The Physics and Chemistry of Color

THE FIFTEEN CAUSES OF COLOR

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Preface

> **The mystery of color**
> GEORGE BERNARD SHAW

Technical questions can be answered at many levels of sophistication. In answer to the child's question, "Mummy, why is grass green?" one answer could be: "Because!". This clearly implies that "green" is an inherent property of "grass" and that further questions are unwelcome.

At the next level of insight it might be explained that grass is green because it reflects green light and absorbs all other colors. A further elaboration would attribute this phenomenon to the presence of specific chemical substances, including chlorophyll.

The aim of this book is to take the next step and investigate just how an organic pigment such as chlorophyll interacts with white light to produce a green color, why the sky is blue, why ruby is red, to what processes gold owes its yellow color, and how a gem opal or the wings of certain butterflies can display all the colors of the rainbow. The fundamental concepts needed to understand these phenomena are covered so that no specialized knowledge is required.

The ultimate level of complexity is the monograph volume, dealing with only one type of calculation for only one type of color theory. This level can usually be fully grasped only by the specialist with graduate level training in just that branch of physics or chemistry. There appear to be no books covering the wide voids between the extreme of the monograph and general expositions on color, books on optics that deal with light but only peripherally with color, and books on color measurement and color perception. This book is intended to fill this serious gap.

These are subjects for which there is rarely time in courses in physics and chemistry, yet which represent a direct bridge from theory to phenomena observed every day. Color impacts on many other fields: on biology, geology, and mineralogy, on atmospheric studies, on many important branches of technology, and also in significant ways on the visual arts. This treatment provides insight into the wide variety of subtle and curious color occurrences.

In stating that "The purest and most thoughtful minds are those who love color the most," John Ruskin was using his poetic license to the fullest. Yet even a complacent mind cannot help but note and wonder about the color in our environment. It is my hope that in investigating the varied causes of color this book will allay some of the wonderment but not diminish awe for one of nature's triumphs.

There is no one single approach that explains all the causes of color, and at least five theories or formalisms are invoked. A rigorous treatment of any one of these would require at least a full volume of its own, but significant insight can nevertheless be gained from the descriptive account presented here. Inevitably, it is necessary to begin with a discussion of the nature of light and color in Part I.

The quantum theory leads to an understanding of excitations and energy level transitions and to colors produced by incandescent objects, flames, and vapor excitation light sources, including the auroras as well as gas lasers, as dealt with in Part II. Also covered are the vibrations of molecules which cause the blue color in water and ice.

The effect on electronic energy levels of the ligand field leads to color in compounds of the transition elements as discussed in Part III. This explains the colors in most inorganic paint pigments and in many minerals and gems such as red ruby and green emerald, as well as fluorescence and crystal lasers.

Molecular orbitals are discussed in Part IV, and their interaction with light explains the colors in most organic substances such as vegetable, animal, and synthetic dyes and pigments, as well as some minerals and gemstones such as lapis lazuli (called ultramarine when used as a pigment), and blue sapphire.

The energy band formalism of Part V leads to the color of metals and alloys such as copper, gold, and brass, of some inorganic substances such as the red mercury ore cinnabar (called vermilion when used as a pigment), of some gems such as blue and yellow diamonds, as well as color centers in amethyst and smoky quartz; here there are also light emitting diodes and semiconductor lasers.

Geometrical and physical optics theory covers a wide range of colors including those of opal and the rainbow, the blue of the sky and the red of the sunset, the colors in an oil slick on water, and some insect colorations, covered in Part VI.

All in all, 15 causes of color are investigated. Some color-related topics, including pigments and dyes, bleaching and fading, colored glasses and gemstones, biological coloration, vision, fluorescence, phosphorescence, lasers, electroluminescence, art preservation, and the like, are discussed along the way and in Part VII.

A number of relevant topics are covered at a somewhat deeper technical level in the appendices, although these are not essential for an understanding of the text. They will give the reader a feel for the type of theory involved. Should the reader decide to pursue such subjects more deeply, it is hoped that the appendices will act as a bridge toward these at times quite arcane subjects. There are occasions, such as in Chapter 6, where the somewhat more technical material does not lend itself to segregation into an appendix. The reader will find that the continuity remains even if such material is merely skimmed.

Problems are given at the end of each chapter. The reader is encouraged to work through these, particularly those at the end of Chapter 1, to ensure that he has grasped the necessary fundamentals. There may not always be definitive answers to all of these questions; just as in everyday life, the unexpected can occur!

Recommendations for further reading are given in the Appendix G.

KURT NASSAU, Ph.D.

Bernardsville, New Jersey
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I am particularly indebted to my wife, Julia, not only for typing the manuscript—and not just once—but also for her enthusiastic support in this extended effort.

K.N.

Contents

PART VII. COLOR-RELATED TOPICS

Part I
Light and Color

Nature and Nature's law lay hid in night:
God said, **Let Newton be!** *and all was light;*
ALEXANDER POPE

It did not last: the Devil howling "Ho!
Let Einstein be!" restored the status quo.
SIR JOHN COLLINGS SQUIRE

1

Some Fundamentals: Color, Light, and Interactions

COLOR

The term *color* is properly used to describe at least three subtly different aspects of reality. First, it describes a property of an object, as in "*green* grass." Second, it describes a characteristic of light rays, as in "grass efficiently reflects *green light* while absorbing light of other colors more or less completely." And, third, it describes a class of sensations, as in "the brain's interpretation of the specific manner in which the eye perceives light selectively reflected from grass results in the *perception of green*." By careful wording one can always indicate which of these three meanings of "color" is intended in any given usage.

Sometimes the difference is critical: "black" as used for the color of the surface of an object has an exact meaning, namely, zero transparency and zero reflectivity; as the property of a light ray it has no meaning at all; in perception it can be viewed conveniently as being merely the total absence of sensation.

In actual practice this distinction among these three usages of "color" is not usually made, nor is any extended effort made here to do so except when the difference is critically important. The mere knowledge that these three different aspects exist enables one to identify the intended meaning and saves the use of many unnecessary words. At the same time, it may be noted that some philosophical discussions on the subject of color are almost totally meaningless just because of confusion among these three aspects.

Dean B. Judd, one of the pioneers of color science, felt that he could best define color with words having no more than four syllables as:

Color is that aspect of the appearance of objects and lights which depends upon the spectral composition of the radiant energy reaching the retina of the eye and upon its temporal and spatial distribution thereon.

EARLY VIEWS OF COLOR

Light and color are the stimulants of vision, one of our most important senses; accordingly, they have occupied the thinking of natural philosophers throughout history. The Greek philosopher, Plato (about 388 B.C.), held a rather pessimistic view on the possibility of a science of color:

There will be no difficulty in seeing how and by what mixtures the colors are made. . . . He, however, who should attempt to verify all this by experiment would forget the difference of the human and the divine nature. For God only has the knowledge and also the power which are able to combine many things into one and again resolve the one into many. But no man either is or ever will be able to accomplish either the one or the other operation.

The view of the Greek philosopher Aristotle (about 350 B.C.) came to dominate in the preexperimental stage. Aristotle did not distinguish color from light: "Whatever is visible is color and color is what lies upon what is in its own nature visible." He noted that sunlight always became darkened or less intense in its interaction with objects. Since such interaction often produced color, he viewed color as some type of mixture of black and white. His color scheme can be represented on a sphere as in Figure 1-1, all colors lying between white and black. He said, for example:

Thus pure light, such as that from the sun has no color, but is made colored by its degradation when interacting with objects having specific properties which then produce color.

This view held sway until Newton's discovery of the spectrum.

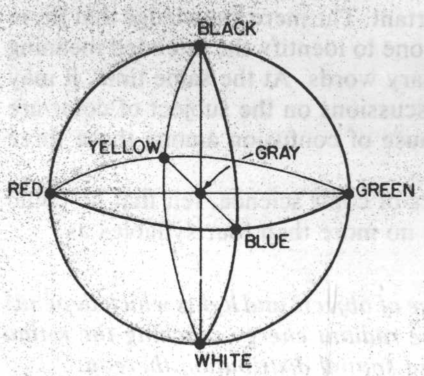

Figure 1-1. The color scheme of Aristotle.