LIGHT and COLOR

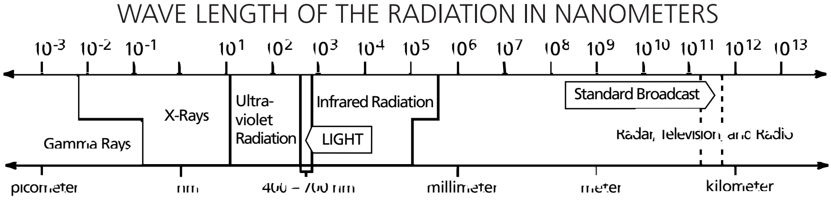
To understand any process of color photography, we must have a definite idea of what is meant by “color”. And since color depends first of all on light, it is well to start by examining the nature of light itself.

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.

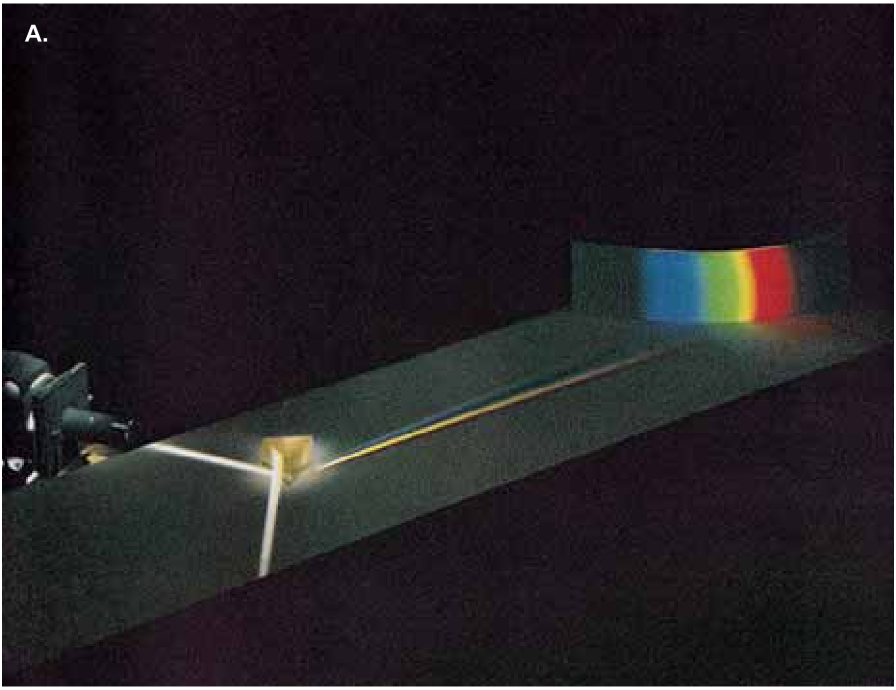
Below 400 nanometers are the ultraviolet rays, and above 700 nanometers are the infrared rays. Though we cannot see either, it is easy to demonstrate that they are very similar to the radiations constituting light. For example, it is well known to photographers that infrared rays can be focused by a 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*.

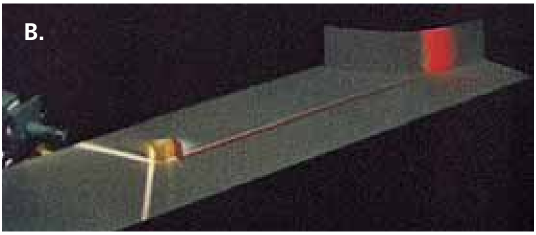
With this definition in mind, we can draw some further distinctions. Radiant energy is *physical*, because it can be said to exist independently of a human observer. In the wave-length range to which the eye is sensitive, however, radiant energy serves as a stimulus which acts on the eye and produces 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

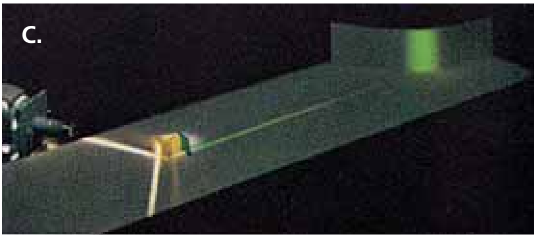
So far we have been considering the physical nature of the radiations that give rise to the visual sensation of light. We have noted that the eye has a certain wave length range of sensitivity, but that the rays to which it responds are not particularly different from others. The wave lengths comprising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



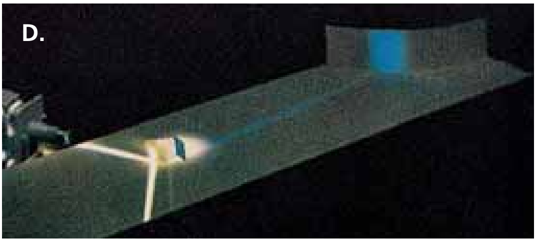
A. The prism bends light of the shorter wave lengths more than light of the longer wave lengths, thus spreading a narrow beam of white light out into the visible spectrum. (The beam extending toward the bottom of the picture is reflected from the surface of the prism without entering it.)



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

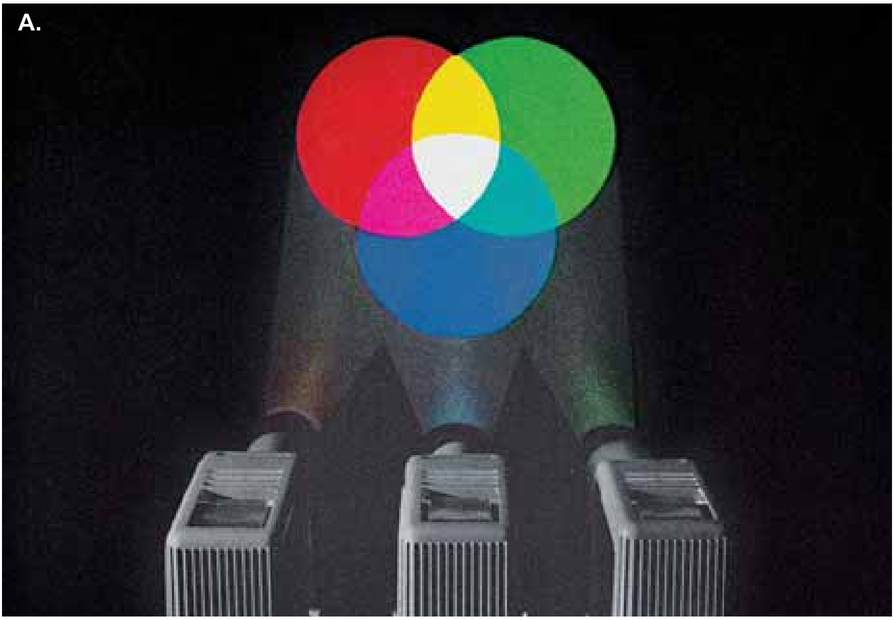
In order to understand how the human eye sees colors, let us consider the action of light filters, shown by the three small illustrations on page 5. If we place a red filter in the path of the light coming from the prism to the screen, we find that the blue, blue-green, green and most of the yellow regions 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.

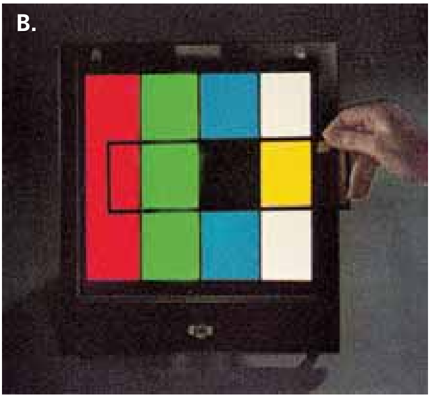


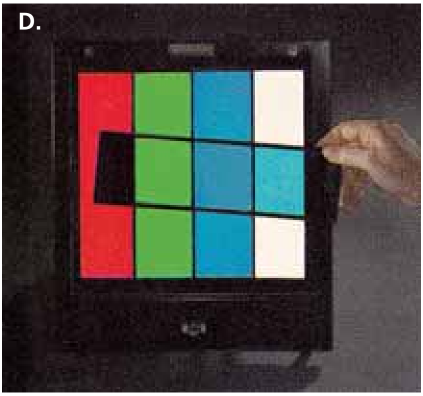
A.) Additive mixture of the colored light from projectors covered by red, green, and blue filters. Combined in pairs, the beams give cyan, magenta, and yellow. Where all three beams overlap, all three of the visual receptor systems are stimulated, and the screen appears white.

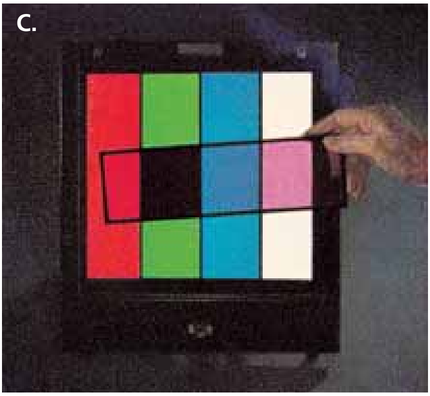
B.) A yellow filter absorbs blue light, transmitting green and red light.

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.

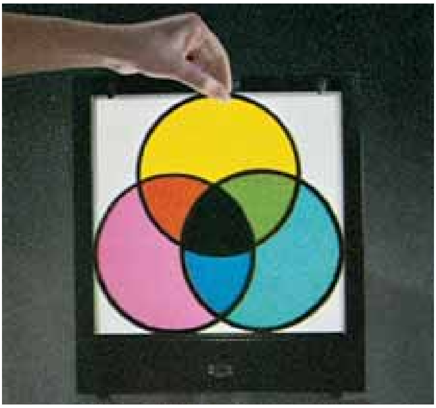
With the cyan, magenta, and yellow filters, however, this is not the case. Since each of the filters transmits about two-thirds of the spectrum, we can superimpose them over a single light source to produce other colors, as shown at the top of page 13. The combined subtractions of any pair give one of 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.

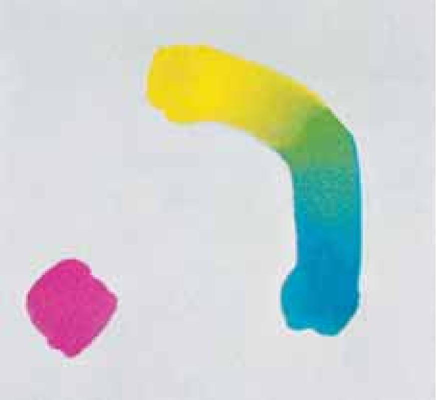
As everyone who has ever used a set of water colors probably knows, a large variety of colors can be matched by making appropriate mixtures of three suitably chosen primaries, commonly called “red,” “blue,” and yellow. If the range of colors so produced is to be as complete as possible, however, the “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.