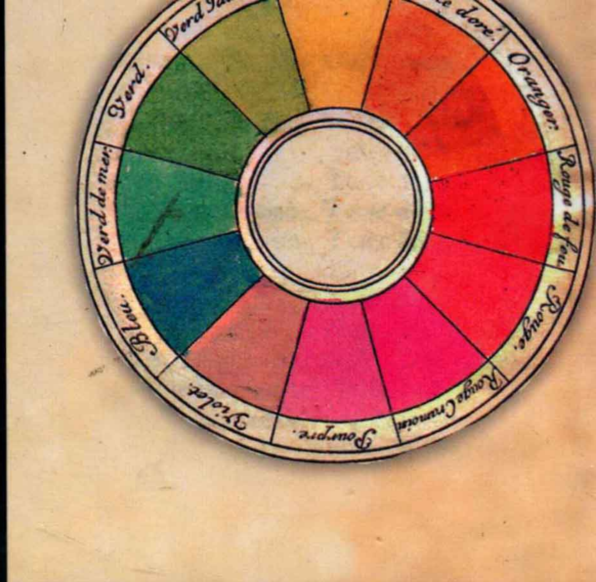
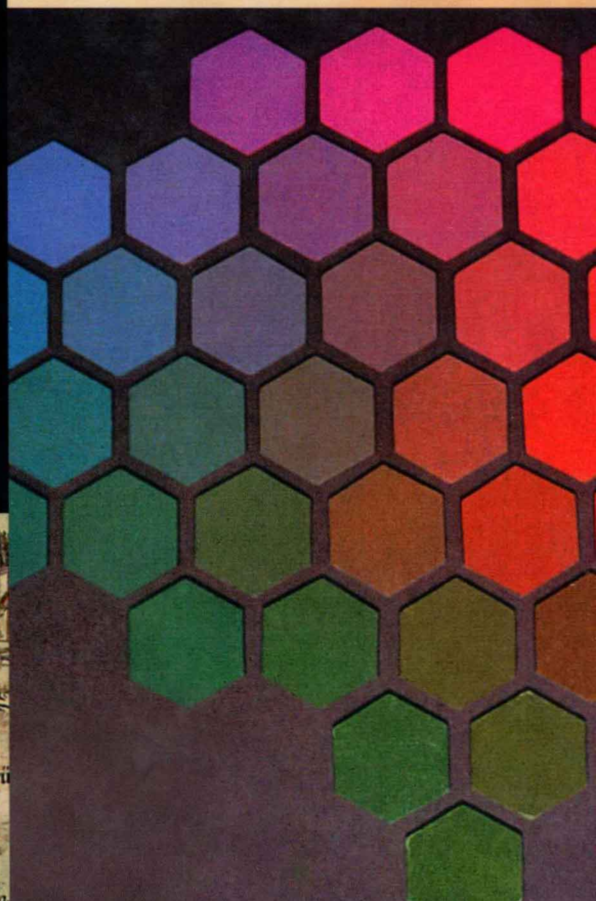
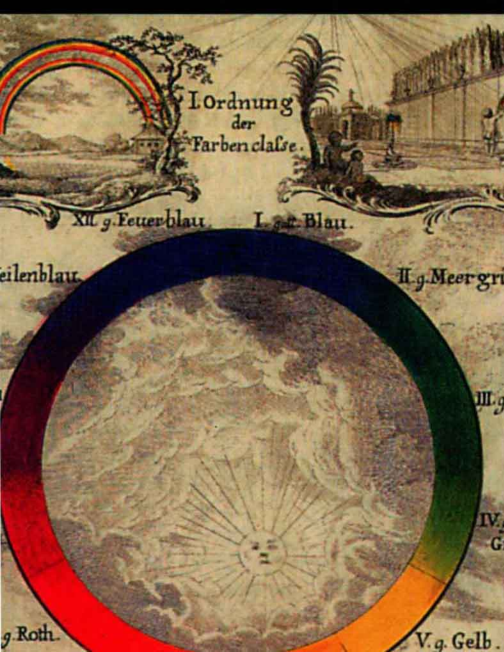
COLOR SPACE

and Its Divisions

Color Order from Antiquity to the Present







Rolf G. Kuehni

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To the memory of Dorothy Nickerson and David L. MacAdam, and to Andreas Brockes for their encouragement to continue the pursuit of color order and color difference

All that is alive tends toward color, individuality, specificity, effectiveness, and opacity; all that is done with life inclines toward knowledge, abstraction, generality, transfiguration, and transparency.

Johann Wolfgang von Goethe

Preface

Our color experiences are an important component of our visual experiences and as such form a significant aspect of our consciousness. Color experiences are the outcome of processing by the brain of information acquired as a result of interaction of light energy with the three types of retinal cone cells in the eyes. The three cone types filter the spectral complexity of our surroundings and from the three kinds of signals the brain constructs complex experiences that allow us to interact with our surroundings in a purposeful way. Luminance contours are important input for the generation of these experiences but much of the original complexity of the information arriving at the eye is in terms of spectral signatures translated by the brain into colors. It has been estimated that we can distinguish between color experiences that number in the millions.

Given the human predilection for ordering experiences and given the large number of different possible color experiences, it is not surprising that the question of how to bring order to this multiplicity is one that humans thought about since antiquity. Confusion created by the seemingly different result of mixing colored lights and colored materials has complicated the search for answers considerably. Only in the later eighteenth century have color experiences begun to be sorted into three-dimensional arrangements, and three attributes of color experiences have only been defined unambiguously in mid-nineteenth century. Ordering color into a uniform color space means the creation of a geometrical model that is considered to be isomorphic (one-to-one correspondence) with experiences. It is evident that this cannot be a simple effort. Alternately, it can mean ordering color stimuli in a regular way so that the most general psychological ordering principles are observed.

This text presents a history of the significant steps in development of thinking about color order in the Western world from ancient Greece to the present. Not surprisingly, given the complexity of the matter and the fact that it involves a sense, several fundamental questions continue to be unanswered. Among other things this has to do, despite hundreds of years of concentrated effort by many individuals, with the absence of a scientifically satisfactory experimental database of how humans perceive colors and color differences. The text is limited to issues of color space as viewed against a simple achromatic surround. It does not address issues of color appearance under widely varying surround conditions.

Every space is divisible and a given color space is inextricably linked with the definition of the divisions used. A dividing line is drawn between uniform color spaces where distances in all directions are isomorphic to perceived differences of equal magnitude and general color spaces that are ordered according to some other principles. The plural is used because it has become evident that there is no single uniform color space but each such space is related to a quite highly specific set of viewing and general experimental conditions. Uniform color spaces are of particular interest for color quality control purposes in industries manufacturing colorants or colored goods. A considerable variety of general regular spaces are in use, for example, in the graphics industry and in computer display technology.

Regular arrangements of colors fit into euclidean space and can have many different simple geometrical forms, depending on the definition of distance. It is not evident that a uniform color space can have euclidean form (there are no obvious reasons why it should).

The book begins with a general introduction to the subject in Chapter 1. Following the historical account of color order systems in Chapter 2, fundamentals of psychophysics, the branch of science concerned with the relationship between stimuli and experiences, are presented in Chapter 3. Chapter 4 describes the results of perceptual scaling of colors according to attributes. In Chapter 5 these scales are related to scales based on psychophysical modification of physical measurements (reflectance or spectral power distribution measurements). The history until the present of the development of mathematical color space and difference formulas is described in Chapter 6. Three of the color order systems presented in Chapter 2 have been selected for more detailed description of their development, their psychophysical structure, and the problems associated with them in Chapter 7. Chapter 8 contains an analysis of the agreements and discrepancies in psychophysical data describing color at levels of difference ranging from color matching error to large. Chapter 9, finally, draws conclusions and offers an experimental plan for the kind of reliable, replicated perceptual data needed to make progress in this field.

Aside from offering the first extended historical account of this fascinating field, the book contains new analytical results of perceptual and psychophysical color data and a synthesis of data developed for different purposes and under different circumstances. I believe it to be not only of interest to experts and educators in industry and academe but also to neuroscientists and philosophers grappling with problems of awareness and consciousness, to designers, graphic artists, art historians, students of vision, psychology, design, and, last but not least, the general reader with interest in the subject matter.

This book represents the culmination of some forty years of interest in the subject. During these years I had many discussions with fellow devotees in industry, academe, the Inter-Society Color Council, and other organizations that helped shape my knowledge and views. I am grateful to all that helped me to see the issues clearer.

The text was read and commented on in its entirety by Dale Purves. Individual chapters have been read by Larry Hardin and Andreas Schwarz. I am grateful to all three, but any remaining errors are my own.

A note about certain conventions: An author's name with an associated year relates to a complete reference at the back of the book. Comments in angled parentheses are by the author, except in Chapter 2 where they usually contain Greek and Latin color names.

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Chapter 1

The Concept of Color Space and Color Solid

1.1 INTRODUCTION

Attempting to understand our place in the world and classifying things and experiences is a well-known human trait. Already ancient Greek philosophers thought about the multitude of color perceptions, but they despaired of finding a system in which to place them. First, colors were logically sorted according to lightness, regardless of hue. Early in the second millennium we begin to find descriptions of tonal scales of individual hues or mixed tones, like flesh color. They were achieved by adding lighter or darker pigments of similar hue, even black or white, to saturated chromatic pigments. Systematic hue circles began to appear in the late seventeenth century. The concept of a three-dimensional logical arrangement of color perceptions began to take shape only in the eighteenth century.

Color space is a three-dimensional geometric space with axes appropriately defined so that symbols for all possible color perceptions of humans or other animals fit into it in an order corresponding to the psychological order. In this space each color perception is represented as a point. The symbolic representations of color perceptions in this space form the color solid. The earliest proposals for color solids had simple geometrical forms: triangular double pyramid, sphere, cone, and so forth. There is, of course, no a priori reason why a systematic arrangement of color perceptions should fit into a simple geometrical solid. What controls the form of the solid is the definition of the axes of the space and their divisions.

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There is ample evidence that the colors we experience in various conditions from a given spectral stimulus can vary widely. According to one view they are determined by empirical rules derived on an evolutionary basis for our species and for each individual. There is strong evidence that the color attributed to an object depends on the nature and complexity of the surround in which the object is seen. In scientific experiments the complexity of surrounds usually is minimized (elementaristic approach).[1] Color experiences from given stimuli under elementaristic conditions depend on the exact conditions and change to a smaller or larger extent as quality and complexity of the surround and lighting change. Only under closely controlled conditions can a color space for the average color normal human observer be represented by spectral stimuli. In these relativized circumstances terms such as *color stimulus* and *object color* have applicability restricted to the experimental conditions and cannot claim the level of universality that has generally been assumed from the eighteenth to the twentieth century. Critics of the idea of color space have pointed to its lack of solid foundation. While this is ultimately true in the end such criticism appears simply to address the fact that at this point in time we do not have an understanding of consciousness. Color perceptions are the result of brain activity; they are subjective and private. As for all other sensory feelings and beliefs we do not know how in a given situation a given light stimulus can result in our seeing an object, and this object to have the appearance of red. It is not clear that humans will ever gain an understanding of this process. Color scientists have over the years built conjectural models based on what must, in the absence of true knowledge, be called coincidental relationships between stimuli as viewed in controlled circumstances and visual perceptions. In a perfect world this is not an acceptable process. Given the lack of fundamental understanding of consciousness it is an empirical approach having produced many reasonably well established, coincidental or otherwise, relationships.

Within the framework of an evolutionary development model, some key questions concern what forces in our early history shaped the development of visual sense and what strategies were implemented during its evolution by neurochemistry to deal successfully with the pressures of these forces. The simplistic color perceptions and attributes on which color scaling is based are doubted by some psychologists as having anything to do with the fundamental perceptual processes embedded in our visual system as a result of interactions with the environment. We appear to be only at the beginning of a process to find answers. Questions such as why color space is (at least) three-dimensional and why there are four psychologically fundamental hues and not more or less have started to be asked only recently.

The issue of a systematic arrangement of color perceptions under simplified viewing conditions is a relatively abstract matter, removed from such considerations. It is probably not surprising that it took shape in the age of Enlightenment with its belief in a universal rational order. In the twentieth century, aside from fundamental considerations of trying to understand our place in the world, the quest was shaped by technical and economic issues of color control of manufactured colored goods.

A color space belongs in the domain of psychology. The description of stimuli that under standard conditions result in perception of colors in that space is an aspect of physics. Together they form the uneasy domain of psychophysics that attempts to connect stimuli with perceptions (see Chapter 3). The stimuli are messages to us from the outside world. An alternative view is that we actively search for them when viewing the world. They enter through the pupils of the eyes and are absorbed by the retinal layer. There they trigger a complex chain of events that result in our perceptions. These events belong into the domain of neuroscience and are part of the conundrum of consciousness.

The number of different color experiences we can have is unknown, but large. Given a particular starting point in color space the finest perceptual division of color space is represented by visual threshold increments deviating from that point in all directions. A color space of given definition can only be expressed in terms of differences within the related color solid against a chosen surround because it is only applicable to those conditions. The smallest difference in a color solid as related to a given starting point, therefore, consists of a pair of different color stimuli displayed against a particular (usually neutral) surround and seen as having a just perceptible difference.

Generally, a color space and the related color solid may be defined as an economic systematic description of subjective color experiences, and as such it is not subject to engineering precision. It is indicative of our visual strategies vis-à-vis the world.

Personal Color Spaces and Color Solids

Each person with normal color vision has individual, personal (relativized) color spaces and related color solids (depending on the conditions under which they were established). Such individual solids vary within limits, based on the detailed implementation in an individual of his/her color vision apparatus. (Relativized personal spaces generally are at least in ordinal if not in interval order compared to that of the average observer.)[2] What it means is that if the reader and the writer sense the spectral power distribution representing a particular object color field in a particular surround and illumination, the resulting experience is likely to be somewhat different. Such a statement assumes that both observers are "color normal" and that color normal individuals have in essence the same fundamental color experiences. It does not consider the possibility, raised by some philosophers, of what is loosely called "spectrum inversion." It cannot be excluded with certainty that, for example, the reader actually experiences as green what the writer experiences as red, regardless of how it is named.

How different the experience resulting from a given spectral power distribution might be in terms of hue can be judged from individual determination of unique hues and, to less extent, from color perceptions judged to be intermediate between unique hues. Unique hues are those four primary hues that do not contain perceptual components of other hues. A unique red hue is neither yellowish nor bluish: it is just red. Color stimuli resulting in unique hue perception vary among color normal observers.[3] This variation depends on the hue in question. It ranges approximately from 5% to 12% of the total hue variation in a hue circle experienced under standard viewing conditions (i.e., approximately two to five Munsell 40-hue steps; see Chapters 2 and 7 for information on the Munsell system). Because of the absence of unambiguous criteria, it is not possible to meaningfully assess the stimulus variability for other hues. It is quite evident that there is also variability in the experience of gray scale steps, in adaptation and constancy response and other visual mechanisms, resulting in considerable variability of individual experience when looking at a given scene of color stimuli. Persons with impaired color vision have implicit color spaces significantly different from those of color normal observers. Their nature cannot be conveyed with certainty. Theoretical considerations of the genetics of color vision indicate that as much as 50% of the female population have the potential for four rather than the normal three cone types even though none has so far been identified as having four cone types.[4] Richer color experiences than those had by standard trichromatic observers have recently been determined for females with the genetic potential for four cone types. In how many ways their color experiences are richer remains to be determined.

Adaptation and Conspicuousness of Differences

Color experiences, in the normal case, result from the impact of light energy on the retina in our eyes. They are known to depend on the absolute level of light energy. This level can differ by a ratio of 1 million to 1 (on a retinal illumination basis). There are mechanical (pupil size) and neurochemical processes to manage such large variation, known under the general term of adaptation.[5] The complete process adjusts the range of incoming light to an output capability with a range of approximately 100:1. The adaptation process works to map the energy pattern in a given viewing situation to the total output range so that contrasts between different areas are seen roughly as the same under a wide range of illumination. At very low intensities of light we see no hued colors and neither do we at very high intensities. Probably because of the importance of very low light levels (night) in the lives of some early ancestors, we have a separate set of receptors for that situation, the rods. Rod signals pass through the same postreceptoral cells into the brain as cone signals. If they have any effect on daylight color vision, it is very small. The response pattern as a function of light intensity of our daylight-level sensors, the cones, is S-shaped, but the response has a considerable range that is approximately linear in the center region. There are issues at low and high levels of response of cones that cannot be of concern in this discussion. This text is largely limited to color spaces and solids represented by reflecting materials at mid levels of illumination, say 500 to 1500 lux.[6]

Earlier, mention was made of the lack of constancy of color perceptions resulting from most stimuli as a function of surround or illumination changes. Chromatic adaptation is a seemingly opposite process. Its purpose appears to be to provide a considerable level of color constancy for reflecting objects with certain spectral signatures. Among terrestrial nonhuman mammals trichromatic color vision is limited largely to fruit eaters and pollinators. For them it is important to recognize their objects of interest in all natural lighting conditions. Color is an important part of the stored memory of the appearance of objects and helps to recognize them rapidly when encountered again. Without chromatic adaptation, colored objects in the natural world might change their appearance significantly over time as a result of changes in ambient illumination. With independent adaptation capabilities for each cone type, likely together with additional processes, our ancestors could recognize the colors of most natural objects as essentially the same regardless of the quality of illumination and surround. This is less true today than it was at a time when there were only natural objects and all light was sunlight, direct, scattered, or reflected. Today we have a large number of artificial colorants and various artificial light sources that have complicated the issue considerably, resulting in smaller or larger changes in the appearance of objects as a function of surround and illuminant. This text does not consider most issues of chromatic adaptation but considers color spaces and related solids only in terms of colored objects as viewed against achromatic backgrounds of varying levels of lightness under a standard light source.

The visual system has developed in a way that favors the conspicuousness of small differences in reflectance signatures of objects. Its cause may have been an escalating battle between camouflage and detection, a matter of life and death. Highest discrimination of small reflectance differences between objects is provided in a surround with reflectance intermediate to those of the objects compared. This results in improved detection of highly camouflaged predators or prey in natural surroundings. The principle also applies when the number of objects with different color increases and/or the differences between them become larger. Best discrimination is provided in this case by an average (i.e., mid-level) achromatic surround. The best surround to view a complete color atlas, by this reasoning, is a mid-level gray.

Mathematical Color Appearance Models

Our complete color experience is much wider than what was just discussed. We view natural scenes, color television, computer monitors, projected slides, projected digital images, the output of many coloration devices under many different light sources, metameric objects under different light sources, and so on. It has become important to be able to predict for an average observer the appearance of colored objects in many different conditions. This is the