01076566 Multimedia Systems

Chapter 4: Color Theory

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Outline

- The color problem
- Trichromacity theory
- Color calibration
- Color space
- Gamma correction and monitor calibration

The Color Problem

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- The expectation is that the rendered or reproduced color image on the end terminal should "**look the same**" as the color image of the original object, irrespective of which device captured the visual image, or which is rendering it.

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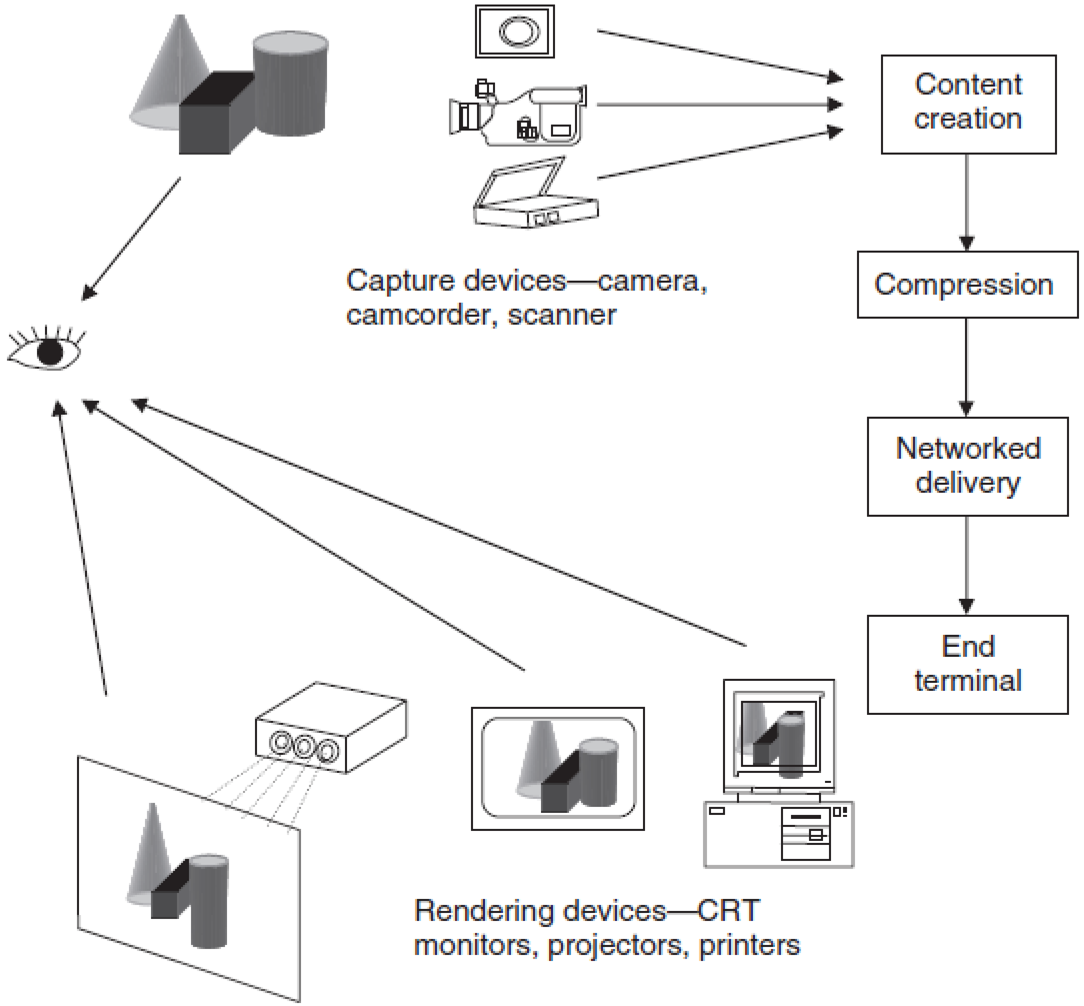

History of Color and Light

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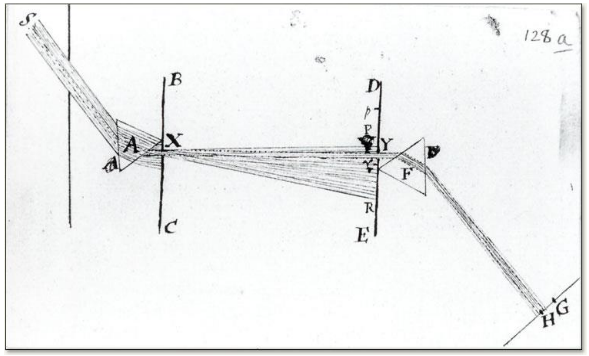

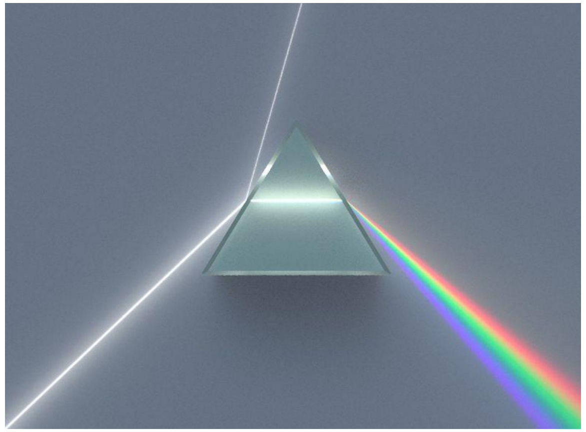

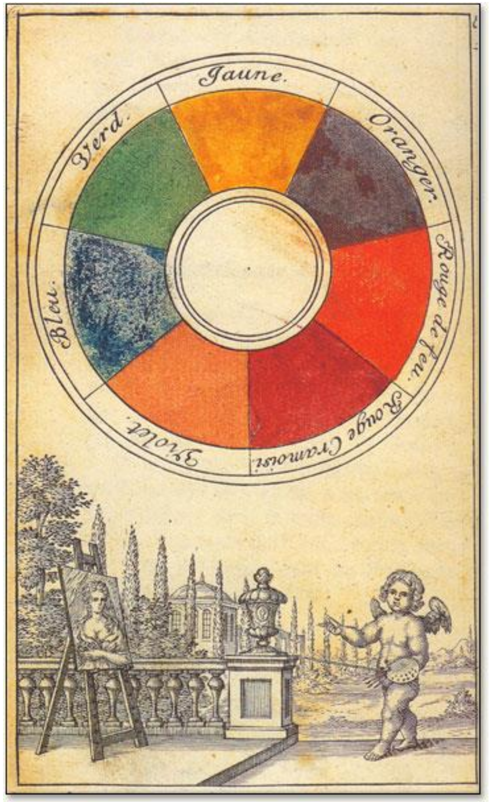

The Nature of Light

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- The visible spectrum of white light contains all wavelengths from 400 to 700 nanometers
- Wavelengths below 400 nm (known as ultraviolet)
- Wavelengths above 700 nm (known as infrared)

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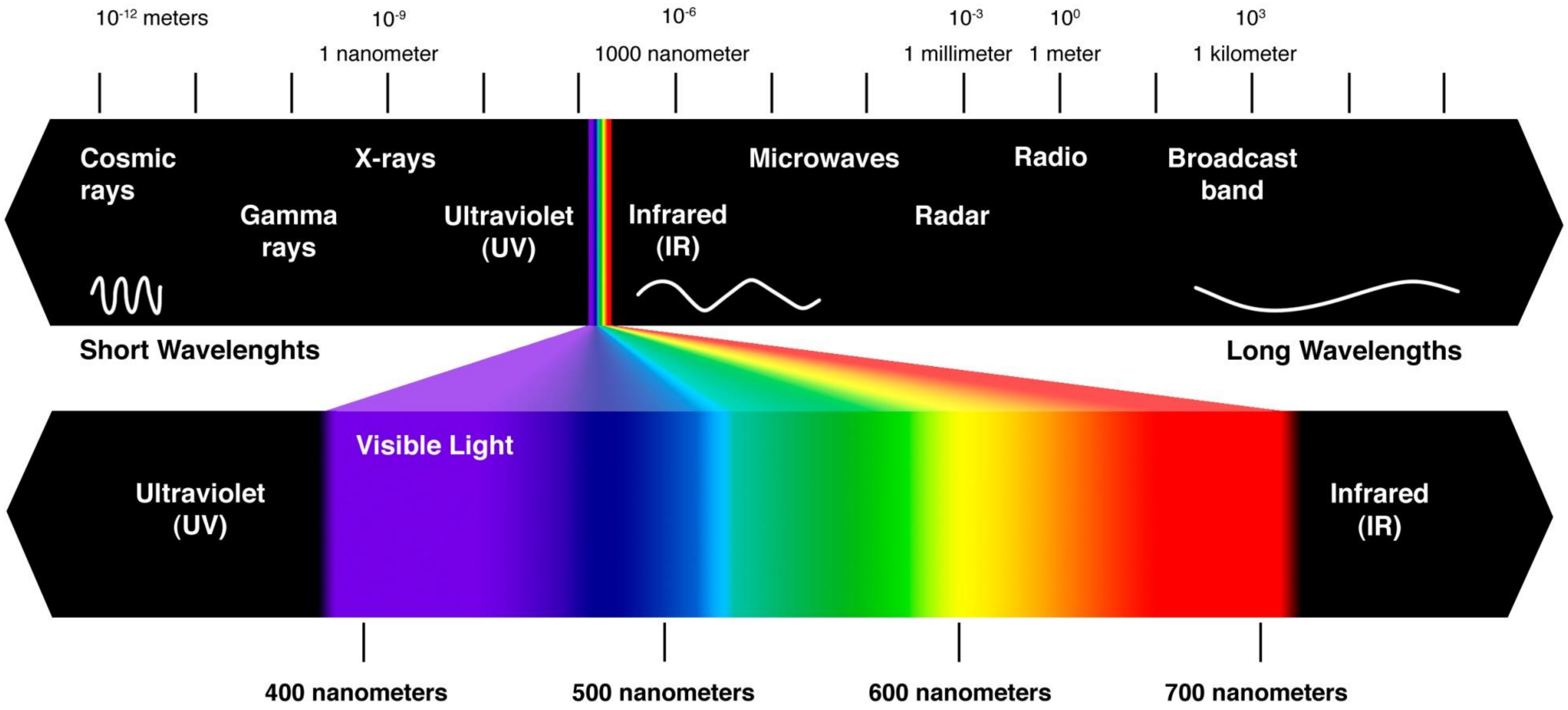

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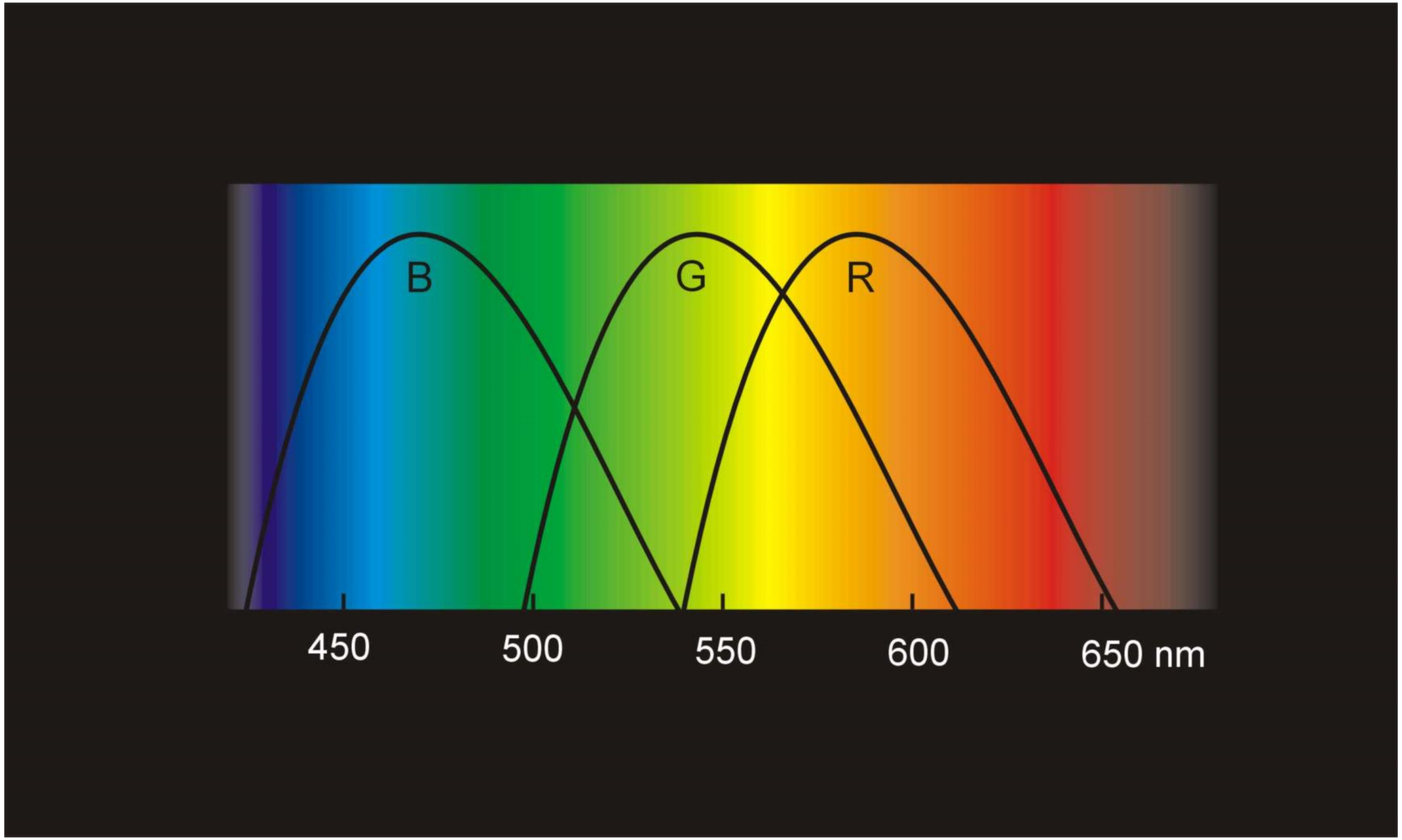

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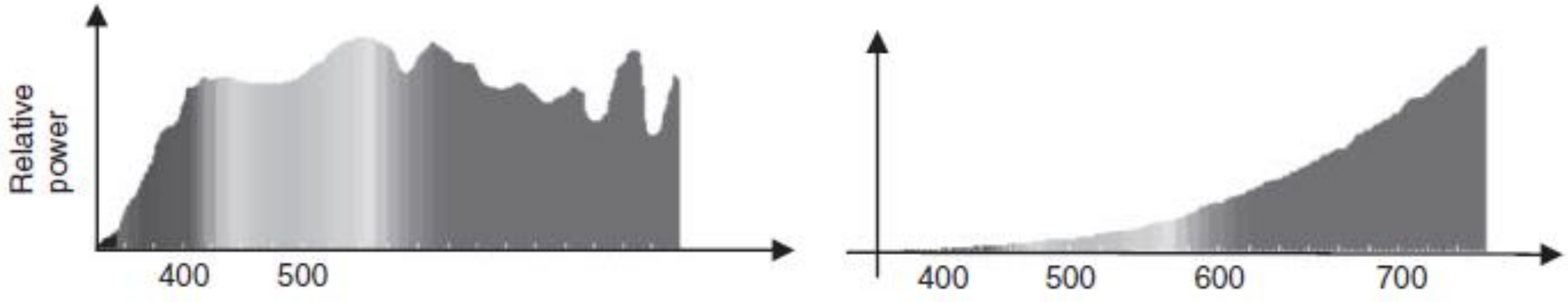

The distribution of relative spectral power density for the spectra from daylight (left) and an incandescent light (right).

Theories of Computer Vision

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- Young-Helmholtz theory proposes a theory of trichromatic color vision

Thomas Young

Hermann von Helmholtz

Human Color Sensing

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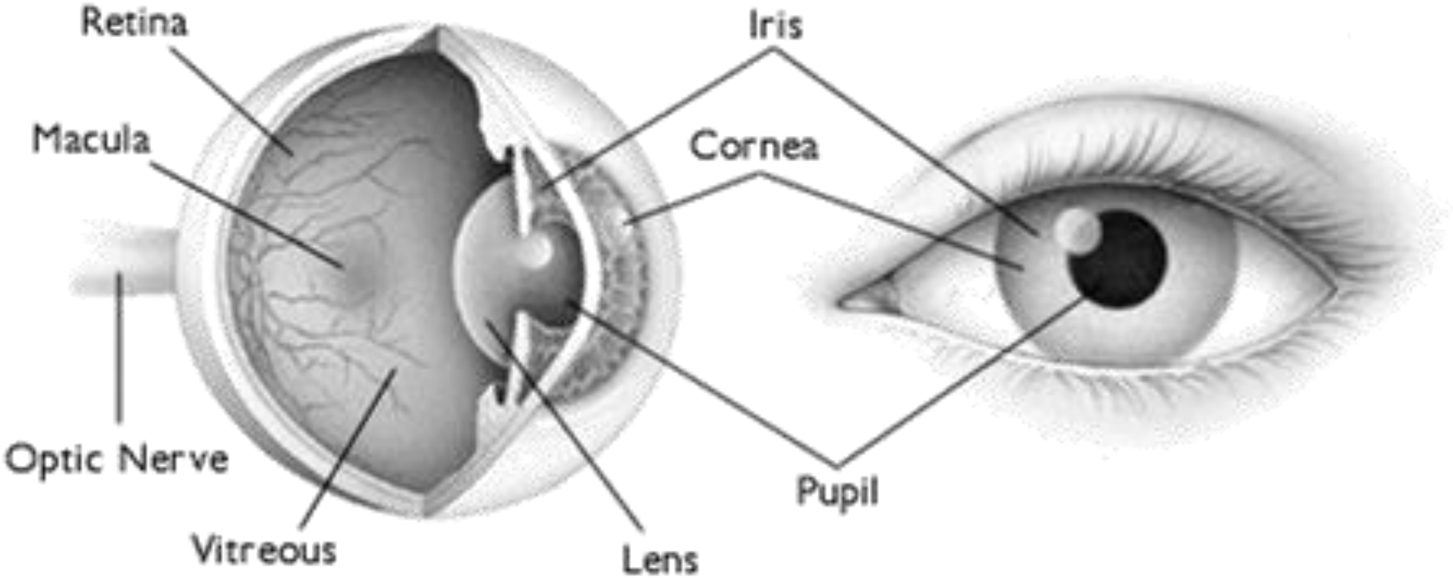

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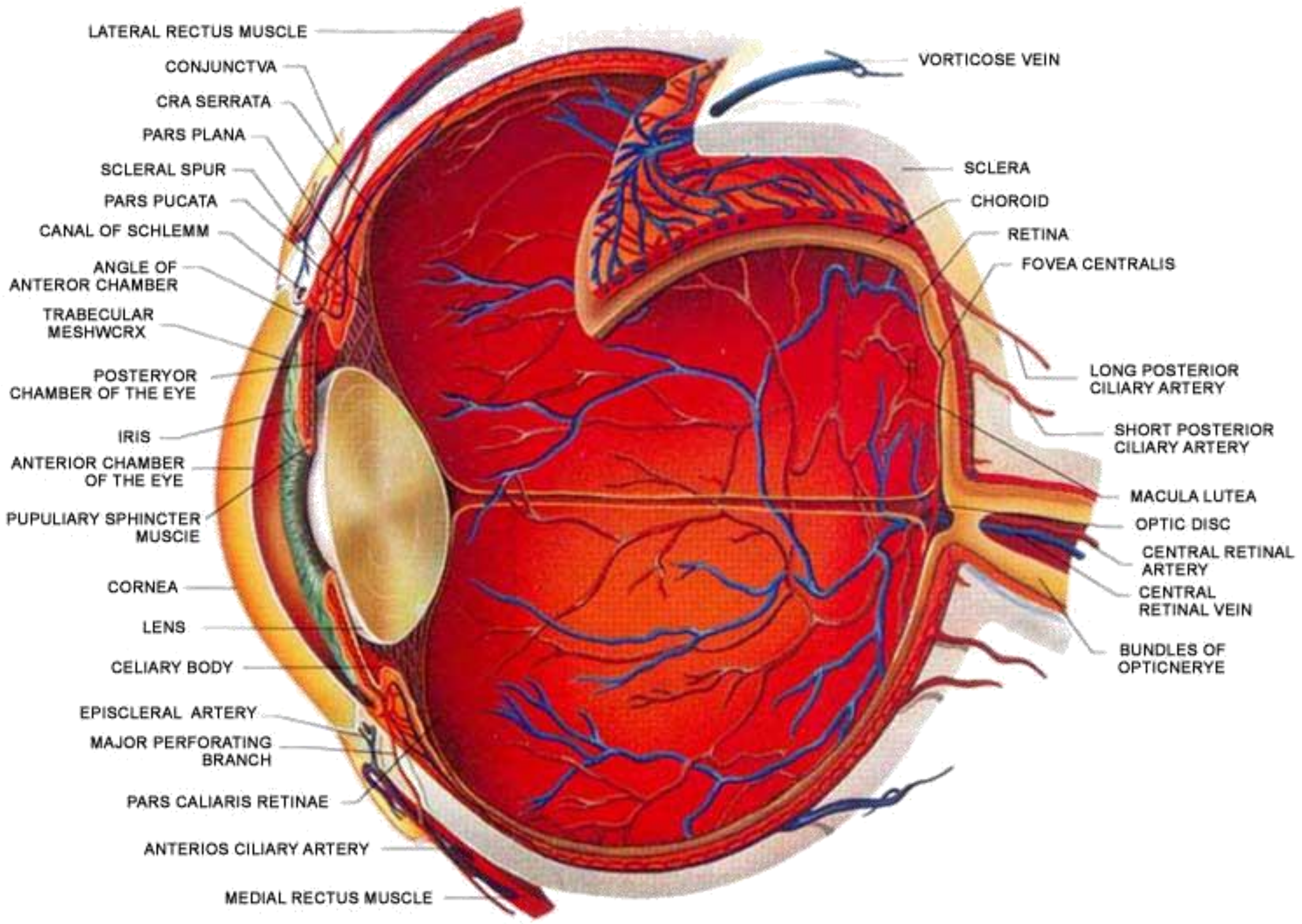

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- The eyes sense illumination using photoreceptors on the retina
- The retina contains two types of photoreceptors: rods (≈ 120 million) and cones (≈ 7 million)
- The rods are (a thousand times) more sensitive and distributed more uniformly than cones
- The cones are more concentrated near the fovea
- The cones are of three different types
  - "red" cones
  - "green" cones
  - "blue" cones

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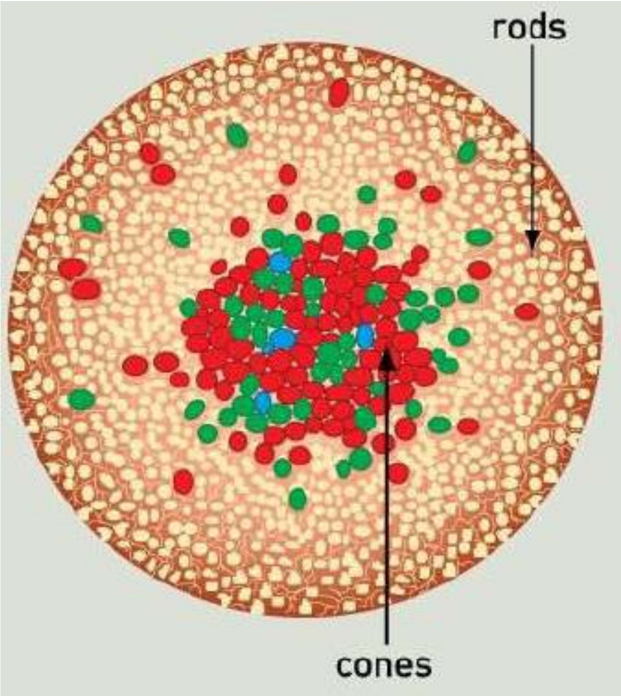

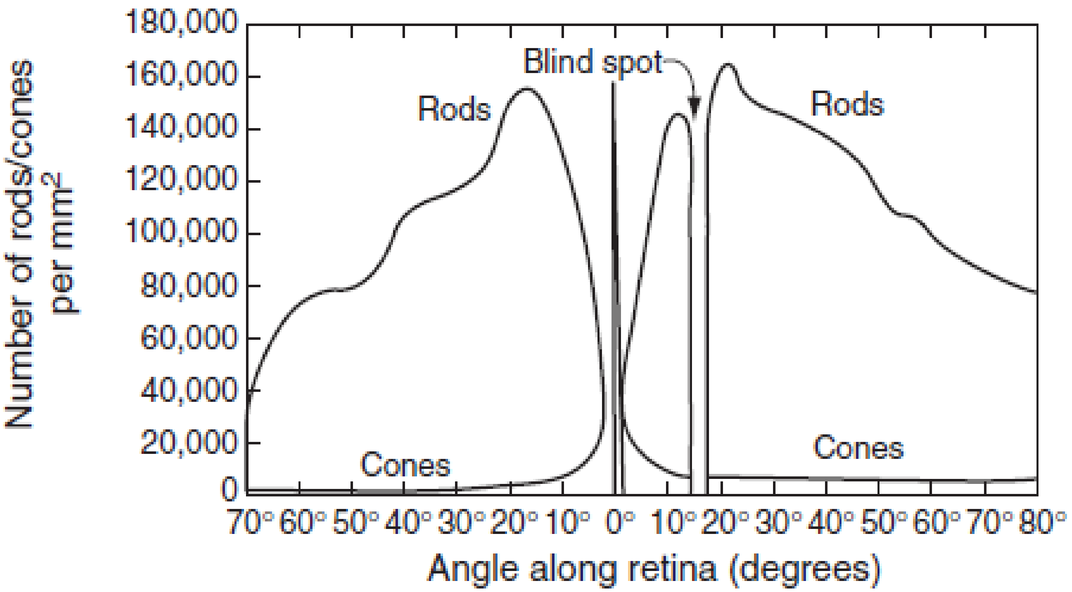

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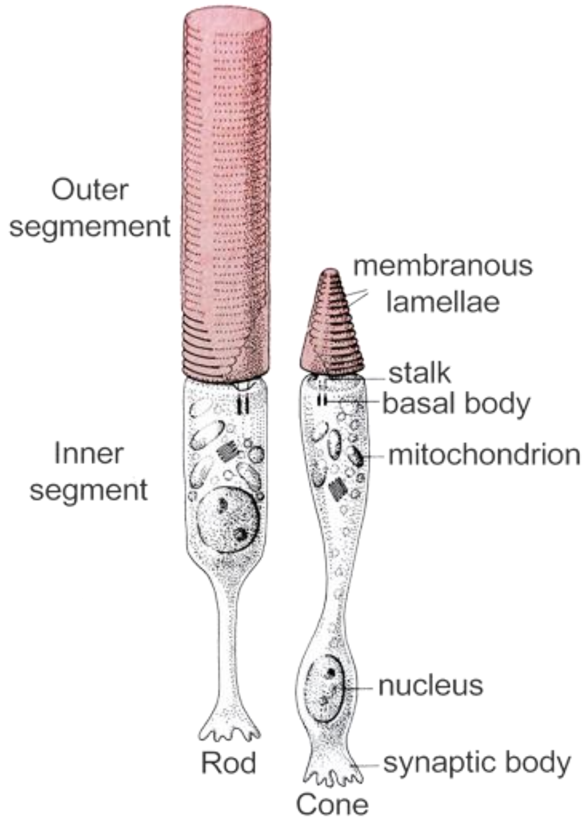

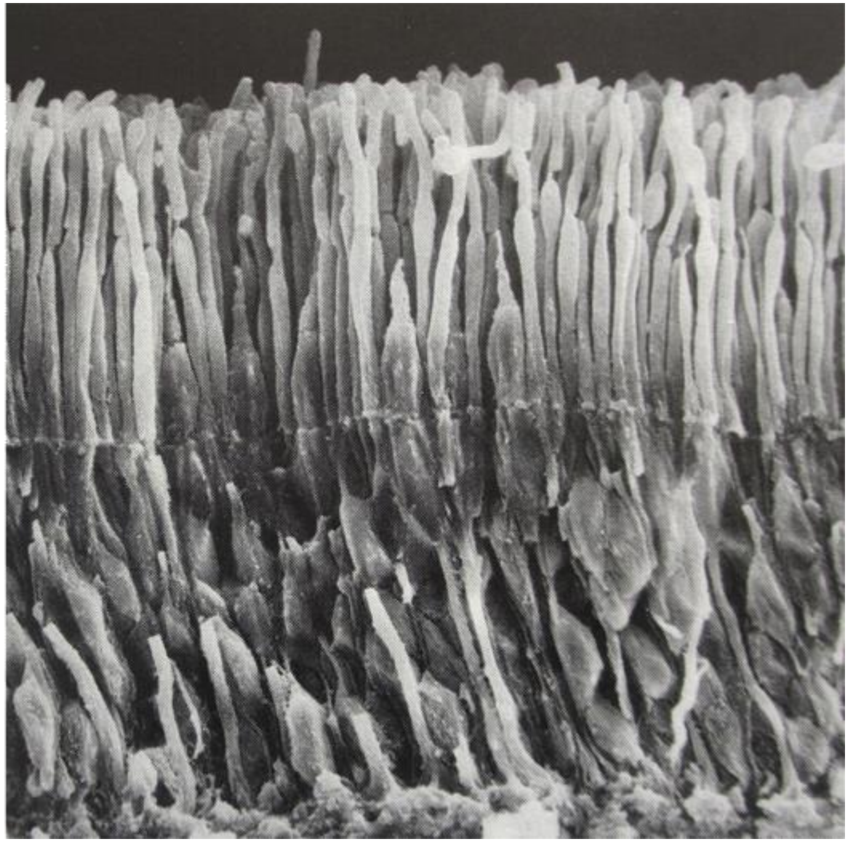

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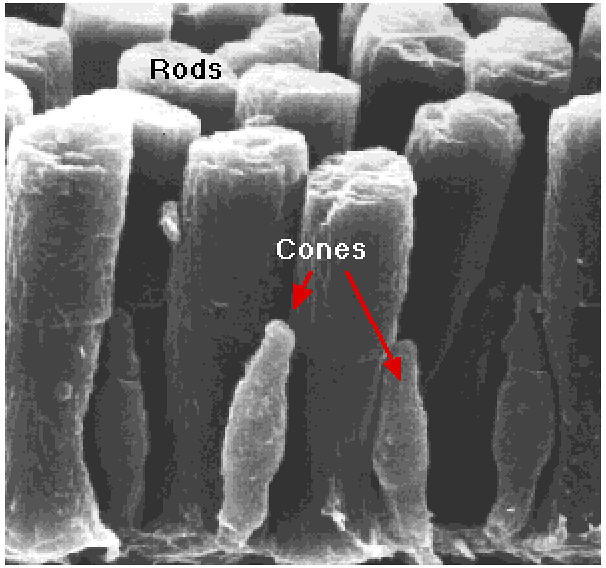

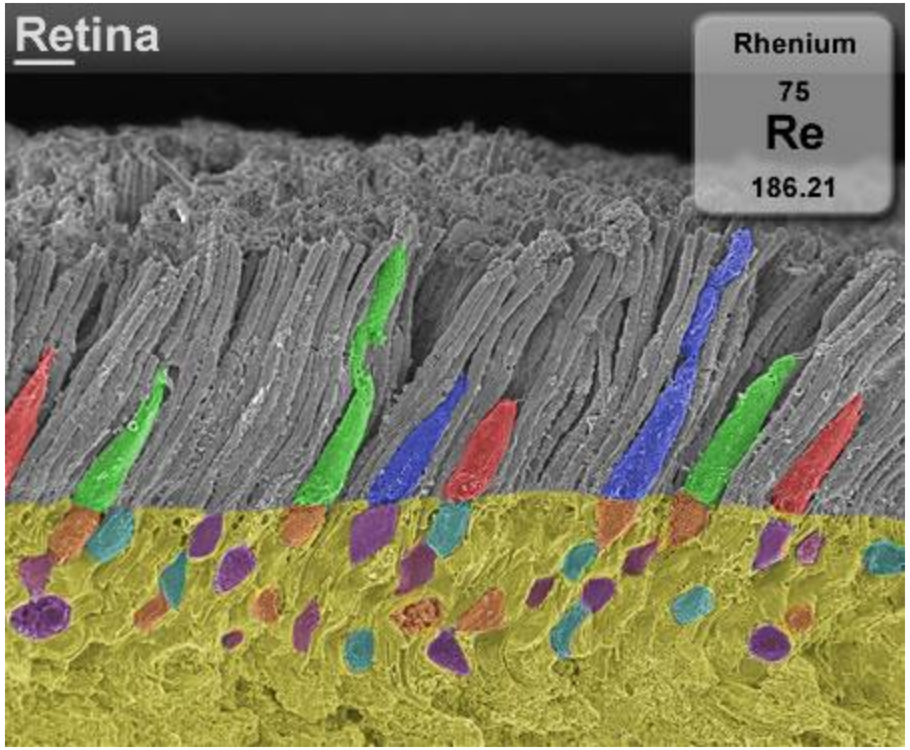

Cones : R=60%, G=36%, B=4%

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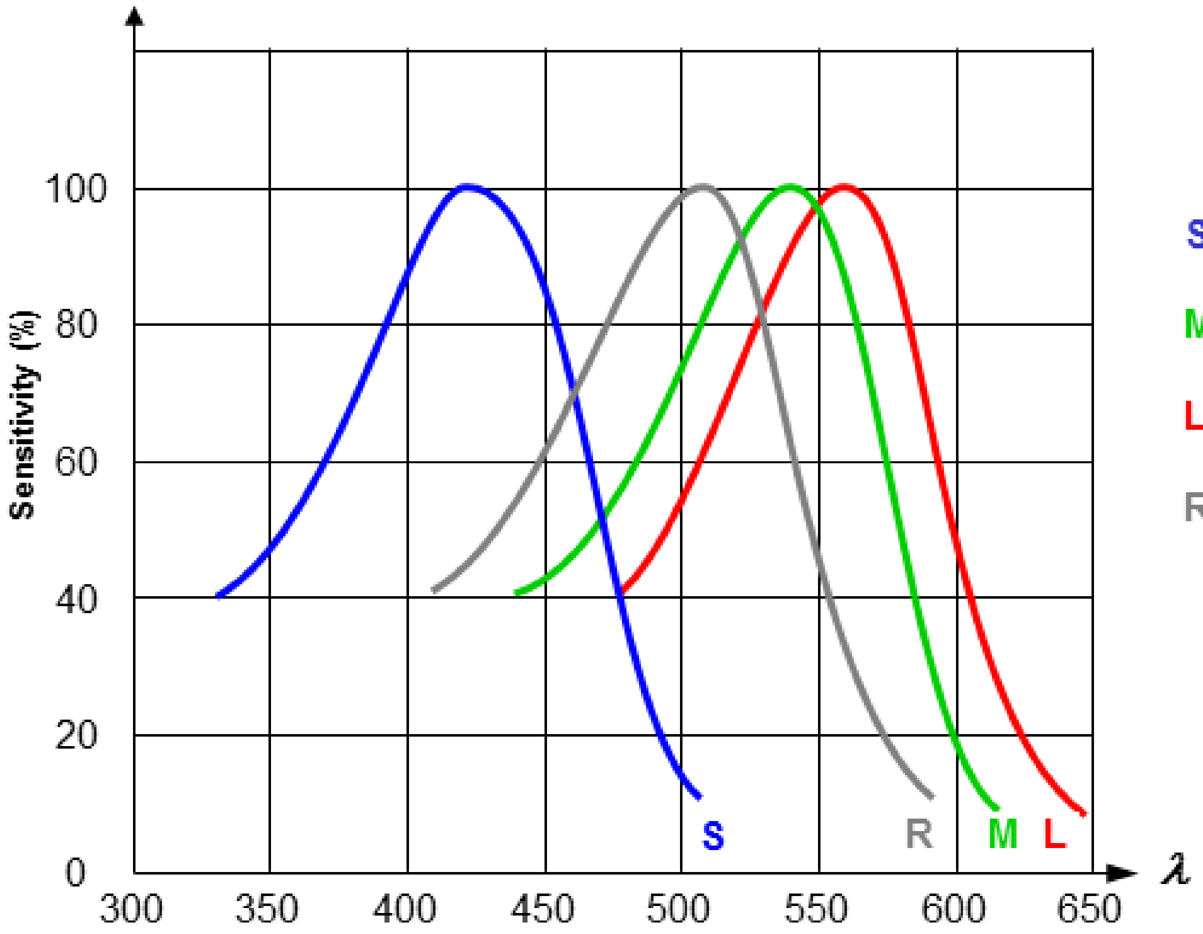
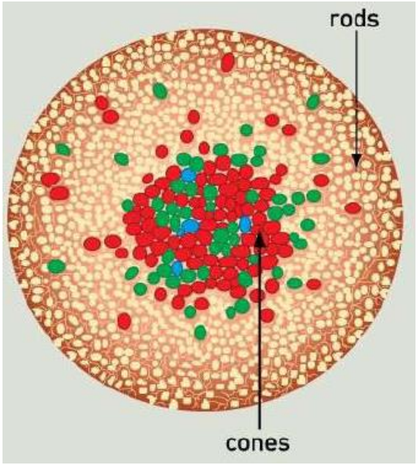


S: Cones sensitive to blue

M: Cones sensitive to green

L: Cones sensitive to red

R: Rods



Let's test our eyes

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Ishihara test

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- A color perception test for **red-green** color deficiencies.
- Named after its designer, **Dr. Shinobu Ishihara**, a professor at the **University of Tokyo**, who first published his tests in 1917

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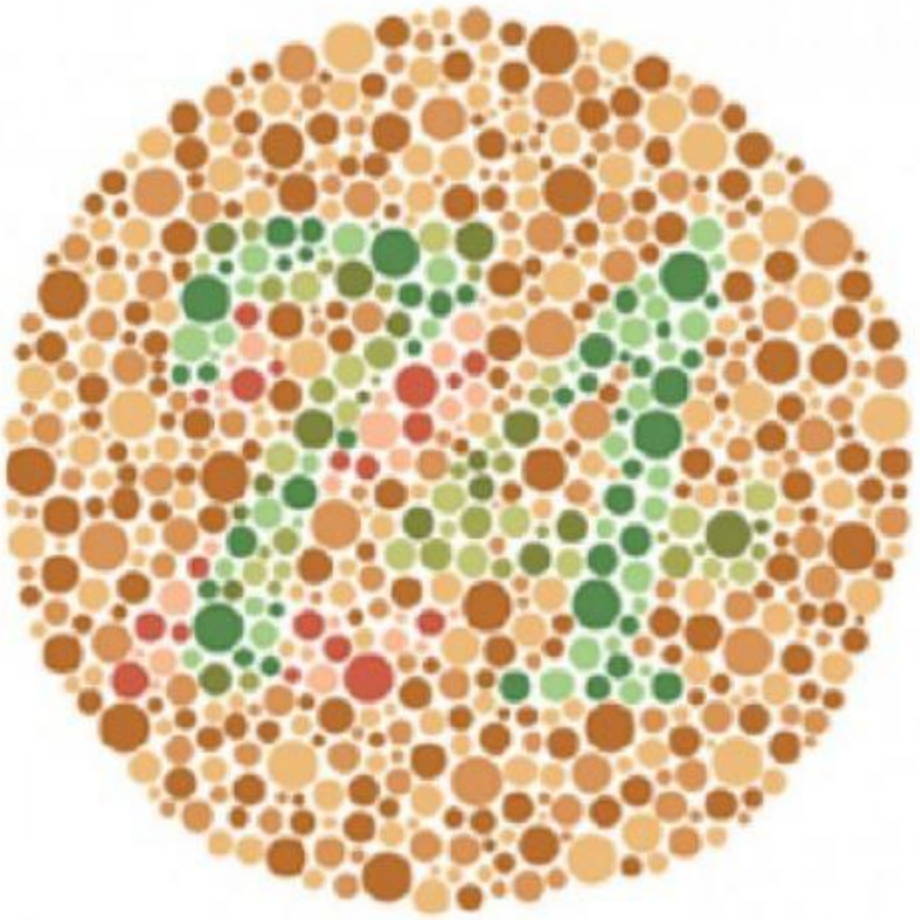

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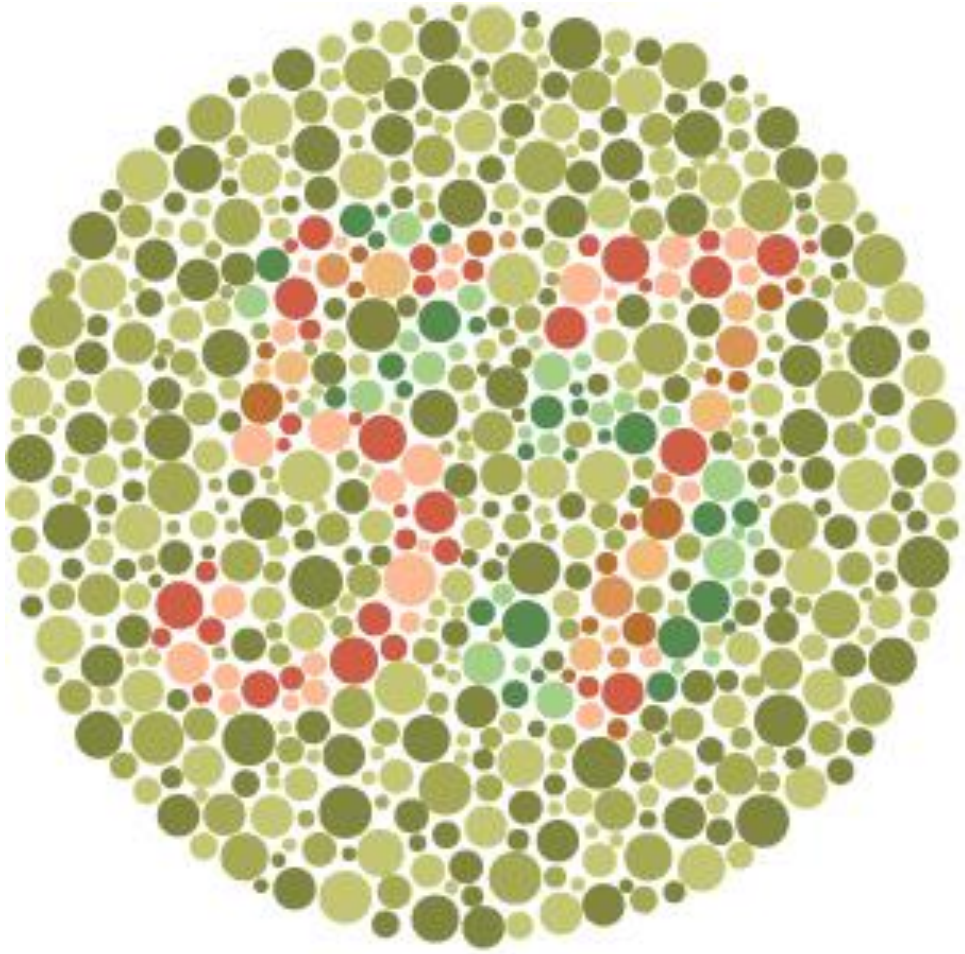

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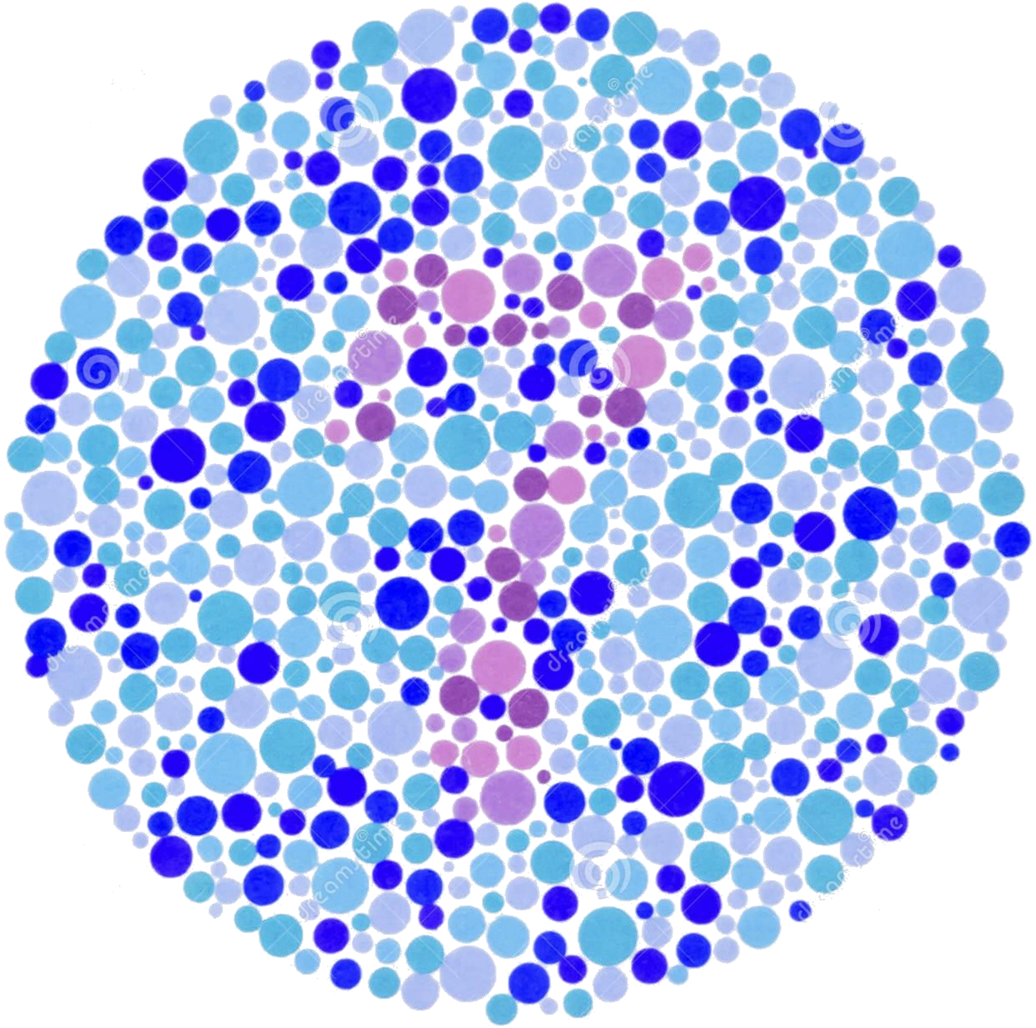

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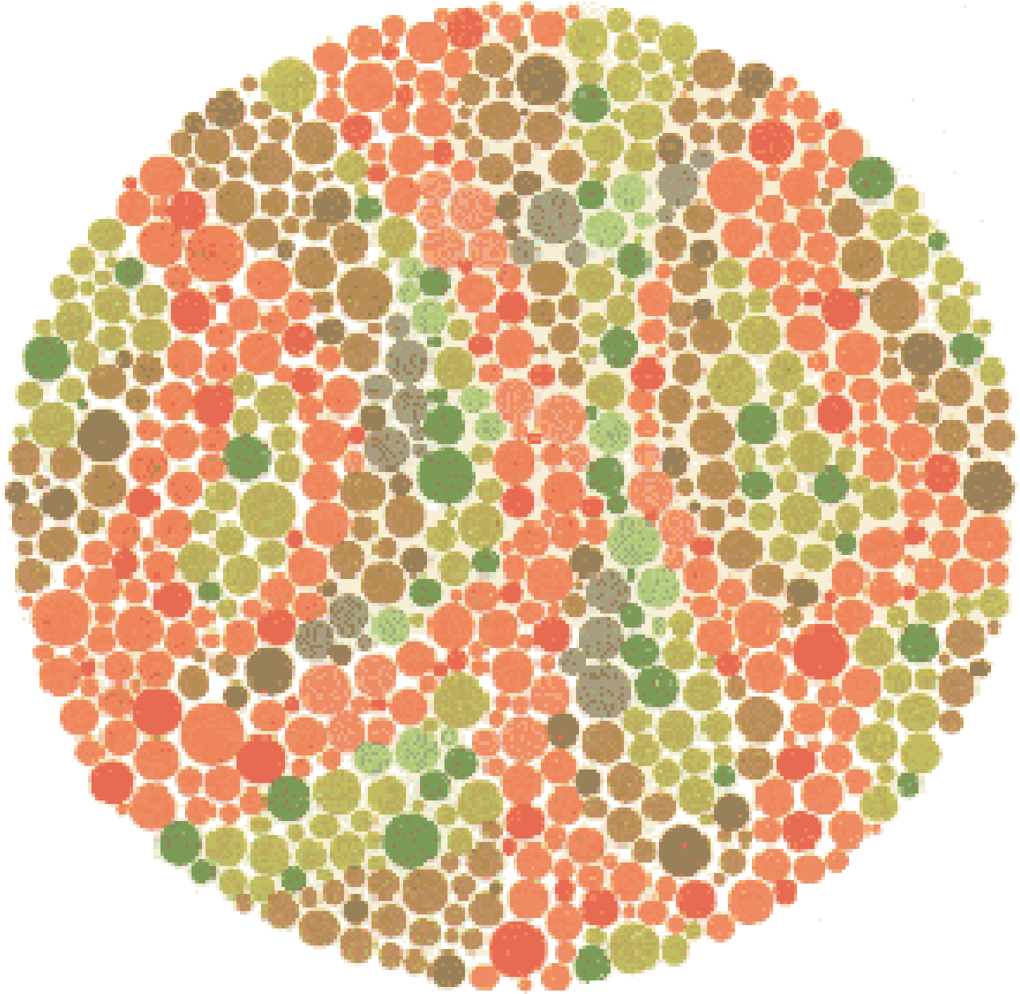

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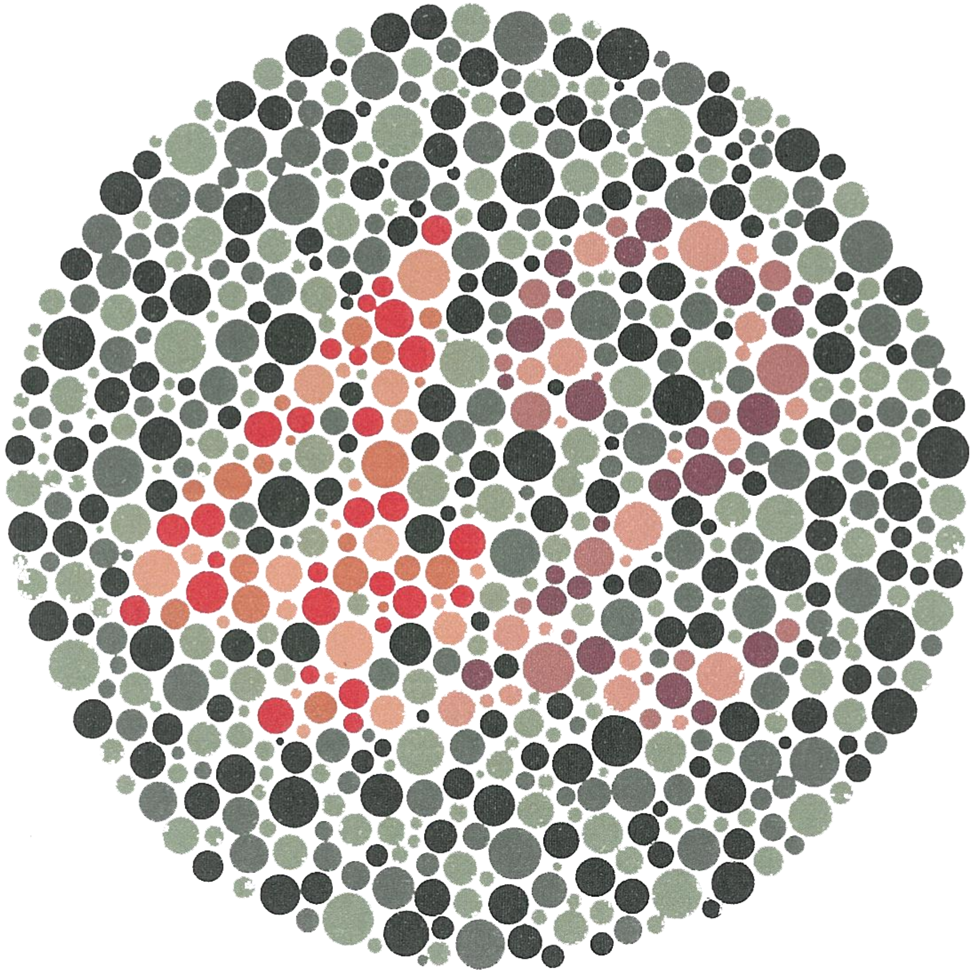

Types of Color Blindness

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- **Trichromacy**
  - Normal color vision uses all three types of light cones correctly and is known as **trichromacy**. People with normal color vision are known as **trichromats**.
- **Protanomaly**
  - a reduced sensitivity to red light.
- **Deuteranomaly**
  - a reduced sensitivity to green light and is the <u>most common form of color blindness</u>.
- **Tritanomaly**
  - a reduced sensitivity to blue light and is extremely rare.

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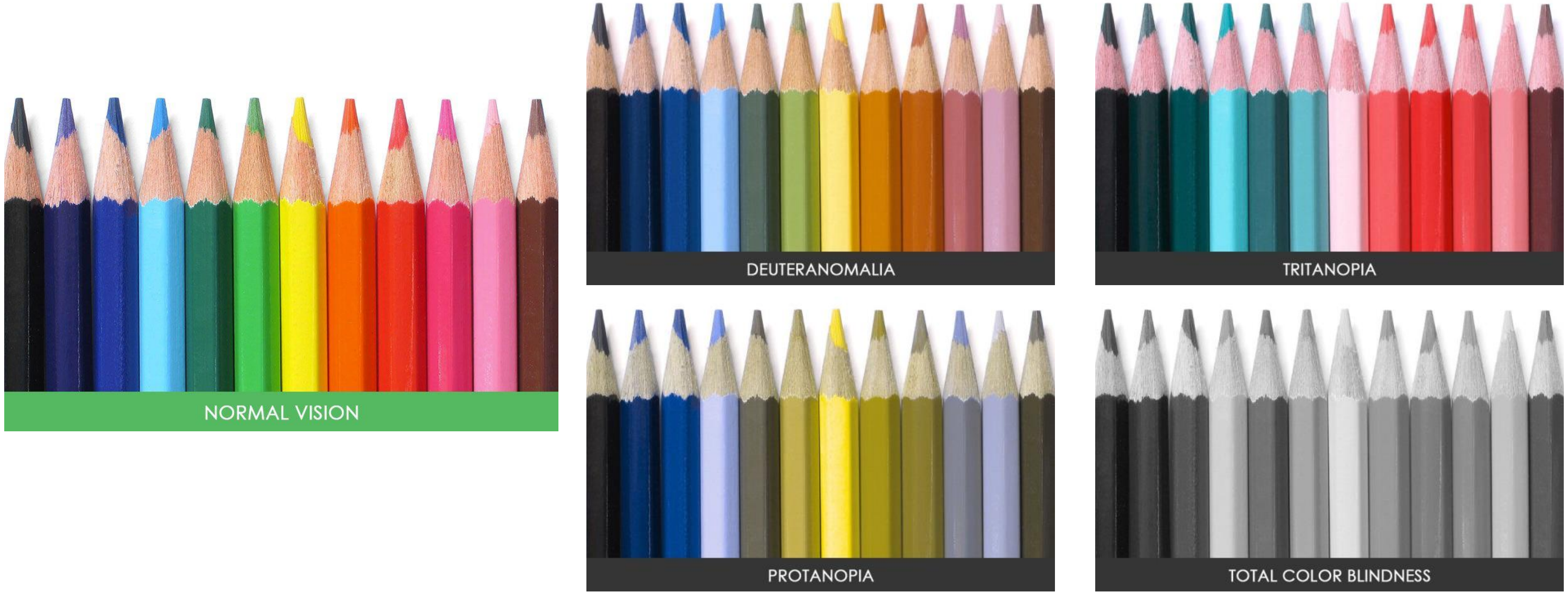

http://ce.upyim.co/20004/
Retrieved on May 1, 2017

Protanomaly : reduced sensitivity to red light.
Deuteranomaly : reduced sensitivity to green.
Tritanomaly : reduced sensitivity to blue light.

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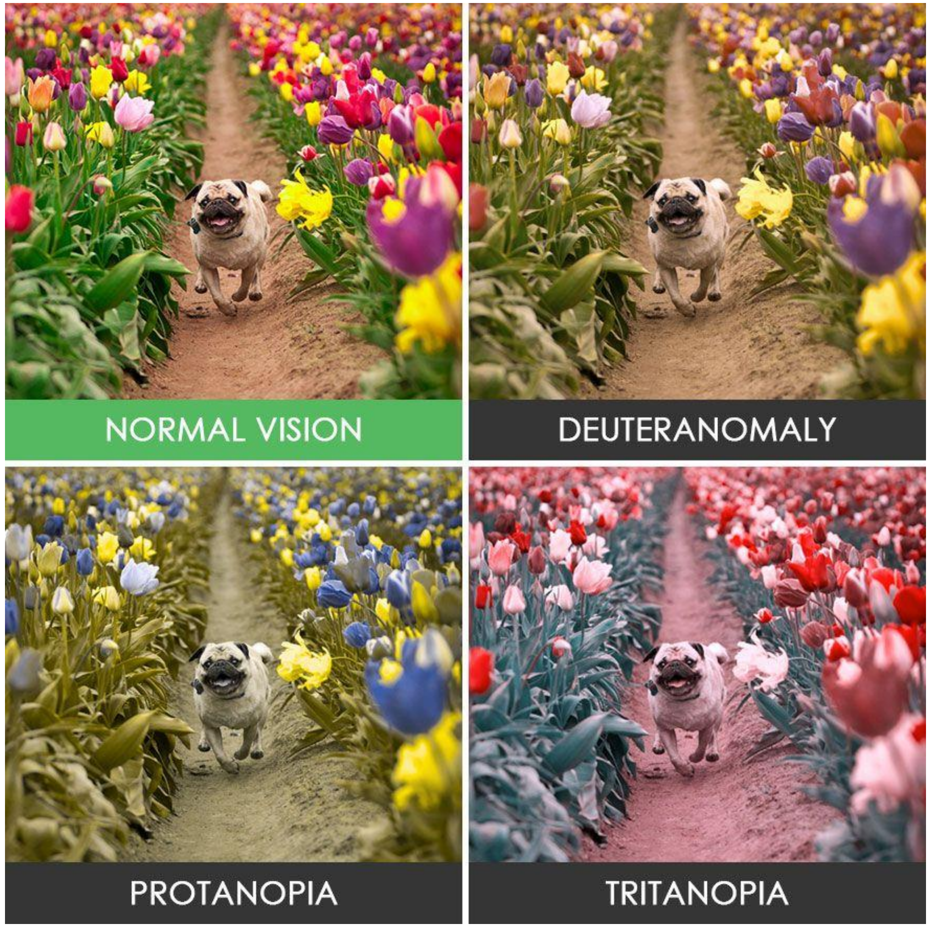

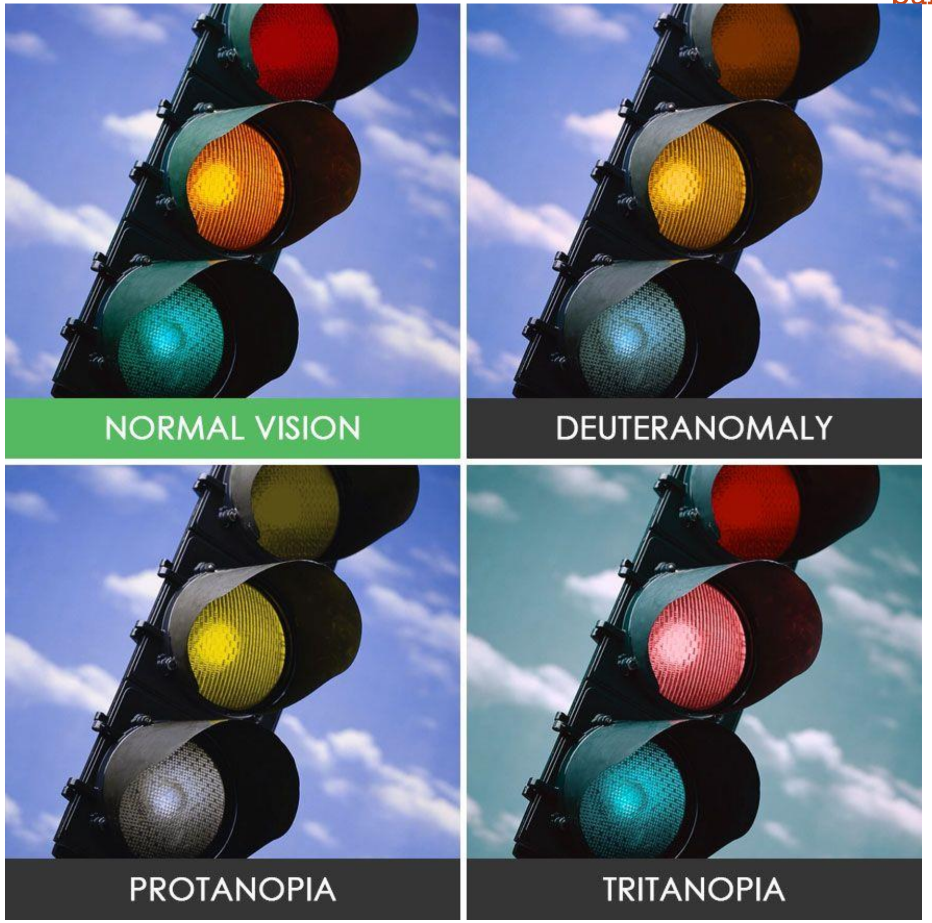

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Human Color Perception

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- Ewald Hering proposed opponent color theory
- Color perception is not a strictly local process, but depends on a spatial neighborhood

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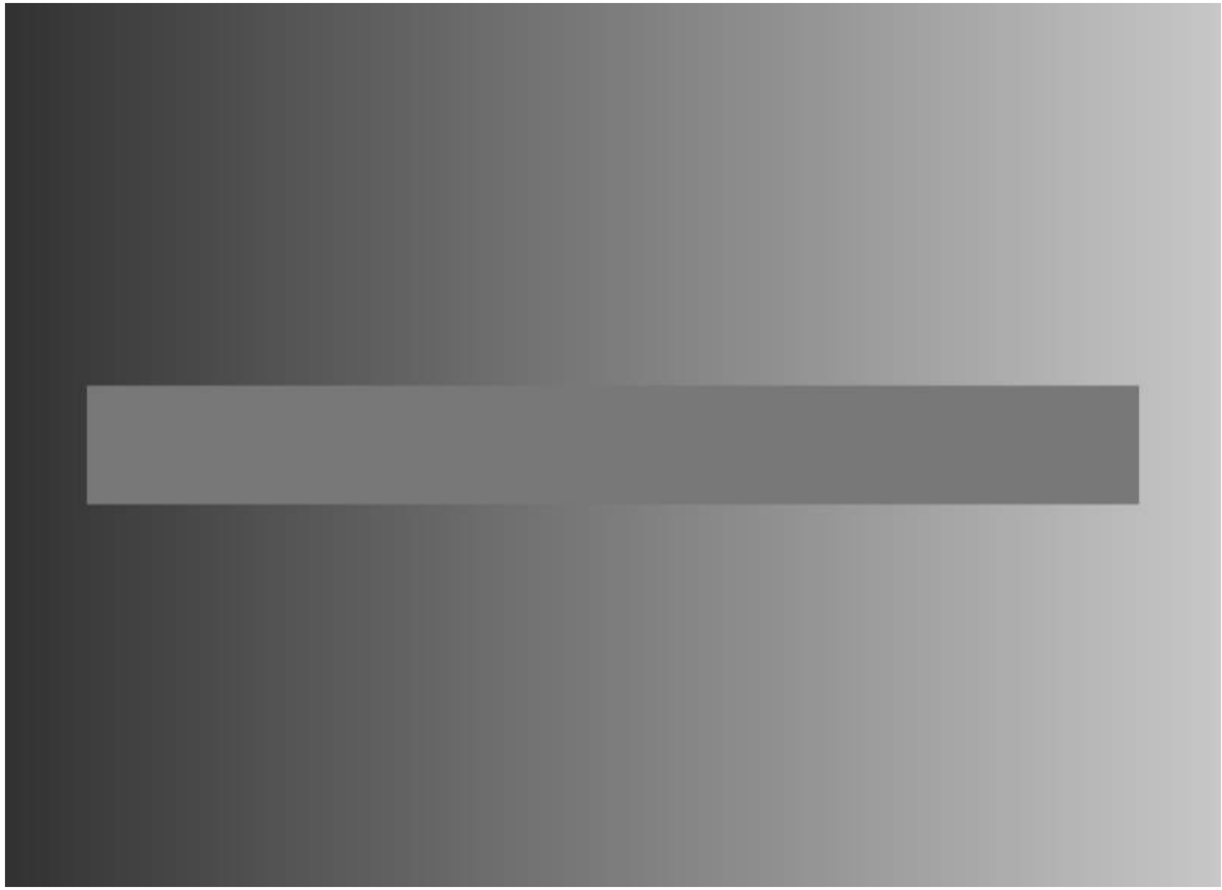

A region looks much darker when the
surrounding region is more illuminated

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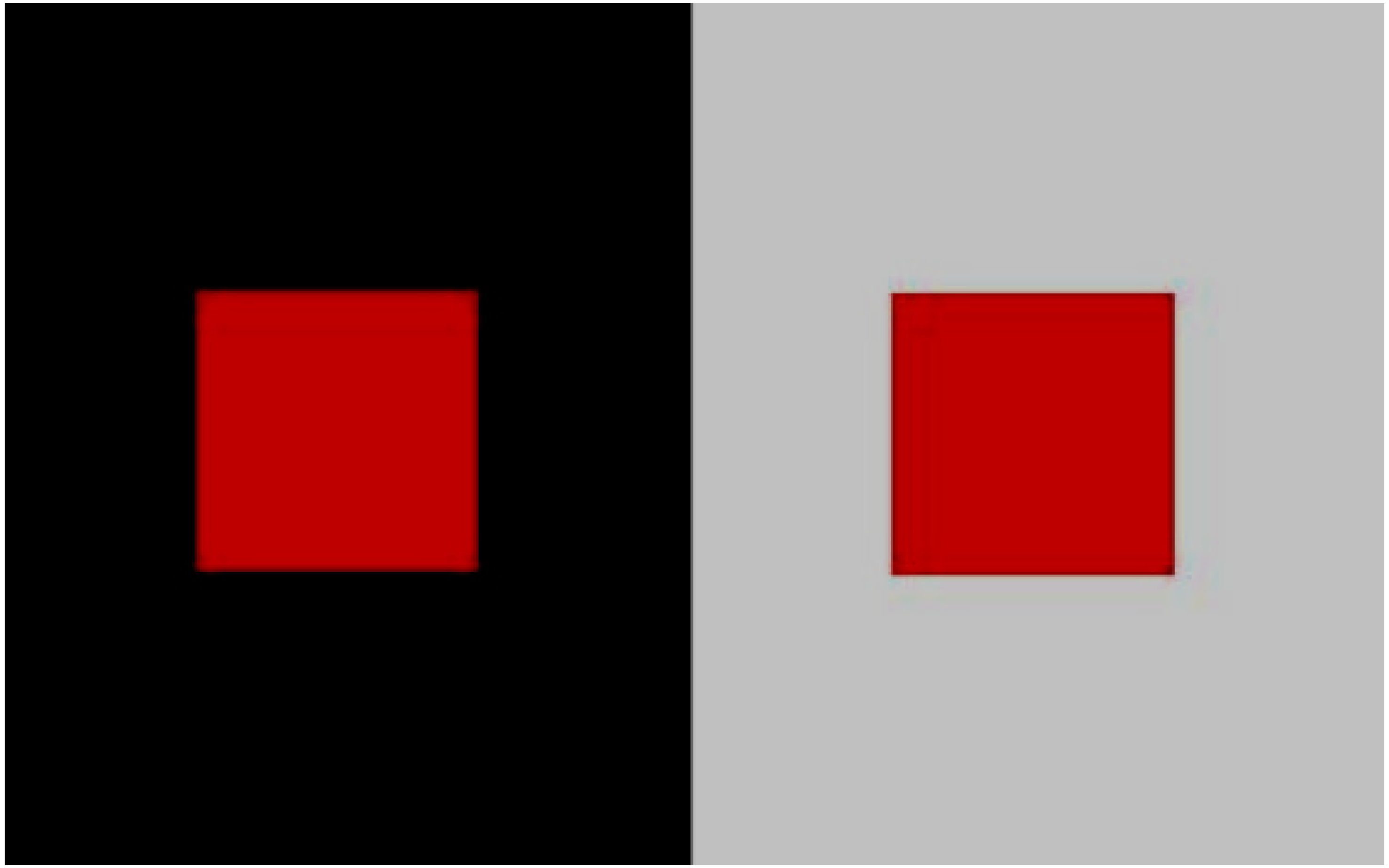

The same light stimulus can trigger different color appearance – dependent on the color of the surrounding region.

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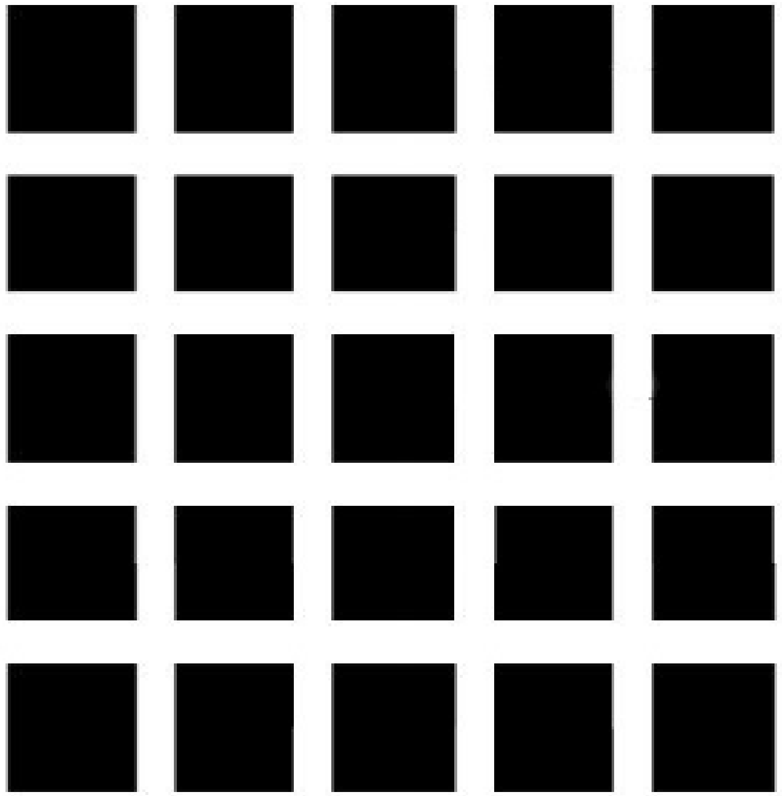

The brightness is not a simple function of intensity

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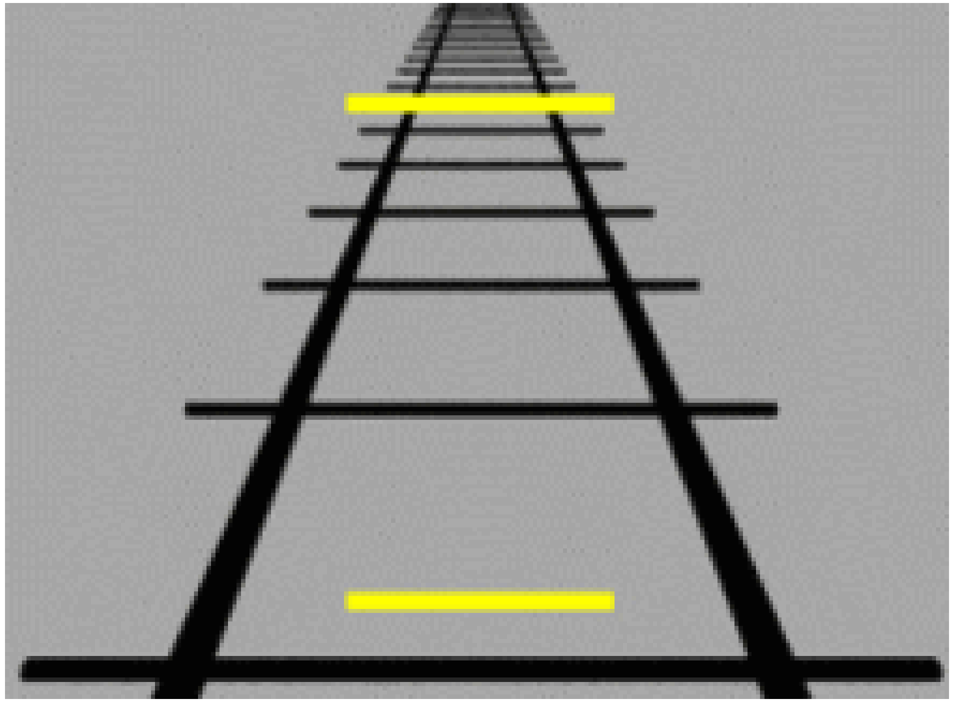

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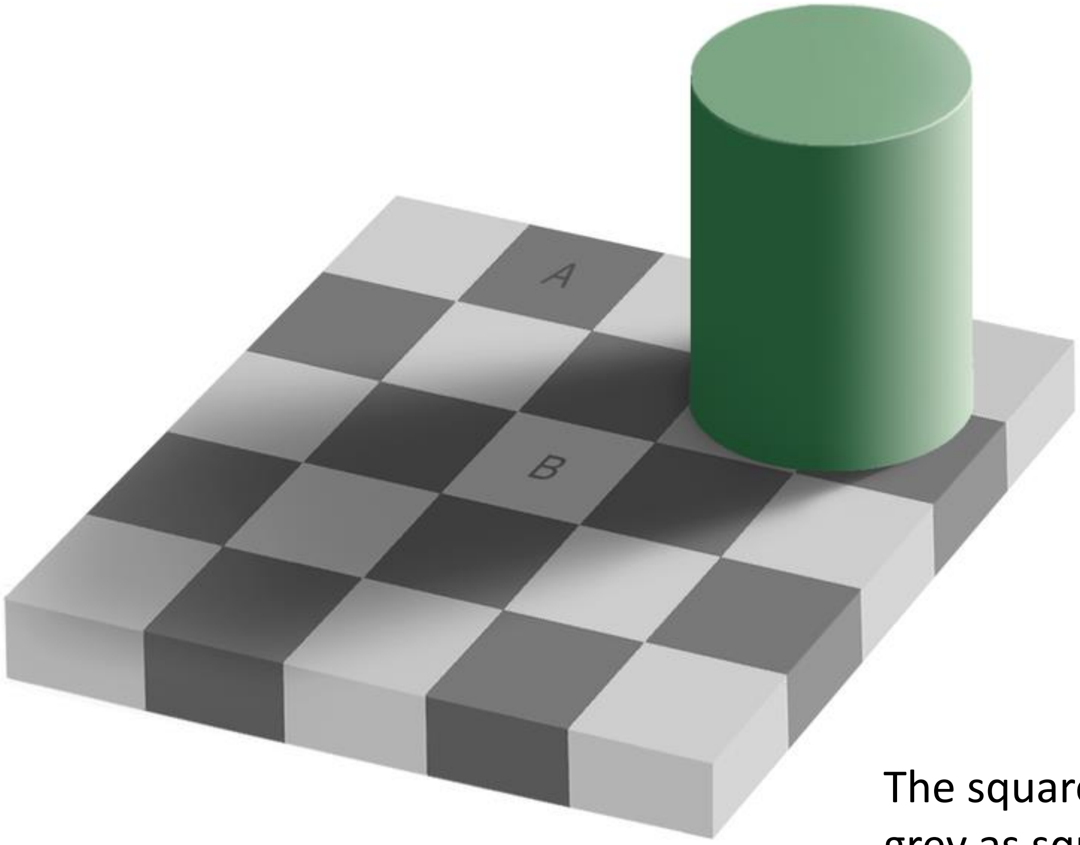

The square A is exactly the same shade of grey as square B.

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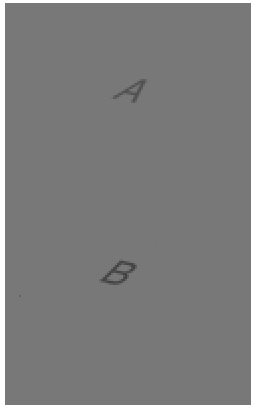

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Trichromacity Theory

- Theoretically and physiologically, three types of receptors are necessary to generate the perception of the variety of colors in the visible spectrum.
- Trichromacy (three receptors) is exhibited by human and a few primates.
- Most mammals exhibit dichromacy (two receptors)
- Monochromacy (one receptor) is common among sea mammals.

Cone Response

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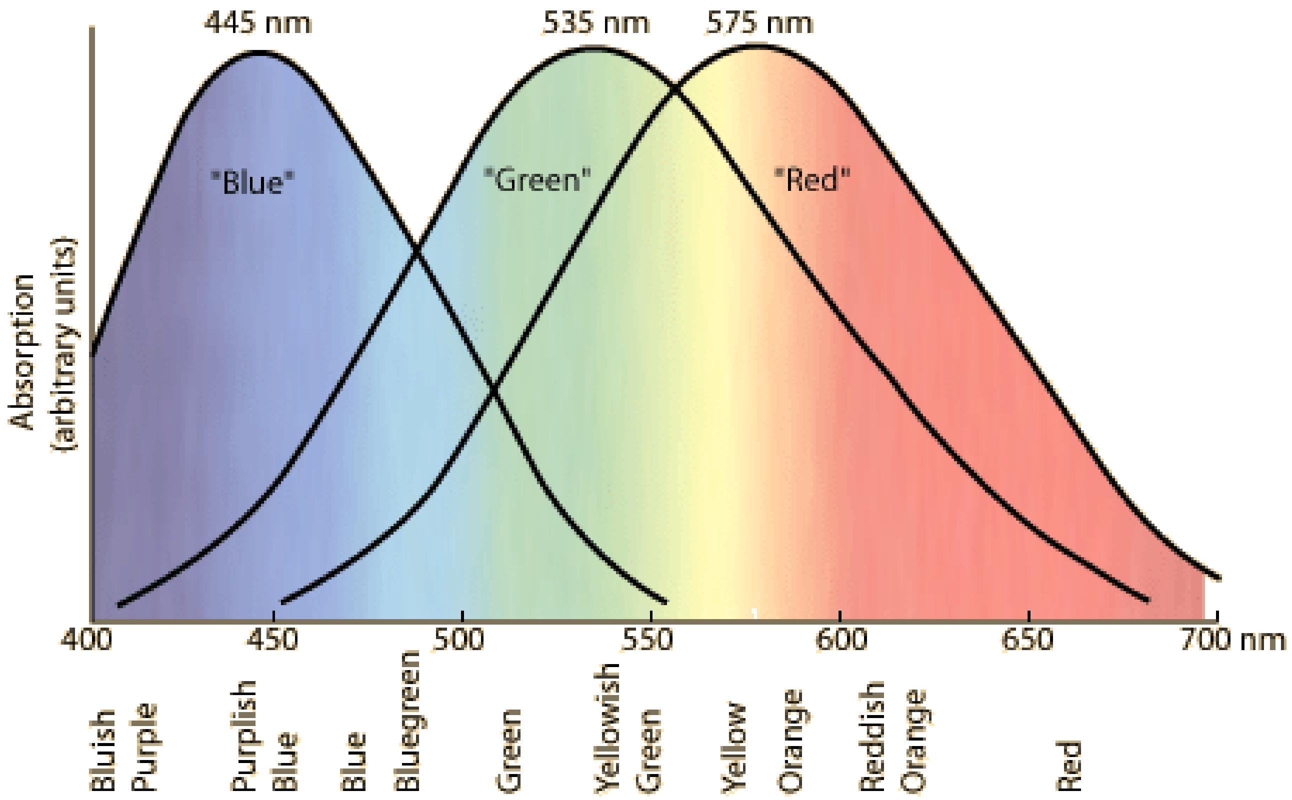

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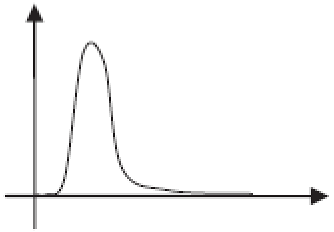
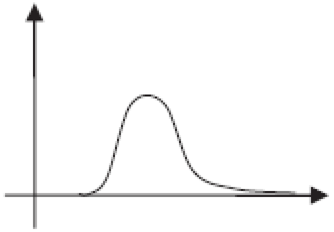
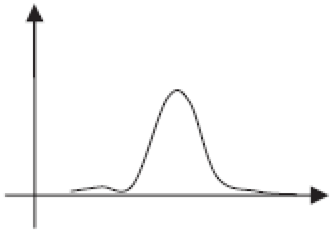


$$c_1 = \int_{\lambda=400}^{\lambda=700} s_1(\lambda)\, f(\lambda)\, d\lambda$$



$$c_2 = \int_{\lambda=400}^{\lambda=700} s_2(\lambda)\, f(\lambda)\, d\lambda$$



$$c_3 = \int_{\lambda=400}^{\lambda=700} s_3(\lambda)\, f(\lambda)\, d\lambda$$

The selective sensing of a cone can be mathematically modeled as parametric curve function $s(\lambda)$

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- The different responses are not the same for all people, but they do have a similar overall structure
- An understanding of this design should help explain a few common observations, abnormalities, and pathological conditions. E.g.,
    - Two individuals can correctly differentiate between tomatoes and oranges based on the color.
    - However, the two might not agree on which tomato exhibits the reddest color – this is because the red cones can have minor differing responses in both individuals.

Color Camera

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- Charge-coupled device (CCD) camera
- A CCD sensor consists of a rectangular grid of electron-collection sites laid over a thin silicon wafer to record the amount of light energy reaching each of them
- When light protons strike the silicon, a charge is released proportional to the amount of light energy incident on the sensor area site

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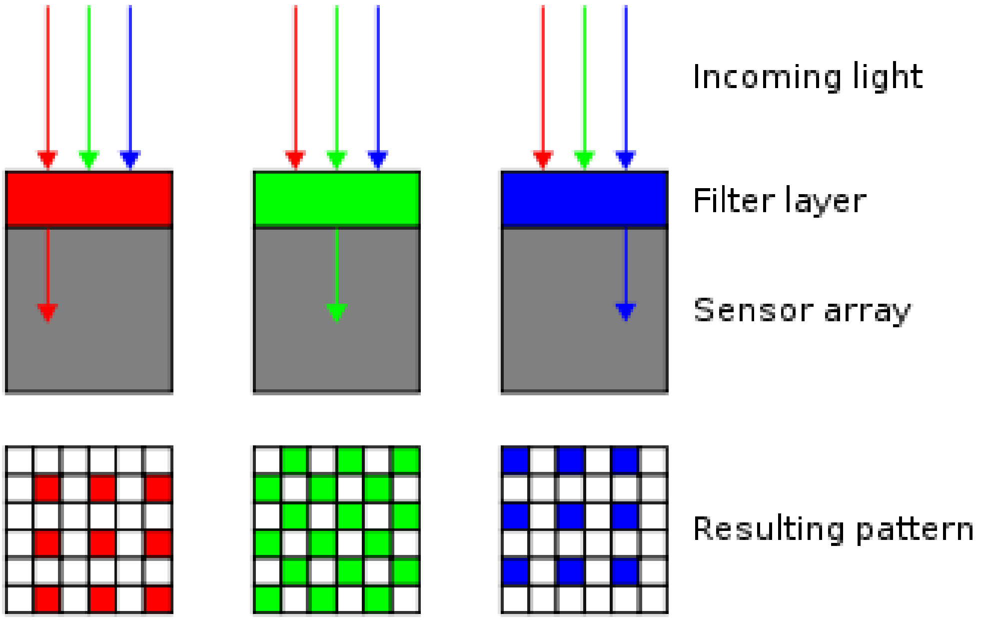

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- For most inexpensive consumer-level devices, a color grid that performs the role of a filter is overlaid over the silicon CCD sensors.
- The filters are made of transparent materials that allow selective parts of the spectrum to pass through
- The filters are organized in a pattern known as the Bayer filter pattern, which has more green filters than red and blue
- The bias toward green is because of the increased sensitivity needed for the green parts of the spectrum

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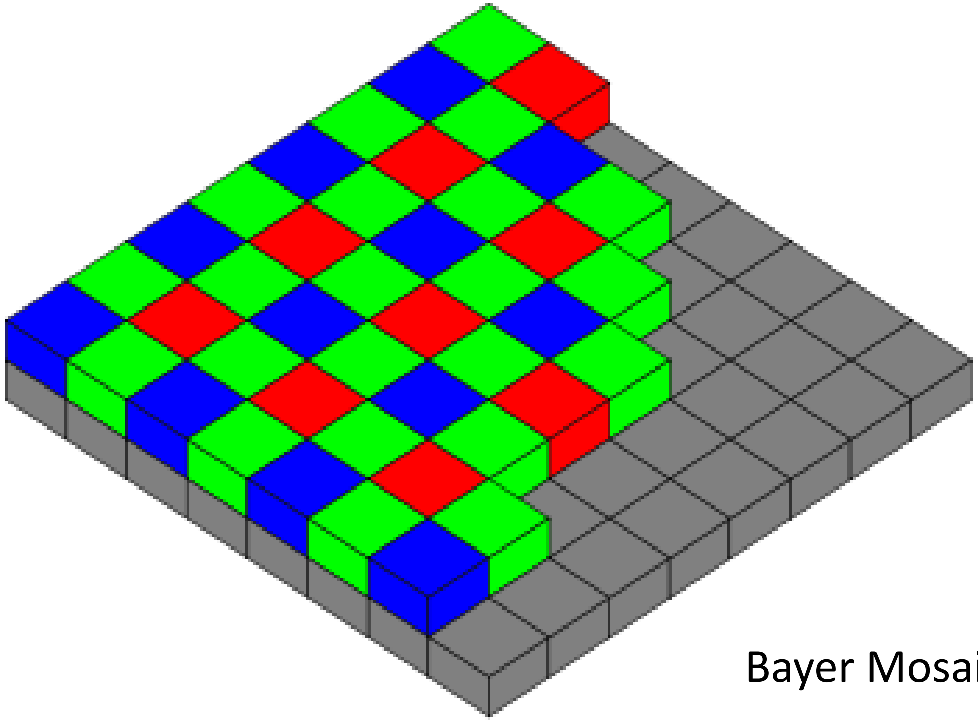

Bayer Mosaic Pattern

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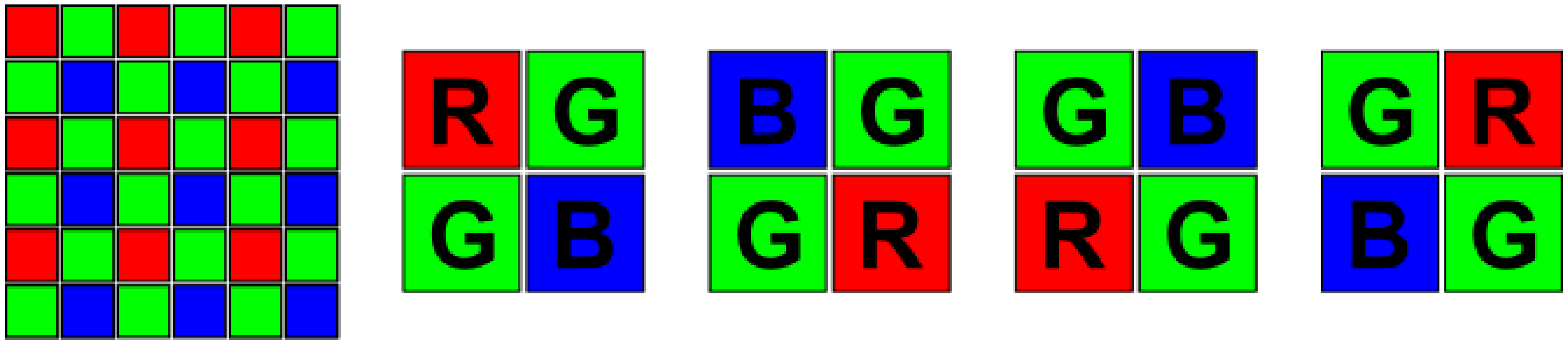

Color Filter Array RGGB BGGR GBRG GRBG

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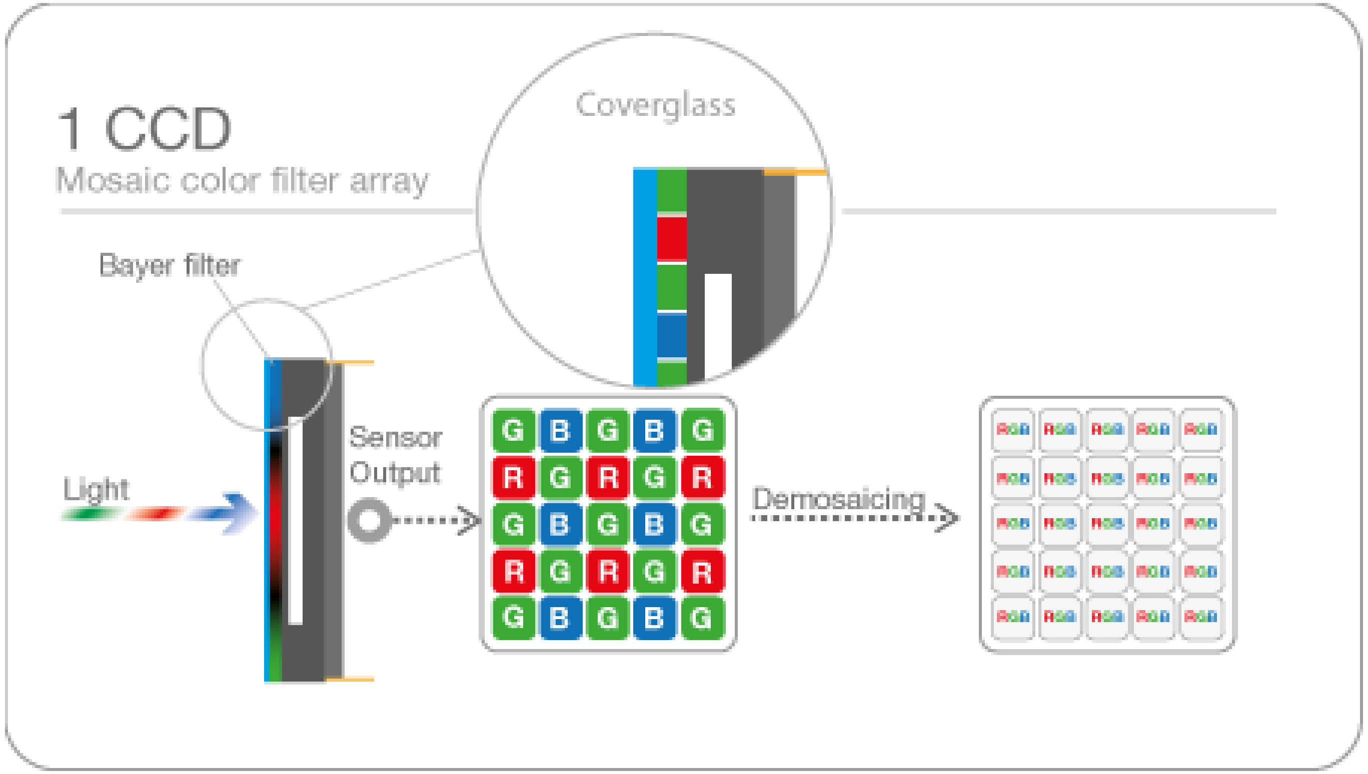

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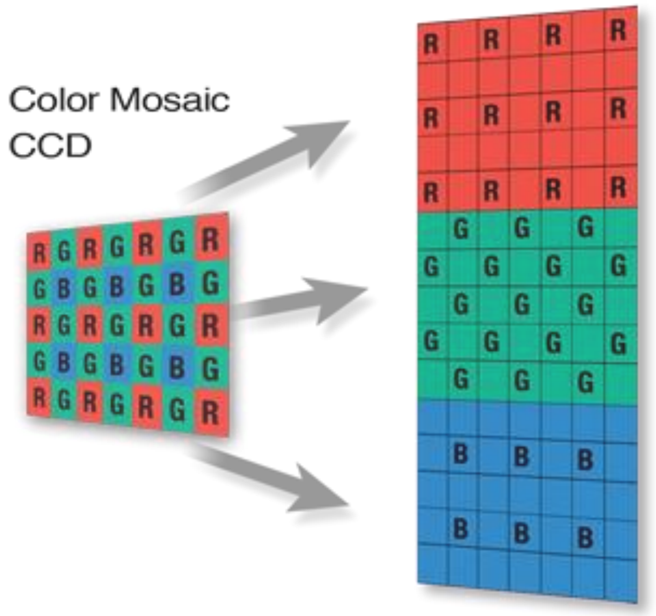

SONY RGBE Mosaic Pattern

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- RGBE filter is an alternative color filter array to the Bayer filter(GRGB).
- It similarly uses a mosaic of pixel filters,
  of red, green, blue and "emerald" ("like cyan" according to Sony)
- It was developed by Sony and so far is used only in the ICX456 8 megapixel CCD and in the SonyCyberShot DSC-F828 camera.[1]

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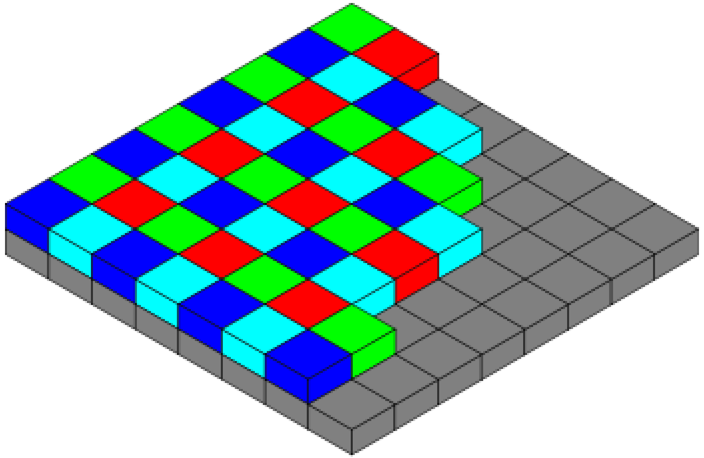
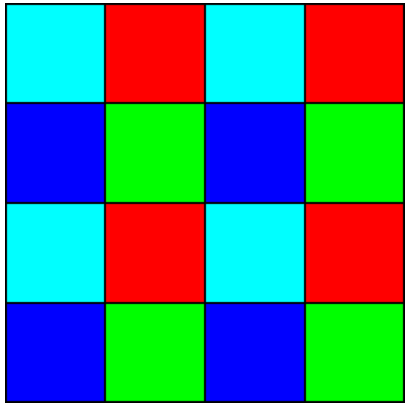
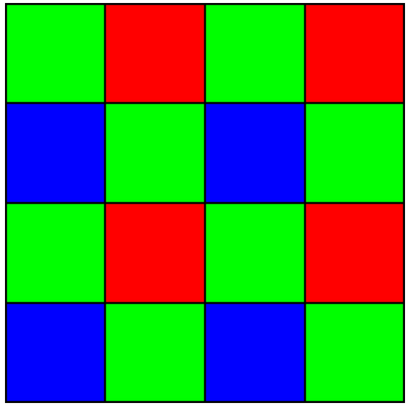


SONY RGBE Mosaic Pattern



SONY RGBE Mosaic Pattern



Bayer Mosaic Pattern

Fujifilm "EXR" color filter array

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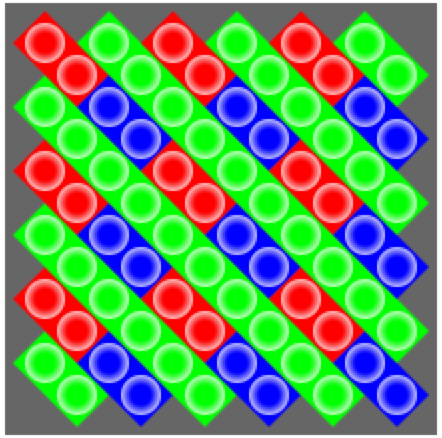

Fujifilm "EXR" color filter array

- Fujifilm's EXR color filter array are manufactured in both CCD (SuperCCD) and CMOS (BSI CMOS).
- As with the SuperCCD, the filter itself is rotated 45 degrees.
- The main reason for this type of array is to contribute to pixel "binning", where two adjacent photosites can be merged, making the sensor itself more "sensitive" to light.
- Another reason is for the sensor to record two different exposures, which is then merged to produce an image with greater dynamic range.

Fujifilm "X-Trans" filter

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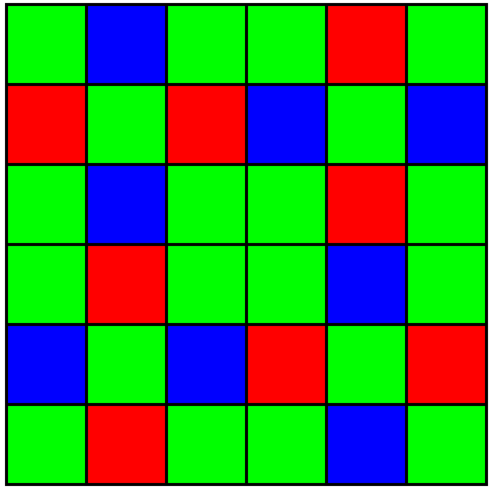

Fujifilm "X-Trans" filter

- The Fujifilm X-Trans CMOS sensor used in the X-Pro1
- Provide better resistance to color moiré than the Bayer filter
- This in turn allows cameras using the sensor to achieve a higher resolution with the same megapixel count.

Foveon X3 sensor

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- Use an array of photosites, each of which consists of three vertically stacked photodiodes, organized in a two-dimensional grid.
- Each of the three stacked photodiodes responds to different wavelengths of light, i.e., each has a different spectral sensitivity curve.
- This difference is due to the fact that different wavelengths of light penetrate silicon to different depths
- The signals from the three photodiodes are then processed, resulting in data that provides the three additive primary colors, red, green, and blue.

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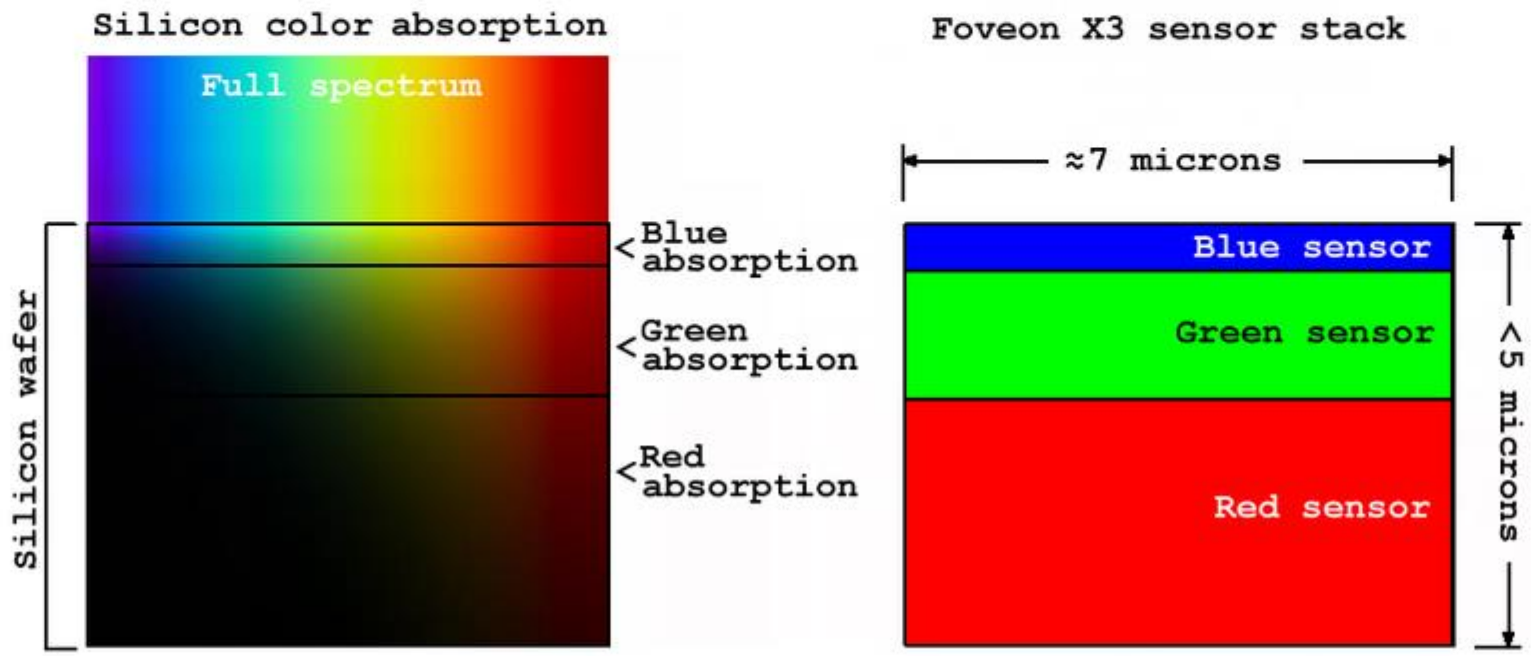

Rendering Devices

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- Visual display devices attempt to create various spectra, using three electron guns in the cast of a CRT

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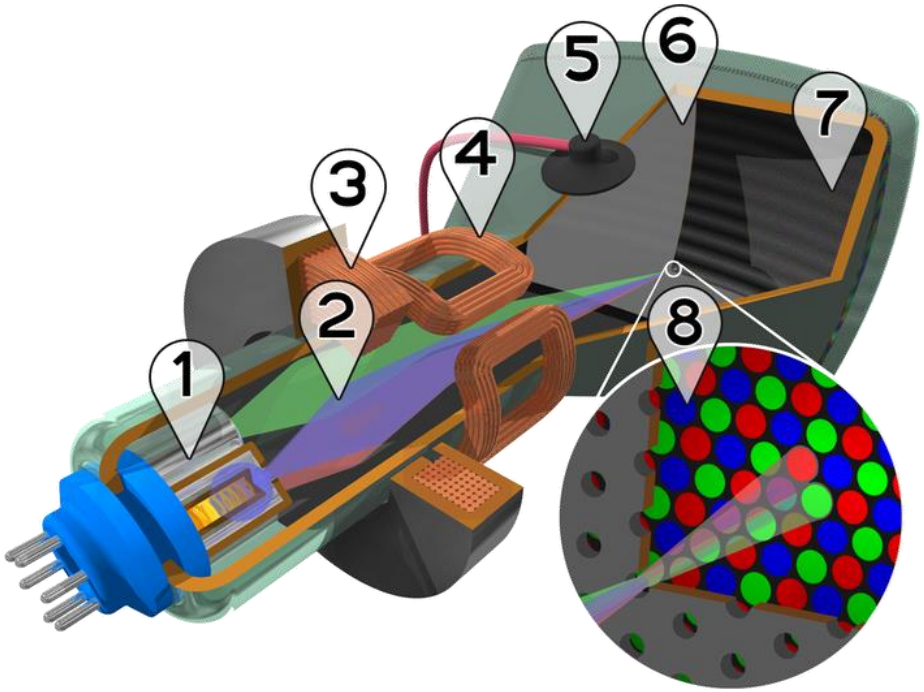

Cutaway rendering of a color CRT:

1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen

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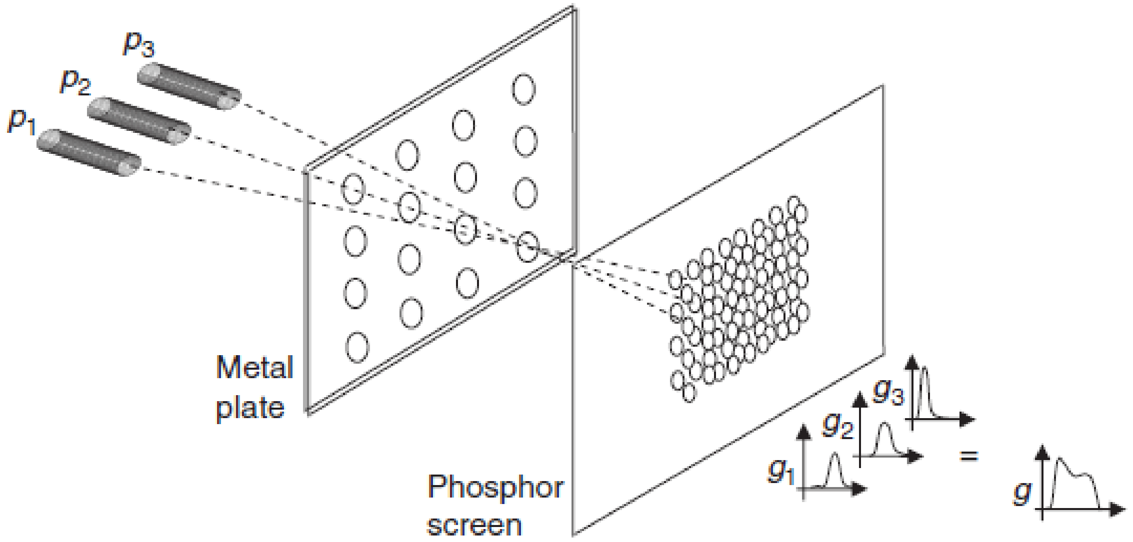
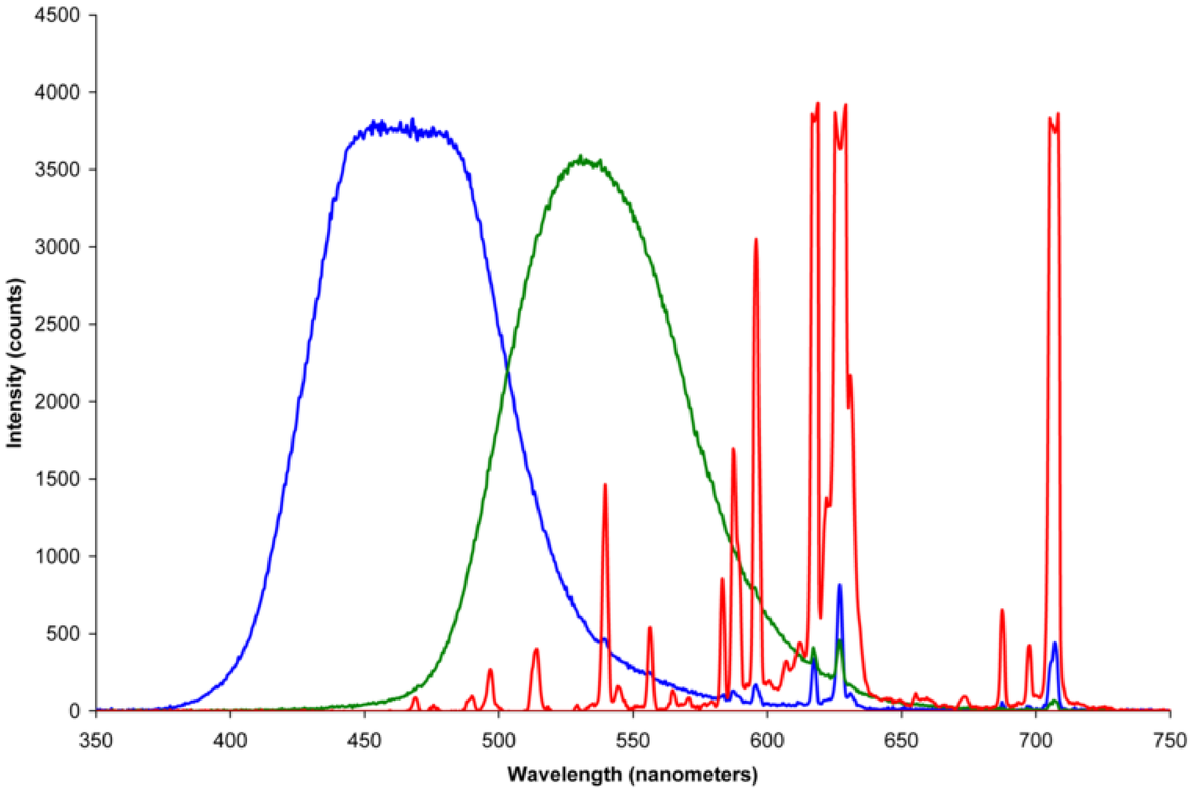
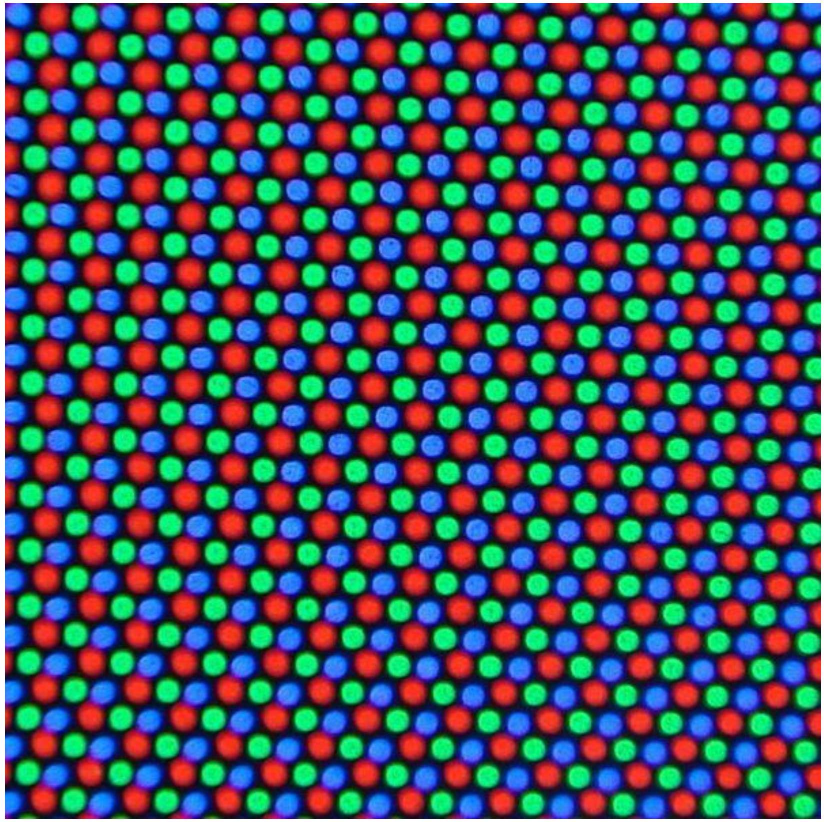


Figure 4-8 A typical CRT system showing primaries p_1, p_2, and p_3. The individual spectra g1, g2, and g3 produced by them get additively mixed to produce a combined spectrum g, which the observer will perceive as a color.

$$\boxed{g = g_1 + g_2 + g_3 = v_1 p_1 + v_2 p_2 + v_3 p_3 = vp}$$



Spectra of constituent blue, green and red phosphors in a common CRT



Magnified view of a shadow mask color CRT

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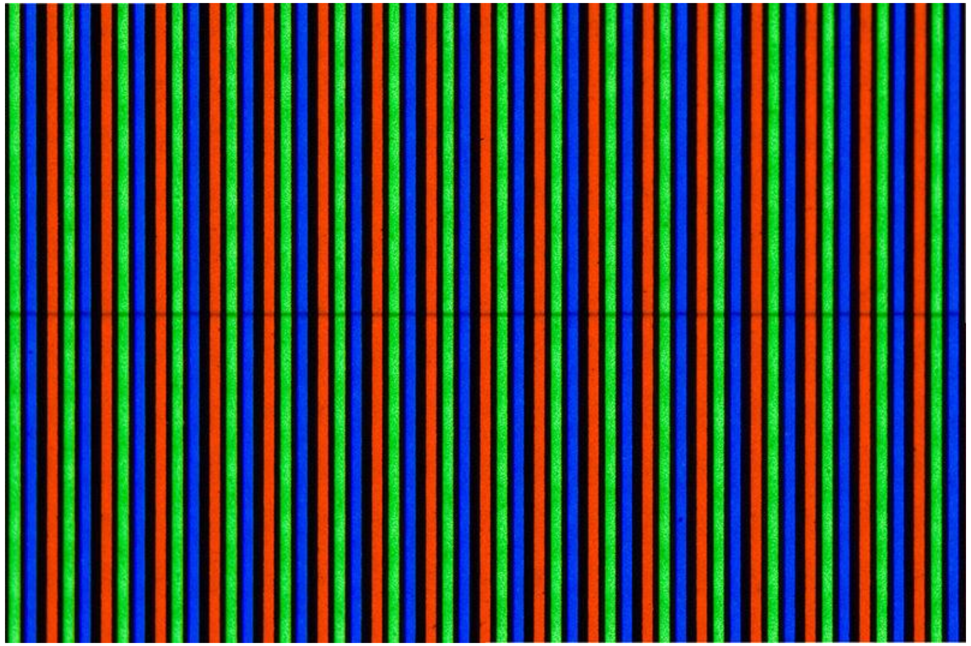

Magnified view of a Trinitron color CRT

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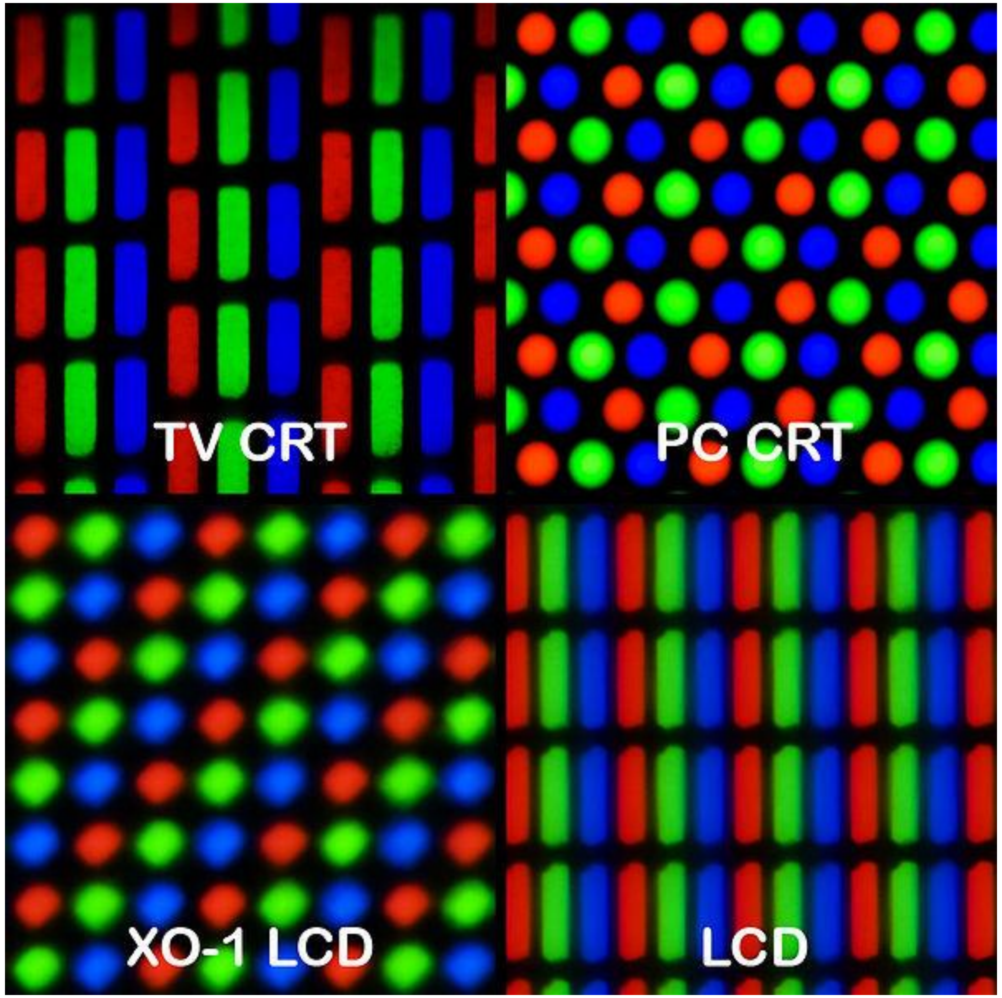

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- CRT displays are no longer the display of choice for consumer applications, and are no longer manufactured
- The competing technologies are
  - LCD (Liquid Crystal Displays)
  - Plasma

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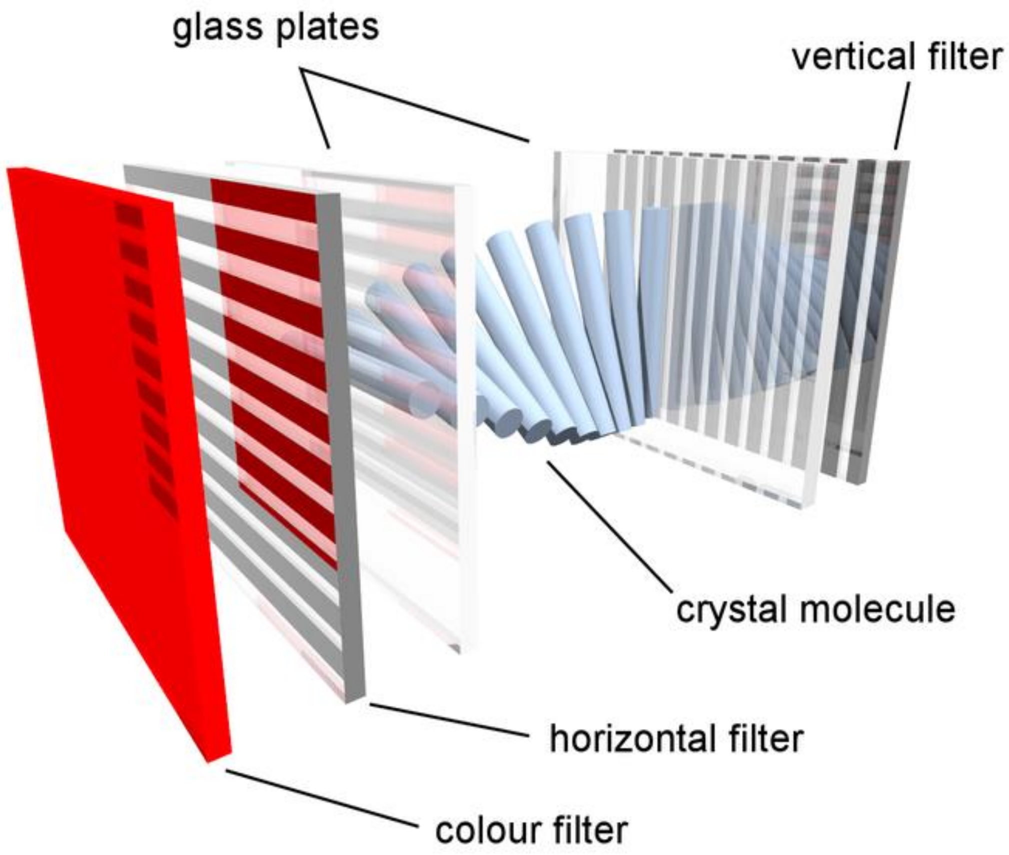

LCD Subpixel

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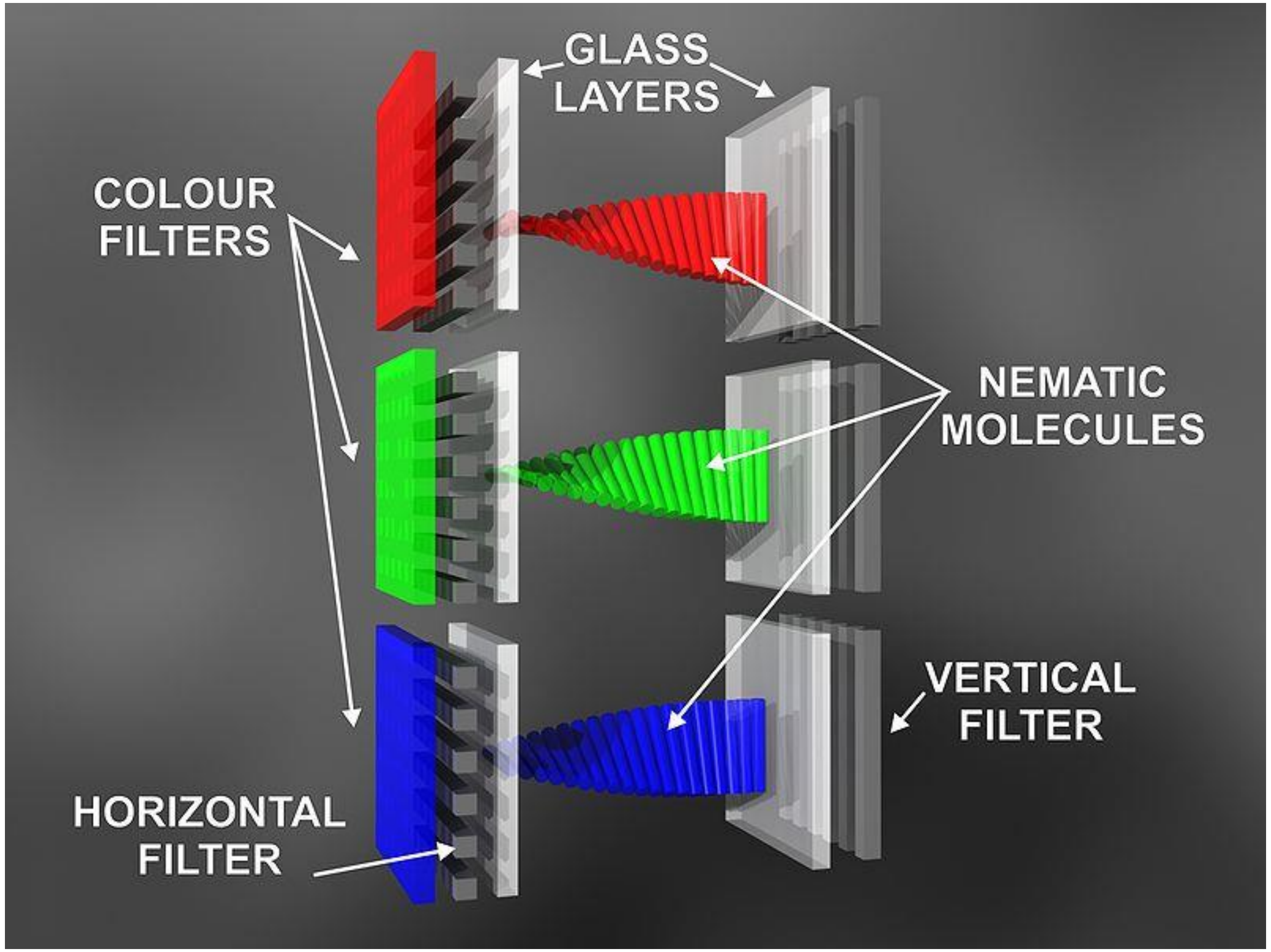

Plasma Display

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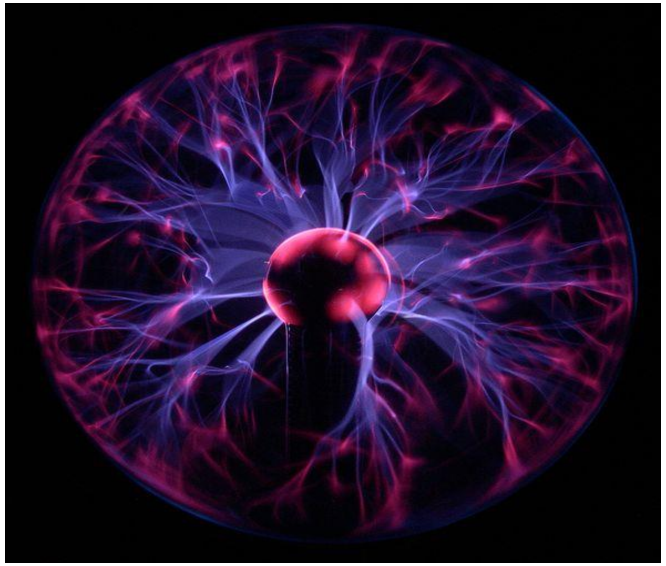

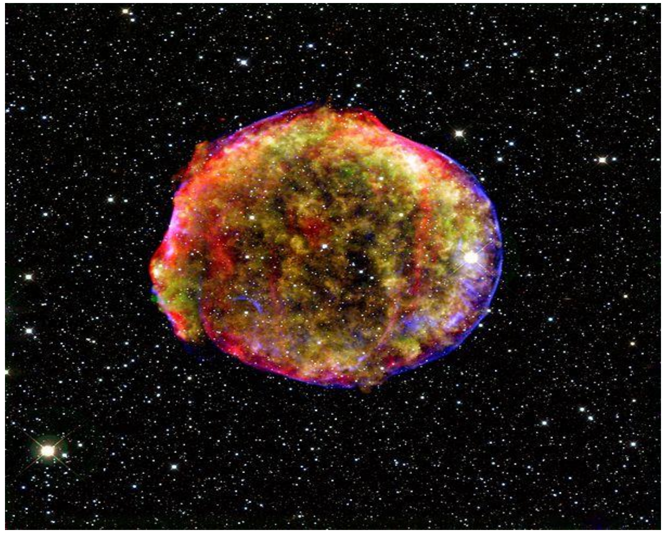

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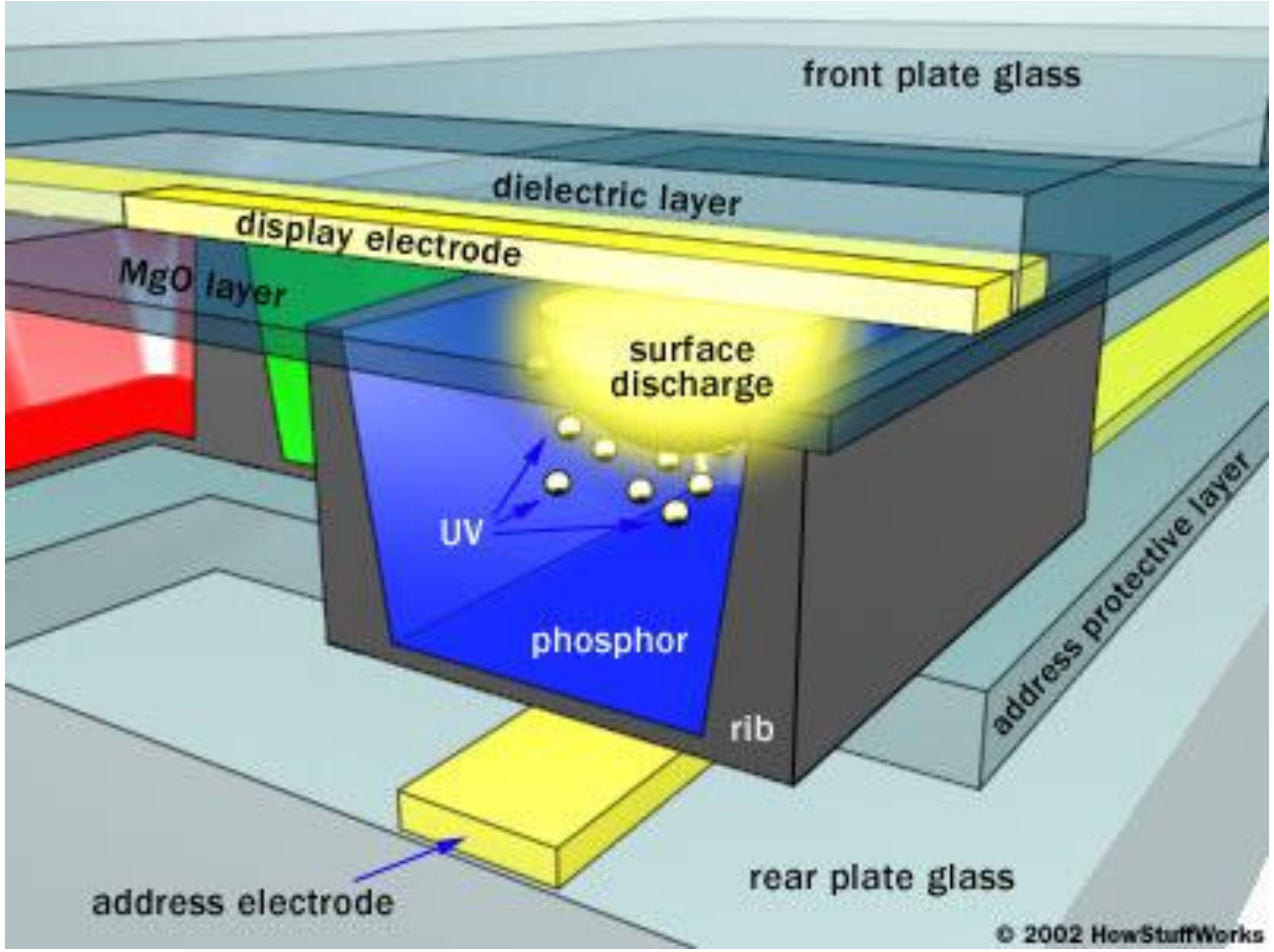

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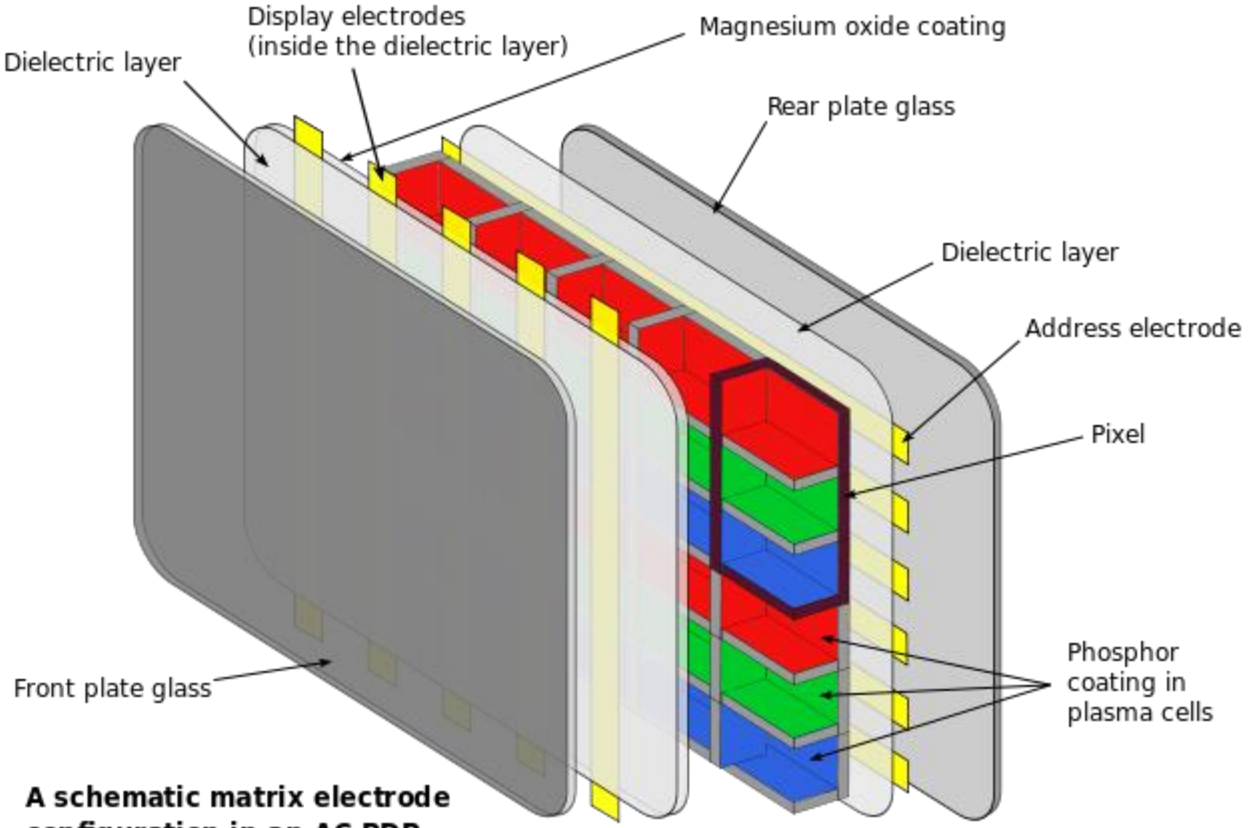

A schematic matrix electrode configuration in an AC PDP

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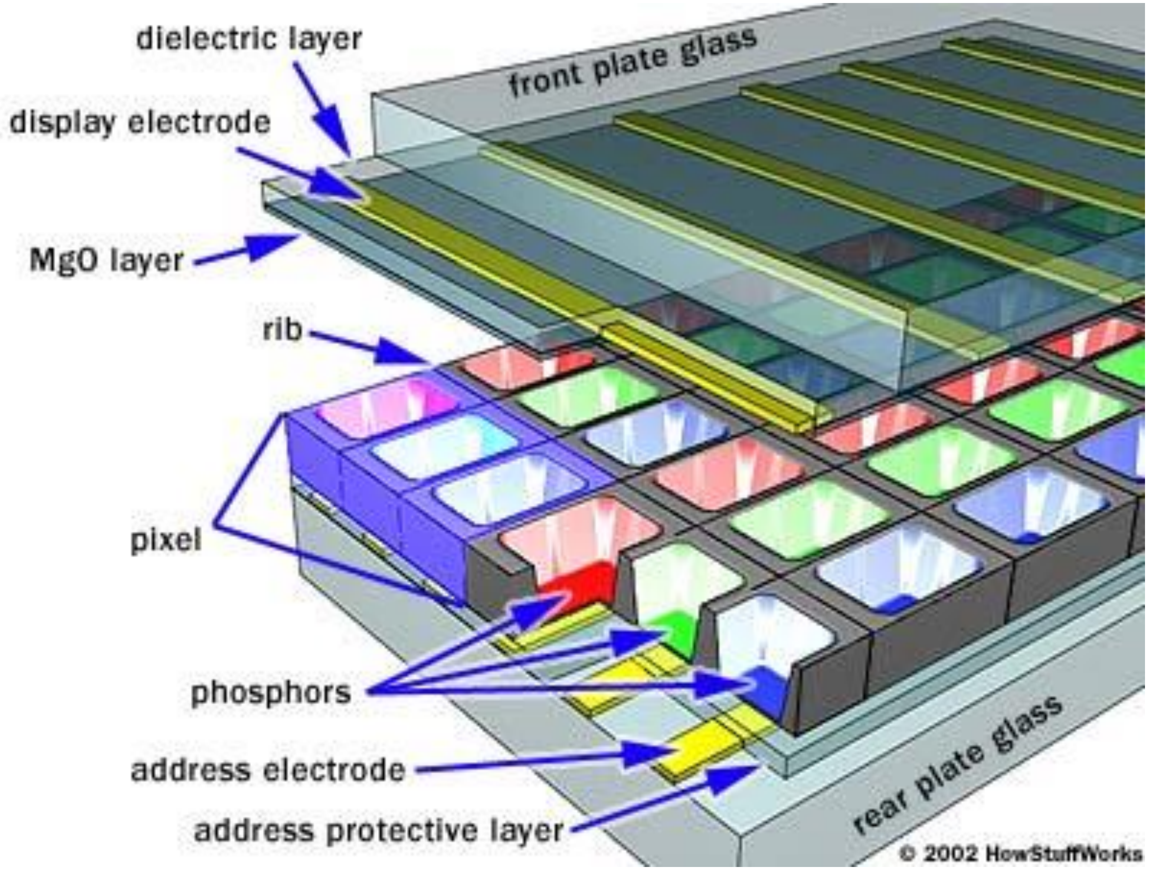

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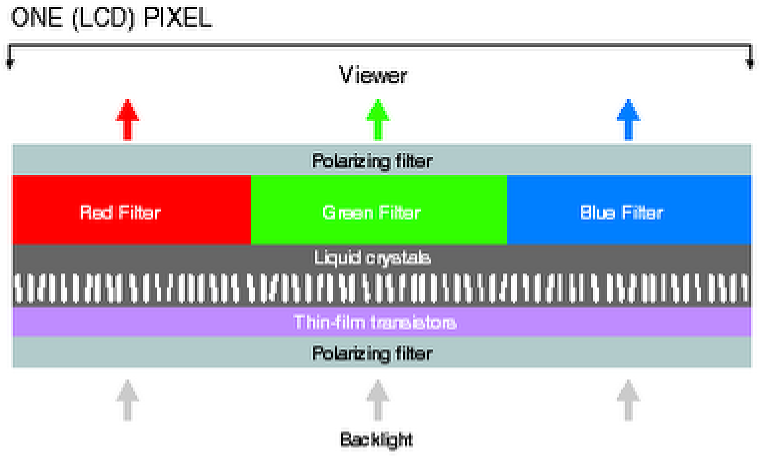

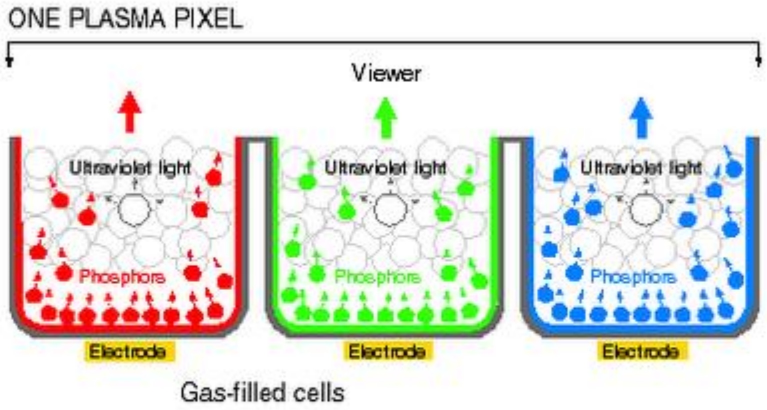

The Calibration Process

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- The objective of the calibration process is to ensure that the spectrum *g*, which is produced by the display device, generate the same color perception as the spectrum *f*, which was captured by the camera

$$\boxed{S^T g = S^T f}$$

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- The camera captures a_1, a_2, and a_3 for a spectrum f falling at a pixel location.

$$\boxed{\begin{aligned} g &= g_1 + g_2 + g_3 = a_1 p_1 + a_2 p_2 + a_3 p_3 \\ g &= Pa \end{aligned}}$$

$$\boxed{\begin{aligned} &S^T g = S^T f, \text{ and } g = Pa \\ &S^T Pa = S^T f \\ &a = (S^T P)^{-1} S^T f \end{aligned}}$$

CIE Standard and Color-Matching Functions

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- The variation in primaries in the display devices makes it impractical to manufacture standardized capture and display devices such that the colors captured by any capture device match the colors rendered by any display device
- CIE (Commission Interationale de l'Eclairage) proposes that the primaries p_1, p_2, and p_3 be fixed
- The primaries selected by CIE were p_1 = 700.0 nm (red), p_3 = 546.1 nm (green), and p_3 = 435.8 nm (blue)

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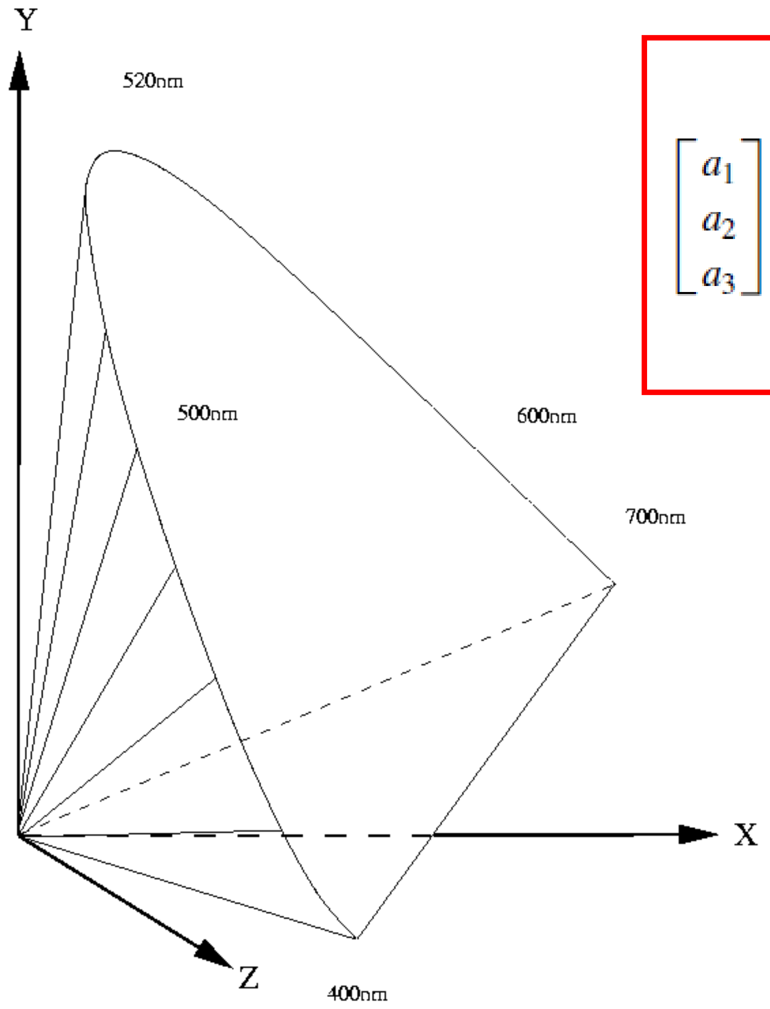

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = M^T f = \begin{bmatrix} m_1(\lambda_1) & m_1(\lambda_2) & \dots & m_1(\lambda_n) \\ m_2(\lambda_1) & m_2(\lambda_2) & \dots & m_2(\lambda_n) \\ m_3(\lambda_1) & m_3(\lambda_2) & \dots & m_3(\lambda_n) \end{bmatrix} \times \begin{bmatrix} f(\lambda_1) \\ f(\lambda_2) \\ \vdots \\ f(\lambda_n) \end{bmatrix}$$

Color Spaces

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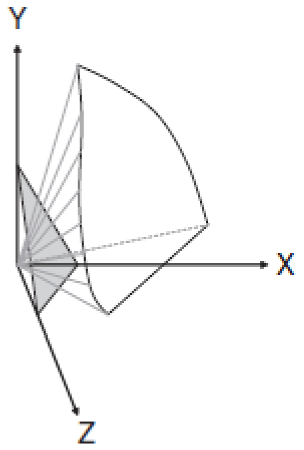

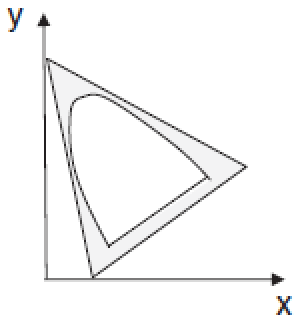

- A color space is a model in which colors are represented in terms of fixed intensity values
- Three-dimensional color spaces are typically used to describe the choice and range of commonly perceived colors

The CIE XYZ Color Space

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- The XYZ space allows colors to be expressed as a mixture of the three tristimulus values X, Y, and Z, which are the color matching functions arrived at by the CIE

$$\boxed{(x,y,z) = \left(\frac{X}{X+Y+Z}, \frac{Y}{X+Y+Z}, \frac{Z}{X+Y+Z}\right)}$$

$$\boxed{Z = 1 - X - Y}$$

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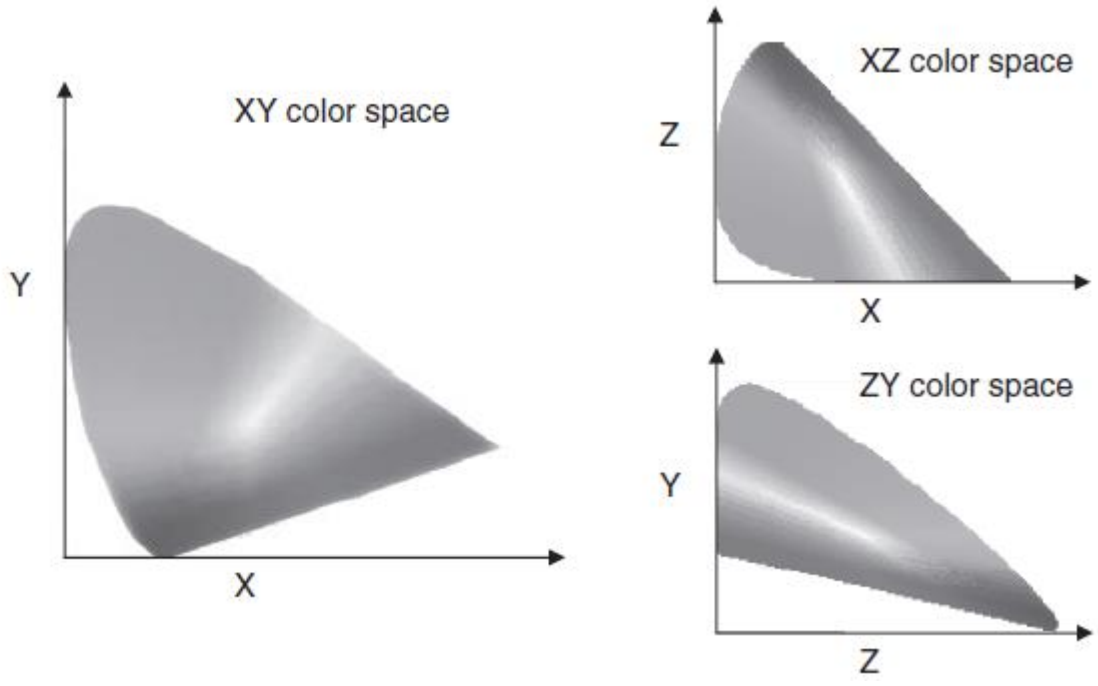


Y
X
Z

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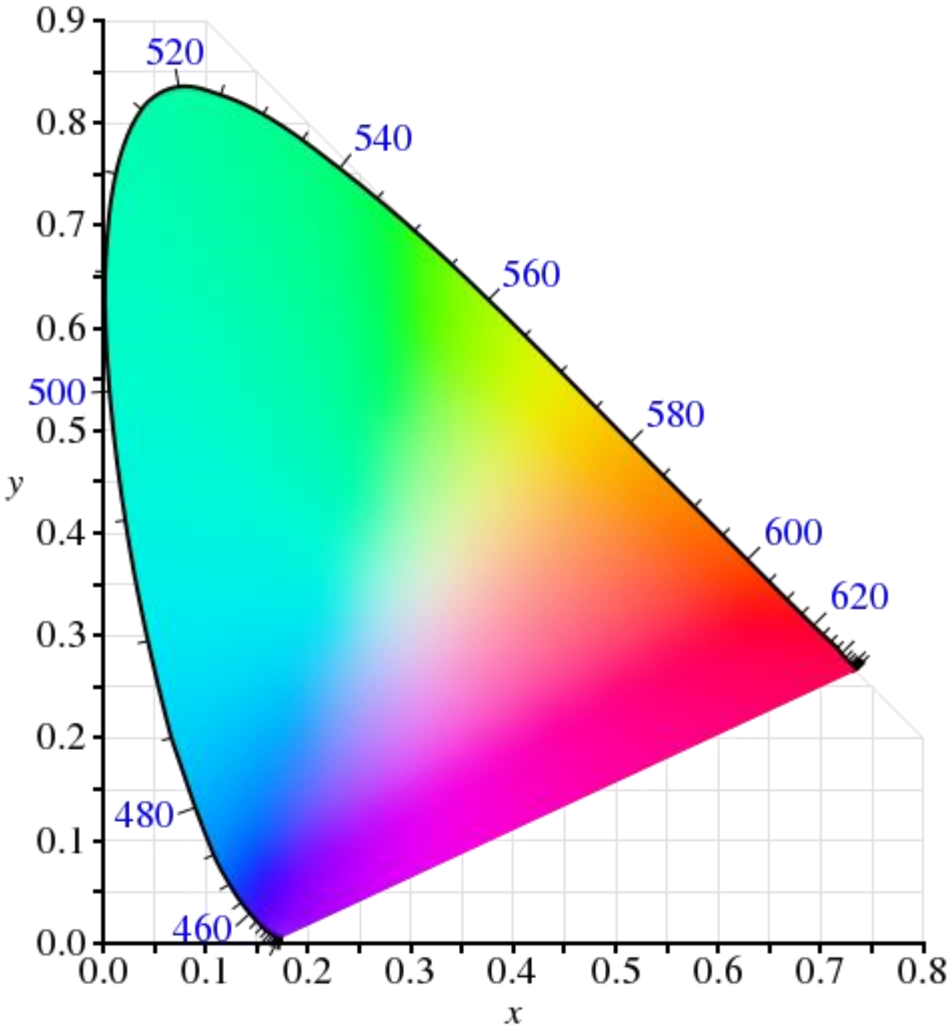

The CIE 1931 color space chromaticity diagram

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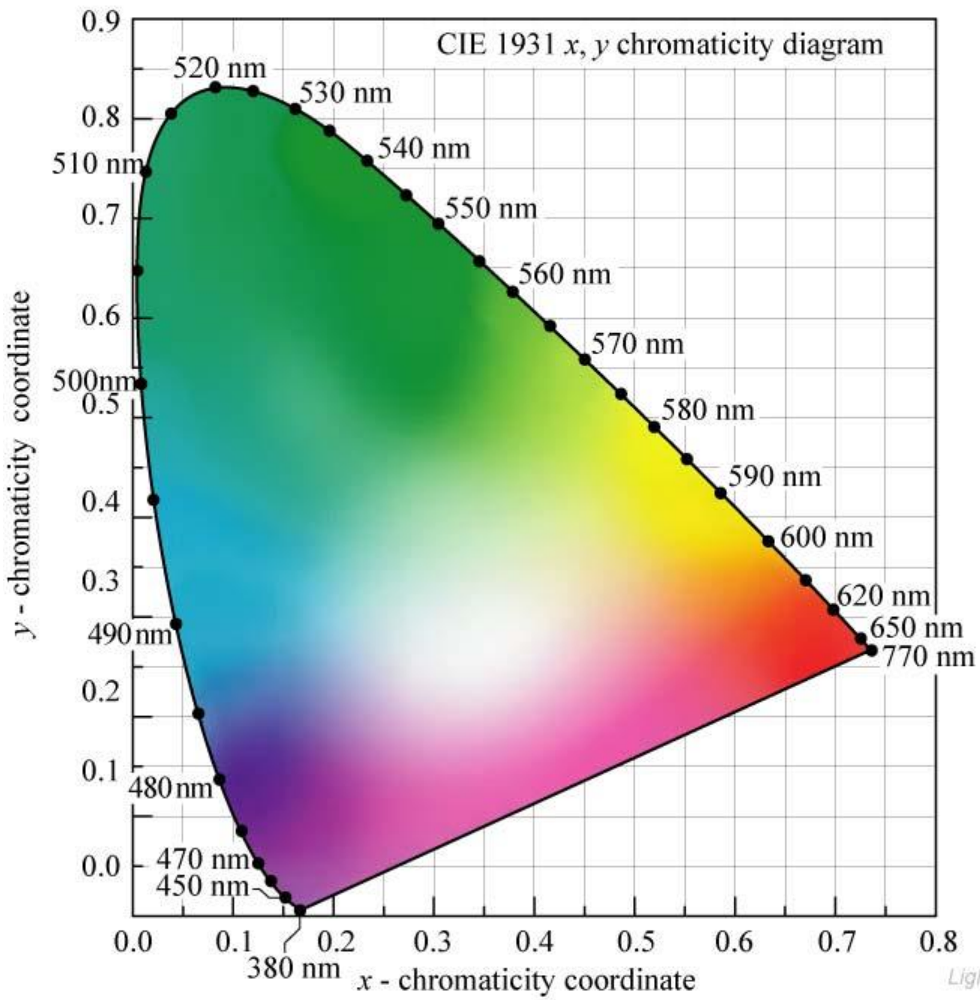

Fig. 17.2. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter and white light is located in the center of the diagram.

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www.LightEmittingDiodes.org

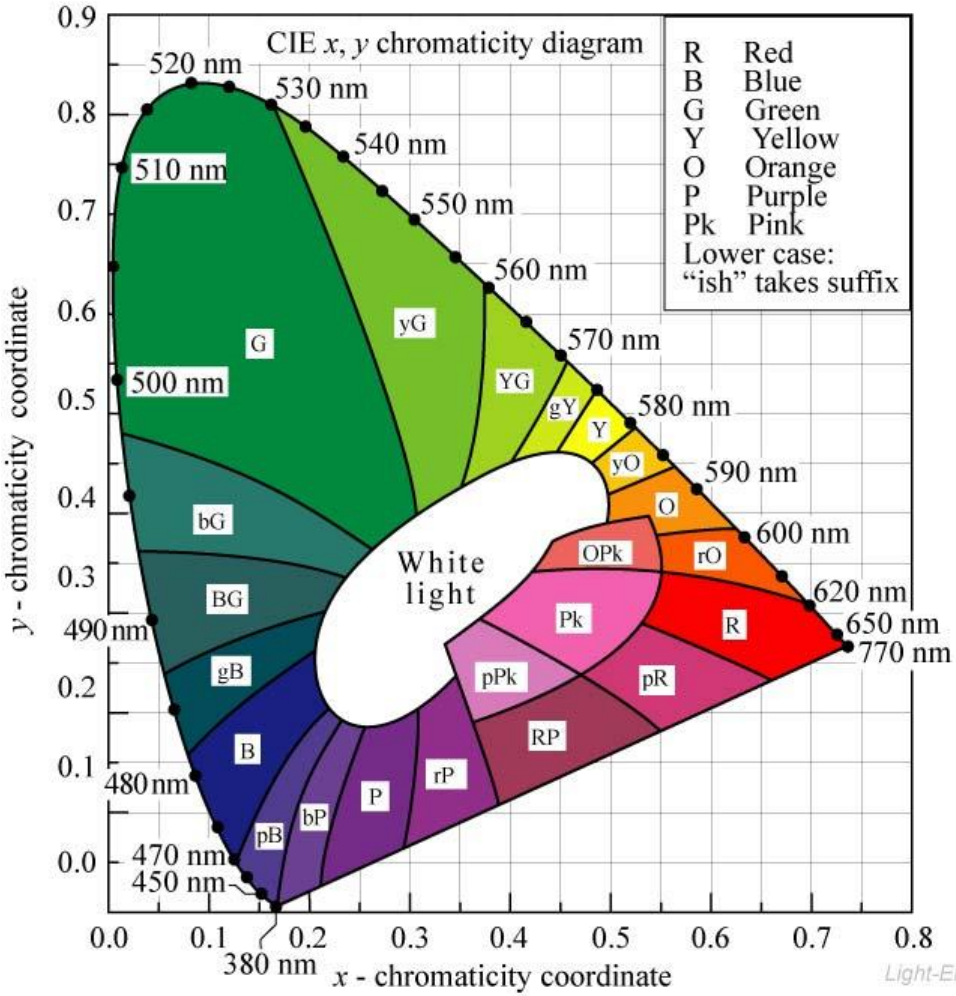

Fig. 17.3. 1931 CIE chromaticity diagram with areas attributed to distinct colors (adopted from Gage *et al*., 1977).

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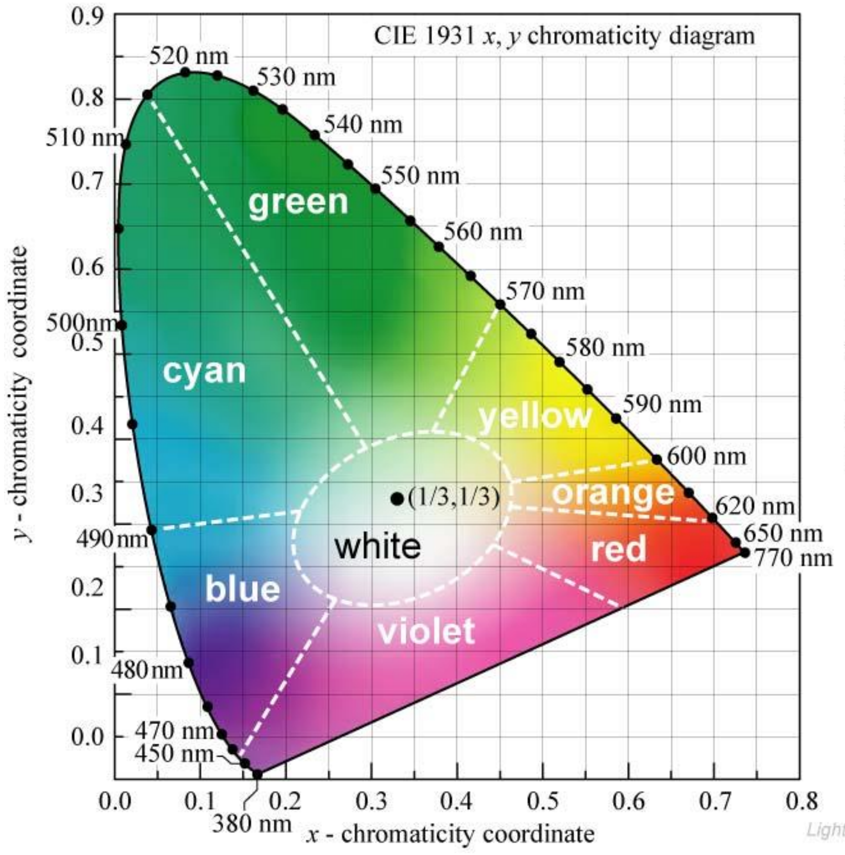

Fig. 17.4. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter. Color saturation decreases towards the center of the diagram. White light is located in the center. Also shown are the regions of distinct colors. The equal-energy point is located at the center and has the coordinates $(x, y) = (1/3, 1/3)$.

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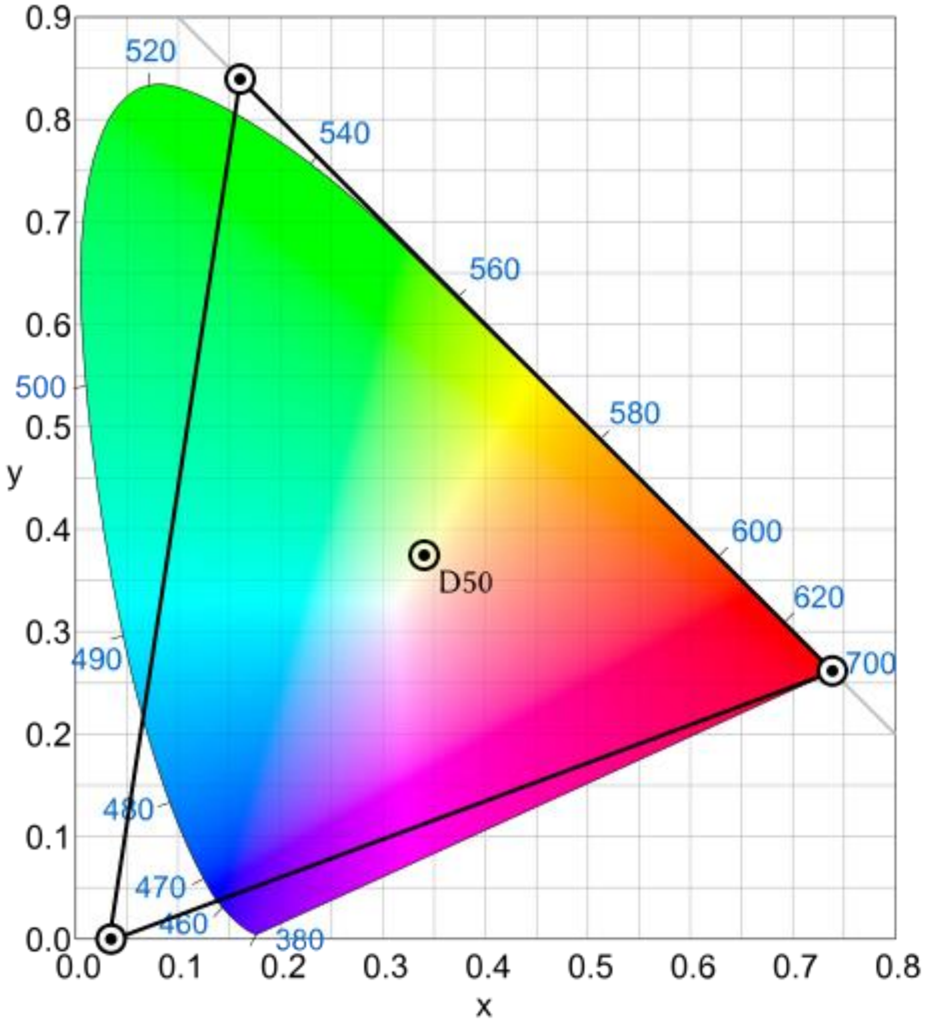

The ProPhoto RGB color space uses imaginary green and blue primaries to obtain a larger gamut (space inside the triangle) than would be possible with three real primaries. However, some real colors are still irreproducible.

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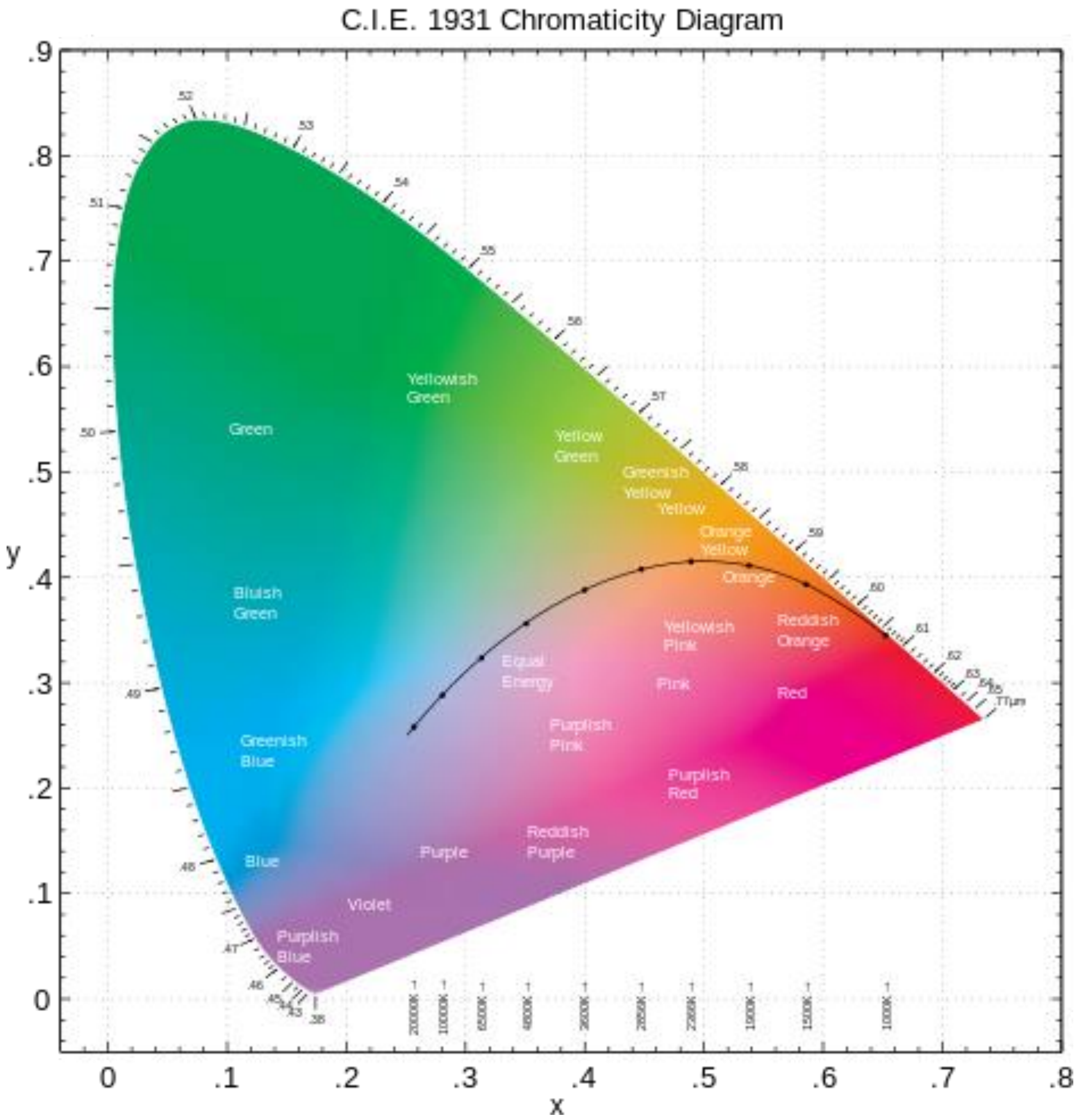

The CIE 1931 color space chromaticity diagram rendered in terms of the colors of lower saturation and value than those displayed in the diagram above that can be produced by pigments, such as those used in printing. The color names are from the Munsell color system.

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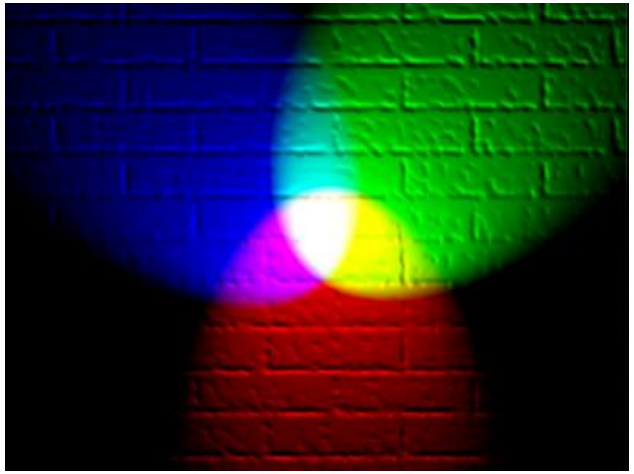
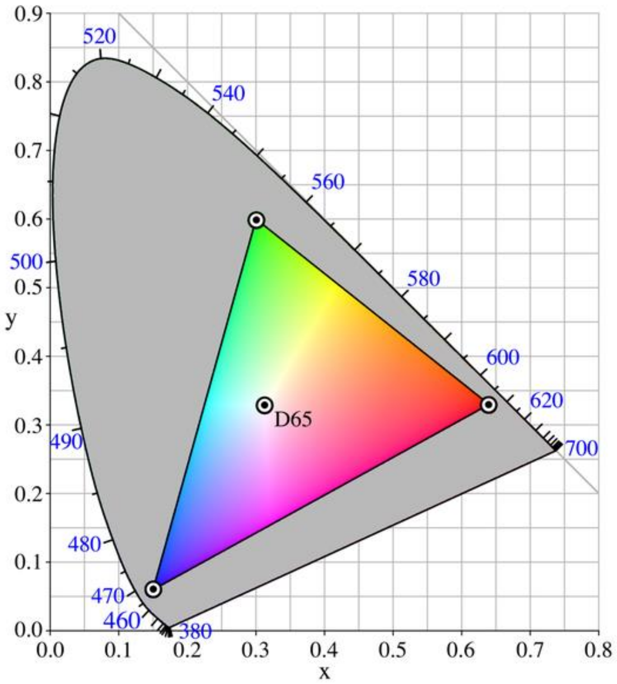
- The RGB color model is an additive color model in which red, green, and blue light are added together in various ways to reproduce a broad array of color





Color mixing

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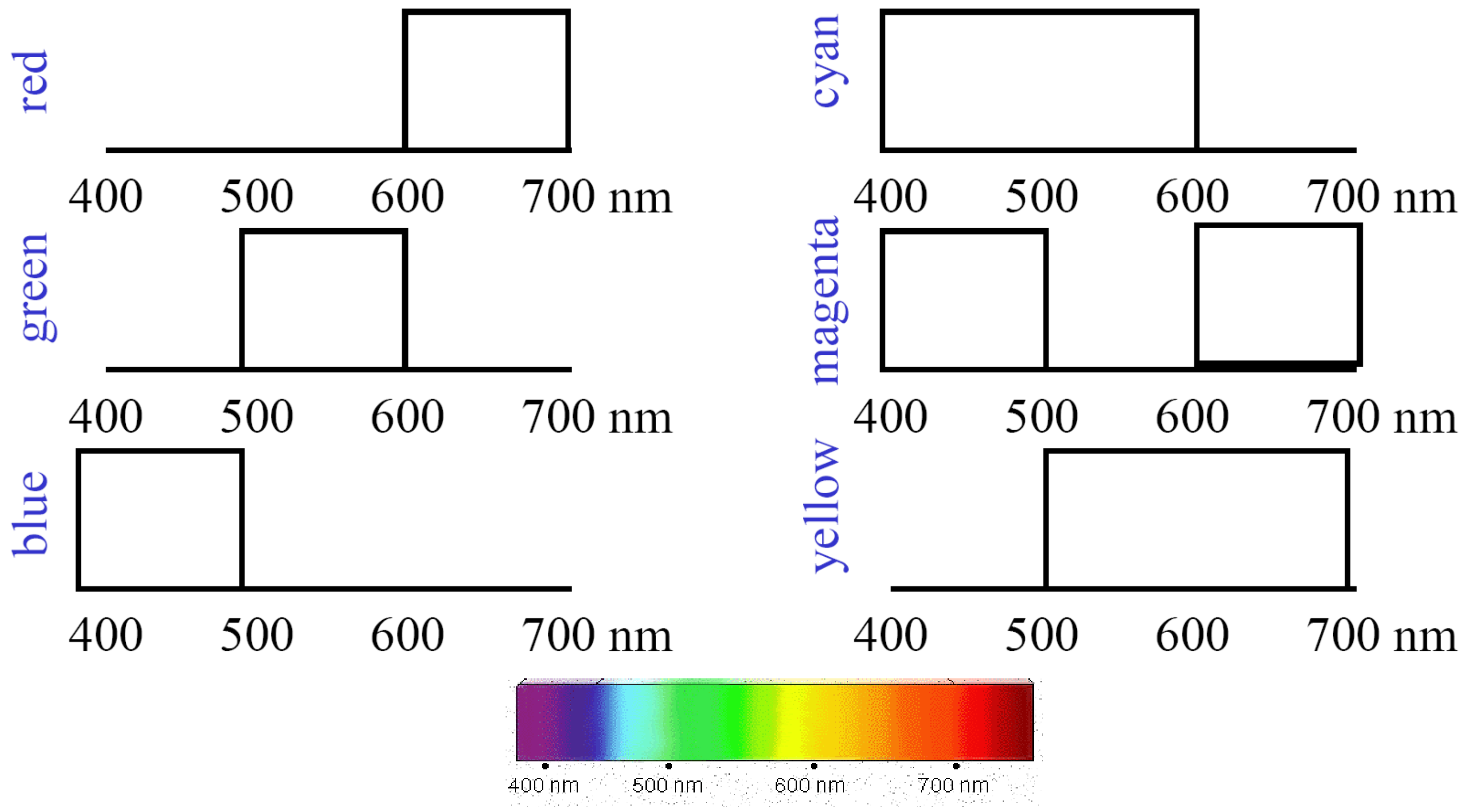
Cartoon spectra for color names:



Source: W. Freeman

Additive color mixing

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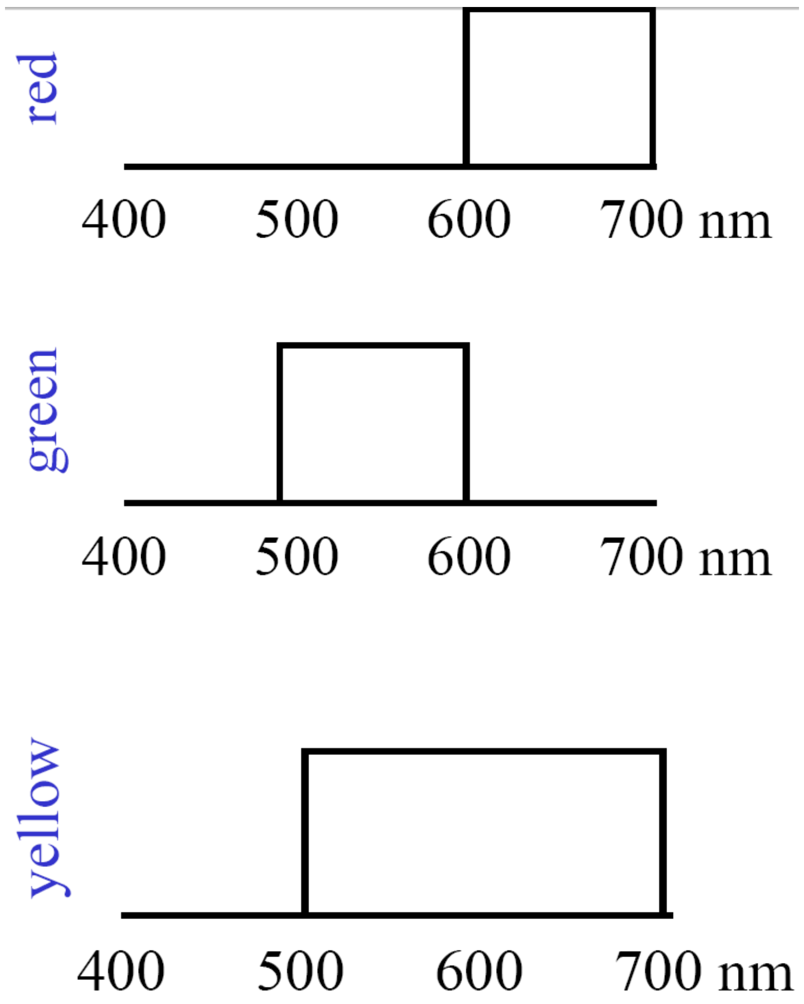
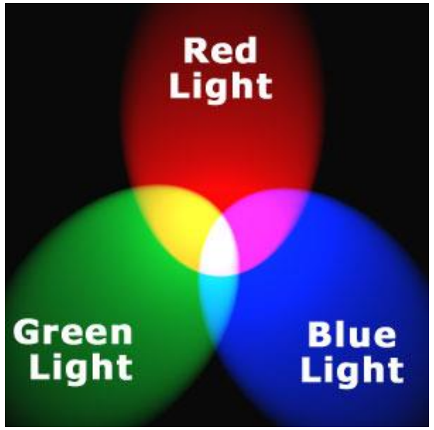


Colors combine by *adding* color spectra



Light *adds* to black.

Source: W. Freeman

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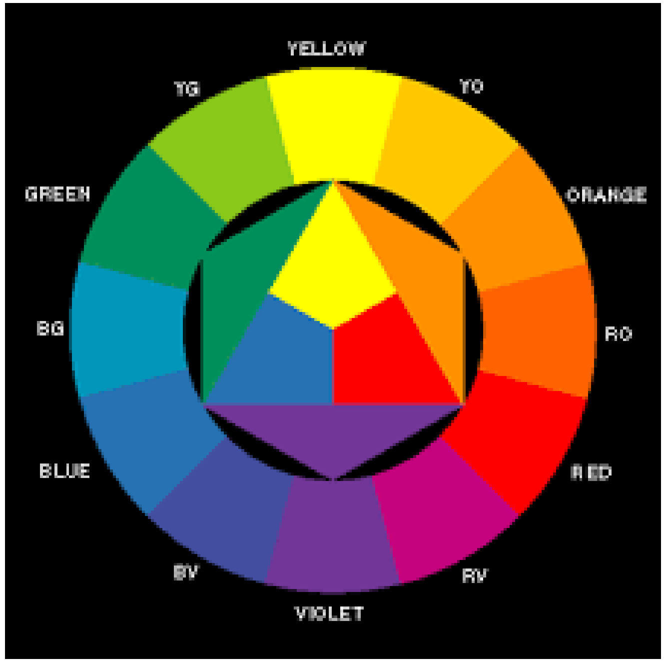

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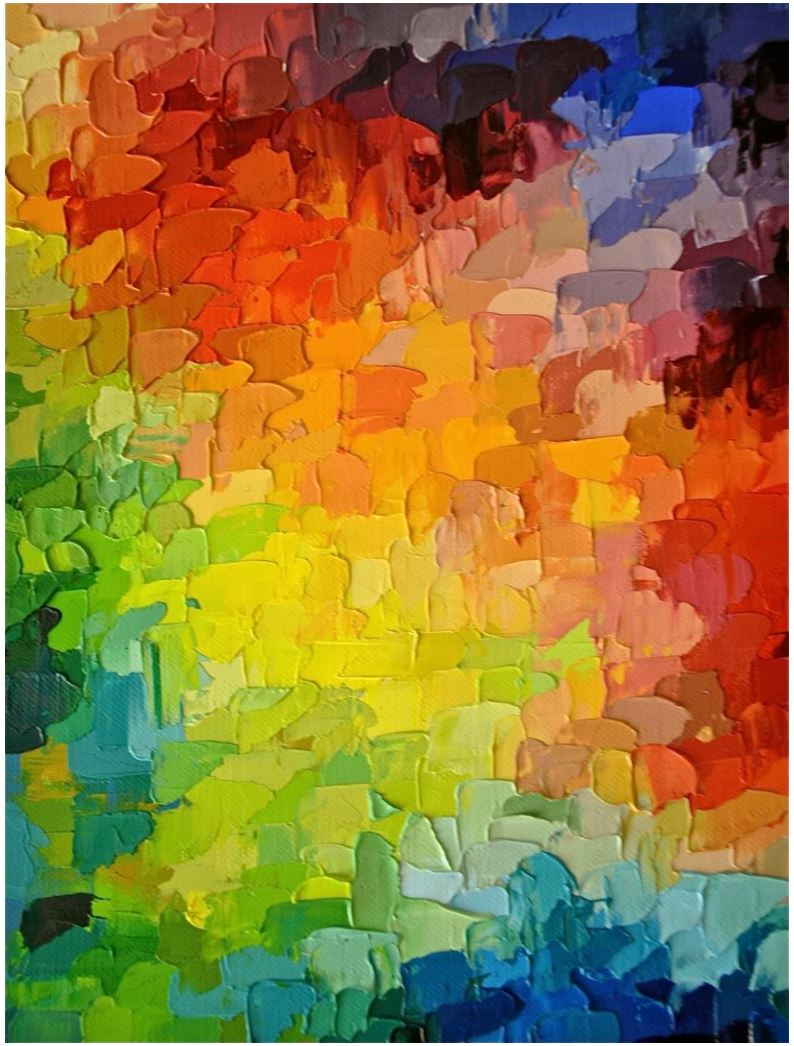

Examples of additive color systems

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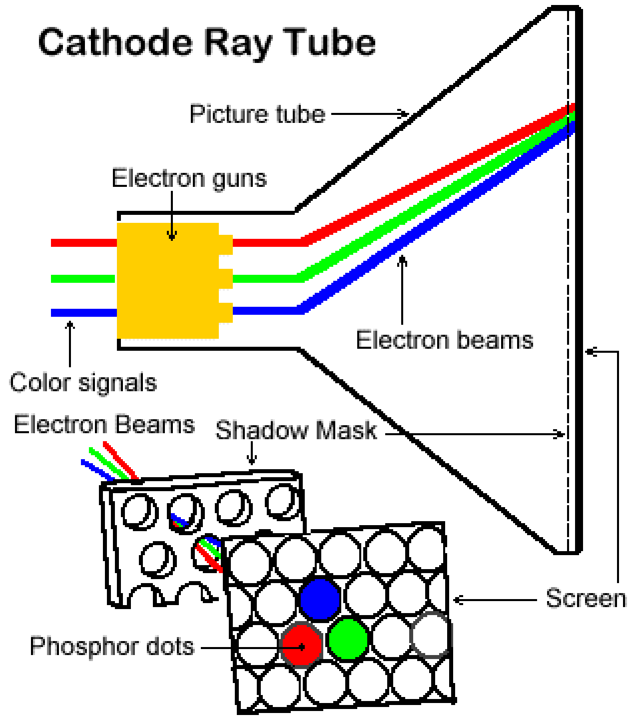

CRT phosphors

multiple projectors

http://www.jegsworks.com

http://www.crtprojectors.co.uk/

Superposition

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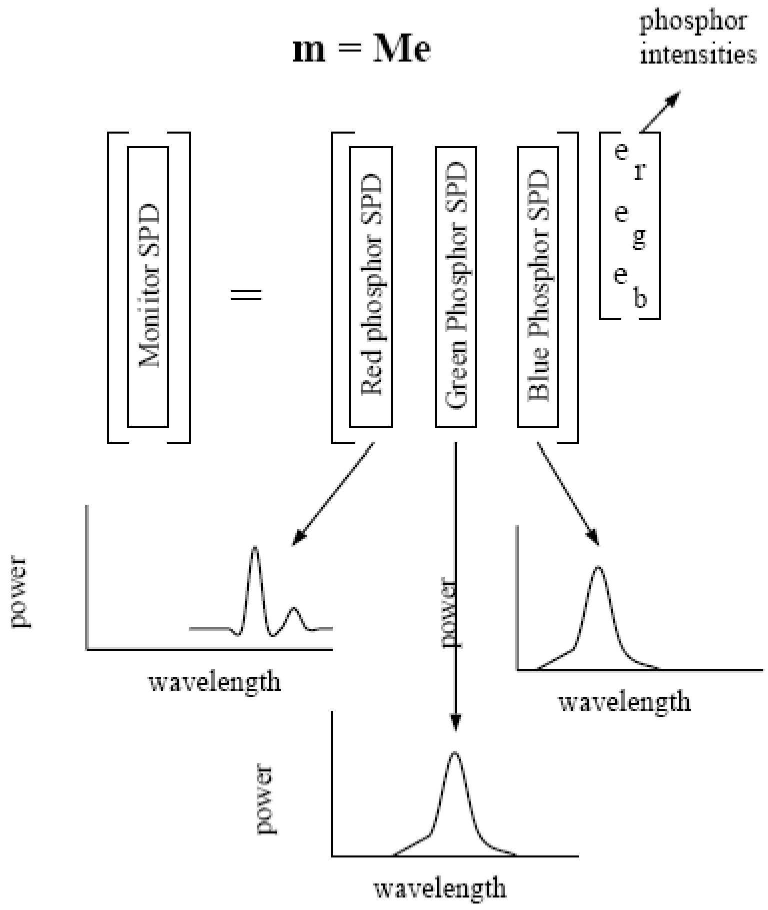

Figure from B. Wandell, 1996

- Additive mixing:

  The spectral power distribution of the mixture is the sum of the spectral power distributions of the components.

Subtractive color mixing

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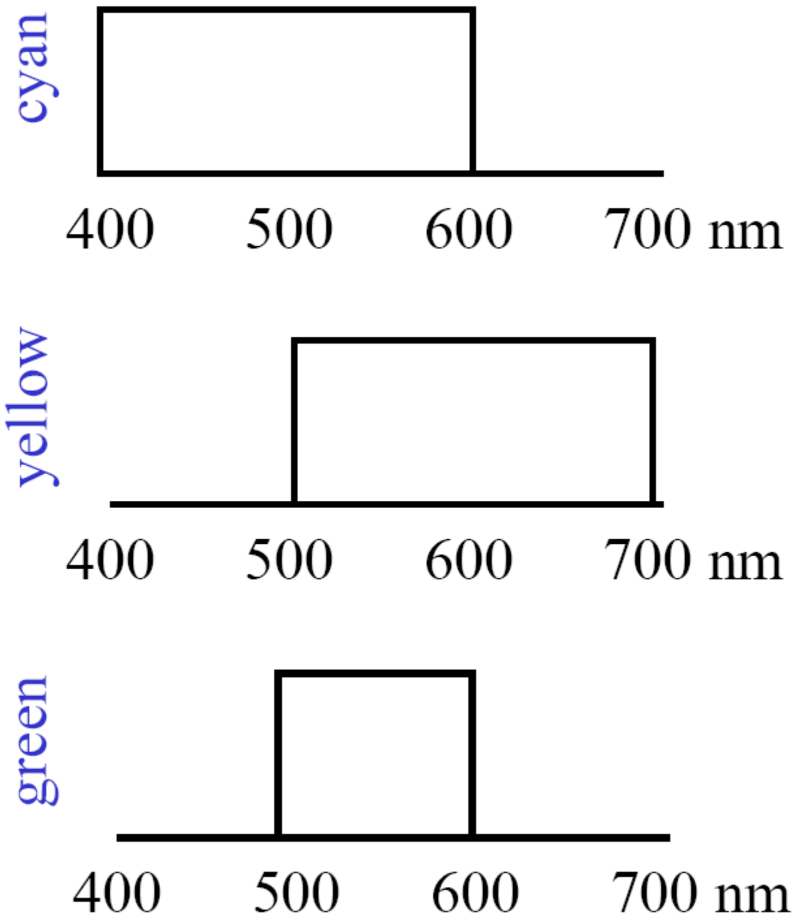
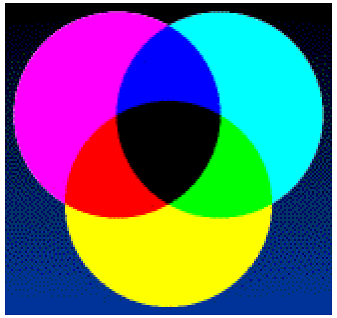


Colors combine by *multiplying* color spectra.



Pigments *remove* color from incident light (white).

Source: W. Freeman

Examples of subtractive color systems

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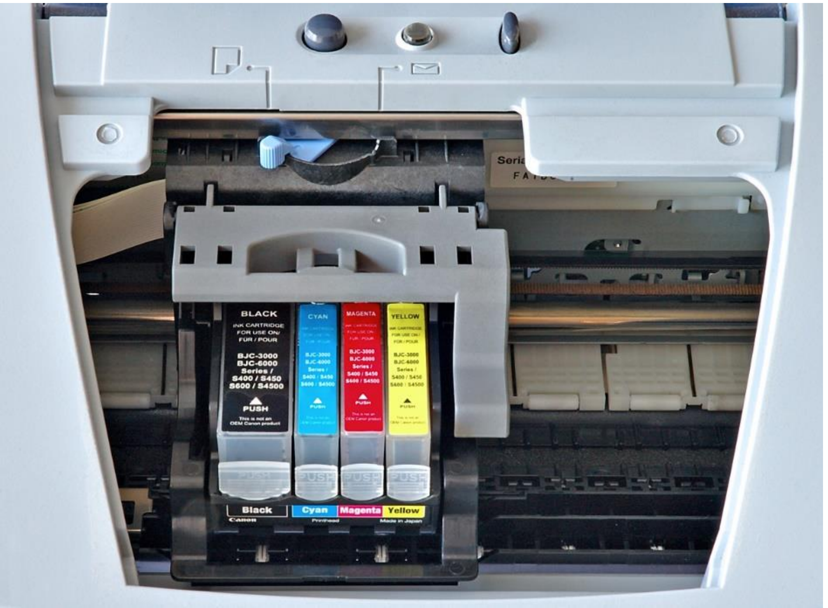
- Printing on paper
- Crayons
- Most photographic film



CMY or CMYK Color Space

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- The CMY color space stands for cyan, magenta, and yellow, which are the complements of red, green, and blue, respectively
- The CMY colors are called *subtractive primaries*

CMY or CMYK Color Space

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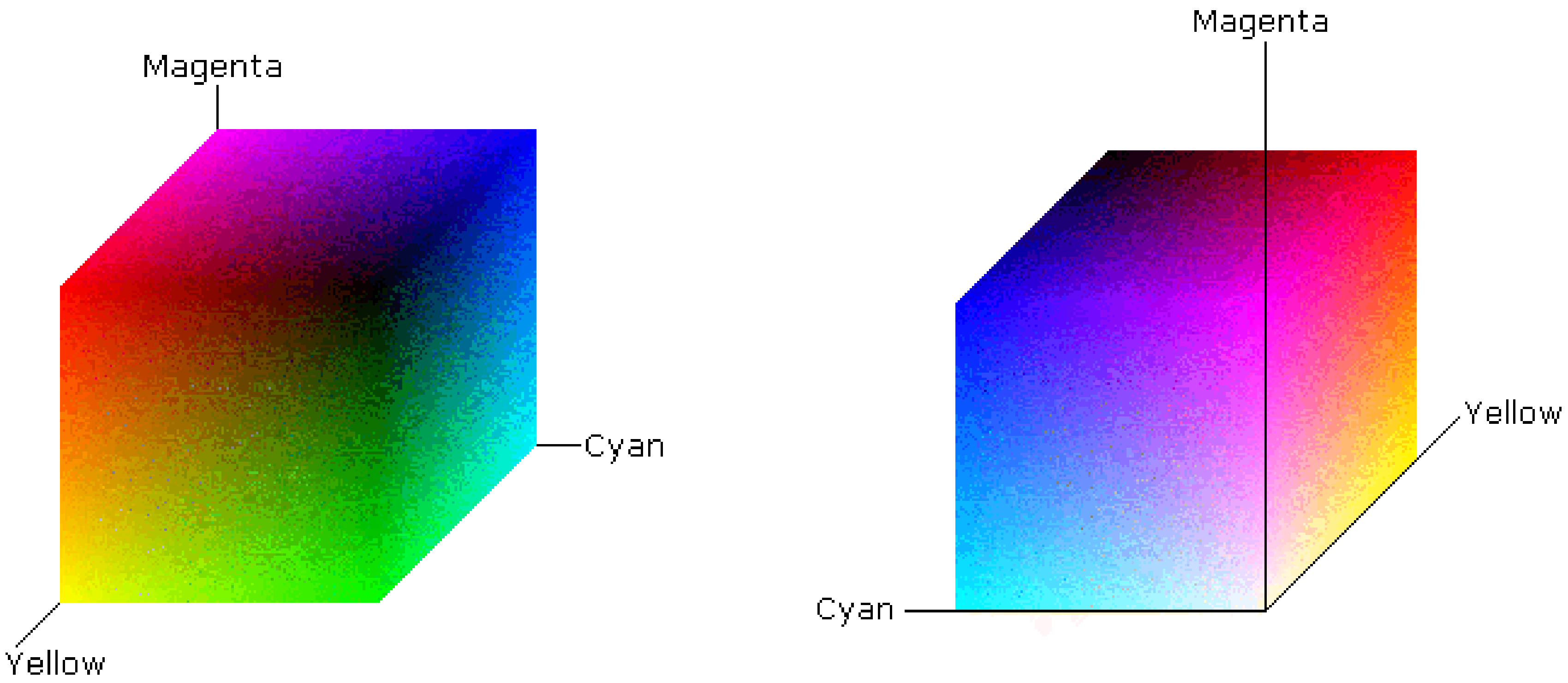

CMY color space cube at minimum values

Why the CMY / CMYK is used in printing

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- If white light is incident on a printed paper, the color ink pigments absorb part of the spectrum and the complement of the incident white light spectrum is reflected to the observer's eye
- The ink that prints on the paper has to absorb the complement of that RGB color, which is the color's CMY equivalent
- The C, M, and Y combine subtractively to form black.
- While printing, to print white in CMY is very trivial and can be obtained by setting C M Y 0 (that is, no pigment is printed)
- Conversely, equal amounts of C, M, and Y should produce black

- it is impractical to use all three C, M, and Y pigments each time to produce black
  - First, consuming all three pigments to produce black can prove expensive.
  - Second, while in theory black is produced this way, in practice, the resulting dark color in neither fully black nor uniform.
- Hence, a fourth pigment K is commonly used in the CMY system to produce true black.
- Use of K along with CMY generates a superior final printed result with greater contrast

YUV Color Space

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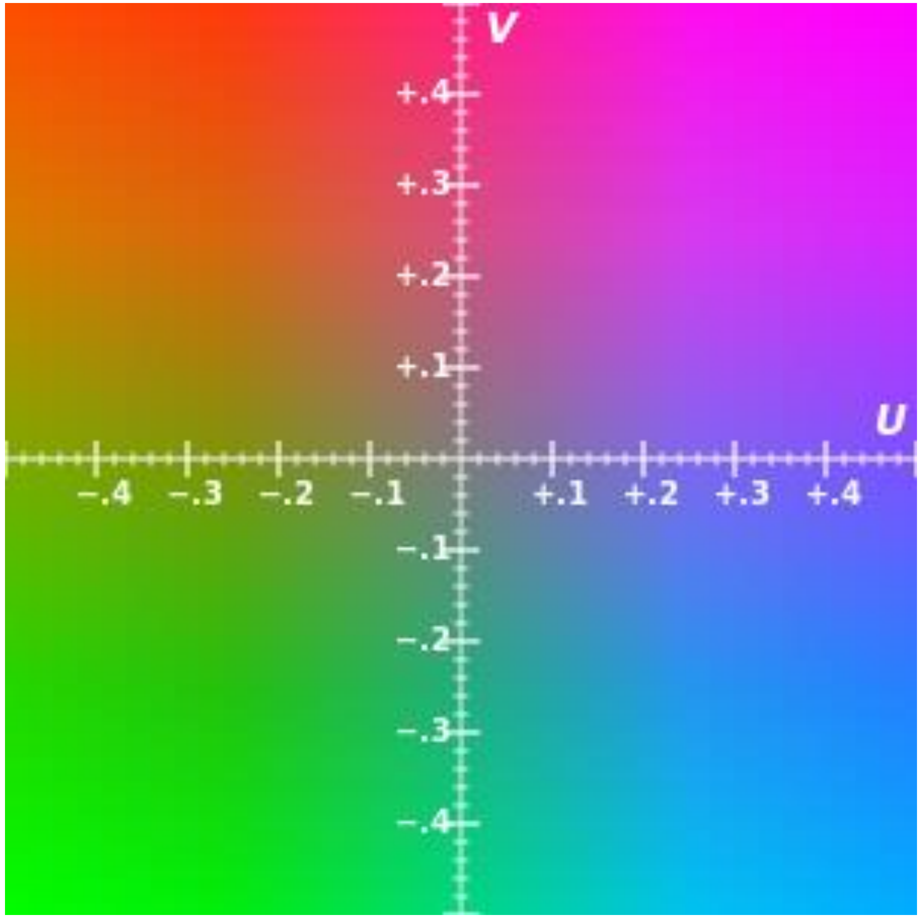
- YUV is a color space typically used as part of a color image pipeline
- It encodes a color image or video taking human perception into account, allowing reduced bandwidth for chrominance components
- Typically enabling transmission errors or compression artifacts to be more efficiently masked by the human perception than using a "direct" RGB-representation.



Example of U-V color plane, Y' value = 0.5, represented within RGB color gamut

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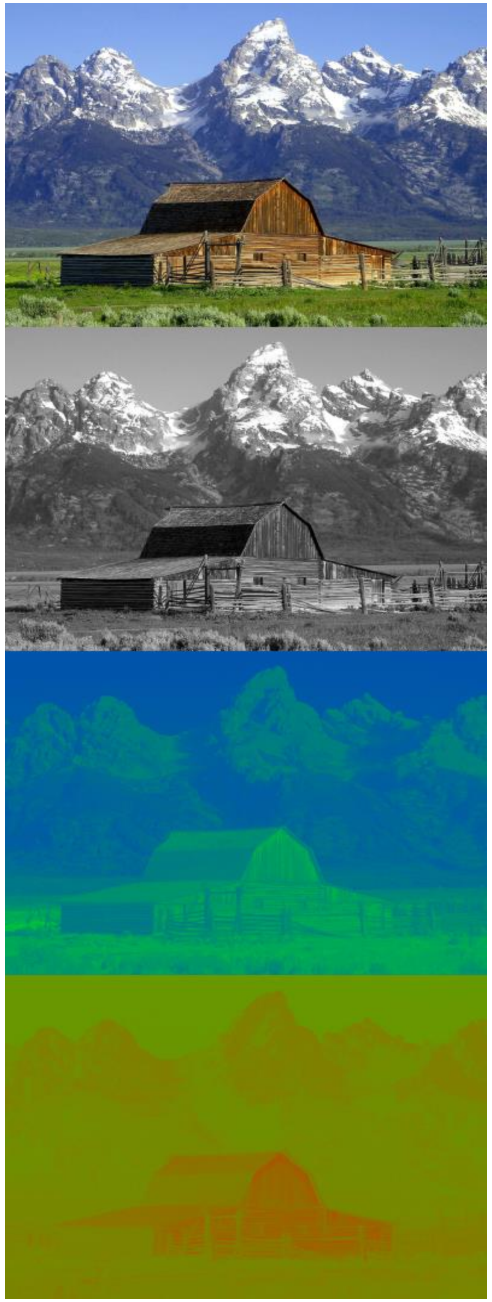

An image along with its Y', U, and V components respectively.

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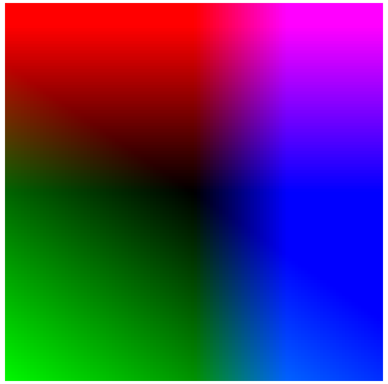
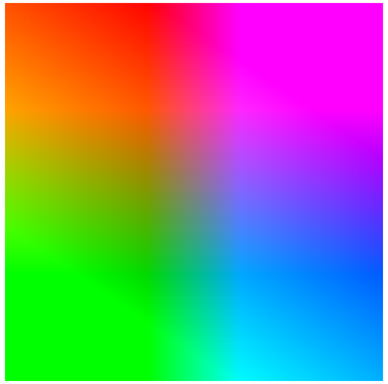
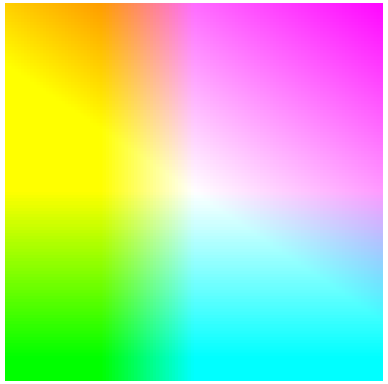


Y' value of 0



Y' value of 0.5



Y' value of 1

HSV Color Space

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- For a human observer, the colors defined in these spaces might not necessarily encode properties that are common in language, or that are important in digital imagery applications

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- Useful color terms include the following:
  - Hue
    - The property of a color that varies in passing from red to green.
    - Roughly speaking, hue represents the dominant wavelength in spectral power density of that color.
  - Saturation
    - The property of a color that defines the colorfulness of an area judged in proportion to its brightness
    - Roughly speaking, the more the spectral energy that is concentrated at one wavelength, the more saturated the associated color.
  - Brightness
    - Also sometimes called lightness or value, the property that varies in passing from black to white

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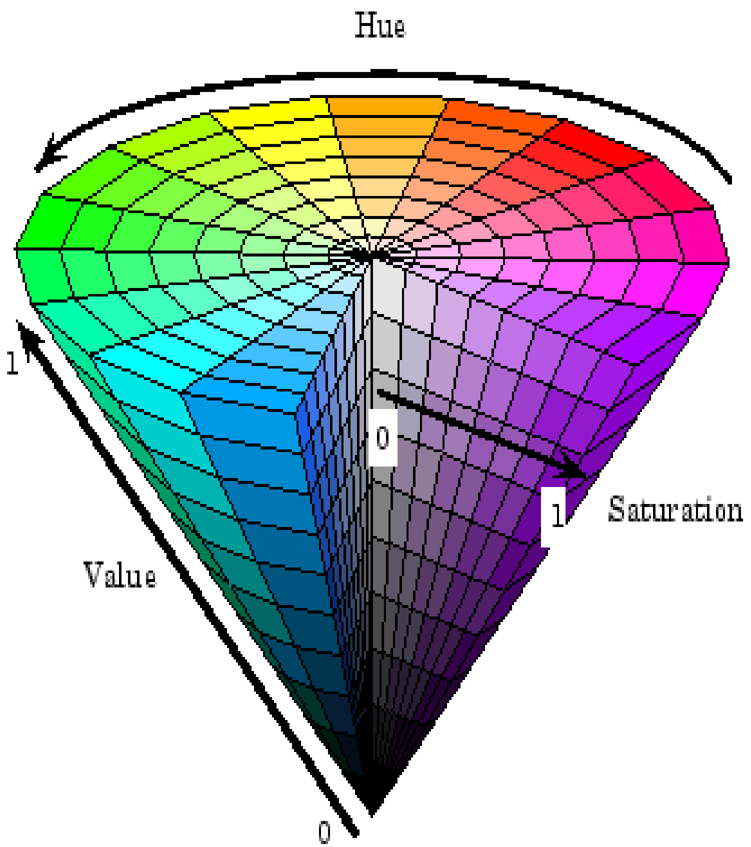

Uniform Color Spaces

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- Evaluating and comparing color differences is needed in many applications
- The color spaces dealt with so far do not make this a necessarily easy task

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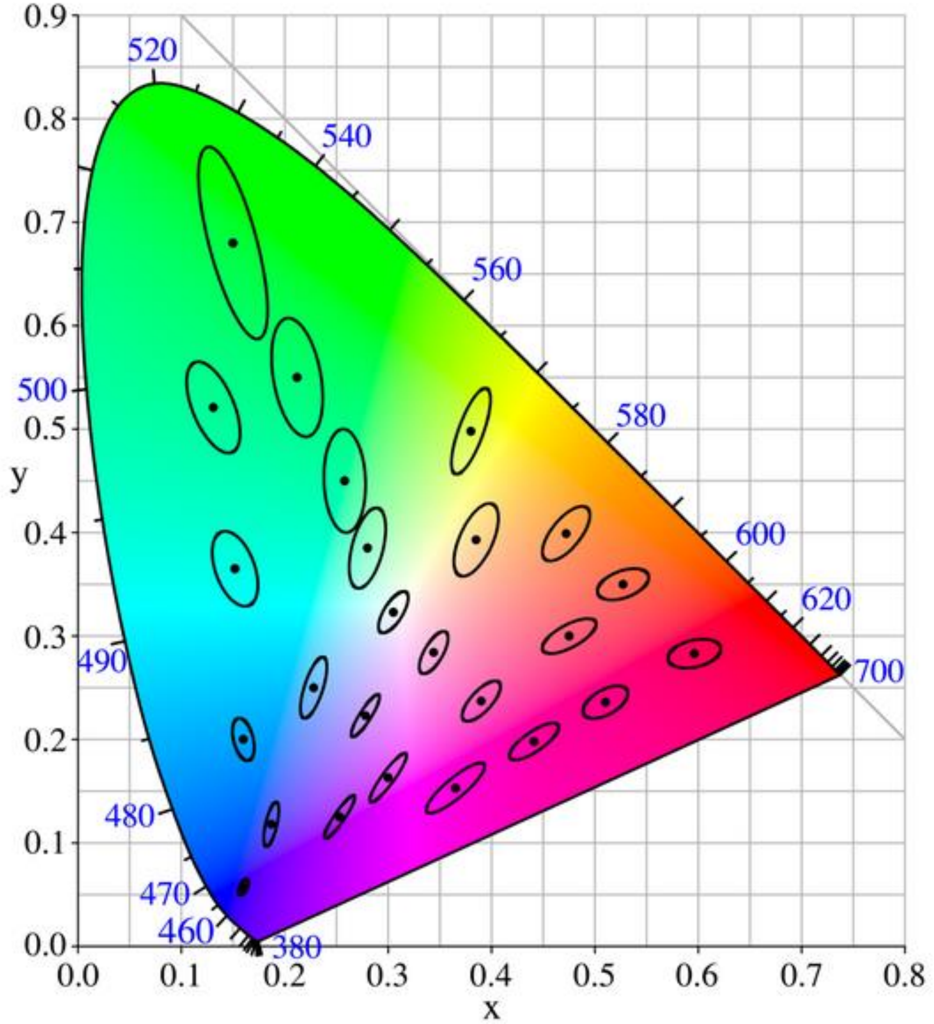

- MacAdam ellipses refer to the region on a chromaticity diagram which contains all colors which are indistinguishable, to the average human eye, from the color at the center of the ellipse.

- The contour of the ellipse therefore represents the just noticeable differences of chromaticity.

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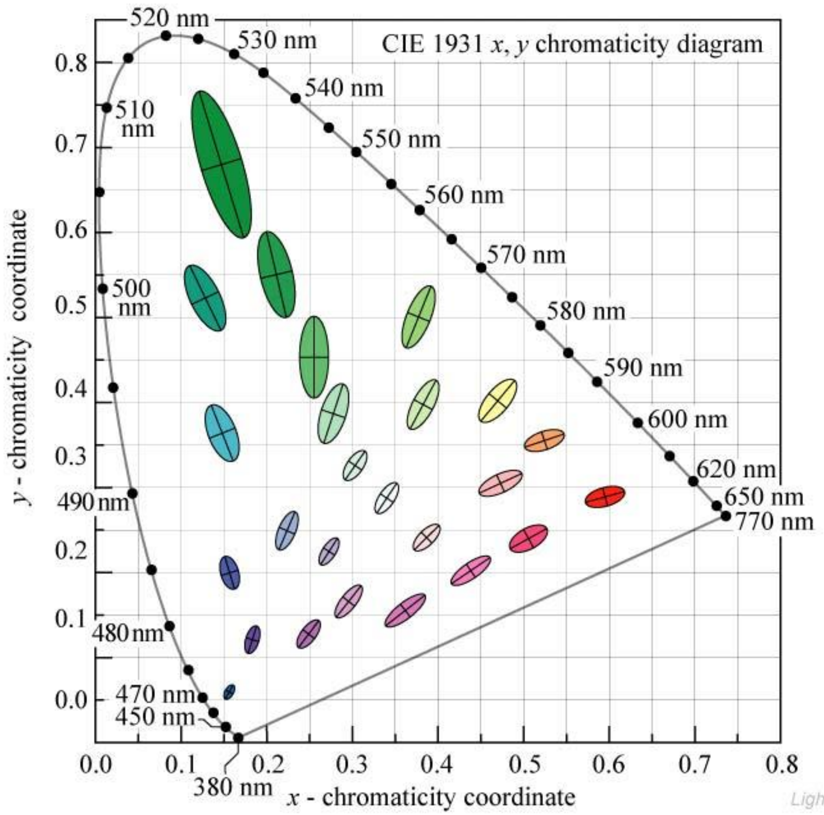

Fig. 17.5. MacAdam ellipses plotted in the CIE 1931 (x, y) chromaticity diagram. The axes of the ellipses are ten times their actual lengths (after MacAdam, 1943; Wright, 1943; MacAdam, 1993).

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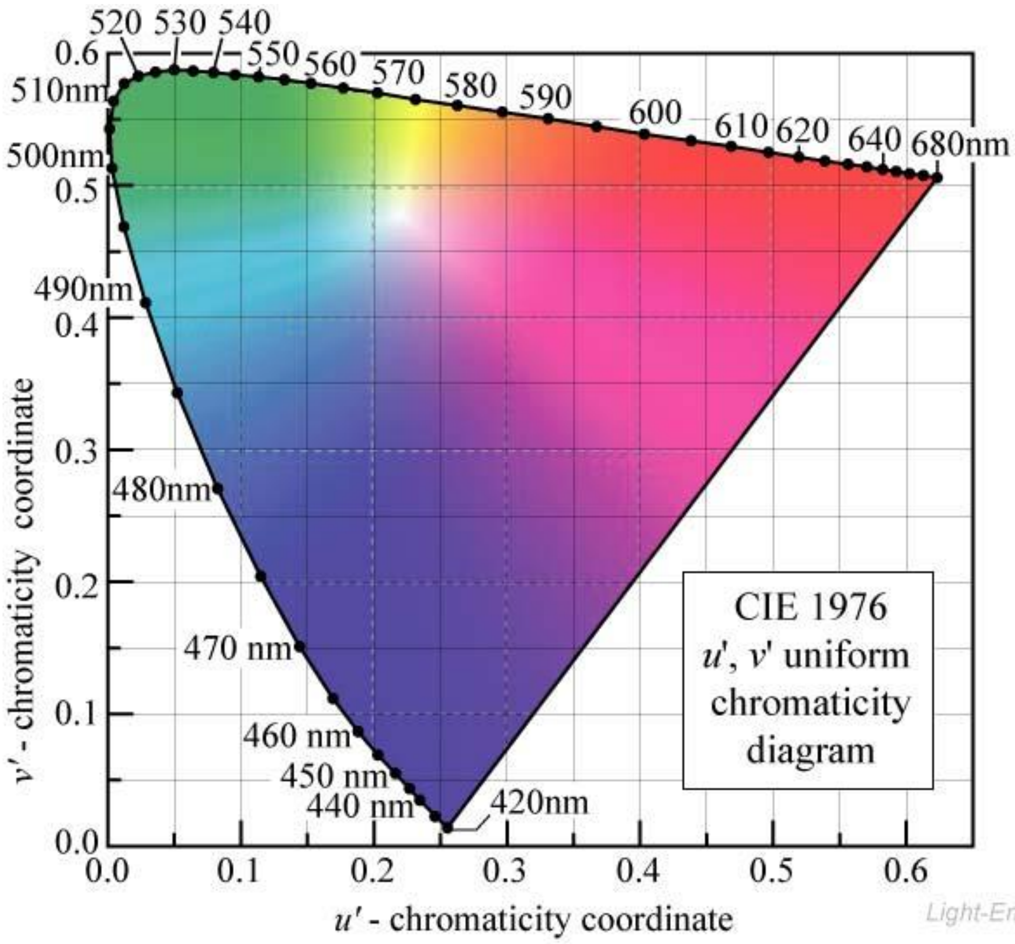

Fig. 17.6. CIE 1976 (u', v') uniform chromaticity diagram calculated using the CIE 1931 2° standard observer.

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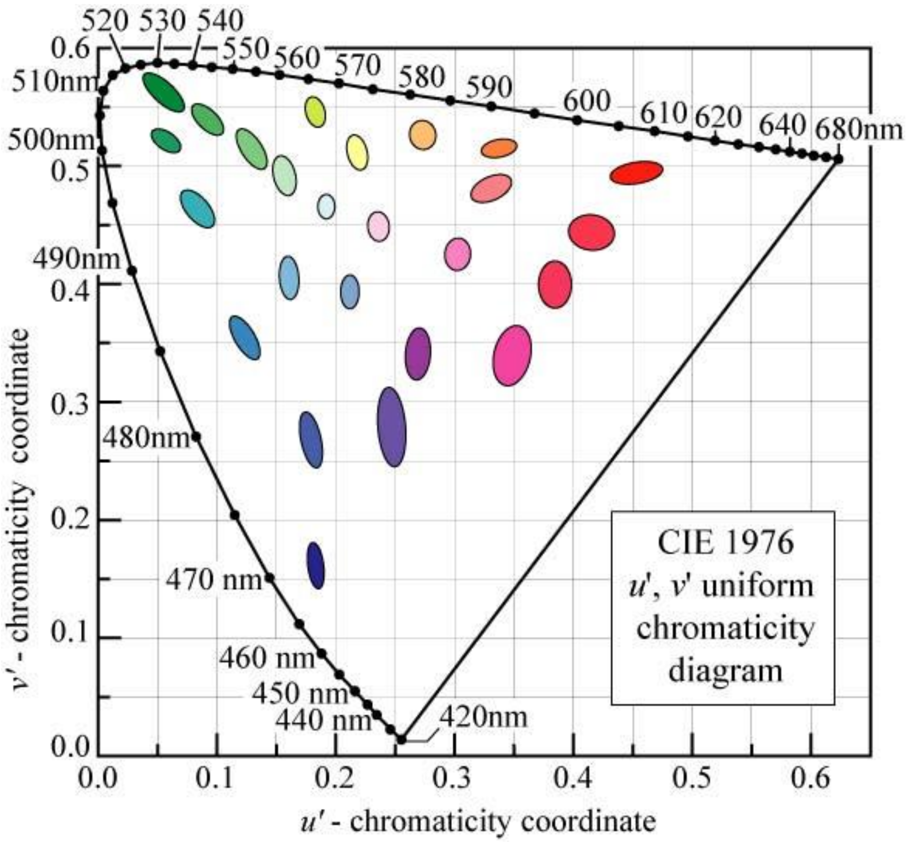

Fig. 17.7. MacAdam ellipses transformed to uniform CIE 1976 (u', v') chromaticity coordinates. For clarity, the axes of the transformed ellipses are ten times their actual lengths. Transformed ellipses are not ellipses in a strict mathematical sense, but their shapes closesly resemble those of ellipses. The areas of the transformed ellipses in the (u', v') diagram are much more similar than the MacAdam ellipses in the (x, y) diagram.

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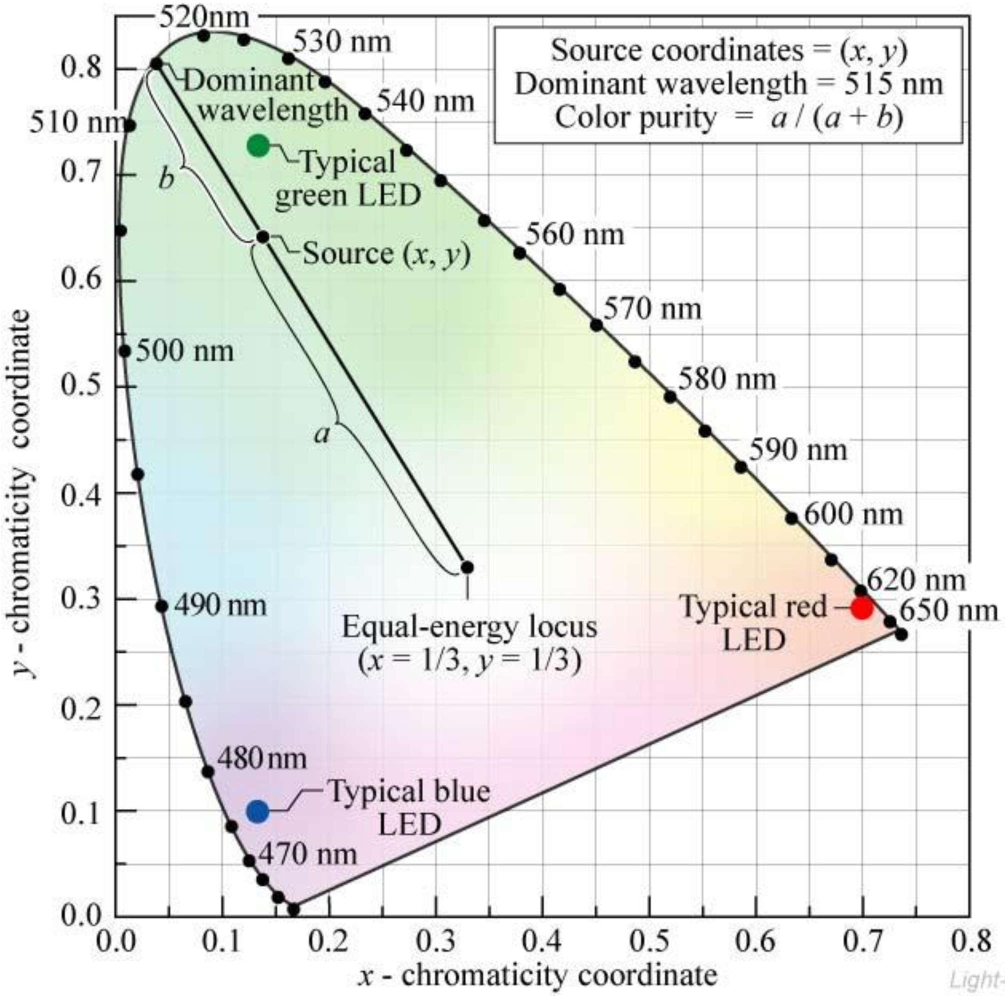

Fig. 17.8. Chromaticity diagram showing the determination of the *dominant color* and *color purity* of a light source with chromaticity coordinates (x, y) using the equal-energy locus ($x = 1/3$, $y = 1/3$) as the white-light reference. Also shown are typical locations of blue, green, and red LEDs.

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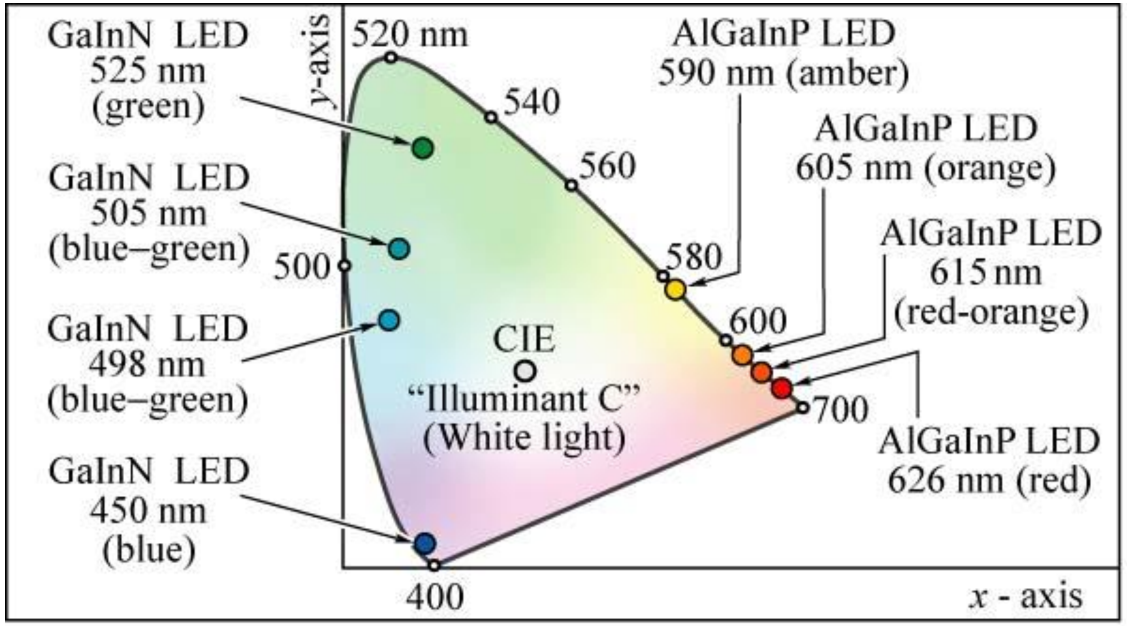

Fig. 17.9. Location of LED light emission on the chromaticity diagram (adopted from Schubert and Miller, 1999).

Device Dependence of Color Spaces

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- Based on the CIE standard, devices are supposed to use the same primary frequencies R, G, and B as their basis for producing the gamut or ranges of colors.
- In practice, obtaining the same R, G, and B frequencies might not be possible because of manufacturing problems and the different devices might have very similar, though not the necessarily the same frequencies for R, G, and B.
- This means that RGB and CMY color spaces vary from monitor to monitor and from printer to printer and, hence, are called device-dependent color spaces.
- This device dependence of color is induced by a variety of reasons, such as not using the exact primaries, temperature-based changes in color frequencies, and monitor gammas.

Gamma Correction and Monitor Calibration

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- For each gun in a CRT, the power of the emitted light $S_i(\gamma)$ *is a function of* the control voltage v_i, *which is approximated as follows*

$$S_i(\gamma)=\left(\frac{v_i}{v}\right)^{\gamma} p_i(\lambda)$$

- The previous transformation is called gamma correction

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- The gamma value, therefore, defines the relationship between the amount of light given out from the device and the 8-bit RGB values in the original signal
- Typical CRT displays have gamma values between 1.5 and 3.0 and the value is constant for all the channels
- 2.2 is a frequently used standard
- Some graphics hardware partially compensates for this response function, bringing the effective system gamma down to 1.8 or 1.4.
- The correct display of images, whether computer-generated or captured, requires proper correction for the system's gamma response

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- Unlike CRT displays, liquid crystal displays do not follow a pronounced nonlinear luminance-voltage transfer function that can be emulated by the power law function
- To produce correct chrominance and luminance, LCD displays typically have gamma lookup tables, one table for each of the primary R, G, and B colors
- These lookup values are arrived at statistically and work well when the color of a pixel does not change
- In the case of LCD displays, gamma tables have been useful but at the same time are unable to produce high-quality color characteristics as seen in CRT displays

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Q & A

RGB color space

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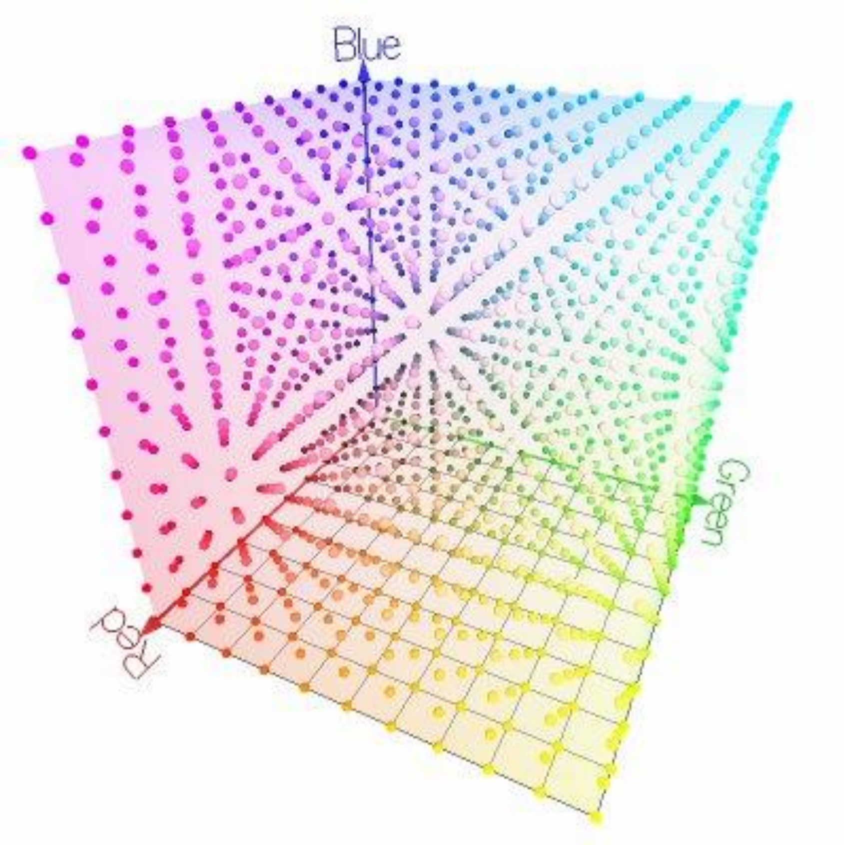

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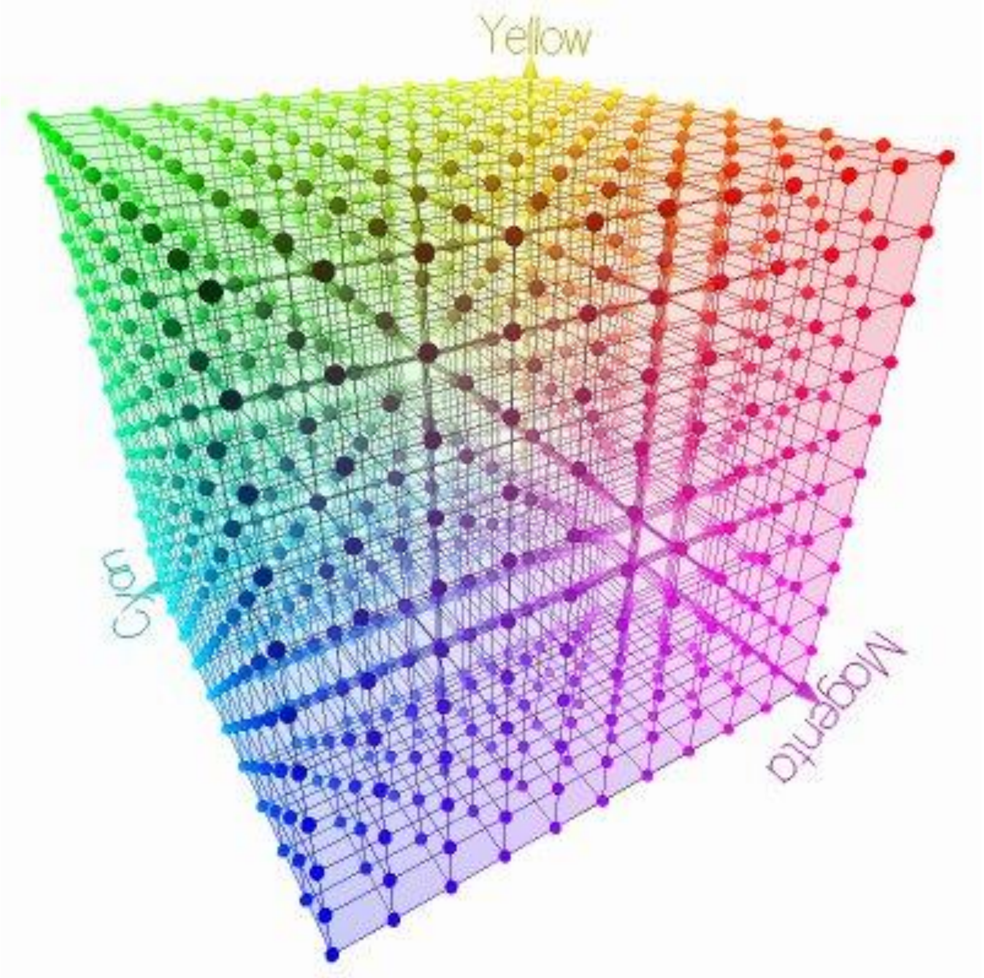
CMY color space



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

XYZ (CIEXYZ) color space

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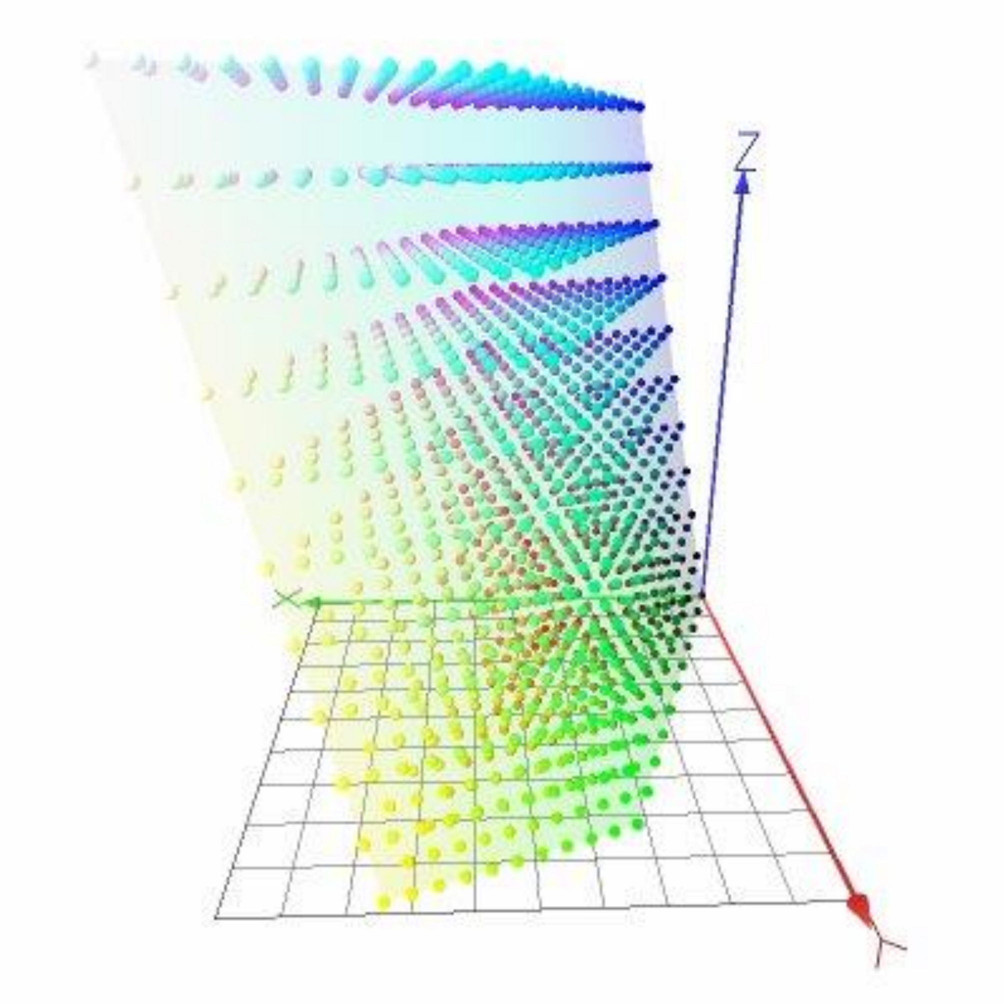

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A.\begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} X_{offset} \\ Y_{offset} \\ Z_{offset} \end{bmatrix}$$

xyY color space

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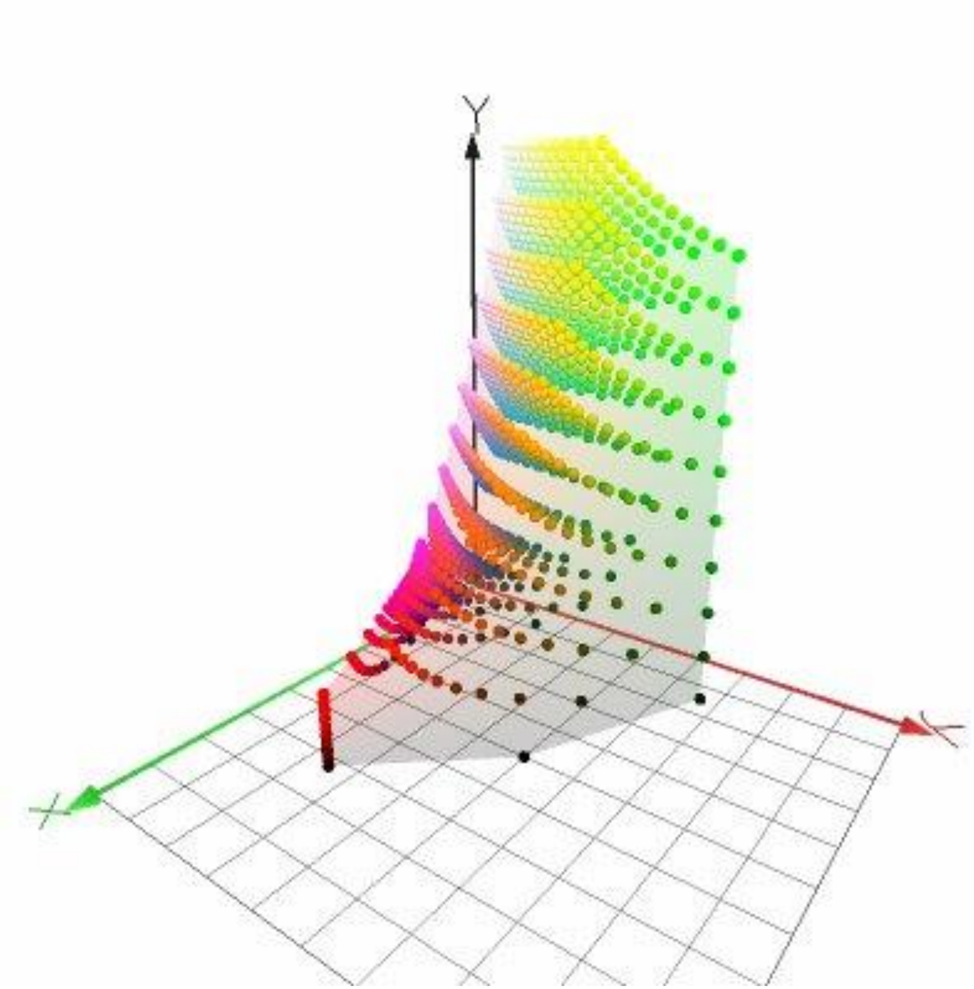

$$\begin{cases} x = \frac{X}{X+Y+Z} \\ y = \frac{Y}{X+Y+Z} \\ Y = Y \end{cases}$$

L*a*b* (CIELAB) color space

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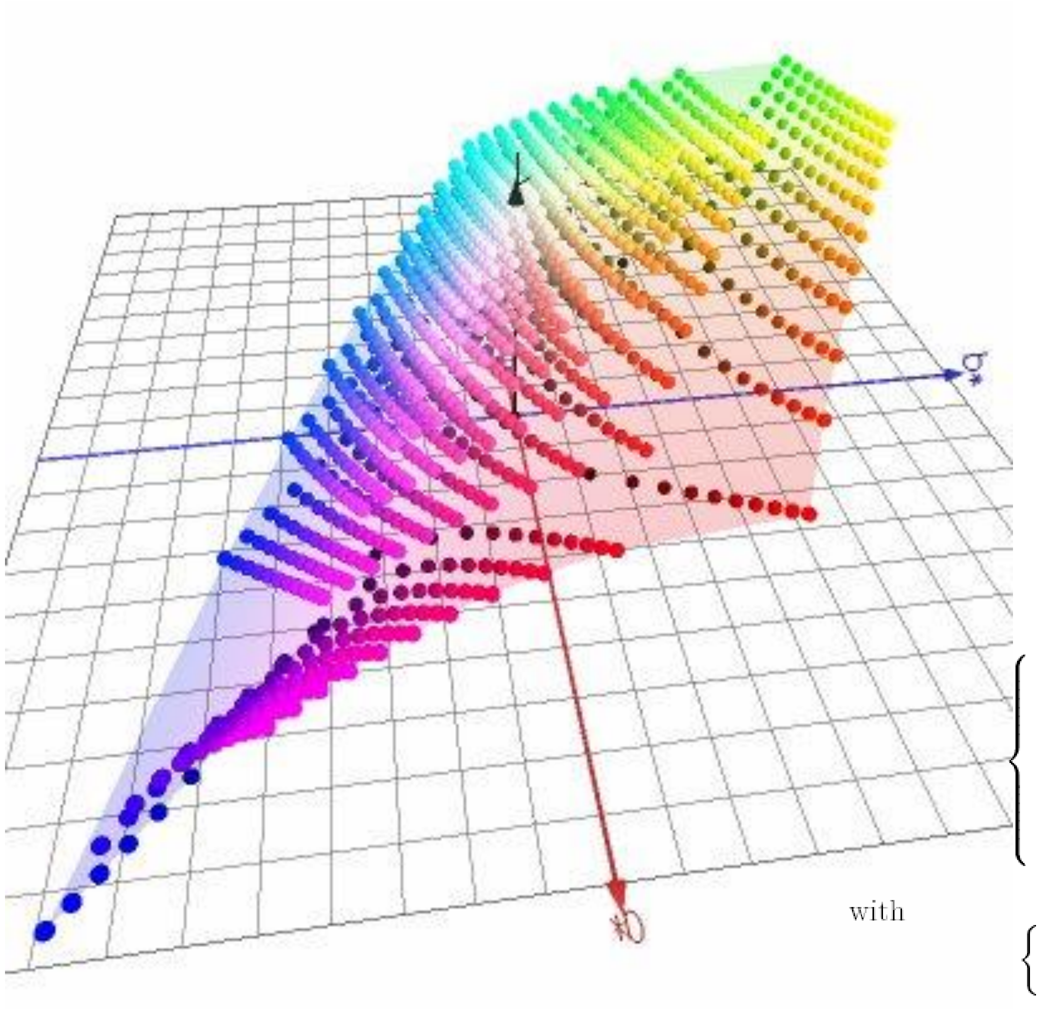

$$\begin{cases} L^* &= 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \text{if } \frac{Y}{Y_0} > 0.008856 \\ L^* &= 903.3\left(\frac{Y}{Y_0}\right) & \text{if } \frac{Y}{Y_0} \leq 0.008856 \\ a^* &= 500\left[f(\frac{X}{X_0}) - f(\frac{Y}{Y_0})\right] \\ b^* &= 200\left[f(\frac{Y}{Y_0}) - f(\frac{Z}{Z_0})\right] \end{cases}$$

with

$$\begin{cases} f(U) &= U^{\frac{1}{3}} & \text{if } U > 0.008856 \\ f(U) &= 7.787U + 16/116 & \text{if } U \leq 0.008856 \end{cases}$$

and

$$U(X,Y,Z) = \frac{4X}{X + 15Y + 3Z} \quad \text{et} \quad V(X,Y,Z) = \frac{9Y}{X + 15Y + 3Z}$$

L*u*v* (CIELUV) color space

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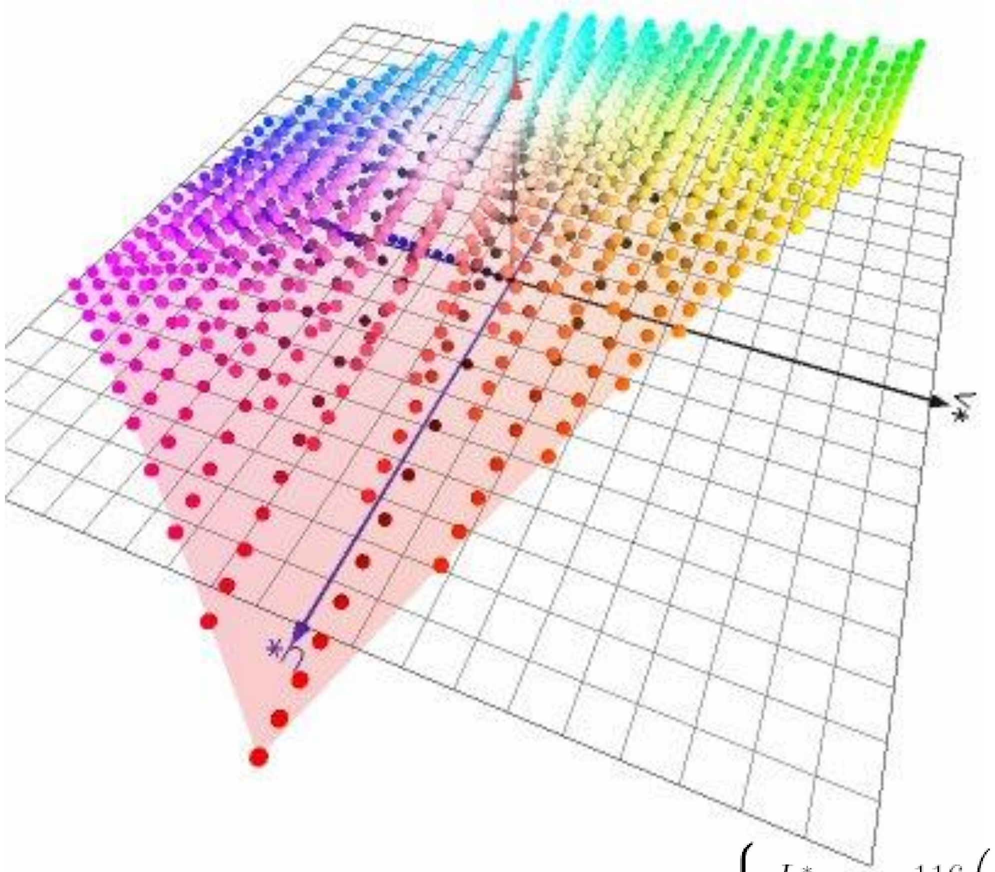

$$
\begin{cases}
L^* &= 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \text{if } \frac{Y}{Y_0} > 0.008856 \\
L^* &= 903.3\left(\frac{Y}{Y_0}\right) & \text{if } \frac{Y}{Y_0} \le 0.008856 \\
u^* &= 13L^*\left[U(X,Y,Z) - U(X_0,Y_0,Z_0)\right] & \\
v^* &= 13L^*\left[V(X,Y,Z) - V(X_0,Y_0,Z_0)\right] &
\end{cases}
$$

YUV color space

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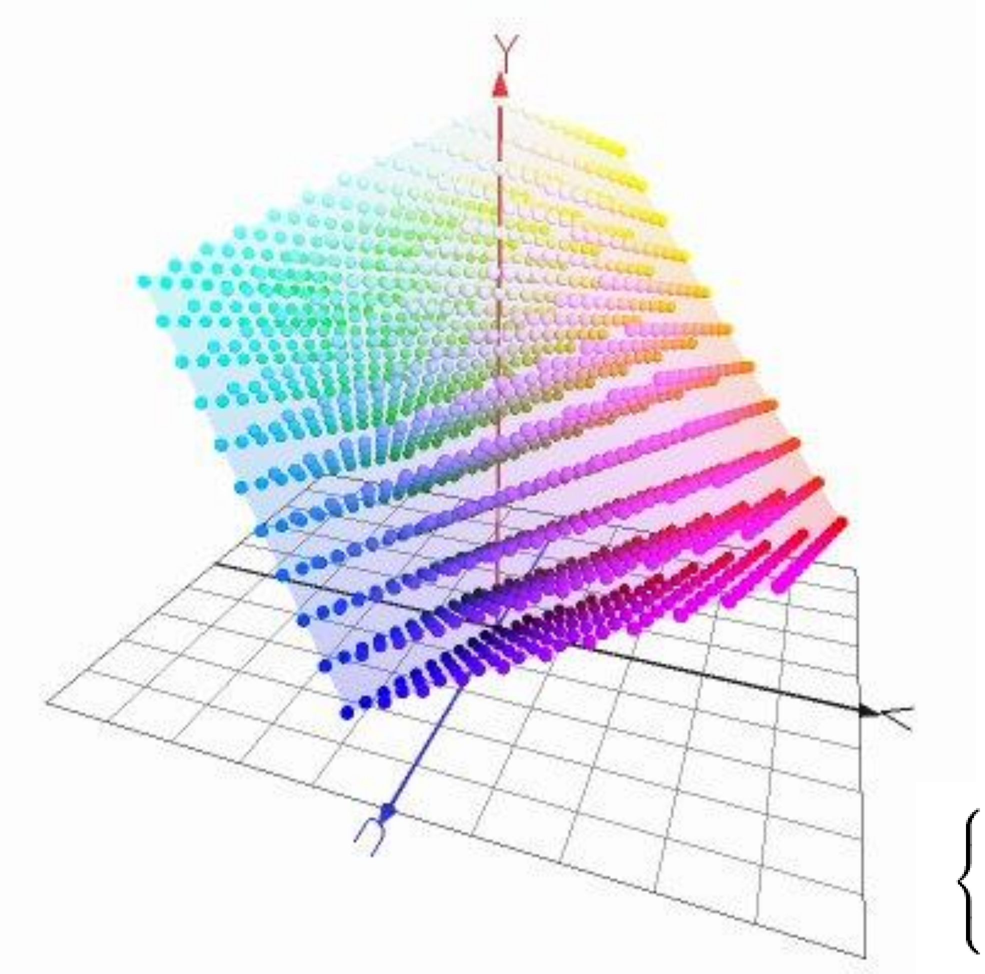

$$
\begin{cases}
Y = 0.299 \times R + 0.587 \times G + 0.114 \times B \\
U = -0.147 \times R - 0.289 \times G + 0.436 \times B \\
V = 0.615 \times R - 0.515 \times G - 0.100 \times B
\end{cases}
$$

YIQ color space

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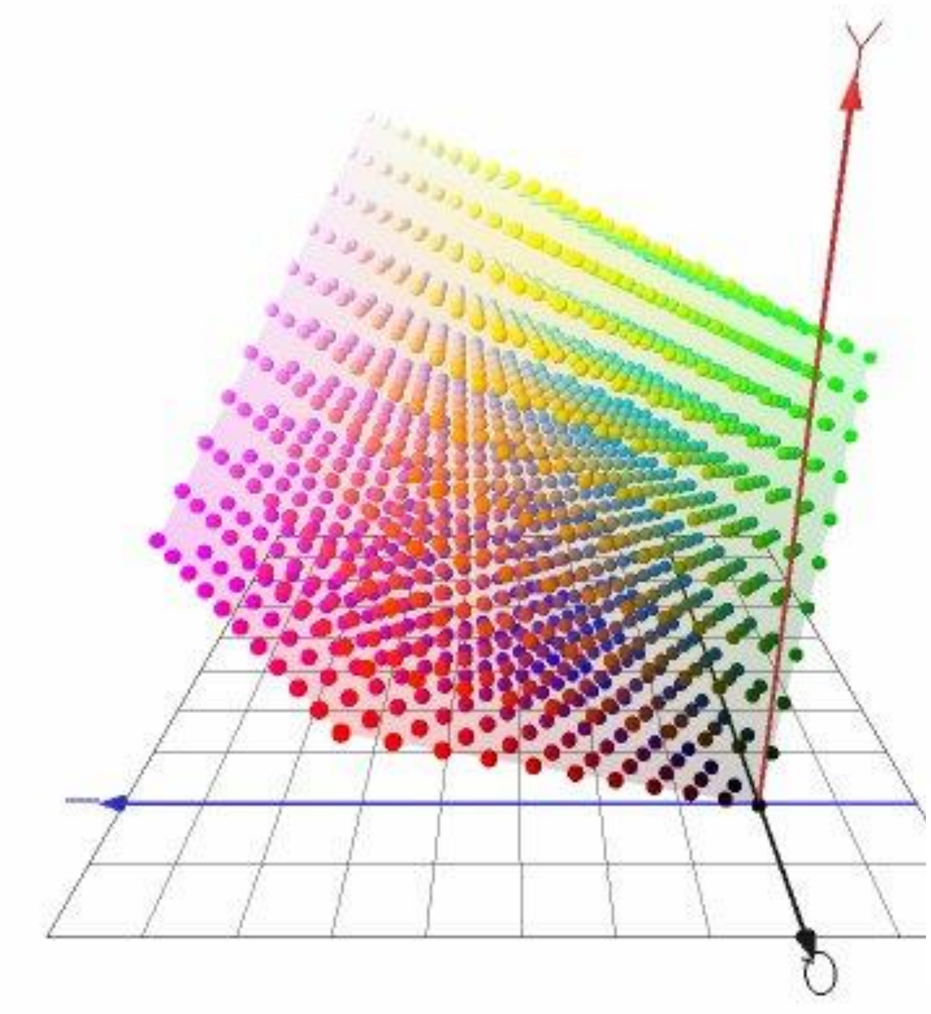

$$\begin{cases} Y &= 0.299 \times R + 0.587 \times G + 0.114 \times B \\ I &= 0.596 \times R - 0.274 \times G - 0.322 \times B \\ Q &= 0.212 \times R - 0.523 \times G + 0.311 \times B \end{cases}$$

YCbCr color space :

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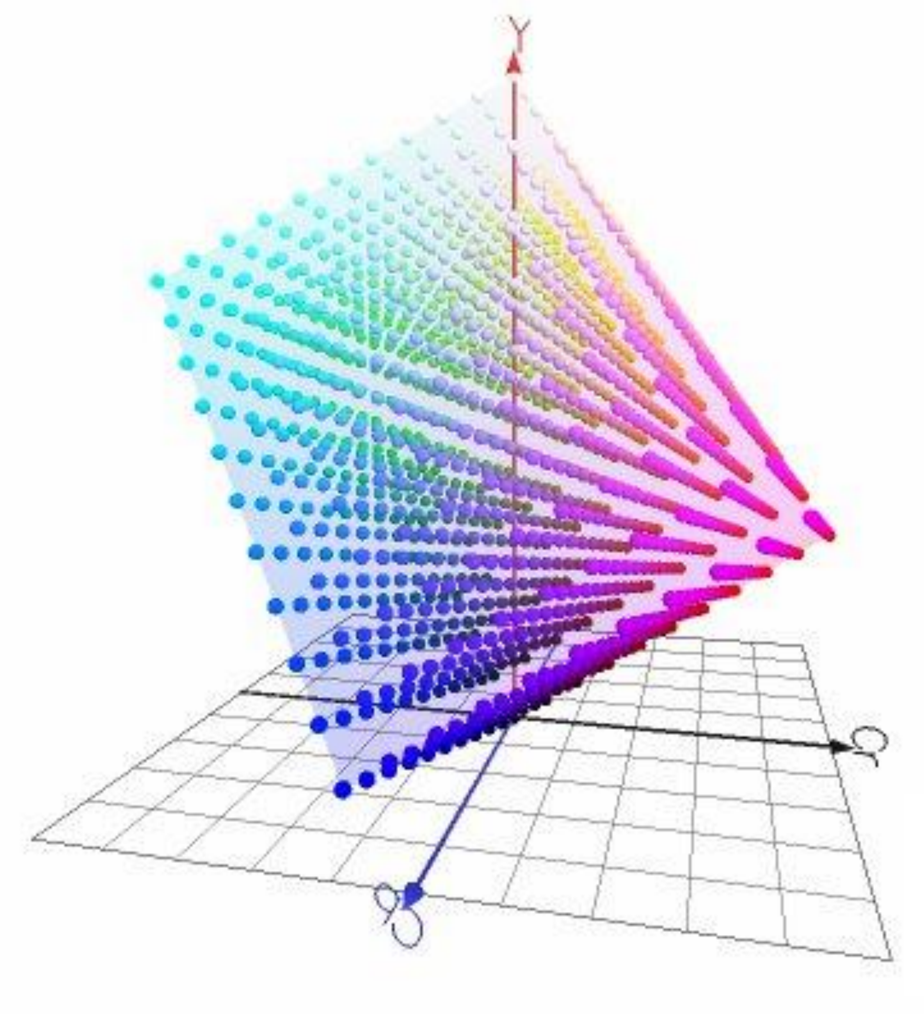

$$\begin{cases} Y &= 0.2989 \times R + 0.5866 \times G + 0.1145 \times B \\ Cb &= -0.1688 \times R - 0.3312 \times G + 0.5000 \times B \\ Cr &= 0.5000 \times R - 0.4184 \times G - 0.0816 \times B \end{cases}$$

I1I2I3 color space

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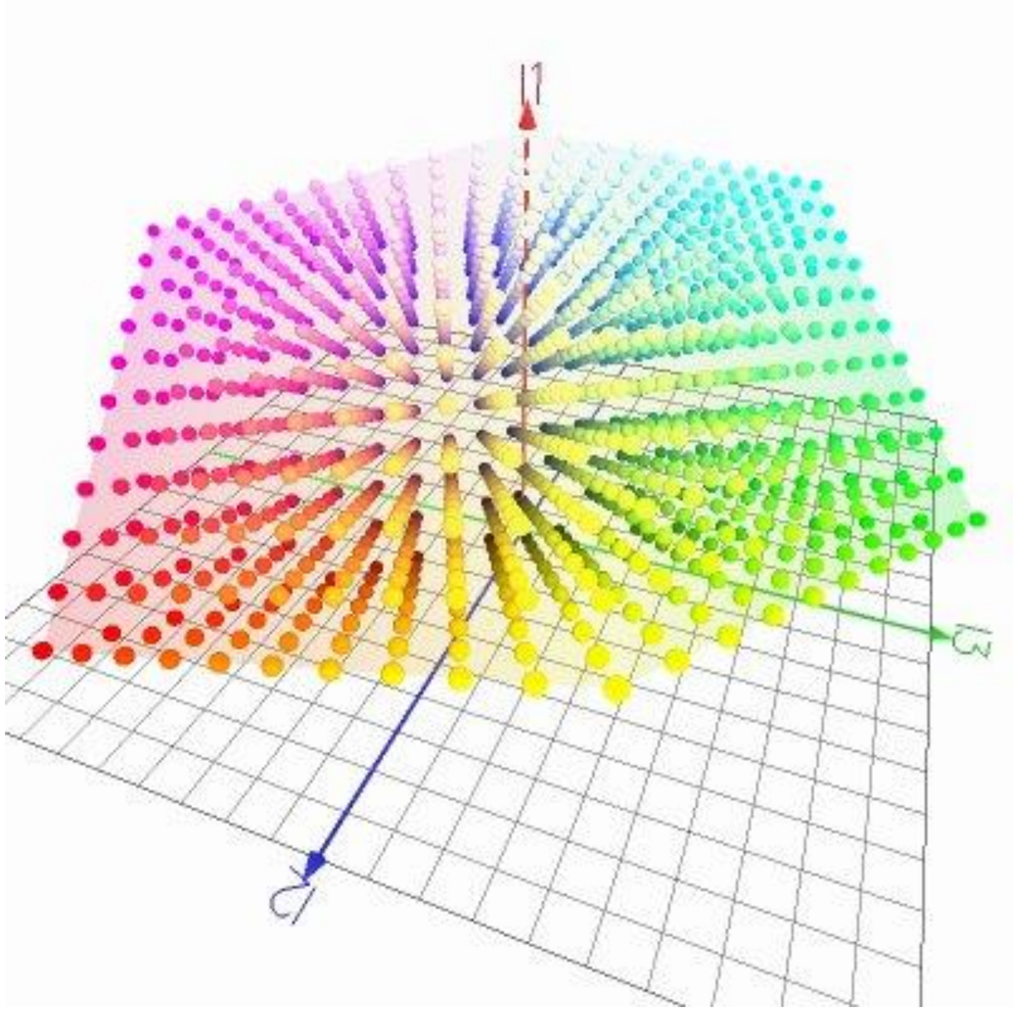

$$\begin{cases} I_1 &= \frac{1}{3}(R+G+B) \\ I_2 &= \frac{1}{2}(R-B) \\ I_3 &= \frac{1}{4}(2G-R-B) \end{cases}$$

LSLM color space

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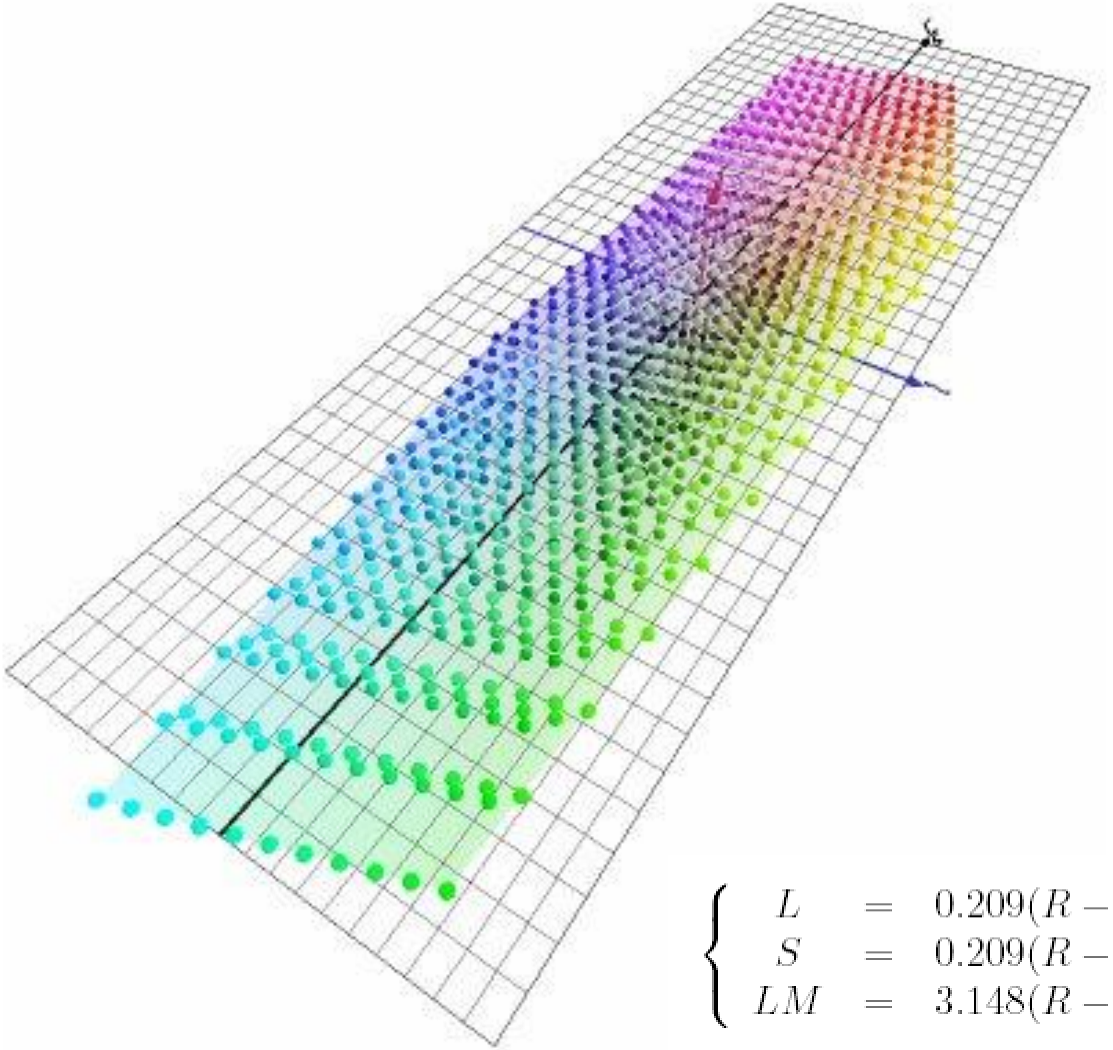

$$\begin{cases} L &= 0.209(R-0.5)+0.715(G-0.5)+0.076(B-0.5) \\ S &= 0.209(R-0.5)+0.715(G-0.5)-0.924(B-0.5) \\ LM &= 3.148(R-0.5)-2.799(G-0.5)-0.349(B-0.5) \end{cases}$$

UVW color space

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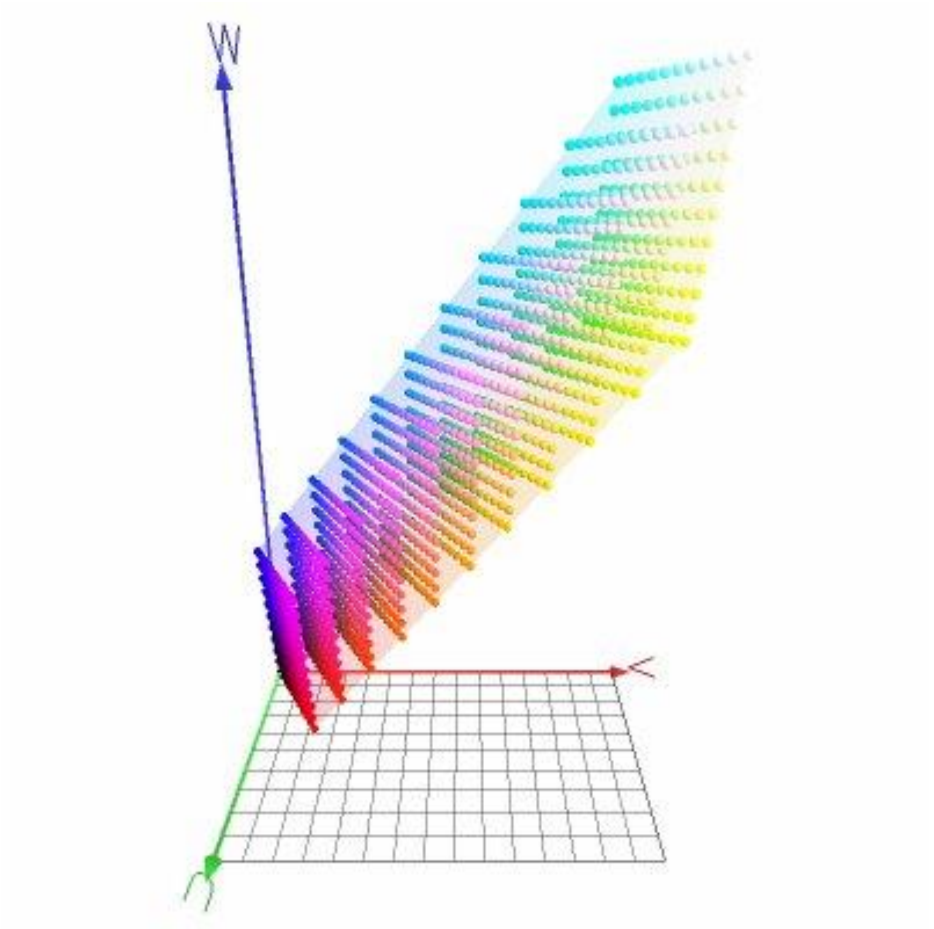

HSI color space

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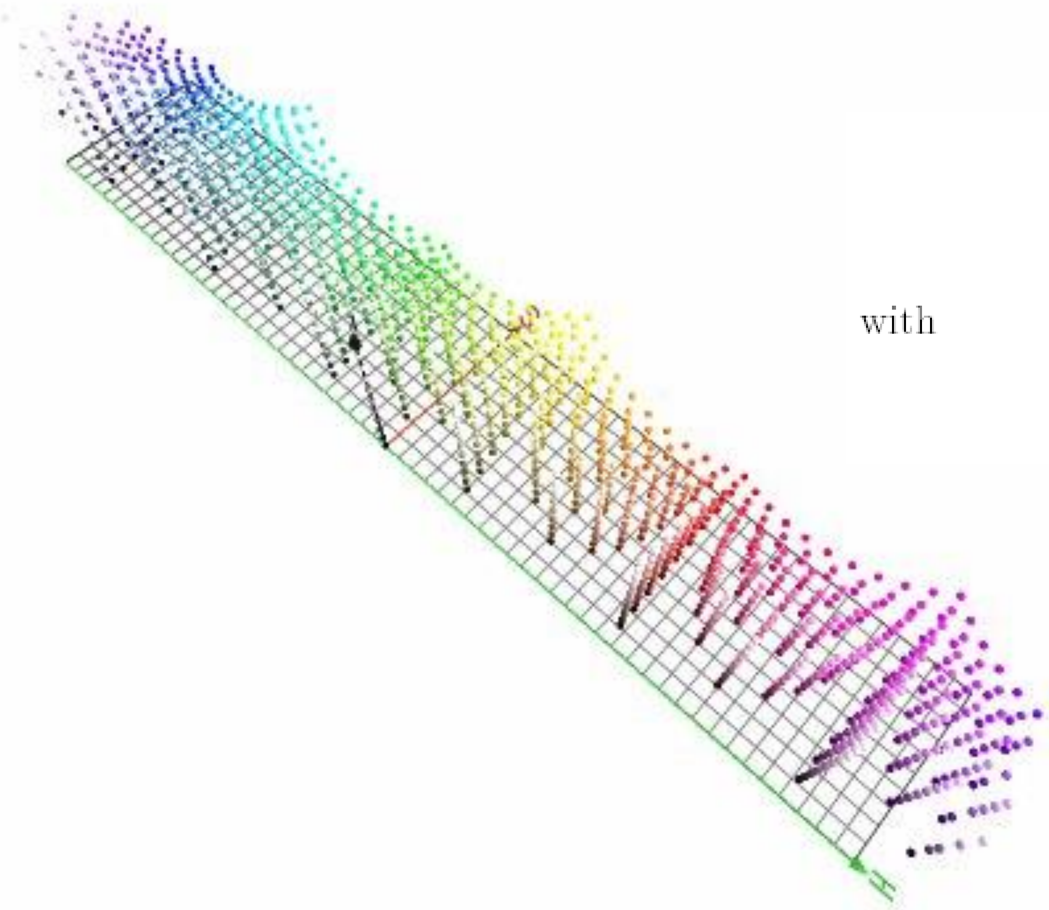

with

$$\begin{cases} H &= arctan(\frac{\beta}{\alpha}) \\ S &= \sqrt{\alpha^2 + \beta^2} \\ I &= (R + G + B)/3 \end{cases}$$

$$\begin{cases} \alpha = R - \frac{1}{2}(G + B) \\ \beta = \frac{\sqrt{3}}{2}(G - B) \end{cases}$$

HSI Polar color space

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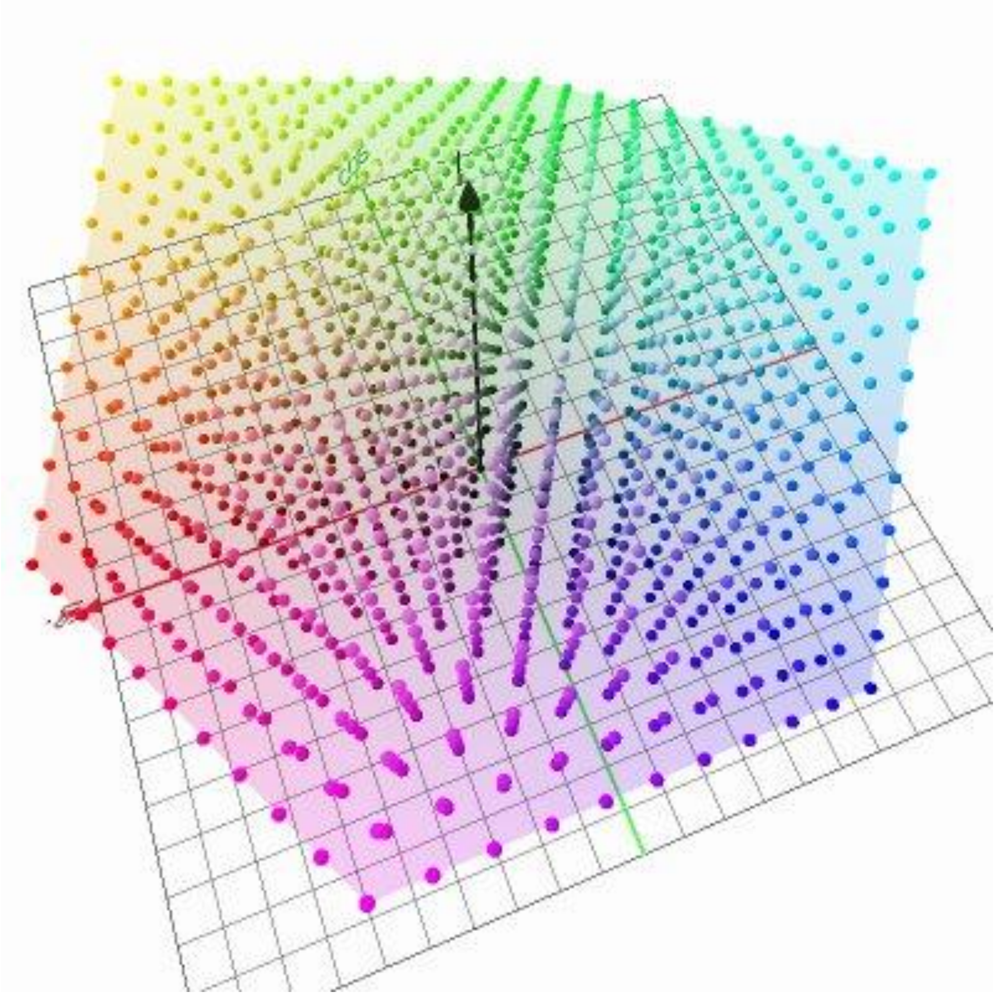

HSV color space

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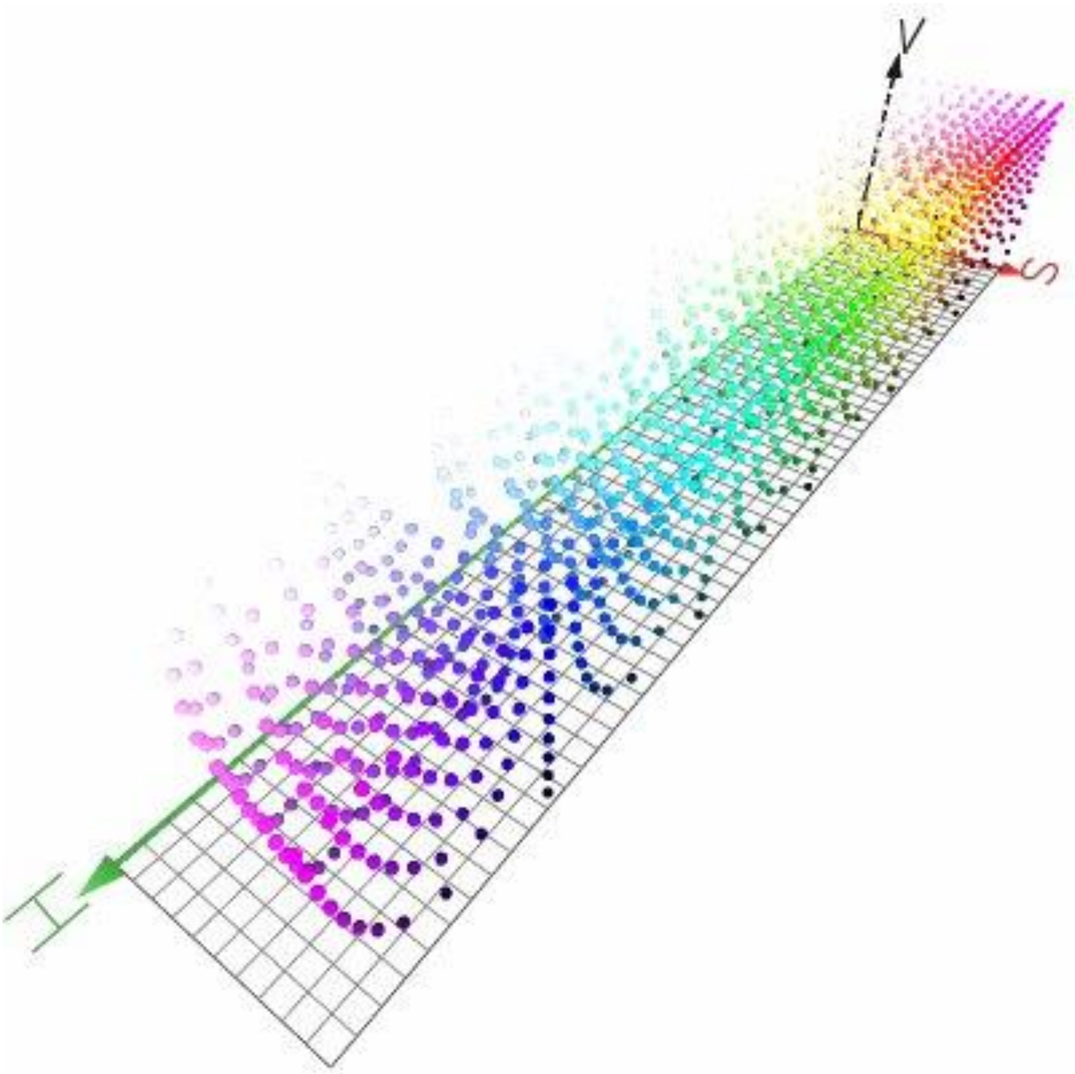

HSV Polar color space

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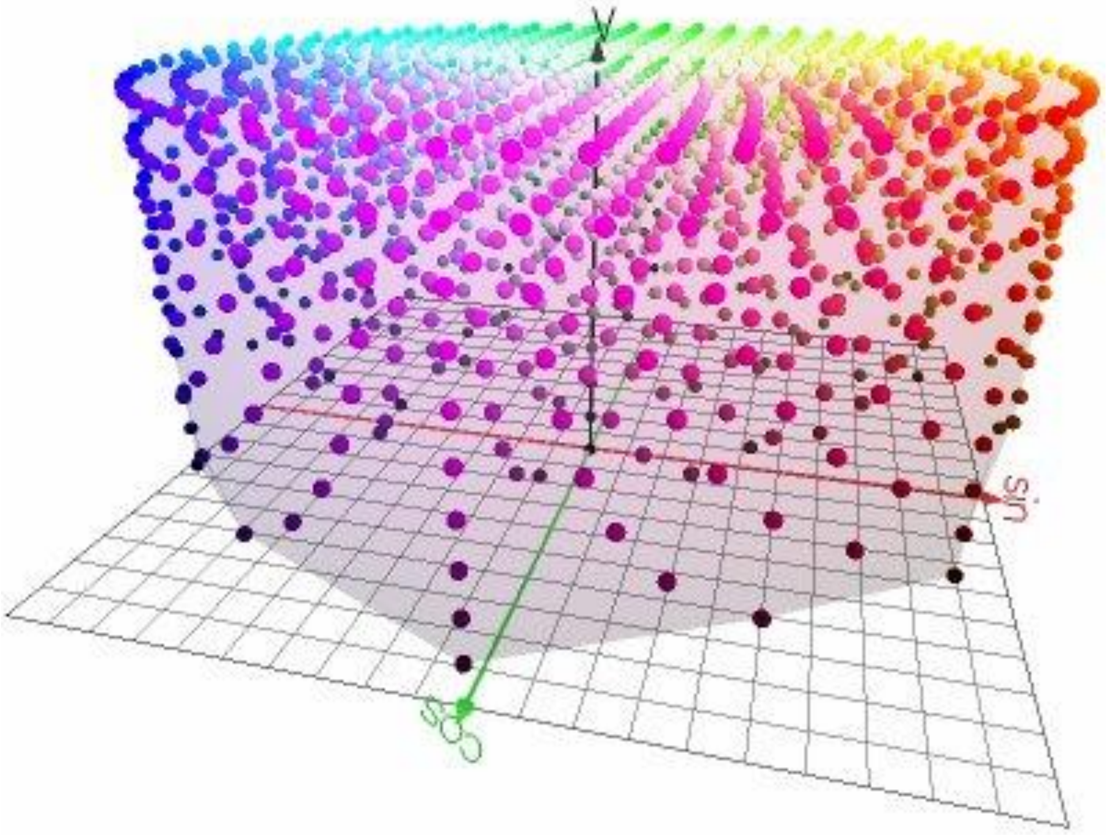

LHC color space

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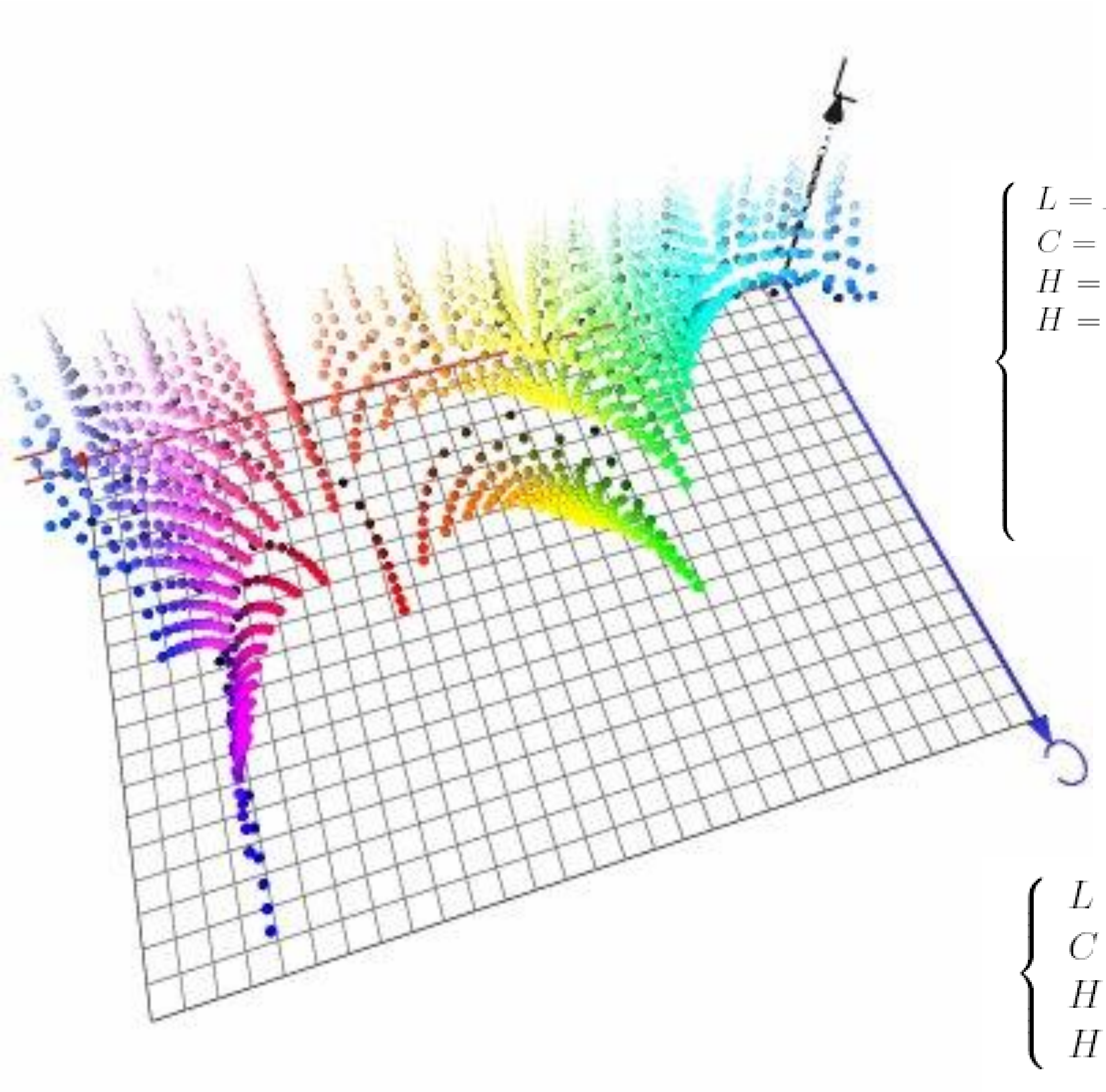

$$
\begin{cases}
L = L^* \\
C = \sqrt{a^{*2} + b^{*2}} \\
H = 0 \text{ whether } a^* = 0 \\
H = (arctan(b^*/a^*) + k.\pi/2)/(2\pi) \\
\quad \text{whether } a \neq 0 \text{ (add } \pi/2 \text{ to } H \text{ if } H < 0) \\
\quad \text{and } k = 0 \text{ if } a^* >= 0 \text{ and } b^* >= 0 \\
\quad \text{or } k = 1 \text{ if } a^* > 0 \text{ and } b^* < 0 \\
\quad \text{or } k = 2 \text{ if } a^* < 0 \text{ and } b^* < 0 \\
\quad \text{or } k = 3 \text{ if } a^* < 0 \text{ and } b^* > 0
\end{cases}
$$

$$
\begin{cases}
L = L^* \\
C = \sqrt{a^{*2} + b^{*2}} \\
H = 0 \text{ whether } a^* = 0 \\
H = \frac{180}{\pi}(\pi + arctan(\frac{b^*}{a^*}))
\end{cases}
$$

LHS color space

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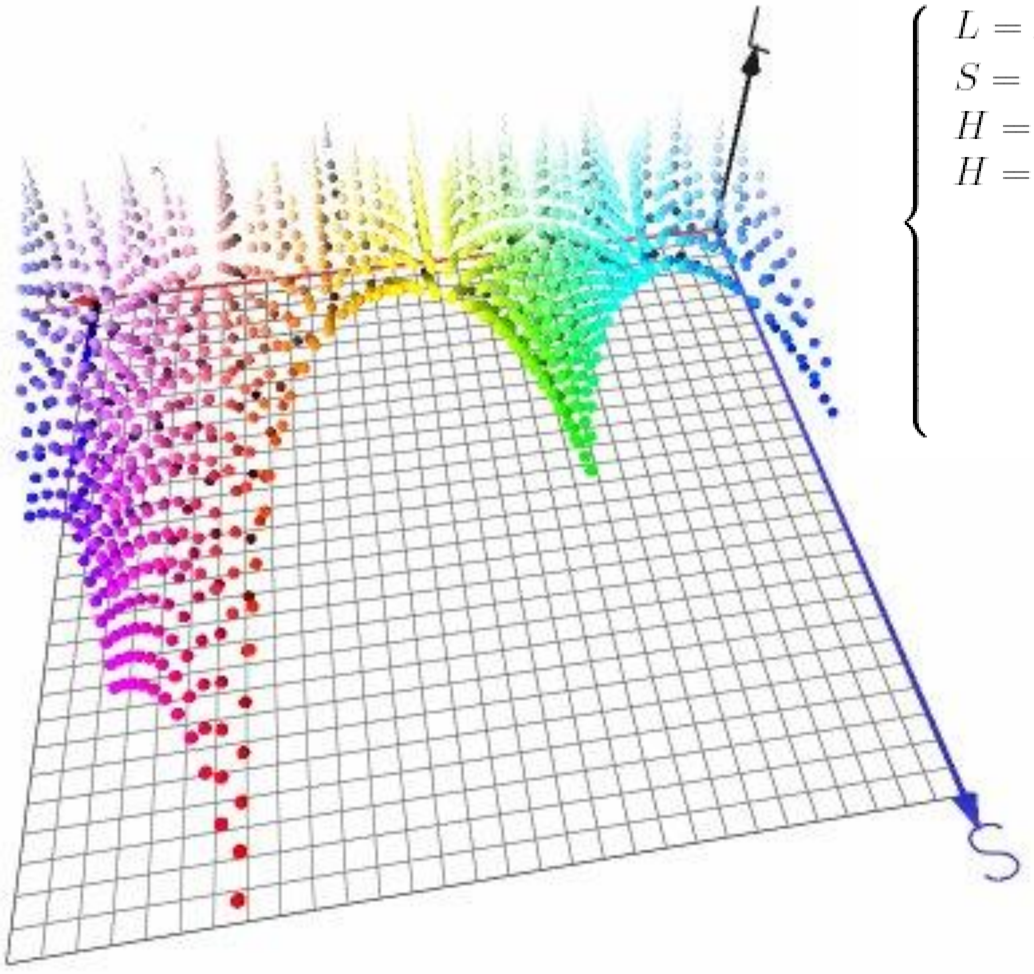

$$\begin{cases} L = L^* \\ S = 13\sqrt{(u^* - u_w^*)^2 + (u^* - u_w^*)^2} \\ H = 0 \ whether \ u^* = 0 \\ H = (arctan(v^*/u^*) + k.\pi/2)/(2\pi) \\ \qquad whether \ u \neq 0 \ (add \ \pi/2 \ to \ H \ if \ H < 0) \\ \qquad and \ k = 0 \ if \ u^* >= 0 \ and \ v^* >= 0 \\ \qquad or \ k = 1 \ if \ u^* > 0 \ and \ v^* < 0 \\ \qquad or \ k = 2 \ if \ u^* < 0 \ and \ v^* < 0 \\ \qquad or \ k = 3 \ if \ u^* < 0 \ and \ v^* > 0 \end{cases}$$

$$\begin{cases} L = L^* \\ S = 1.3\sqrt{(u^* - u_w^*)^2 + (v^* - v_w^*)^2} \\ H = 0 \ whether \ u^* = 0 \\ H = \frac{180}{\pi}(\pi + arctan(\frac{v^*}{u^*})) \end{cases}$$