated; sky blue unsaturated
  - pastels are less vivid, less intense
- **Lightness**: perceived achromatic intensity of reflecting object
- **Brightness**: perceived intensity of a self-luminous object, such as a light bulb, the sun, or a CRT
- Perceptual color models: HSL, HSV



HSL **HSV**

https://en.wikipedia.org/wiki/HSL_and_HSV

Psychophysics of color

- Tint, shade, and tone: subjective. Depend on observer's judgment, lighting, sample size, context…
- Colorimetry: quantitative; measurement via spectro-radiometer (measures reflected/radiated light), colorimeter (measures primary colors), etc.
- Physiology of vision, theories of perception still active research areas
- Note: our auditory and visual processing are very different!
  - both are forms of signal processing
  - visual processing integrates/much more affected by context
  - more than half of our cortex devoted to vision
  - vision probably dominant sense, though it is apparently harder to be deaf than blind

Perceptual term	***Colorimetry term***
Hue	Dominant wavelength
Saturation	Excitation purity
Lightness (reflecting objects)	Luminance
Brightness (self-luminous objects)	Luminance

Three Layers of Human Color Perception

- **Receptors in retina** (for color matching)
  - rods, three types of cones (tristimulus theory)
  - primary colors (only three used for screen images: approx. red, green, blue (RGB))
  - Note: receptors each respond to wide range of frequencies, not just spectral primaries
- **Opponent channels** (for perception)
  - other cells in retina and neural connections in visual cortex
  - blue-yellow, red-green, black-white
  - 4 psychological color primaries*: red, green, blue, and yellow
- **Opponent cells** (also for perception)
  - spatial (context) effects, e.g., simultaneous contrast, lateral inhibition

* These colors are called "psychological primaries" because each contains no perceived element of others regardless of intensity. (www.garys-gallery.com/colorprimaries.html)

Receptors in retina

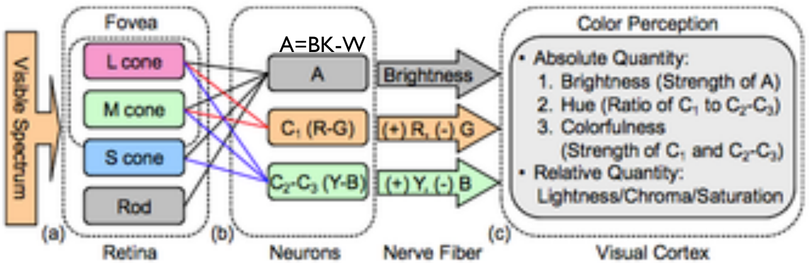
- Receptors contain photopigments that produce electro-chemical response; our dynamic range of light is 10^{11} => division of labor among receptors
- **Rods** (scotopic): only see grays, work in low-light/night conditions, mostly in periphery
- **Cones** (photopic): respond to different wavelengths to produce color sensations, work in bright light, densely packed near center of retina (fovea), fewer in periphery
- Young-Helmholtz tristimulus theory[1]: 3 cone types, sensitive to all visible wavelengths of light, maximally responsive in different ranges
- Three receptor types can produce a 3-space of hue, saturation and value (lightness/brightness)
- To avoid misinterpretations, S (short), M (medium), L (long) often used instead

[1] Thomas Young proposed idea of three receptors in 1801. Hermann von Helmholtz looked at theory from a quantitative basis in 1866. Although they did not work together, theory is called Young-Helmholtz theory since they arrived at same conclusions.

Opponent channels

- The opponent color theory (Hering theory) suggests that there are three opponent channels: red versus green, blue versus yellow, and black versus white (the last type is achromatic and detects light-dark variation or luminance)
- Additional neural processing
  - three receptor elements have excitatory (+) and inhibitory (-) connections with neurons higher up that correspond to opponent processes
  - one pole activated by excitation, other by inhibition
- All colors can be described in terms of 4 "psychological color primaries" R, G, B, and Y
- However, a color is never reddish-greenish or bluish-yellowish: idea of two "antagonistic" opponent color channels, red-green and yellow-blue

opponent colors



K – black
W - white

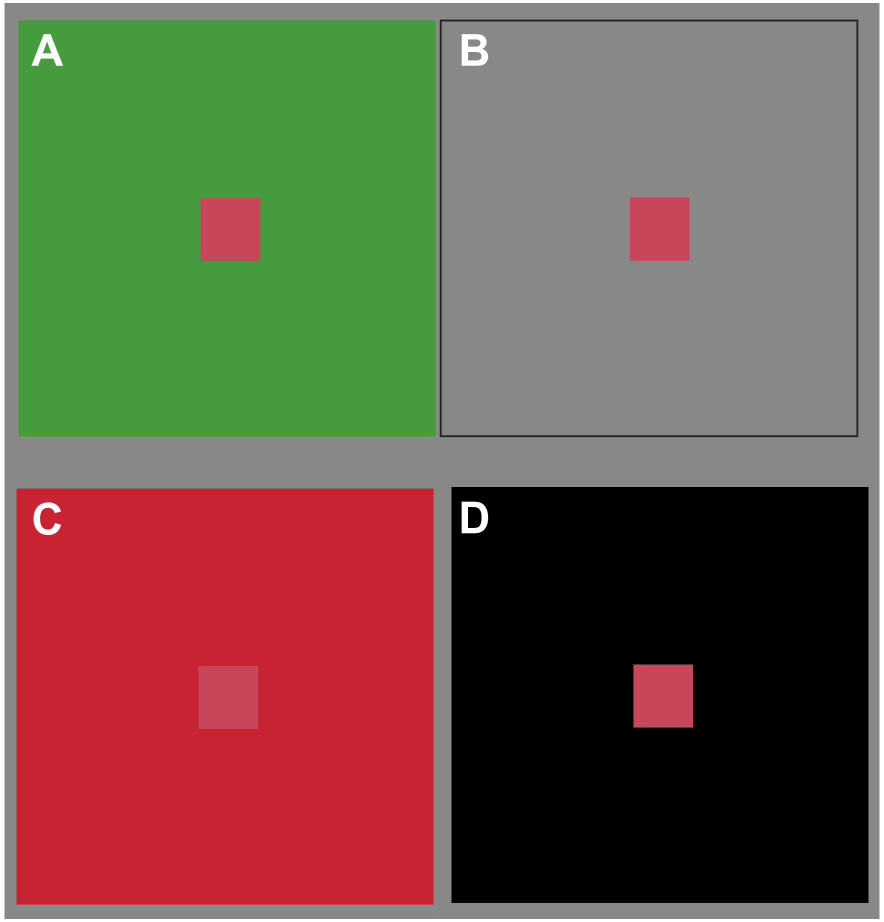
color opponent process

https://en.wikipedia.org/wiki/Opponent_process

Double-opponent cells

- The color perception in the cortex results from the combined activity of two kinds of color-sensitive neurons: single-opponent and double-opponent cells.
- Double-opponent cells (located in opponent channels) are also spatially opponent, and are responsible for a type of lateral inhibition, which is responsible by the contrast enhancement at boundaries between regions: edge detection.
- Double-opponent cells are responsible for effects of simultaneous contrast and afterimages.
- An afterimage is an image that remains to appear after ceasing the exposure of someone to the original image. This phenomenon may be a normal (physiological afterimage) or may be pathological (palinopsia).
- Color perception strongly influenced by context, training, etc., abnormalities such as color blindness (affects about 8% of males, 0.4% of females)

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3121536/

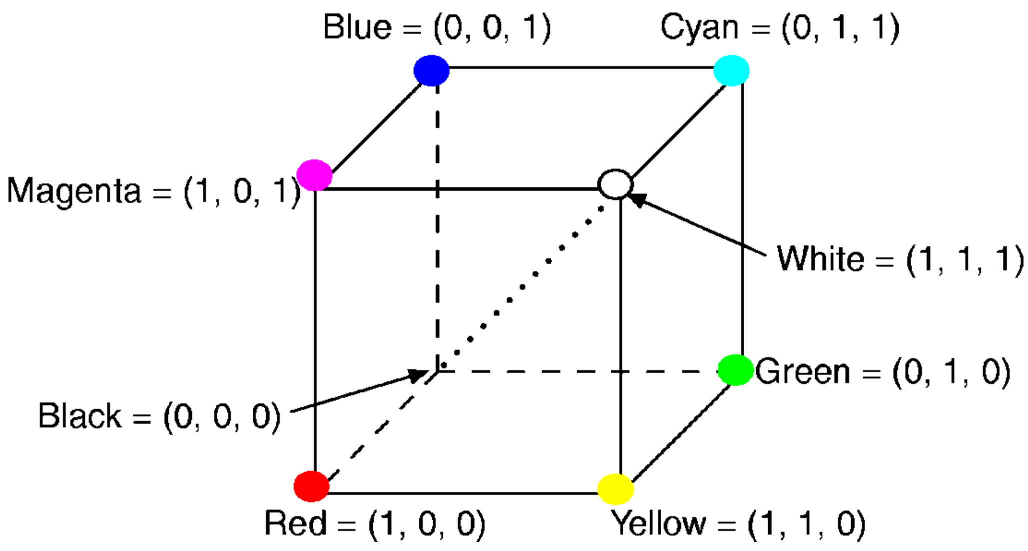


Color contrast, brightness contrast and color appearance. All four central squares have identical wavelength spectra. Yet the color appearance of each central square can be strongly influenced by the surrounding region. (A) the red disk surrounded by an equilluminant green or (B) an equilluminant grey results in a saturated red disk. (C) when the surround is red but reduced in luminance compared to the central patch then the central red square appears a desaturated pink and almost white. (D) The red square on a black background results in the perception of reduced saturation and increased apparent brightness, a bright pink square.

Color Models

RGB

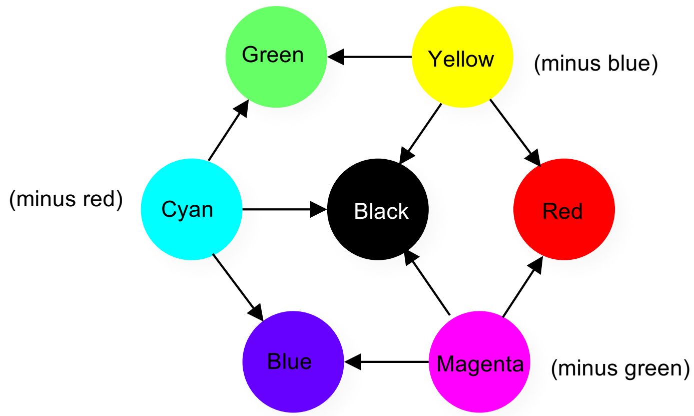
- It applies to computer screens
- RGB primaries are additive
- Main diagonal => gray levels
  - black is (0, 0, 0)
  - white is (1, 1, 1)
-



CMYK

- Used in electrostatic and in ink-jet plotters that deposit pigment on paper
- Cyan, magenta, and yellow are complements of red, green , and blue
- Subtractive primaries: colors are specified by what is removed or subtracted from white light, rather than by what is added to blackness
- Cartesian coordinate system
- Subset is unit cube
  - white is at origin, black at (1, 1, 1)

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



subtractive primaries (cyan, magenta, yellow) and their mixtures

YIQ

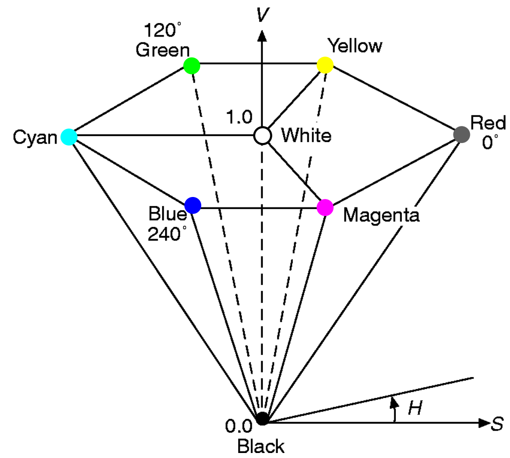
- Recoding for RGB for transmission efficiency and downward compatibility with B/W broadcast TV; used for NTSC (National Television Standards Committee (cynically, "never the same color"))
- Y is luminance – same as CIE Y primary
- I and Q encode chromaticity
- DEMO: http://www.cs.rit.edu/~ncs/color/a_spaces.html
- Only Y (= 0.3R + 0.59G + 0.11B) shown on B/W monitors:
  - weights indicate relative brightness of each primary
  - assumes white point is illuminant C:

    $x_w = 0.31$, $y_w = 0.316$, and $Y_w = 100.0$

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

HSV

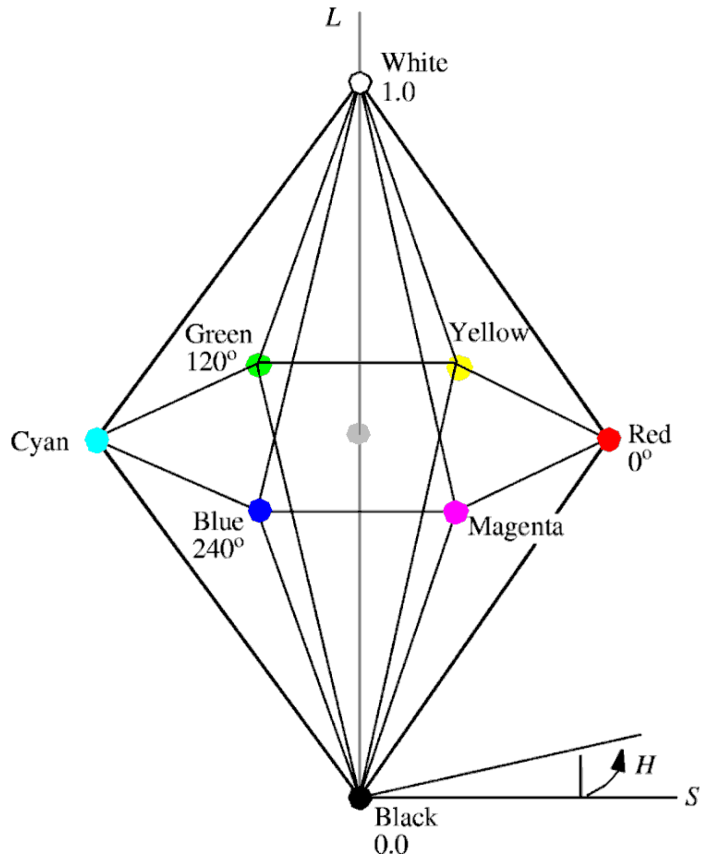
- Hue, saturation, value (brightness)
- HSB-space invented by Alvy Ray Smith—described in his 1978 SIGGRAPH paper, *Color Gamut Transformation Pairs*.
- Hexcone subset of cylindrical (polar) coordinate system
- DEMO: http://www.cs.rit.edu/~ncs/color/a_spaces.html
- Has intuitive appeal of the artist's tint, shade, and tone model. Based on perceptual variables vs. monitor phosphor colors
  - pure red = H = 0, S = 1, V = 1; pure pigments are (1, 1, 1)
  - tints: adding white pigment n decreasing S at constant V
  - shades: adding black pigment n decreasing V at constant S
  - tones: decreasing S and V



Single hexcone HSV color model. (The V = 1 plane contains the RGB model's R = 1, G = 1, B = 1, in the regions shown)

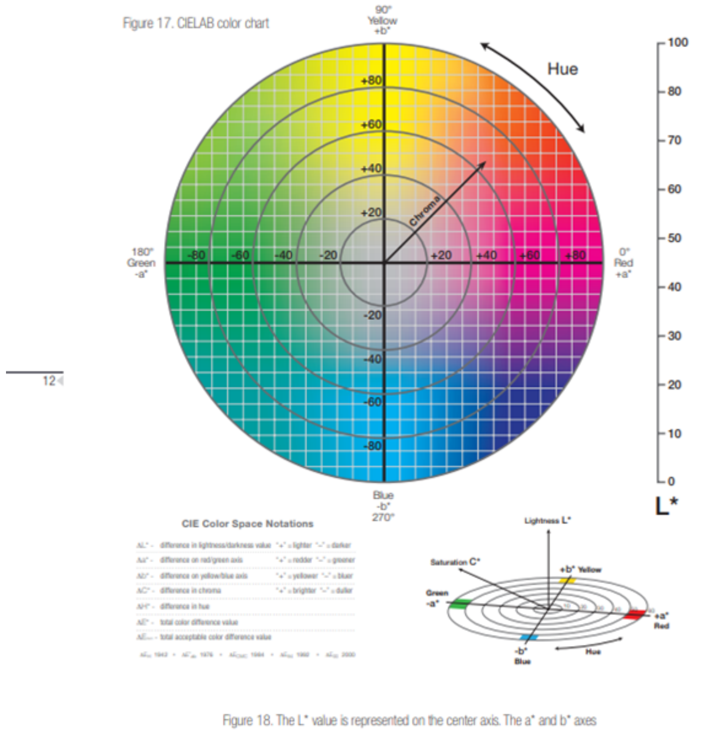
HSL

- Hue, lightness, saturation
- Double-hexcone subset
- Maximally saturated hues are at S = 1, L = 0.5
- Less attractive for sliders or dials
- Neither V nor L correspond to Y in YIQ!
- Conceptually easier for some people to view white as a point

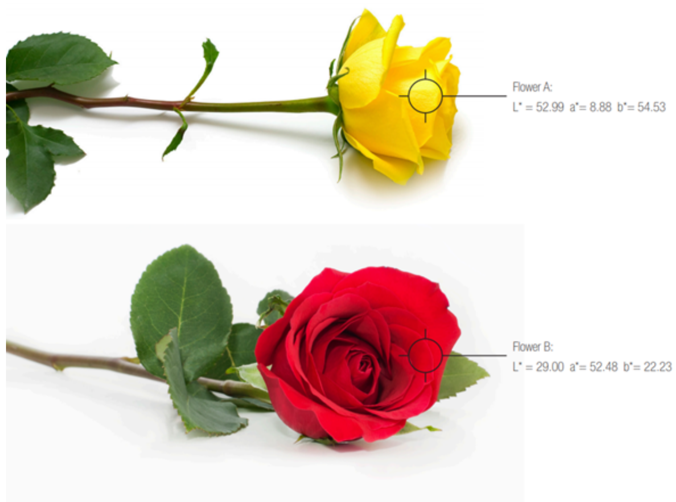


CIE Lab

Taken from https://www.xrite.com/blog/lab-color-space



- CIE Lab was introduced in 1976
  - popular for use in measuring reflective and transmissive objects
- Three components: L^* (luminosity), a^* (red/green axis), and b^* is yellow/blue axis
- Mathematically described space and a perceptually uniform color space:
  - move through color space from color C_1 to a new color C_1' through a distance ΔC: $C_1' = C_1 + \Delta C$
  - move through the same distance ΔC, starting from a different color C_2: $C_2' = C_2 + \Delta C$
  - the change in color in both cases is mathematically equal, and it is also perceived as equal
- RGB, HSV, HSL are not perceptually uniform.
- Historically, the first perceptually-uniform color space was the Munsell system (early 1900s)



Summing up pros and cons

- **RGB**

  + Cartesian coordinate system

  + hardware-based (easy to transform to video)

  + tristimulus-based

  - hard to use to pick and name colors

  - doesn't cover gamut of perceivable colors

  - non-uniform: equal geometric distance => unequal perceptual distance

- **HSV**

  + easy to convert to RGB

  + easy to specify colors/intuitive

  - doesn't cover gamut of perceivable colors

  - non-uniform

- **CIE**

  + covers gamut of perceived colors

  + based on human perception (matching experiments)

  + linear

  + contains all other spaces

  - non-uniform (but CIE Lab is closer to Munsell)

  - xy-plot of chromaticity horseshoe diagram doesn't show luminance

- **CIE Lab**

  + perceptually uniform

  + based on psychological colors (y-b, r-g, w-b)

  - no visualization of the color space

  - very difficult to determine what values mean if you are unfamiliar with the space

  - primarily used to convert between RGB and CMYK

Summary

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FIM