L3 (Color)

Beam of sunlight passing through a glass prism yields a **continuous spectrum** of colors
Perceived color
It is the color that is determined by the nature of light **reflected** from object
Objects reflecting light balanced in all visible wavelengths appear white

Color Units

Radiance

- Total amount of **energy** emitted by a light source, reflected, transmitted or received by a surface, per unit solid angle per unit projected area ($Wsr^{-1}m^{-2}$)
  Spectral radiance
- Radiance of a surface per **unit frequency**: $\frac{\text{Radiance}}{\text{Unit Frequency}}$
  Luminance
- Amount of light that passes through a particular area: $cd * m^2$(nits)
  Brightness
- **subjective perception** caused by the luminance of a visual target.

Neuroscience

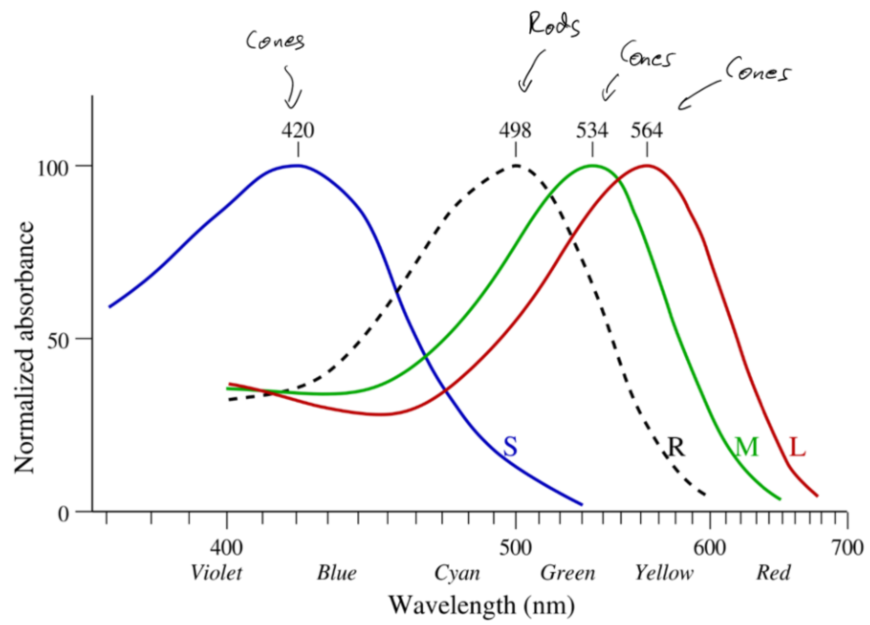
Cones are responsible for color perception and are concentrated on **fovea centralis**. They are less sensitive than rods which are responsible for night vision. (Purkyne effect)

Cones

There are three types of cones:

- L-cones, long wavelengths (65%)
- M-cones, middle wavelengths (33%)
- S-cones, small wavelengths(2%)

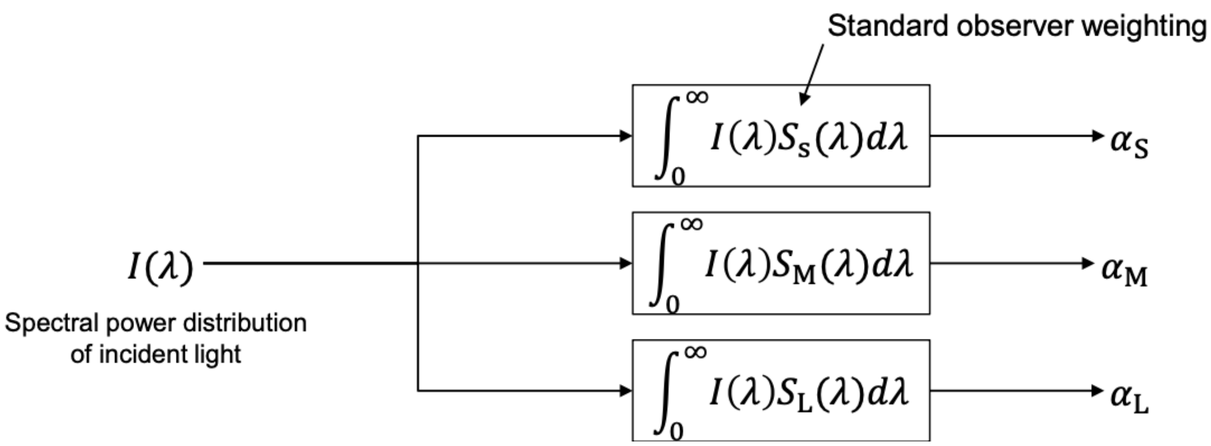
Color Perception



Note: curves are normalized, S-Cones are **much** more sensitive

Why S-cones are more sensitive?

Trichromacity



Tristimulus values (α_S, α_M, α_L) are the activations of cone cells. So, in theory, these 3 numbers are sufficient to represent any color.
All $I(\lambda)$ that have the same (α_S, α_M, α_L) will have the same tristimulus color

Metamerism

- If you look at pure yellow light (like from a yellow LED), your eyes see it as yellow.
- If you mix green and red light together in the right proportions, your eyes ALSO see it as yellow - even though there's no actual yellow light present!

This works because our eyes have three types of color receptors (called cones), and as long as these receptors are stimulated in the same way, we perceive the same color - even if the actual light creating that color is different. It's like fooling your eyes with a clever shortcut! This is **Grassmann's Law** and it's why we can see colorful screens without needing a separate light source for every possible color.

Color Matching

Given 3 primary light sources with spectra $I_1(\lambda)$, $I_2(\lambda)$, $I_3(\lambda)$, how can we mix them so the result looks identical to a different light source with spectrum $I(\lambda)$?

$$\alpha_i = \int_0^{\text{inf}} S_i(\lambda)[\beta_1 I_1(\lambda) + \beta_2 I_2(\lambda) + \beta_3 I_3(\lambda)] d\lambda =$$

$$= \beta_1 K_{i,1} + \beta_2 K_{i,2} + \beta_3 K_{i,3}$$

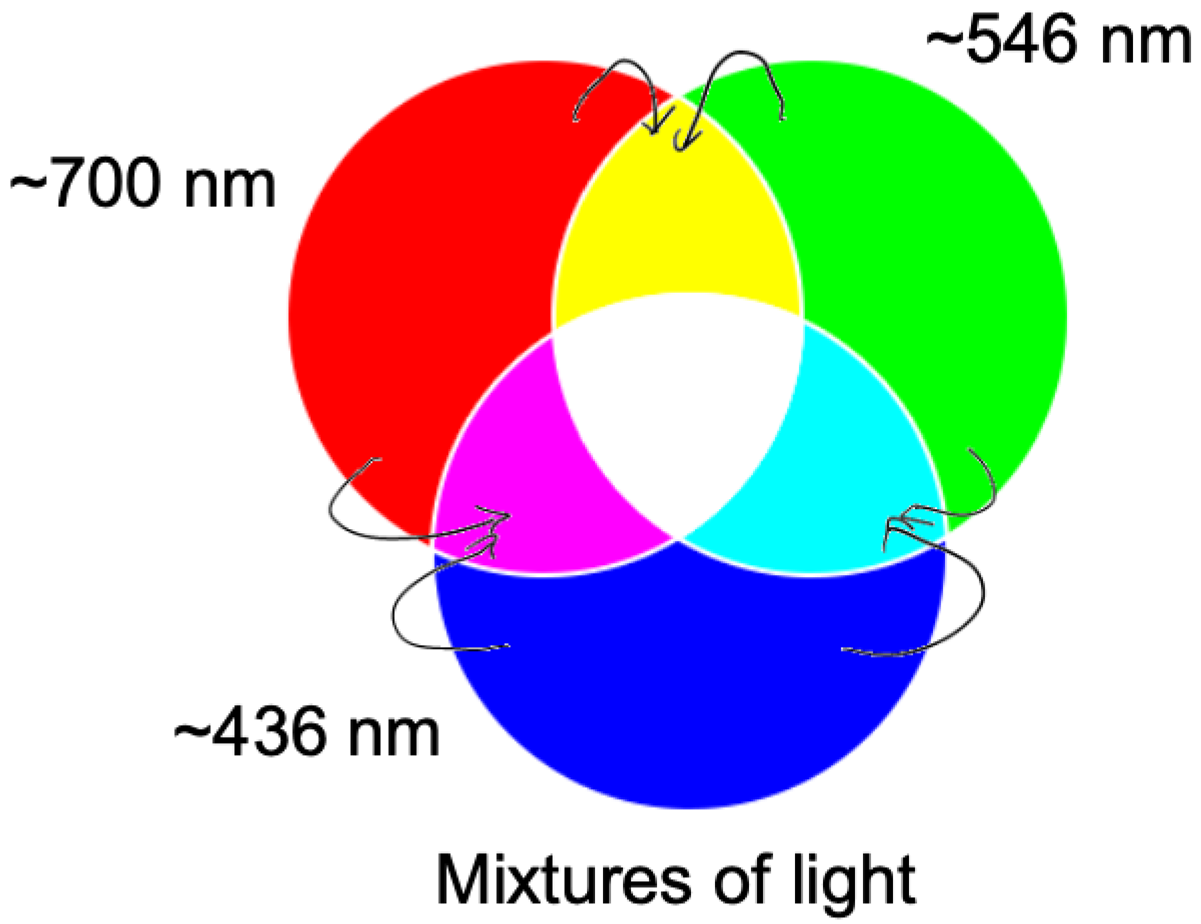
with $K_{i,j} = \int_0^{\text{inf}} S_i(\lambda) I_j(\lambda) d\lambda$ **(fixed value)**
So, we just replace I with $\beta_1 I_1 + \beta_2 I_2 + \beta_3 I_3$ (they are metameric matches) and thus produce the same tristimulus activations (α_S, α_M, α_L).

Primary colors

Light

Primary colors of **light** are red(700 nm) , green(546 nm), and blue(436 nm). Mixing them produces wide range of colors but **not** all visible colors.
Secondary colors of light: magenta, cyan and yellow. They lie at the double intersection of

primary colors (additive primaries):



Pigments

Primary colors of **pigments** are magenta, cyan and yellow. They absorb a primary color of light and reflect the other two. Subtractive primaries

CIE Chromaticity Diagram

There are three color descriptors: brightness, hue, saturation.

- brightness is achromatic notion of intensity
- hue is dominant perceived color
- saturation relative purity

Hue and saturation taken together are called **chromaticity**.
Denote the cone activations (tristimulus values) as the following:

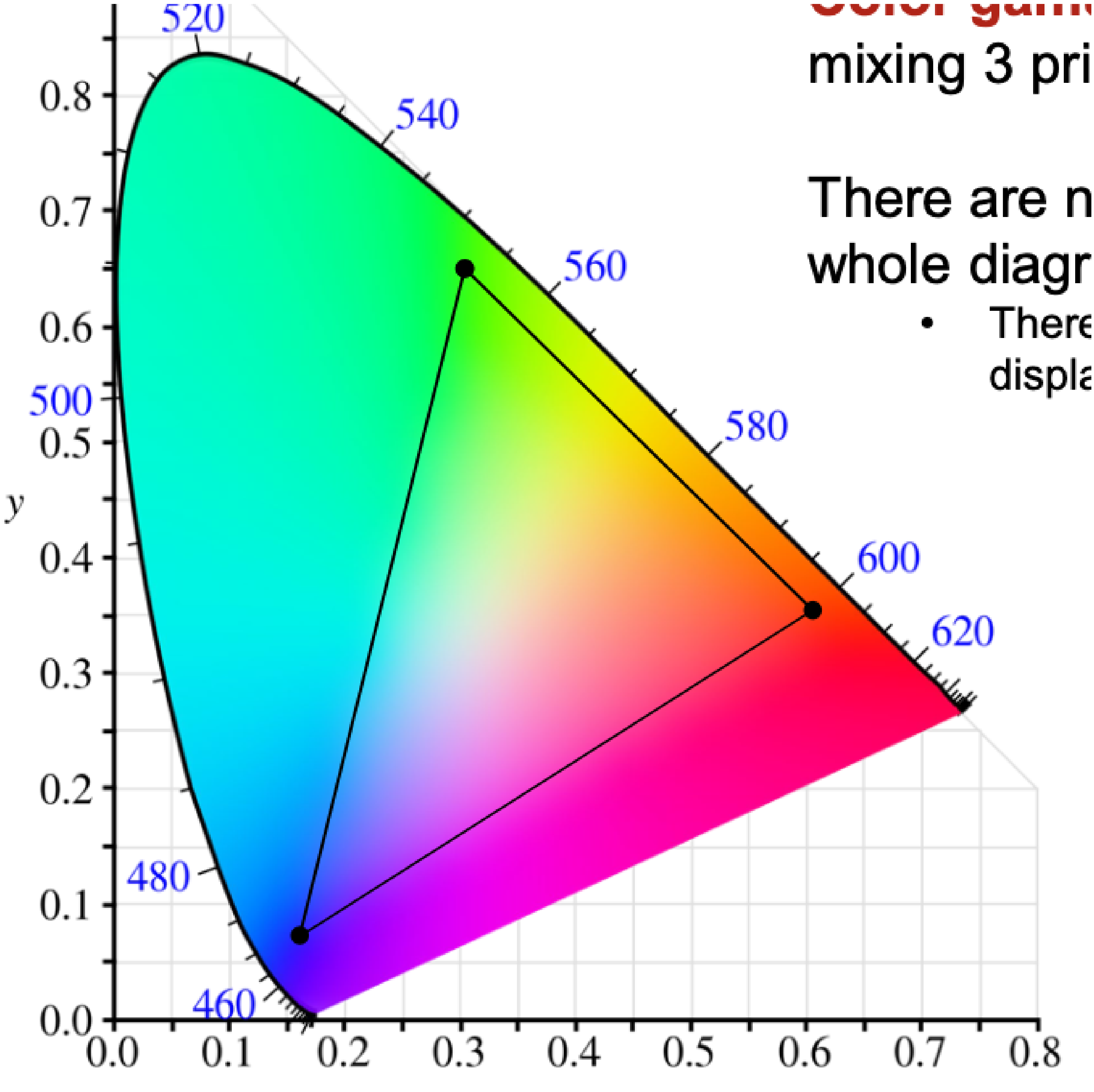
$$X = \alpha_s, Y = \alpha_M, Z = \alpha_L$$

Trichromatic **coefficients** are then defined as :
$x = \frac{X}{X+Y+Z}$
$y = \frac{Y}{X+Y+Z}$

$z = \frac{Z}{X+Y+Z}$
and they are normalized to 1. This means we only need two coefficients to determine a color (**hue, saturation**)

Color Gamut

It is the range of colors produced by mixing 3 primary colors. No monitor can display full gamut diagram because there are not 3 fixed colors that enclose the whole diagram:



Color Models

There are 3 different color models:

- RGB (additive): resembles human vision system
- CMYK

- HSV

RGB

It requires full color recording for each color R, G, B and it is quite expensive in practice to record those. Therefore, we use Bayer Filter that leverages the fact that our vision is much more sensitive to intensity resolution than to color changes.
The final image is reconstructed by demosaicing.

CMY

Relationship to RGB: $CMY = 1 - RGB$ in vector form. It is used in printing. Additional black ink is used here because mixing CMY to get black is expensive.

Halftoning

Halftoning is a technique used to create the illusion of continuous-tone images using a limited number of colors (or grayscale levels). It is commonly used in printing, where small dots of varying sizes and spacing simulate different shades of color. By adjusting the density and arrangement of these dots, the human eye perceives a smooth gradient.

Dithering

Dithering is a related concept that introduces intentional noise to reduce visual artifacts caused by quantization (color reduction). When reducing the number of available colors in an image, dithering spreads the quantization error across nearby pixels, making the transitions appear more natural. This improves perceptual quality at the cost of **worst quantization error (PSNR)**.

Floyd-Steinberg Dithering

Floyd-Steinberg dithering is a specific error diffusion method used in dithering. It works by distributing the quantization error of a pixel among its neighboring pixels in a predefined pattern. This method helps maintain smooth gradients and prevents visible banding.

- the quantization error of a pixel is distributed to its surrounding pixels instead of being discarded

- a predefined matrix determines how the error is spread among adjacent pixels

$$\frac{1}{16}\begin{bmatrix} 0 & 0 & X \\ X & \bullet & 7 \\ 3 & 5 & 1 \end{bmatrix}$$

Since quantization can make a pixel either **brighter** or **darker** than the original value, Floyd-Steinberg dithering compensates for this by adjusting nearby pixels. If a pixel becomes too dark due to quantization, its neighbors are brightened, and vice versa. This maintains an overall balance in perceived brightness.

HSV

RGB is unintuitive, let's do something bettter!
Hue (color value), saturation (purity), value (brightness)

RGB to HSV

Value

Value is given by max of R, G, B :

$$V = max(R, G, B)$$

Hue

for dominant red (if V=R):

$$H = \frac{G - B}{R - min(G, B)}$$

$-1 < H < 1$
for dominant green (V=G):

$$H = 2 + \frac{B - R}{G - min(R, B)}$$

$1 < h < 3$
for dominant blue (V=B):

L3

$$H = 4 + \frac{R - G}{B - min(R, G)}$$

$3 < H < 5$
Hue is then normalized: $H = \frac{H}{6}$, $-\frac{1}{6} < H < \frac{5}{6}$
If $H < 0$ then $H = H + 1$

Saturation

$$S = 1 - \frac{min(R, G, B)}{V}$$

Special case: grey pixels (including black and white):

- pixels with no color saturation $S = 0$
- $H = 0$ (arbitrary, to avoid divisions by zero)

HSV to RGB

Preparation

- Hue denormalization, i.e. $H = 6H$ so that $0 \leq H < 6$
- Residual color: $\rho = H - \text{floor}(H)$

Processing by color sectors (**primary** colors)

- Red sector ($0 \leq H < 1$)

$$\boxed{R = V \qquad G = V\big(1 - S(1 - \rho)\big) \qquad B = V(1 - S)}$$

- Green sector ($2 \leq H < 3$)

$$\boxed{R = V(1 - S) \qquad G = V \qquad B = V\big(1 - S(1 - \rho)\big)}$$

- Blue sector ($4 \leq H < 5$)

$$\boxed{R = V\big(1 - S(1 - \rho)\big) \qquad G = V(1 - S) \qquad B = V}$$

Color Constancy

Two scene acquisitions under different illuminants are related by independent regulation of the three imaging channels(von Kries hypothesis):

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \begin{pmatrix} k_R & 0 & 0 \\ 0 & k_G & 0 \\ 0 & 0 & k_B \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Color Balancing

Normalization of images to produce better subjective color impression

- Color channels are scaled independently

White patch algorithm based on reference white $(R, G, B)_{\text{white}}$

8bit image

$$k_R = \frac{255}{R_{\text{white}}} \qquad k_G = \frac{255}{G_{\text{white}}} \qquad k_B = \frac{255}{B_{\text{white}}}$$

Gray world algorithm

- Assumes that a scene, on average, is gray (holds for “colorful” scenes)

$$\bar{R} k_R = \bar{G} k_G = \bar{B} k_B$$

Scale-by-max algorithm

- Scale each channel by its maximum

Delta Function Property

The delta function has the fundamental property that

$$\int_{-\text{inf}}^{\text{inf}} f(x)\delta(x-a)dx = f(a)$$

and

$$\delta(x-a) = 0$$

for $x \neq a$

For calculating the fixed values in color matching if intensity I is a delta function, then evaluation of integral is easier:

$$K_{i,j} = \int_0^{\inf} S_i(\lambda)\delta(\lambda - a)d\lambda = S_i(a)$$

It picks out the value of the other function at a. Note that for $\lambda < 0$: $S(\lambda) = 0$, so this part of the integral contributes nothing.

Chroma Keying

Colors spaces that have a dedicated hue ("color") component HSV, HSI, HSL are most suitable for classifying pixels based on their color. The reason is that pixels can be classified based on a specific range of hue values.

The function `cv2.cvtColor(image, cv2.COLOR_BGR2HSV)` converts the image representation from three RGB values for each pixel, to a Hue, Saturation and Value value for each pixel. Hue gives the essential color (approx. equivalent to the wavelength), Saturation gives the intensity of that color and Value gives the overall brightness of the colour at that pixel.

By specifying a tight range of Hue values, and a very wide range of Saturation and Value values, we can identify all regions that contain objects of a given colour in the image, regardless of lighting conditions. The print statement in the program will output the HSV values of the centre pixel of the image to the terminal.

The variables `lower_green` and `upper_green` in the program are used to specify Hue between 55 and 95, which is roughly the green of the chroma keying material, and Saturation and Value values between 50 and 255 (i.e. ignore low intensity, poor brightness areas but keep everything else up to a strong and bright green colour).