COLORING OF PLASTICS

Fundamentals

Second Edition

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COLORING OF PLASTICS

Fundamentals
Second Edition

Edited by
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Cleveland, Ohio

WILEY-
INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Coloring of plastics / edited by Robert A. Charvat.– 2nd ed.
v. cm.
Includes index.
Contents: v. 1. Fundamentals
ISBN 0-471-13906-8 (v. 1 : acid-free paper)
1. Plastics—Coloring. I. Charvat, Robert A., 1930–
TP1170.C64 2003
668.4′1—dc21 2003005321

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

Contents

Preface

This publication represents the work of many people working in the color and appearance industry. Each one is regarded as most knowledgeable in the field they have covered in their chapters. Their contributions to the basic science of coloring plastics and other polymeric materials will serve industry for years to come.

Coloring of materials must start with an understanding of the basics of light, how light interacts with objects, and, finally, how humans react to and respond to the visible light reaching the eye and then interpreted by the brain. It should not be a surprise to anyone that no two people will see and interpret a colored object exactly the same. It is these variations and others that make the industry of coloring of plastics so interesting. The subjects in this publication have been designed to cover the most important technical and scientific issues involved in the coloring of plastic materials. This publication will be a valuable resource to those looking for information on the many aspects of plastics coloring.

This book covers our understanding of color as a science. It provides the foundation for many additional technological subjects. Measurement information along with matching, visually and instrumentally, will give the reader an understanding of the issues involved. Color specifications and a look at how statistical analysis can improve consistency, not only of colored polymer production runs but also of the colorants used to match the color, are addressed. The basic families of colorants are explained to give the reader an understanding of their properties. Basic information on the techniques usually employed to incorporate colorants into polymers as compounds or concentrates is presented. Environmental issues as well as issues of reuse of discarded materials are covered. An all-important issue, the potential interaction between colorants and other additives, is described to make the reader aware of potential problems with his or her projects. A diligent reader of this volume will come away with an enhanced appreciation of the technology, issues, potential problems, and considerations a colorist must consider if a plastics-coloring project is to succeed.

Volume 2 will cover polymers, by giving an overview of the major polymer issues. The differences between a commodity and an engineering (exotic) polymer will be discussed. The impact of these differences will influence the reader when evaluating a strategy for a coloring of plastic design. The other chapters in Volume 2 will describe the major polymer families. This description will cover such things as properties, advantages disadvantages, and typical markets and applications for the polymer families. This will be followed by general requirements for colorants in these polymers. Next, basic information will be given on methods normally used to incorporate colorants into these polymer. Special issues concerning the coloring of the polymers, including any particular problem or pitfalls that should be avoided are described. This should give the reader or researcher vital fundamental information that will help to avoid major upsets in a coloring project. An important additional piece of data given in each polymer chapter is a coloring matrix. This matrix lists the more important colorant chemical family types and their expected performance in the polymer under discussion. This fundamental information will supply information that will serve as a basic guideline to the reader, thus providing data which will help avoid a catastrophic failure involving the colorants used to color that specific polymer. This should be particularly useful to anyone approaching a coloring project using a polymer and/or colorants new to the reader. Basic attributes such as, but not limited to, colorant heat stability, physical properties, dispersability and any special issues connected to the colorant/polymer combination are covered.

Finally, one should not overlook the important issue that coatings and inks are polymers. It is quite possible the technical and process information contained here will also apply directly or indirectly to these associated polymeric materials. Therefore, this publication should have serious application capability to the coatings, ink and other related industries.

Robert A. Charvat

Acknowledgments

This publication is dedicated to the authors and the many hours they committed to their work on each chapter. At the personal level, I thank the authors for responding cordially to my many calls and reacting professionally to my frustrations in completing this work. Also, a special thanks to my wife, Nancy, for her valuable assistance with the mechanics of good writing.

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CHAPTER 1

Introduction

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The goal of this textbook is to expose the reader to the many aspects of coloring of plastics. To accomplish this objective, the technologist must understand colorants for what they are and what they are not. He or she must understand the performance of colorants not only during the processing and manufacturing steps but also during the life cycle of the final product. Today it is important to consider the issues of recycling the product after its useful life has come to an end. This publication will not make the reader a world-recognized expert. However, the color technologist will find useful information within these pages. The information will improve his or her capabilities, as the knowledge of many technical experts are contained here. This book should be a resource center, or a starting point, for anyone beginning a coloring of plastics project where they are proceeding into unfamiliar territory. This book should also provide support to the accomplished colorist who desires to fill in that one area or areas where his or her background is not as strong or complete as it might be.

The creation of this publication started with the Color and Appearance Division (CAD) of the Society of Plastics Engineers. In 1979, a small volume was published titled *Coloring of Plastics*. This volume, with numerous authors, was edited by Thomas G. Webber under the sponsorship of the Color and Appearance Division. This was the first publication dedicated totally to the coloring of plastic materials. Thomas Webber's book was the first and only volume truly focusing on the subject. This book was the primer for the coloring of plastics industry. However, many years later the book was hopelessly outdated. The need for such a volume now is as great,

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if not greater, than ever. The CAD Board of Directors has promoted the preparation of a new, comprehensive, and up-to-date book for some time. The CAD Board of Directors approved the development of a new *Coloring of Plastics* book. This publication hopes to meet the challenge presented by the CAD Board of Directors. The board also selected the Chairman of its Education Committee Robert A. Charvat as editor. This started the long road of the development of a new *Coloring of Plastics* book under the sponsorship of the CAD.

The organization of the new book needed to include a number of issues and subjects not covered or not known at the time of the Webber book. The technology of colorants is light years ahead of where it was those many years ago. The ability to measure color and colored materials has made significant advances. The ability of computers to match colors accurately and quickly is standard procedure today but was very difficult, if not impossible, years ago. Our understanding of how we see color is significantly better now than years ago. The number of polymers available today is tremendously larger than at the time of the *Coloring of Plastics* book by Webber. The ability of new polymers to perform in demanding applications requires colorants also have the ability to meet these same demanding requirements. Keeping up with the introduction of these new polymers and their new applications is a problem not faced years ago.

All the above is prolog to this publication. This new publication is divided into two major parts. Volume I deals with the many technology issues that impact the coloring of plastics today. Volume II will cover the major polymer families and deliver *basic* information on the coloring of those polymers.

Volume I covers our understanding of color as a science. It provides the foundation for the many additional technological subjects. Measurement information along with matching, visually and instrumentally, will give the reader an understanding of the issues involved. Color specifications and a look at how statistical analysis can improve the consistency not only of colored polymer production runs but also of the colorants used to match the color are addressed. The basic families of colorants are explained to give the reader an understanding of the properties of these families. Basic information on the techniques usually employed to incorporate colorants into polymers as compounds or concentrates is discussed. Environmental issues as well as reuse of discarded materials are covered. An all-important issue, the potential interaction between colorants and other additives, is described to make the reader aware of potential problems with his or her projects. A diligent reader of Volume I will come away with an enhanced appreciation of the technology, issues, potential problems, and considerations a colorist must take into account if the coloring of a plastics project is to succeed.

Volume II will consider polymers, by giving an overview of the major polymer issues. The differences between a commodity and an engineering (exotic) polymer will be discussed. The impact of these differences will influence the reader when evaluating a strategy for the coloring of a plastic design. Volume II also describes the major polymer families. This description will cover such things as properties, advantages, disadvantages, and typical markets and applications for these polymer families. This followed by general requirements for colorants in these polymers. Basic information will be given on methods normally used to incorporate colorants into the polymers under discussion. Special issues concerning the coloring of polymers, including any particular problems or pitfalls that should be avoided, are described. This should give the reader or researcher vital information that will help to avoid major upsets in a coloring project. Each polymer chapter has a coloring matrix, which lists the more important colorant chemical family types and their expected performance in the polymer under discussion. This will supply information that will serve as a basic guideline to the reader, providing data that may help avoid a catastrophic failure involving the colorants used to color a specific polymer. This should be particularly useful in a coloring project using a polymer and/or colorant new to the reader. Basic attributes such as, but not limited to, colorant heat stability, physical properties, dispersability, and any special issues connected to the colorant/polymer combination are covered.

Finally, it is important to note that coatings and inks are polymers. The technical and process information contained here may also apply directly or indirectly to these polymeric materials. Therefore, this publication should have serious application capability to the coating, ink, and related industries.

CHAPTER 2

Color as a Science

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2.1. INTRODUCTION

In our everyday life we are surrounded by the sights and sounds of our world. For the most part we take for granted the complexity of these sights and sounds and how our lives are impacted by our surroundings, that is, until we decide to take music lessons of some sort or we try to match the paint we bought three years ago to paint our family room. Then these complexities take on a new reality for us. For those of us in industry who have to deal with color problems every day, it is extremely frustrating how much the "science of coloring plastics" is trivialized. The result of this trivialization is often a crises situation where "color" was considered a nonissue until parts are rejected for color: "They don't look the same as they did in my office" or "All we did was change to a different polymer. That should not impact the color, should it?" or "You mean it makes a difference if I use the 2° observer instead of the 10° observer in my color difference calculations?" We could list hundreds of quotes to make our point, but it is not our intent to "preach" to the reader. We only wish to establish that the coloring of plastics is an elaborate, multivariable puzzle that requires a sound scientific approach and a clear understanding of all the components that make up this intricate world of color. It is the intent of this chapter to establish for the reader an accurate perception of the complexity of color science as well as a means to deal with this science in a logical manner. We will do this by helping the reader to gain a clear understanding of the variables associated with color science and how they interact. It is not the intent to re-create a text in detail

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of the science of color, for there are already several good books on the subject and we will reference these as we go along. Now, let us begin to explore this complex world of coloring plastic materials.

2.2. THE TRIAD

As we see color from strictly a physiological point of view we must consider a special "triad." This triad consists of a source of energy (the *light source*), an object that is illuminated by the energy (the *object*), and a detector (the *Observer*). The observer could be a human observer or alternatively a photosensitive detector attached to a computer. In the case of the human observer the eye is the detector, with the brain as the perceiver of the information sent to it from the eye. This combination of the eye and the brain creates the unique situation of *interpretation* of the physical information. This means that color exists in the mind of the viewer. This adds another dimension to color, the psychological dimension. We will cover this in more detail in another section. It is key to remember as we go through the discussion of the physical aspects of color that this human interpretative quality is, for us, the most important aspect. This triad is in a constant state of interaction. When it comes to the physical color stimulus, the three components of the triad do not act independent of each other. This means that as one progresses through this chapter, you keep in mind this constant interaction between the light source, the object, and the observer.

2.3. THE LIGHT SOURCE

Even though its the same color, it looks different. Why? Many conditions affect the way color appears. One of these is the light source. For instance, an apple may appear a bright delicious red under the sunlight at the farmer's market, but somehow does not look as good under the fluorescent lights at home. Except in rare situations, we do not see color without light. Furthermore, the light we see depends upon the characteristics of the light source under which an object is seen.

The light source is that which illuminates the object we are viewing. This light source emits energy in the electromagnetic spectrum. Light is the segment of electromagnetic radiation that also includes X rays, ultraviolet and infrared radiation, radio and TV waves, and cosmic radiation. The human eye can respond to electromagnetic radiation between 380 and 780 nm as light (colorimeter range is 400–700 nm). The part of this continuum that we are interested in is known as the visible spectrum. This is the portion of the electromagnetic to which our eyes respond. The visible spectrum, like all other portions of the entire spectrum, are divided into small segments that are described either by their frequency (cycles per second) or by the wavelength of one cycle. For the visible portion of the spectrum wavelength is most used. These wavelengths are expressed in units called nanometers ($1\,nm = 10^{-9}\,m$). Light with a short wavelength appears blue or violet. As the wavelength increases, the color appears to change through green, yellow, orange, and red. Radiation combining all the wavelengths of the visible spectrum in about equal amounts is

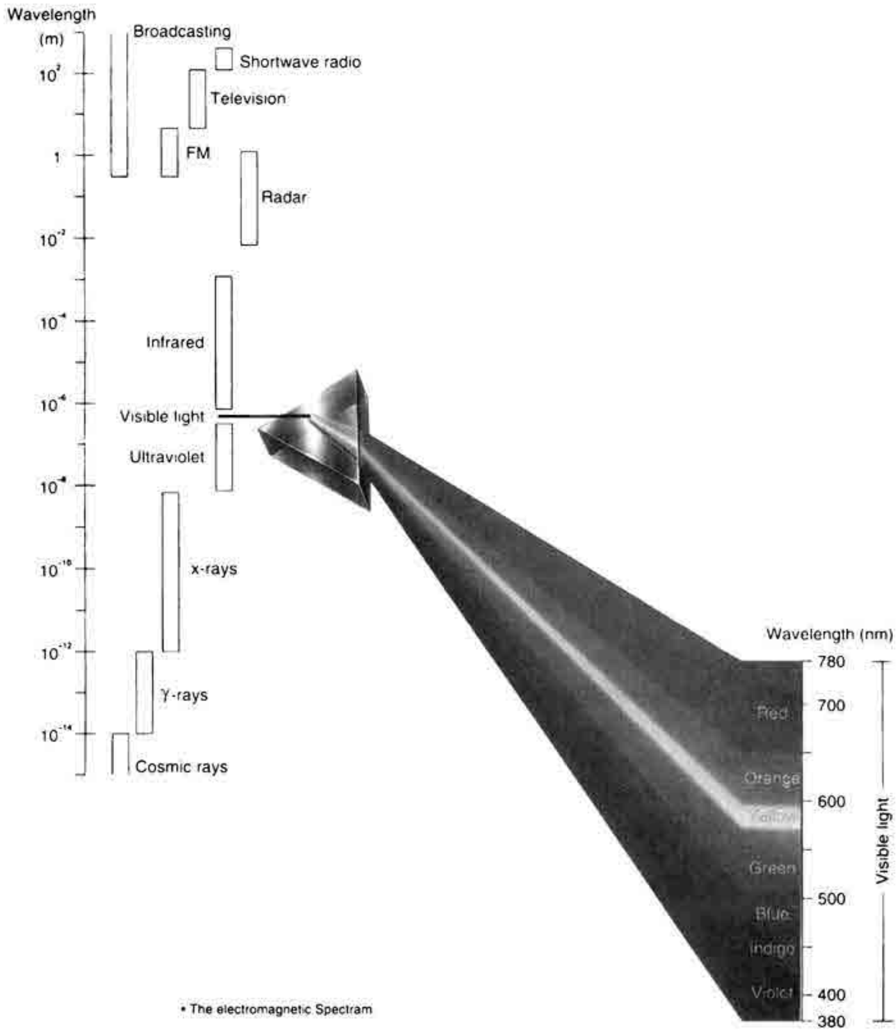

Figure 2.1. The electromagnetic spectrum and the portion that we see as visible light (Minolta, 1993).

perceived as white. This is best described with an illustration (see Fig. 2.1) (Minolta, 1993).

Radiant energy also affects the perception of color. More important to the perception of color than the radiant energy is the spectral distribution of the radiation from the light source. Everyone has experienced a colored object looking different in the sunlight, under cloudy skies, under fluorescent light, or under normal electric light bulbs. It is therefore essential to select a light source before defining color tolerances, whether these are for use in visual assessment or in colorimetry. Even northern light varies greatly depending on the time of day or season for reproducible result to be obtained, so as a general rule, an artificial light source is used.

Light sources can be described by their spectral power or energy distribution. This simply plots the amount of light (relative power) as a function of wavelength. Figures 2.1–2.5 are examples of standard light sources (Billmeyer and Saltzman, 1981).

For artificial light sources, two values are important: the color temperature in degrees Kelvin and the relative spectral distribution of the light source $S(\lambda)$, where λ shows that the radiant energy is dependent on wavelength.

2.3.1. Blackbodies

An important group of light sources are called *blackbodies*. We will not take the time here to discuss in detail the science of these sources, because they are well described in other texts (e.g., Billmeyer and Saltzman, 1981; Judd, 1964). The color temperature of a lamp is based on the radiation emitted by a blackbody. The important point to note here is that these sources are based on absolute temperature in degrees Kelvin (K = degrees Celsius + 273) of standard blackbodies such as tungsten-filaments. Thus, a 6500 K (D65) source is a blackbody heated to 6500 K. Figure 2.2 shows two such sources. The main principle to gain from this section on the light source is; each source has its own unique spectral power distribution and therefore will interact with the other two components of the triad according to this uniqueness. In other words, an object illuminated with a 6500 K source will appear different from the same object illuminated with a 2854 K source.

The total amount of energy from the source is also an important factor in the perception of color. If the energy is too low, we are not able to see the full color results. If the energy is too high, we are "blinded by the light." The ASTM standard D 1729–89 addresses the issue of level of illumination under section 5.1.2, Photometric Conditions; this is an excellent practice to adopt for color laboratories as it focuses on the visual evaluation of color in a controlled environment (ASTM D 1979–89).

The CIE (Commission Internationale de l'Eclairage) has selected a number of light sources from the wide range available with different spectral distribution and color temperature. The use of these standard illuminants is recommended and those used most commonly are listed here:

- Standard illuminant D65 (6500 K) represents average daylight.
- Standard illuminant A (2856 K) represents evening lighting in rooms (e.g., normal light bulb).
- Illuminant F2 (4230 K) refers to a cool white fluorescent (CWF) lamp.
- Illuminant F11 (4000 K) refers to a triple-band lamp (TL).

D65 is considered to be a better representation of natural daylight than illuminant C, which has a lower proportion of ultraviolet (UV) radiation than D65 (Huff, 1994).

Color assessment should be carried out using the illuminants specified and in a color assessment booth, such as is available from a number of manufacturers. The booth is usually equipped with at least three lamps to produce the various illuminants. A UV lamp is normally included as well. The inside of the color booth is painted neutral gray in order to prevent inaccuracies produced by reflection from the walls. *External light must be blocked out.*

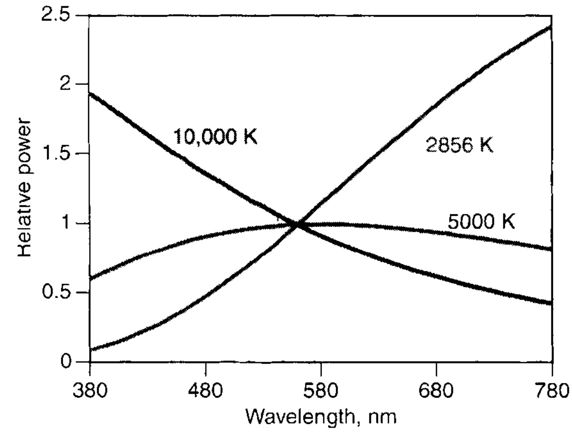

Figure 2.2. Spectral power distribution of blackbodies with color temperatures of 2854 K (source A) and 6500 K (Pivovonski, 1963; Billmeyer and Saltzman, 1981).

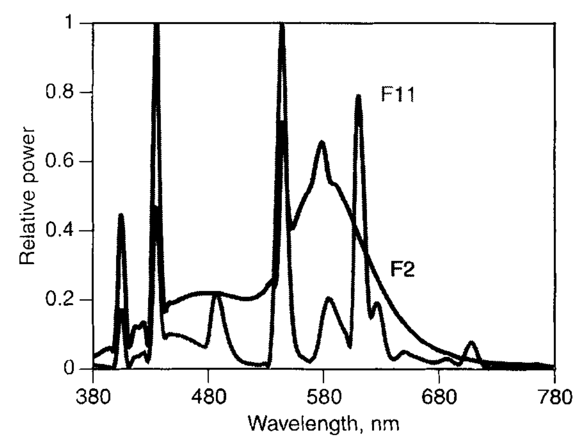

Figure 2.3. Spectral power distribution of cool white fluorescent lamp (IES, 1981; Billmeyer and Saltzman, 1981).

The objects that we often consider sources of light (the sun, light bulbs of many types, etc.) are seen by our eyes as white or almost white. Through a series of experiments using a prism, Newton discovered that this white light actually consists of all of the visible wavelengths described above (Newton, 1730). This is true when the source is said to be polychromatic, meaning it contains all wavelengths of light from 400 to 700 nm. It is important to note that some sources that "appear" to be white may not contain all of the wavelengths of the visible spectrum. Some of the mixed halide lamps such as sodium and mercury are such sources. These present problems when viewing objects because they are not polychromatic. Later in the chapter we will discuss why this is true.

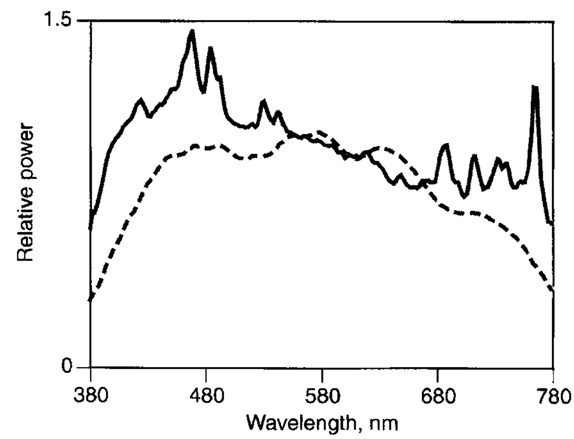

Figure 2.4. Spectral power distribution of a typical line source, a mercury arc lamp (IES, 1981; Billmeyer and Saltzman, 1981).

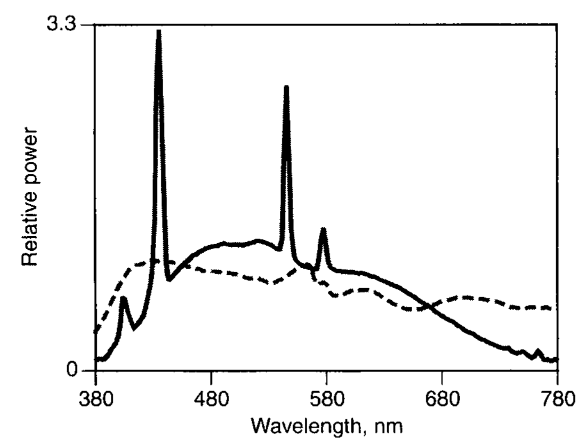

Figure 2.5. Spectral power distribution for some standard light sources used in describing color (Wyszecki, 1967, 1970; Billmeyer and Saltzman, 1981).

2.4. THE OBJECT

The object is the second part of our triad. Here we will discuss how materials interact with the energy from the light source. In this book we consider objects made of polymeric materials. Generally, polymers are colorless or at best weakly colored, and the aim always seems to be to "cover up" the undesirable color of the polymer in favor of the more desirable color selected by the designers. This requires the addition of colorants (pigments and dyes) to the polymer. The subject of colorants will be covered in depth in another chapter. However, because colorants become part of the object, we will first discuss some aspects of how they interact with light.

2.4.1. Refractive Index and Transmission

Looking at the model in Figure 2.3, note that the first few micrometers of the surface of our object is polymer rich. This fact becomes very important as we consider how our object interacts with light at the surface of the model. When energy strikes our model, one or more things occur. First the energy can be *transmitted* through the object. The energy passes through the object and is essentially unchanged; however, a small amount (about 4% for refractive indices of 1.5) is scattered at the surface of the object (Fig. 2.4). This scattering is due to a property of the material referred to as the *refractive index*. This property is why we must consider what happens at the surface of our model. Two materials (two different polymers) having different refractive indices will scatter light differently. This means that the two materials would have different appearances even though they could be colored with exactly the same colorants. Because scattering at the surface is wavelength dependent, which is why a prism can break white light into its components (Newton, 1730), if our two materials above are viewed at different angles, their appearance will change in relationship to the angle at which they are viewed. This is often called "flop." This property has a pronounced effect on both visual and instrumental color assessment, especially in darker, more chromatic colors. This subject is covered in detail by Donald and Mathew (SPE, 1989), who give a detailed discussion of the impact of the refractive index on color measurement. The important principle to remember here is that the refractive index is a property of the material (polymer) and light will interact at the surface differently if we have two different materials possessing different refractive indices.

2.4.2. Absorption

The second way a material can interact with light is by *absorption*—the conversion of visible light to longer wavelengths (heat) or the energy of the visible light being used in a photochemical process called polymer or colorant degradation. If the material absorbs only part of the light, it will appear colored. For example, if the object absorbs all but the green portion of visible light, the object will appear green. This of course assumes the light source is polychromatic and contains the green portion of the spectrum. If the light source would happen not to contain this green portion of the spectrum, then our object would appear to be black or gray. This is why it is important to understand the makeup (spectral energy distribution) of the light source. If the object absorbs all of the visible spectrum of a polychromatic source, then the object will appear black.

There are two fundamental laws to consider when we discuss absorption: Beer's law and Lambert's law. Lambert's law states that equal thickness of materials cause equal amounts of absorption. Beer's law states that equal amounts of absorbing material cause equal absorption. Figure 2.5 illustrates these laws (Billmeyer and Saltzman, 1981). Both laws will only work in the absence of scattering and are not applicable in opaque or translucent materials. They are very useful in transparent materials, where the scattering due to the colorants and the polymers themselves (low refractive indices) is very low.

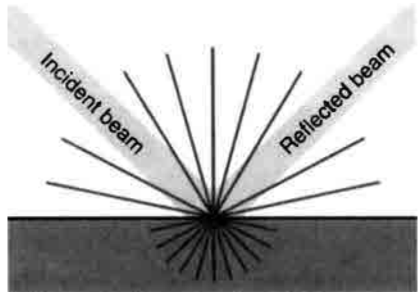

Figure 2.6. Illustration of relationship between the particle of a material and its scattering ability Billmeyer and Saltzman, 1981).

2.4.3. Scattering

The last and most complicated interaction that our object has with light is *scattering*. For the most part scattering in plastic materials is caused by the inclusion of particulate matter into the plastic. This particulate matter we call pigments and fillers. Pigments, like all other forms of matter, have the properties of refractive index, transmission, absorption, and scattering. When we put pigments into a plastic material of a given refractive index, we are introducing materials of a different refractive index, different absorption, and different scattering (see Fig. 2.3). This means the color of our object depends on the accumulative amount and kind of scattering and absorption that take place. If there is little to no absorption and about equal amounts of scattering at all the visible wavelengths, then the object appears white. If some of the visible light is absorbed by the pigment, then the object appears colored. The scattering in these cases is caused by light falling on pigment particles that have different refractive indices than the surrounding plastic medium (see Fig. 2.6) (Billmeyer and Saltzman, 1981). The amount of light scattered depends on two factors: the difference between the two refractive indices and the particle size of the pigment. The relationship between scattering and these two properties is illustrated in Figures 2.6 and 2.7 (Billmeyer and Saltzman, 1981). It is important to note that these two properties will act independently of each other. For example, the same pigment (same refractive index) with a different particle size will scatter light differently. This means that if scattering properties (particle size) vary from lot to lot of pigment, then the inclusion of that pigment into a plastic medium will also appear different. This is only one of the issues associated with pigment that have an impact on the appearance of an object. Another aspect of pigments that needs to be noted is that they all do not "produce" color by the same physical mechanism. Nassau, in his book *The Physics and Chemistry of Color*, discusses the 15 causes of color. Not all of them pertain to pigments, but a number do. For example, some pigments (e.g., zinc oxide, cadmium yellow, and cadmium orange) produce color because they are semiconductors. When they are illuminated with an energy source (light), electrons move from the valence band to the conducting band through the band gap. Depend-

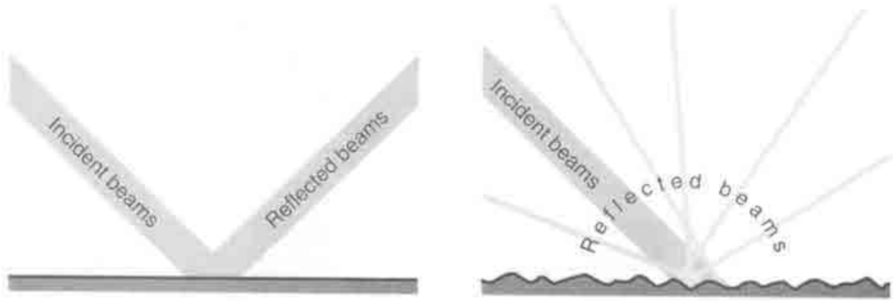

Figure 2.7. Illustration of relationship between two materials and their refractive indexes (Billmeyer and Saltzman, 1981).

ing on the width of this gap, some of the visible light will be absorbed while the rest is reflected back. Cadmium yellow has a band gap of 2.6 eV (electron volts). This gap absorbs energy in the violet and blue part of the spectrum, leaving all others, which leads to its yellow color. Reduce the band gap slightly to 2.3 eV and it absorbs violet, blue, and green, leaving the characteristic color of cadmium orange. The color produced in other pigments will be caused by other methods, such as transition metal compounds or transitions between molecular orbitals of organic compounds (Nassau, 1983). The point is that because these materials interact with light in different ways, the object, depending on its make up, will have a very complex relationship with the light source.

All of the above relationships create a situation where the assessment and control of colored plastic materials are not trivial issues. Just like trying to figure out your phone bill, sorting out problems associated with just the object itself can be quite a task. A check list of questions is provided at the end of this chapter that we hope will be helpful in working through some of these complex issues. The main principle to take from this section on the object is that objects interact with light from the source in multiple ways and the refractive index of the polymer contributes to this interaction.

2.5. THE OBSERVER OR DETECTOR

We will discuss two types of observers: the human observer and the instrumental observer. In visual assessment the observer is the human eye, and in colorimetry it is the instrument receiver. Because the human observer is much more complex, we will start there.

2.5.1. Human Observer: Physiological Response

Given the importance of color, it is amazing how little we understand its nuances or appreciate its power. What is color, anyway? Against all intuition, it turns out to be not a quality of objects but rather an attribute of our brains. Color is a paradox. It exists in light, which to the human eye seems colorless. It does not exist in a rainbow, apple, grass, or paint, which appear colored. Few objects possess inherent color or pigment. Color is seen when light waves reflected off an object meet the eye. An object appears colored because it absorbs some wavelengths and reflects back others. Think of a green leaf. When light hits it, only green rays are reflected from its surface. All other rays are absorbed by the leaf. We classify it as "green" when in reality it is every color but green.

Human vision has laws that may vary from person to person. The laws of physics play a part in our perception of color, but they only provide the starting point for a process that is influenced by the physiology of the eye and the psychology of humans. In broad terms, the physiology of the visual system has been understood for a long time. Only recently however, has progress been made in identifying the substance in the eye that is specifically responsible for sensitivity to see one of the three primary colors: red, green, or blue. Jeremy Nathans of Stanford University identified three genes that enable the eye to see color. The genes direct cells in the retina of the eye to produce three pigments, each sensitive to one of the three primary colors. The existence of pigments had been previously deduced but never before demonstrated.

In humans, light from the sample passes through the pupil of the eye and through the lens to be projected with variable focal lengths on the retina, where, in the case of the normal observer, it is brought into focus. This is similar to a picture that is thrown upon a film by a camera. In the retina at the back of the eye there are two types of photosensitive receptors: rods and cones. The rods, named because of their shape, are responsible for colorless vision in conditions of dim illumination; the cones, operating at higher light levels, are responsible for color perception. Visual acuity is greatest in the fovea, where the density of the receptors is greatest.

The first stage in the transformation of light into neural impulse is a photochemical process that involves the breakdown of various visual pigments that are later resynthesized. One such pigment is rhodopsin, the photochemical substance contained in the rods. This process initiates the electrical message of the rods to be conveyed to the brain. The cones, the color receptors, are further specialized into three types: blue, green, and red. Each type has a different pigment making it sensitive to a different color of light. Their combined power is such that a person with normal vision can distinguish millions of hues, shades, and variations of color. Only when the light and color signals from the eye reach the brain do we "see" color (Fig. 2.8) (Billmeyer and Saltzman, 1981).

2.5.2. Human Observer: Psychological Response

Color is essential to full enjoyment of the world. How we learn to classify and label colors is based largely on our culture. Because colors are not really "out there" but are constructed in our retinas and brains, it stands to reason that culture and psychology play a great role in our perceptions of color. People are drawn to color from an emotional standpoint. Color preferences are rooted in associations arising from our culture, how we were raised, our feelings about ourselves, and what we were taught.

The different wavelengths of light affect our brains differently as well, triggering specific responses in our bodies. For example, the longer wavelengths of red light "excite" the brain and stimulate the heart and nervous system. Colors we wear affect

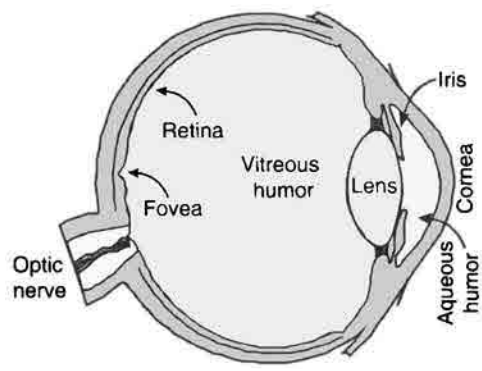

Figure 2.8. Cross section of the human eye (Burnham, 1963; Billmeyer and Saltzman, 1981).

our bodies, our minds, our moods. Bright, clear colors help us feel more joyous and light hearted and can actually counteract depression. Blacks, dark grays, and browns and dull, muddy colors tend to depress us, while the green tones are healing.

Studies have been done to determine the effects of colors on humans. For example, when preschool children in New Zealand were placed in a pink room, their physical strength and positive mood increased; the reverse was true of children placed in blue rooms. Blue light, with its shorter wavelengths, tends to "calm" the brain. Green rooms where actors wait before a performance are painted that color because green has a restful effect without the sometimes depressing effect of blue.

Color selections almost always send symbolic messages. Bright, clear colors are positive in nature and action, pure and clear, untainted by ulterior motives. Pastels show immaturity or weakness in the area signified by the color. Dark or muddy colors reveal the negative qualities of doubt, fear, hate, anger, greed, and so on. Wearing these colors will intensify these feelings. Extremely vivid implies an impending lucid state. Colors are indicative of our emotions, each hue having a different meaning taken from the actual observation of clairvoyants who long ago noted the correspondence between certain feelings and the resultant colors visible in the aura.

It is interesting to study some of the meanings related to colors. For example, black denotes the unknown, the mysterious, darkness, death, mourning, hate, or malice, especially when associated with fear or uncertainty. However, in dreams, if the feeling associated with black is joy or happiness, it is thought to imply unmanifested spiritual gifts or qualities. Blue is thought to represent awakened spiritual forces, one who has found his or her life work, also considered the color of honest intentions and mild passions. Brown is earthy or worldly, physically oriented, practical, and materialistic. Tan is associated with purity and noble ideals tinged with doubt, depression, and earthly reason ("I'm only human" or "I must be realistic"). Green is often associated with vigorous growth, renewal and immortality, or youth's inexperience. It is associated with both healing and sickness. Yellow symbolizes hope and a bright future, associated with enlightenment and wisdom. Red is a particularly strong color that commands attention. It is the symbol of activity and power, energy, warmth, talent, and courage. On the negative side it conjures up violence, passion, and anxiety. Purple is a mystical and religious color. Purple partakes of both the integrity of blue and the power of red. Today associations to purple are mainly between faith and spirituality and dreams or superstition. White is purity, the non-color of light. It is associated with innocence. On the other hand, it is also seen as the white flag of surrender or whitewashing or covering up. These have even filtered into our language in expressions such as "green with envy," "seeing red," "having the blues," and so on.

Color is used widely in business and advertising. Advertising provides the best examples of the use of color in its various functions: to attract attention, as a vehicle for encoding information, and as a rich source of symbolism and evocation. Color, working on a subliminal level, is frequently the first thing perceived in an advertisement and can, in a fraction of a second, establish the content of the image and suggest a range of values to the customer.

Color can even prove beneficial for your health. Doctors have long made use of the healing power of light by manipulating wavelengths outside the visible spectrum. X rays, lasers, and radiation treatments have been a standard part of medical practice for years. Some believe that just as lasers can use the power of invisible light to cut through diseased tissue, visible light can be used to alleviate a variety of ailments through its effects on the central nervous system. In ancient times multi-chamber temples of color were used for physical and spiritual rejuvenation. Today color therapists have adapted ancient Hindu belief that the body's internal balance is maintained through seven chakras, or energy centers, which respond to different frequencies of light that we experience as colors.

2.5.3. Human Observer: Color Deficiencies and Color Blindness

About 8% of males and less than 1% of females are born with defective color vision. As was discussed earlier, a person with normal color vision—the trichromat—has three kinds of color-sensitive cones: red-, green-, and blue-sensitive cones. Dichromatism is when only two colors are perceptible and one color is difficult to recognize.

Color blind is a loose term because it implies a complete lack of ability to see color, and total color blindness is rare. Because color deficiencies do occur within the population, it is important to know this for individuals who are matching or evaluating color. The Farnsworth–Munsell 100-hue test is an excellent tool for both color discrimination and analysis of color vision defects. Because the observer is a significant variable in the color equation, it is important to understand their color vision capabilities.

2.5.4. Instrumental Observer

After looking at the complexity of the human observer, the instrumental observer may seem simple in comparison. Colorimetry is an attempt to express numerically that which is seen by the human eye. Today there is virtually no industry in which color does not play a major role and in which a colorimetric system is not used. One of the difficult problems we face today in the plastics industry can be attributed to this fact. This attempt to mimic the human interpretation of color via numeric values as seen through the eyes of a mechanical device is asking for a lot. Most, if not all, the spectrophotometers today do a commendable job of analyzing how objects interact with light. They describe this interaction through the result of a spectral reflectance or transmission curver. However, to our brains this is only a line on a chart and has little to do with color as we see it. A spectral curve cannot describe the beauty of a pink rose or the mystery of deep brown eyes. These are qualities left only to our brain. As we described above, real color exists in the mind of the human observer. Even with all of this in mind, humans appear to have a need to apply a quantity to everything, and so we use the spectrophotometer. Spectrophotometry will be dealt with in detail in another chapter of this book. Here, we want to point out that the difference between the instrumental observer and the human observer is significant.

Nonetheless, plastics manufacturers frequently employ colorimetric techniques for calculating and correcting color formulations and for quality control. Plastics processors and industrial end users are mainly interested in the application of this science in quality assurance. The advantages of colorimetry are obvious. Time is saved in formulating new colors, and there is less need for recoloring work during production. Also, it provides the basis for statistical quality control and for objective discussion between supplier and customer. Unless one considers the previous paragraph, the disadvantages of colorimetry are not so evident at first glance. They include measurements that do not correspond to or even appear to contradict the visually perceived color and the variation of measurements obtained by supplier and customer.

Even today, despite enormous progress made in recent years, the numerical expression of a sensory perception is still subject to certain preconditions, not least because the standard colorimetric systems in use still have faults and limitations. Unfortunately, many manufacturers of colorimeters contribute to the uncertainty with impressive software and by claiming a degree of accuracy to so many decimal places that simply is not possible. Users often trust blindly in the manufacturer's claims, although any number of good books are available that describe the problems of colorimetry.

The lack of correlation of the current mathematical models of converting spectrophometric data to visual sensory perception is a very big contributor to the problems of colorimetry. As we will see later, a number of factors contribute to this correlation problem, the major one being that humans do not see uniformly over the entire visible spectrum. This necessarily means that our model must accommodate this nonuniform behavior, which turns out to be a difficult mathematical problem.

2.6. DESCRIPTION OF COLOR AS A LANGUAGE

Like any foreign language, color has its own terms and definitions. When colors are classified, they can be expressed in terms of their hue (color), brightness (lightness), and intensity (saturation or chroma). Hue is used in the world of color for the classification of pure color, like red, green, blue, or yellow. Brightness refers to how light or dark a color is. Intensity is seen in terms of saturation: vividness or dullness. Each can be measured independently of the others. Figure 2.9 and illustrates how these