Introduction to the Kodak Color Management System

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SunSoft
A Sun Microsystems, Inc. Business

The Nature of Color

A fundamental knowledge of color can help you understand how color is used by imaging systems and how it is managed on the desktop computer. This white paper helps you to better understand some of the complexities of the color problems that confront today's desktop computer systems and the solution that the Kodak Color Management System provides.

This chapter introduces the physical, physiological, and psychological aspects of color.

What is Color?

Color is the eye's response to a mixture of different wavelengths of light. It is a visual sensation that requires three things: an object, a light source, and an observer. Light travels from a source, reflects from or transmits through an object, and reaches the eye of the observer (Figure 1).

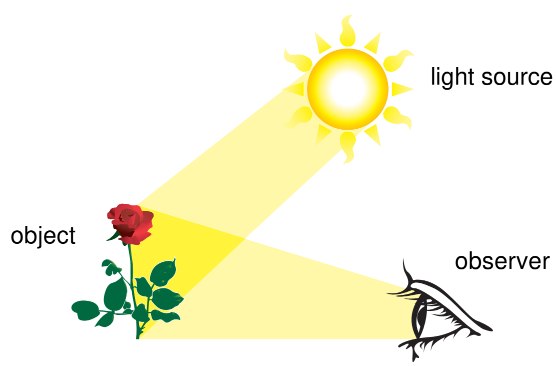

Figure 1 Light Source, Object, and Observer

The color of an object, such as a rose, seems to be in the object itself. However, if the object is viewed under sunlight, then under a tungsten lamp, its color may appear different. Which is the "real" color, the color under the sun or the color under the lamp?

Neither color can be said to be the "real" color. Not only does color depend on the object, but it also depends both on the type of light source under which it is viewed and on the observer.

Although colors may be defined in terms of physical quantities, they are actually perceived as sensations in the mind. To understand fully the nature of color, you must therefore consider all sides of the story: physical, physiological, and psychological.

The Physics of Color

Like radio waves and x-rays, visible light is a form of electromagnetic radiation, which is made up of electrical and magnetic vibrations. Although wavelengths of electromagnetic radiation vary from over a mile (for some radio waves) to a millionth of a millimeter (for x-rays) and less, the human eye is responsive to only a very narrow range of these electromagnetic waves (Figure 2).

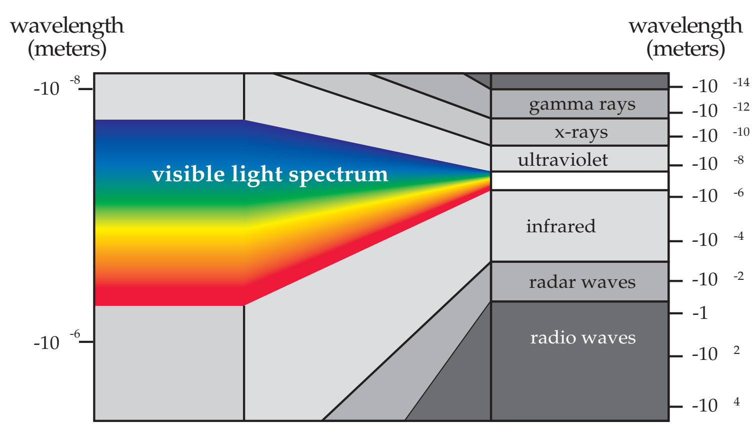

Figure 2 Electromagnetic Spectrum

This small segment of electromagnetic radiation is called visible light, which ranges from approximately 400 nanometers (abbreviated nm) to about 700 nm in wavelength (Figure 3). One nanometer is a millionth of a millimeter, or 10^{-9} of a meter. The radiation that you see from all the things around you, with all their colors, falls within this narrow portion of the electromagnetic spectrum.

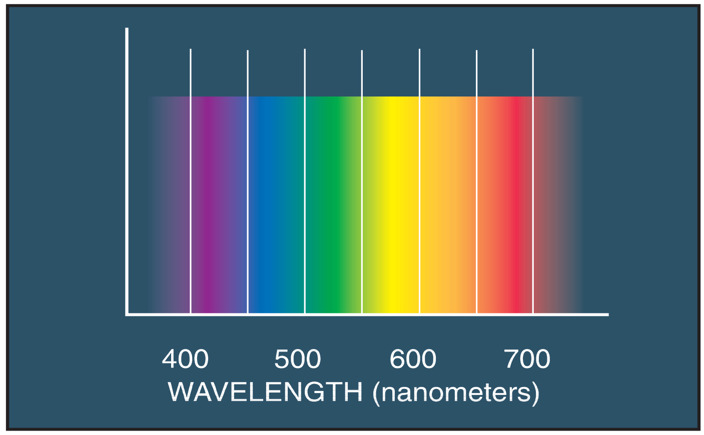

Figure 3 Visible Spectrum

Newton's Experiment

White light, such as sunlight, is generally made up of all the visible wavelengths of light. White light can be separated into its different wavelength components by bending it with a prism, as Sir Isaac Newton did in his 1666 experiment. He made a small hole in the wall of a dark room and then directed rays of the sun onto a glass prism. The prism separated the light into a spectrum of colors like that of a rainbow (Figure 4). The longest wavelengths (seen as red) were bent the least while the shortest (seen as violet) were bent the most.

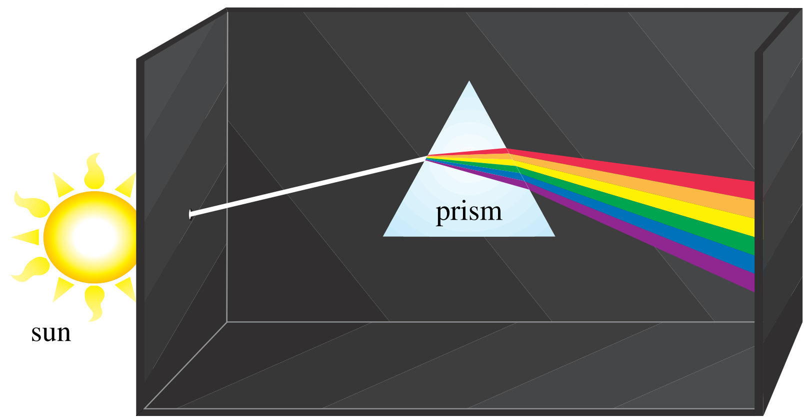

Figure 4 Prism Bending Light

The Color of Things

When light falls on an object, the chemical and physical structure of the object divides the light into three parts (Figure 5):

- Reflected light bounces back from the object, like a ball from a floor.
- Transmitted light passes through the object.
- Absorbed light is actually trapped in the object and does not escape. Trapped light is usually turned into heat, which cannot be seen.

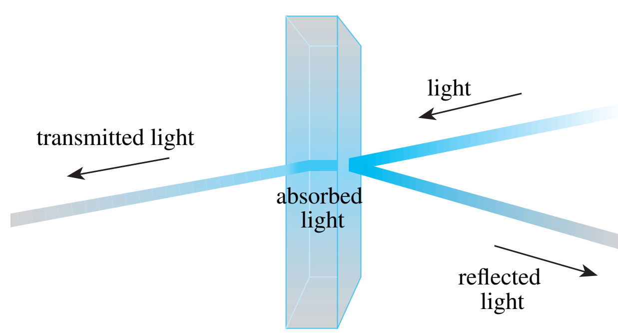

Figure 5 Reflected, Transmitted, and Absorbed Light

The color seen depends on the interaction of light with an object. Different objects interact with light in different ways.

Opaque objects reflect some wavelengths of light while absorbing others. The color perceived for the object depends primarily on the part of the spectrum reflected from the object that reaches the eye.

An item, such as a sheet of paper, appears white if it reflects a high percentage of all wavelengths of a white light source equally (Figure 6). If an object absorbs all the light that reaches it and reflects none back, its color appears black. Grey occurs when all wavelengths are reflected about equally, but at a lower level than for white. Hues occur when the reflected wavelengths are out of balance, that is, some wavelengths are reflected more than others.

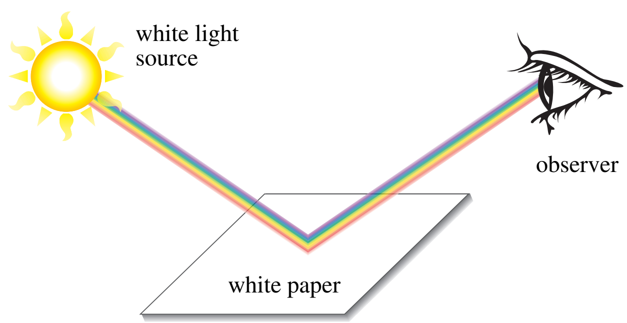

Figure 6 Light Reflecting From a Sheet of White Paper

Most colors you see, such as the red of a rose or the red on a printed page, do not consist of a single wavelength. Colors are usually combinations of many wavelengths. Analysis of the light reflected from the red rose shows that it contains light of all wavelengths, but a greater amount of light comes from the longer-wavelength (red) end of the spectrum than from the shorter-wavelength (blue) end (Figure 7).

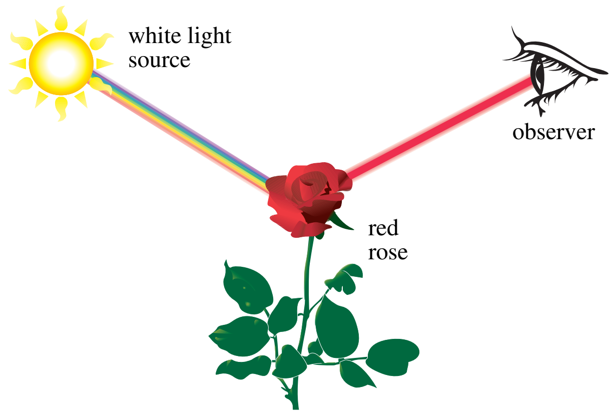

Figure 7 Light Reflecting From a Red Rose

Objects that transmit light, such as a stained glass window or a 35mm slide, let pass certain wavelengths while absorbing others. The wavelengths that pass through are the ones that you see and thus determine the color of the object. For example, a piece of stained glass that appears green absorbs most light from the blue and red ends of the spectrum while letting the green wavelengths pass through (Figure 8). However, as with the light reflected from a red rose, the light transmitted through the green glass may also contain smaller amounts of all the visible wavelengths.

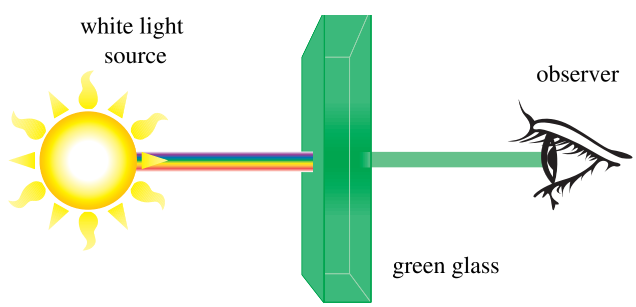

Figure 8 Light Transmitted Through Green Glass

When considering the green glass, a white light source was used, which contains a mixture of all wavelengths. Now imagine that the light source is not white light, but red light. How would the green glass look if red light were projected through it? Which part of the spectrum would reach the eye?

The answer is that little light would reach the eye. Most of the red light would be absorbed and the glass that appeared green with a white light source would now look black (Figure 9).

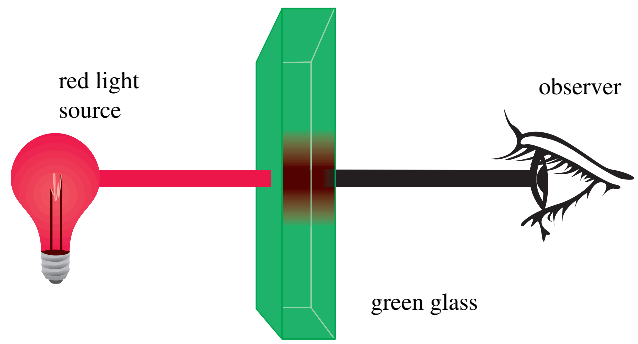

Figure 9 Red Light and Green Glass

You can see that the color of an object depends not only on the object itself, but also on the light source. Objects do not really have an inherent color because the light source plays such a critical role. Color of an object is assigned by the brain based on how the object reflects or transmits various wavelengths of the light that strikes it.

The appearance of color objects varies depending on the type and amount of light used to illuminate them. Incandescent light brings out the warm colors, such as reds and yellows, which explains why it is often used in displays of fruits and vegetables. Fluorescent light usually brings out the blues and violets—not quite as appetizing for fresh produce. Different fluorescents with special phosphors can be used to enhance colors of vegetables or other foods, such as meats.

Light Sources

Light sources turn other kinds of energy into visible radiation. A candle uses chemical energy. The sun uses nuclear energy. Most common light sources use electrical energy.

Light sources affect the apparent color of objects viewed under them, including images displayed or printed by desktop publishing systems. Each light source or illuminant emits a different proportion of energy at different wavelengths of the visible spectrum. For example, the spectrum of a tungsten light contains proportionally less short wavelength light (blue and violet) than does sunlight.

The proportions of wavelengths that an illuminant radiates can be expressed as color temperature. Color temperature, expressed in degrees Kelvin (K), may be assigned to any light source by referencing the source to a blackbody radiator. A blackbody is a hollow chamber whose color looks black only when cold. When heated, a blackbody's color temperature, and therefore its color, depends only on its temperature and not on its composition. Tungsten filaments, such as those used in incandescent bulbs, closely approximate blackbodies.

The temperature at which the blackbody spectrally matches the color of a light source is the color temperature of the source. Many non-blackbody light sources can be described by the color temperature of the blackbody that they most closely resemble visually. This is also called their correlated color temperature and is expressed in degrees Kelvin. Degrees Kelvin are also used to describe the color of a monitor screen's white point (see ""Monitors" on page 24).

Because the human visual mechanism tends to adapt to the color of different light sources, humans tend to perceive each light source as white. When the light sources are side by side and you cannot adapt to them individually, you are more aware of the differences among them.

Take one example of a light source: the white light on a computer monitor. When viewed alone, the white produced by a monitor may appear to be "white." But if you view two monitors side by side, you may find that the white that each produces is quite different. One "white" may appear more yellow; the other "white" may appear more blue.

As described before, the specific color spectrum of "white" light affects the appearance of an object viewed under that light. The same object may look different under different light sources.

On the other hand, two objects may appear to match—that is, to have the same color—when viewed under one light source, but not under another source. These objects are exhibiting what is known as metamerism. Metameric colors look alike under one light, such as tungsten, but appear different under another light source, like the sun. This is why you may match two items of clothing inside a store only to wear them outside and find that they no longer match.

As you use your desktop publishing system to make prints, keep in mind the light source under which the final result will be viewed. The print you make under one light source may be viewed under another, such as daylight, which itself varies greatly, changing with the time of day and the weather conditions (Figure 14-10). Incandescent or tungsten light, perhaps the most common household indoor illumination, tends to be redder than daylight. Fluorescent lamps emit large amounts of energy at several distinct wavelengths. While they may have correlated color temperatures similar to daylight, the spectral power distribution is fundamentally different.

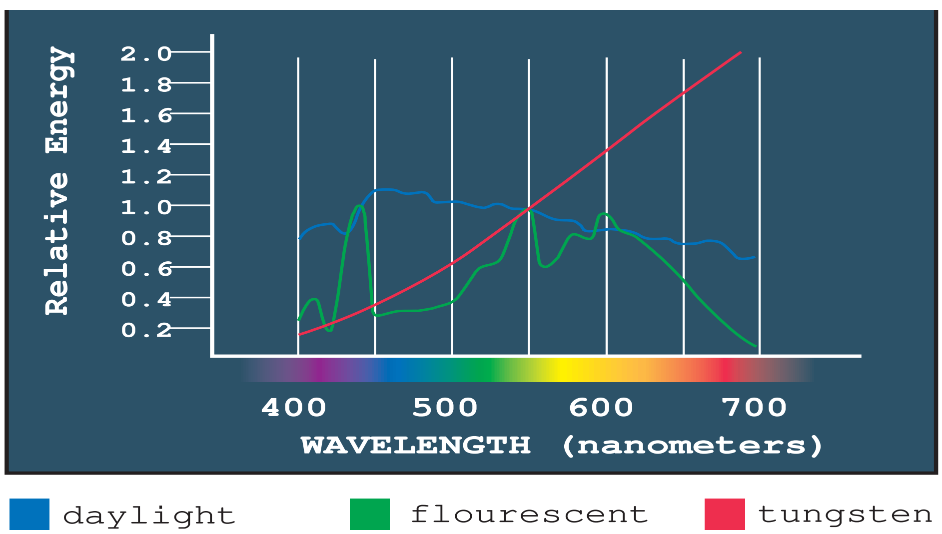

Figure 10 Spectral Power Distribution of Light Sources

Because there are so many different light sources, several standard light sources and illuminants have been defined by the International Commission of Illumination (Commission Internationale de l'Eclairage, or CIE).

Standard illuminants are defined by spectral power distribution. The CIE Daylight D series of illuminants, such as D50 and D65, represent average natural daylight. D stands for daylight. The 65 stands for a correlated color temperature of 6500 Kelvin. The 50 stands for 5000 Kelvin.

The Physiology of Color

When light reaches the eye, it first passes through the cornea, the transparent membrane that protects the eye, then through the lens (Figure 11). The cornea and lens work together to focus an inverted image directly on the retina, the light-sensitive membrane that lines most of the interior of the eye.

The retina consists of nerve cells and two types of visual receptors: rods for sensing light in dim conditions and cones for detecting color. These cells translate the light reaching them into nerve impulses that travel to the brain via the optic nerve. The point where the optic nerve connects to the retina is not sensitive to light and is therefore called the blind spot.

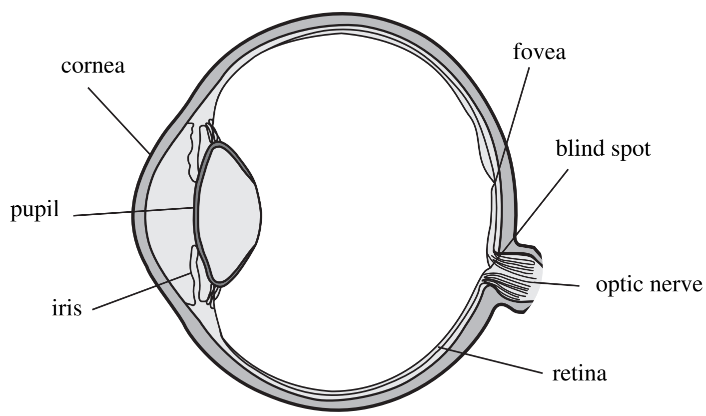

Figure 11 Structure of the Eye

The retina is not uniform in sensitivity. The proportion of rods and cones varies from only cones in the fovea, the central 1-1/2° of the visual field, to mostly rods beyond 40° from the visual axis. This outside area is essentially monochromatic and used mainly for the detection of movement.

Rods, which number about 100 million in each eye, are sensitive to light intensity, but possess almost no color function. Because rods give you mainly "black-and-white" vision, they cannot distinguish between changes in intensity and changes in wavelength (color). The pigment found inside rods, formed from vitamin A and a protein, is sensitive to blue-green light and is virtually insensitive to red. That is why red objects appear black at night.

Rods operate in low light, such as full moon and darker, when cones cannot function. "Night blindness" occurs when a person's rods do not work. Rods play little or no part in vision in daylight.

Cones, the color receptors, function in bright light. Each of the approximately 6 million cones per eye contains one of three distinct mechanisms that preferentially absorb light of different, but overlapping sections of the spectrum. Each type of cone reacts to a range of wavelengths. The ρ (rho) cones are sensitive to longer wavelengths (red region of the spectrum), the γ (gamma) cones to medium wavelengths (green region), and the β (beta) cones to short wavelengths (blue region). Consequently, cones make a three-part decomposition of light.

The light-sensitive mechanism in the cones produces nerve impulses when light hits them. These impulses are converted into red-green or blue-yellow color difference signals, plus an achromatic signal that indicates lightness or darkness.

Basically, color is determined in terms of opponent colors: how red or green it is, and how yellow or blue. These are the four unique hues that the brain identifies. A color cannot be reddish green since these colors are on the same axis. However, a color can be reddish yellow.

The Perception of Color

Although color starts as a physiological process, color itself is a perception that exists only in the mind of the observer. This perception is influenced by adaptive and psychological factors, which affect the relationship between the physics of a color and our perception of that color.

Effect of Background on Color

When two identical samples of color are displayed against two different background colors, one light and the other dark, the sample seen against the dark background appears lighter than the sample seen against the light background (Figure 12).

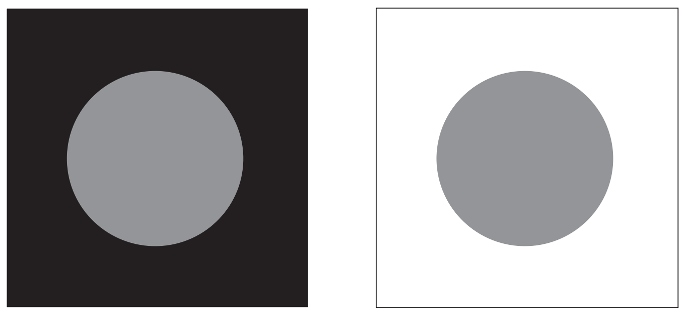

Figure 12 Identical Grey Spot Against Light and Dark Background

Also, the color of a background affects the perceived hue of an object in the direction of the color complementary to the background. For example, if you view a patch of the same green against both a dark blue and a yellow background, the green on the blue background appears lighter and more yellow. The green on yellow looks darker and bluer (Figure 13).

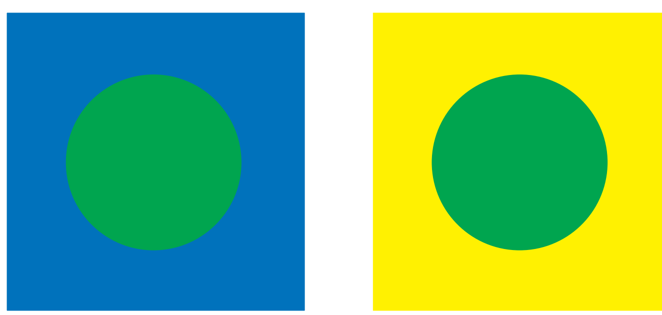

Figure 13 Identical green spot against blue and yellow background

The bluish cast of a monitor's "white" surrounding the image displayed on your screen affects your perception of all colors in the image.

Effect of Chromatic Adaptation

Chromatic adaptation is the adjustment of the visual mechanism in response to the overall color of a stimulus field to which the eyes are exposed. For example, when your eyes are exposed sufficiently long to a reddish-yellow stimulus, such as tungsten light, the ρ cones (sensitive to long wavelengths) become relatively desensitized, and the β and γ cones (sensitive to short and medium wavelengths) become more sensitive in comparison.

As with other perceptual adaptation effects, chromatic adaptation does not occur so readily in viewing pictures. This is true in part because a reproduction usually fills only a small part of the observer's field of view. You take clues from the room and consider the pictures as one object in a larger setting.

Because images produced by a desktop imaging system may be viewed under a variety of light sources or displayed on monitors with different white points, the color management system has to take into account the chromatic adaptation of the observer to those varying conditions.

Effect of Psychology on Color

When you view a reproduction of a scene (such as a photograph), you generally do not see it side by side with the original. Even so, you are usually quite certain about how the colors in the scene ought to appear; you seem to know instinctively what the proper colors are. This effect persists regardless of the length of time that passes between viewing the original and the reproduction. In fact, you feel certain that you can accurately judge certain aspects of a reproduction's color fidelity (such as the color of the sky or of a person's skin) without ever having seen the original at all.

This means that you are not really comparing the reproduction with the original, but with our conception of the original's colors. This conception is based mainly on certain colors called memory colors.

Memory colors are colors that you see regularly, remember, and expect to look a particular way. Skin color, green grass, and blue sky are the most common memory colors. For an image to look right, memory colors, and especially the skin tone, should approximate our memory of the real object's color. If memory colors are off, the image looks unnatural. Other colors in an image are usually less important.

Effect of Observer on Color

People perceive colors differently from one another. Not only are colors associated with personal preferences and memories, but because of slight variations in the spectral responses of observers with normal vision, colors may appear different from one person to the next. Two objects may appear identical in color to some observers and different to others. This is called observer metamerism. The effect becomes more pronounced as the differences in spectral composition between the samples become larger.

Another difference among observers stems from age: because of the gradual yellowing of the lens in the eye, observers with a wide range of ages do not perceive colors the same way.

What are Primary Colors?

Primary colors are the building blocks of color. There are two basic systems of producing color: the additive and subtractive color systems. Each system is built on three different primary colors. When the three primary colors in each system are mixed together, they produce a wide range of colors.

Additive Color Primaries

The additive color system, which reproduces colors by adding colored lights, has red, green, and blue (RGB) as its three primary colors (Figure 14). When mixed together in various proportions, the additive color primaries of red, green, and blue give you a wide range of the colors that you see. Examples that use the additive color system are color televisions and monitors.

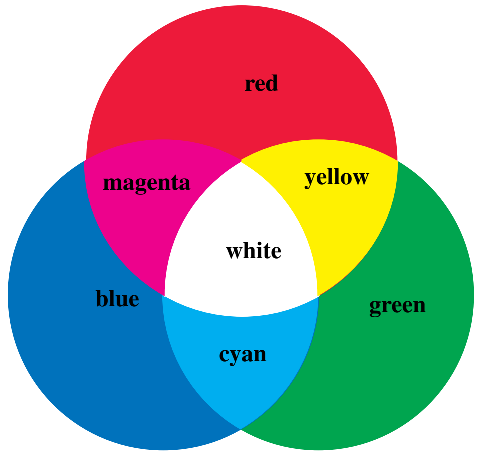

Figure 14 Additive Color Primaries

Notice that in the areas where two primary colors overlap, a secondary color appears. Green and blue create cyan when overlapped. Blue and red produce magenta. Red and green produce yellow. When added in equal proportions, red, green, and blue result in white light. The absence of all three results in black. Intermediate colors are created by varying the proportions or intensities of two or three of the additive primaries. A wide range of colors can be produced from the three additive color primaries.

Subtractive Color Primaries

The three subtractive color primaries—which are also the secondary colors for the additive color system—are cyan, magenta, and yellow (CMY). They are the basis of the subtractive color system, which deals with colorants on surfaces (Figure 15).

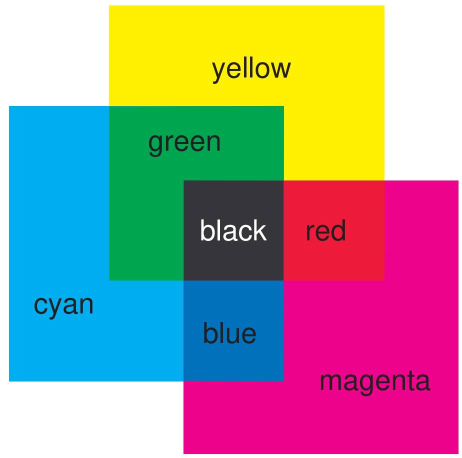

Figure 15 Subtractive Color Primaries

Cyan, magenta, and yellow, the subtractive color primaries, absorb (subtract) particular wavelengths of light, thus removing them from the light that reaches the eye. Magenta, for example, absorbs mostly green (its complementary color) and transmits red and blue light, which together appear magenta. Cyan absorbs mainly red light, and yellow absorbs primarily blue. Black, which is a combination of all three subtractive primaries, absorbs most light so that very little reaches the eye.

While monitors combine the additive primaries to create colors, printers use the subtractive primaries to reproduce colors. The subtractive color system includes not only inks, dyes, and other colorants on paper and other reflection media, but also slides and overhead transparencies, which filter white light, subtracting out parts of the spectrum and letting others pass through.

The Color Wheel

If you place the additive and subtractive color primaries in a circle with their secondary colors between them, you have a color wheel that applies to both the additive and subtractive color systems (Figure 16).

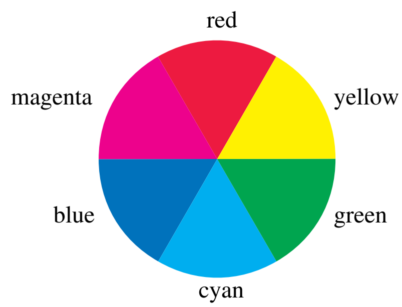

Figure 16 Color Wheel

Opposite each color on the wheel is its complementary color. For example, the complementary color for red is cyan. You can think of complementary colors as opposites. To make a print less red, you can add more cyan. To make an image redder, you can take out cyan and thus make it more red.

A color wheel can be expanded by placing additional colors between these six main colors. When you mix adjacent colors, you come up with a color wheel as illustrated in Figure 17.

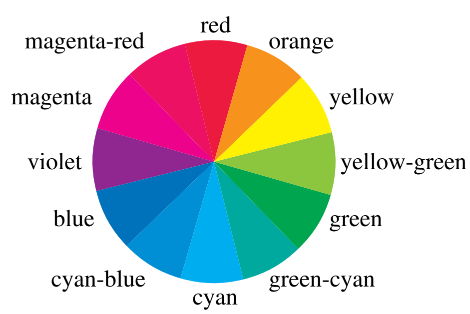

Figure 17 More Detailed Color Wheel

Even this wheel can be subdivided further. But no matter how often you subdivide the wheel, you are still left with imprecise names for colors that leave much room for interpretation.

What is needed then is a system that describes color more precisely. Color order systems fill this need.

Color Order Systems

Colors are created by two main methods: adding or subtracting light. Once created, colors can be categorized in a number of different ways, depending on both need and preference.

Why organize colors into color order systems? Colors are organized and labeled to enable people or machines to communicate a specific color, to compare colors, to find a particular color, or to match it. It's impossible to verbally describe a shade of green, even bright lime green, so that another person knows exactly which shade of green you have in mind. Not only is that an impossible task, but also matching colors from memory cannot be done accurately.

Without an exact specification from a precise color order color system, you simply cannot communicate colors accurately. And if you cannot communicate colors precisely, you cannot reproduce them on desktop publishing systems.

The following sections describe some of the common color order systems.

Munsell Color System

Artist Albert H. Munsell recognized the problem of imprecise color communication. In 1905, he devised an early system based on human perception for organizing and defining colors. His system uses number/letter designations to specify a particular color.

The Munsell system is a perceptually uniform system. Adjacent color samples represent approximately equal intervals of visual perception along each axis of the three Munsell color attributes—*hue*, *value*, and *chroma*.

Munsell hue refers to the name of the color, a property described with the words red, yellow, green, blue, and purple. *Munsell value* refers to the lightness of a color. Value is the quality that distinguishes a light color from a dark one. *Munsell chroma* refers to the strength of a color, how far it departs from neutral grey, the intensity of the hue.

The Munsell color system is available as a collection of color chips published in the *Munsell Book of Color*.

Pantone Matching System

Another color system that relies on visual samples is the Pantone Matching System (PMS). It was created in 1963 to enable the graphic arts and printing industries to specify color.

Pantone colors are used mainly for specifying spot colors: localized areas of a particular color, often accents, logos, or headlines. However, many Pantone colors can also be simulated by the standard three subtractive primary colors typically used for inks.

Pantone colors can also be specified on certain computer platforms, software programs, and printers.

Device-Dependent and Device-Independent Color Spaces

Color spaces are color order systems used for arranging and describing color. A color space might be based on particular samples (like Munsell and Pantone), on specific devices, or on colorimetric quantities (see "CIE color space" later in this chapter).

A *device-dependent color space* is one that is measured in terms of the characteristics of a specific device or family of devices. A device-dependent color space is limited by the physical capabilities of the device that generates it, such as the primary colors of phosphors in monitors or colorants used by printers.

A device-dependent color space may represent a characterized family of devices, in which case it is somewhat idealized, or it may represent a specific device as calibrated at a particular time.

A *device-independent color space* does not rely on the characteristics of any physical device.

The color space that a device uses internally to represent colors is usually device-dependent and may not be suitable for exchange of color data. An internal color representation should be converted to a standard device-independent color space for exchanging color data with other devices.

On the other hand, for a device to print or display color data, it needs to convert the data from a device-independent color space to one specific to it, such as RGB for a color monitor or CMY for a printer.

RGB Color Space

RGB (red, green, and blue) color space is the native space and industry norm for color monitors. RGB relates directly to the monitor, describing color in terms of the intensity of the three phosphors that produce colors on the screen. (For more information, see "Monitors" on page 24.)

RGB color space can be thought of as a solid cube. If you stood the cube on one corner, the bottom corner would be black and the top corner white. Of the remaining six corners, three are red, green, and blue, and opposite each of these primaries is its complementary secondary color: cyan, magenta, and yellow.

There are many RGB color spaces, each based on different sets of RGB primaries. An RGB color space can be based on the actual RGB primaries in a device, such as a monitor's phosphors, or on hypothetical primaries. Also keep in mind that although monitors and some scanners use RGB color spaces, these color spaces are not the same and are not directly interchangeable. Even the RGB color spaces used by monitors from different manufacturers are different.

If you transfer RGB values directly from one device to another that uses a different RGB space, the values will not produce identical colors.

CMY and CMYK Color Space

CMY and CMYK are the native spaces for color printers. These spaces define a color with basic components of cyan (C), magenta (M), yellow (Y), and sometimes black (K) colorants, depending on the printer. Not all printers use a black colorant.

There are many CMY and CMYK color spaces, each based on different sets of primaries. A CMY or CMYK color space can be based on the colorants (inks, dyes, or waxes) used by a device, or on hypothetical primaries.

If you transfer CMY/CMYK values directly from one device to another that uses a different CMY/CMYK space, the values will not produce identical colors.

CIE Color Space

In 1931, the Commission Internationale de l'Eclairage (International Commission on Illumination) standardized a system for color measurement (colorimetry). The CIE system is based on the premise that color is a combination of object, light source, and observer.

The Commission standardized a methodology for deriving numbers that provide a measure of a color seen under a defined source of illumination by a standard observer. The standard observer is representative of the average human population having normal color vision.

A color is expressed by a set of three numbers known as tristimulus values X,Y, and Z. These numbers can be computed from the spectral reflectance of the object, the spectral power distribution of the light source, and the spectral responsivities of the standard observer. With this system, minute color differences can be expressed and communicated.

Color on Desktop Publishing Devices

Color Devices Used for Desktop Publishing

A desktop computer system is made up of several components: a capture or input device (such as a scanner, digital camera, or video camera); a display device (the monitor); an output device (such as a printer or plotter); and the software and hardware in between (Figure 18). Each component can limit the selection of colors producible with your system.

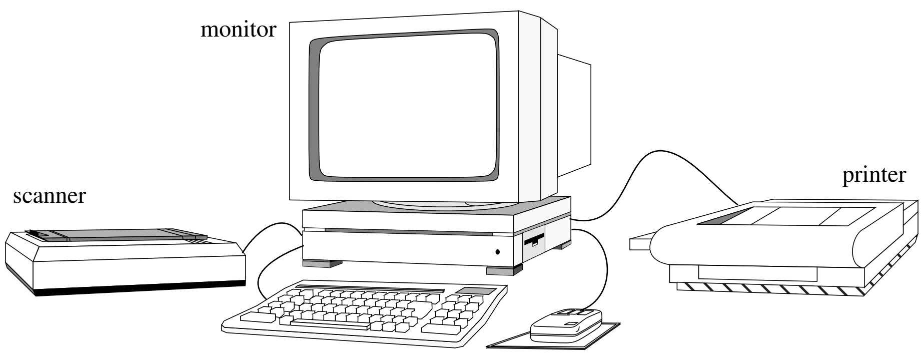

Figure 18 Desktop Publishing System

To help you understand why colors differ among the system components, this chapter explains the way scanners, monitors, and printers function.

Scanners

A scanner is a device for converting photographic images, line art, halftones, or continuous-tone artwork into digitized data. *Flatbed scanners* are used for flat art, *slide scanners* for transparencies or negatives.

Most desktop scanners are capture devices that break down images into three channels of information. Scanners reduce images into percentages of the three primary colors for each picture element (pixel). A scanner digitizes a color image by measuring its reflected or transmitted red, green, and blue light, and then assigns a value to each of the three colors.

Monitors

Monitors use the additive color system to display color. To produce a representation of the scanned image on a monitor, the computer must translate the digital files created by the scanner into signals appropriate for the monitor. Using these signals, a monitor recreates a likeness of the original on screen. By lighting combinations of the red, green, and blue phosphors that line the inner surface of the picture screen, a monitor produces a wide range of colors.

The color gamut (the range of colors that can be produced) of a particular monitor depends, in part, on the color characteristics of its red, green, and blue phosphors. Color characteristics differ from one manufacturer to another as well as from one monitor to the next. The settings of brightness and contrast also change the possible range of producible colors. The same scanned image displayed on two monitors will often look quite different.

To achieve different colors on a display, there must be at least one bit for each primary color, or three bits per pixel. Each bitplane controls the intensity of one of the three electron guns for the red, green, and blue colors in a display. Thus the bitmap specifies the color of each pixel.

The two most common displays have 8-bit or 24-bit color. The greater the bit depth, the greater the number of colors that can be simultaneously available on-screen. Both systems select from a palette of millions of colors, but an 8-bit setup can display only 256 (2^8) different colors at once. In contrast, the 24-bit system has 16.8 (2^{24}) million color values and theoretically can display any of 16.8 million colors at a time. However, the human eye cannot distinguish that many colors, so many of the 16.8 million color values result in the same color.

A color look-up table (CLUT), a software matrix of all colors that can be displayed on the screen at one time, is used to determine which colors will be selected and under what circumstances. For colors to get to the display, they need to be converted into voltage levels. The color value selected from the CLUT is sent to the digital-to-analog converters, one for each color component, where the RGB color values are converted to voltage levels. These voltage levels control electron guns, which produce streams of electrons that strike the phosphors to produce the colors on a monitor.

Phosphors

The picture tube in a color monitor, like that in your color TV, is a cathode ray tube. The images that you see are produced by glowing phosphorescent material lining the front interior of the tube. These phosphors are arranged in stripes, triads (groups of three), or other patterns of the additive primary colors.

All the colors you see on a monitor are created by adding different proportions of light from the red, green, and blue phosphors, which are excited by three beams of electrons produced by the electron guns (Figure 19). The electron guns are aimed differently so that each strikes only its own phosphor color.

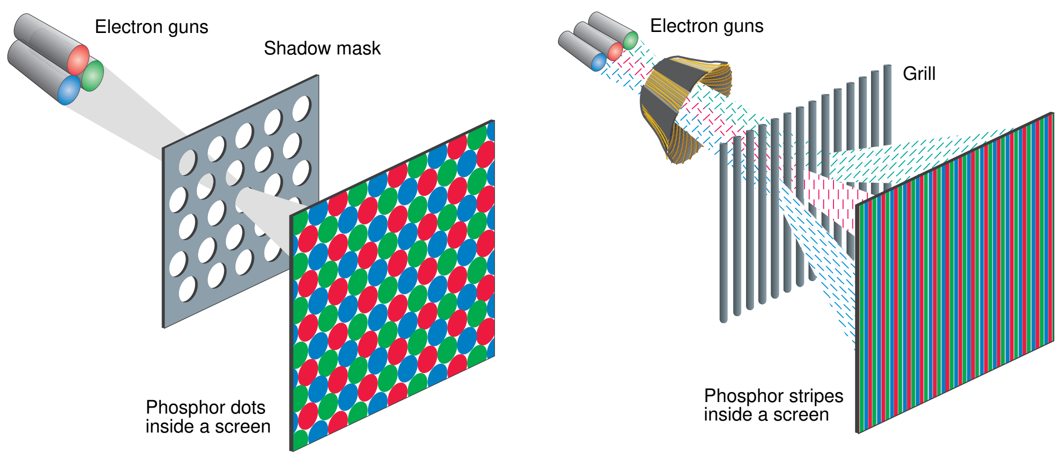

Figure 19 Light Generation Inside a Monitor

When struck by electrons, a phosphor emits light. The amount of light given off by each phosphor element depends on the strength of the electron beam, which can be varied individually for each phosphor by adjusting voltage to the electron guns. The individual spots or stripes of phosphor are not discernible at a typical viewing distance, so the eye blends the phosphors into the colors you see.

The accuracy of the color on the monitor is affected by many factors, including the precision of the electron guns and the adjustment of gain and offset of each of the guns.

When electron guns fire precisely and in balance, grey is produced. If any beam varies from the others, the grey will have a color cast, and if that is the case, every image will have an unwanted tint.

White Point

In "The Nature of Color" we discussed the color temperature of various light sources considered "white light." Monitors also create "white light," and the color temperature of that white light can vary from monitor to monitor. A monitor's white, when all three phosphors are lit to maximum level, is called its white point. The white points of monitors can range from 5000 Kelvin to above 9300 Kelvin (a bluish cast).

White point is a function of the monitor's internal adjustments ("set-up"). Different manufacturers set the white point of their monitors at different color temperatures. Also, due to variations in manufacturing, monitors from the same manufacturer can have different white points. Even the same monitor can change white point over time because of changes in its electronics.

The white point of a monitor is an important factor. It affects all the colors on the display.

Gamma

The amount of light emitted by the phosphors and the voltage levels that drive the electron guns are not linearly related. An increase in voltage does not result in a linear increase in light output. If voltage and light output are plotted on a logarithmic scale, the slope of the resulting relationship is called the *gamma* of the display.

Gamma is a physical characteristic of the individual monitor, and along with white point, can change with the age of the monitor, temperature, humidity, and other factors.

There are many factors that affect color in monitors, but the variance among monitors may seem small when compared to the fundamental differences between monitor images and printed pieces.

Printers

Most printing is created by a pattern of dots. Although you perceive a full spectrum of color from a distance, close inspection of a printed page through a magnifying glass will reveal minute dots of the three subtractive primaries, cyan, magenta, and yellow. Each individual dot is so small that your eye blends it with neighboring dots. For example, magenta dots next to or on top of yellow ones appear red. By overlaying dots of the three colors of ink, a printer can produce a wide gamut of colors.

There are two ways to print: using a three-color (CMY) process or a four-color (CMYK) process. Three-color printing is based on cyan, magenta, and yellow colorants; four-color printing also uses black. K is used to refer to black to avoid confusion with B for blue. The additional black colorant improves contrast and provides a blacker black than the printer's CMY colorants could produce.

The type of ink and the printing method affect the quality and range of attainable colors. Some inks are transparent; others are opaque. Inks can be laid down in coarse dots or vaporized to a gas so they blend before reaching the paper.

While traditional printing presses that use halftone can vary the size of the dots used in printing, desktop printers are restricted either to laying down a dot or to leaving the spot blank. Only the color and position of the dots can be varied. A printer can overlay two or more dots, creating dots of different colors. For example, cyan and yellow dots overlaid create green dots.

By overlaying dots of the three subtractive primaries, a basic palette of eight colors is created:

- Cyan
- Magenta
- Yellow
- Red (magenta + yellow)
- Green (cyan + yellow)
- Blue (cyan + magenta)
- Black (cyan + magenta + yellow)
- White (no colorant)

Dithering

Dithering is used by both printers and monitors to expand the range of displayable or printable colors.

On a monitor, dithering is a way of creating the illusion of an unavailable color by interspersing two available colors. At viewing distance, the eye blends the two colors into a third color.

In printing, dithering is a way for printers to expand their color palette by varying the arrangement of fixed-size dots. To produce the appearance of a color outside the palette of eight basic colors, a set of dots or pixels is grouped into a larger pixel or dither cell, which is made up of single pixels arranged in a pattern. Dither cells are arranged in rows and columns, like a mosaic of tiles.

The size of the dither cell differs for different printers and with different software. For example, a dither cell could contain 4 dots in a simple 2 by 2 matrix. Since each primary color (CMY) can have from 0 to 4 dots turned on (that is, printed), five combinations are possible for each color. Because the colors can be overlaid, the possible combinations increases to 5 x 5 x 5, or 125 colors. If the matrix is increased from 2 by 2 to 4 by 4, nearly 5,000 apparent colors can be produced (17 x 17 x 17).

There are many different types of dither patterns. One way to dither is to create a pattern. The pattern repeats in each dither cell. Another dither pattern is scatter. For scatter, dots are placed randomly within the dither cell. This reduces the geometric dot patterns that you can see with pattern dithering. No single dither pattern is best for all images. Each gives a very different effect when repeated throughout a page.

While dithering expands the color palette of a printer, it does so at the expense of resolution. The printer's resolution is defined by the number of dots per inch (dpi) that it prints. The more dots per inch, the sharper and cleaner the image. In a 300 dpi printer, for example, using a 4 by 4 dither cell reduces the effective printout resolution to 75 dpi. An 8 by 8 cell would reduce the effective resolution further to 37.5 dpi.

Moiré, an undesirable and distracting pattern, is caused by a bad dither pattern when the pixels of two or more of the ink dots form conspicuous interference patterns. It can be particularly obvious at low resolutions.

Ink-Jet Printers

Ink-jet printers use a variety of techniques to print color. Basically, small nozzles spray tiny ink droplets onto paper. The variations in design change how the droplets are produced or how the paper is positioned.

In *continuous* ink-jet printing, a thin jet of ink is forced at high pressure through a nozzle. The jet of ink is broken up into tiny regularly-spaced droplets, which are directed towards the paper. Each droplet either is charged and then deflected into a recycling receptacle or is left uncharged and allowed to pass onto the paper.

Drop-on-demand ink-jet printers are more common and less complex. Drops of ink are created and expelled, usually by a piezoelectric crystal, only when needed. It's not necessary to recycle ink.

Bubble jet ink-jet printers use heated bubbles to force ink through nozzles towards the paper. Ink dries somewhat faster with this method, but otherwise it's similar to drop-on-demand.

The above three types of ink-jet printers should be used with special clay-coated paper. If rough paper is used, the paper fibers spread the ink, causing the dot edges to blur. Clay-coated paper prevents this.

Phase-change ink-jet (also called solid-ink or hot-melt ink-jet) printers use color ink-sticks that are solid at room temperature, but are melted into a liquid during printing. A small reservoir holds the molten ink at the proper temperature until needed. To produce a picture, the printer draws a small amount of the required ink, heats it further, then propels the tiny droplet of ink towards the paper. The melted ink immediately solidifies and adheres to the surface of the paper or transparency, giving it an embossed look. A cold-pressure fusion process smooths the surface of the image after printing.

Thermal-Wax Printers

Thermal-wax printers melt dots of colored wax or plastic supplied on wide ribbons of page-sized blocks of cyan, magenta, yellow, and sometimes black. The transfer mechanism in the print head is often a set of heated elements, wires, or pins. The wax containing the dye is transferred onto paper by mechanical pressure.

After one color has been transferred, the print engine transfers successive colors in a similar fashion. As the paper is peeled away, the melted dye sticks to the paper while the unmelted wax or plastic remains on the ribbon. Thermal-wax prints usually are made on smooth paper because the colors don't flow into the voids between raised fibers. Ink binds onto the surface of the paper.

A problem with thermal-wax printers is that the dyes are not completely transparent. If you choose a color that is created by adding two subtractive primaries, such as red, the top layer of dye becomes the dominant color. Black created from the three primary colors can have an undesirable tint, so usually four-color printing that has a separate black is preferable.

Thermal Dye Transfer Printers

Thermal dye transfer printers, such as the Kodak XL7700 printer, use a continuous-tone process. Dye is transferred from the ribbon to the paper or transparency by the application of heat. Thermal dye transfer printing does not require the creation of a dither cell, so there are no visible patterns.

The strength of each color is controlled by the temperature of the heating element: the hotter the element, the more dye is released. Because they do not have to lay down individual dots, thermal dye transfer printers have the smoothest transition of colors and produce the highest quality prints. However, thermal dye transfer printers require special coated paper and dyes on color donor ribbons, which are expensive.

The dyes used for thermal dye transfer printing are transparent, and when placed on the coated paper or transparent support, they can produce photographic-quality results.

Thermal dye transfer printers are also called dye-sublimation printers, dye diffusion thermal transfer printers, dye-diffusion printer, and sublimal-dye printers.

Color Laser Printers

Color laser printing is an expensive and complex system. It uses the same technology as most office copiers and black-and-white laser printers, except that a color laser printer runs every page through the entire process four times, each time with a different color toner.

First, a static charge is applied to a photoreceptive drum. A laser beam exposes areas *not* to be printed, leaving the areas that are to be printed charged. A negatively-charged dry toner is applied and sticks to the charged areas of the drum. The image on the drum is transferred electrostatically onto positively-charged paper. Once the plastic toner is transferred to the paper, heat and pressure fuse the toner to the paper to produce an image. The entire process is repeated for each color.

Media

Print quality depends on several factors: the type of printer used to create the print, the amount of ink printed on the page, how the ink is printed, and the kind of medium on which an image is printed.

Transparencies have a gamut larger than that of paper and most closely simulate the appearance of color on a monitor. Smooth, glossy paper is better than rough paper. The reflective property of glossy paper increases the gamut of color produced by the printer, especially for ink-jet printers, which do not produce highly reflective colors.

The coating of glossy paper holds the colorants near the surface of the paper instead of absorbing them. When the paper surface is rough, the light rays reflecting from the surface are scattered, and thus the color from any given spot is diluted.

Gamuts of Devices

The range of colors that a particular device can produce is known as its gamut. The potential gamut for a physical device is determined by its color primaries, such as the phosphors of a monitor or the colorants of a printer. The potential gamut may not be realized on an actual device, however, due to optical limitations and other restrictions of the system. The fact that devices have different gamuts is one of the major reasons that color management is necessary.

Gamuts of monitors vary because of the color differences of the RGB phosphors used to produce the red, green, and blue primary colors. The dynamic range (difference between lowest and highest intensity) of each color channel also affects gamut. In addition, the viewing conditions may well be the single biggest factor affecting gamut. Ambient lighting can add stray light to an image displayed on a monitor, thus desaturating the colors. Monitors should be set up to minimize stray light reaching the screen.

Color gamuts of different printers can differ significantly from one another because of the colorants used, resulting in varying ranges of colors. The dynamic range (lowest to highest density) of each colorant affects gamut. The type of media used for printing also affects gamut. The gamuts obtainable on glossy paper are larger than those possible on standard copier paper. Transparencies typically have a gamut that's even larger than that of glossy paper because of the way they are viewed.

The principal difference between monitors and printers is that monitors use the RGB additive primaries and emit light while printers use the CMY subtractive primaries to create prints that reflect light. Often, some RGB colors are outside a typical CMY color gamut. However, some printed cyans and yellows may be outside a monitor's gamut.

Generally, it's easier for additive systems to produce light, high-chroma colors, but it's easier for subtractive systems to produce dark, saturated colors.

Gamut adjustment is the regulation of colors (by compression or expansion) to account for device capabilities and limitations. With gamut compression, a color representation that contains colors beyond the capabilities of a device can be mapped into colors that the device can actually produce. If gamut compression was not used, the result would be that colors existing outside the gamut would block up against the periphery of the gamut in an undifferentiated mass.

Characterization

The Kodak Color Management System provides consistent color across input, output, and display devices. The key to the Kodak Color Management System is characterization: the description of a device's characteristics, which include color gamut, operation, dynamic range, interaction of colors, and color data transfer characteristics.

The characterization information is encapsulated in digital form and included in your system as a device color profile or DCP. Other information that can be included in a device color profile includes the type of media used and the viewing conditions.

Each device color profile must take into account not only the peculiarities of the device, but also the conditions under which the device is to be operated (such as ambient lighting condition and the media on which the result is viewed) and the intended form or *interpretation* of the data. For this reason, there may be several different sets of color profiles applicable to a single device.

A device color profile can be used to:

- Maintain consistent color from device to device

  By taking into account a device's gamut and other characteristics, the Kodak Color Management System can use the DCP information to manipulate color data to provide constant colors from device to device.

- Adjust colors to simulate device limitations

  Because of the different gamuts for printers and monitors, some colors that the monitor is able to produce cannot be reproduced by a printer. And some colors that a printer can print cannot be displayed on a monitor. Device color profiles specify the range of colors a device can encompass and thus make it possible to simulate on the monitor screen what the printed results will look like on your printer(s).

- Compensate for the effects of different media

  An image looks different printed on transparency material versus paper. And glossy paper gives the final result more contrast than a print on plain paper. These differences can be compensated for to some degree when an image is created on different media. However, the color gamuts of some media are more restricted than others, so some distortions or changes will be necessary to have the most acceptable images in each medium.

A device must be characterized for it to be able to run a color management program. With a characterized device, you can input a given set of values and know what colors will come out. A characterized device converts input color data to the appropriate "color-corrected" output color data, colors that the device can actually create.

Because device behavior changes over time, device color profiles may be updated when devices are calibrated.

Calibration

Calibration is the process of correcting any deviation from a standard. Calibration provides the ability to duplicate the same colors and images over time. Devices must be adequately calibrated in order to run the Kodak Color Management System successfully.

Scanners require calibration to ensure that the scanner light, mechanics, focus, and filters are adjusted so that the color components will be separated correctly. Many scanners are calibrated to a target, a page or transparency with appropriate patches that can be read in to determine how the scanner is behaving relative to how it's expected to behave. When a scanner is calibrated, the new calibration data is used to update the scanner color profile.

Monitors should also be calibrated at whatever frequency is necessary to ensure consistent colors on the display. Displays drift from changes in temperature, especially during warming up, which affect the electronics and thus the colors. Color balance and other factors also change from the aging of components, and from changes in alignment and intensity of electron guns. Calibration solves the problem of variations in monitors. As in scanner calibration, new calibration data for monitors is used to update the monitor color profile.

If color quality appears to have changed, try recalibrating the device.

Device Differences

Desktop publishing lacks consistency in color. What is stored is not always what is displayed because every device in a computer system uses different numbers to describe the same color.

This holds true even within a single desktop publishing product line. The color values are not linked by a common color description, so the same image data produces different results from monitor to monitor and from printer to printer. A lavender color on one monitor may look pink on another, while the printed color may turn out purple.

The problem is compounded by the use of additive (RGB) color devices and subtractive (CMY/CMYK) color devices within the same computer system.

Without color management, the only way to predict color would be to use trial and error and to work backward from color swatches produced on your own printer. The Kodak Color Management System automates the process of matching the color on the monitor to the color output on your printer.

Device Instability

Devices also tend to drift—for example, their color balance changes over time. Scanners emit light to scan an image, and the color balance of this light may shift with use and time.

A monitor's colors change from the time you turn it on until it is warmed up. As the unit ages, the colors on the monitor drift because of variations in the electronics and a decline in the efficiency of the electron guns. But the most common cause for a shift in colors is the adjustment of the brightness and contrast controls. Once a monitor is calibrated, these controls should not be touched.

The output of printers also changes for a variety of reasons. For example, in a thermal-wax printer, the pressure of a print head against the media varies. In color laser and ink-jet printers, the colorant supply decreases in unequal quantities, depending on use. In a color laser printer, the temperature and pressure of the fuser roller changes. In an ink-jet or dye-sublimation printer, the internal temperature fluctuates and causes changes in the amount of colorant released to the paper. In any printer, the electronics drift with age.

Even ambient temperature and humidity can affect the performance of a scanner, monitor, or printer. For these reasons, all devices require calibration to keep them working consistently.

Viewing Conditions

The environment in which we view colors varies dramatically. This variation affects the perceived colors. Some effects are due to physics; others effects are strictly perceptual.

For example, the colors of a printed piece may look different under fluorescent light than in daylight, and different still under an incandescent bulb due to the different spectral output of these light sources.

Ambient lighting may add stray light to an image. This results in a physical loss in effective dynamic range and in the desaturation of colors. For this reason, monitors should be set up in an appropriate viewing environment away from bright lights or windows.

Because of the different surrounds of the viewing environments, our perception of the same transparency is different when it is placed on a light table than when projected into a darkened room.

Media

Not only do the viewing conditions make a difference, but the medium on which you view the result—displayed on a monitor, projected on a screen, or printed on paper—affects the gamut of colors that can be reproduced and the perceived result. Even the type of paper that you use for printing—glossy or matte—makes a significant difference in the final output.

Physiological Variables

The detection of color is made possible by the cones (the color receptors) in the eye. The effective spectral sensitivities of these receptors can vary slightly from one individual to the next. Other differences among observers relate to age. As a person ages, the lens of the eye yellows, altering the perception of color.

Thus, color perception can differ from person to person. Observers may disagree on whether two colors match. The greater the spectral difference between the colors being matched, the more pronounced this effect.

Then, of course, there's the problem of color-vision deficiency or "color blindness." About eight percent of the males and one-half percent of the females in the U.S. are color-vision deficient. Of these color-vision deficient persons, most have reduced sensitivity to green or red variations in color.

In the future, a color management program may be able to simulate this type of color-vision deficiency so that persons with normal color vision can better target a presentation of color overheads to a large audience sure to contain some color-vision deficient viewers.

Psychological Effects

Not everyone interprets color in the same way. Expectations vary from one individual to another based on personal experiences. One person may expect the golds of autumn leaves to be reproduced as one shade of yellow while another person remembers autumn gold to be a darker, redder color. The difference becomes heightened when one individual bases his "autumn gold" on Colorado's aspens and the other person bases it on her experience of upstate New York's maple trees.

Your Expectations of Color

You expect colors to look a certain way. If you take a photograph of a person under a tree with a blue sky overhead, the slide or print that you get back from the photofinisher should represent the scene in a way that looks right to you. That does not mean that the photograph identically matches the original scene; rather, the skin tone, tree, and sky should be the colors that you expect, colors that you remember of that scene. In fact, an exact colorimetric reproduction of the scene on a piece of paper or film may not be satisfactory. Moreover, as the photograph is most often viewed in an environment that differs from that of the original scene, a colorimetric reproduction would be inappropriate.

A pleasing likeness, therefore, does not always mean an exact copy. This applies not only to photography, but also to desktop publishing. In some cases you may want an exact duplicate of the original. But in most cases, people prefer images that are not merely copies of the original scene. The Kodak Color Management System strives to maintain the appearance of the original image while allowing the user the necessary flexibility to achieve the desired creative effects.

Kodak has over a century of experience in imaging. Kodak has learned how to make a print or slide produce an excellent representation of the scene. This is one of the strengths of the Kodak Color Management System: Kodak's expertise expressed in color profiles that produce the results you expect.

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