Chapter 9

LIGHT AND COLOR

What Is Color?

Different wavelengths cause the eye to see different colors.

Color is a human phenomenon. To the physicist, the only difference between light with a wavelength of 400 nanometers and that of 700 nm is wavelength and amount of energy. However a normal human eye will see another very significant difference: The shorter wavelength light will cause the eye to see blue-violet and the longer, deep red. *Thus color is the response of the normal eye to certain wavelengths of light.* It is necessary to include the qualifier "normal" because some eyes have abnormalities which makes it impossible for them to distinguish between certain colors, red and green, for example.

Only light itself causes sensations of color.

Note that "color" is something that happens in the human seeing apparatus—when the eye perceives certain wavelengths of light. There is no mention of paint, pigment, ink, colored cloth or anything except light itself. Clear understanding of this point is vital to the forthcoming discussion.

Color vision is complex and not completely understood.

Colorants by themselves cannot produce sensations of color. If the proper light waves are not present, colorants are helpless to produce a sensation of color. Thus color resides in the eye, actually in the retina-optic-nerve-brain combination which teams up to provide our color sensations. How this system works has been a matter of study for many years and recent investigations, many of them based on the availability of new brain scanning machines, have made important discoveries. These discoveries have made it evident that the workings of color sensation, indeed, all elements of seeing, are even more complicated than previously thought. Nevertheless, after taking these new-found complications into consideration, it appears that the basic three-color theory based on three kinds of receptors in the eye still holds. The manner in which nerve impulses from these receptors are processed however is complex indeed. Fortunately, the lighting designer or technician need not be involved in this complexity.

To be accurate, any reference to sensations of color should be attributed to the eye-optic-nerve-brain complex. This terminology is awkward. Therefore henceforth in this text references to the eye should be read to include the entire eye-optic-nerve-brain complex.

Eye = eye-optic-nerve-brain

Color vision is probably the most precise determination that our senses make. The wavelength difference between one color sensation and another is only a few hundred-millionths of a centimeter, yet the trained eye of a color expert can perceive millions of hues and never mistake one for another. Anyone with normal vision can do almost as well.

Readers may wish to refer to Chapter 5 where physical nature of light is detailed. As noted there, a number of kinds of spectra are commonly discussed by physicists, astronomers and other scientists. However "the spectrum" to artists, including lighting designers, refers to that part of the vast radiant energy spectrum that the normal eye can see, with occasional references to those wavelengths just longer or just shorter than visible light, i.e., infrared and ultraviolet. In the past the spectrum has, for artists and lighting technicians, referred to a continuous spectrum, often compared to the rainbow. This is still applicable but with the caveat that some modern light sources produce line spectra and the technician and artist must deal with the way these affect color mixing.

The spectrum

Continuous spectrum

Labeling Colors

The spectrum provides the physicist with a catalogue of all of the individual wavelengths the normal human eye can see. Wavelength, as displayed by spectral analysis, is still the most accurate way to describe the potential capacity of a beam of light to affect the eye or to react physically. However there are color sensations called *nonspectral hues* some of which are not represented by individual wavelengths of the spectrum. These are sensations produced by mixtures of red and blue light; there are no single wavelengths which can elicit them. They are commonly identified scientifically by referring them to their complements, which do lie on the spectrum and can be identified by a single wavelength. Thus a purple-magenta might be referred to as the "complement of 530 nm green." However artists are apt to leave this scientific notation to the laboratory and depend on more artistically friendly ways of organizing colors for reference. Perhaps the most universal of these is the color wheel.

Identifying nonspectral hues

Color Identification: the Color Wheel

The color wheel shown in Plate VI is, in effect, the spectrum simplified into samples of color and curled around on itself to allow for the inclusion of the red-blue mixtures. Thus the color wheel can be said to be a simplified map of all the colors the eye can see. However it is important to note that most color wheels are labeled according to the subtractive system because they refer to colorants. Therefore the primaries are identified as red, yellow, and blue, and secondaries as purple, green and orange. *Primaries* are colors which cannot be made by mixing other colors within the system, *secondaries* are equal mixes of primaries.

Primaries and secondaries

The color wheel tends to be a tool for those who work with pigments instead of light. It is particularly useful for working out color harmonies. A number of other color labeling systems are also in use. One of the most complex and comprehensive is the Munsell system which arranges all pigment colors into a "color solid." Yet another, much used in printing and graphic arts, is the Pantone color system which is a catalogue of color samples together with formulae for producing the colors using printing inks. All of these systems relate mainly to color in dyes, inks and paints. Their ability to represent colors in light is limited because of limited brightness. In lighting, there is, theoretically, no brightness limit and, indeed, the practical limits far exceed anything possible with pigments or dyes. Therefore lighting artists often find the C.I.E. Chromaticity Diagram (hereafter, C.I.E. Diagram) (Plate I) more useful because it deals directly with the way wavelength mixtures affect the eye. While the C.I.E. Diagram also has its limits as far as brightness is concerned, it is so arranged that one can extrapolate brightness outside of the range of its printed version. The color triangle, discussed in detail below, is a simplification of the C.I.E. Diagram often used by lighting artists to estimate the effects of mixing colored light and/or the use of colored light on colored objects.

Munsell system

C.I.E. Chromaticity Diagram

Spectroanalysis for Color Identification

Spectroanalysis

In the scientific world, spectroanalysis (analyzing light by breaking it into a spectrum and measuring the amount of each wavelength present) is a highly precise tool used, for example, to identify the presence of even exceedingly minute amounts of elements in a sample and by astronomers to determine the composition of distant stars by analyzing their light. The theatre takes advantage of this major scientific procedure to accurately describe color media—a much less precise but very useful procedure. Practically every manufacturer of color media provides sample books of its product accompanied by simple spectroanalysis charts (i.e., spectrograms) of the transmissivity of each sample. These spectrograms are simplified versions of graphs created by a spectrophotometer set to plot the sample against a known standard such as equal energy white light. Although Plate III shows such a spectrogram superimposed over a spectrum in color, no color medium booklet will provide this much assistance. The user must picture the spectrum from the numbers (usually stated in nanometers) arranged across the bottom of the graph.

Spectrograms of color media

A major advantage of a spectrogram is that the user can closely estimate the amount of light being transmitted by the filter at any wavelength and can estimate from this what the effect of this light will be on any pigment illuminated by it. A resourceful lighting artist or technician can also mentally sum up the transmission from two media to find out what the effect will be on objects lit by the combination in, for example, a cross-spotting situation.

Overall transmission

An additional bit of information accompanying most theatrical spectrograms is the inclusion of an overall transmission figure. This sums up the light from all visible wavelengths transmitted and gives the user some idea of the brightness that an instrument equipped with this medium will contribute to the stage, ignoring color. Just as important, it tells the user what percentage of the light striking the medium will be absorbed into the filter and converted into heat, which will ultimately destroy most media.

Those lucky enough to be using very sophisticated luminaires equipped with dichroic filters (see below) should note that these filters can be evaluated by the amount of each wavelength they transmit but that, instead of absorbing the rest, usually including the infrared, they reflect it elsewhere.

Sources of Colored Light on Stage

Even with all of the recent advances in lamp technology and the development of new, more efficient, light sources, most colored light used on stage is made in the old-fashioned, highly wasteful way: an inefficient (by modern standards) incandescent lamp is used to make white light which is then filtered to get the color(s) wanted. The remainder of the white light plus an unavoidable and often large portion of the light sought, is absorbed by the color media and turned into heat which can degrade many filter materials and harm equipment.

Making colored light by absorption is wasteful.

Some more efficient alternatives to this method are now available but have yet to find widespread use in the theatre because of high initial cost and, more complicated electrical and optical arrangements. These will be discussed later.

Stage color filters: absorption

The filters discussed below all work the same way: They screen out the unwanted wavelengths, plus a share of those wanted and pass the remainder on to the stage.

Lamp dip

Early vacuum lamps ran cool enough to allow the use of colored lacquers as colorant. These lamp dips were applied by dipping the bulb into the lacquer while it was on and allowing the heat to dry the lacquer. The lamps were then used in early borderlights and footlights.

This process was no longer practical when gas-filled lamps were developed because their bulbs ran at temperatures high enough to char the dip. Presently lamp dips are occasionally listed in supply catalogues to be used with very small vacuum lamps in property devices such as artificial “fires” or for painting projection slides.

Glass

Colored glass has been made for centuries and was used as a light colorant even before electrical lighting entered the theatre. It was and still is expensive, heavy, and breakable, not only if dropped but also by heat stress. However, barring breakage, it is practically permanent. Pieces of colored glass many hundreds of years old still retain their color. However, as lamps became more powerful and the heat became greater, glass soon became obsolete, with the exception of colored glass roundels used in footlights and borderlights. These persist to the present. They are available in primary red, green and blue, pink, white and sometimes other

Glass is “permanent.”

Roundels

colors. Roundels are usually molded to perform lens functions as well as serving as a colorant. Many are shaped into a crude fresnel cylindrical lens which aids in controlling light distribution, others are shaped with a bumpy or mottled surface to even out light distribution.

Gelatin

The first replacement for glass and lamp dip was gelatin. This was simply the food material that had been dyed, poured out in sheets and allowed to dry. It was fragile, dried out to even greater fragility, faded rapidly and, if it encountered dampness returned to its original gelatinous state as a lump of gluey uselessness. Nevertheless, it served the theatre's needs for a number of years and gave its name to the process of installing color media in equipment: *gelling*. The term now applies to all color media and to the process of installing them: Whatever its composition, it was and is called gel. The name has persisted through several "generations" of color media, each an improvement over the predecessor. Presently, many technicians would be hard-put to explain where the name originated and might not recognize a sample of gelatin color medium if presented with one.

"Gel" has become part of the theatre vocabulary.

Plastics

Acetate media

After gelatin came a series of plastics beginning with cellulose acetate. It faded, warped and was flammable. Later came other plastics until presently proprietary formulations of polyester, polyvinyl acetate, polycarbonate, or similar high-heat-resistant materials are in use. Dyes have improved as well, making many color media almost as durable as glass. The best is so durable, and expensive that some manufacturers offer differing grades of medium depending on the amount of heat the user expects it to encounter. Failure, when it finally comes, may be a progressive deterioration of the surface of the medium accompanied by warping which ultimately makes it unusable. Even then, fading may not occur.

Plastic color medium is the "standard" in the theatre, being available in a very wide variety of colors and in several brands. Sample color books are part of every lighting designer's or technician's equipment. Most designers can cite the brand names and numbers of their "favorite" colors from memory. Plastic media are also available in frost which disperses the beam and in a variety of striated forms that spread the light beam at right angles to the striations leaving it unchanged (except for some diffusion) parallel to the striations.

Media that also control distribution of light

However plastic color media suffer from another handicap besides their ultimate failure from heating. In the case of saturated colors, particularly blue and green primaries, they are inefficient both as to the amount of the desired light transmitted and as to the transmission of unwanted wavelengths. Primary blue is notorious in this regard. Some blue primaries transmit only 50-60 percent of the wanted blue light and still leak significant amounts of deep red. When this problem is added to the fact that incandescent light is already deficient in blue, it is clear that producing a pure blue field, say on a cyclorama, is a costly, power consuming process. Efficiency, as measured from the input of electrical energy through to the blue light delivered on stage, may be as low as one per-

Inefficiency in saturated cool colors

cent. Other hues in the blue and green range are also inefficient, more so as they become more saturated. Therefore the arrival of a kind of filter that produces pure blue or green efficiently and with few impurities is good news even at much higher cost.

Dichroics

Unlike all other filters used in the theatre, dichroics do not work by absorbing light and dissipating the energy, mostly as heat. Instead, they utilize a phenomenon known as *interference*, one of the classic proofs of the wave theory of light. An effect of interference is often seen when a thin film of oil is somehow dispersed over a still pool of water. Light striking the pool is broken into colors that depend on the thickness of the oil film and the angle at which the light strikes. Dichroics separate out various wavelengths by precisely controlling the thickness of layers of materials carried on a glass substrate. This makes them capable of sorting out wavelengths, reflecting some and allowing others to pass through producing beams of colored light of great purity and with relatively little loss of the wavelengths wanted. Note the sharp cutoff and high efficiency of the spectrogram of the dichroic filter in Figure 9.1.

Interference

Dichroics are a high-efficiency means of sorting light waves.

Dichroic materials are made by placing a substrate (a foundation material, usually heat resistant glass) in a vacuum chamber. Various materials are then vaporized in the chamber and deposited on the substrates to form very thin (molecule thick), layers whose thickness is adjusted to under half of the wave length of the light to be controlled. A variety of materials is used by various manufacturers to make up dichroic coatings including aluminum, silver, gold and oxides of silicon and titanium. These filters have several applications for the theatre:

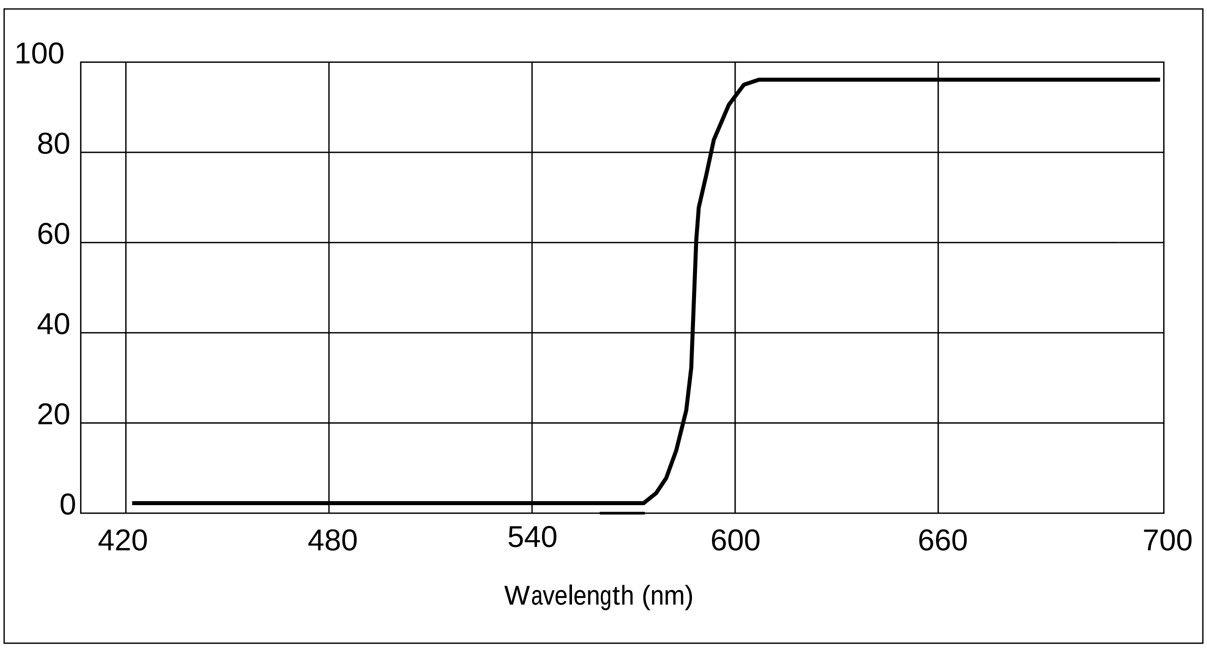

Figure 9.1. Approximate spectrogram of a red dichroic filter. Note the sharp cutoff, the lack of impurities and the high level of transmission of wanted light.

- *High quality light filters:* The dichroic material can become a filter of very high efficiency which produces light of exceptional purity, including pure blue.
- *Heat control mirrors:* The material can be used to make reflective surfaces that can sort heat wavelengths (infrared) from visible light thereby controlling the path of waste heat in a luminaire
- *Multicolored gobos:* Multicolored gobos can be made up displaying images created by controlling the deposition of the material on the substrate. Such gobos produce colors of high purity and efficiency and are very durable because they absorb little heat.
- *Anti-reflection coatings for high-quality lenses:* Projection lenses and camera lenses can be treated with dichroic coatings to reduce surface reflection, thereby increasing the efficiency of the lens. This process is too expensive for use in most theatrical spotlight lenses, but not for the more sophisticated lenses used in scenic projection or in automated luminaires.

Dichroic filters

These can be made to pass a wide variety of wavelengths, but the most useful are those that produce the primary colors, (RGB) from white light making three-color mixing a much more efficient process than when absorption filters are in use.

Dichroic primary filters are commonly installed in modern automated luminaires where they are used to produce a huge variety of colors. Since they are normally left installed in these luminaires, they are not subject to the kind of handling that might cause breakage. Although they are expensive, they have a very long life. Dichroic glass is also available (albeit expensive) in sheet form for installation in other equipment.

Dichroic mirrors

Although not a color medium itself, the dichroic mirror is a development that contributes much to the life of color media. It consists of a different application of the dichroic principle: Instead of sorting white light to produce colored light, the material is used to sort infrared from visible light, i.e., dichroic mirrors are heat control filters. There are two types: cold mirrors and hot mirrors. A *cold mirror* will transmit a major part of the system's heat and reflect the visible light (Figure 9.2B). For example an ellipsoidal cold mirror will allow the IR to pass through into the rear of the luminaire but reflect the visible light forward into the lens system. A *hot mirror* does the opposite—it reflects the heat and transmits the visible light (Figure 9.2A). Such a mirror might be mounted just before the slide in a projector, protecting the slide from IR heat. A system utilizing both a cold and hot mirror can remove as much as 99% of the IR heat from an optical system while transmitting about 90% of the visible light. Operators must remember that the back of such luminaires will get much hotter than that of a conventional luminaire of the same type.

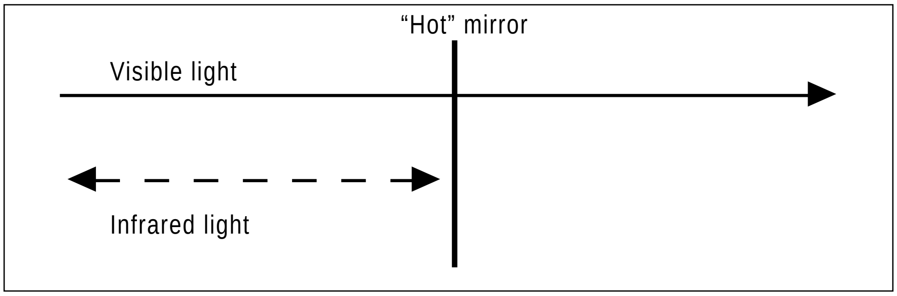

Figure 9.2A. "Hot" Mirror. Note that the dichroic coating transmits the useful light toward the stage but the infrared light is reflected by the mirror and dissipated away from the heat-sensitive slide or effects device.

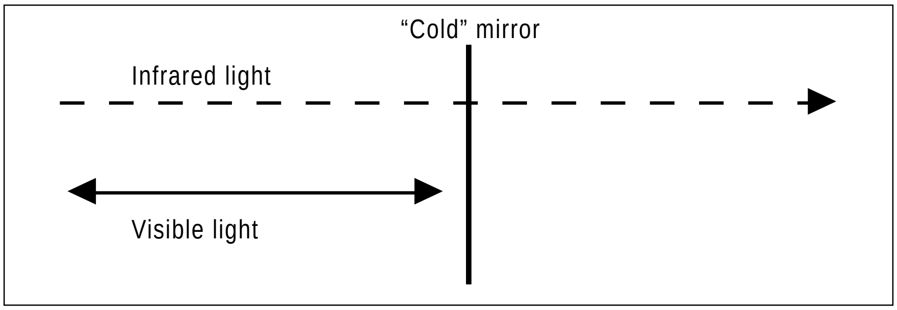

Figure 9.2B. "Cold" Mirror. This mirror allows the infrared light to pass and reflects the visible light. It is often formed into a spherical, ellipsoidal or parabolic mirror which collects useful light and passes the infrared to the back of the luminaire where it is dissipated.

Dichroic gobos

Conventional gobos are made from heat resisting metal and can project a silhouette onto the stage when installed in an ellipsoidal reflector spotlight or a modern automated luminaire. A single color may be added to the lighted parts of the silhouette by adding a color filter.

Colored gobos

More sophisticated gobos are available, although at a price. One type of these is made of dichroic-coated glass and may be had in a single color or multicolored. In addition to providing a colored image, these gobos operate with the same efficiency and low heat absorption characteristics as regular dichroic filters.

Other Sources of Colored Light on Stage

It is clear that the incandescent lamp is a poor source of visible light and an even poorer source of cool colored light. HID lamps, for example, operate much more efficiently than incandescent lamps, particularly at the blue end of the spectrum. Thus even with no change in the quality of the filters used, overall efficiency can be raised substantially by using HID lamps. Using dichroic filters further increases efficiency.

The ideal light source would be one that could be tuned to produce any wavelength or combination of wavelengths needed as a point source without filtration, dimmable, and without wasting energy. This goal remains elusive although there are available a number of sources that produce single wavelengths or narrow bands of wavelengths. These include lasers, long arc discharge lamps, such as sodium vapor lamps and "neon" sign tubes, and fluorescent lamps with special phosphors to produce "pure" colors. Unfortunately none of these meet the remainder of the specifications for the "perfect light source." They all need extra equipment such as ballasts, are far from point sources, usually cannot be dimmed other than mechanically and still waste a sizeable portion of their output as heat or unwanted non-visible light. Thus, for the present, the theatre must make do with the inefficiency of the incandescent lamp or, only somewhat better, the complications of short-arc gaseous discharge lamps.

Color by Reflection

A commonly overlooked source of colored light is the colored light reflected from colored objects. An aggravating example is the green light that bounces off a grassy lawn and lights up the lower parts of faces in photos taken of people standing on the grass. The eye ordinarily learns to ignore this effect, which, although present most of the time, is usually unnoticed. However when a photo is taken, the green "footlighting" is suddenly very evident and disliked.

Bounce light

Bounce light on stage can act the same way, producing sometimes distracting colored shadows on faces and flooding parts of the setting with unwanted color. The solution is to track down the offending luminaires and reangle or re-gel them or to remove or cover the surface causing the reflection.

Color Mixing

Additive and subtractive systems

Since all sensations of color, with the exception of those few induced in laboratory experimental situations, originate when light enters the human seeing apparatus, we begin our discussion of color and color mixing with an examination of that apparatus. Be sure to keep in mind that, for the purposes of our discussion, the word "eye" will be shorthand for "the eye-optic-nerve-brain complex" that creates and interprets our color sensations. As our discussion proceeds we will find evidence that there appear to be two "systems" that describe color mixing: the *additive system* and the *subtractive system*. It will eventually be apparent that these two are really interlocking parts of a single comprehensive explanation of color. This problem is further complicated by semantic confusion. Color names refer to entirely different colors as the discussion moves from one "system" to the other. This too will need to be dispelled as we proceed.

Three sensors for red, green and blue

The study of the physiology of color vision has progressed over the years but its original concept, the Young-Helmholtz theory remains intact. Thomas Young's assertion in the late 1800s that the eye contains three types of sensors, one for each of the three fundamental color sensations, has since been verified by examining the chemicals in each of the three types of sensors thereby verifying their responses to light of specific wavelengths.

However continuing research into the remainder of the seeing apparatus has brought both more understanding and more confusion about the details of the chain of nerves that moves the signals from the eyes to the brain and, in the process, makes major changes in their nature. Indeed, the safest comment on the whole process is that it seems to be considerably more complicated than was earlier thought and that we do not yet have all of the answers.

Rods and Cones

The retina of the eye is the layer of sensitive cells on which the image formed by the lens is focused. Its surface layer is made up of the sensitive ends of special cells, many of which are shaped like minuscule rods and other like cones, their flat ends toward the image. The rods are sensitive to light of all visible wavelengths but do not distinguish between wavelengths, although their sensitivity tapers off at either end of the visible spectrum. Therefore rods do not contribute to color vision. They do, however, have greater sensitivity to light than the cones and function in very low light situations that the cones cannot handle. Thus in very low light we are all color blind.

Rods are "color blind" but function in very low light levels.

The cones are the focus of our attention; they are responsible for our color vision. There are three types, each containing a unique chemical that is sensitive to a part of the visible spectrum. When light of proper wavelength strikes these chemicals, they change and the body immediately strives to return them to their original state. In this process, messages start on their way through the optical nerve to ultimately arrive at the brain where they are interpreted as color sensations. If a single-color stimulus is presented over the entire visual field for an extended period of time, the strength of the sensation generated diminishes. This visual fatigue reduces the attention value of the stimulus and leads to the saying: "All of a color is none of a color." The design problem this phenomenon generates will be dealt with later.

Cones provide color vision.

Visual fatigue

Also, when a strong color stimulus is presented for a period of time, the chemical reaction in the cones tends to overshoot. Then when the original stimulus is removed, the eye produces the sensation of the complement to the one originally presented. This effect is called an after image which will usually alternate between the color of the stimulus and its complementary.

Adaptation

The pupils of our eyes adjust to protect the eyes from too-bright light. This is known as *adaptation* and is done by the iris, the colored circle of tissue that surrounds the pupils, contracting to make a small size opening when exposed to bright light. Closing down happens very rapidly when bright light strikes the eyes but the reverse, opening up when the light is dim, happens much more slowly. This slow adaptation to dim light after exposure to bright light is what makes us nearly blind upon entering a dark room such as a movie theatre from the bright, sunny outdoors. This phenomenon must be taken into account when changing from brightly lit to dark scenes on stage and can also be exploited to accomplish open-curtain scene changes in near darkness. If the crews await the end of a brightly lit scene with their eyes closed, they will be able to see to make the shift while the audience is still bright-adapted and thus

Adapting to dark scenes

nearly "blind." However speed is necessary, the audience' eyes will soon begin to adapt.

Persistence of Visual Images

Motion pictures

The sensing process that takes place in the eye-optic-nerve-brain complex is not instantaneous. It takes a small but measurable amount of time to develop and, more important, a longer time to diminish after the stimulus is removed. Thus still pictures presented at more than about sixteen frames per second are seen as continuous movement, i.e., as motion pictures. Visual persistence also makes possible one type of color mixing discussed below.

Contrast and Brightness Changes

Contrast depends on the overall brightness of the stage.

Contrast is the apparent difference in intensity between two parts of the visual field. At very low light levels, even low degrees of contrast are apparent; as the overall brightness of the field increases the eye becomes less sensitive to contrast differences. At very high brightness levels it takes a much higher contrast difference to be apparent to the observer. Thus a small change, say, one half point on a dimmer, will be very apparent on an otherwise almost dark stage. Such a change will not even be noticeable when the stage is brighter.

Color Stimulus Mixing

Response to mixed stimuli involves much of the optical chain.

As we have indicated, various wavelengths presented to the eye will produce sensations representing a synthesis of the stimuli presented. This synthesis does not take place, or at least is not completed at the retina, a fact which can be demonstrated by holding a piece of color medium, say a light straw, over one eye and a piece of, say, light steel blue, over the other. This will produce two separate color sensations, one in each eye. If one closes an eye, one sees the color covering the other eye, etc. When both eyes are open and the viewer is looking at a white surface, he or she will see the mixture of the two colors, sometimes, depending on the individual, as a stable mix and sometimes alternating between the mix and the individual colors. Clearly, the mixing is taking place somewhere along the optical chain beyond the individual eyes. Complex research in the laboratory also confirms what this simple test reveals: The mixing of color sensations is indeed a complicated process.

Primaries are defined by the peaks of the sensitivity curves.

The peak of sensitivity for each type of cone encompasses a band of closely spaced wavelengths any or all of which can produce essentially the same sensation. These three peaks define the three primary colors, red, green and blue, which will be discussed in detail below.

How We Control the Color Sensations We Experience

Except in the laboratory where some visual effects can be created from within the seeing apparatus, all the visual sensations we experience, including color, are caused by stimuli from outside of the body. Thus "seeing colors" is the result of the entry of various wavelengths into the eye.

Terminology

- *Color sensation*: as noted above, this is a response to the entry of light into the human seeing apparatus (assuming that the subject is not blind or color blind). This response may be verbalized as "pink," "blue" or any color name.
- A *colorant* is any material that has the property of absorbing some wavelengths of light and reflecting others. Note that colorants cannot generate light; they can only affect light already present.

Color mixing: two definitions

1. The mixture of color sensations in the eye. This can be done in any of the several ways discussed below, but the result is always the direct stimulation of the seeing apparatus.
2. Mixing colorants. This is done by mixing paints, dyes, pigments and the like. The result is a combination of pigments that reflects any wave lengths reflected by all of the ingredients. No stimulus to the eye results unless the proper wave lengths of light are used to illuminate the mixture.

Unfortunately these two definitions get used indiscriminately adding confusion to the understanding of the art and science of color.

We will first study color mixing as defined according to definition 1 above. It can be done in several ways:

1. Different wavelengths or bands of wavelengths of light can be presented to the eyes at the same time. This is the common theatrical method: For example, specific wavelengths are filtered from white light and directed toward a cyclorama from which they are reflected to the eye where they elicit color sensations.
2. Various sets of wavelengths may be presented to the eye in rapid succession. If this is done rapidly enough, the persistence of vision will cause the sensations to blend together producing the same effect as if all of the wavelengths were presented at once. This is the method of color television which presents red, green and blue images in such rapid succession that the eyes see them as one full-color picture.
3. Color sensations can be divided into tiny parts of the visual field, so tiny that the eyes see them as blended together. This is the basis of pointillage, a painting technique developed by the impressionists and also the basis of much color printing where tiny dots of color are laid down on the page in a way that causes the eyes to see them blended together.

Note that each of these methods has the effect of adding together stimuli in the eye. Thus they are called additive color mixing or the *additive system*. In contrast, the mixing of colorants is termed the *subtractive system*. It will be detailed presently. To understand additive color mixing more completely we must examine the way the three kinds of color sensors in the eye respond. The groups of wave lengths at the peak of each of the three curves are called *the primary colors*. "Primary" means that combinations of these colors can be used to mix

The three primary colors

any other color but that no mixture of other colors within the system can produce the sensations of the primaries. *Secondary colors* are equal-brightness mixes of two primaries.

Confusion caused by the two definitions of color mixing begins here: The terms, "primary" and "secondary" are also applied to the mixing of colorants (color mixing definition number two) which refers to a different set of colors and produces very different results. The first step in eliminating this confusion is to clarify exactly what the additive primary colors are. This is best done by reference to their wavelengths:

Primary colors

WAVELENGTHS OF ADDITIVE PRIMARY COLORS

Color Name	Approximate Wavelengths
red	780 nanometers
green	520 nanometers
blue	480 nanometers

Still more confusion must be resolved: color names. The names *blue* and *red* refer to very different colors depending on whether one is talking about color sensations in the eye or mixing colorants. Therefore, it is important to note the actual hues as they are reproduced on Plate I or, better still, on a computer reproduction of the *Commission Internationale de l'Eclairage* Chromaticity Diagram (C.I.E. Diagram) mentioned below as displayed on a well-calibrated color monitor.

Secondary colors

Secondary colors are yellow, cyan (blue-green) and magenta. They can be evoked by equal-brightness mixtures of the primaries:

R + G = Yellow
G + B = Cyan
B + R = Magenta

The C.I.E. Diagram

Although there are a number of ways of organizing color relationships, most of them concerned with relationships between colorants, the one most useful to lighting artists and technicians is the C.I.E. Diagram (Plate I). It shows the way the primaries, red, green and blue intermix to produce sensations of all of the colors on the spectrum and also those nonspectral colors that are mixtures of blue and red. Moreover, it is precise if the user has the proper data to exactly locate colors on it. Until the development of Gelfile, a software catalogue of color media that locates almost every color medium available on the C.I.E. Diagram, the designer was reduced to making an educated guess as to the exact location of a color to be referenced. This reduced the precision of the diagram and left many designers with a preference for the color triangle (below) although it is far less accurate. Gelfile is available on the Internet from GAMPRODUCTS.

Once colors have been located on the map, two-color additive mixes are easily worked out by joining the two colors with a line. All mixes will be located on that line, their position depending on the relative brightness of the two sources. Thus the designer will have available the entire array of mixes between the two colors he or she has under consideration. One can even attempt an estimate of dimmer ratios apt to produce the color sought. However there is a catch: dimming shifts the color temperature of incandescent sources toward red and throws off the calculations based on the diagram. Most designers simply depend on their experience instead of attempting to reach a quantitative answer.

Red shift throws off color calculations.

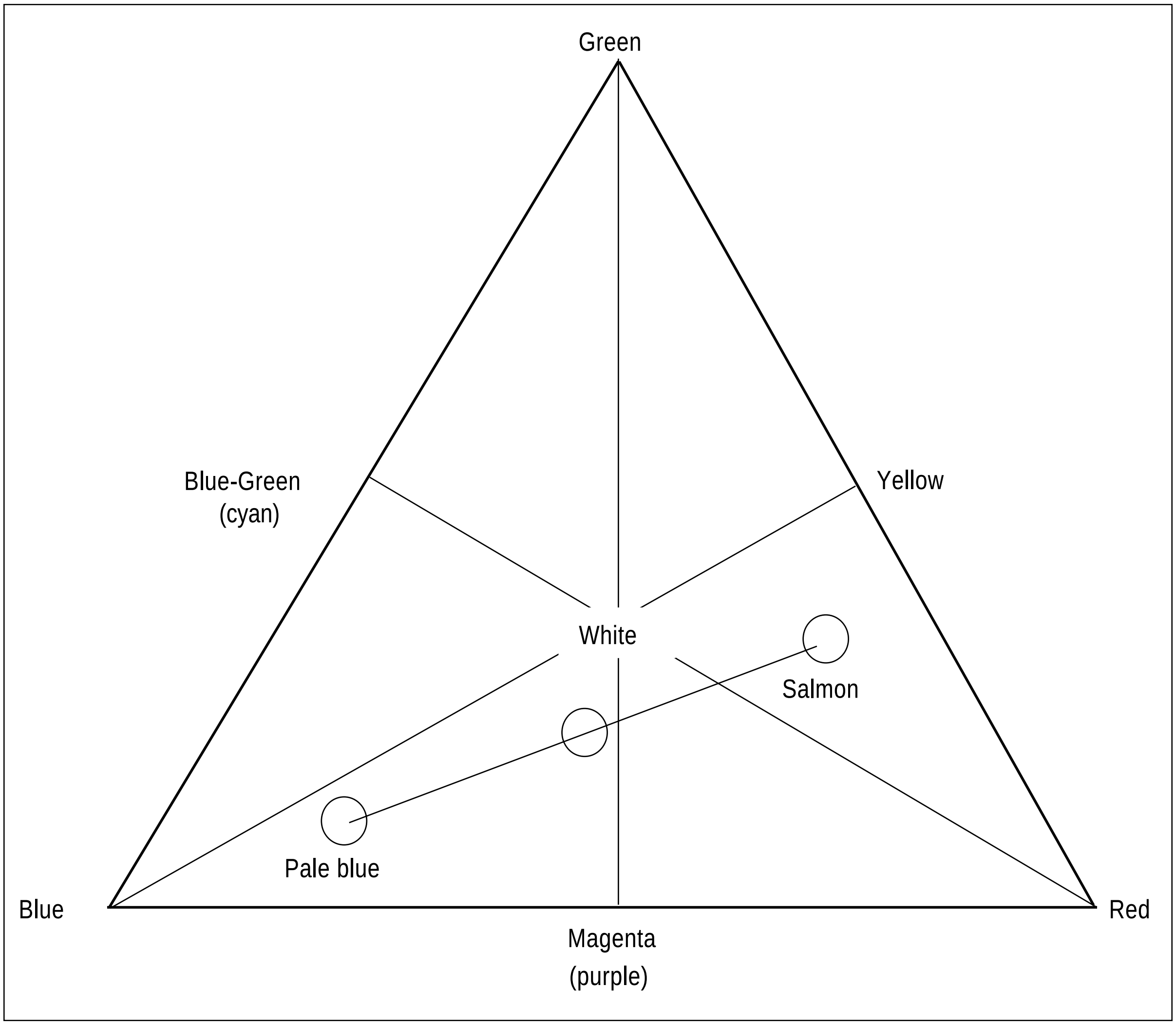

Figure 9.3. Color Triangle. Essentially the C.I.E. Diagram (Plate I) simplified by reducing it to an equilateral triangle with the three light primaries located at the apexes, this diagram is useful for quick estimates of additive color mixing. A sample mix of salmon and pale blue has been plotted to illustrate its application:

1. Locate the approximate position of the two hues on the triangle using eyeball estimates or by referring to the Gelfile version of the C.I.E. Diagram (available on the Internet) and transposing this information to the triangle. Note that some manufacturers of color media may include the C.I.E. coordinates of their media in their spectrogram booklets.
2. Draw a line between the two points located. This line will be the locus of all additive mixes of the two hues, the position of the resultants depending on the relative amounts of the two hues. If the amounts are equal (as estimated by brightness to the eye), the resultant will be at the midpoint of the line, as shown. Other proportions can be estimated by moving the resultant point toward the color which predominates in the mix.

Those using either system should keep in mind that mixes worked out apply *only to luminaires at "full."* Any dimming will shift the mix toward red.

The Color Triangle

While the C.I.E. Diagram has increased in usefulness with the publication of the locations of all available color media, the color triangle (Figure 9.3) remains a very useful tool for working out color problems. It is a simplification of the color diagram in the form of an equilateral triangle with the three additive primary colors located at the three corners. Secondaries are located at the three halfway points and "white" is placed in the center. Colors may be located on the triangle in the same manner as the C.I.E. Diagram and mixes may be predicted, although less accurately. It can also be adapted to aid in predicting subtractive mixes.

"White" Light

Sensations of white light may be evoked by presenting the eye with any of the following:

- An equal brightness combination of all visible wavelengths such as light from the sun or from an incandescent lamp
- A combination of many line spectra which contains enough wavelengths to stimulate the three sensors in the eye to a roughly equal degree. HID sources frequently appear white because their light is so composed.
- An equal brightness mixture of red, blue and green sensations (RGB) produced by mixing the narrow bands of wavelengths at the peaks of the three sensitivity curves of the eye. This is the method often used to light a theatrical cyclorama.

White light is always a mixture.

There is no single wavelength or narrow band of wavelengths that produces the sensation *white*.

The "white" central area of the C.I.E. Diagram or the color triangle encompasses a wide variety of very pale colors which when viewed by themselves will be identified as white by most observers. Nevertheless, there are important and noticeable differences between these very pale colors which will be apparent if several of them are viewed side by side. For example, the "white" light produced by incandescent lamps is noticeably warmer than that produced by HID lamps or the white displayed on a computer screen. Although the eye will adapt in a short time to whatever "white" is presented to it, neutralizing any sensation of "warm" or "cool," the ability of these whites to subtly accent pigment colors will remain.

As discussed in Chapter 6, the white light produced by various light sources is often described by the color temperature (kelvin) system. However this terminology is only rarely used to describe white light created by mixing the primaries or by the mixing of complementary tints.

All Additive Mixes Tend Toward White

Adding wave lengths moves an additive mixture toward white.

Both the C.I.E. Diagram and the color triangle reflect the tendency of wavelength mixing to move toward white, i.e., the more wavelengths added to the mix, the closer the resulting color sensation will be to white. Therefore "adding color to the stage" cannot be effective if more colors of light are simply superimposed upon one upon the other—the result will move closer to white. A "more colorful stage" will result only if carefully separated and contrasted areas of color are created.

Combining equal brightness portions of red, blue and green primaries is a very inefficient process on stage where the primaries are made by filtering already white light Nevertheless RGB mixing is much used because of its flexibility; any of a wide variety of colors may be had in short order. Note that this same primary-mixing process is very efficient when applied to a color TV screen. The difference is that the phosphors on the TV screen produce only the red, green and blue needed—no wasteful filtering is required.

Spectral and Nonspectral Hues

Spectral and nonspectral hues

As noted near the beginning of this chapter, color sensations produced by a single wave length or, more likely, narrow bands of wavelengths adjacent to each other on the spectrum, are termed *spectral hues*. There are also many *nonspectral hues*, which are the result of mixing disparate wavelengths, for example, red and green which create the sensation of yellow, or blue and red, which create the sensation of magenta. Many other combinations are possible and when the mixtures are in the form of tints, they form the basis of a major kind of lighting for acting areas.

While many nonspectral hues can be matched on the spectrum, yellow, for instance, the entire array of colors ranging from primary blue to primary red across the bottom of the C.I.E. Diagram has no single-wavelength equivalents. These sensations are often identified by referring to their complements, as already noted.

There are also many nonspectral hues that do have spectral counterparts. Spectral and nonspectral hues that produce the same sensation, such as spectral and nonspectral yellow, cannot be differentiated by the unaided eye although they produce drastically different results when used to illuminate colorants.

Pure spectral hues are typically produced by narrow band sources such as gaseous discharge lamps and lasers. They can also be produced by filtering using dichroics or special pure absorptive filters. Note that conventional plastic filters pass both spectral and nonspectral colors whenever this is possible. For example, ordinary yellow color medium passes red, spectral yellow and green (the red and green comprising nonspectral yellow). This makes for greater efficiency and avoids the color distortion that pure spectral colors create. While most pigments reflect both spectral and nonspectral hues when these are present, some are made to reflect only spectral colors.

When spectral colors are being used, for example spectral yellow from a low pressure sodium vapor lamp, it is important for the designer to remember that these colors contain only a narrow band of wavelengths. Therefore red and green pigments will appear black or grey under spectral yellow although they would retain their original colors if illuminated by nonspectral yellow or by light containing both spectral and nonspectral yellow.

Complementary Colors

Contrast

Complementary colors

Finding complementary pairs on the C.I.E. Diagram

The term, *contrast* describes the tendency of colors displayed adjacent to each other to stand out from each other and to increase each other's apparent brightness. *Complementary* describes pairs of colored light which display maximum contrast when placed next to each other and which, when mixed in equal proportions as sensations, produce the sensation of white. Complementary colors can be found on the C.I.E. Diagram by passing a line from any color mapped at the edge of the diagram, through the point on the black body locus that represents the color temperature of the light to be used, usually 2848 K, and continuing to the other side of the diagram. Any two colors on that line and equidistant from 2848 K will be complimentary but those at the ends of the line will display the most contrast. Complementary colors may also be defined on the color triangle in a similar, but less accurate manner.

After Images

Colored and black/white afterimages

When the cones in the retina, say those sensitive to red, are stimulated by red light entering the eye, and the stimulus is removed, there is a lag before the cones return to their non-stimulated state. The more powerful the stimulation, the greater the lag. Moreover, if the stimulus is sufficiently powerful, it will cause the cones to overshoot the quiescent state and send a nerve signal indicating the complement of the color that just stimulated them, In our example, the red light would cause the cones to signal cyan, the complement of red. These sensations, known as *afterimages*, are a common experience for anyone who has fixed his or her vision on a brightly lighted object for a period of time and then looks at some other object. If the first stimulus is white, instead of a colored afterimage, a flare of white light will appear which alternates with a black afterimage until the cones re-stabilize. If the original stimulus is colored, the after image will display the complement of that color, often alternating with a display of the original color.

Colored after images contribute to the contrast between complementary fields of color by creating a fringe of complimentary afterimage around the color fields. This effect, which heightens the apparent brightness of the colors is called *simultaneous contrast*.

Finding complementary pairs by using afterimages

Since afterimages tend to appear in the complementary to the stimulus which created them, they offer a means of determining with considerable accuracy what the complementary of a given color may be. Simply stare at the color for a period of time and then at a white surface. The color of the afterimage is the complementary.

Subtractive Color Mixing

Although there are rather exotic ways of producing monochromatic light such as lasers, gaseous discharge tubes and some fluorescent lamps, almost all of the colored light used on stage is produced by filtering. Light containing a broad mixture of wavelengths is produced and passed through a filter to get the wavelengths needed.

It is now our purpose to study these filters and the ways they interact. This filtering process is known as the *subtractive color system* for the obvious reason that filters subtract from the beam of light which passes through them. The result is always less light than was in the beam before filtering. The fundamental rule of the following discussion is this:

Absorptive filters

> *Filters never add anything to a beam of light, they can only subtract.*

Ironically, this rule appears to contradict the common notion: "Pop in a gel to add color to the light." The filter can indeed cause color to appear where only white was evident before, but the amount of light is diminished.

Filters sort wave lengths.

Filters, with the exception of those that work on the dichroic principle, do their job by absorbing some of the wavelengths that strike them. This absorbed light is usually converted into heat which must be somehow dissipated, often at the expense of damaging the filter. Dichroic filters are also subtractive; they sort out the wave lengths they are designed to control, allowing some of them to pass through and sending the others off in another direction instead of absorbing them.

Opaque, Translucent and Transparent Filters.

All filtering of light involves the light passing through the colorant. It may pass through in a straight line coming out filtered (a transparent filter), it may pass through coming out diffused (a translucent filter), or it may penetrate into the colorant, pass through parts of it and then be reflected back toward its source (an opaque filter—see Figure 9.4). Actually, many filter materials allow two or even all three of these processes to happen at the same time. Moreover, a filter may also display surface reflection: light that only strikes the surface of the filter and is reflected without passing though anything.

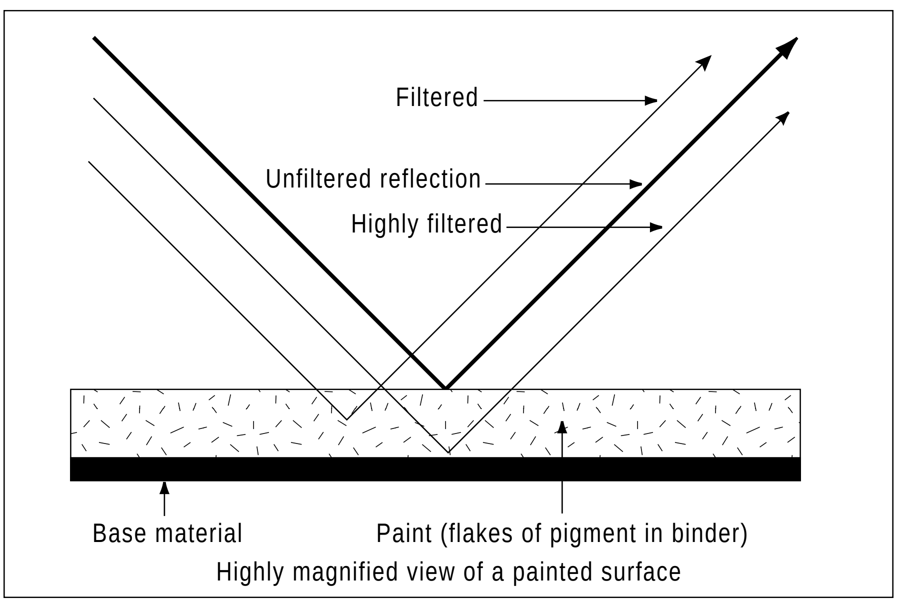

Figure 9.4. How Opaque Filters Work. Note that the light must pass through some of the colorant if it is affected by the filter.

Traditional Color Mixing: the Subtractive System

Mixing colorants is not the same as mixing light.

Mixing filters, i.e., causing light to pass through more than one of them, is the common color mixing method of the painter, the printer and the photographer. It is what we all learned at an early age with finger paints: mix the primaries, red, yellow and blue, to "get all the other colors."

It must be made clear as we continue: we are discussing the mixing of the absorptive capabilities of colorants, not beams of light causing sensations in the eye. Of course, when the results of these mixtures of colorants are illuminated and the resulting colors transmitted to the eye they act upon it additively. The eye will respond the same to any beams of light, whether they are the result of being reflected from or transmitted through a complex mixing of colorants or directly produced colors such as those that appear on a color television tube.

Subtractive Primaries and Secondaries

These are the all-too-familiar red, yellow and blue of the paint box; the secondaries are green orange and purple. Clearly, the names, "red" and "blue" must mean something different than the same names when used in the additive system. A careful matching of colors, not names, reveals that the "red" primary in the subtractive system colorant is a match for magenta on the C.I.E. Diagram (Plate I), the "blue" a match for the cyan, and the yellow a match for secondary yellow. Semantics is our undoing, along with the fact that many so-called pigment primaries are so impure that they cannot be trusted to produce anything like the results that theory would predict. If high quality color printers' inks or even top quality theatrical paint colors are compared with colors on the color diagram, it will confirm that, names ignored, the primaries of the subtractive system are color matches for the secondaries of the additive system. Again, if high quality colorants are used, it can be shown that the reverse in also true: the secondaries of the colorant (subtractive) system match the primaries of the additive system. The following table is another way of interrelating the color names:

COLOR NAMES IN ADDITIVE AND SUBTRACTIVE SYSTEMS

Names used in additive system	Names used for the same colors in subtractive system
Red	Red-orange or orange
Green	Green
Blue	Blue-purple
Magenta	Red
Yellow	Yellow
Cyan	Blue

Mixing Colorants

The general principle of mixing colorants is completely different from that which governs the additive mixture of sensations. Each colorant in the mix must be analyzed to determine which wavelengths are passed and which are absorbed. Once this is done the process is arithmetical: Begin with the complete list of wavelengths in the light striking the colorant mix and subtract any wavelength that is absorbed by any colorant in the mix. The remainder will be what is seen by the eye as an additive mix. Where the incident light is white, it may be represented by samples in the form of the primaries and secondaries instead of an impossibly complicated list of all wave lengths. This is done in the diagrams below.

The following diagrams illustrate this process by clarifying why blue colorant added to yellow colorant results in green colorant:

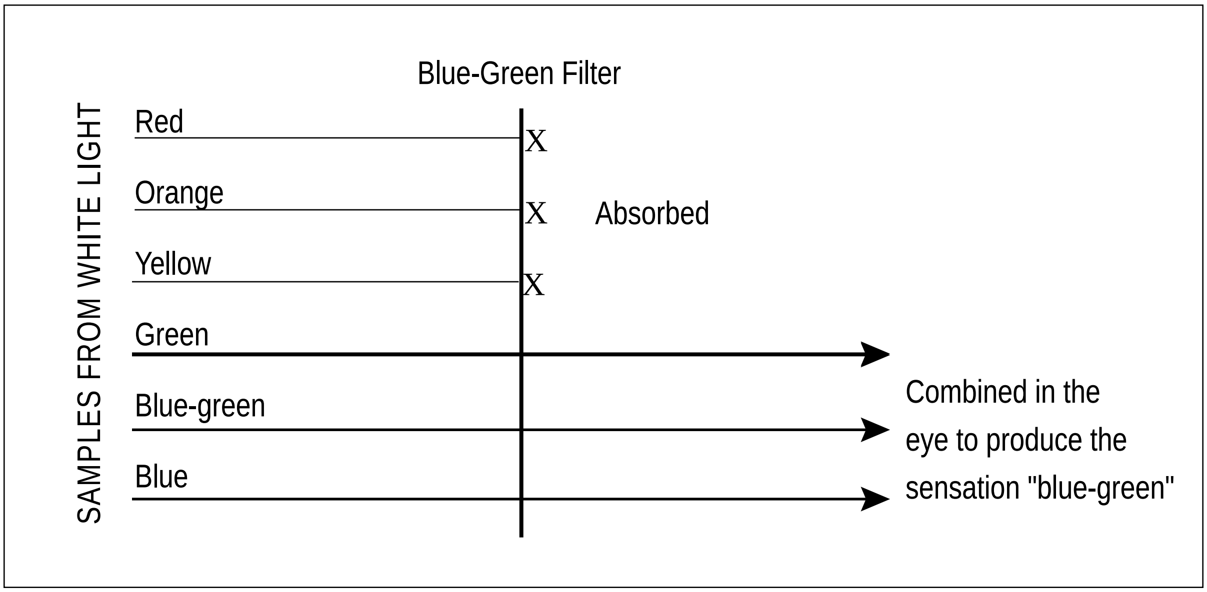

Figure 9.5A. This diagram summarizes the absorption/transmission characteristics of a hypothetically perfect blue-green colorant which would be named “blue” in the subtractive system.

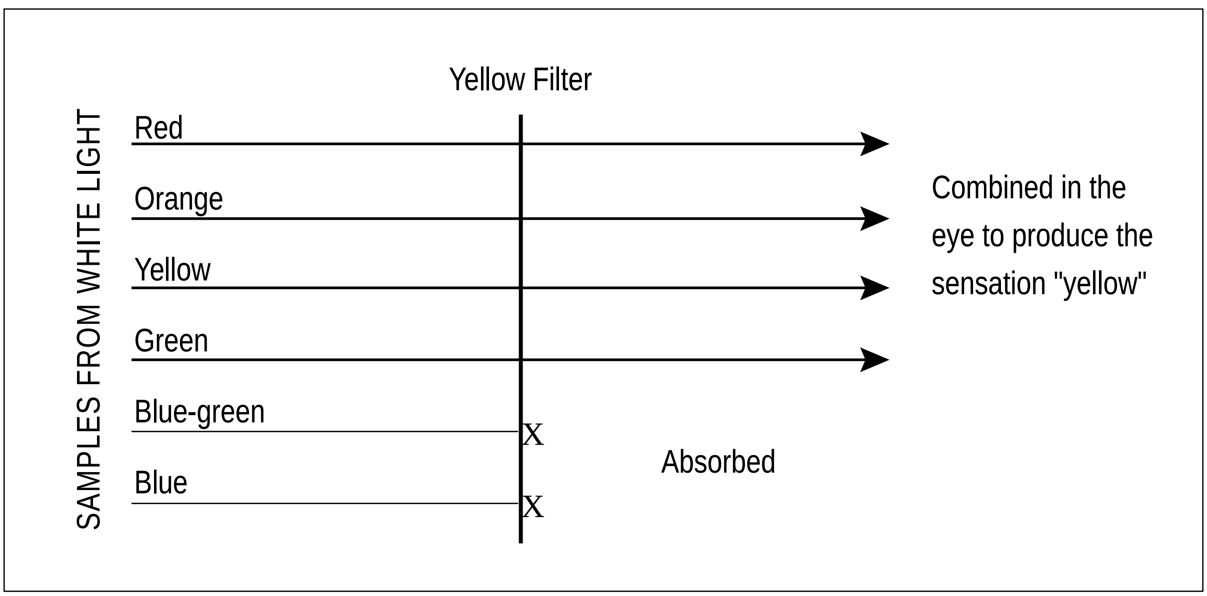

Figure 9.5B. This diagram does the same for a hypothetically perfect filter known as “yellow.”

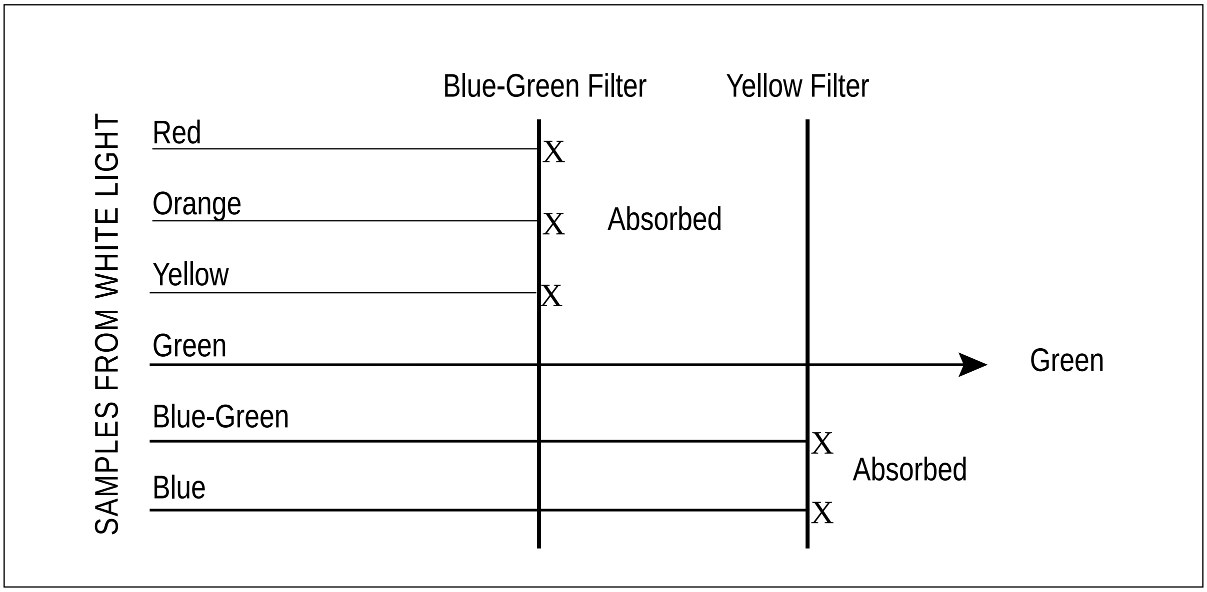

Figure 9.5C. This diagram illustrates how the filtering characteristics are combined when the two colorants are combined.

Note that it makes no difference which filter the light passes through first. It also makes no difference whether the filter is transparent, translucent or opaque. Light that actually passes through the filtering material, whether it continues onward or is reflected back, is altered in the same way.

Colored Light on Colored Objects

In most non-theatrical situations, colored objects are viewed in white light, either daylight at about 6000 K or incandescent light at about 2900 K Under either of these sources, colored objects will be rendered with acceptable accuracy in most cases, although professionally accurate color matching will usually require light nearer to equal energy white than the 2900 K light of the typical general service lamp. The theatre is another matter. Highly filtered light is often used, usually with no ambient light from daylight or general room illumination. Under this condition, the effect of colored light can be drastic. Colors of pigments can be completely changed, reduced to near black or ugly brown or blended together. Therefore it is important that the lighting artist be able to predict what the effect of colored light will be on each colored object on stage.

This requires a two-step process. The steps may be done in either order: 1) The designer determines which wave lengths are available in the colored light to be used. If highly saturated primaries or secondaries are to be used, their wave length content should be already known to the designer. If other colors are to be used, their spectrograms will provide this information. 2) The designer then determines what wavelengths the colored object will reflect. The wavelengths common to both lists will be added to make up the resultant color. If, for example, an object colored magenta (red-blue) is illuminated only with cyan (blue-green) light, the reasoning will be:

Available wavelengths: **blue + green**
Object can reflect: **red + blue**
Object will appear: **blue**

Note that this is theoretical—it assumes that all of the colorants are completely pure, which is seldom the case. After making the theoretical determination, the designer or technician must use his or her experience with the colorants involved, possibly consulting the spectrograms again, to determine what the practical result will be. In this example there is a high probability that the spectrogram of the cyan color medium will reveal that it leaks a significant quantity of red light. If this is the case, the result will be a dulled-down bluish magenta instead of blue. If the magenta object must be made to appear blue, another filter will have to be chosen, one that transmits less red.

The chart below lists the results of illuminating saturated colorants which match the primaries and secondaries of the subtractive system with pure light in the primary and secondary colors of the additive system. In a real-world situation, unless high quality dichroic filters are in use, most of the "black" results will turn out to be dull and unpleasant remainders of red. This is because it is difficult to make absorptive colorants that do not leak red light.

COLORS RESULTING FROM COLORED LIGHT ON COLORED PIGMENT

INCIDENT LIGHT COLORS / **PIGMENT COLORS**	RED	GREEN	BLUE	YELLOW	MAGENTA	CYAN
RED	red	black	black	red	red	black
GREEN	black	green	black	green	black	green
BLUE	black	black	blue	black	blue	blue
YELLOW	red	green	black	yellow	red	green
MAGENTA	red	black	blue	red	magenta	blue
CYAN	black	green	blue	green	blue	cyan

Colored Light and Color Contrast

Color contrast is a major factor in stage design. Most of the factors controlling it are fixed relatively early in the process of finishing the staging as paints are applied and fabrics chosen and worked into drapery, costumes, and properties. Once set, changing these elements is difficult and expensive, and sometimes impossible. In some cases and to a limited extent, lighting can ameliorate color contrast problems by exploiting the capability of colored light to emphasize or de-emphasize colors.

Lighting may be able to correct one color problem at a time.

Generally, only one contrast problem can be solved at a time and that only to the extent that other colors on stage can withstand the sometimes color-distorting effect of colored light chosen to adjust contrast instead of for the best lighting of the actors and the staging as a whole. Note that these adjustments may also affect the makeup which, fortunately, can usually be changed very late in the production process. Obviously, if a color is emphasized or de-emphasized by these techniques all objects of this color will be effected that are within the specially illuminated stage space.

Contrasts between colors can be altered by choosing lighting that will separate the colors or bring them together. The methods are these:

Increasing contrast

1. To increase the contrast between a color and the background, provide an abundance of the wavelength the color reflects best plus enough white or near-white light to make the background appear normal.

Example: To bring up a green costume from the background add green to the acting area illumination while keeping the general color of the stage near the same as it was before. An additional luminaire gelled with light green and brought up just far enough to get the effect wanted may do the trick. Check makeup for over-emphasis of any green shadows or liners.

De-emphasizing a color

2. To de-emphasize a color, deprive it of the wavelengths it reflects best.

Example: To "take down" a blue sofa, use light with less blue in it for the acting areas and reduce blue in any blending or effects lighting that strikes the sofa. Acting area tints of orange instead of rose will do this, but makeup may have to be adjusted.

Separating two tints

3. To separate two tints that appear too much alike, decide which is to receive emphasis and determine which wavelengths it reflects better than the other color. Provide more of those wavelengths and, if possible, less of the wavelengths best reflected by the other color.

Example: To separate a rose-pink from an orange-pink (assuming you have decided to emphasize the rose pink) add pale magenta to the acting area lighting and reduce any straw or light amber. Adjust makeup as needed.

4. To bring together two tints that don't quite match: choose wavelengths they both reflect equally well and reduce any color favoring one or the other as much as possible.

Example: To bring together the two pinks in example three, choose tints of true red while reducing the amount of blue-pink or orange-pink. Makeup may need adjusting.