The colors of objects appear, at first glance, to be inherent properties of those objects. We say, for example, “this flower is blue,” “this apple is red,” “the grass is green,” and “this painting is colorful.” The tendency to treat color as a property of objects is strengthened by mechanisms that maintain a color constant world with changes in the illumination. The flower, the apple and the grass appear to have more or less the same color under the various phases of daylight illumination. It is easy to show, however, that color constancy is not perfect. The hue of an object is strongly affected by certain light sources, as well as by preceding and/or surrounding light, as scientists and artists have observed in many circumstances described in this book. These latter observations suggest that color, as we experience it, is not an inherent property of objects but is associated with the spectral distribution of light reflected from them in the context of preceding and surrounding illumination.

Just as experienced color is not a property of objects, color is also not a property of the light. The perceived color of an object depends on the spectral content of the light that is absorbed by the cone photoreceptors which initiate a cascade of physiological reactions in the retina and the brain. Newton (1704) recognized this when he wrote “for the Rays to speak properly are not coloured” (p. 124). He came to this view by observing that there are numerous combinations of physically different lights that appear identical, called metamerists. Maxwell (1860) and Helmholtz (1867) later established an empirical basis for three-dimensional metamerist-matching spaces from which they concluded, correctly, that color vision is made possible by three classes of photoreceptors.

The appearance of color is also not explained, however, solely by the activity of three classes of cone photoreceptors, although like the physical properties of the stimulus, trivariance represents an indispensable component in color vision processing. Introspection shows that all experienced colors can be described in terms of six elementary sensations: red, green, blue, yellow, black and white. This is represented in Figure 1. Hues are represented on the circumference, with blue and white.
yellow, and red and green, plotted opposite each other because the pairs red/green and blue/yellow never occur co-spatially and/or co-temporally. They are thus called opponent colors (Hering, 1920). The achromatic colors, black and white, are shown at the apices. The three planes orthogonal to the black-white axis illustrate colors having different levels of lightness and darkness. Hering recognized that constraints on how colors appear imply constraints on how colors are coded by the nervous system. The perceptual bases for Hering’s ideas have been verified by psychophysical experiments and their physiological foundations have been proven in general to be correct by neurophysiological measurements.

**Perspectives from Different Disciplines**

What is left to explain in color science? This depends on one’s discipline and perspective within that discipline. This book provides a sampling of perspectives beginning with an historical discussion of research on color vision in art and science. The artist who composes a picture must know about the effects of light on our perception (e.g., color assimilation, contrast and color constancy) to avoid unintended side effects. While artists continue to show provocative effects that beg for physiological and psychological explanation, color scientists sometimes look at the problem the other way around: asking to what degree artistic achievements can be explained by what is currently understood from color science.

Color perception is based on a number of neural processing stages and while each level of processing is essential to understanding color appearance, there is not a one-to-one mapping between physical stimuli, physiological responses and color appearance. The physiological concept of three photoreceptor types and the psychological experience of six elementary colors obviously do not match each other. Von Kries (1882), however, proposed a zone theory in which the activity of the three receptor types is transformed at a stage of opponent-color processing. This view is now well accepted but, as discussed in several chapters in this book, the mathematical transformations used to map the photoreceptor activity to the neural code, and ultimately to perception, are still being investigated.

The links among a number of physiological processing stages are also explored in this book through research from several different disciplines: the relations between photoreceptor signals and various transformations into a color-opponent code carried through processing stages in the retina and higher-levels of the brain; the molecular genetics of the cone photopigments and their influences on color-matching; and, the relations between neural computations and behavior, not only in normal and color deficient primates, but in animals such as the honeybee where the neuronal circuits are simpler and more tractable both electrophysiologically and computationally.

Despite extraordinary leaps in technical methods for investigating color vision (such as electrophysiology, brain imaging, molecular genetics, etc.), the meaning of the information yielded is not always self-evident. Ultimately, we can never be sure that two humans have the same color experience, even if they identify the same stimulus using the same words. Inferences about sensations are even more difficult in the case of different animal species with which we can only communicate via behavioral experiments. For this reason, philosophers remain useful in guiding our thinking about further criteria that, if satisfied, might allow a reasonable person to infer whether two people or two different species experience the world in the same way.

Finally, the transformations from color metrics to displayed colors is a matter of great practical importance. The use of color has become more prevalent in everyday life. Until very recently, books containing as many color illustrations as this one were reserved for those wealthy popes and dukes who could afford illuminated manuscripts. Color television and computer displays are now common place. While engineering moves ahead, principles from other disciplines also come to the fore. Precise color management is in the process of being developed in some cases on the basis of results from basic color science, but the practical issues in color imaging can also raise thorny questions for color theory.
Integrative Views

It seems clear from the chapters in this book that progress in the various disciplines of color science often depends not only on progress within that discipline, but also on conceptual developments in related fields. The successful search for single cells in the visual pathway that respond in a spectrally-opponent manner was motivated by perceptual studies implying that our nervous system must be organized in this manner (although not necessarily at the level of single cells). In this example, as in many others, there was a period during which interdisciplinary interest surged to the benefit of several disciplines interested in color coding. Often, however, the disciplines are widely out of step with one another as witnessed by the long lag between Hering's proposal of perceptual-opponent coding and the much later discovery of its possible cellular basis. Following a period of interdisciplinary progress, some concepts lose their energizing force for one or the other discipline and new cycles ensue. We now see, for example, a search for specific neural mechanisms to explain the more complex aspects of color perception such as color contrast, color constancy or the filling-in of color information beyond the spatial coverage of receptive fields of single neurons. While one approach, usually the perceptual, moves ahead of the other for a period of time, the lag between disciplines today is shorter than in the past.

Nowadays, as in the past, color vision is not so much investigated by interdisciplinary teams but by researchers working in different disciplines. The investigations usually aim to solve specific problems within their specific area, but because of the causal chain structure of color processing, ideas and methods are imported from other disciplines as the problem dictates. Thus, the separation amongst the disciplines varies over time and ultimately vanishes into an integrative view on color vision. At the risk of being called "color vision chauvinists," we submit that there is no other field where our understanding of the physical, physiological and perceptual foundations of a behavior are better understood than in color vision. Thus, the area of color vision stands as a model for investigations of other aspects of brain and behavior where disciplinary barriers must be broken to make further progress.

References