Color Spaces: Language and Framework for Color

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Introduction

What color is it? This is a deceptively simple question with a surprisingly complex answer. Color is thought of in many ways. It can be a certain kind of light or material, its effect on the human eye or the perceived effect in the mind of the viewer. The description of a color can evolve from instrumental measurement or from human visual assessment and in turn, such data can be further embellished by the human observer in the communication of color information. Color is also strongly affected by the context in which it is viewed with surrounding colors having a marked effect on perceived sensation. As a result, the accurate description of color is often problematic.

Over the years, numerous *Color Spaces* have evolved to facilitate the systematic definition and specification of color. These schemes vary tremendously in their design principles and, consequently, in the level of accuracy, repeatability and intuitiveness with which they define color sensation. Each is also realized somewhat differently. Some providing purely mathematical three-dimensional descriptions of color while others embody physical samples to illustrate a color as well as its relationship to other colors. Some attempt to equate numerical representation with a perceptual correlate while others have no basis in color perception at all.

Such *Color Spaces* can be considered both language and framework—providing a system of reference and, in some cases, of order where the relationships between colors is easily communicated or perceived and a given color can be defined in relation to all other colors. This paper will provide a brief review of color spaces emphasizing their structure, use, and underscoring their role in the effective transformation and transportability of color.

Fundamentals

There is one thing that all colors have in common. Each can be represented as a distribution of energy between 380nm and 780nm, the visible portion of the electromagnetic spectrum. It can be thought of as a fingerprint, which identifies a colors unique response and differentiates it from other colors. While a spectral curve can tell us a great deal about the nature of a color—it cannot tell us everything about the way that color looks to a human observer. This is due to the fact that the object itself is only one aspect of the color experience. Ultimately, an object is illuminated by light (or is a source of light itself) which is then subject to sensation by the eye and interpretation by the human being. It is the integration of these three elements; object, illuminant, and observer which form the cornerstone of the science of colorimetry.

People, however, don't think in terms of energy distributions. They are not convenient representations and are difficult to relate to perceived color attributes. What, in fact, are the perceived attributes of color? It is widely accepted that color is a composite, three-dimensional entity consisting of a lightness attribute and two chromatic attributes all of which are mutually orthogonal. The attribute of lightness describes a color's progression between dark and light - a measure of luminance or relative brightness. The first chromatic attribute is closely coupled to the spectral sensitivity curve that defines a color. The relative power at various wavelengths, defines the color family—or hue. The visible wavelength range between 380nm and 780nm is often observed as unidimensional, such as seen when white light is split by a prism into the familiar ROYGBIV distribution. These hues, however, are regarded as a continuum, often represented as a circle. The reason for this becomes obvious when the nature of the spectral curves of colored objects are examined. The other chromatic attribute is one of vividness—where a color exhibits a relative concentration of its hue. This is often described using terms such as "vibrant" or "dull."

Thus, there are two primary means of defining color. One is purely mathematical and is closely coupled to the physics of visible electromagnetic energy. The other relies on perceptual correlates which are influenced further by culture, context, age and the experiences of the human observer. Color spaces used throughout history employ these principles to some degree and form the basis of fundamental color communication. There are auxiliary means for defining colors that are used throughout various industries which must be examined in terms of the accuracy and repeatability with which they can be transformed into a meaningful specification of either primary type.

It is conceivable that such a retrospective could start with the work of Isaac Newton, however, this review will be limited to more modern work.

The Evolution of Tristimulus Colorimetry

In the early part of the 20th century, beginning with fundamental spectral definitions that described a standard observer and the character of illuminants, the CIE began its work on the standardization of methods and parameters for the scientific description of color. This was the first step in defining the fundamental process of *tristimulus colorimetry*. In tristimulus colorimetry, the spectral response of each of the elements of the color system are integrated to provide the three numerical designations X,Y and Z. XYZ together constitute a complete description of a color, however, they do not correlate with any meaningful color attribute scales, nor do they progresses uniformly. As a result, the 1931 x,y Chromaticity Diagram was developed to provide some basic corollaries to appearance concepts. However, this system was not designed to provide insight into uniform color appearance.

Looking at the tristimulus color coordinates that enjoy widespread use today, XYZ is still utilized heavily.

However, the need for systems that attempt to more closely equate numerical description with perceived sensation sparked an evolution that resulted in the uniform color systems that are most widely used today, namely, CIELAB and CIELUV (with its companion 1976 u' v' Uniform Chromaticity Scales Diagram) . Figure 1 illustrates the rich history that has resulted in the CIELUV and CIELAB color metrics.

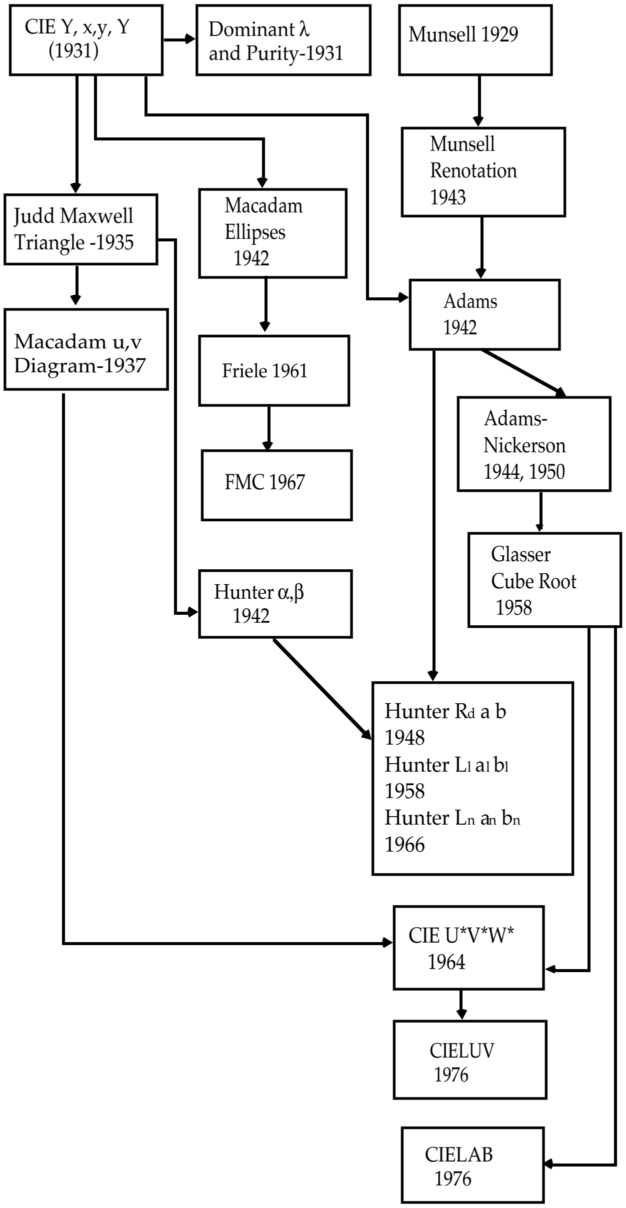

Figure 1. A historical perspective of the evolution of mathematical tristimulus colorimetry Adapted from Hunter and Harold.[1]

All of these systems are very powerful means of color definition. They demonstrate great industrial utility in forming color specifications and as a tool in formulation and quality assurance. The ability to numerically define color leads very quickly to a desire to express the differences between two or more colors with some form of numerical indices. As a result, a vast array of metrics have evolved over the years to facilitate quantitative measurement of color difference. Many are directly related to the different historical color spaces seen in Figure 1.

However, the color of objects is something we objectively compare continually in day to day living. Even the youngest children are taught to describe the color of things by direct comparison with other colored objects. This qualitative process is essential and its utility should not be underrated. As anyone who utilizes color from a creative or design point of view will tell you, purely mathematical color systems have one very noticeable drawback. Namely, that they do not provide physical samples which enable the user to see what a color looks like and examine its appearance in the context of an application or in relation to other colors. One need only look at numerical color difference metrics in use even today to understand the need for more than just numbers to communicate color information.

Color-Order Systems and Embodiments

By definition, a color-order system is a systematic appearance-based arrangement of color samples. These systems vary somewhat in their layout, design concepts and optimizations. However, they are generally organized according to the three basic perceptual attributes discussed earlier; those of lightness, hue, and vividness. The parameters of the system can accommodate definition for all realizable colors but physical embodiments can be limited by the nature of the colorants utilized.

The Munsell System

In 1905, Albert H. Munsell developed the Munsell System, one of the most widely used color-order systems. Munsell identified the three orthogonal attributes of Hue, Value, and Chroma, the general arrangement of which are shown in Figure 2. A standard designation for a Munsell Color is H V/C. A goal of the system design was to arrange and designate colors so that the perceived difference between two adjacent samples is constant throughout the space.[3] This is negated somewhat by the polar coordinate notation system utilized—a unit difference in hue will depend upon how chromatic the adjacent colors are. The Value or gray scale is divided into 10 steps, with White at 10, Black at 0. The system contains five fundamental hues (also referred to as "Hue Leaves"); Red, Yellow, Green, Blue, and Purple and additional divisions are made for further refinement into 40 primary hues. The distance that a color is from a gray of the same Value represents the perceived Chroma. Interpolation between colors is possible along all three attribute scales. The Munsell System is defined assuming illumination under CIE Illuminant C. It should be noted that the magnitude of color differences depends upon the attributes that are changing. For example, the perceived magnitude of one unit of Munsell Value is generally, equivalent to two units in Munsell Chroma.

The most common physical form of the system is the Munsell Book of Color®[4], which utilizes paint samples and represents a limited gamut. Other embodiments include the SCOT System for textiles and the Chroma Cosmos 5000, another paint-based set whose pages illustrate constant chroma, developed by the Japan Color Research Institute.

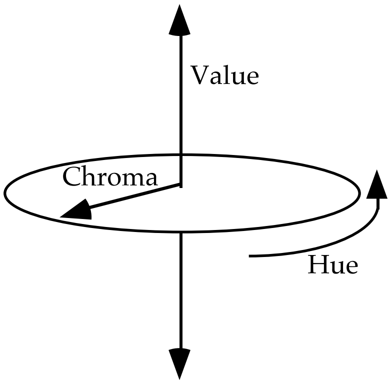

Figure 2. The three-dimensional polar coordinate representation of Munsell Hue, Value, and Chroma.

The Natural Color System (NCS)

This system, which enjoys widespread standard use in Scandinavia, and elsewhere, is an outgrowth of the Hering-Johansson opponent-color vision model. This system organizes color according to its similarity to the elementary color sensations of whiteness, blackness and relative to two of the four elementary opponent hues; redness, yellowness, greenness, blueness.[5]

The three-dimensional model of the system is a double-ended cone seen in Figure 3.

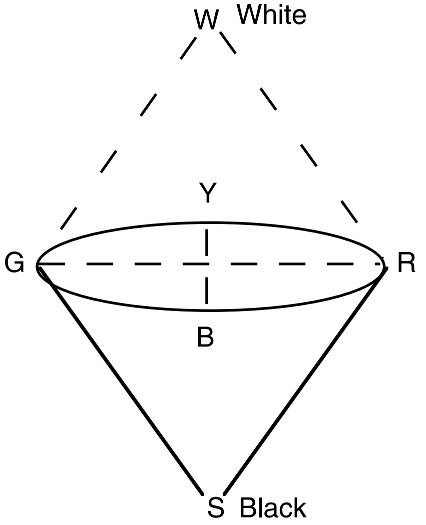

Figure 3. The double-ended cone construct of the NCS System

The hue circle is divided into 4 quarters with each quarter further divided by nine percentage steps for a total of 40 hue designations. It is generally agreed, however, that this does not lead to equal perceptual steps around the hue circle. Each hue is represented as a triangular plane consisting of the whiteness/blackness line and the fully saturated hue located at the middle edge of the solid. A color's position on the triangle is expressed as percentages of white, black, and hue content.

A sample-based atlas of the NCS System[6] is organized as a bound volume of triangular hue pages illustrating a pigment-based gamut of 1530 samples. This is fewer samples than dictated by the theoretical limits of the system but represent color reproducible with currently available pigments.

The DIN System

The DIN (Deutsches Institut für Normung or the German Standardization Institute) System had it roots in work done in the 1930's by Manfred Richter[7]. The three coordinates of the DIN System are Farbton (hue), Sättigungsstufe (saturation) and Dunkelstufe which is an axis of relative lightness/darkness. There are 24 principle hues which were selected to represent equal hue differences spaced around a hue circle. The system assumes a CIE D65 illuminant, the CIE 1931 Standard Observer, and a 45°/0° measurement geometry. The hue coordinate is somewhat similar to CIE dominant (or complimentary dominant) wavelength while saturation is similar to CIE color purity. However, the transformation between DIN and CIE coordinates is not straightforward.

This system is embodied in the DIN Standard 6164, DIN Color Chart[8] color card system whose samples are constructed using acrylic paints.

The Coloroid System

The Coloroid color-order system[9] was developed at the Technical University in Budapest, Hungary, for use in environmental color design. The goal of this system is to achieve a color space that approximates aesthetic uniformity fairly well while permitting an unambiguous mapping into the CIE system.

Assuming the 1931 Standard Observer and Illuminant C as a reference illuminant, the Coloroid color space is embedded in an orthogonal circular cylinder with a central lightness axis, ranging between black and white. Limit colors, which are spectrum colors from λ=450nm to λ=625nm on the 1931 CIE x, y Chromaticity Diagram spectrum locus as well as the those along the "line of purples, are located on a curve traced on the shell of the cylinder. Specifications consist of three numbers including hue (colors with equivalent dominant or complimentary wavelengths), chromatic content, T, and lightness, V.

The Color Sample Collection[10], an atlas of Coloroid System colors, is available for purchase.

The OSA Uniform Color Scales

In 1977, The Optical Society of America published the Uniform Color Scales as another effort to create a perceptually uniform color-order system.[11] What makes this system truly different is that there is no attempt made to preserve the constructs of hue, lightness and vividness seen in most other systems. Instead, the primary aim is to create a system where the perceived difference between any two colors is directly related to the physical distance that they are separated in the system. Samples are arranged in a regular rhombohedral lattice (cubeoctohedral) so that physical distances between a sample and any of its 12 nearest neighbors represent equal perceived color differences. There are thirteen lightness planes, each of which varies in terms of two chromatic attributes: j = yellow/blue and g = red/green. The lightness planes are alternately staggered, resulting in numerous arrays of "cleavage planes", which vary in their color content. The UCS has been shown to demonstrate reasonable color uniformity[12] but the system, with unit color difference of 14-15 just-noticeable difference (JND) units, is not well-suited to evaluation of small color differences.

The System is available as a 558 sample set[13] with all pigment-based samples being specified in terms of both CIE 1931 and 1964 Standard Observer as well as the CIE D65 illuminant.

The Colorcurve® System

The most recent entry into the color-order arena, the Colorcurve System[14] provides a dynamic approach combining four key elements into a visual and numerical system for color definition:

- Color aim-points in CIELAB color space,
- Samples that represent the aim-points, assuming the CIE 1964 10° Standard Observer and CIE Illuminant D65,
- Data tables and spectral descriptions of the aim-points, and
- Computational/Formulation methods

Simplifying the CIELAB notation by designating 18 L* lightness levels and identifying the a* b* axes, Colorcurve assigns directional color names (e.g. red/yellow, red/blue). The system utilizes systematic, regularly sampled organization illustrated in Figure 4, and most colors in the system have up to 26 colors around them, showing subtle variations in hue, lightness and saturation. Eight base pigments are used in formulating the system colors and were chosen to help assure uniform color transitions (minimize the effects of metamerism) for viewing under light sources other than D65.

1229 samples for the system are available as The Colorcurve Master Atlas with an additional 956 available in an auxiliary Gray and Pastel Atlas.[15] Swatch decks are also available. All samples are constructed using the eight base pigments dispersed in a nitrocellulose lacquer vehicle and coated on a specially formulated paper.

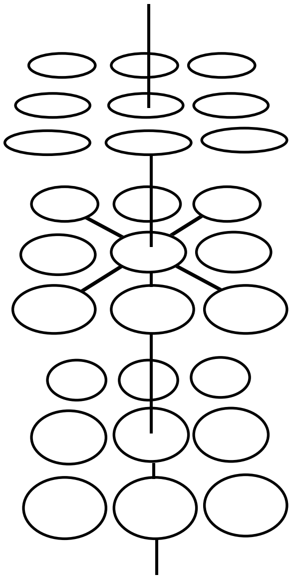

Figure 4. Layout and sampling of the Colorcurve system permits viewing of up to 26 colors around a central color, showing subtle variations in hue, lightness and saturation.

Color order systems are dynamic tools for color selection and appearance verification. It is possible to sample the defined color space in any one of a number of ways for a variety of creative applications. They are easily comprehended and, in general, can be related to colorimetric values.

However, there are a number of disadvantages to color order systems too.[16] One is that there is no single system in use, and it is often difficult to transfer color specifications between differing systems. Care must also be taken to adhere to the viewing conditions under which the system was designed. It is also necessary to try to use an embodiment of a system whose medium is the same or close to the application.

Colorant-Order Systems

In many industries, such as the coating or the printing industry, colors are created by mixing together a small number of highly chromatic colorants, black, white, and gray. In both the paint and ink industry, this approach is highly favored since it provides a noticeable reduction in the required inventory-on-hand. Only base colors are stocked and any possible tint or blend can be mixed in the required quantities when needed.

Historical Systems

One of the earliest colorant-order system, the Ridgway *Color Standards and Color Nomenclature*[17] was developed in 1886. Based on work by Maxwell in disk colorimetry, the 1115 sample Ridgway set is based on the mixture of a set of colorants with white. The system's primary uses are for color identification in agriculture and horticulture.

In 1930, Maerz and Paul's *A Dictionary of Color*,[18] is one of the most comprehensive collections ever created for industrial use with 7056 color samples using a set of base inks and variable-density overprinting. Colors are arranged according to hue and names are assigned to many of the samples.

A more widely known colorant-order system based on disk colorimetry is the *Ostwald System*.[19] Postulated in 1931, this system combines lights reflected from a spinning disk consisting of black and white segments as well as a high chroma segment taken from one or a binary combination of 8 primary hues. The Ostwald system was somewhat limited because as more saturated pigments became available for industrial color production, they were essentially out of gamut until the base colorants could be updated to reflect the improved materials.

The spatial layout of the system is similar to that of the Natural Color System (Refer to Figure 3), with color on each "page" varying in terms of its white, black, and full-color content.

The closest embodiment of the Ostwald System was the Color Harmony Manual,[20] however, this collection has been out of print for a number of years.

Current Systems - Color

One of the most widely available colorant-mixture systems in use today is the Pantone Matching System. Originally intended as a system for defining "spot" colors, users can take sample swatches to specify a design color while the printer can utilize it for the purpose of matching inks. The system enjoys a large following due to the wide variety of swatch decks, sampling arrangements, colored supplies, and raw materials, over which the company maintains quality assurance.

While printers have found the system of great utility, is somewhat difficult to use due to an arbitrary numbering system, and lack of an overall organization principle.

A more recently developed system, Trumatch, approaches printing ink colorant-mixing from the perspective of 4-color process printing. The more than 2000 colors represented were derived using computer simulation of process screening only using much finer increments to create visually proportional gradations of color. The Trumatch Colorfinder fandeck is organized with color samples arranged in a spectral order which makes sample location somewhat easier. The system uses three numerical designations; a Hue Number, tint code, and a shade code for a full color designation.

The system also assumes the use of inks that conform to the SWOP[21] standard. The system will be predictable for someone who utilizes inks that conform to the SWOP standard but it will incorporate color variations that are due to an ink manufacturer's ability to maintain that standard. This isn't system calibration but it is an attempt to assert and maintain some control over the process parameters, in an attempt to achieve more predictable color rendering. There are a number of colors from the Pantone set, with special appearance attributes (e.g. metallic, high fluorescence) that the Trumatch system would not be able to reproduce.

Either of these systems provide any perceptual-based order in the same sense as a color-order system but they demonstrate color variation as a function of colorant concentrations or print densities. None of the systems are generally furnished with equivalent CIE tristimulus values. But it is important to remember that the system's were designed principally for colorant-order. The increased usage of these systems in the electronic display and print industry has, however, necessitated that such information be incorporated into system characterization/calibration profiles for usage with computer color management systems. Data for both the Pantone and Trumatch Systems has been incorporated into various electronic color design and print products. There are also "Color Simulators" that Pantone makes available for translating its specifications into 4-color process printing. All of the Trumatch colors may be generated using computerized image setters, CEPS, and most electronic typesetters.

Process Parameter Color Systems

In image sciences such as computer display generated color, color printing, television, etc. arrays of colors may be produced through systematic variations of process parameters.[22] Complete, systematic variation produces the possible gamut of achievable colors.

In the CRT display device, three electron guns are used to address the three primary color phosphors which emit light characterized as "red", "green", and "blue." The RGB color model uses a Cartesian coordinate system that describes all possible additive color variations within the confines of a cube. The number of distinct addressable colors within that cube is a function of the number of system bits. The color space that results is highly non-uniform, and does not progress along any kind of predictable perceptual attribute scales. Attempts to massage the RGB space into something more perceptual have been made over the years, such as HLS, HSB[23], etc. However, if the device dependent nature of the RGB space is retained, consistent color rendering will always be problematic.

The CMY(K) system utilized with printers is very much the same in its construction. The model uses a Cartesian coordinate system that, again, forms a solid cube. The number of available colors within that cube depend on the number of print density levels printed (on a press) or the number of system bits in an electronic printer. It will also be affected by whether the system is 3- or 4- color process. Other imaging techniques such as halftoning or dithering will effect the overall content of the colors within the cube, as well. A variant on this solid was proposed by Foss[24] in 1973 but it does not specifically define the colorimetric characteristics for the primary colorants. As with the RGB system, if the device (primary) dependent nature of the CMY(K) space is retained, consistent color rendering will be problematic.

The RGB and CMY(K) color spaces are attractive to electronics manufacturers and users since they do represent device control levels. Any attempt to utilize extensive transforms to redefine these values often results in an expensive increase in computation time that many are unwilling to pay. As a result, color encoding spaces are often employed to help streamline the transmission of device data, enhancing it to a degree, and linking it to some standard definitions in an attempt provide some consistency of color rendition. The various broadcast transmission encoding schemes are an example of this. Another example is Kodak's YCC[25] encoding space, which is based on broadcast television encoding and phosphor specifications.

Systems that utilize RGB and CMY(K) color specifications, in one form or another or that employ refinements such as the Kodak YCC or a television encoding space, can use them more repeatably and accurately only through system characterization. The system primaries and the various blends of color must be distinguished in terms of a true colorimetric specification to enable precise color translation. In addition, system devices must be calibrated to determine their absolute capabilities and their inherent variations. Together, colorimetric characterization and calibration provide the necessary framework for use of process parameter color system specifications to yield consistent accurate color over time.

Conclusion

This paper has attempted to provide a very rudimentary review of the many types of color spaces that are used in the communication of color information. Many of these systems evolved out of a very particular need while others attempt to be more general utility.

How good is a system when it comes to communicating color information? The answer is straightforward - it depends on what you want to do with it. Different systems are suited to different tasks and as a result, the best system for a particular job will depend on the tasks at hand. A system should be relatively straightforward to use and should conform to the user's need for functionality, accuracy, and repeatability. It is also important that a system work in the context of the application in which it will be used. For example, it is unrealistic to expect a colorant-mixture system based on a set of inks to render reliable information on color mixing for paints. Color spaces, like spoken language must be chosen with care so that the proper message is delivered, in context and fully understood.

There are a number of additional color spaces and colorant-mixture systems of both historic and current interest. Space does not permit discussion of all of these. The reader is encouraged to consult general color-science texts to delve further into this topic.

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