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.

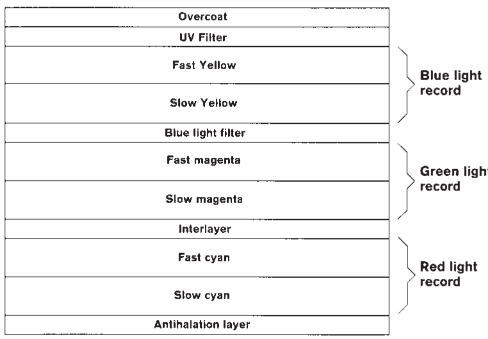
A frame of motion picture film is a remarkable piece of engineering. Packed into its microscopically-thin layers is an incredibly complex system of chemical and physical processes that must all interact perfectly to produce a color image.

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.

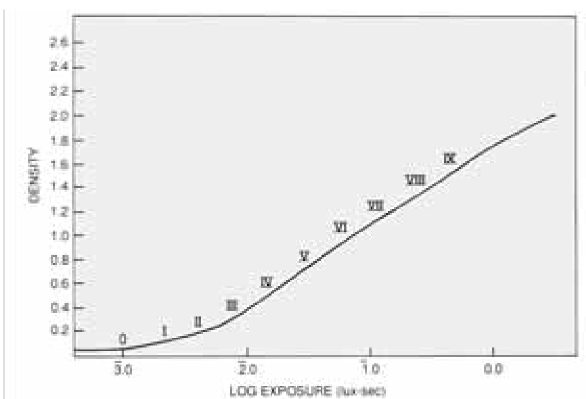
When the color film must be exposed by light of a color quality other than that for which it is balanced, correction can be made by the use of filters. It should be noted, however, that errors in color rendering may result even when using the most appropriate color filter.

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

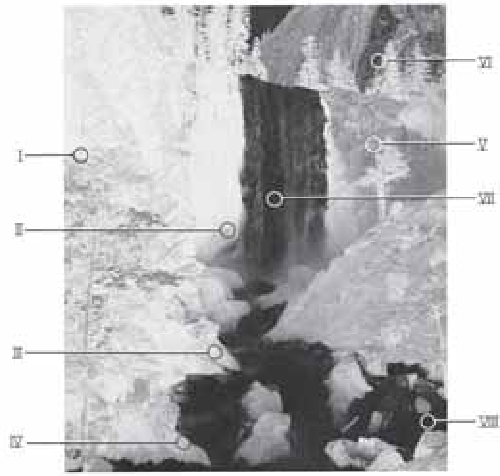
REFERENCE KEY

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.

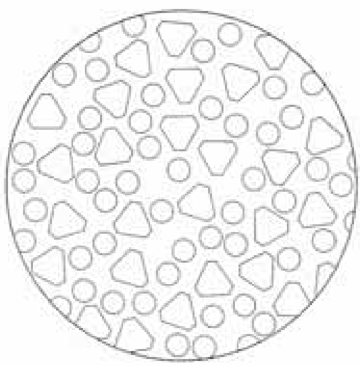
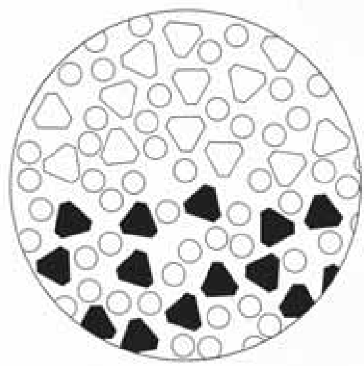
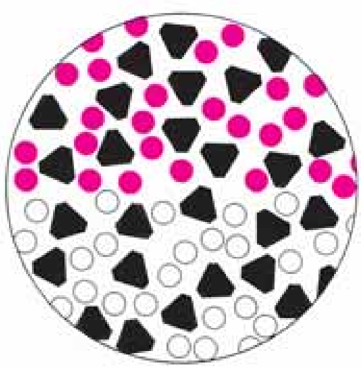


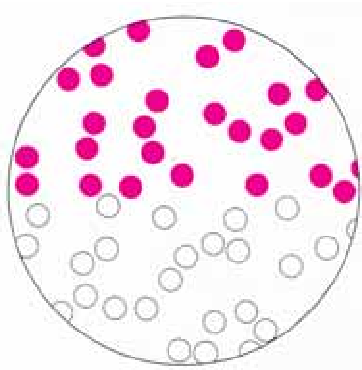
Diagram of Ektachrome film emulsion, showing crystals of silver halide and globules of carrier dispersed in gelatin.



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.

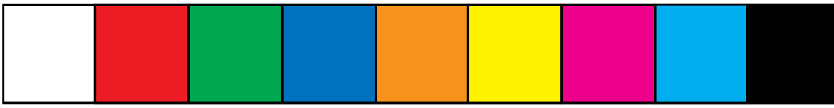
Intermediate tones and colors are secured by partial absorptions, as shown in the center of the diagram. Here a certain shade of orange is produced by a heavy deposit of yellow dye, half the maximum amount of magenta dye, and no cyan dye.

DYE CHARACTERISTICS

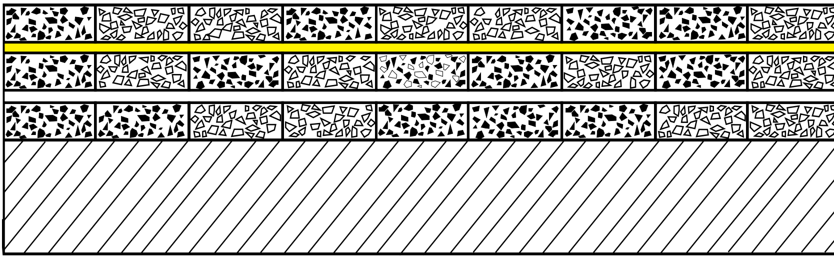
The best available dyes, pigments, and printing inks absorb some light which they should transmit. For example, a perfect cyan dye would absorb only red light, and would transmit green and blue light freely. Actual magenta dyes transmit red light freely, but absorb some blue light. Of the three dyes 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.

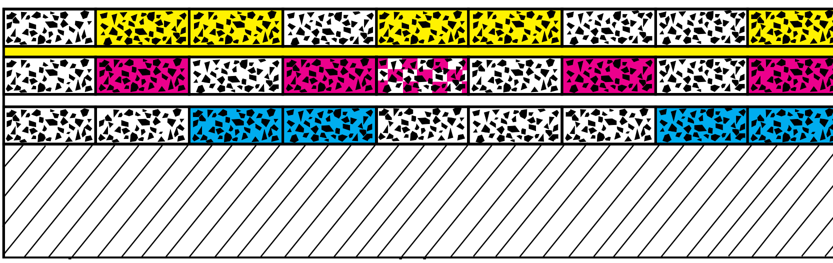
If a color process is to reproduce grays as grays, the quantities of the three dyes must be balanced so that the absorptions of blue, green, and red light are about equal. However, since the cyan and magenta dyes both absorb some blue light, less yellow dye can be used than would be the case if the yellow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



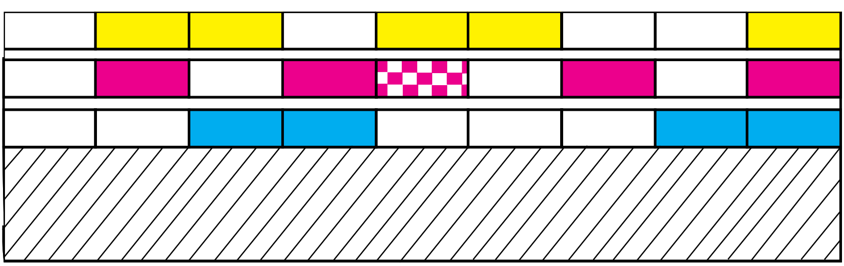
Original subject, represented schematically by color patches.



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.

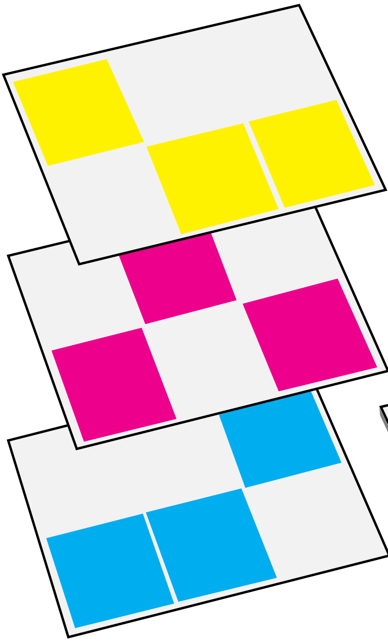
The unwanted blue absorption of the magenta dye cannot be eliminated, but its effect can be neutralized by choosing a magenta-forming coupler which is yellowish in color and *absorbs the same amount of blue light that would be absorbed if it were converted to magenta dye*. The middle layer then appears 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.

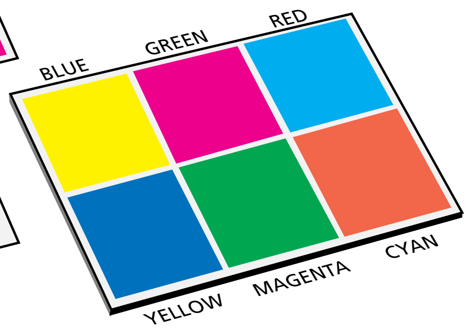
Similarly, the cyan forming coupler in the bottom or red sensitive layer is reddish in color, to absorb green and blue light in proportion to the unwanted green and blue absorptions of the cyan dye. After the film has been developed, the unused coupler remains in the film and allows the cyan dye to control 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.