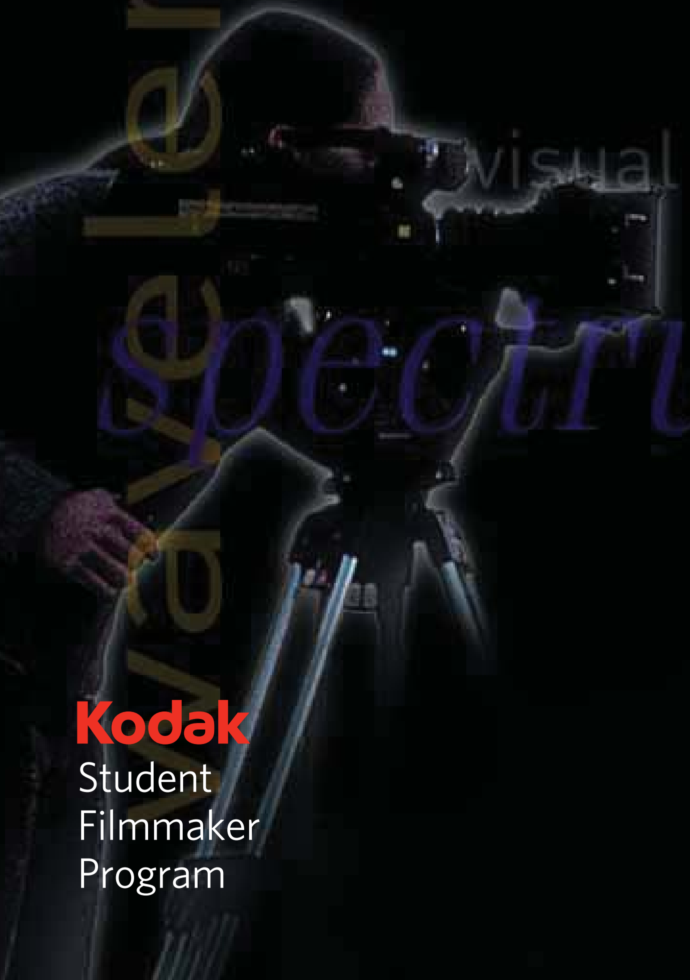
EXPLORING THE
COLOR IMAGE



Kodak
Student
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Kodak

Exploring The Color Image

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Exploring The Color Image

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This book is a derivative of *Color As Seen and Photographed* (E-74), published by Eastman Kodak Company in 1950 and later revised in 1972. Some content has also been taken from *An Introduction to Color* (H-12) and *EASTMAN Professional Motion Picture Films* (H-1), both published by Kodak in 1996 and 1994, respectively.

Other material added to the original text (page 44, 48 and 49 within the dotted lines) was written by Woody Omens, ASC.

The *Kodak* Worldwide Student Program
of the
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Gratefully Acknowledges The Contributions
of
Woody Omens, ASC
Dr. Rod Ryan
Bruce A. Block

"Without your love of the color image and your dedicated work this publication would not have been possible. On behalf of Eastman Kodak Company, we thank you."

"The future generations of filmmakers who read this publication and learn from it will all benefit from your contributions. Your work will help shape the future of The Color Image."

E. G. Rodli

Eric G. Rodli
Eastman Kodak Company

If You Love Color, Read This

The book *Color As Seen and Photographed* has been a Kodak classic for more than 45 years. It has been a little gem of a resource. Its greatness resulted from its simplicity. And its simplicity was directly traceable to one man, Ralph Evans. In his lectures and writing, he took complex color ideas and made them understandable to everyone. The book was truly distinguished even among the heavyweight texts on the subject.

So, after years of being out of print, it was my dream to have *Color As Seen and Photographed* come back in a new edition. As we began to revise it, we realized that it would be wiser to let the classic be.

What you are about to read is not a revised edition. It is rather a selection of highlights from the original presented here with updates and clarifications to fit better into new technological times. But even here, in this modified form, it is still the quintessential Evans.

Of course, I never planned to be on the team which was to create this publication. But when Jim MacKay asked me to work on it, I could not refuse. As a cinematographer, I can say with conviction that what you are about to read will change how you see color, think about color, and use color in any creative work. The most advanced technologies cannot outdistance the principles laid down here. These are important principles of physics and perception.

Color is a sensation we experience. It may be pure information and it can generate emotion. It is language. It is a form of communication. It means so many things to so many people. It is red, white, and blue patriotism to Americans and to the French. It is the lifesaving red or green, stop/go of a traffic light. It is a complementary color mood of night: cool blue night air contrasted with warm red-orange campfire. It is the desaturated color of mental depression in the film *The Red Desert* or the garish saturated color in the film *Dick Tracy*.

After reading these pages, you will never take color for granted again. How we are able to detect it, how it works physically, and how perception of color is sometimes deceiving is to be found here in simplified terms. Perhaps this will encourage you to read more on color; but most of all, we hope you will explore and test color ideas yourself. It is even thought that color has healing properties. What do you think?

Every still you shoot, every film or video you make, every painting you create, every computer graphic image you invent are each playgrounds for exploring color. But you will not take color for granted again. Considering that it is so small a part of the electromagnetic spectrum, it is a miracle that we have the precise sensors in the retina to recognize such a microspectrum.

Color is a source for infinite invention. How you use it is your choice.

I wish to thank Dr. Rod Ryan and Bruce A. Block for working with me to make this publication possible. Rod is a former Kodak engineer and guru on the subject of color. Bruce is a film producer and adjunct professor at the University of Southern California School of Cinema-Television.

Eastman Kodak Company and James F. MacKay are to be congratulated for having heard my prayer and for deciding to publish this document as a gift to educators and students working in the vast array of imaging arts.

Woody Omens

Woody Omens, ASC

CONTENTS

INTRODUCTION

This publication is intended more as a connected discourse than as a reference work containing practical "how-to-do-it" information. It is a brief discussion of the tremendously complex subject of color from a single point of view, that of the photographer or cinematographer. The reader who wishes a more comprehensive treatment of the many other aspects of color is urged to consult AN INTRODUCTION TO COLOR, by Ralph M. Evans, John Wiley & Sons, Inc., New York, NY, 1948. Another book by the same author, EYE, FILM, AND CAMERA IN COLOR PHOTOGRAPHY Wiley, 1959, is an excellent guide to color photography as a creative medium.

Information on the history of color photography has been deliberately omitted from this edition. Instead, the space has been devoted to a more complete discussion of the principles underlying the practice of certain current processes which have proved in actual use to lie within commercial limits of skill, time, and expense. Other processes, including many which have failed to survive the test of time, are described in the following books:

PRINCIPLES OF COLOR PHOTOGRAPHY, *Ralph M. Evans, W. T. Hanson, Jr., and W. Lyle Brewer, John Wiley & Sons, Inc., New York, NY, 1953 (Now out of print, but available in libraries for reference and sold in photocopy form by University Microfilms, Inc., Ann Arbor, MI 48107)*

PHOTOGRAPHY, ITS MATERIALS AND PROCESSES, *C.B. Neblette and Collaborators, Litton Educational Publishing, 1977 (The chapters on color photography, by Howard C. Colton, include brief descriptions of some of the historically important processes.)*

HISTORY OF COLOR PHOTOGRAPHY, *Joseph S. Friedman, 1944; Focal Library reissue, Amphoto, New York, NY, 1968*

THE HISTORY OF THREE-COLOR PHOTOGRAPHY, *E. J. Wall, 1925; Focal Library reissue, Amphoto, New York, NY, 1970*

LIGHT and COLOR

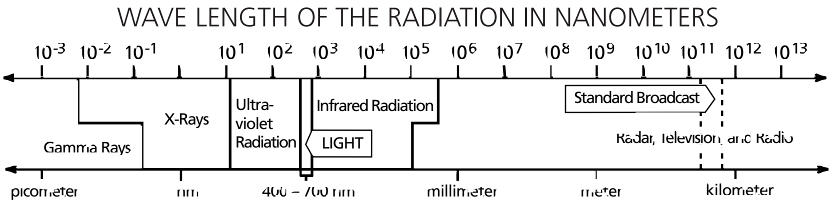
To understand any process of color photography, we must have a definite idea of what is meant by "color". And since color depends first of all on light, it is well to start by examining the nature of light itself.

NATURE OF LIGHT

Light is one of a number of known forms of radiant energy which travel with wave motions. (The wave theory does not provide a complete explanation of the behavior of light, but it is the only theory that needs to be considered here.) These forms of energy travel at the same tremendous speed, about 186,000 miles per second in air, but they differ in wave length and frequency. Wave length is the distance from the crest of one wave to the crest of the next, while frequency is the number of waves passing a given point in 1 second. The product of the two is the speed of travel.

The speed of the various forms of radiant energy is constant for any given medium, but varies with other media. For example, the speed of light in ordinary glass is only about two-thirds of its speed in air. Knowing that the speed of light in glass is lower, we can easily see that the wave length must be shorter or the frequency must be lower, or both. Actually, it is only the wave length that changes; the frequency remains constant. However, frequency is much more difficult to measure than wave length, which can be determined with great accuracy. Hence we customarily identify a particular type of radiation by its wave length, bearing in mind that we are speaking of the wave length in air.

The various forms of radiant energy form a continuous series of wave lengths, each differing from its neighbors by an infinitesimal amount. This series, known as the electromagnetic or energy spectrum, includes the main (and somewhat arbitrary) divisions shown in diagram form below. At one end are the extremely short waves of gamma rays, emitted by certain radioactive materials, and at the other end are the waves of radio, the longest of which are miles in length.



THE ELECTROMAGNETIC SPECTRUM

Toward the center of the electromagnetic spectrum are the waves of light, which range from 400 nanometers (billionths of a meter) to 700 nanometers in length. These two wave lengths are not the actual limits of visible radiation, but since the eye is relatively insensitive at either extreme, they can be considered as the practical limits.

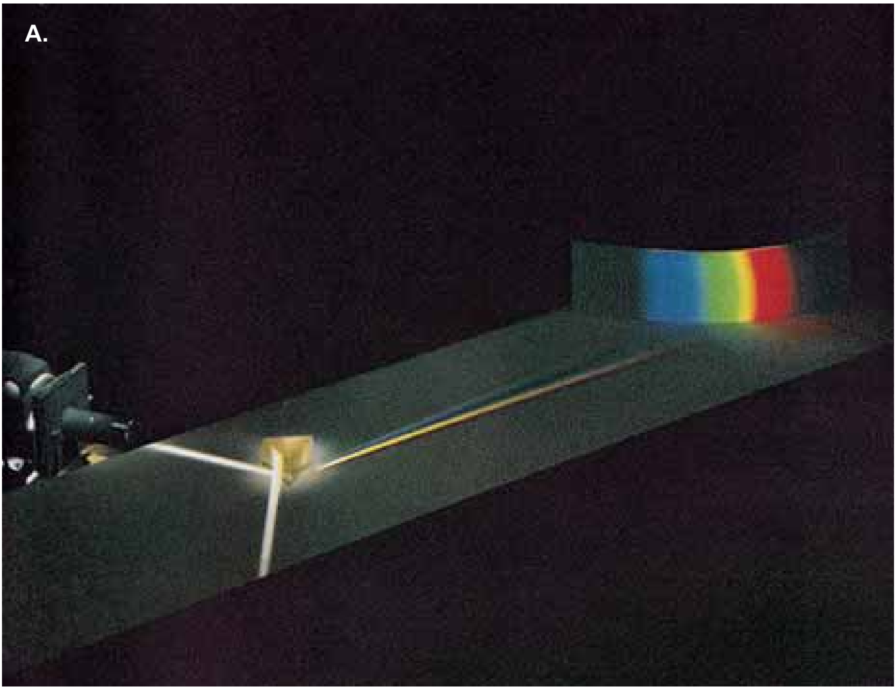
Below 400 nanometers are the ultraviolet rays, and above 700 nanometers are the infrared rays. Though we cannot see either, it is easy to demonstrate that they are very similar to the radiations constituting light. For example, it is well known to photographers that infrared rays can be focused by a camera lens and used to record details in distant views that to the eye are entirely obscured by atmospheric haze and therefore invisible. Another example, this time of ultraviolet radiation, is furnished by an effect most of us have seen in stage presentations. With all the normal stage lighting turned off, costumes are made to glow in the dark under ultraviolet radiation directed on them by lamps covered with filters to absorb all visible radiation. Fluorescent dyes in the costumes absorb the invisible ultraviolet radiation and return some of it to the eye as visible radiation or light.

By definition, all light is visible. For this reason, the word “visible” is superfluous in the common expression “visible light.” By the same token, what is not visible cannot be light; hence we speak of “ultraviolet radiation” rather than “ultraviolet light.” The actual scientific definition of light is *the aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye*.

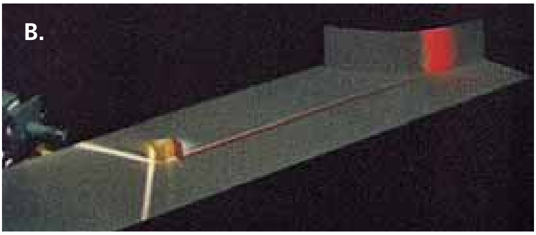
With this definition in mind, we can draw some further distinctions. Radiant energy is *physical*, because it can be said to exist independently of a human observer. In the wave-length range to which the eye is sensitive, however, radiant energy serves as a stimulus which acts on the eye and produces a visual sensation or perception. The words “sensation ” and “perception” describe mental processes and hence are *psychological* expressions. The definition of light, since it includes both radiant energy and visual sensations, is expressed in *psychophysical* terms, that is, terms which interrelate physical and mental processes.

VISUAL RESPONSE

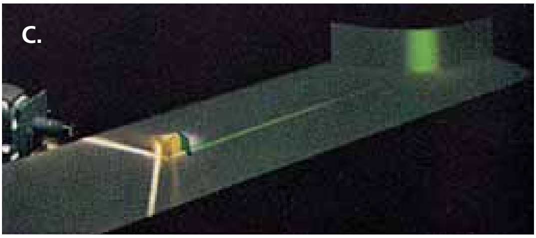
So far we have been considering the physical nature of the radiations that give rise to the visual sensation of light. We have noted that the eye has a certain wave length range of sensitivity, but that the rays to which it responds are not particularly different from others. The wave lengths comprising light form a comparatively narrow band in a much larger series of wave lengths which are very similar in their physical behavior.



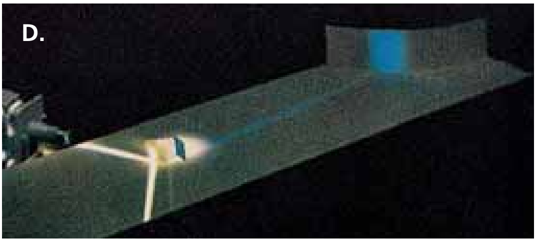
A. The prism bends light of the shorter wave lengths more than light of the longer wave lengths, thus spreading a narrow beam of white light out into the visible spectrum. (The beam extending toward the bottom of the picture is reflected from the surface of the prism without entering it.)



B. A red filter between prism and screen allows only light of the longer wave lengths to pass.



C. A green filter passes only the center part of the spectrum, absorbing blue and red light.



D. A blue filter passes only light of the shorter wave lengths, absorbing green and red light.

It is easy to see that the eye *could* have been sensitive to an entirely different band of wave lengths; there is nothing in the physical nature of light itself which decrees that human vision shall respond to it. Thus we can consider visual response to light only in terms of human beings. Since human beings vary in their physiological and psychological characteristics, visual processes and phenomena cannot be described in terms of a particular individual. Rather, it is necessary to consider them in terms of an imaginary individual representing the average “normal” visual response.

WHITE LIGHT

When all of the wave lengths between 400 and 700 nanometers are presented to the eye in certain nearly *equal* quantities, we get the sensation of colorless or “white” light. There is no absolute standard for white, because the human observer's visual processes *adapt* to changing conditions. We frequently notice the changes in the intensity of daylight with time of day and with different atmospheric conditions. On the other hand, we are less conscious of the fact that daylight varies considerably in color quality, that is, it contains different proportions of light of the various wave lengths.

This is another way of saying that we adapt quickly to any reasonably uniform distribution of energy in the prevailing illumination. For example, at night (or during the day in locations where little or no daylight is available for comparison), we tend to accept tungsten light as being white. It appears white even though, for the same visual intensity, it contains far less blue and far more red than daylight. When tungsten lamps are of low wattage, we may be conscious of some yellowishness, but the effect is only slight. In a room illuminated principally by daylight, however, a tungsten lamp appears distinctly yellow, because we are now adapted to daylight.

THE SPECTRUM

Under suitable conditions, we can analyze white light into its constituent radiations. This is done on a majestic scale in nature when sunshine, falling on the curved surfaces of raindrops, is dispersed into the familiar rainbow.

In the laboratory, the same experiment can be performed by passing a narrow beam of white light through a glass prism. In the illustration at the top of page 5, the resulting band of colored light, called the *visible spectrum*, is seen falling on a screen of white paper, from which it is reflected to our eyes. The principal colors we can discriminate in the printed reproduction are red, yellow, green, blue-green, and blue. In viewing an actual spectrum, we would be more aware of its continuous nature; we would see that the color shifts gradually as the wave length of the light changes, and that we can distinguish many more different colors in the spectrum itself than in the reproduction. The colors of an actual spectrum are physically the purest colors possible, because they are unaffected by mixture with light of other wave lengths.

FILTERS

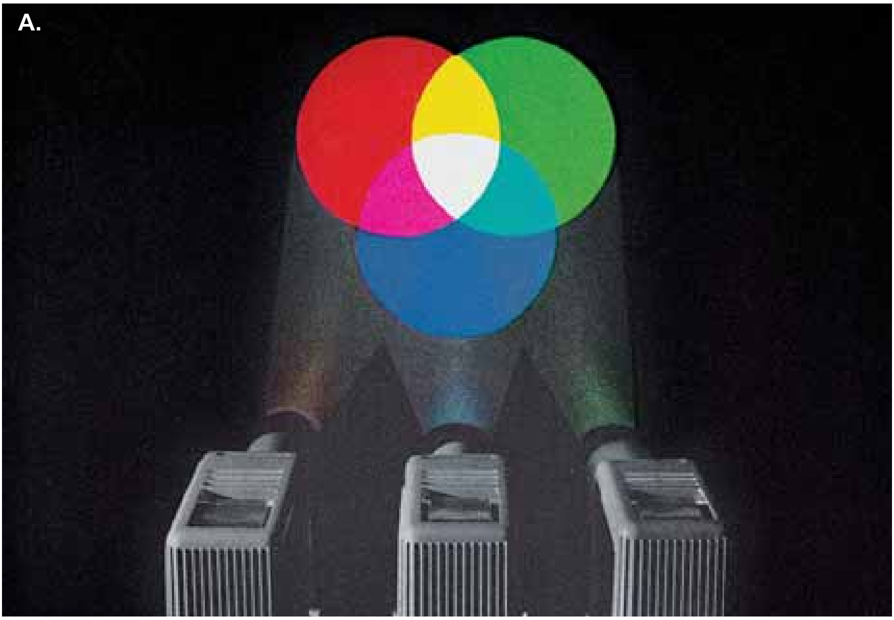
In order to understand how the human eye sees colors, let us consider the action of light filters, shown by the three small illustrations on page 5. If we place a red filter in the path of the light coming from the prism to the screen, we find that the blue, blue-green, green and most of the yellow regions of the spectrum are now missing. This experiment shows that the red filter has absorbed the rays giving rise to these sensations from the light which fell on it. Here, in fact, is the reason that the filter looks red: simply that it filters out of white light all radiations except those giving rise to the sensation of redness. For the same reason, a green filter looks green because it transmits to a screen or to the eye only the middle, predominantly green region of the spectrum, and a blue filter looks blue because it transmits only the predominantly blue region of the spectrum.

COLOR VISION

Many theories of color vision have been proposed, only to be discarded because they failed to give a satisfactory explanation of some important aspect of the way in which we see color. However, as a result of many thousands of experiments, it is possible to state the practical principles of color vision which form the basis of color photography.

To clarify these principles, we may compare the eye to a radio. Both are sensitive to certain band of wave lengths, 400 to 700 nanometers in the case of the eye. A radio is selective in its reception, that is, it can be tuned in on one station at a time, even though waves from several hundred stations may be present at the antenna. In contrast to a radio, the human eye has no tuning mechanism, and it therefore responds simultaneously to all radiation within the visible band, regardless of wave length. Light of one particular wave length cannot be distinguished by the eye unless it is presented alone. For example, the eye identifies a certain green when it is seen in the spread-out spectrum, but is quite unable to isolate a green sensation from white light.

Since the eye interprets all the light that strikes it without analyzing the various mixtures of wave lengths, we may logically conclude that it does not possess a separate sensitivity mechanism for each wave length of light.

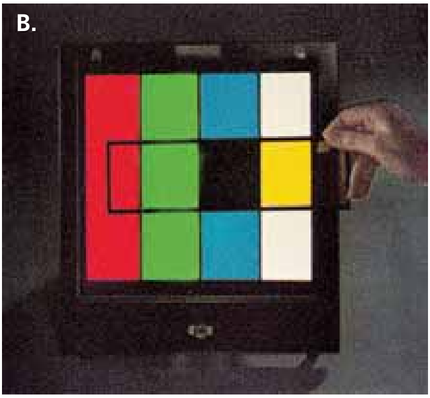


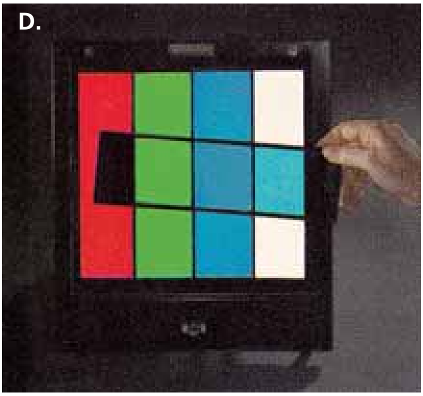
A.) Additive mixture of the colored light from projectors covered by red, green, and blue filters. Combined in pairs, the beams give cyan, magenta, and yellow. Where all three beams overlap, all three of the visual receptor systems are stimulated, and the screen appears white.

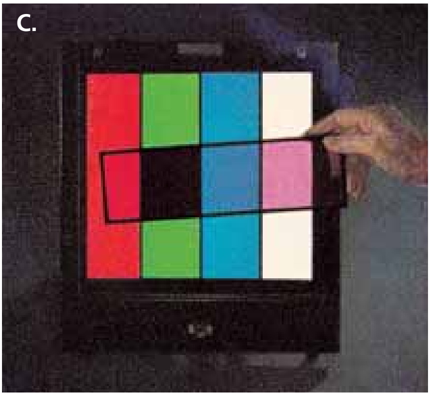
B.) A yellow filter absorbs blue light, transmitting green and red light.

C.) A magenta filter absorbs green light, transmitting blue and red light.

D.) A cyan filter absorbs red light, transmitting blue and green light.







How, then, do we see colors at all? The answer to this question is not really known, but it has been found that almost all colors can be matched by suitable mixtures of red, green, and blue light. Hence red, green, and blue are known as *primary colors in the additive system*.

The response factors in human color vision appear to relate directly to these three colors. Here we refer to vision rather than to the eye, because the eye itself does not contain all of the mechanism for color vision. Continuing research indicates that the translation of wave lengths of light into color sensation is to a large extent a function of nerve connections and of the brain. It is for this reason that the psychological factors in color vision and color photography are so important.

A possible mechanism of human color vision can be outlined as follows (though it must be borne in mind that we are dealing here with assumptions, not with proved facts): The light-sensitive elements of the retina are connected to the brain through a complicated network of nerves. This network is so arranged that it forms three light-sensitive systems, one responding to red light, one to green light, and one to blue light. Since there is no method available for isolating any one of these receptor systems so that its response can be studied as a function of wave length, we have no exact knowledge of the spectral sensitivities of the systems. However, there are compelling reasons for believing that the three systems overlap considerably in sensitivity. As we view the spectrum formed by a prism, for example, we have no difficulty in distinguishing all of the blue-greens from all of the yellow-greens, even though there must be a wave length in the blue-green which stimulates the green receptor system to exactly the same degree as some other wave length in the yellow-green. It is only logical to suppose that the difference in appearance is due to simultaneous, and unequal, stimulation of the red and blue receptor systems.

From microscopic examination of tissues, it has been shown that the communication system between eye and brain involves many millions of nerve fibers and nerve connections. Considering the fantastic complexity of this nerve network, we should not be surprised to find slight variations in color vision among individuals, any more than we are surprised at differences in fingerprints. Imperfect organization of the optic-nerve connections may be responsible for the more serious departures from normal color vision which are known as “color blindness”.

ADDITIVE COLOR MIXTURE

The illustration at the top of the opposite page shows the effect of projecting primary red, green and blue light in partial superimposition. Where all three beams overlap, the effect is white because all three receptor systems of the eye are stimulated *equally*.

Hence, for all practical purposes, white light can be thought of as a mixture of red, green, and blue light in the proper ratio.

That blue-green should be formed where the blue and green overlap is not surprising, nor is the formation of magenta from a mixture of blue and red light. In both cases, we feel we can trace the contributions made by the parent colors. That a mixture of red and green light should appear yellow is, however, surprising at first sight. This phenomenon is easier to understand if it is borne in mind that we are not speaking here of the yellow seen in the spectrum, which is confined to a narrow band of wave lengths between the approximate limits of 575 and 590 nanometers. We are speaking, rather, of a broad band of wave lengths which includes substantially all the wave lengths of light except those in the blue region of the spectrum. Actually, by using, over two separate light sources, a green filter which transmits no light of wave length longer than 575 nanometers and a red filter which transmits no light of wave length shorter than 590 nanometers, we can obtain the sensation of yellow without using any light of the wave lengths which appear yellow in the spread-out spectrum. Thus the essential factor is equal stimulation of the red and green receptors. It does not matter what wave length or wave lengths stimulate the receptors, provided their responses are roughly equal.

The yellow colors of reflecting surfaces seen in nature and in everyday life are due to the fact that the surfaces absorb blue light from the white light falling on them. Red and green light are reflected, and in combination they give rise to the sensation of yellow. It is interesting to note that if a surface reflected only light of wave length 575 to 590 nanometers, it would reflect so small a proportion of the light falling on it that it would appear nearly black. Only in rare cases do we have a yellow color due to the presence of these wave lengths alone; the sodium-vapor lamps sometimes used for street and highway illumination are an example.

By mixing red, green and blue light in varying proportions (that is, by varying their relative intensities), almost all colors can be produced, even the purples and magentas, which do not occur in the spectrum. Most spectrum colors (and those of nearly equal purity) can only be approximated, but any ordinary color can be matched exactly.

It should be noted, however, that there are two types of color match. One is a match in which the two colors contain light of the various wave lengths in the same proportions. The other is a match in which the component energies are different, but their effect on the visual receptor systems is such that the two colors *appear* the same. The distinction between the two types of color match is important, because the latter type is essential to the successful operation of color photography.

If it were necessary to duplicate the actual physical stimuli reaching the eye, reproducing a scene in color would be a practical impossibility.

Since matching a wide range of colors with red, green, and blue light involves addition of the colored lights, the primary colors are often specified further as the *additive primaries*. The exact nature of the primaries is variable. Three wide bands of wave lengths, or even three single wave lengths, can be used. The only requirement is that no two of the primaries, when mixed, may match the third.

In color photography, the three colors produced by mixtures of the additive primaries in pairs are of particular importance. The colors blue-green (or cyan, to use the shorter term by which it is known in color photography), magenta, and yellow are known as the *subtractive primaries*. Since each represents white light minus one of the additive primaries, they are the complementaries of the additive primaries. Thus, for example, cyan is complementary to red. In other words, cyan light and red light add together to give colorless or white light. Similarly, magenta is complementary to green, and yellow to blue.

SUBTRACTIVE COLOR MIXTURE

A cyan filter transmits blue and green light, but absorbs red light; hence it subtracts the primary red from white light. Similarly, a magenta filter, which transmits blue and red, subtracts green from white light; and a yellow filter, which transmits green and red, subtracts blue from white light. These effects are shown in the smaller illustrations on page 8.

In our demonstration of additive color mixture, we used three projectors, one covered by a red, one by a green, and one by a blue filter. We could not place all three filters over one light source because to a considerable extent the filters were mutually exclusive, that is, none of them would transmit the light passed by the other two.

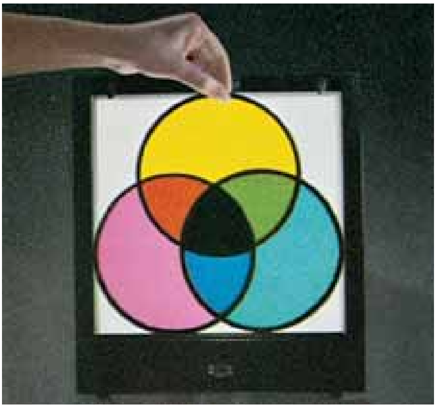
With the cyan, magenta, and yellow filters, however, this is not the case. Since each of the filters transmits about two-thirds of the spectrum, we can superimpose them over a single light source to produce other colors, as shown at the top of page 13. The combined subtractions of any pair give one of the additive primaries. For example, the cyan filter subtracts red from white light, whereas the magenta filter subtracts green; where the two overlap, only blue light is left. Where all three filters overlap, the yellow subtracts the blue, and all the light is cut out.

To produce other, intermediate colors by mixture of the subtractive colors, we must vary their relative strength. We could, of course, do this with three series of filters (such as the KODAK Color Compensating Filters CC–C, CC–M, and CC–Y) containing various concentrations of cyan, magenta, and yellow dyes, but instead we may turn to a more familiar example of subtractive color mixture.

As everyone who has ever used a set of water colors probably knows, a large variety of colors can be matched by making appropriate mixtures of three suitably chosen primaries, commonly called “red,” “blue,” and yellow. If the range of colors so produced is to be as complete as possible, however, the “red” will really be a magenta and the “blue” will really be a blue-green or cyan. It is unfortunate that the quoted names have so often been used, because their use in this sense has undoubtedly acted as a bar to a more widespread understanding of the principles of color mixture.

Suitable cyan, magenta, and yellow water colors are shown on the opposite page. In the illustration at the upper right, cyan and yellow have been mixed to produce green, just as they did when filters were used. The larger illustration shows the full range of colors produced by this particular set of primaries. Toward the center, the white paper shows through more and more as it is covered by less and less dye, and the colors become progressively lighter. Also shown is a scale of grays obtained by mixing cyan, magenta, and yellow together in the proportion required to produce a neutral color, but in smaller quantities as the scale moves away from the black.

The range of colors which can be produced by subtractive mixture of three dyes is quite large and makes possible the modern processes of color photography which depend on the subtractive principle as does the printing of any book with full-color pictures. In all such processes, the real function of the subtractive primaries is to control the red, green, and blue light to which the three visual receptor systems are sensitive. Thus cyan, which subtracts red light from white light, is used in various amounts to control the amount of red light reaching the eye. Similarly, magenta and yellow are used to control green and blue light, respectively.



Cyan, magenta, and yellow filters partially superimposed. The combined subtractions of the filters in pairs give red, green and blue. Where all three filters overlap, no light is transmitted.

Cyan, magenta, and yellow water colors. Cyan and yellow have been mixed to make green, just as they did when filters were used. Other colors obtained with these primaries are shown below.

The range of colors produced by mixing the primaries at the upper right in varying proportions. Toward the center, the quantities were decreased, and the white paper shows through more. At the right, all three primaries were mixed in the proportions required to produce a neutral, but in varying amounts. The result is black shading through a scale of grays to white.

CHARACTERISTICS OF COLORS

To bring color firmly within the grasp of understanding, we need to know how it is caused, how it varies, and how it is affected by viewing conditions. Most important of all, we need to know what the variable *quantities* of color are, for only with these is it possible to evaluate color as a *quality*.

PRODUCTION OF COLOR

There are a number of different ways in which color can be produced. Those which are most important to the practical color photographer are described in the following paragraphs.

Absorption. The colors of most ordinary objects are due to the fact that they do not absorb the same amount of light at each wave length. We have already noted that a green filter absorbs from white light all waves except those giving rise to a sensation of greeness. The color of an object such as green construction paper is due to the same cause; in both cases the coloring material has such a physical structure that it absorbs red and blue light. The surface of the paper is an irregular arrangement of translucent fibers which have been treated with the coloring materials. Into these fibers the light penetrates fairly deeply. Before it is reflected to the eye of the observer, it has passed through several of the fibers, and the coloring material has absorbed the blue and red components of the original white light. Thus, whether the paper is viewed by reflected light or whether it is held over a strong light source and viewed by transmitted light, it always appears green, and the color is due to the removal of light that is not green.

Other surfaces, whether rough or smooth, act in the same way. Light falling on them penetrates far enough to undergo the absorption which is characteristic of the surface and then returns to the observer to cause the sensation of color. In the case of a surface covered with paint, the color is influenced by the absorption characteristics of the vehicle in which the pigment particles are suspended, the size of the particles if they are opaque (this is the usual case), and the color of the surface underneath if the particles are transparent as shown in the illustration at the upper left of page 16.

Surface Characteristics. A few materials, chiefly polished metals like copper or brass, have the property of selective reflection at their front surfaces. This phenomenon gives rise to "surface" or "metallic" colors, as distinguished from the more common "body" or "pigment" colors. An example is gold, which has a surface quite unlike that of most nonmetallic objects. Specular or mirror-like reflections from gold are always of a characteristic color which indicates the selective reflection of yellow and red light. They are not white, as they would be in the case of most other objects such as the paint layer illustrated on page 13.

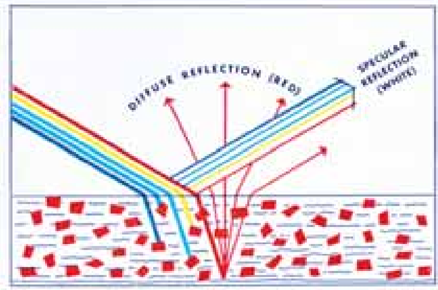
The distinction between surface and body color is emphasized by what happens with a piece of gold leaf thin enough to transmit light. Here, white light falling on the gold film can be reflected, absorbed, or transmitted. Since red and yellow light are strongly reflected, and blue is strongly absorbed, such a film appears predominantly green by transmitted light. Certain brightly colored insects and the crystals of some organic chemicals also exhibit this type of metallic coloration.

Scattering. The color of the blue sky is due to scattering of light by the atmosphere, shown diagrammatically on page 16. Variations in the density of the atmospheric gases act in such a way that they scatter light of the shorter wave lengths at the blue end of the spectrum much more than they scatter light of the longer wave lengths at the red end of the spectrum. When the air is dusty or contains water in the form of droplets or ice crystals, the particles scatter more light of the longer wave lengths. Thus the sky is bluest when it is clearest, and whiter when it is less clear. If there were nothing in the atmosphere to scatter light, the sky would always be dark and the stars would be visible at any hour of the day or night.

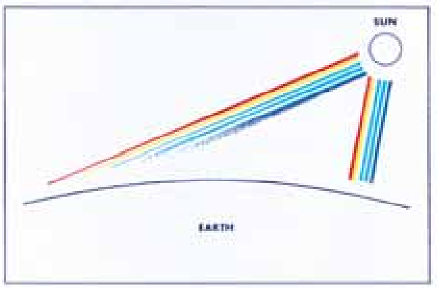
Scattering of light by the atmosphere is also responsible for the reddishness of the sun when it rises or sets. When the sun is high in the sky, the direct rays pass through the atmosphere without noticeable subtraction of blue light by scattering. Early or late in the day, however, the rays of the sun strike the earth approximately at a tangent, as shown in the illustration, and consequently they must pass through a much greater thickness of atmosphere. Depending on the angle of the rays and the sizes of the particles present in the atmosphere, light of different wave lengths is scattered and the sun appears yellow, orange, or even a fairly deep red.

On a sunny day, distant mountains appear a hazy blue, lacking in detail, because the blue light arising from scattering in the atmosphere is superimposed on the light reaching the observer from the mountains themselves. Any distant object on the horizon is thus seen through a veil of blue haze which strongly affects its appearance.

Some other colors in nature are due to the same cause. For example, blue feathers often contain not blue pigment but finely divided particles, which are suspended within a translucent framework and scatter blue light more effectively than light of other wave lengths.

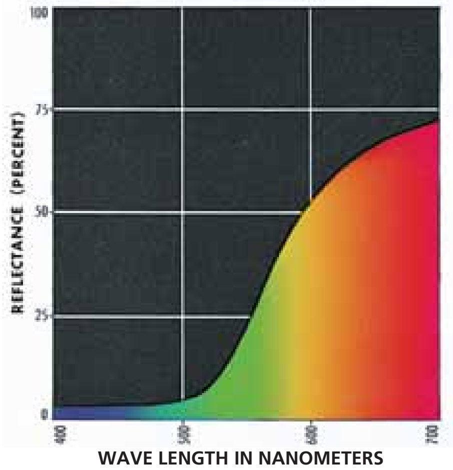


The specular reflection of white light from a smooth red surface is also white, but the diffuse reflection is red, because the light of other colors has been absorbed.

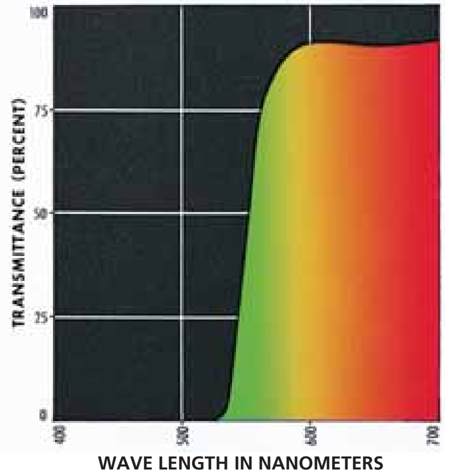


At sunset, the path of sunlight through the atmosphere is longer than at noon, and increased scattering of blue and green light makes the sun appear reddish.

Orange peel and standard white surface mounted in spectrophotometer. The spectral reflectance curve determined by the instrument is shown in color at the right.



The filter above approximately matches the orange, but its purer color is shown by the sharper break and greater exclusion of wave lengths from 400 to 530 nanometers.



Scattering also explains why veins close to the surface of the skin are bluish rather than reddish, as might be expected from the color of blood. Actually, the red hemoglobin in these veins is present in such a high concentration that it effectively absorbs all of the light striking it. Hence the usual reflection of light from the deeper tissues does not occur. The only light reflected to the eye is the blue light scattered by the vein wall and the skin layers just above it.

Interference. Color can also be produced by the interference of light waves in thin films. Examples are to be found in a soap bubble or a film of oil floating on water. The light reflected from the top surface of such a film undergoes a reversal of phase, but the light reflected from the bottom surface does not undergo this type of change. With films that are extremely thin in comparison to the wave length of the light, the two reflected rays interfere with each other and cause the film to appear very dark. If the films are somewhat thicker, waves of some lengths interfere, while waves of other lengths reinforce each other, giving rise to colors which vary with the thickness. The reflected light is variously colored, even though the film is illuminated by white light and contains no differentially absorbing materials.

Interference phenomena are also responsible for the colored patterns known as Newton's rings which sometimes cause trouble in color printing work. In this case, the difficulty is due to the proximity of two smooth optical surfaces, such as those of glass and the base side of photographic film. Since neither surface is a perfect plane, there are some areas of actual contact and others where the two surfaces are separated to varying degrees. The colored patterns are formed by interference among the light rays reflected from the two surfaces.

Fluorescence. The use of fluorescence in stage costumes has already been mentioned in another connection. Here the molecules of the fluorescent material absorb energy at one wave length and reradiate it at another. The same principle was used during WW II in the manufacture of colored signalling fabrics. These materials could be seen from remarkable distances because of the intense coloration produced by fluorescent dyes. As a matter of fact, a number of fluorescent dyes are regularly used in the textile industry, because they extend considerably the range of colors which can be made available in finished cloth.

Dispersion. Finally, color may arise from differences in the refractive or bending power of a transparent medium for light of different wave lengths. The rainbow and the spectrum formed by a prism are examples. The flashes of color seen in viewing a cut and polished diamond illuminated by a concentrated light source are also due to dispersion.

SPECTRAL REFLECTANCE AND TRANSMITTANCE

In the laboratory, the color of any surface (with the exception of one that fluoresces) can be specified in terms of its reflectance at each wave length in the visible spectrum. The instrument used in making such determinations is called a spectrophotometer. Essentially, it consists of an optical system in which the light from a lamp is dispersed into a spectrum by a prism. One narrow band of wave lengths at a time is reflected in such a way that half of the beam of colored light is allowed to fall on the sample being tested, the other half on a standard white surface. In the automatic recording type of spectrophotometer, a photocell measures the relative intensities of the two halves of the beam after they have been reflected from the two surfaces. As the comparative reflectance of the sample is measured, the instrument draws a continuous graph, wave length by wave length, such as those shown on page 16. In the illustrations, the areas under the curves are shown in color so that the behavior of the samples at the various wave lengths can be visualized more readily. The spectrophotometer can also be adapted easily for measuring the spectral transmittance of translucent samples such as filters.

In spectrophotometric determinations of reflectances, the light source must emit light of all the wave lengths at which measurements are to be made. The reason for this requirement is obvious when we consider that if no light of a given wave length were available, the photocell in the instrument would have no way of measuring the relative reflectance of sample and standard at that wave length. As long as reasonable amounts of light at each wave length are provided, however, the spectral reflectance curve determined by a spectrophotometer is the same regardless of the color quality of the light source. Furthermore, the same curve is obtained whether the eye, a photocell, or a photographic film is used to receive the light from sample and standard.

Since the characteristics of human vision do not enter into the determination of a spectrophotometric curve, the curve can be considered as a purely physical measurement. Two samples which have identical curves will match in appearance under all viewing conditions. In the case of reflecting samples, it is also necessary that the surface texture be the same. *If two samples match in appearance under one set of viewing conditions, however, we cannot assume that their spectrophotometric curves are identical.* This statement follows from the fact, already pointed out, that colors can be matched without matching the distribution of energy at each wave length.

From the point of view of color photography, the converse of the italicized statement above is even more important: *In order to match visually, two samples need not have identical spectrophotometric curves.*

Thus a color transparency which matches a certain area of the subject visually may not match it spectrophotometrically. The fact that a spectrophotometric match is not necessary enormously simplifies the problem of obtaining satisfactory color reproduction.

It is also of interest from the photographic point of view to note that two colors which appear alike may not photograph alike. Furthermore, while two colors which appear alike may photograph alike on one type of film, they will not necessarily do so on another type of film.

Since the spectrophotometric curve does not take human vision into account, it does not, by itself, describe the visual sensation aroused in viewing the sample. Although a smooth curve provides a rough indication of the appearance of a sample, an irregular curve usually does not, even to a trained worker.

EFFECT OF LIGHT SOURCE AND VIEWING CONDITIONS

Since light sources vary in their distribution of energy throughout the spectrum, the distribution of energy after reflection from a given colored sample will also vary from one light source to another. In other words, the physical stimulus reaching the eye will vary. As a result, the visual sensation aroused in viewing the sample will depend on the character of the illumination. This effect is not so pronounced as might be expected, owing to a visual phenomenon known as *approximate color constancy* (see page 59). However, the shift in appearance is quite noticeable with surfaces which are highly selective with respect to wave length in their absorptions, or in other words, surfaces which show sharp peaks and depressions in their spectral reflectance curves. It is also quite noticeable with light sources having energy distribution curves of a similar character.

Certain types of fluorescent lamps are relatively so rich in some wave lengths and so poor in others that they exert a marked influence on the apparent colors of objects. Most of us have noticed the color distortion produced by such lighting, especially the rather unnatural skin tones. Similarly, the appearance of fluorescent dyes is likely to change when the light source is changed. With the introduction of a number of fluorescent textile dyes, it is not uncommon to find fabrics which change color to a much greater extent than other objects.

Surroundings also affect visual judgment of a color. In the group of four illustrations on page 21, the central patch of color is physically similar in all cases, yet its appearance is strikingly different. Thus it is apparent that we cannot establish the relationship between the physical characteristics of a surface and the visual sensation it arouses unless the viewing conditions are specified. A standard set of conditions, recommended by the International Commission on Illumination (abbreviated CIE for Commission Internationale de l'Eclairage),* has gained general acceptance for this purpose. The CIE recommendations include specifications for standard light sources and for the visual response characteristics of a “standard observer”.

The “standard observer” is an imaginary observer whose color vision is described by the average of the response curves of a number of actual observers. In selecting the actual observers, those having any detectable abnormalities in their color vision (see pages 9 and 50) were excluded. However, it has long been recognized that even so-called “normal” color vision varies slightly from one individual to another. To obtain a representative set of response curves, it was therefore necessary to average the results obtained with a number of observers.

COLOR AS A SENSATION

According to the modern scientific definition of color, it is not legitimate to ascribe color to an object, but only to the light reflected from it. However, it is a convenience, even a practical necessity, to assign colors to reflecting surfaces seen under customary types of illumination such as daylight or tungsten light. When we do so, we are referring to the capacity of a surface to modify the color of the light falling on it. We should remember that an object has no single characteristic color, because its appearance is affected by a number of factors, the most important of which are the quality and intensity of the illumination.

If we are asked the color of an object such as a sweater, our first reaction may be to say, for example, that it is red. By this means, we identify the *hue* of the object, that is, whether it is red or yellow or purple.

However, we are all conscious, at least in a vague way, that this description is inadequate. In an effort to be more specific, we may say that the sweater is light red or dark red. When we do this, we are describing the *brightness* of the color. If we stop to think about it, we realize that this characteristic of a color is independent of the hue, that is, we can have two colors which are of the same hue but of different brightness.

We might also say of the sweater that it is a dull red or a bright, vivid, or brilliant red. Here we are attempting to describe still another characteristic of a color, that is, its *saturation*. The saturation of a given color may be regarded as a measure of the extent to which it departs from a neutral gray of the same brightness. For further reading and additional examples, see Josef Alber's INTERACTION OF COLOR (Yale University Press, 1963) also available in interactive CD-ROM.

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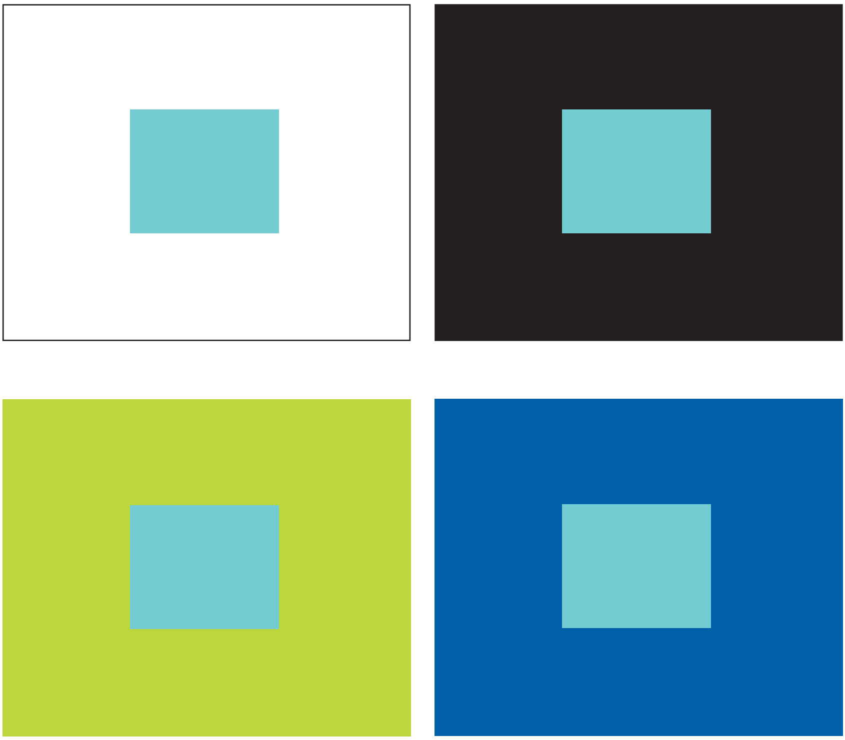
* International Commission of Illumination, *Proceedings of the Eighth Session*, Cambridge, England, 1931.



A color is affected by the color of its surrounds. All four blue-green patches are exactly the same color. When surrounded by white, the patch looks darker. When surrounded by black, the patch looks lighter. When surrounded by yellow-green, the patch looks bluer and of medium brightness. When surrounded by dark blue, the patch looks greener and lighter.

Thus any color perception has three characteristics, any one of which can be varied independently of the other two. In psychological usage, the correct term is *attributes*, because we are really describing sensations, not the object or the physical stimuli reaching the eye.

While we experience little difficulty in detecting hue differences, we frequently become confused in judging brightness and saturation differences because we cannot decide whether two colors differ only in brightness or whether their saturation is also different. This fact is of some importance in color photography, because it affects our judgment of color rendering. For example, an excessively deep blue sky in a color picture may give the impression of high saturation when it is actually low in brightness. If the reproduction of the sky is compared with a Kodak Wratten No. 47 (blue) Filter, the relatively low saturation in the photograph is immediately apparent. The confusion between saturation and brightness is typified by the frequency with which the word "bright" is used in everyday speech to describe a highly saturated color.

SYSTEMS OF COLOR SPECIFICATION

Frequently we attempt to describe a color more or less completely by a single term, sometimes the name of some object which is more or less familiar to everyone. For example, pink, cherry, cerise, dusty pink, rose scarlet, vermilion, crimson, and rust are all used to describe various reds. The difficulty is that each term means different things to different people. We would all agree that pink describes a red which is high in brightness, fairly low in saturation, and slightly bluish in hue. Even within these limitations, however, there are many possibilities; we would certainly not think of buying yarn to complete a half-finished sweater, specifying only that it was to be pink. Instead, we would match the two yarns directly, and with some experience in the ways of color, we would also make sure that the two samples matched both in daylight and in artificial light.

The need for an accurate language of color becomes acute when, as often happens, circumstances do not permit direct comparisons. Actually, we do not have a universal language, but we do have systems of color specification and notation which answer most of our needs. The Pantone Color System and various computer graphic software, in addition to the Munsell System, provide the color user with many options.

Munsell System. In the United States, one of the best known systems of color notation is that developed by Albert H. Munsell. Essentially, this system is an orderly arrangement into a three-dimensional solid of all the colors which can be represented by actual surface samples prepared from stable pigments. The general shape of the solid is shown on page 24.

The various hues are spaced horizontally around a circle in such a manner that they appear approximately equidistant to a normal observer, provided they are examined under illumination of the correct quality. The circle, also shown on page 24, is divided into ten Major Hues, consisting of five Principal Hues (Red, Yellow, Green, Blue, and Purple) and five Intermediate Hues (Yellow-Red, Green-Yellow, Blue-Green, Purple-Blue and Red-Purple). Each of these ten Major Hues is number 5 of a hue series of 10 numbers. Thus the complete hue circle consists of 100 hues, 40 of which are represented by actual samples in the *Munsell Book of Color**. This book is supplied as a Matte Finish Collection and a Glossy Finish Collection. An abridged collection† designed for student purposes is also available.

Extending vertically through the center of the hue circle is the scale of reflectances, know as *values* in the Munsell System. Numbered 10, at the top of the value scale, is a theoretically perfect white (100 percent reflectance); numbered 0, at the bottom, is a theoretically perfect black (0 percent reflectance). In between, there are value steps represented by actual samples.

From a photographic point of view, the value scale deserves more than passing notice. Superficial reasoning would indicate that the midpoint of the scale should have a reflectance of 50 percent, that is, it should reflect 50 percent of the light falling on it. However, the eye tends to see as equal tone steps not equal differences in reflectance (e.g., 10, 20, 30 and 40 percent, where there is a constant difference of 10 percent), but rather equal ratios of reflectance (e.g., 10, 20, 40, and 80 percent, where the ratio of each reflectance to the preceding one is 2). As a result, the gray which impresses the eye as falling midway between white and black actually has a reflectance of about 20 percent. It is interesting to note that this value is close to the 18 percent reflectance of the gray side of the KODAK Gray Card, which is used as an exposure-meter target to represent the over-all reflectance of an average scene.

Radiating out from the scale of values, which is the central core of the color solid, are the steps of saturation, known as *chroma* in the Munsell System. Here again the steps appear approximately equidistant to a normal observer. The numbers extend from 0, which is the neutral gray, to numbers as high as 16, depending on the degree of saturation attainable with a given hue at a given value level. Because of variations in attainable saturation with hue and value, the color solid is not symmetrical.

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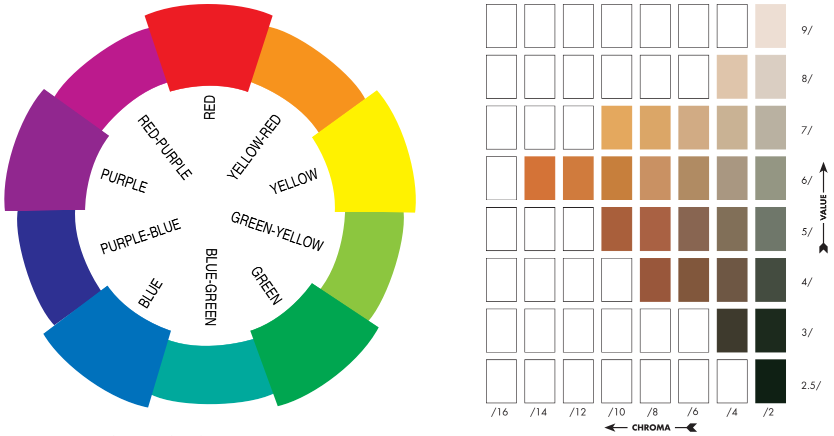
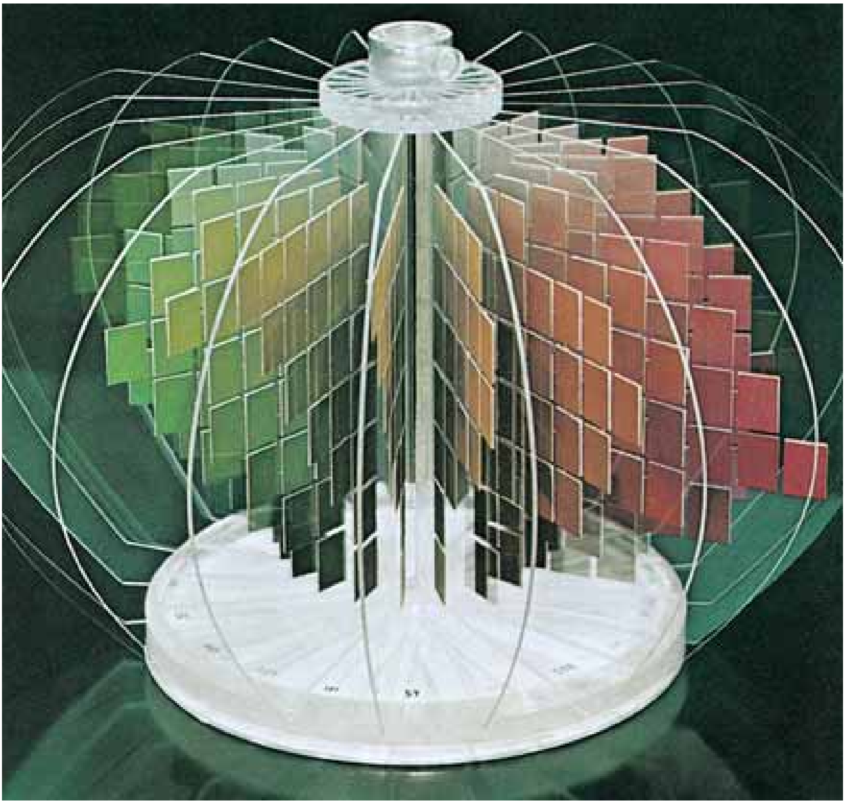
*Published by Macbeth; New Windsor, N.Y.

†Published by Fairchild Publications; New York, N.Y.



THE MUNSELL SYSTEM

(Left) Hue circle showing the Major Hues. Each is number 5 of a family of 10 adjoining hues. (Right) Chart showing variations in value and chroma for 2.5YR. (Below) Color tree showing the 3-dimensional relationship of hue, value, and chroma. (Illustrations by Munsell Color Company).



For glossy samples, the highest chroma of 5 Red is 14, whereas the highest chroma of 5 Blue-Green, opposite Red, is only 8. Yellow reaches its maximum chroma at a high value; Purple-Blue, opposite Yellow, reaches its maximum chroma at a low value. The Munsell System has the advantage over some other systems that if a new pigment is produced which permits samples of higher saturations to be prepared, there is no difficulty in adding the new samples to the appropriate hue chart.

The *Munsell Book of Color* can be used to describe colors by comparing them with the actual samples in the book. The arrangement in notation of hue, value and chroma is H V/C. A certain blue, for example, might be identified as 5B 4/6. If no sample that matches the color exactly is found in the book, an intermediate notation can be estimated.

Strictly speaking, any system of color specification which relates our perceptions to their physical causes, as the Munsell System does, must be considered to be a psychophysical system. The Munsell System is unique, however, in that primary emphasis has been placed on the judgment of observers in spacing the color samples when they are illuminated by a standard source. Consequently, the steps in the Munsell scales of hue, value, and chroma correspond rather closely to our mental or psychological concepts of equal steps in hue, brightness, and saturation.

Much research has been done by the National Bureau of Standards and the Optical Society of America to improve and standardize this system. As a result, the *Munsell Book of Color* provides the method recommended by the American National Standards Institute for the popular identification of color. Tables have been published which give the equivalent specifications in terms of the technical standard system described in the following paragraphs.

CIE System. In connection with the effects of light sources on color, we mentioned the recommendations of the International Commission on Illumination. Acknowledgment of the need for a basic standard has led important scientific groups the world over to adopt the CIE recommendations and the psychophysical system of color specification which is based on them.

We have already seen that by mixing three colored lights, a red, a green, and a blue in the proper proportions, we can match almost any color. All spectrum colors cannot be matched with real primaries, but the data obtained with real primaries can be transformed mathematically to arrive at a set of imaginary primaries with which all the spectrum colors could be matched. The fact that these primaries cannot be obtained experimentally does not detract from their value.

The CIE System, in effect, specifies colors in terms of the amounts of each of three selected primaries necessary to form a match with the sample in question. The color mixture curves for the "standard observer" show the amounts of each of the three primaries required to match each wave length of the spectrum.

The other essential of the CIE System is standardization on a few light sources, such as daylight and tungsten light. The spectral energy distributions of the standard sources are accurately known and can be reproduced by well defined means.

Given the "standard observer" and a standard light source, we need only the spectrophotometric curve of a sample to compute its color specification.* Since the system is based on data accepted internationally, the specification means the same thing everywhere and is not dependent on the visual characteristics of a single individual.

On page 29 is shown the *chromaticity diagram* of the CIE System. This diagram is of particular interest because it forms what might be described as a map of all possible colors. The relationship of a given sample to all the colors can thus be visualized readily.

The horseshoe shaped boundary represents the positions of the colors which have the highest possible saturations; these are the spectrum colors. The colored area represents the limits of saturation possible with a set of modern process printing inks. Near the center of the colored area is the "illuminant point" for daylight, likewise the position of any neutral gray illuminated by daylight.

Since, as we have already noted, color as perceived has three dimensions, hue, brightness, and saturation, it is obvious that the two-dimensional chromaticity diagram cannot describe a given color completely. Actually, it provides indications of hue and saturation relative to other samples. The hue is indicated by the direction of a straight line drawn from the illuminant or neutral point toward the position of the sample. If this line is extended to intersect the curved line representing the spectrum colors, the hue can be specified in terms of the wave length at the intersection of the two lines. Such a specification is called the *dominant wave length*.

The straight line at the bottom of the horseshoe represents the magentas and purples of maximum saturation. Since these colors do not occur in the spectrum, their hues are expressed in terms of the wave lengths of green light to which they are complementary.

As we move away from the neutral point toward the spectrum colors, saturation increases, or in other words, the colors become more pure.

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*See *The Science of Color*, by the Committee on Colorimetry of the Optical Society of America, Thomas Y. Crosell Company, New York, NY, 1953.

If the distance from the neutral point to the sample point is divided by the total distance from the neutral point to the spectrum line, a measure of purity is obtained. This is called *excitation purity* and is expressed in percent. A spectrum color is 100 percent pure, whereas white, gray, and black have zero purity.

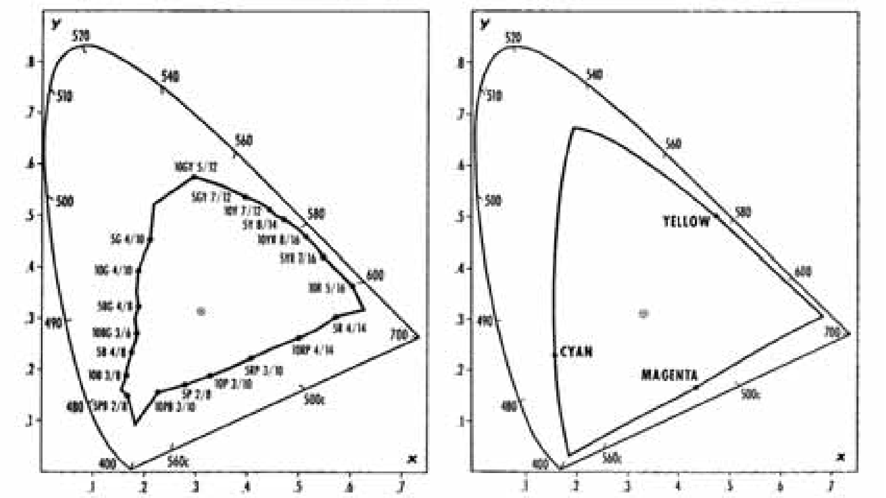
To make the specification of color complete, we must also include the brightness aspect of the sample, which is expressed in terms of *luminous reflectance* or *transmittance*. In this usage, the word "luminous" indicates that the value takes into account the color quality of the light source and the visual response characteristics of the standard observer.

Luminous reflectance (or transmittance) is a weighted average of the spectral reflectances (or transmittances) of the sample. The weighting function is the product of the spectral distribution of the illuminating light source and the spectral sensitivity of the standard observer, multiplied wave length by wave length. The spectral sensitivity of the standard observer, which is called the *luminosity function*, has been standardized internationally and is part of the CIE System.

Values for luminous reflectance (or transmittance) range from 0 to 100 percent. With any given sample, the value can be noted beside the point at which the sample plots on the chromaticity diagram. Two samples which differ only in reflectance (or transmittance) thus plot at the same point and are distinguished by the figures beside it.

In preceding sections, we have touched on the fact that, strictly speaking, color is defined in terms of light rather than the characteristics of an object or the attributes of the sensation aroused in viewing the object. Since light is a psychophysical concept (see page 4), the CIE System is a purely psychophysical method of color specification. As such, it does not always agree exactly with our mental (psychological) concepts of color. For example, the colors lying on a straight line between the illuminant point and the line representing the spectrum colors do not necessarily appear to have exactly the same hue. However, the CIE System is valuable in that it provides a scientific standard for the measurement of color. Its descriptive terms, dominant wave length, excitation purity, and luminous reflectance or transmittance (or other appropriate photometric quantity), are the psychophysical counterparts of hue, saturation, and brightness.

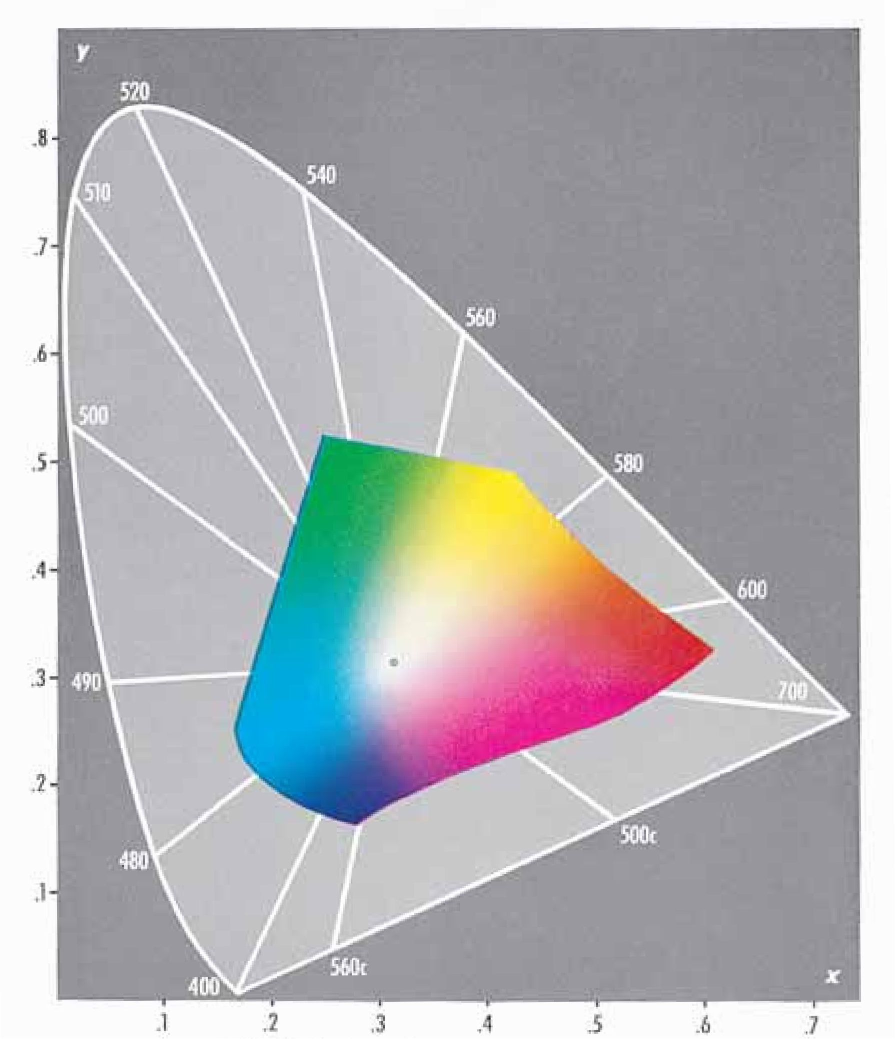
The diagram at the upper left of page 28 shows the limits of saturation obtained with the pigments used in preparing the samples in the *Munsell Book of Color*. At the upper right are shown the limits of color reproduction obtainable with a set of three subtractive dyes of the same type as those used in Kodak color films. This illustration indicates that the subtractive dyes are very satisfactory in regard to the range of chromaticities which they are potentially capable of reproducing.



The diagram at the left shows the range of colors bounded by glossy Munsell samples, each of which has the highest excitation purity for the given hue. At the right is shown the range of colors which can be produced by mixing three subtractive dyes of the type used in Kodak color films. (The method of plotting the colors is explained on the opposite page.)

Since the luminances corresponding to this gamut of chromaticities are not the same in different parts of the diagram, we should not expect a color film to provide good reproductions of colors at all levels of luminance even within this range of chromaticities. We obviously should not expect a film to provide good reproduction of colors having chromaticities that fall outside this gamut, as is the case with the saturated spectral colors. The appearance of a rainbow can be approximated in a color photograph only because most of the colors are less saturated than those of a pure spectrum. Some are due to mixtures of broad bands of wave lengths rather than narrow bands presented alone, and all colors are desaturated by the surrounding skylight.

In connection with the color gamut of a set of subtractive dyes, a comment on the shape of the gamut as plotted on the chromaticity diagram may be of interest. If we were dealing with additive mixtures of three colored lights, the boundary of the colors which could be matched would be a perfect triangle, with the primaries at the corners. Subtractive mixtures follow a different law, and thus plots of mixtures of any two of the dyes lie outside a straight line connecting the two points which represent the two dyes alone and at maximum concentration.



CIE CHROMATICITY DIAGRAM – On this "color map," the horseshoe-shaped boundary line around the light gray area shows the position of the pure spectrum colors. Some of these are identified by their wave lengths in nanometers. The straight line closing the horseshoe shows the positions of the magentas and purples, which are complementary to the greens of the spectrum. The edge of the colored area shows the purest colors which can be printed with a typical set of modern process inks. Near the center of this area is the "illuminant point" for the standard light source equivalent to daylight; this is also the position of any neutral gray illuminated by daylight. By simple mathematics, the spectrophotometric curve of any color sample can be translated into values of x and y. The position of the color can then be plotted on the diagram to show its relationship to all other colors.

KODAK COLOR FILMS

As previously mentioned, the appearance of most colors can be matched by mixing red, green, and blue light in suitable proportions. This characteristic of vision is the basis for modern color photography.

MULTILAYER FILMS

A direct approach to obtaining separate records of the red, green, and blue light reflected from a photographic subject is to provide three separate emulsions, one sensitive to each of the primary colors or having its sensitivity confined to the proper region of the spectrum by a filter. There are several ways in which three emulsions can be used. The most straightforward is by coating all three emulsions on the same support, so that we have an integral tripack or multilayer film. The first commercially successful application of the multilayer principle was Kodachrome film, introduced in 1935. A cross-sectional photomicrograph of a piece of Eastman color negative film, greatly enlarged, is shown at the top of page 31. The emulsion layers are coated on safety film base which has an antihalation backing. Each layer is so thin that the total emulsion thickness, including that of the gelatin layers between the sensitive layers is actually less than many black-and-white films.

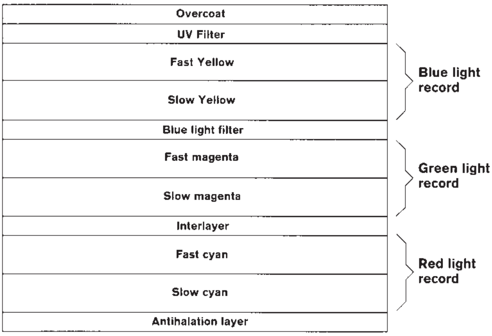
The multilayer principle has been responsible in large part for the rapid advancement of modern color photography. Since the introduction of Kodachrome film, other Kodak color films including Eastman films, all embodying the same basic principle, have shared in the truly remarkable expansion of this field.

A frame of motion picture film is a remarkable piece of engineering. Packed into its microscopically-thin layers is an incredibly complex system of chemical and physical processes that must all interact perfectly to produce a color image.

The three color records of the film are stacked as shown on the middle of page 31, with the fast and slow cyan dye-forming layers (the red light sensitive record) at the bottom, the magenta layers (the green sensitive record) next, and the yellow layers (or blue sensitive record) on top. The blue record goes on top because all forms of silver halide are sensitive to blue light. A yellow filter beneath the blue sensitive layer keeps blue light from penetrating deeper into the film and forming unwanted latent images in the magenta and cyan layers. Each color record is separated from its neighbor by a gelatin layer. This prevents silver development in one record from causing unwanted dye formation in another. Other special-purpose layers include a UV-filter layer on top of the pack, because

Cross Section of Eastman film

Before exposure After processing



Features of a typical motion picture film emulsion

silver halide is sensitive to ultraviolet light. An antihalation layer prevents reflected light from the film support from scattering back up into the tri-pack. Such diffuse back-scattered light degrades sharpness and is most noticeable as a “halo” around bright objects. In many motion picture films, this antihalation protection is provided by a layer of finely-divided carbon on the back of the film. Called “rem-jet”, it is scrubbed off during processing prior to development.

While the physical structure of modern motion picture film is complex, the real marvel is how much sophisticated chemistry is packed into each tri-pack. Consider one of the biggest breakthroughs in modern film design: the development of tabular grain (T-Grain) silver halide crystals. Conventional silver halide crystals look like lumpy cubes, T-Grain crystals are flat or tabular shaped. That gives them a much larger surface area and enables them to present a considerably larger surface area to light. That's important because while blue light absorption by silver halide is proportional to crystal volume, red and green light absorption depends on the surface area available for dye sensitizing. T-Grain crystals thus have the great advantage of allowing film designers to create emulsions in which the crystal surface area increases, but crystal volume remains constant or is even reduced. That makes it possible to use smaller crystal volumes to design faster films with less granularity. In addition, the unique geometry of the T-Grain crystal, and its tendency to lie flat, allows film designers to build films with thinner emulsion layers. That reduces the scattering of light as it passes through the layers of film, resulting in significant gains in image sharpness in multilayer color films.

COLOR SENSITIVITY

Although the various Kodak color films used in cameras are processed differently, they all form the original records of the red, green, and blue in the subject in precisely the same manner. The picture on the top emulsion is taken by blue light, on the middle emulsion by green light, and on the bottom emulsion by red light. This result is not accomplished by the use of blue, green, and red filters, but in the following way.

The top emulsion is sensitive to *blue* light only. Since *green* and *red* light pass through it without effect, the blue light alone makes the exposure. A yellow filter layer above the middle emulsion absorbs any unused blue light and prevents it from reaching the two lower emulsion layers. The yellow color in the filter layer has no permanent effect on the appearance of the film, because it is destroyed during processing. The middle emulsion is sensitive to *green* light, but not to *red* light. Like all emulsions, the middle layer is also sensitive to *blue* light, but blue light cannot reach it. The exposure in this layer is therefore made by green light alone.

The bottom emulsion is sensitive to *red* light, but its sensitivity to *green* light is so low as to be negligible. It is also sensitive to *blue* light, but blue light cannot reach it. Hence the exposure in this layer is made by red light alone.

COLOR BALANCE

For a reversal film to reproduce colors approximately as the eye sees them, its responses to the red, green, and blue parts of white light must bear the same relation to each other as do the responses of the eye to these same colors. If the film has relatively too much sensitivity to red light, for example, red objects in the scene will appear too light in the color reproduction, assuming that the exposure is correct for green and blue objects, and white objects will appear reddish.

Matching the color sensitivity of the eye would be simpler for the film manufacturer if the three receptor systems involved in human vision were constant in their response to light. The actual situation is that the receptors shift in relative sensitivity as the eye adapts to the prevailing illumination. As we go from daylight to weaker and yellower tungsten light, for example, the sensitivities of all three receptors increase, but the sensitivity to blue light increases to a much greater extent than the sensitivity to red light, thus partially compensating for the lower proportion of blue in the tungsten light. In the less usual circumstance that the tungsten light is stronger than the daylight, the sensitivities decrease, but the sensitivity to blue light decreases less than the sensitivity to red light. This type of adaptation is a convenience in everyday life, reducing our consciousness of the color variation of illumination and thus tending to make the apparent colors of objects approximately constant (see page 59). A color film, however, is necessarily limited in its response to a single adaptation level, or in other words, it has a certain *color balance*, which is determined at the time of manufacture. With a negative film, it is usually easy to adjust color balance during the printing operation.

In practical use of the film, the color balance may be affected by such factors as high temperature or high humidity during storage (either before or after exposure) and variations in processing. Regardless of these considerations, however, the film can "see" a scene only with respect to one particular set of sensitivities. Thus the best possible reproduction can be obtained only when the illumination is of the particular color quality for which the film is balanced.

Not only do daylight and the various types of artificial light differ in color quality, but individually each is subject to considerable variation. For example, two extremes of illumination which both occur on a clear day are the reddish sunlight late in the afternoon and the bluish skylight reaching a shaded subject. Since it is obviously impractical to supply special types of films balanced for every lighting condition, it has been necessary to standardize on a few films designed for use with the most common light sources, daylight and tungsten. In each case, the film is adjusted to give the best color rendering of the subject when it is exposed under the specified lighting condition.

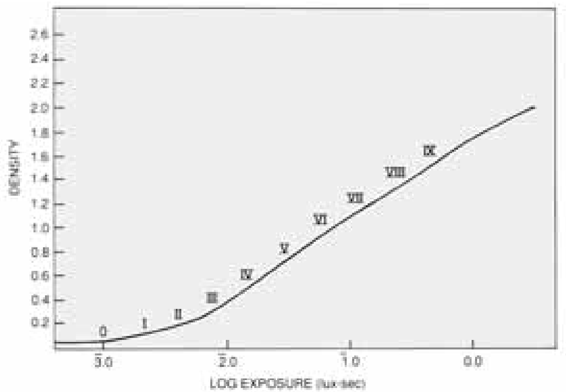
When the color film must be exposed by light of a color quality other than that for which it is balanced, correction can be made by the use of filters. It should be noted, however, that errors in color rendering may result even when using the most appropriate color filter.

REVERSAL FILMS

A normal black-and-white emulsion, exposed in a camera and developed in the usual manner, yields a *negative* reproduction of the original scene, that is, the silver deposit is heaviest in areas corresponding to the brightest areas of the subject, and lightest in areas corresponding to the darkest areas of the subject. From such a negative, it is simple to make as many positive black-and-white prints as may be desired.

In the Kodachrome and Ektachrome processes, the reversal technique is employed to produce positive color images. The basic procedure is the same in both cases: First the film is developed in a black-and-white developer, which produces a negative silver image in each of the three emulsion layers. Then the film is re-exposed to fog the remaining silver halide and render it developable. By coupler development (described on page 36), the silver halide is used to form three positive dye images: yellow, magenta, and cyan. The film is next treated in a bleach which, without affecting the dyes, converts the silver to salts which are soluble in hypo. Fixing, washing, and drying complete the process.

The black-and-white photograph of the waterfall and illustration of the characteristic curve show the relationships between subject brightness and negative density. These differences are shown by Roman numeral points on the waterfall and characteristic curve where different brightness levels normally fall. In the actual photograph, there is a one-stop difference in brightness between each of the numbered points. Point VIII on the characteristic curve (the waterfall) would reproduce as a diffuse highlight, and point I (a tree) reproduces as just lighter than black. There is a difference of seven *f*-stops between steps I and VIII, which is the typical range for normal luminance subjects. The picture density range of the negative between these two points is about 1.05. There are two numbers shown on the characteristic curve but not the photographs, IX and O. IX will reproduce as a specular highlight and O as a maximum black. Color films will typically have similar relationships as noted here for black-and-white films.



Black-and-White Negative Film – Characteristic Curve

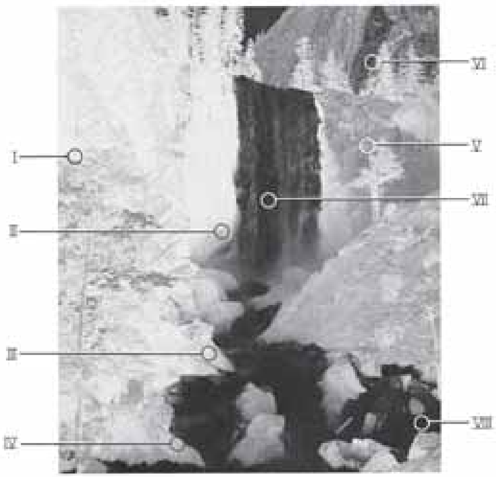
REFERENCE KEY

Negative Densities:

O	Not on photograph
I	Tree shadow area
V	Cliff edge
VIII	White water
IX	Not on photograph

Positive Densities:

O	Maximum black
I	Just lighter than black (on film)
V	Mid-tone (on film)
VIII	Diffuse highlight (on film)
IX	Specular highlight



COUPLER DEVELOPMENT

A method of producing dye images in color photography is supplied by the chemical reaction known as *coupler development*. As the developer reduces the exposed silver halide to form metallic silver, the developer itself is oxidized by the reaction, and it then combines with another chemical substance known as a *coupler*. The product of this secondary reaction is a colored compound, that is, a dye. The dye-forming reaction produces dye in proportion to the amount of silver developed, and since the dye is insoluble, it remains where it is produced to form a photographic image in color.

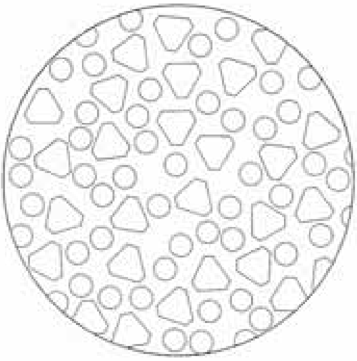
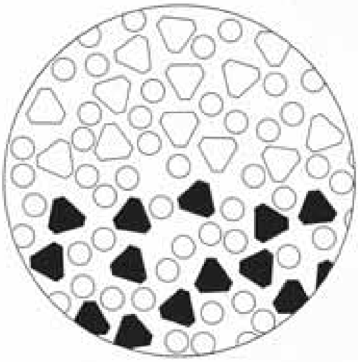
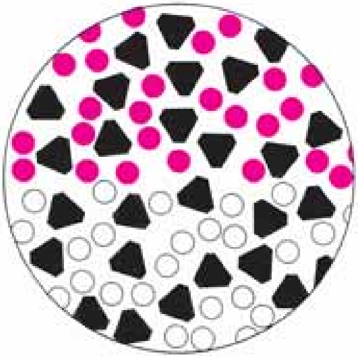


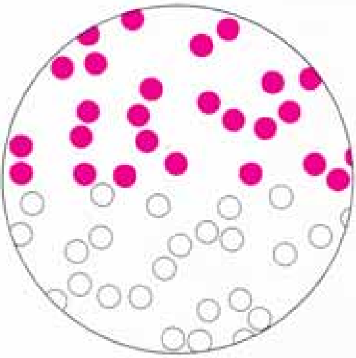
Diagram of Ektachrome film emulsion, showing crystals of silver halide and globules of carrier dispersed in gelatin.



In the lower half of the circle, the first developer has reduced the silver halide crystals to metallic silver.



In the upper half of the circle, oxidized color developer has combined with the coupler in the carrier.



The silver developed by the first developer and the color developer has been removed, leaving only the magenta dye.

In the Ektachrome and Eastman Color processes the coupler components of the dyes are placed in the emulsion layers during manufacture. A single color developer then serves to produce the three differently colored dye images.

Couplers coated directly in the emulsion layers have some tendency to wander through the gelatin. To prevent this effect, they are carried in microscopic globules of organic materials which are dispersed throughout the layers as shown on page 36. The organic materials protect the couplers from the gelatin and at the same time protect them from any chemical reaction with the silver halide. Hence a process of this type is known technically as a *protected-coupler* process. When the film is developed in a color developer, the oxidation product of the developing agent diffuses into the globules and there reacts with the coupler. The color of the dye formed in each layer depends on the nature of the coupler used.

On the other hand, in the Kodachrome process, the coupler components of the dyes are put into the film from processing solutions. As a result, it is necessary to use a black-and-white negative developer and three separate color developers, one for each dye. To confine color development to one emulsion layer at a time, selective re-exposure of the layers is also necessary. Each of the eight or more solutions must be carefully controlled for concentration of ingredients, temperature, and agitation. The processing is thus so complex that it requires elaborate equipment, together with accurate chemical control.

REPRODUCTION OF COLORS BY REVERSAL FILMS

The essential steps in the reversal process and the reproduction of colors by the processed film are shown on page 39. For purposes of illustration, the original subject is represented schematically by a row of color patches which includes the three additive primaries, the three subtractive primaries, and black and white.

First development produces a silver image in each layer which corresponds in density to the amount of exposure in that layer. Where the subject was white, for example, red, green and blue light were reflected to the film, and there is heavy density in all three layers. Where the subject was blue, blue light was reflected, while green and red light were absorbed. Thus there is density only in the blue-sensitive top layer; the silver halide in the other two layers remains undeveloped. Where the subject was yellow, green and red light were reflected, while blue light was absorbed. Hence there is density in the middle and bottom layers, but none in the top layer.

Coupler development produces from the remaining silver halide a positive dye image in each of the three layers, together with a positive silver image. When the silver images, both negative and positive, have been removed, only the three dye images remain. Perfectly registered, these images form a positive color image which can be viewed by transmitted light or projected.

When the processed film is placed over a source of white light, the various colors of the original subject are reproduced by subtraction of different components from the white light. For example, blue is obtained where cyan and magenta dye, but no yellow dye, are present. The cyan dye absorbs red light, leaving green and blue light; then the magenta dye takes out the green, leaving only blue. White is produced by the unobstructed passage of light through all three layers. Black is produced by heavy dye deposits in all three layers; these deposits absorb light of all colors.

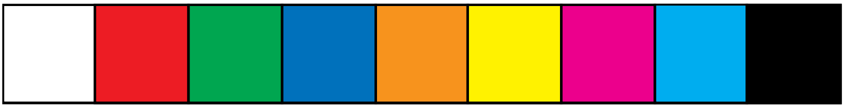
Intermediate tones and colors are secured by partial absorptions, as shown in the center of the diagram. Here a certain shade of orange is produced by a heavy deposit of yellow dye, half the maximum amount of magenta dye, and no cyan dye.

DYE CHARACTERISTICS

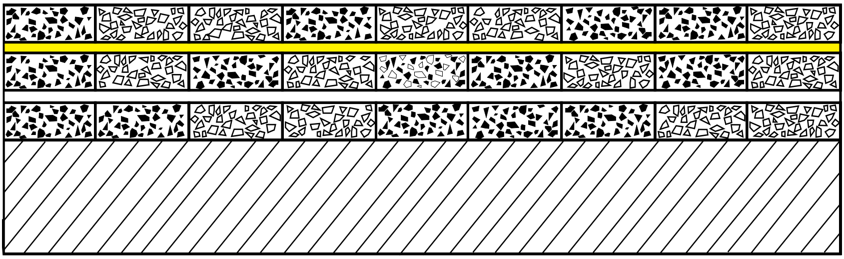
The best available dyes, pigments, and printing inks absorb some light which they should transmit. For example, a perfect cyan dye would absorb only red light, and would transmit green and blue light freely. Actual magenta dyes transmit red light freely, but absorb some blue light. Of the three dyes used in subtractive color photography, the yellow is the closest approach to the ideal. If equally good cyan and magenta dyes were available, definite improvements in accuracy of color reproduction could be obtained.

At first glance, it might seem that the dye imperfections would affect only the reproduction of colors more saturated than the dyes themselves. Unfortunately, however, the colors encountered in average photographic subjects are also affected, even though most of them are considerably less saturated than the dyes. Some colors are reproduced darker than they should be, and some are actually changed in hue.

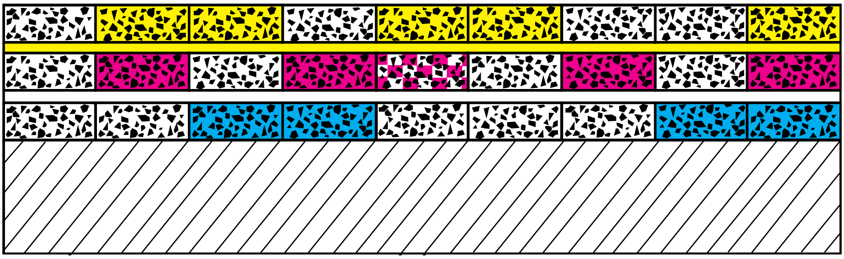
If a color process is to reproduce grays as grays, the quantities of the three dyes must be balanced so that the absorptions of blue, green, and red light are about equal. However, since the cyan and magenta dyes both absorb some blue light, less yellow dye can be used than would be the case if the yellow dye were the only one absorbing blue light.



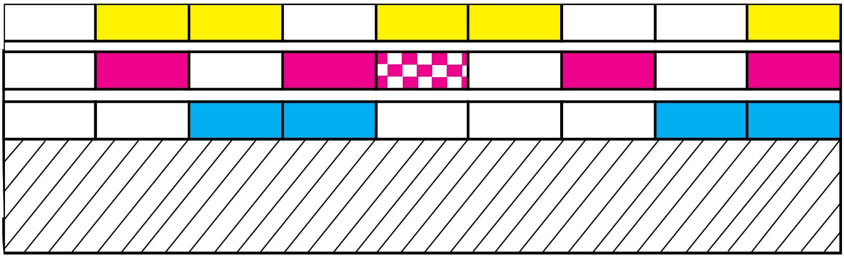
Original subject, represented schematically by color patches.



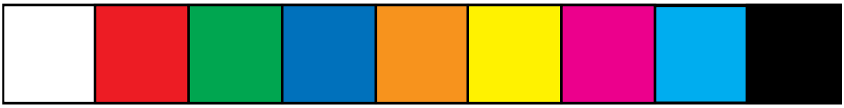
Cross section of color film after the silver halide grains exposed in the camera have been developed to produce negative silver images.



Cross section of color film after the remaining silver halide grains have been exposed to light and developed to produce positive silver and dye images.



Cross section of color film after both negative and positive silver images have been removed, leaving only the positive dye images.



Dye images as they appear when the film is viewed by transmitted light.

REPRODUCTION OF COLORS BY A REVERSAL COLOR FILM

As a result, there is not enough yellow dye in the film to reproduce yellows accurately. Thus when the exposure is correct for the picture as a whole, yellows are desaturated and too light, even though the yellow dye itself has better absorption characteristics than either the cyan or magenta dye.

This is one illustration of the fact that the nature of the dyes which are available makes it impossible to secure simultaneously the most accurate reproduction of all colors. Since experience has shown that at least four-fifths of all color pictures are taken of scenes including people, in practice, color processes are balanced to give the most pleasing reproduction of flesh tones. These tones, which require substantial amounts of yellow dye, are especially important because they are often very prominent in the picture and because the average observer tends to view a color reproduction with a rather firmly fixed idea of how flesh tones ought to look. With the adjustment of a color process to favor the reproduction of flesh tones, slight departures from neutrality may occur in the rendering of grays.

COLOR NEGATIVE FILMS

Color negative films have the coupler components of the dyes incorporated in the emulsion layers at the time of manufacture. After exposure in the camera, they are developed in a color developer which produces a dye image along with a silver image in each layer. The dye images perform exactly the same function that they do in the case of reversal color films, that is, each one controls the transmission through the processed film of the primary color of light which was used to expose that layer. Thus the same colors are used: cyan in the red sensitive bottom layer, magenta in the green sensitive middle layer, and yellow in the blue sensitive top layer. After color development, the silver images formed along with the dye images are removed by bleaching and fixing. The dye images which remain are negative with respect to the tone gradations of the original subject, and taken together, they are approximately complementary to the colors of the subject.

MASKING BY COLORED COUPLERS

We can now consider methods for overcoming the effects of incorrect dye absorptions in color printing processes. Photographic methods of color correction are known collectively as *masking*. As the word is used here, it refers to the superimposition of one photographic image on another in order to modify the results obtained in reproduction.

A mask may be either a negative or a positive and may be used with either a negative or a positive. Without masking, two types of errors occur in reproductions. The first are relative brightness and saturation errors, which distort the tone rendering of one color in relation to that of another. Blues, cyans, and greens tend to be too dark, while reds, oranges, and yellows tend to be too light. Losses in saturation of the colors occur, though the hues may remain unchanged. Second, and equally serious, are hue-shift errors, which change the actual hues of colors. With the coloring materials currently available, reds usually shift toward orange, magentas toward red, and cyans and greens toward blue.

Basically, making a color print from a color negative involves exactly the same reproduction errors as printing or duplicating a positive original. In contrast to positive originals, however, color negatives are not intended for direct viewing. Thus it is possible in the case of negatives to modify the color rendering in order to secure better quality in prints, disregarding the visual appearance of the negatives. The necessity for supplementary masking procedures can be eliminated by an ingenious "built-in" masking method which depends for its operation on the use of colored couplers.

The manner in which colored couplers improve color reproduction is best considered in terms of the three emulsion layers, top, middle, and bottom, which go to make up the color negative. As we have already seen, the real function of the dye images in these layers is to control transmission of the primary colors of light (blue, green, and red, respectively) through the negative when the color print is made.

For correct color reproduction, good "separation" of colors must be obtained, that is, each dye image must control one primary and *only one*. For example, the magenta image in the middle layer should absorb only green light, in varying amounts which depend on the proportions of green in the original subject. At the same time, the magenta image should transmit blue light and red light freely, or in other words, it should disappear when viewed through a blue or red filter. Actually, as shown in the upper illustration on page 43, an uncorrected magenta dye image absorbs some blue light, and it therefore interferes with proper control of blue light by the yellow dye image alone.

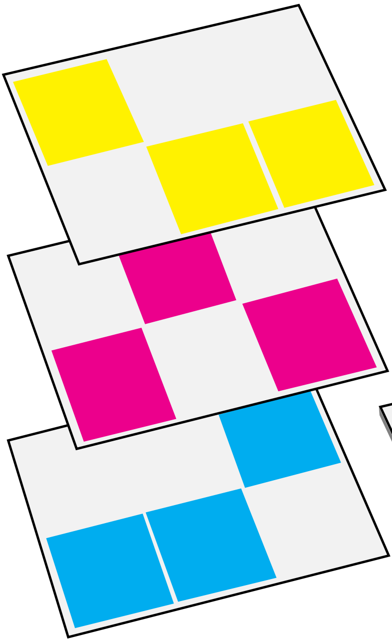
The unwanted blue absorption of the magenta dye cannot be eliminated, but its effect can be neutralized by choosing a magenta-forming coupler which is yellowish in color and *absorbs the same amount of blue light that would be absorbed if it were converted to magenta dye*. The middle layer then appears as shown in the lower illustration. Where the layer has been exposed, the coupler has lost its yellow color, but the blue absorption of the coupler has been replaced by the blue absorption of the magenta dye. Thus the absorption of blue light is the same everywhere in the middle layer, regardless of the distribution of exposed areas. The important result is that the magenta dye image now, in effect, absorbs only the green light which it should absorb. In other words, the combination of an actual magenta dye image and a yellowish coupler acts like an ideal magenta dye image plus a uniform sheet of light yellow filter.

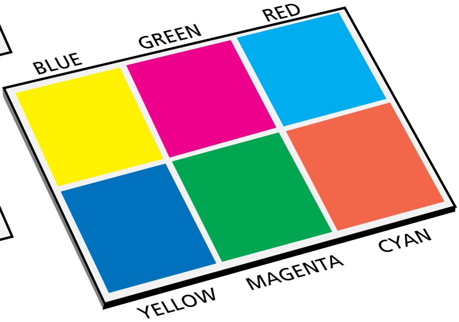
Similarly, the cyan forming coupler in the bottom or red sensitive layer is reddish in color, to absorb green and blue light in proportion to the unwanted green and blue absorptions of the cyan dye. After the film has been developed, the unused coupler remains in the film and allows the cyan dye to control only the transmission of red light. The coupler prevents the unwanted absorptions of the cyan dye from interfering with control of blue light by the top layer or control of green light by the middle layer.

The yellow forming coupler in the top or blue sensitive layer is colorless . The yellow dye formed from it absorbs almost no red light and very little green light. Thus color correction in this layer is less necessary than it is in the other two layers.

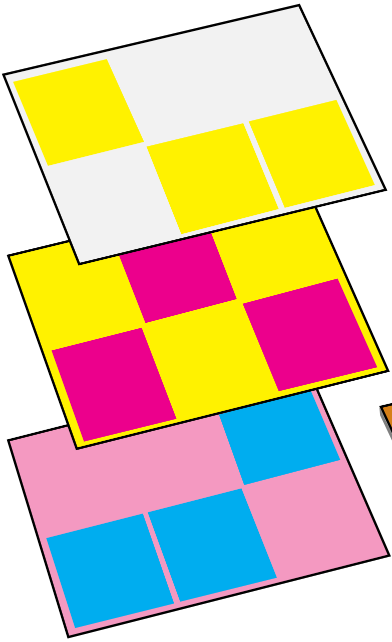
As a result of leaving colored couplers in the middle and bottom layers, the developed negative has a strong, over all, orange cast. In printing the negative, it is necessary to adjust the exposures through red, green, and blue filters to compensate for the absorptions added by the color-correction masks. When these adjustments have been made, the results obtained in prints closely approach those which could be obtained if dyes of perfect absorption characteristics had been used in the negative.

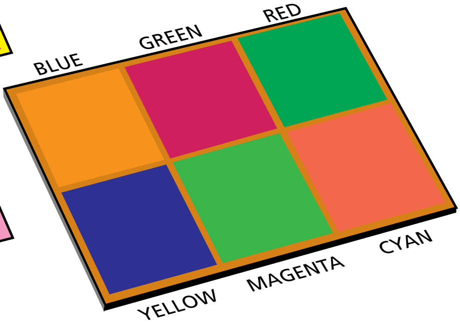
The color negative below was prepared from colorless couplers. At the left are the three emulsion layers as they would appear if they could be peeled apart. Examine the layers through KODAK WRATTEN No. 29 (red), No. 61 (green), and No. 47 (blue) Filters. If the dyes forming the images were perfect, each image would be visible only through the complementary filter. Actually, the magenta image is also visible through the blue filter, and the cyan image is visible through all three filters.





This negative was prepared from colored couplers. The unused yellowish coupler in the middle layer makes the magenta dye image apparent only through the green filter, and the unused reddish coupler in the bottom layer makes the cyan dye image apparent only through the red filter. Thus blue, green, and red light are controlled independently by the yellow, magenta, and cyan dyes, respectively. The dye images do not interfere with each other to cause errors in color prints.





PROBLEMS IN COLOR PHOTOGRAPHY

The following paragraphs describe some of the basic practical problems which to a greater or lesser degree are peculiar to color photography.

COLOR QUALITY OF ILLUMINATION

Though virtually negligible in black and white photography, the color quality of the light source is an all-important consideration in color photography. Essentially, the problem in color work arises from the fact that a color film does not always “see” colors as human beings see them. For example, if the cover of a book appears green in daylight, that is, in illumination which is a combination of sunlight and skylight, we think of it as having the same color in tungsten light. Although the difference in the quality of the illumination actually effects the quality of the light reaching the eye, our vision automatically compensates for the change. A color film, having no such automatic compensation, *reproduces color approximately as the eye sees it only when the illumination is the same as that for which the film is balanced.*

Contemporary photography accepts artistic license in the use of light sources which do not necessarily match the film’s color sensitivity.

Thus the book will be reproduced as green by daylight type film exposed in daylight, or by artificial light film exposed in tungsten light. If daylight type film were to be exposed without a compensating filter in tungsten light, it would reproduce the book as yellowish-green. Similarly, artificial light film exposed without a filter in daylight would reproduce the book as bluish-green. These variations in color rendering are illustrated on page 46.

Since, as suggested above, we tend to perceive colors as they appear in daylight, the objective of color films balanced for exposure in artificial light is to make the picture appear as if the light source were of daylight quality. This is also the objective of filters recommended for use when a color film must be exposed under lighting conditions other than the one for which it is balanced.

It must be emphasized that, *except for special applications, light sources which are appreciably different in spectral energy distribution cannot be mixed for any one exposure.* In viewing an original scene lighted by two different light sources, the eye adapts to an intermediate color quality, thus tending to minimize the visual effects of the color differences between the two sources. The film, however, has no power of adaption and will show the full color difference in parts of the subject illuminated by a light source differing in quality from that for which the film is balanced.

Color Temperature. For visual purposes, the color quality of a light source is evaluated in terms of the color of a perfect radiator, or "black body", heated to a certain temperature. This temperature is expressed in degrees Kelvin (K), obtained by adding 273 to the temperature in degrees Celsius. When the light source matches the black body in color, it is said to have a *color temperature* equal to the actual temperature of the black body in the Kelvin scale.

The color of light is bluer with higher color temperatures and yellower with lower ones. *Note that color temperature refers only to the visual appearance of a light source and does not necessarily describe its photographic effect.* For example, one type of "white" fluorescent lamp is rated at 3500K, but the spectral distribution of the light it emits produces photographic results quite different from those produced by a tungsten lamp operated at the same color temperature. *Color-temperature values for various daylight conditions also tend to be misleading when they are applied to color photography.* Tungsten lamps, however, have spectral qualities closely resembling those of black-body radiators, and in this case, color temperature is a reliable indication of photographic effect.

SUBJECT CONTRAST

At first glance, subject contrast might be considered as a property of the physical subject matter before the camera lens. Suppose, for example, that we are photographing a model wearing a white shirt and dark pants. If the shirt reflects eight times as much light as the pants, and these are the lightest and darkest objects in which detail must be reproduced, we might assume that the subject contrast ratio is 8 to 1. Actually, 8 to 1 is the reflectance ratio. From the point of view of the film, subject contrast involves an additional and very important factor, the *lighting contrast*.

Lighting contrast can be defined as the ratio between the highest and lowest amounts of illumination falling on the principal subject. Continuing with our example, let us assume that we are going to make a close-up with the simplest type of lighting, involving the use of only two lamps. One might be placed at the same distance from the subject as the camera, but on a line forming an angle of about 45° with the camera axis. This light would be the *key light*, and would cast shadows which, seen from the camera position, would delineate the contours of the subject's face. But the shadows cast by this single light would be very dark and would obscure some of the important detail of the face. To soften them, we might place another light close to the camera. This would be a *fill light*, because it would partially fill in with light the shadows caused by the key light.

Daylight type film exposed in daylight.

Daylight type film exposed with 3200K lamps.

Tungsten type film exposed with 3200 K lamps.

Tungsten type film exposed in daylight.

These photos show the results of matching or mismatching film stocks and light sources. Any combination may be acceptable depending on the color quality desired. The background in all four pictures is 18% gray; the woman is holding a blue notebook (Pantone color 2925U).

Great differences of light and dark in any scene cannot be reproduced successfully unless the lighting is adjusted to offset the extreme differences in brightness. Otherwise, dark areas will be much too dark and off-color, while light areas will be "burnt out", lacking color and detail.

Color negative films allow more leeway in the matter of lighting contrast than the reversal films, because you can make some adjustments for color balance during printing and/or in electronic transfer.

In this discussion, we have been speaking principally in terms of indoor work, which allows control of lighting contrast by variations in the placement of the lights. In outdoor work, the sun can be considered as the key light and the sky as the fill light. On a clear day, the ratio of sunlight to skylight is frequently too high for satisfactory detail in both shadows and highlights, especially with near by side or back lighted subjects. In such cases, the lighting contrast can be reduced by supplementing the natural skylight illumination of the shadow areas, either with a suitably balanced light source (which approximately matches daylight in color quality), or with reflectors to direct sunlight into the shadows. On a hazy day, the natural lighting is softer, and supplementary lighting is seldom necessary.

EXPOSURE ACCURACY

Compared to black and white or color negative materials, reversal color films have much less exposure latitude. In other words, there is a much smaller difference between the greatest and least amounts of exposure which will produce satisfactory results. Lens settings must therefore be determined with a correspondingly greater degree of accuracy.

In the determination of camera settings, an exposure meter can be of real assistance, especially under unusual lighting conditions and with complex studio lighting arrangements. Furthermore, photographers must be fully aware of the characteristics and limitations of the meter if they are to obtain consistently reliable exposure indications. For the most critical work, an actual photographic exposure test is recommended.

Daylight lighting conditions such as clear sun, hazy sun, etc., are constant enough so that it is practical to give fixed exposure recommendations in the form of tables, guides, and built in camera computers. These recommendations give excellent results under the specified conditions.

COLOR PERCEPTION

Color pictures occasionally show colors which appear faulty to an observer inexperienced in color photography, but which were actually present, unnoticed, in the original scene. In judging results, the photographer is frequently unable to compare the picture directly with the subject and uses a memory of the image instead.

If the photographer has not learned to observe color, that is to recognize subtle mixtures and reflections, colors which were not noticed in the original subject may appear when the photograph is viewed. These unnoticed colors are due largely to the effects of the lighting conditions and the surroundings.

An example is a snow scene, photographed in bright sunlight under a clear blue sky. Although it might be thought that shadows on white should be colorless, snow often contains bluish shadows. Actually, the shadows are bluish, and they appear so largely because the light that does reach them comes from the blue sky.

Claude Monet, *The Magpie* 1869, Musee d'Orsay, Paris, France. Giraudon/Art Resource, NY

A COMMENTARY ON THE MONET PAINTING

By Woody Omens

No one in the history of painting so keenly observed the nature of light and color like Monet. His eye, actually his retinal, sensitivity to color was superhuman. He saw fragile color most of us miss. Where most of us would see white snow everywhere, he saw it as warm one place and cool another. When it came to painting, he was not misled by the phenomenon *approximate color constancy* (see page 59). Monet's intuitive understanding of this phenomenon, in part, contributed to his unique color vision.

He never tired of seeing how the environment produced infinite coloration effects. He observed snow to be a substance upon which light *falls* and from which light is *reflected*. Light from the sun and the sky fell on the snow (*illuminance*) only to return to his eyes as a warm yellow gold tint in the sunny portions of snow, and cooler bluish in the shadow portions (*luminance*). The expanse of open blue sky above produced the fill light which caused the shadows to appear bluish. In this painting, he worked from actual observation of color, not from his memory of color. He painted the shadows on white snow as they actually were.

This painting is a masterful example of Monet's powers of observation long before refined color photography was available to demonstrate the accuracy of his color vision. Monet's eye was natural, instinctive, and expressive.

Exercise: Each day, observe these and other effects as light plays upon surfaces. Also study the color of human skin. How do various light and dark skin tones reflect environmental light differently? Think like Monet. Beware of the *approximate color constancy* phenomenon and other factors in the chapter on Perception.

Here are two books on Monet:
Monet by Robert Gordon and Andrew Forge. Harry N. Abrams, Inc., New York, NY., 1989
Monet by Christoh Heinrich. Barnes and Noble, New York, NY., 1996

A second example is a color photograph exposed early in the morning or late in the afternoon. The color of sunlight during these hours is quite orange, and as a result the picture comes out orange. The warmth of color and shadow effects obtained early or late in the day may be desirable.

Still a third example is a portrait of a model posed near a strongly colored reflecting surface. The face and arms may look perfectly natural at the time the picture is taken, but the colored light reflected on them may produce an unnatural effect in the finished picture. It is interesting to note that if colored surroundings are actually included in the shot, the resulting picture will seem more natural because the reason for the unexpected color in the subject is evident.

There are two reasons why such color effects are more difficult to recognize in viewing the original scene than in viewing a reproduction of the scene in the form of a color photograph. First, we commonly think of the color of a real subject as characteristic under all circumstances, and therefore do not expect any change. Second, in viewing the original scene, the eye tends to reduce disturbing illumination color by adapting to it in a way quite beyond the powers of the film. These factors will be considered at greater length under the heading *Perception* (page 51); here it is sufficient to point out that the photographer can learn to detect unwanted color effects in the original scene and take steps to prevent their appearance in the color picture. Photographers can attain a better appreciation of color and will improve their ability to remember colors and to control the results.

The foregoing should not be interpreted as indicating that Kodak color films will provide a perfect reproduction of the colors of the light which is reflected from a subject into the camera lens. If we make critical measurements on the very best color photographs, we find considerable differences between their colors and those of the original subjects. Actually, there is no available process of color photography which can be said to give entirely accurate and repeatable reproduction of color. Kodak color films, properly used, give satisfactory color rendering for their intended purposes, but in the present state of technical knowledge it is not possible to design materials suitable for making precise color records, or for matching or measuring colors. Further, since the reproduction of a physical subject by means of a color transparency or print involves psychological factors in the response of the observer, it can never be "perfect" in any simple sense.

Color photography allows full scope to originality and individual taste. An observant eye can find endless ideas for effective color schemes in paintings, printed and woven fabrics, interior decoration, and in the purely accidental combinations that occur in everyday life. The effectiveness of a given color scheme depends not only upon the colors themselves, but also upon their comparative areas and their distribution in the scene area. The textures of the colored surfaces are also important, because they lead to different color rendering under different lighting arrangements. Ease in composing with color is to a great extent the result of experience and observation.

COLOR BLINDNESS

A final consideration in our discussion of problems in color photography is the matter of color blindness. Few people realize how large a proportion of the population has defective color vision. Statistics on the subject vary because of differences in testing equipment and technique, however, it is safe to say that approximately 8 percent of men and 0.4 percent of women have some degree of anomalous color vision. Of those displaying defective color vision, approximately 2 percent of men and 0.03 percent of women are afflicted in such a way that it is dangerous for them to engage in occupations requiring the proper recognition of colored signal lights. Such cases can be identified with the test charts that oculists and qualified optometrists have.

Anomalous color vision usually dates from birth, but may also be acquired as the result of certain types of injury, disease, or poisoning. There are many types and degrees, some individuals see one part of the spectrum as gray; others see another part as gray. Usually, people who have defective color vision merely experience difficulty in distinguishing and naming colors. In many cases, the deviation from normal color vision is so slight that it is never recognized.

There is no reason why the majority of people with anomalous color vision cannot engage in and enjoy color photography. In serious cases, however, duplicating and color printing processes should be undertaken with caution, because the individual control allowed by such processes may lead to results which are not acceptable to those having normal color vision.

PERCEPTION

In the section on color films, we touched on the deficiencies of the dye systems used in subtractive color photography. We should now consider some of the other reasons why a color photograph does not always turn out as we expect it to. At first glance, it might seem that if we had a color process capable of yielding a point for point reproduction of the subject, we could obtain a color photograph equivalent to the subject. Actually, however, such a color process, though physically perfect, could not take into account the psychophysical factors in our visual process, because the response of the film to the original scene must always be fixed, not variable like our visual response. Furthermore, the reproduction could not change itself to compensate for variations in the lighting conditions under which it, in turn, might be viewed. The following paragraphs discuss not only the more important of the visual effects which influence our judgement of a given scene, but also the photographic consequences which these phenomena entail. In this discussion, we shall confine ourselves to effects which are experienced by all observers having normal vision, disregarding effects which vary with individuals. On the other hand, it must be recognized that the perception of color is often affected by such factors as experience, emotional mood, stimulation of senses other than vision, and personal associations of colors and objects with ideas.

BRIGHTNESS ADAPTATION

There are three main types of brightness adaptation: general, local, and lateral. All three are constantly at work in the process of vision.

General Brightness Adaptation. One of the most remarkable characteristics of the visual mechanism is its ability to operate over a tremendous range of illumination levels. Dilation and contraction of the iris of the eye can account for a change in the light energy falling on the retina of only 16 times, at the most. The process which allows great extension of this range by changes in the sensitivity of the retina is called *brightness adaptation.* Sensitivity increases in dim light and decreases in bright light in such a way that the effective response of the eye is maintained more or less constant.

General brightness adaptation, or adaptation to the average brightness of the scene, is valuable in allowing us to see well at almost any given illumination level. From a photographic point of view, however, it has the disadvantage that we are unable, because of the variable sensitivity of our eyes, to estimate the actual intensity of the light.

Although the central patch is exactly the same in all cases, simultaneous brightness contrast makes it appear to vary from dark to light as the background is changed from light to dark.

For example, when we enter a room from outdoors, the lower illumination level causes a gradual increase in sensitivity, and we may eventually get the impression that the indoor scene is as bright as the outdoor one. Hence, we are often surprised at the relatively long exposures which must be given in making pictures under interior illumination. We may learn by experience what the exposures should be under conditions which are familiar and more or less reproducible, but we are at a loss when confronted with conditions which are out of the ordinary. We may then rely on some purely physical instrument such as an exposure meter. In any case, the necessary adjustments in camera lens settings can be considered as substitutes for the power of general brightness adaptation which the film lacks.

In connection with exposure determination, it is interesting to note that our judgment of the brightness of a scene is influenced to a considerable extent by the contrast of the lighting. For example, an outdoor scene on a gray day appears less bright than a contrasty stage scene, yet the average brightness is usually much higher in the case of the low contrast scene. Color effects also enter into the comparison. Overestimation of the brightness of the stage scene is due in part to our tendency to associate high saturation of colors with bright sunlight conditions.

Local Brightness Adaptation. In the process of viewing any given scene, the eye views one object after another, stopping for a brief interval at each point of interest. At each of these stops a readjustment of brightness adaptation takes place locally. The readjustment is very rapid, but sometimes we are aware of “afterimages” due to a lag in recovery of the local sensitivity of the retina. For example, if we look long enough at a bright light, we see a dark image of the light when we shift our gaze to a light-colored reflecting surface.

Lateral Brightness Adaptation. Sensitivity changes in local areas of the retina are often accompanied by similar changes in adjoining areas. This "sideways" or lateral brightness adaptation is exemplified by what happens when we look at a moderately dark object surrounded by considerably brighter ones. The sensitivity of the retina is decreased in the light areas of the image formed in the eye, but at the same time the decrease in sensitivity extends into the dark areas of the image, thus producing an apparent darkening of the dark object. Such changes in the appearance of adjoining objects are known as *simultaneous brightness contrast* effects. They depend to a considerable degree on the relative areas and positions of the objects; in extreme cases the amount of detail visible in a dark object may be decreased. The illustration on page 52 shows the differences in the appearance of the same gray patch when it is seen against different backgrounds.

BRIGHTNESS CONSTANCY

Though we seldom stop to think about them, we are continually making mental adjustments in what we see. By making such adjustments, we become aware of the "true" characteristics of an object, and are not misled by the purely physical aspects of the light reaching our eyes.

Various "constancy phenomena" are prominent among the mental adjustments we make. Size constancy, for example, is illustrated by the fact that people at a distance do not *look* smaller than those close at hand. A man at 100 yards forms a retinal image which is one-tenth the size formed at 10 yards, and yet he doesn't look smaller– he simply looks further away.

Approximate brightness constancy, a similar effect, makes us tend to see objects in terms of their *reflecting power rather than the amount of light they actually reflect*. Thus we can almost always identify a piece of white paper as white even though it is placed in shadow where it actually reflects much less light to the eye than a piece of gray paper in full illumination. In its psychophysical basis, brightness constancy is closely related to general and lateral brightness adaption.

Although brightness constancy effects are very strong in viewing the original scene, they are usually much weaker in viewing a reproduction of the scene. This fact is extremely important to the photographer, because it means that to obtain the most realistic effect, he or she must almost always make compensating adjustments in the lighting of the scene.

The problem of photographing an indoor scene furnishes excellent illustrations of the adjustments that must be made. Before considering the effects involved, however, we should have clearly in mind the basic difference between sunlight and most types of artificial light.

An outdoor scene, illuminated by sunlight, has the same amount of light falling on all unshadowed areas, assuming that no reflector or supplementary light is used. The illumination is the same over all parts of the scene area, because the sun is such a tremendous distance away that any differences in the distances of various objects from the light source are negligible. Indoors, the situation is entirely different. Here the light sources are usually close to objects in the scene and the decrease in illumination with distance from a light source assumes vastly greater importance, especially since this decrease is roughly proportional *to the square of the distance*.

With an indoor scene which has considerable depth, the falling away of light from the front to the back of the set is a serious problem. Unless corrective measures are employed, it will show up very strongly in the reproduction, even though brightness constancy makes it difficult to see at the time the picture is taken. Brightness constancy tends to make all objects in the set and immediate surroundings appear normal to the eye, in spite of the fact that some of them may be illuminated to far too low a level for proper rendering in a photograph.

Background Rendering. Proper rendering of the background is very important in color work. When the subject is close to the background, say within two feet of it, separate illumination of the background is usually unnecessary. When, however, the background is several feet behind the subject, separate background illumination may be employed, because the falling away of illumination with distance is more serious and because the farther the background is from the principal subject, the more it will tend to be seen as an unrelated area in the reproduction. The more unrelated the background appears, that is, the less it is connected to the principal subject by the shadows falling on it, the weaker will be the brightness constancy effect carried over into the reproduction. Accurate color representation of the background will be obtained when the illumination falling on that background is equal to the key light falling on the subject in the foreground.

Shadow Effects. The effects of brightness adaptation and brightness constancy are pronounced in large shadowed areas of a scene. Such areas may be perceived in three ways: first, as part of the scene as a whole (general brightness adaptation): second, with the intent of seeing as much detail as possible within the shadow (local brightness adaptation); and third, the shadow goes completely unnoticed as being a shadow (local brightness adaptation and the maximum brightness constancy effect). These variations in the perception of shadows are not theoretical but thoroughly practical, as will be apparent from examination of the illustrations on the next page.

(Upper Left) This photo approximates the actual tonal range of the location. The lighting contrast between the sunny areas and the shadows is so great that very little shadow detail is visible.

(Upper Right) This photo illustrates how our perception uses the brightness constancy effect. We will tend to interpret objects in the shadow areas brighter than they really are based on our knowledge of their customary brightness not their measured brightness in this location.

(Lower Left) When the viewer approaches the subject and eliminates the bright sunlight, the iris of the eye opens up and the shadow detail becomes truely visible and the brightness constancy effect diminishes. The shadow which was acting as a fill light in the other two photos is now the key light.

When we see a familiar face, we seldom notice the shadow of the nose or whether the eyes are hidden in shadow. Instead, we picture that face mentally as if it were lighted in such a way that no shadows existed. Consequently we are surprised, and perhaps blame the limited latitude of the film, when we look at our first images and find the face half buried in deep shadow. Brightness constancy has caused us to see a scene that was not there at all.

The strength of the brightness constancy effect carried over into a still photographic print (either a black and white or color) depends strongly on the degree to which the nonuniformity of the illumination falling on the original scene is evident in viewing the print, as shown below. However, in a two-dimensional print, there is always a serious loss of brightness constancy, because the print is viewed as an object in its own surroundings. *Hence shadows always appear darker than they did in the original scene.* As a consequence, the most realistic results are obtained only when the lighting is arranged in such a manner that the *lighting contrast* of the scene as viewed by the eye is very much *less in all respects* than is desired in the final picture. This statement indicates the true meaning of the term “flat lighting,” which was so often recommended for color photography.

It should be noted that flat lighting cannot be produced with a single light unless the light is placed over the camera lens, and that this procedure fails completely if there are objects at various distances from the lens.

In the left photo, the left-hand gray scale looks darker than the right-hand scale. When seen from a different angle in the center photo, its clear that the left-hand scale is darker because it’s in shadow. In the right photo showing the partition removed, both scales are revealed as being identical.

Lighting Distribution. We have already seen that a background far enough behind the subject to appear unrelated to it must be illuminated to approximately the same level as the subject if normal color rendering is to be obtained. Otherwise we may find that a poorly illuminated light background, for example, comes out darker in the reproduction than a strongly lighted dark object in the scene.

Actually, the same precaution applies to all parts of an indoor scene which are not visibly related to the principle subject in their lighting. Thus normal color rendering in all areas of the scene will be obtained *only when the whole scene is adequately illuminated.* If the lighting is not carefully distributed, there may be areas that will be reproduced so dark that color and detail are lost. Such areas will be plainly visible in the transparency or print, even though the visual effects already described make them difficult to recognize in viewing the original scene at the time the photograph is made.

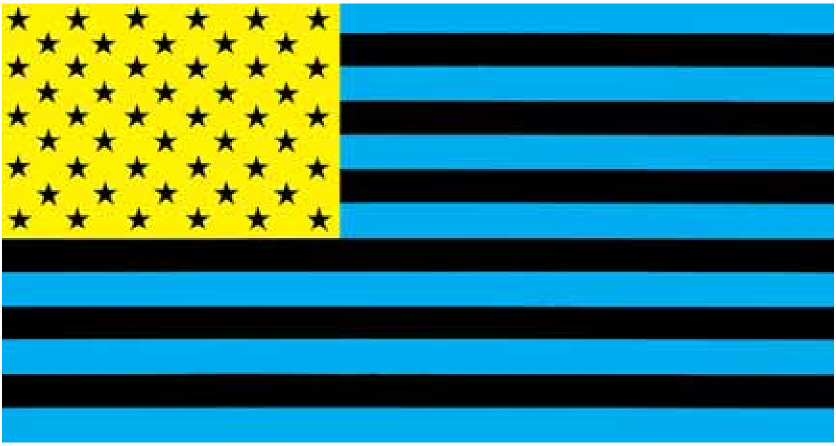
COLOR ADAPTATION

Like brightness adaptation, color adaptation can be classified into three main types which operate simultaneously in the process of seeing. To a considerable extent, all three function independently of brightness-adaptation effects.

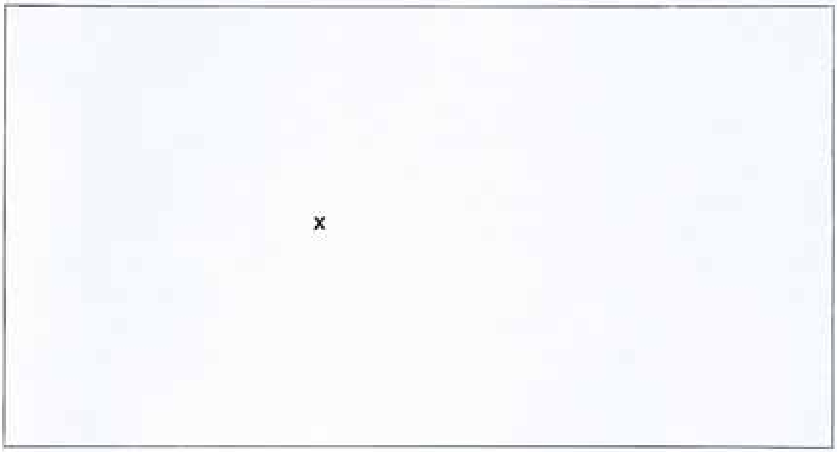
General Color Adaptation. In viewing any given scene, the visual mechanism adapts its color sensitivity in such a way that the illumination tends to appear colorless. This power of adapting to the color quality of the prevailing illumination is known as general color adaptation. By means of it, we become less aware of the physical conditions existing at the time and gain a better idea of how the scene would appear if viewed under conditions of our own choice. Thus we are not "misled" for example, to the conclusion that objects seen at sunset are actually ruddy in hue. As previously emphasized, however, a color film, having no powers of adaptation, will reproduce the over-all color balance of the scene as the eye sees it only when exposed under illumination of the quality for which the film is balanced.

If the scene is illuminated by two light sources which differ in color quality, the eye minimizes the color differences by adapting to an intermediate illumination color. Thus the effect of a greenish condenser lens, a reflector which is not neutral, or a lamp of the wrong type is difficult to see in viewing the original scene.

Local Color Adaptation. When there are fairly intense colored areas in the field of view, sufficient exposure of the eye affects subsequent vision in the corresponding areas of the retina. Fixation of the eye on a particular area for a brief time, followed by a fixation on another surface, gives rise to characteristic colored afterimages. A familiar example is shown on the page 58.



With this page illuminated by a fairly strong light, stare fixedly at the star in the lower right corner of the yellow field while counting 20 seconds. Then quickly shift your gaze to the black cross in the rectangle below. The flag will immediately appear in colors complementary to those printed above. The afterimage seen in this way is due to local color adaptation. In the area of the retina where the yellow field is first imaged, for example, the sensitivities of the red and green receptor systems are reduced by prolonged exposure to a mixture of red and green light. Thus, when the yellow field is replaced by white paper, red and green are subtracted from the neutral white, and a blue image results. As the receptor systems recover their sensitivities, the afterimage fades.



Lateral Color Adaptation. The effect of colored areas on the appearance of an adjacent colored area is similar to that induced by lateral brightness adaptation, except that here the result is an enhancement of color contrast, known as *simultaneous color contrast*. The group of four illustrations on page 21 demonstrates both brightness-contrast and color-contrast effects. The bluer appearance of the central patch at the lower left is due to simultaneous color contrast.

COLOR CONSTANCY

Perhaps the most important of all effects due to visual adaptation is the phenomenon known as *approximate color constancy*. Although, as previously mentioned, the character of the radiant energy reflected from a colored object varies considerably, depending on the spectral energy distribution of the illumination, we are not ordinarily aware that there is much difference in the appearance of the object. In fact, we are accustomed to think of most colors as not changing at all. This effect is due in large part to our tendency to remember colors rather than to look at them closely.

We do at times *fear* that the color of an object may look different in daylight from the way it appears under tungsten light. For example, in buying clothing, we may take it to a window. There we form a mental impression of its appearance in daylight, and this appearance becomes the "real" color, which remains approximately constant even if we later see the clothing under a wide variety of illumination conditions. Our tendency to accept the daylight color of an object as our mental standard may be based on the fact that humans have always depended on the sun as the most important source of illumination.

Although the color constancy effect is strong for most colors and most light sources, under certain conditions the color of an object may change decidedly. The conditions under which color constancy fails were described on page 19.

SUGGESTED READING on Color and Color Cinematography

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- Light and color
- Characteristics of colors
- Kodak color films
- Problems in color photography
- Perception
- Suggested reading

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