Color Spaces

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1 Introduction

We often take the role color has in our lives for granted. It has long been known that it has a great effect on human psychology, but until recently there has been little effort in modeling it mathematically. This has however become necessary to achieve the range and consistency that most of today's devices boast. It turns out that color is much more complex than it appears at a glance, how many people really understand how a color picker works? In this paper we will give an overview of the basics of color science, building up towards color spaces. We will then talk about some of the more important ones, what the motivations behind them were, how they work, what they're used for.

2 Perceiving light

What is color though? Color is the visual experience of electromagnetic radiation. Essentially, it is how our brains interpret light. The colors we observe correspond to wavelengths of light between about 380 and 750 nanometers. A range of wavelengths is called a spectrum, and thus the aforementioned range is called the visible spectrum. In it, light with lower wavelengths corresponds to bluish colors, while higher wavelengths correspond to reddish colors, as can be seen in Figure 2.1.

The light entering our eyes from any given direction carries many wavelengths at differing intensities, and it is this distribution of intensity over wavelength that determines what color we see. This function is called the spectral power distribution (SPD) and an example can be seen in Figure 2.2. "Intensity" here was used intuitively, the appropriate radiometric terms are radiant flux (radiant energy received per unit time; also called radiant power), radiant intensity (radiant flux received per unit solid angle) and radiance (radiant intensity received by a surface per unit projected area) which can all be plotted with an SPD.

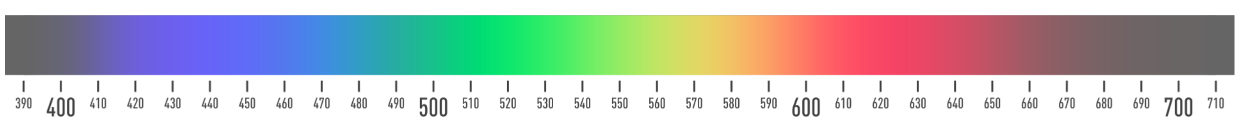


Figure 2.1: *The visible spectrum corresponding to wavelengths in the [390, 710] range. [1]*

When light hits our eyes, it stimulates the rod and cone cells inside. The rods are sensitive to the light's intensity, have the biggest role when light is dim and do not have a significant role in perceiving color. Meanwhile, the cones function best in bright light and are used to perceive color. Human eyes have three types of cones: S-cones, M-cones and L-cones. S-cones give the highest neural response when hit with short wavelengths, M-cones with medium wavelengths and L-cones with long wavelengths. Here, "short", "medium" and "long" is relative to the visible spectrum [3] [4]. The spectral sensitivity of human cones and rods can be seen in Figure 2.3. The important conclusion for us here, is that the colors

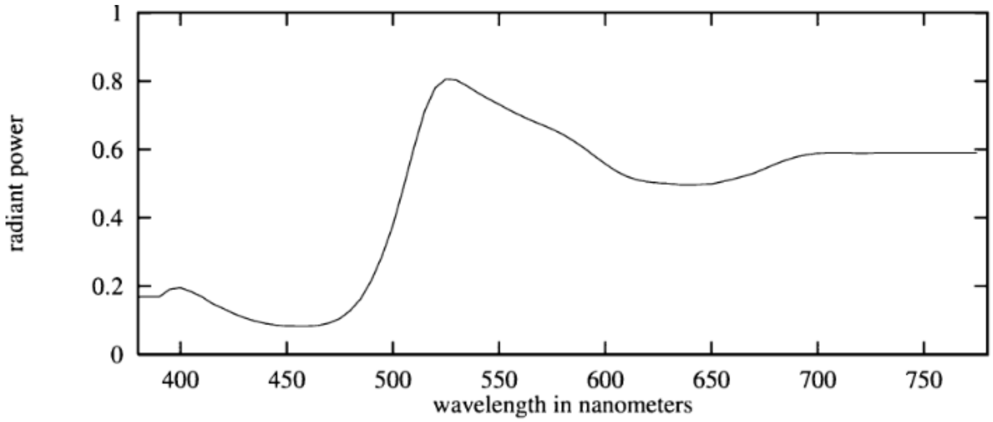


Figure 2.2: *"The spectrum of a brown banana under white light." [2]*

humans see are encoded in only three values, this is also known as the thristimulus color theory[1].

After the light gets captured by our eyes according to the spectral sensitivities of our cones and rods it undergoes a neurological transformation taking on a different encoding. Particularly, the opponent process color theory states that the signal takes the form of three channels, each encoding an opposing pair of colors: red versus green, blue versus yellow, black versus white (brightness). Many important color spaces rely on this model of human vision.

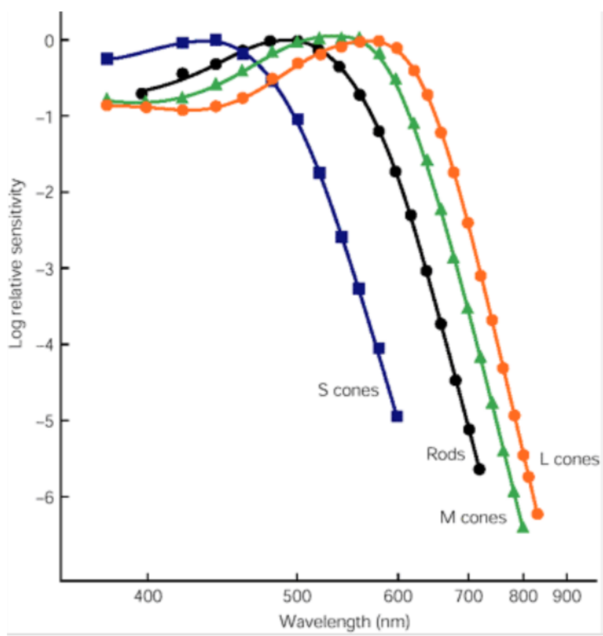


Figure 2.3: *"Spectral sensitivities of the three classes of cones and the rods." [3, 5]*

[1]Which was, interestingly, theorized decades before we proved there were three types of cone cells in the human eye.

An interesting observation to be made is that the input our eyes get is a continuous function (the SPD), while our [2] perception is three dimensional, meaning our perception of visible light isn't a 1:1 encoding. One way this manifests is with metamers - colors that look the same but have differing SPDs (Figure 2.4).

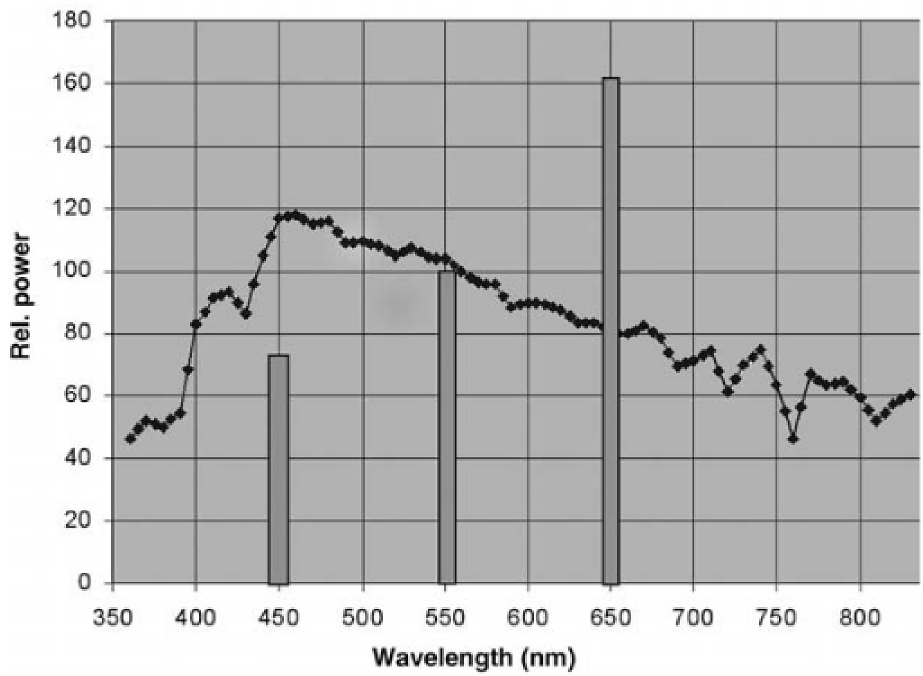


Figure 2.4: *Two lights with differing SPDs that appear the same to the average human observer - metamers. [6]*

3 The first color space

A color space is a specific organization of colors which provides a way to transform between a physical and a digital representation of a color. While color spaces aren't vector spaces per se (they are more so volumes in space), there are many similarities which will become apparent as we go. Naturally, there isn't only one way to define a mapping between an SPD and some three values, but the first ones that set out to do this were the Commission Internationale de l'éclairage (engl. International Commission on Illumination; CIE) in 1931. The "basis vectors" for the color space were chosen to be lights composed of a single wavelength (monochromatic), in particular 700 nm (red), 546.1 nm (green) and 435.8 nm (blue). Every other color in our color space will be able to be represented through these three, which are also called primary colors or primaries[3]. They were chosen to correspond

[2]Human. There are species of animals with varying numbers of cone types, and thus varying dimensionality in their color perception.

[3]Every color space has its own primaries.

to the spectral sensitivities of our cones, and in accordance with the technology (to create such light) available at the time [6].

The first step in creating the mapping was figuring out the relationship between the colors defined by our primaries and the colors defined by any given visible monochromatic light. This was done experimentally: subjects were given a monochromatic light to be matched, and three knobs they could turn. These three knobs changed the intensities of three lights shining the primary colors, overlapped on eachother. When the overlapped color matched the monochromatic light, the values of the knobs gave us the representation of that light (i.e. wavelength) in our color space. This was repeated incrementally for wavelengths in the [380, 780] range. Notably, the knobs were allowed to have negative values[4]. When a knob's value was negative its corresponding primary light was overlapped with the monochromatic light to be matched, instead of the other primary lights (essentially like moving a value to the other side of the equation to simulate subtraction, i.e. negative intensity, which is physically impossible). Interpolating the knob values for the primary lights over the matched wavelengths gives us three functions, $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$, known as "color matching functions" (CMFs), which can be seen in Figure 3.1.

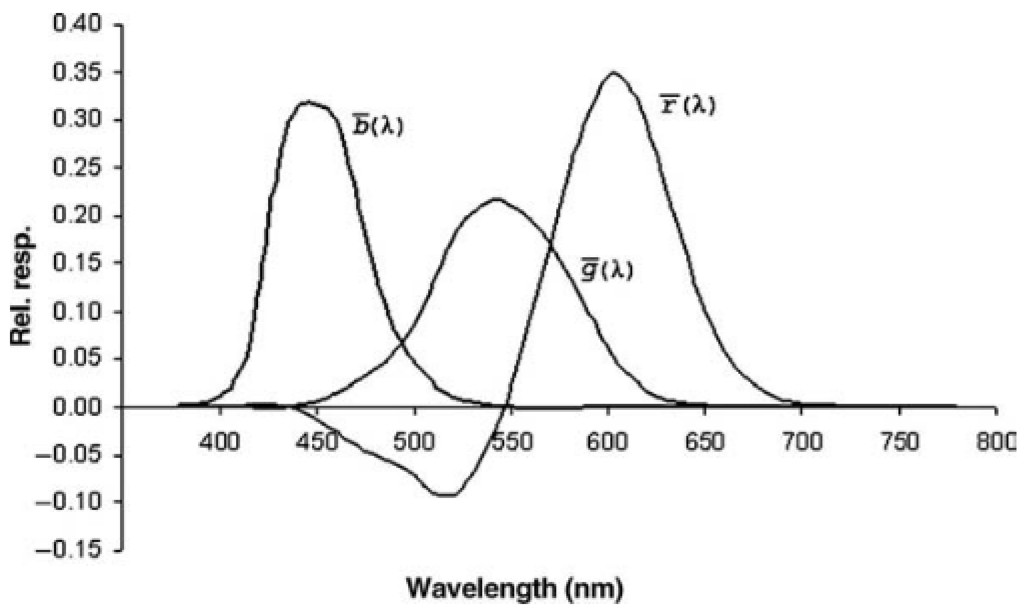


Figure 3.1: "$\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ *Color matching functions of the CIE 1931 standard colorimetric observer.*" [6]

Now, the color defined by any given wavelength has coordinates in our color space, which we can get by reading off the values of the red, green and blue (RGB) color matching curves at that wavelength. Furthermore, we can get the coordinates of the color, some SPD gives us, by multiplying it with the color matching functions and then taking the integral under the curves. So for an SPD $S(\lambda)$ and our CMFs $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$, we get the coordinates R, G, B

[4]This was necessary in order to be able to map all wavelengths.

in the following way:

$$R = \int_{380}^{780} S(\lambda)\bar{r}(\lambda)d\lambda, \tag{3.1}$$

$$G = \int_{380}^{780} S(\lambda)\bar{g}(\lambda)d\lambda, \tag{3.2}$$

$$B = \int_{380}^{780} S(\lambda)\bar{b}(\lambda)d\lambda. \tag{3.3}$$

Finally, we have achieved a connection between physical light, and the human experience of color. This particular color space (defined by $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$) is called the CIE 1931 RGB color space.

4 XYZ

While the CIE 1931 RGB color space made sense when doing the experiments, a need arose for a more mathematically useful color space. Particularly, calculations with negative values were cumbersome, so one requirement for the new color space was that the matching functions needed to be non-negative. The other requirements were that: at least one of the values should provide a photometric quantity; the constant energy whitepoint should be at $X = Y = Z = 1/3$; and the volume of the tetrahedron set by the XYZ primaries should be as small as possible [6]. Thus, the CIE 1931 XYZ color space was born. It is defined in terms of the CIE 1931 RGB color space via the following transformation matrix:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.768892 & 1.751748 & 1.130160 \\ 1.000000 & 4.590700 & 0.060100 \\ 0 & 0.056508 & 5.594292 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{4.1}$$

The $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ matching functions can be seen in Figure 4.1. The $\bar{y}(\lambda)$ function was chosen to correspond[5] to $V(\lambda)$ - the luminous efficiency function which describes how bright our eyes perceive each wavelength. The XYZ color space is known as an absolute color space as it encodes all visible colors. Many color spaces in use today are not absolute, but are defined via a transformation of an absolute space, most often XYZ. As a consequence, notable effort has been put into visualizing color spaces and their relations to one another, and especially to XYZ. This is not trivial however, as a color space is essentially a 3D volume.

[5] The relationship is $\bar{y}(\lambda) = \frac{V(\lambda)}{683}$. [7]

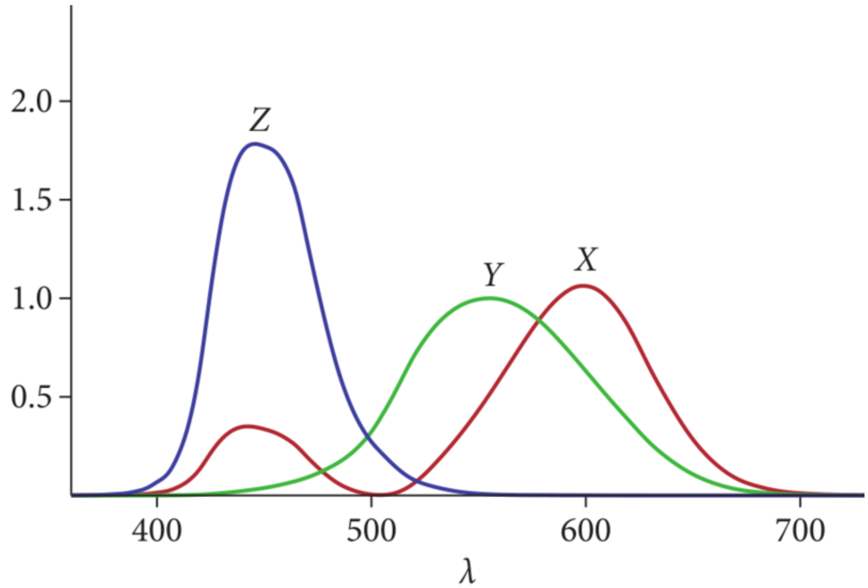


Figure 4.1: *"The XYZ Color Matching Curves" [7]*

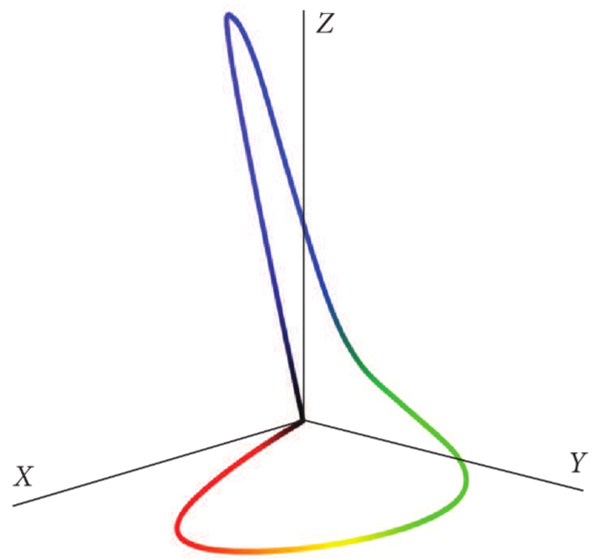


Figure 4.2: *"Plot of XYZ color coefficients for the wavelengths of light in the visible range. The curve is shaded with the RGB color associated with each wavelength." [7]*

In Figure 4.2 we can see all visible monochromatic lights plotted in the XYZ space. Every SPD (spectral power distribution) has a corresponding point inside the 3D volume defined as some linear combination of the points on this curve. Interestingly, the points outside of this volume are valid XYZ coordinates, but do not have a corresponding SPD. One intuitive explanation behind this is that any given wavelength is likely to contribute to multiple of the XYZ color matching functions, so values like $[0, 0, 1]$ are "hard to craft". These coordinates do not correspond to colors that physically exist, and are fittingly termed *imaginary colors*. To dive a bit deeper, the XYZ CMFs are closely tied to the spectral response curves for cones in our eyes, and there doesn't exist, for example, a wavelength that excites only M cones.[6] All of the XYZ primaries (with coordinates $[1,0,0],[0,1,0],[0,0,1]$) are imaginary colors.

Color can be separated into lightness and chromaticity. Lightness describing how bright a color is, while chromaticity can be further separated into hue and colorfulness. We are particularly interested in chromaticity, so we will separate lightness out by doing the following:

$$x = \frac{X}{X+Y+Z} \tag{4.2}$$
$$y = \frac{Y}{X+Y+Z} \tag{4.3}$$
$$z = \frac{Z}{X+Y+Z} \tag{4.4}$$

leaving us with only two meaningful coordinates (as, for example, $z = 1-x-y$). Arbitrarily taking x and y and plotting them, gives us the CIE 1931 xy chromaticity diagram as seen in Figure 4.3. Every valid color lies inside this upside-down horseshoe shape. In colorimetry, gamut refers to the set of colors which are in a given color space. The xy chromaticity diagram represents the gamut of the XYZ color space, and thus of all the colors the human eye can see.

As Y is defined as the luminance of the color, a popular color space derivative of XYZ is the xyY color space.

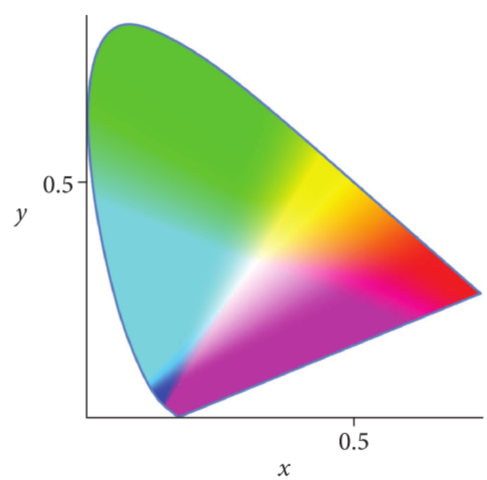


Figure 4.3: *"xy Chromaticity diagram" [7]*

[6] That being said, chimerical colors exist: doing certain things can fatigue the cones in our eyes, shifting their spectral response curves and allowing us to see some imaginary colors we can't see otherwise.

If we take some set of points inside the diagram, all colors that can be created by mixing those lie inside the convex hull of that set of points. It is obvious that there doesn't exist some three point set inside the colored region, whose triangle covers the whole colored region. This means that we can never get all visible colors by mixing some three (non-imaginary, physical) colors. This confirms what was observed in the 1931 experiments: that additive combinations weren't enough, "subtracting" colors was sometimes necessary.

5 Other important color spaces

Now that we have covered some of the basics and history of colorimetry and color science, we can get into how new color spaces evolved and the purposes they serve.

5.1 LMS

One might ask, if we know the spectral sensitivity of cones and rods (Figure 2.3), why not use that as our matching function? We can, in fact doing so gives us the LMS (long, medium, short) color space. Why was that not the first color space created by the CIE then? Because in 1931, when XYZ was being created, there was no proof that humans actually had three types of cone cells (it was only theorized, and not proven until the 1960s). Simply, the technology for calculating cone sensitivity curves didn't exist yet. The LMS color space can be expressed via a transformation matrix from XYZ [6]:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0.0 & 0.0 & 0.9184 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \tag{5.1}$$

The most notable use of the LMS color space is in simulating chromatic adaptation - the ability of the human visual system to adapt to various illuminants in order to preserve the approximate color of objects. An example can be seen in Figure 5.1. The first and most famous model for performing chromatic adaptation is the von Kries model. It is based on the idea that our cones adapt separately, and gives the following simple set of equations for a given lighting environment [8]:

$$L_a = k_L L \tag{5.2}$$
$$M_a = k_M M \tag{5.3}$$
$$S_a = k_S S, \tag{5.4}$$

where k_L, k_M, k_S are the gain coefficients for the environment, usually calculated as

$$k_L = \frac{1}{L_{max}} \tag{5.5}$$
$$k_M = \frac{1}{M_{max}} \tag{5.6}$$
$$k_S = \frac{1}{S_{max}}. \tag{5.7}$$

Here, $L_{max}, M_{max}, S_{max}$ represent the points of maximum stimulus for the long, medium and short cones. $L_{white}, M_{white}, S_{white}$ are sometimes used instead, representing the coordinates of the color that is perceived as white under the lighting conditions. With these equations, one can easily transform colors of one lighting environment to another. As most color spaces are given in terms of XYZ, it is common practice to transform to XYZ then to LMS then back when doing chromatic adaptation. Denoting the matrix from Equation 5.1 as M, performing the adaptation between two lighting conditions, for colors specified in XYZ, is done according to:

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_{max^2} & 0 & 0 \\ 0 & M_{max^2} & 0 \\ 0 & 0 & S_{max^2} \end{bmatrix} \begin{bmatrix} 1/L_{max^1} & 0 & 0 \\ 0 & 1/M_{max^1} & 0 \\ 0 & 0 & 1/S_{max^1} \end{bmatrix} M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}. \quad (5.8)$$

Figure 5.1: *"Illustration of (a) a scene illuminated by daylight, (b) the same scene illuminated by tungsten light as perceived by a visual system incapable of chromatic adaptation, and (c) the scene illuminated by tungsten light as perceived by a visual system with typical von Kries-type chromatic adaptation (similar to the human visual system). Original lighthouse image from Kodak Photo Sampler PhotoCD." [8]*

Other models have been invented to perform chromatic adaptation more accurately, for example the Nayatani et al. model, Gnuth's model, Fairchild's model, the CIE Chromatic Adaptation Transform models (CATs) etc. Some of them introduce non-linearity, most of them use LMS. These are often used in color correction algorithms (games, photography) to provide a more natural look of a scene.

Additionally, the LMS color space has been used to study color blindness, simulate it, and develop color filters to mitigate it [9].

5.2 CIELAB

As colorimetry continued to develop, a need arose for a uniform color space (UCS) - a color space where the euclidean distance between two colors is proportional to the perceptual distance between them. For example, one can easily see that XYZ is not perceptually uniform by looking at its xy chromaticity diagram (Figure 4.3), and it is even more obvious when looking at Figure 5.2. Essentially, we would want the ellipses in the figure to be circles (and spheres in 3D). After a few attempts at constructing a UCS, the International Commission on Illumination created CIELAB in 1976. It still remains one of the most widely used uniform color spaces to this day.

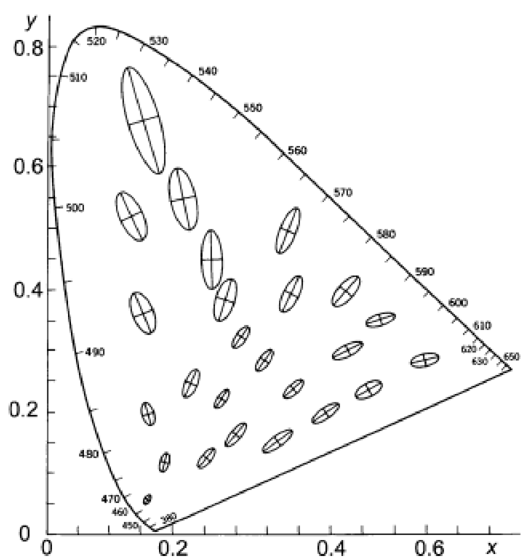


Figure 5.2: *"Ten times just noticeable chromaticity differences according to MacAdam's determination." [6]*

The coordinates for CIELAB are L^*, a^*, b^* and are defined in terms of XYZ as follows [8]:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16 \tag{5.9}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \tag{5.10}$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right] \tag{5.11}$$

$$f(\omega) = \begin{cases} (\omega)^{\frac{1}{3}} & \omega > 0.008856 \\ 7.787\omega + 16/116 & \omega \leq 0.008856 \end{cases} \tag{5.12}$$

In the equations above, X_n, Y_n, Z_n are the $X_{white}, Y_{white}, Z_{white}$ values discussed for the von Kries transform used for chromatic adaptation, and serve the same purpose here. A notable difference is that the coordinates aren't normalized in the LMS space, but directly in XYZ. Later research showed this produces significant abnormalities in CIELAB, particularly near the blue regions [10–12]. In Equation 5.12, the third square root is used to model the relationship between the energy levels of a stimulus, and its perceptual response in humans [13].

All three CIELAB coordinates have nice interpretations. L^* is the brightness of the color, with the value 0 for black, and 100 for a diffuse white. It is intuitive that L^* represents brightness, as it is defined solely by Y and Y_n which represent luminosity in the XYZ space. a^* has positive values associated with how red the color is, and negative values associated with its greenness. Meanwhile, b^* correlates with the yellowness (positive) and blueness (negative) of the color. Essentially the three variables encode the same values that the opponent process color theory describes.

Another color space was proposed by CIE in 1976 called CIELUV. Its construction is similar to that of CIELAB, and it is quite well known due to its historical importance, though due to its inacuracies it remains seldom used.

Since CIELAB can be used to predict the look of a color under different lighting conditions, it is considered a Color Appearance Model (CAM). Color appearance models are systems used to describe color and perform chromatic adaptation while taking into account various factors that affect human perception of color, such as the: Bezold–Brücke hue shift (the hue of monochromatic light changing with luminance), Stevens effect (contrast increasing with luminance), Hunt effect (colorfulness increasing with luminance), and many others. As a CAM's goal is to accurately represent human perception, it must be able to describe color appearance parameters such as lightness, chroma (similar to colorfulness and saturation, describes intensity) and hue ("the degree to which a stimulus can be described as similar to or different from stimuli that are described as red, orange, yellow, green, blue, violet" [8]). We can get the chroma value C^* and hue angle h° simply:

$$C^* = \sqrt{{a^*}^2 + {b^*}^2} \tag{5.13}$$

$$h^\circ = atan(b^*/a^*) \tag{5.14}$$

and combining those values together with L^* gives us the CIELCh color space.

We can see a representation of CIELAB by looking at Figure 5.3, where we are looking in the direction of the L^* axis. The color clearly becomes darker (lower luminocity) "deeper" in the graph. The colors farther away from the center are more saturated i.e. have a higher chroma (C^*), while hue ($h°$) is the angle around the L^* axis.

CIELAB itself doesn't nearly account for all the effects that affect human perception of color, and along with its erroneous use of the von Kries transform leaves moderate room to be improved. That being said, it is very simple to compute and provides a reasonable approximation most of the time cementing its ubiquity.

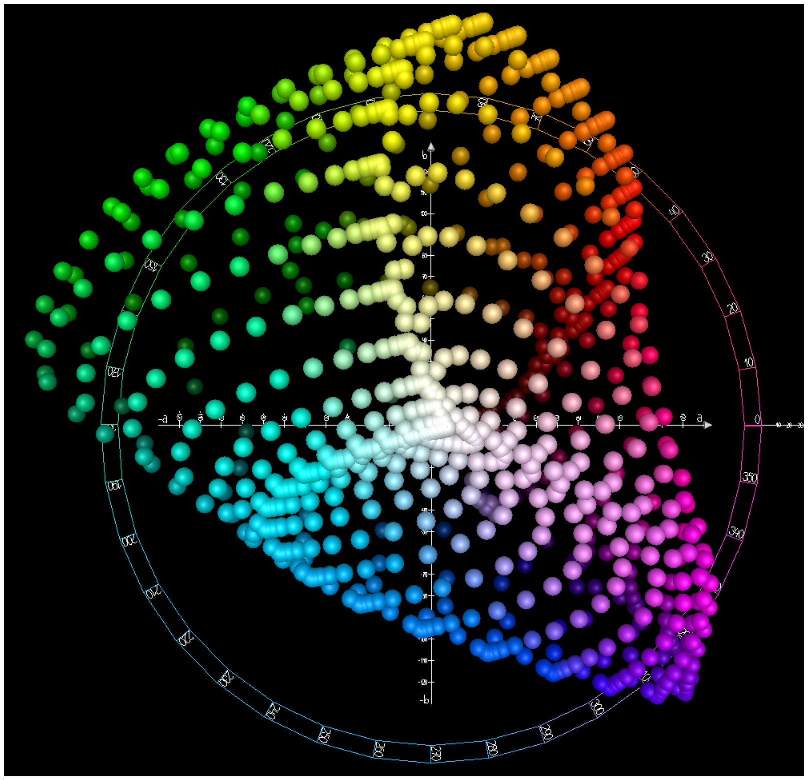


Figure 5.3: *"CIELAB color space top view" [14]*

5.3 sRGB

Now that we have covered the appropriate theory, discussing a major practical application is in order. In the lifetime of an image, from its creation to presentation many devices might be involved, often at least two - one which created the image (for example a photographer with a camera, or a designer with a monitor and graphics editing software) and one which is displaying the image (for example the end users monitor which could be CRT, LCD, LED, etc.). Such a set of devices which are not calibrated to specifically work with one another are called an open system [8]. It would be desirable that the colors of the image at any point in the system remain the same. The process which is set on achieving this is called color management. The obvious problem here is that different devices have different displaying properties - giving two displays the same color data can result in vastly different perceptual experiences.

One of the first solutions to this problem were International Color Consortium profiles (ICC profiles) proposed in 1994. They give a standardized way to describe a devices color properties, usually using XYZ or CIELAB for target coordinates. This allows one to attach the ICC profile of the imaging device along with the image, and any end user viewing the image who also has the ICC profile of their monitor can be certain their image is very similar to the source, and very similar[7] across devices.

While this solution can be appropriate for high end users, it has its drawbacks for the regular consumer. Particularly, saving the ICC profile data along with every image incurs a memory overhead. Furthermore, the potential data transformations necessary can be numerous and complex and not every image file format and display software will be able to support it. Of course, these transforms also incur a time overhead every time the image is displayed.

All of these shortcomings could be alleviated by using a standard color space. Thus in 1996 Hewlett-Packard (HP) and Microsoft proposed "A Standard Default Color Space for the Internet - sRGB" [15]. To this day, thirty years later, sRGB is the color space most display devices and file formats expect, and there is no memory nor time overhead. The most important consideration taken into account when designing the color space was to encode the biggest range of colors that devices at the time supported, while making the color space simple to use. An RGB-like color space was decided upon as that is what most display devices used natively. The transformation matrix from XYZ is

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \tag{5.15}$$

That is not the end however, consider that images are usually stored as matrices of pixels, each pixel with the corresponding red, green and blue value. To save space these values are usually one byte integers (0-255), not floating point values. This type of image is called a 24-bit image. To use this limited range of values efficiently, we have to take into account that humans perceive brightness non-linearly. Differences between darker colors are more apparent than lighter ones, and our encoding should reflect this. We will achieve this using a function of the form $V_{out} = AV_{in}^{\gamma}$, also called gamma correction, analogous to what we saw in the definition of CIELAB in Equation 5.12. So we get [16]:

$$C'_{sRGB} = \begin{cases} 12.92 C_{sRGB} & C_{sRGB} \leq 0.0031308 \\ 1.055 C_{sRGB}^{1/2.4} - 0.055 & C_{sRGB} > 0.0031308 \end{cases} \tag{5.16}$$

[7] We can only guarantee "similarity" since we cannot save the color data to infinite precision, and rounding errors will occur.

where C is one of R, G, B. Note that in some literature C_{sRGB} are called C_{linear} and C'_{sRGB} are C_{sRGB}. These values are now in the $[0, 1]$ range[8] so before quantizing them to 8-bit values we perform

$$C_{8bit} = 255.0 * C'_{sRGB}. \tag{5.17}$$

This simple set of transformations is now the backbone of imaging worldwide.

5.4 HSV

One use case of color spaces we have yet to touch upon is editing and design. When an end user wants to pick some color, usually in relation to other colors in an image, we want to provide them with an intuitive color picker where changing values, turning knobs, moving sliders has a clear perceptual correlation. Using an RGB color space for this can be quite cumbersome as illustrated in Figure 5.4. A common action like getting a slightly lighter variant of a color is non-trivial, even if one were to fiddle with the numerical values directly. For this reason, the Hue Saturation Value (HSV) color space was designed in 1978 by Alvy Ray Smith [17]. Note that the "Value" variable refers to brightness.

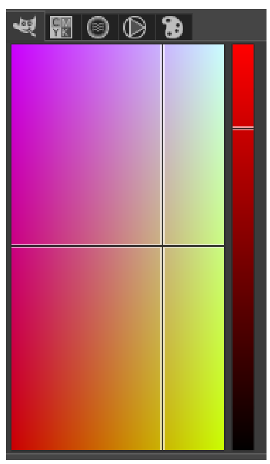


Figure 5.4: *The GNU Image Manipulation Program (GIMP) (version 2.10) RGB color picker. There is a red slider which determines the R value, and a rectangle to the left of it. The vertical axis in the rectangle corresponds to B values, while the horizontal corresponds to G.*

An HSV color space is derived from a given RGB color space (usually sRGB) using the

[8] Clipping them to this range due to low numerical precision may be necessary.

following formulae [17]:

$$M := max(R, G, B) \tag{5.18}$$

$$m := min(R, G, B) \tag{5.19}$$

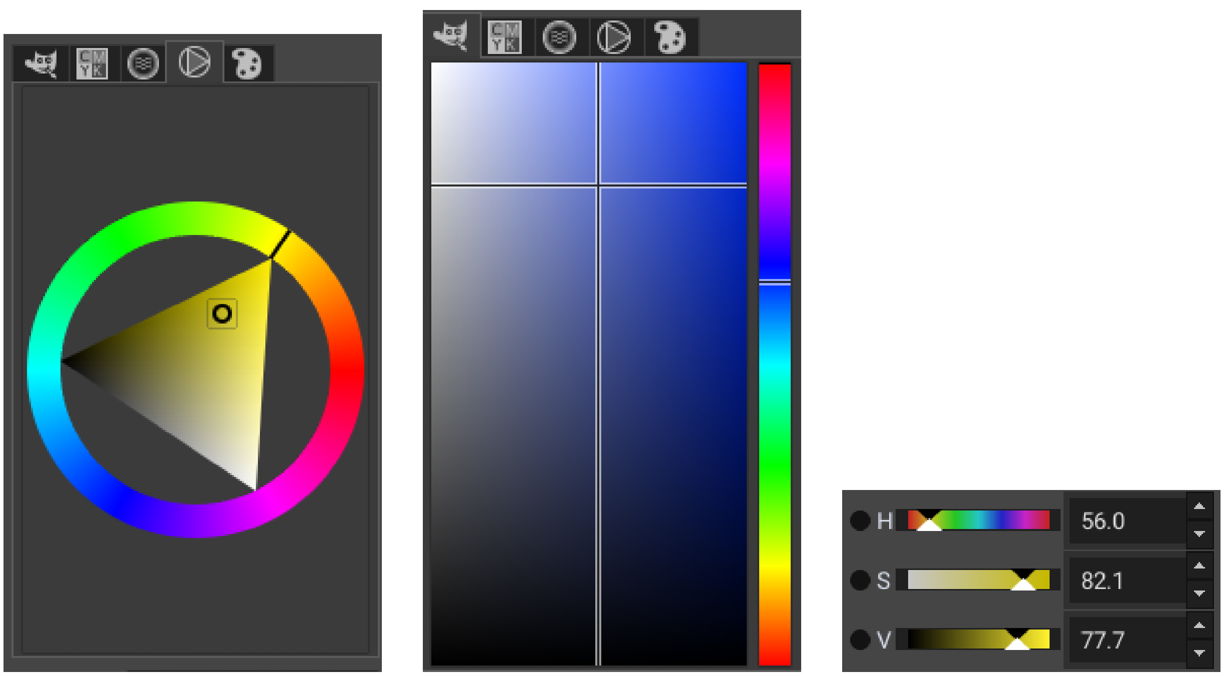
$$C := M - m \tag{5.20}$$

$$V := M \tag{5.21}$$

$$H := \begin{cases} 0, & \text{if } C = 0 \\ 60^\circ \cdot \left(\frac{G-B}{C} \mod 6\right), & \text{if } V = R \\ 60^\circ \cdot \left(\frac{B-R}{C} + 2\right), & \text{if } V = G \\ 60^\circ \cdot \left(\frac{R-G}{C} + 4\right), & \text{if } V = B \end{cases} \tag{5.22}$$

$$S := \begin{cases} 0, & \text{if } V = 0 \\ \frac{C}{V}, & \text{otherwise} \end{cases} \tag{5.23}$$

assuming the RGB values are in $[0, 1]$. An example of an HSV color picker can be seen in Figure 5.5, the advantage over using RGB is clear.



(a) HSV color wheel (b) HSV color picker (c) HSV sliders

Figure 5.5: *The GNU Image Manipulation Program (GIMP) (version 2.10) HSV color pickers. The wheel in (a) represents hue, and the notion of saturation and brightness are more apparent than in the RGB color picker. The slider in (b) represents Hue while the horizontal axis in the rectangle represents Saturation, the vertical Value. This color picker is again much more intuitive than the RGB one. Even using the sliders (c) is reasonable.*

That being said, HSV has also come under a lot of scrutiny. One reason being is that it's not a uniform color space. This is unfortunate as it would be a nice property to have for the end user - nudging the slider for the same amount would yield the same amount of perceptual change everywhere. Furthermore, the Hue variable doesn't really represent hue, Saturation doesn't really represent saturation, and Value doesn't really represent brightness. They are only approximations, and very rough ones at that with egregious edge cases. All of this is quite damning considering that HSV was created after CIELCh which is a UCS with accurate representations of lightness, chroma (similar to saturation) and hue. That could possibly be the reason why GIMP only shows CIELCh by default, hiding HSV behind an extra button. That being said CIELCh is not perfect either, having many imaginary colors defined within its range making use of sliders unintuitive.

6 Spaces not covered here

There are numerous color spaces out there and not all of them could be covered while retaining the brevity of this work, but let us enumerate some of the most interesting ones left.

The Cyan Magenta Yellow Key (CMYK) color space is used for printing purposes. Unlike all the additive spaces covered above, it is a subtractive space describing the mechanism of mixing pigments to achieve a needed color, as opposed to combining light.

Other than sRGB there are many other RGB derivative spaces such as ProPhoto RGB, Adobe RGB, Adobe Wide Gamut RGB which improve the gamut of sRGB. There are also Rec. 709 and Rec. 2100 which are recommendations for high definition and high dynamic range television respectively. The comparison of some interesting gamuts can be seen in Figure 6.1.

On the topic of color appearance models, many improvements came after CIELAB including: the Nayatani et al. model, the Hunt model, RLAB, LLAB, CIECAM97s, IPT, ICtCp, CIECAM02, CAM16 and Oklab. Particularly interesting is Oklab developed by Björn Ottosson and published on his blog in 2020 [18]. Its name stems from Ottosson dubbing it "an OK LAB color space". It is designed to be a UCS good at predicting lightness, chroma and hue while having some nice numerical qualities and simple calculation. Despite its informal inception this color space quickly saw wide adoption as it fixes some mistakes of other UCSs including the previously named CIECAM02, CAM16, IPT etc. A comparison from the blog post can be seen in Figure 6.2.

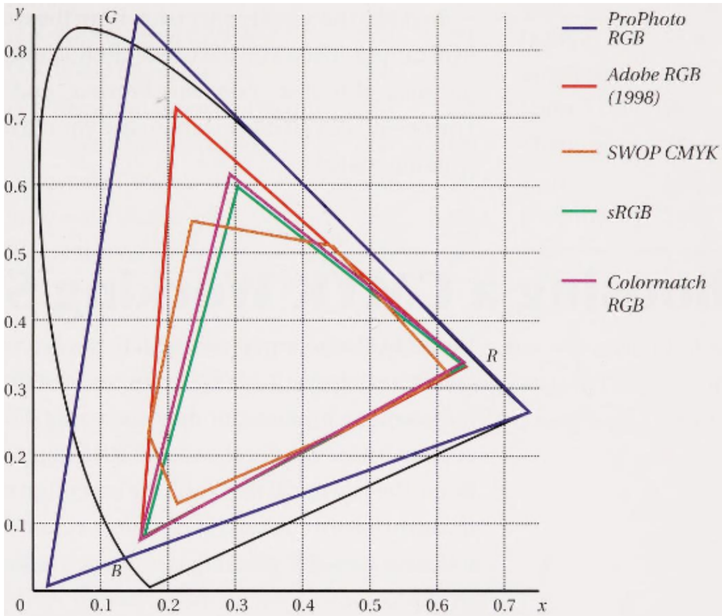


Figure 6.1: *The gamuts of ProPhoto RGB, Adobe RGB, SWOP CMYK, sRGB and Colormatch RGB overlaid on top of the CIE xy chromaticity diagram. [19]*

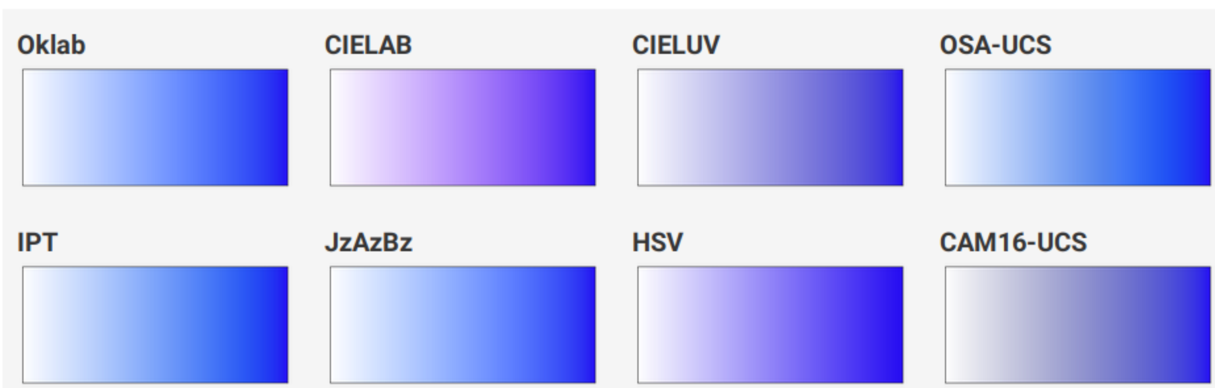


Figure 6.2: *The Oklab color space in comparison to other popular color spaces, showing a blue color blended with white. Some of the color spaces suffer from artifacts such as desaturating too quickly or gaining a purple tint. [18]*

7 Conclusion

As we can see, the fields of colorimetry and color science have vast practical applications across computing, using linear algebra in many places as an essential crutch especially as one moves further away from the physics and into computing. It is a fascinating field of computer science pulling together many disciplines as it continues developing even a hundred years after its inception. Naturally it will only continue to develop further with hardware advancements giving us better displays, and neurological advancements giving us a better understanding of the human visual system. Color is an essential aspect of human life, and we will never stop being fascinated by it.

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