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Color in computing

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CERTIFICE OF APPROVAL

This Thesis is Submitted in Partial Fulfillment
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by Thomas G. Leahy

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Title of Thesis: **Color in Computing**

To Vicky, Brendan, and Sarah with whom I am looking forward to spending more time with.

Abstract

Color in the computing environment, once considered a luxury, is becoming more available compared to being just the occasional exception. As the number of users exploring the uses of color through displayed and printed images increases, the problems associated with its use are becoming widely known. What worked in black and white is not easily translated into color. The use of color needs to begin with the basic understanding of what is color, its terminology and its utilization as an enhancement to communications tool. Only after the basic terminology and effective means of communication are understood will color flourish as a successful means of communication in the computing environment.

Currently, a number of products are seen as solutions in the realm of color usage in the computing environment. Four different contributions, PostScript Level 2 (Adobe), PhotoYCC(Eastman Kodak), Pantone Matching System (Pantone), and TekHVC (Tektronix), each deliver a component of electronic color reproduction. PostScript Level 2 delivers consistent color from monitor to printer, with variations based on printer manufacture and the printing technology utilized. PhotoYCC defines a format for image capture and retrieval with a wealth of possibilities for image sources. Pantone Matching System expands the accessibility of simulated prepress work, coupled with ink formulation and quality control. Tektronix attempted to define TekHVC as an industry standard based on a more uniform color space than that which is defined by previous industry standards. Because of the lack of acceptance, Tektronix has limited this solution to their printers.

Solutions are abundant, but as costs continue to fall, the expectation of consistent color will rise. The adoption of standards across operating environments and software packages is critical to continued increase of the use of color in the computing environment.

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1.0 Introduction

The effects of color and how to produce it find their roots in our elementary school art class. Recall the term *primary colors* and the concept that mixtures of these colors would enable you to produce various colors. After multiple experiments you found that what you usually ended up with was in fact a muddy brown, so you decided to work with the colors your teacher supplied. In todays computing environment the situation is somewhat similar, in that hardware and software manufacturers alike tout the merits of their ability to work with thousands and even millions of colors, yet when you attempt to utilize them, you never quite get the color that you want. For example, displayed on the monitor is the color you desire, yet the printer produces colors other than those displayed, altering your intended message. From this you decide to go back to the colors you know your system produces best, and resign yourself to the fact that what you see on the screen may not even resemble what is produced by the printer.

For those organizations responsible for the production of executive presentations, understanding the request and achieving the desired results are a must. The production of desired results should not be confused with the production of accurate color reproduction. Accurate color reproduction will not necessarily produce the desired result. Previously required to outsource the production of color slides, due in part to the problem of accurate color reproduction, companies are beginning to organize internal color reproduction groups. As understanding of the use of color continues to grow, and as the cost of the associated equipment continues to decline, color output could become as commonplace as text output is today.

The evolution of color in the computing environment can be compared to the evolution of word processing over the past 10 years. Initially, word processing was a computationally intensive, very expensive proposition. Rarely found within a working group, word processing was outsourced to the department responsible for such, in many cases meaning the work was shipped outside the company. As costs declined and availability increased more and more companies expanded their word processing capabilities, eventually moving towards departmental systems. The growth of personal computers, placing on the desktop what previously required a controlled-room environment has placed word processing capabilities throughout the workplace as well as at home.

Color in computing has historically been limited to those with massive computing power and budgets. Technological advances have seen the availability of color computing increase and improve. Scanners, in black/white or color, previously limited to businesses specializing in scanning, are now being found on the desktop alongside personal computers. Computer monitors, initially limited to a single color, are now capable of simultaneously displaying a wide range of colors. Color output devices which were previously limited to specialized shops are available for the desktop computing environment. No longer is color in computing a luxury; it is moving towards a necessity. Unlike the revolution in word processing from typewriter to word processing work stations which both utilized the same keyboard, the predecessor to color was black/white, thus we are beginning to see a radical change in communication possibilities. This migration to color will not gain the acceptance seen in word processors until the industry makes the use of color as easy as the use of text.

In this paper we will explore the aspects of additive and subtractive colors, beginning with basic understanding of human visual systems and how color is perceived . Building from these fundamental concepts, we need to understand what standards exist, their evolution and application to color in computing. The standards on which we will focus are those published by the Commission Internationale de l'Eclairage (CIE). Beginning with the commission's work published in 1931, we will explore updates and changes that are being applied in today's computing environment. Having mastered color fundamentals with a taste of technical details, we will review the four different solutions to color in todays computing environment mentioned earlier:

- PostScript Level 2 (Adobe)
- PhotoYCC (Eastman Kodak)
- Pantone Matching System (Pantone)
- TekHVC (Tektronix)

2.0 Human Vision

The human vision system is capable of detecting only a fraction of the electromagnetic wave from approximately 400 nm to 700 nm. Within this visible region, current computing systems using 8-bit depth for each primary are capable of producing 256^3 combinations (or 16 million colors), of which the eye is capable of distinctly discriminating only a subset. Human vision has varying degrees of sensitivity to different portions of the spectrum. Computers are capable of producing distinct colors that to the human observer have no perceptible differences. No matter what science is applied, the ultimate judge continues to be the human observer.

2.1 Vision - physical aspects

The electromagnetic spectrum covers a wide range of frequencies with names such as cosmic, gamma and ultraviolet, infrared and radio among others. Visible light is nestled between ultraviolet and infrared, with a frequency ranging from 380 to 700 nanometers as shown in Figure 1.

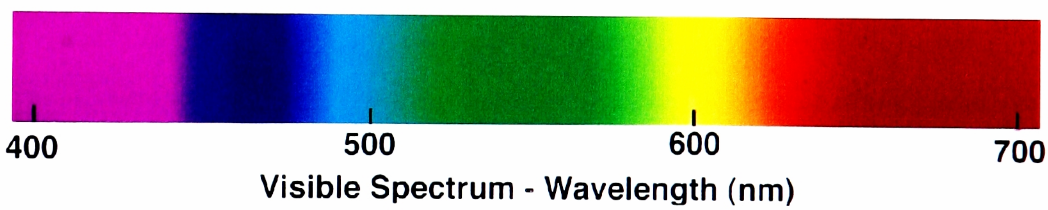

Figure 1. Visible spectrum of the Electromagnetic wave

A cross section of the human eye is depicted below. This complex optical instrument enables detection of light and color through a wide range of viewing conditions. Each component fulfills a purpose in the reception of visual information, passing this information along to the brain for interpretation.

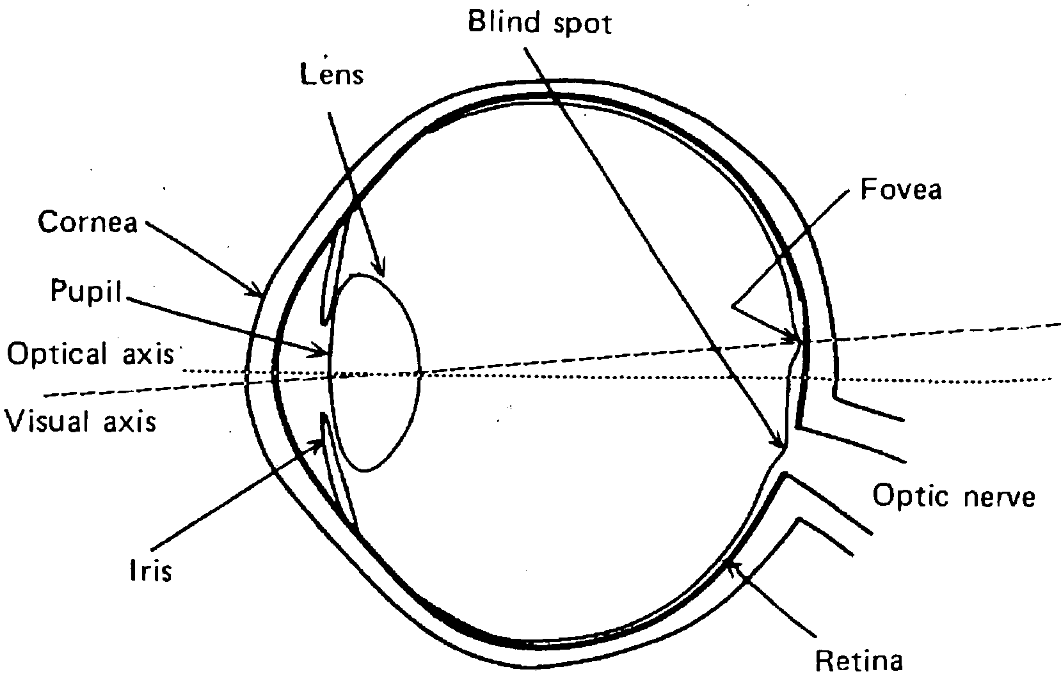

Figure 2.Cross sectional diagram of human eye [HUNT - *Measuring Colour*]

Light entering the eye is brought into focus through the interaction of the cornea, lens and iris. The iris varies the opening through which light reaches the lens. Under bright lighting the iris will maintain an opening of about 2 mm in diameter, while under low illumination the opening will reach a diameter of about 8 mm. The image being viewed will be focused onto the retina, which lines the back of the eye. Here, processing begins on the inverted image being interpreted by the two different types of receptors: rods and cones. While the perception of focusing on an image portrays a single operation, the eye has to frequently refocus to clearly distinguish different colors as each color will focus at different distances behind the lens.

There are known deficiencies and defects associated with the human visual system.
The lens absorbs more light in the blue portion of the spectrum then any other, while the pigmentation between the lens and retina transmits yellow while absorbing blue. These physical limitations explain the sensitivity to colors of longer wavelength and the seeming insensitivity to the blue portion of the spectrum. Additionally, psychological factors influence the interpretation of color.

Rods are responsible for interpretation of *monochromatic* light under low light levels. This use is best illustrated in reviewing visual interpretation under night lighting conditions. Under daylight conditions, one is easily able to interpret the color of a scene such as grass, leaves or the color or houses. Viewing of these same objects under a starlit sky, one will notice the inability to identify specific colors. Identification of different colors is much the same as viewing a Black and White television screen. You are able to identify the presence of different colors, but are unable to identify the color itself. Under higher levels of illumination the rods are basically functional but saturated.

Cones, function at higher intensities of light and are responsible for color sensation. There are three different type of cones; rho(ρ), gamma(γ), and beta(β). The ratio in numbers between the different cones is 40:20:1 respectively. Beta cones are sensitive to light in the blue portion of the spectrum, ranging from approximately 380 nm to 550 nm. Gamma cone sensitivity is greatest within the green portion of the spectrum, ranging in frequency from 430 to 650 nm. The sensitivity of the rho cones is within the red portion of the spectrum, ranging in frequency from 470 to 700 nm.

These receptors occur in different intensities across the retina. The fovea, located 4 degrees off the optical axis, is comprised totally of cones. Outward from there the concentrations vary, leading to strictly rods outside 40 degrees of the optical axis. The peripheral vision resulting from these rods is for the detection of movement rather than the distinct processing or detection of color.

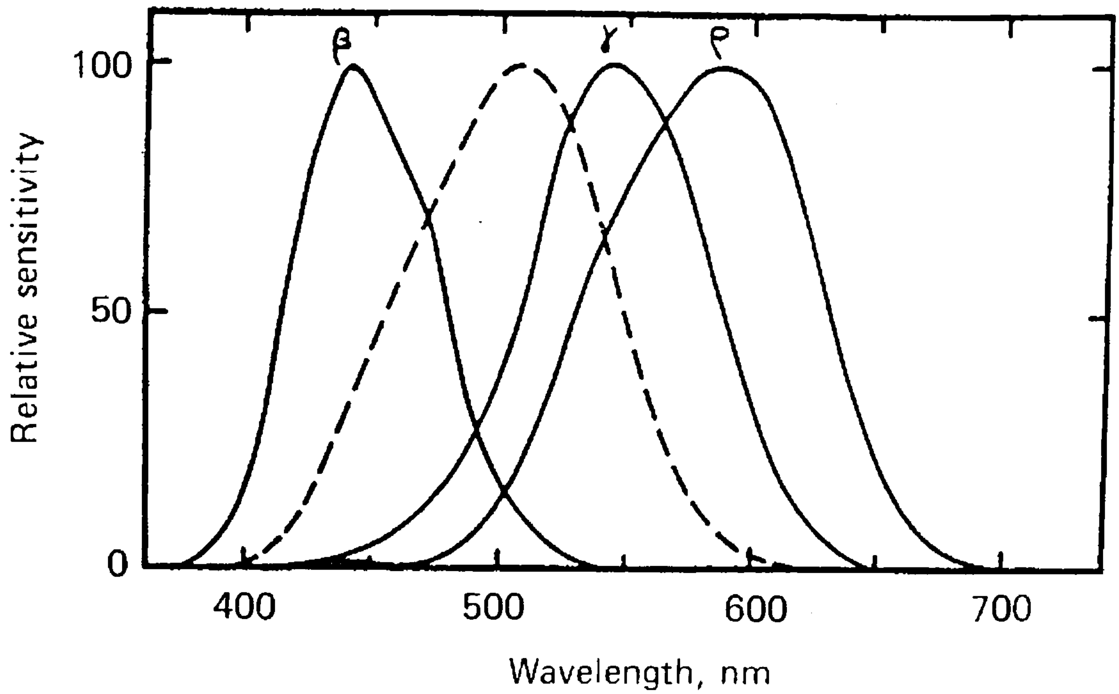

Figure 3.Spectral sensitivity of the human eye. The solid lines represent the response of the ρ, γ and β cones enabling color vision. The dashed line represents the sensitivity of the rods. [HUNT - *Measuring Colour]*

Coupled with the rods, the *achromatic* signal (A) sent to the brain is composed of:

$$A = 2\rho + \gamma + \beta/20 + S$$

Where S is the signal sent from the rods. The three color difference signals originally believed to be sent to the brain for processing are based on the different types of cones. They are calculated as follows:

$$\rho - \gamma = C1$$
$$\gamma - \beta = C2$$
$$\beta - \rho = C3$$

Applying basic mathematics it can be seen that C1 + C2 + C3 = 0, this leads to a redundancy in sending three distinct signals, meaning that given the values of any two of the signals the third can be calculated. Due to this anomaly, the following two signals are currently believed to be sent with the achromatic signal to the brain: C1 and C2 - C3. This concept correlates nicely with two groupings of color consisting of four distinct colors: reddish or greenish (C1) and yellowish or bluish (C2 - C3).

2.2 Vision - Psychological/Physiological

Understanding the physical aspects of human vision is only the beginning, and still more research is needed. To understand some of the limitations and adaptability of human vision, consider the purchase of a colorful shirt, which under the store's incandescent lighting appears to be a rich brown. Upon bringing the shirt out into daylight, not only has the color seemingly changed, it no longer matches the suit which you were planning on wearing it with. What happened?

Under store lighting conditions of the fluorescent lamp, there is significant difference between its spectral distribution vs. that of daylight.

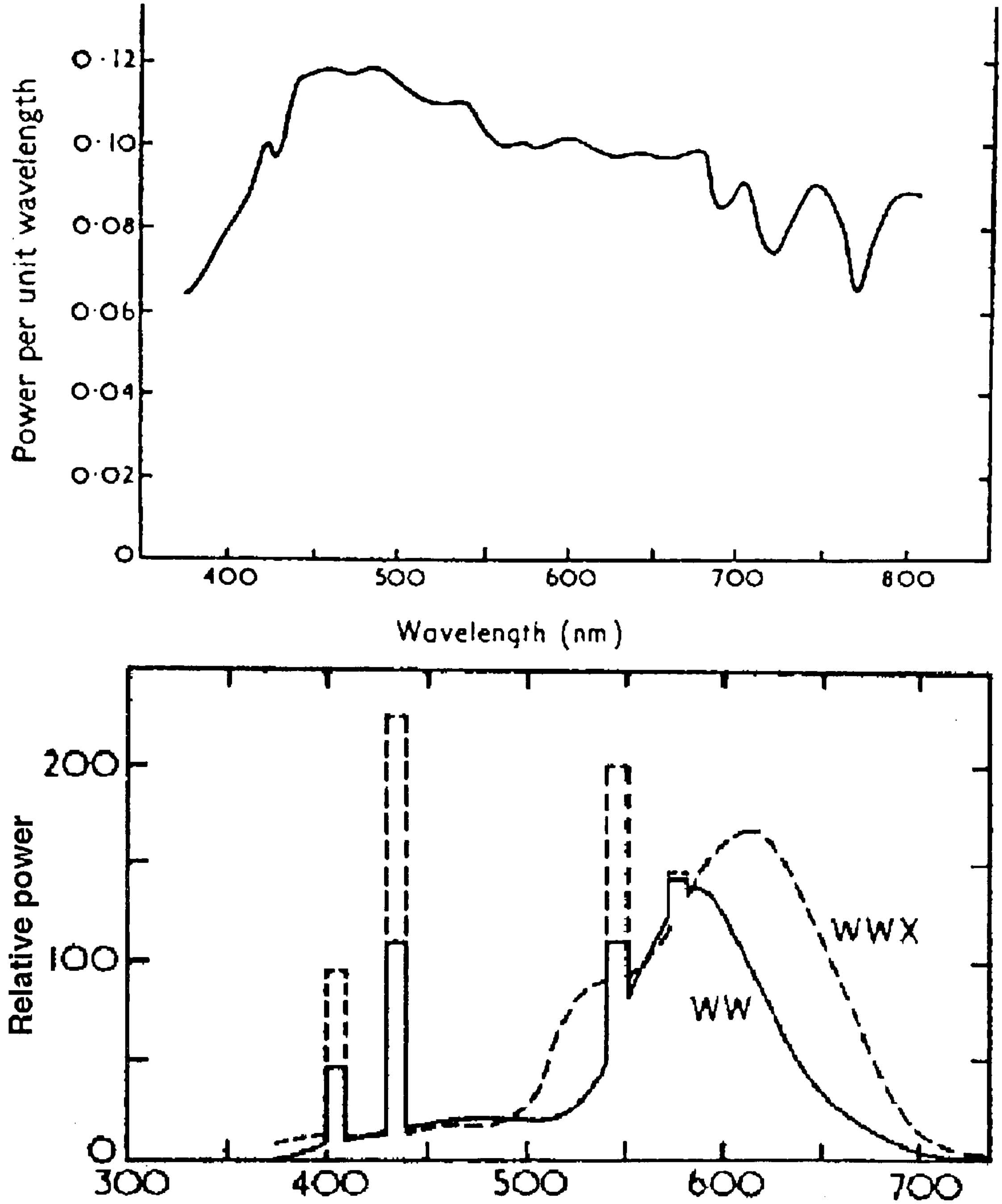

Figure 4. Comparison of spectral power of sunlight environment (upper graph) vs. two different florescent lamps (WW - warm white & WWX - warm white delux) [HUNT - *The Reproduction of Colour*]

The sunlight supplies more light in the lower end of the spectrum than was available in the store thus more light is reflected to the user and the shirt looks distinctly different. This metameric match or metamerism can be traced to the fact that the total area below the power distribution curves of the shirt and suit were equal.

Based on your misfortune in the shirt buying expedition, you might wonder, what other idiosyncrasies we should be aware of as we become more color literate. Human vision is very good at adapting to the whitest object being observed and adjusting the white point of reference to that object. This can best be explained when taking a controlled environment with different lighting conditions. As outlined earlier, the spectral distribution of florescent light versus daylight is significantly different. Yet, under either conditions those objects which appear white under one light source, will appear white under the second light source. This adaptation by the eye occurs without conscious effort by the observer.

Lighting condition is only one of the concerns which determining what color is appropriate. Within different cultures, colors portray different meanings. Awareness of cultural differences with regards to meanings of colors could reduce the likelihood of inappropriate decorations, clothing or furnishing when dealing with different cultures.

3.0 Additive Colors

The additive primary colors of Red, Green and Blue (RGB) can generate a broad spectrum of human detectable colors. As self illuminating colors, they generally obey the additive rules. As depicted below, the combination of the three primary additive colors in equal amounts of light will result in white. We will focus on the utilization of the additive system within the computer monitor environment. As an additional note it should be noted that color scanners also utilize this color space.

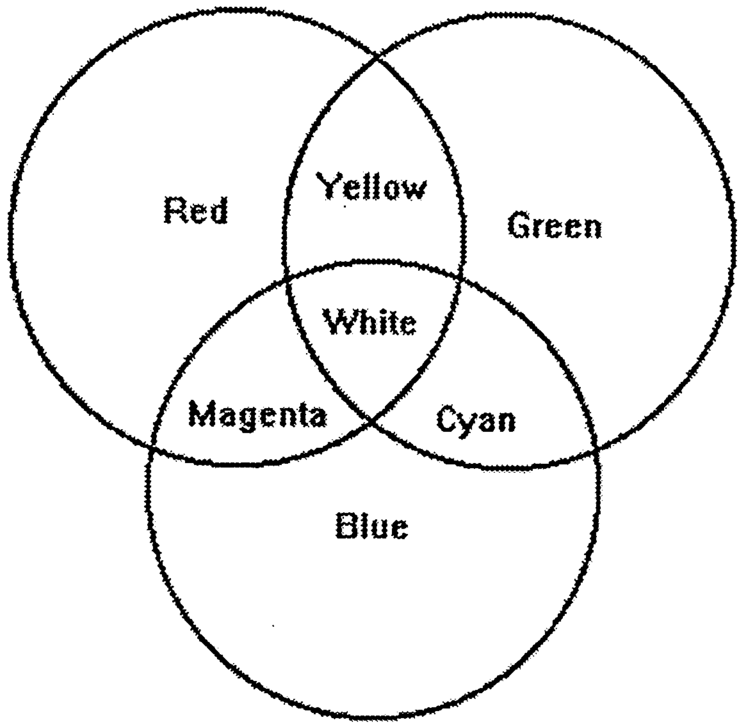

Figure 3.Additive Primary colors depicting resultant colors when the indicated primaries are combined.

The statement above referring to the creation of white from the combination of the three primaries is the theoretical conclusion surrounded with rigid restrictions. The two primary restrictions supporting this premise are that the colors are gray balanced and that equal amounts of light are emitted by the primaries. The gray balance requirement is depicted below over the spectrum of visible light for the three primaries.

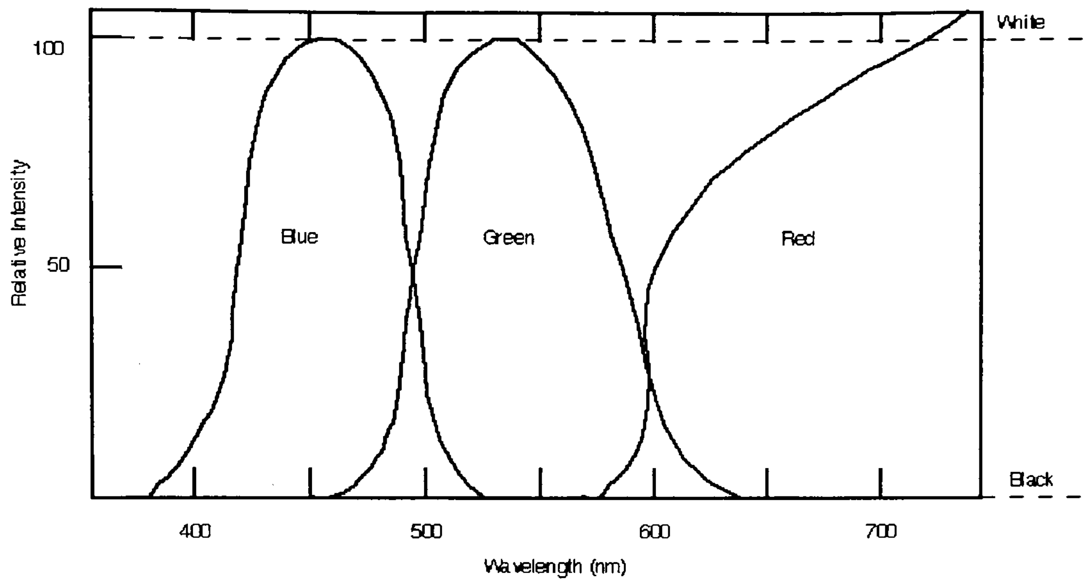

Figure 4.Additive primaries depicting various levels of grey as the three primaries are combined in equal percentages. Above 50 percent, the image will be a lighter grey leading to white, below, a darker grey leading to black.

With each source occupying the same area under each curve, when at full intensity (100%) the resulting visual effect will be the production of white light. Equal reduction of the three primaries from 100%, down to 0% will result in various gradients of the color grey, until at 0%, black is produced.

The various combinations of the additive primaries follow the rules of symmetry, transitivity, proportionality and additivity, that is:

- **Symmetry Law:** If stimulus[1] A matches stimulus B, then stimulus B matches stimulus A.[2]

- **Transitivity Law:** If A matches B and B matches C, then A matches C.

- **Proportionality Law:** If two stimuli, A and B match, then ÞA and ÞB match, given Þ is a factor by which the radiant power is changed with the spectral distribution remaining the same.

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[1]Stimulus refers to the interpretation of the color of an object by an observer

[2]Source - *Color Science Principles for Developers*

- **Additivity Law:** Given four stimuli: A, B, C, D, if A matches B and C matches D then, (A + D) matches (B + C). Where the addition of stimuli denotes additive mixtures of the stimuli.

3.1 Computer Monitors

Computer monitors create color through the illumination of the set of three phosphors: Red, Green and Blue. This additive process is capable of producing a wide spectrum of colors with various intensities of each color. The number of colors a monitor is capable of producing varies based on the technology driving the monitor, ranging from the three basic colors to over sixteen million. The design of monitors accounts for different viewing conditions through the use of different color temperatures. Color temperature affects the cast or underlying hue viewed in each color displayed. With the proper tools, the color temperature can be altered by the user to meet their needs.

The number of possible colors a system is capable of producing is dependent upon the bit depth and phosphors used. Standards outlining tolerances within the acceptable phosphor sets have contributed to color consistency. It should be noted that being able to produce colors having different numerical representation does not indicate the ability of the human eye to perceive a difference between them. The concept is explained through a better understanding of bit depth.

Early computer monitors had a bit depth of 1, meaning that a particular pixel on the screen was either on or off (white or black). Monochrome monitors, as they are referred to, continue to be utilized making use of different color phosphors such as green or amber. Improvements in technology expanded the bit depth, enabling one to emulate a shading effect, in that the pixels no longer had to be on or off, but could have values from 0 to 2^n-1, where n is the number of bits. Common values associated with n and their maximum displayable colors are outlined below:

Bit Depth	Displayable Colors
1	2
4	16
8	256
16	65,535
24	16,777,216

Initial graphics software packages utilized a full spectrum that consisted of only 16 colors. As use of color has increased, no longer is the limitation of 16 colors sufficient. This becomes obvious when dealing with continuous tone type images, where 256 colors are a minimum, with over 16 million quickly becoming required.

4.0 Subtractive Colors

Unlike the additive process in which the colorant itself is a light emitter, the subtractive process requires a light source. If no light shines on the colorant, all you see is black. The color perceived is the reflected light with portions of light being absorbed by the colorant. When no colorant is added, light is reflected and the indicated area remains white. The application of the three primary subtractive colors, Cyan, Magenta and Yellow (CMY), at maximum saturation results in most light being absorbed, and black is produced, this is depicted in the figure below.

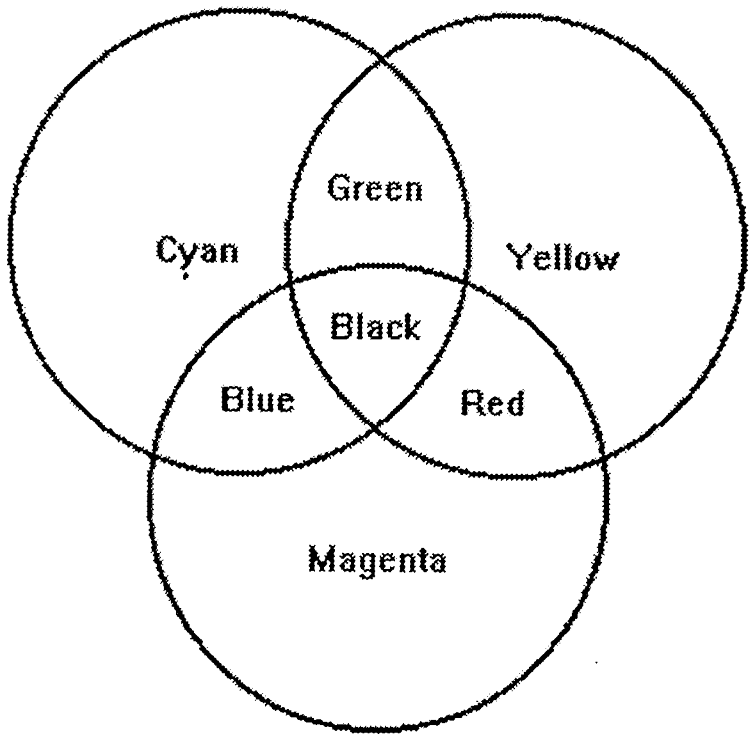

Figure 7.Subtractive primary colors depicting resultant colors when the indicated primaries are combined.

A simple explanation of the subtractive color mixing is given as follows: Beginning with a white media and a source light consisting of equal amounts of Red, Green and Blue the following statements can be made. Cyan results from presence of a colorant which reflects Green and Blue while absorbing Red. Magenta is produced with a colorant which reflects Blue and Red and absorbs Green, with Yellow being produced by a colorant

reflecting Red and Green while absorbing Blue. Based on the theory that absorption of all light will occur in the presence of all three subtractive colorants we should now be able to produce black. The figure below depicts how the various primary (additive and subtractive) colors are produced utilizing the subtractive process.

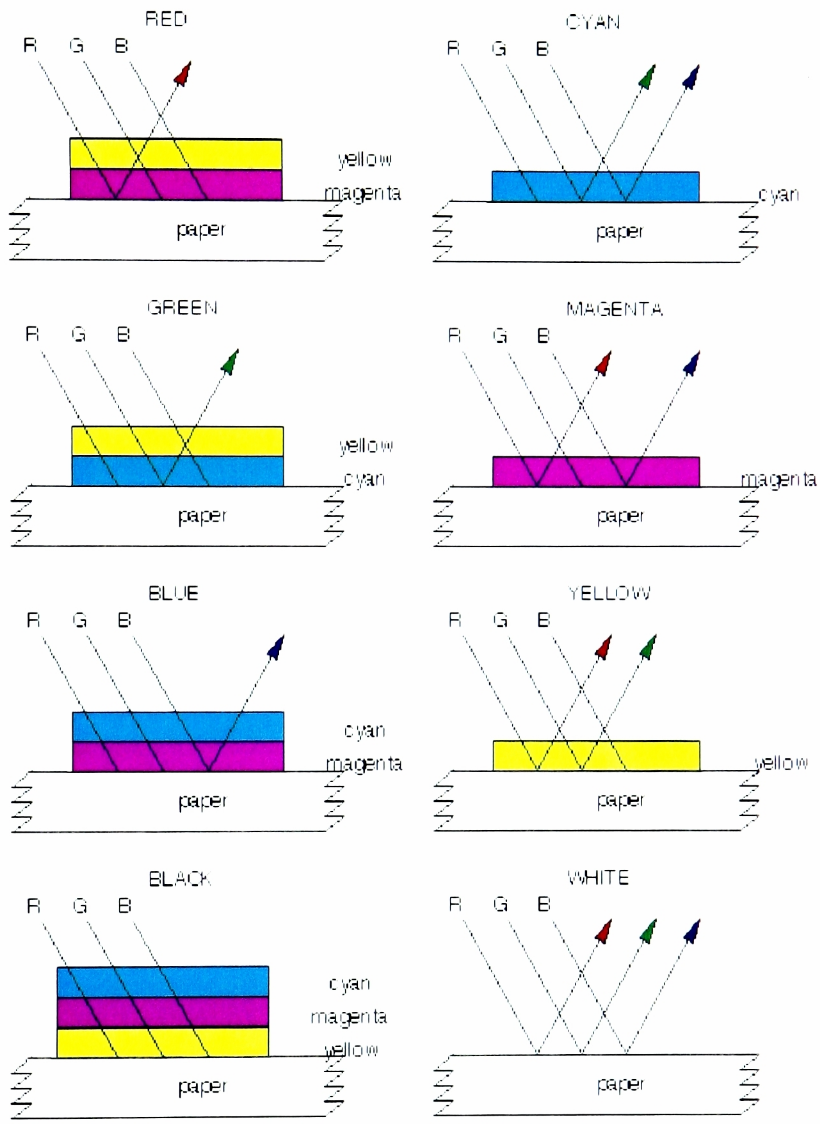

Figure 8.Production of different colors based on full spectrum of colors, utilizing cyan, magenta and yellow inks on white paper.

While theoretically, the process of producing black from the mixture of the subtractive colors is correct, results will vary based on toner/donor/ink characteristics, and it is not always the anticipated black. Having no ideal primaries, the discrepancy between theory

and reality can be traced to the use of Cyan, Magenta and Yellow having unwanted absorptions. The choice of these colorants affects one's ability to accurately reproduce selected colors. Thus, suppliers will alter the colors utilized to best meet the needs of the vast majority of their customer base. Black was introduced as an additional primary as a means of reducing use and thus costs of the colored primaries. The use of the black printer requires Grey Component Replacement (GCR) or Under Color Removal (UCR) to reduce the amount of ink and ink tracking problems associated with a three primary color system.

4.1 Color Printers

Multiple technologies exist for the placement of color images on hard copy media: dye sublimation, wax transfer, electrophotographic, ink jet, just to name a few. The choice of technology is determined by many factors, with one of the primary concerns being price, followed by preferences and anticipated use. The cost of desktop color printers continues to fall as more players enter the market and new technologies are developed. This downward trend will continue as economies of scale are factored in. Generally speaking dye sublimation printers are at the high end, ink jet at the low, with the remaining technologies in between.

The method of producing the image depends on the technology being utilized, many times using different specialized media to optimize the results. Within the scope of creating color output, the means of producing and the process of evaluating have increased in their demands. Initial computer color output was produced on plotters, being limited in colors to the specific inks available. Taking advantage of technology advances, in an effort to meet increasing demands, the computing environment has had to improve its understanding and implementation of halftoning, grey component replacement and color gamut mapping to name just a few. While these terms are not foreign to the production of high resolution color images, only within the last five to seven years have understanding of these terms and their implementation been seen outside the specialty color production shops.

Dithering or halftoning is the process by which discrete dot patterns are used to simulate continuous tones in both black/white and color renditions. This is accomplished by setting specific values to pixels within the halftone cell such that when viewed at normal viewing

distance, human perception causes the integration of the color dots into a shade of color in the area of viewing. Adjoining pixels are grouped together such that the tone variation is related to the dots per cell.

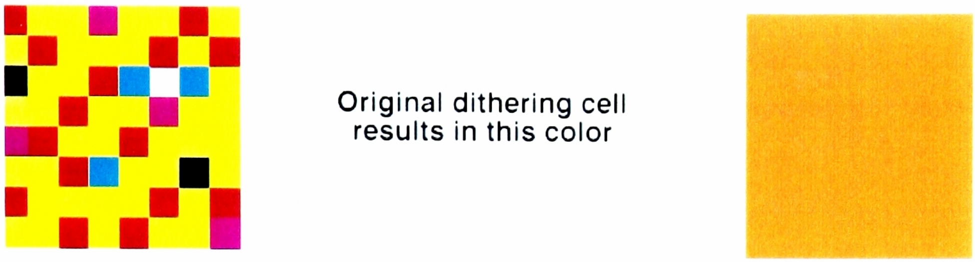

Figure 9.8 X 8 dithering cell and resultant color in 64 X 64

Grey component replacement (GCR) is the process of reducing the total amount of ink placed on the paper in areas where all four colors are being placed. The amounts of cyan, magenta and yellow are reduced and black is increased. This concept is built from the fact that combinations of cyan, magenta and yellow indicate the presence of grey, thus grey component replacement. This process accommodates the limitations on maximum ink concentrations of 260 percent as recommended for press work, while reducing use of higher priced color inks.

4.2 Color Printing Technologies

The ink jet and electrophotographic technologies enjoy wide use in black and white printing. Electrophotographic is utilized in the copier and laser printer business, while ink jet technology is found but not limited to the smaller or portable printers.

There are many kinds of ink jet printers such as the continuous-stream ink jet, drop-on-demand ink jet, and bubble jet. The bubble jet uses the heating of a resistor to create a bubble in the nozzle that forces ink onto the paper. Utilizing dithering patterns, all binary printers are capable of producing a myriad of colors. The quality of the image is affected by the paper used. Different paper stocks will absorb the inks differently, causing the

individual bits of ink to spread out, diffusing edge information while affecting the color perceived by the viewer.

Electrophotographic printers place a dot pattern on a printing drum, apply toner to the drum, then fuse the image from the drum onto the paper. For black and white printers this consisted of a single pass. With the advent of color, this now requires the application of the four colors: Cyan, Magenta, Yellow and Black. This process can be accomplished in one to four passes, depending on the specific vendor implementation.

Thermal wax transfer utilizes the same four (sometimes three) pass concept as in electrophotographic, but applies the image through the heating of individual components of the print head. If the element is heated the donor is melted onto the paper. Dithering is utilized to produce the myriad of colors beyond the subtractive primaries.

Generally the dye sublimation(also known as dye diffusion or continuous tone) printers produce the best quality prints. Utilizing similar technology to that of the wax transfer printers, the dye sublimation printers have a couple of advantages. They are continuous tone printers. The amount of dyes placed on the paper can be varied by altering the amount of heat applied to the element. Colors beyond the primaries are created through layering various amounts of inks on top of each other.

One draw back that each of these printers encounter is that color quality is related to the paper being utilized. Many manufacturers are beginning to release plain paper printers, but you will find the best color quality prints are produced by using specially coated paper. Dye sublimation printers require special media.

5.0 The CIE Color Standards

The 1931 CIE (Commission Internationale de l'Eclairage [International Commission on Illumination]) standard utilized three components in establishing its color ordering system: source, object and observer. The source component is made up of three primary color light sources. With the proper choice of source colors and by varying their intensities one is able to match a wide range of test colors referred to as objects. The determination of matching colors is based on the observations of a standard observer.

Initial experiments and publications were the result of the standardization of work developed in the 1920's. Utilizing the results of the color matching experiment as pictured below, a wide range of metameric color matches can be achieved.

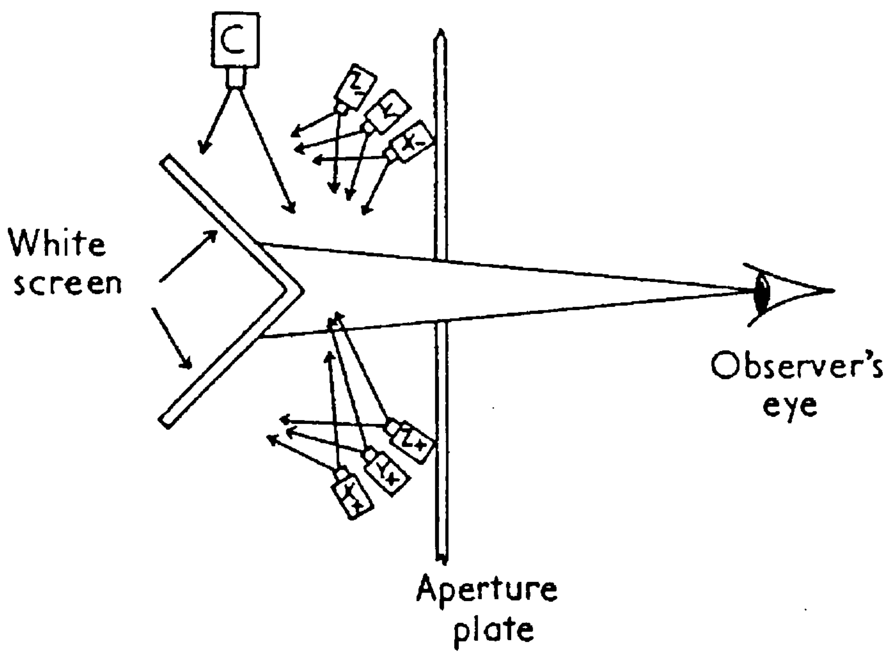

Figure 10.Color matching experiment where the observer is attempting to match the color C, illuminating the upper portion of the screen through manipulation of the color matching lights (X_+, Y_+, Z_+,X_-, Y_-, Z_-). If an observer is unable to match C through the manipulation of X_+, Y_+, Z_+, additional color can be added to the upper portion of the viewing screen through X_-, Y_-, Z_-, essentially utilizing negative portions of the utilized colors to match the original color C. [HUNT - *The Reproduction of Colour]*

It was determined that, through the process of these experiments a large number of color matches were achievable utilizing a defined set of color primaries and no single set was

capable of matching all the test colors. A method of resolving this problem used the addition of primary colors to the object being matched. Thus the combination or addition of two primaries coupled with the subtraction (adding to the object) of the third primary enabled the matching of the comprehensive array of test objects. The relative amounts of each of the primary colors needed by a person with normal color vision to match the full range of colors are plotted below. The results of this experiment created the concept of "the standard observer", in that a person with normal color vision would be able to match the range of colors as plotted below within a 2° viewing range.

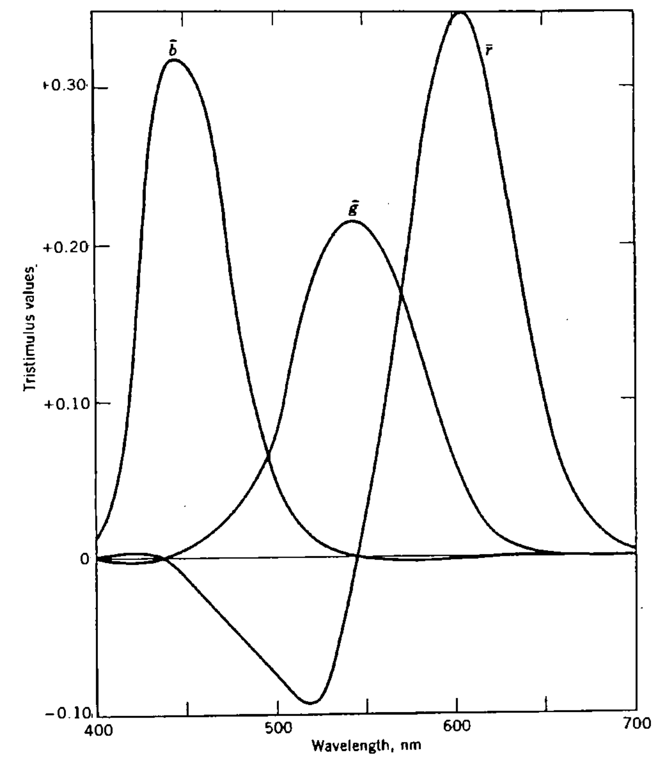

Figure 11. Tristimulus values resulting from 1931 CIE experiment based on standard observer. [Billmeyer & Saltzman, *Principles of Color Technology]*

Having a mathematical model with which to move forward, the presence of negative numbers were deemed unacceptable. In an effort to eliminate such numbers, a transformation from the original set of primaries red, green and blue was devised. The resulting primaries, which were not produceable by any real lamps, are referenced as the color matching function $\bar{x}$, $\bar{y}$, and $\bar{z}$. One attribute lost in this transformation was that in the initial values $\bar{y}$ was selected based on the eyes response to total power. With these

numbers now subjected to a transformation this was no longer accurate. What remained though is that the $\overline{y}$ value maintained a correlation with a color's lightness.

This chromaticity is defined as the normalization of the tristimulus values.

$$x = X/(X + Y + Z)$$
$$y = Y/(X + Y + Z)$$
$$z = 1 - X - Y$$

From this mathematical relationship, having the values of two of the three variables, you can determine the value of the third. Thus we can construct a two dimensional diagram referred to as the chromaticity diagram. The y value is plotted on the ordinate with the x as the abscissa and is referred to as the x, y chromaticity diagram.

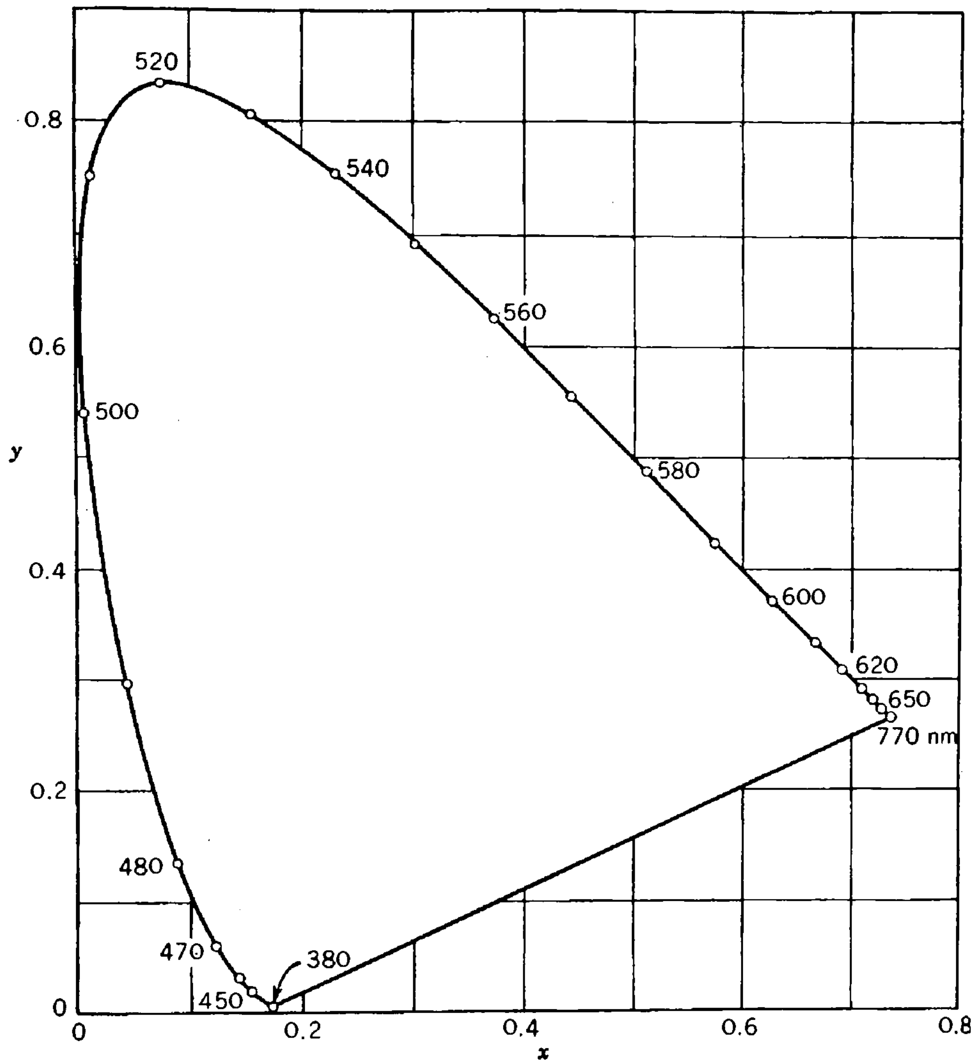

Figure 12.Horseshoe shaped 1931 x,y chromaticity diagram [Billmeyer & Saltzman, *Principles of Color Technology]*

This diagram shows that the spectral colors are located along the perimeter of the diagram. The exception to this phenomenon is the lack of identifiable wavelengths along the line connecting the minimum and maximum wavelengths. While this diagram is not used to identify specific colors the straight line identifies the color purple which is color that cannot be found in the spectrum.

Since this initial standardization, numerous changes have been proposed, applied, and utilized in the analysis and production of color in the various media. The 1931 standard has remained the cornerstone on which to build. In 1964, the CIE adopted an additional

standard observer. Accommodating the technological advances and understanding of the human perception of color it was determined that the limitation of standard observer to a 2° field of vision does not necessarily yield accurate color representation. The fovea, the highest concentration of cones within the retina, is located 4° off the optical axis. Applying this knowledge to the 2° observer, the highest concentration of color receptors is not involved in determining color matches. In an attempt to more accurately measure color matches, the viewing field was increased from 2° to 10°. This expansion of the viewing field slightly effected the tristimulus values and chromaticity diagrams, but the fundamental concepts remained.

While laying a solid foundation this 1931 standard lacked a feature of uniform chromaticity. Uniform chromaticity is based on the concept that equal changes in values of the coordinates will result in equally perceptible changes in the color being viewed. The worst offender occurred in the upper portion of the diagram where the green hues reside. The red portion of the spectrum displays better uniform chromaticity than the purple-blue portion of the diagram. Attempting to correct the uniformity problem the CIE adopted extensions of the 1931 standard the U^*, V^*, W^* system in 1963.

Identifying the use of multiple systems for color measurement within the various industries, the CIE sought to correct the non uniformity uncovered in the U^*, V^*, W^* color space. Beginning in 1973 various committees which included members from around the world, began to mold the future color standards. Accommodating the multiple disciplines, two systems, CIELUV and CIELAB, were proposed and eventually adopted in 1976.

The key component of the Luv standard is the Uniform Chromaticity Scale (UCS) diagram, referred to as the u', v' diagram. This diagram is the result of plotting:

$$u' = 4X/(X + 15Y + 3Z) = 4x/(-2x + 12y + 3)$$
$$v' = 9Y/X + 15Y + 3Z) = 9y/(-2x + 12y + 3)$$

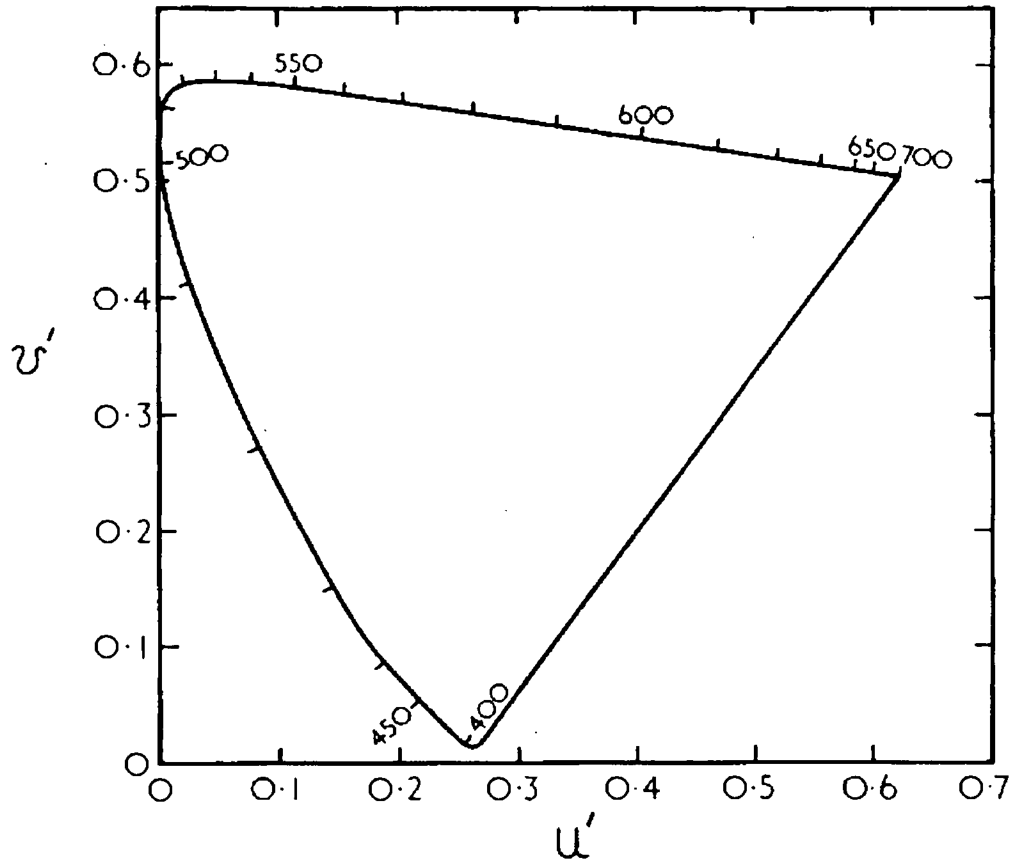

Figure 13.u', v' chromaticity diagram [HUNT - *The Reproduction of Colour]*

Correlating this to the original x, y UCS diagram the following formula are utilized:

$$x = 9u'/(6u' - 16v' + 12)$$
$$y = 4v'/(6u' - 16v' + 12)$$

Identifying L^* with the lightness and bringing all the various values of the system together the following formula should be utilized, where the subscript of 'n' ($_n$) indicates the VALUES of the reference white. This relationship to reference white indicates how viewing conditions can affect the perception of the color being viewed.

$L^* = 116(Y/Y_n)^{1/3} - 16$ for $Y/Y_n > 0.008856$
$L^* = 903.3(Y/Y_n)$ for $Y/Y_n \leq 0.008856$
$u^* = 13L^*(u - u'_n)$

$v^* = 13L^*(v' - v'_n)$
$h_{uv} = \arctan(v^*/u^*)$
$C^*_{uv} = (u^{*2} + v^{*2})^{½}$
$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{½}$
$\Delta H^*_{uv} = [(\Delta E^*_{uv})^2 - (\Delta L^*)^2 - (\Delta C^*_{uv})^2]^{½}$

The above formulas have introduced the terms ΔE, ΔH and C^*_{uv}. The ΔE defines the color difference between two distinct colors. From my experimentation and experience a ΔE of as little as two (2) can be detected, while values of as high as twenty (20) and even more are common place in the color computing environment. While the prepress industry includes this as one of its quality factors, the general computing environment is concerned more with "does it look correct", not the details of what the ΔE values are. As has happened in other disciplines, the expectations of the high end will eventually become the expectations of the common user. Until the market matures, this measurement will continue to be of limited value in the general computing environment.

The ΔH term is similar to ΔE in that it deals with color differences. The ΔH accounts for differences in hue only while the ΔE accommodates differences across all three components of the system.

The C^*_{uv} term defines the chroma of a color. This term correlates to the vibrance or saturation of a color. A color of low chroma is closely related to the greys, while a color with a high chroma is vibrant or saturated.

To accommodate those not associated with the color reproduction industry an additional standard was adopted at the same time as LUV. This new standard was LAB (referred also as L*, a*, b* or CIELAB). This system was derived from the proposed standard of U*, V*, W*, in recognition that the space was not nearly as uniform as initially thought. Such was the error in this UVW that increases of as much as 50% in the V* value would contribute significantly to its color matching capabilities. Through multiple experiments, it was determined that a color system based on the 1964 standard with a 50% increase in the V* value resulted in a system which rivaled the performance of CIELUV. This comparable performance, coupled with the similarities of this system to the Adams-Nikerson model, a system already adopted by various international industrial groups, lead the CIE to the conclusion that a compromise on a single solution would not be achievable.

Thus both proposals were presented and adopted pending a better model which could gain acceptability throughout the color rendering, measuring and reproduction industries.

The associated formula for determining the LAB values are identified below.

$L^* = 116(Y/Y_n)^{1/3} - 16$ for $Y/Y_n > 0.008856$

$L^* = 903.3(Y/Y_n)$ for $Y/Y_n \leq 0.008856$

$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}$

$b^* = 500[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}$

$h_{ab} = \arctan(b^*/a^*)$

$\Delta E^*{}_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$

$\Delta H^*{}_{ab} = [(\Delta E^*{}_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*{}_{ab})^2]^{1/2}$

The choice of color system appears to be one of personal preference. There are technically no advantages between the two.

6.0 Current Approaches for Color Reproduction

The goal of color reproduction in the computing environment is to achieve 'What You See is What You Get'. This goal is promised by many, but the solution is far more limited in scope than what the promises lead one to believe. Four solutions that promote the production of consistent and even WYSIWYG color will be explored here. Through research and use, it appears that the promised land is still out of reach. Technology has progressed sufficiently to the point that what you see resembles what you get (good enough), but not exactly. Key prohibiting factors relate to the use of different sources of information (illuminated vs. reflective), different primaries (additive vs. subtractive) and different color spaces across devices. Each system supports its own optimal solution which, when utilized in a closed or tightly controlled environment, yields improved results compared to utilizing no color management scheme.

6.1 PostScript Level 2

PostScript Level 1 was introduced in 1985 as a device independent means of representing the printed page. It debuted as the page description language for the Apple Laserwriter. Since its introduction it has become the "defacto" standard for Page Description Languages (PDLs) in the computing environment. In its initial offering, commands for rendering color on the printed page were limited to HSB (Hue, Saturation, Brightness)[3] and RGB color spaces.

The demands for expanded functionality grew as the user community began to master and expand beyond the capabilities of PostScript Level 1. Within these new needs were the requirements for the support of color transportability. The 4 pen plotters of the early 80's have given way to high quality, continuous tone, 24-bit color printers of the 90's. The plotter maintains its foothold, but expanded use of color printers will not tolerate the limitations the plotter environment has experienced. Adobe recognized the needs of the color community and defined a full range of color operators. This created translations between each of the defined CIE standards, thus bridging the gap into colorimetric precision.

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3 HSB is a means of specifying RGB values in a different coordinate system.

Having capabilities to define colors in device color spaces (RGB or CMYK) in addition to support of multiple CIE standards, PostScript covers the broadest base for color solutions in the computing environment. The focus of this study is on the CIE based systems XYZ and $L^*a^*b^*$, with limited discussion on the DeviceRGB and DeviceCMYK.

When focusing on the native color spaces of monitors and printers, dealing with the RGB and CMYK appears to be a natural means of achieving desirable color for these devices. On the computer screen colors are created using the RGB's of the monitor, while the production of a hard copy is done via the CMYK color space. Basic color arithmetic would dictate the various colors that could be produced through the following mathematical model:

cyan = 1.0 - red
magenta = 1.0 - green
yellow = 1.0 - blue

Based on the mixing properties of inks it has been determined that the addition of a fourth ink, black, would enlarge the color gamut. Incorporated into this inclusion are the concepts of black generation (BG) and undercolor removal (UCR). With these extensions, the conversion from RGB to CMYK can be achieved. Utilizing the formula above for cyan(c), magenta(m) and yellow(y), coupled with the formula for black(k), PostScript Level 2 enhances the color reproduction based on the formula below:

k = min (c, m, y)

cyan = min(1.0, max(0.0, c - UCR (k)))
magenta = min(1.0, max(0.0, m - UCR (k)))
cyan = min(1.0, max(0.0, y - UCR (k)))
black = min (1.0, max (0.0, BG(k)))

The inverse transformations of information from CMYK to RGB:

red = 1.0 - min (1.0, c + k)
green = 1.0 - min (1.0, m + k)
blue = 1.0 - min (1.0, y + k)

These device specific transforms would appear to fulfill the requirements of color reproduction in the computing environment. But adoption of a closed system as described above would work only in a tightly controlled system (i.e.: one compatible monitor and printer). Having the capabilities to expand beyond one's personal computing environment and still produce consistent color requires a system beyond the capabilities of DeviceRGB and DeviceCMYK. No longer is color reproduction done by one individual at one location, but it could literally include input from people all over the world. This inability to characterize systems outside your immediate domain coupled with the inability to transform to any of the CIE color spaces has reduced the value of these systems.

In recognition of the need for device independent color descriptions which could accommodate internationally accepted standards, PostScript Level 2 defined CIEBaseABC and CIEBaseA color spaces. The BaseA definition is a one-dimensional system usually related to a single component of the BaseABC.
CIEBasedABC color space, utilizing three parameters, can represent a wide range of color components. These arguments represent a variety of color components depending on the parameters they utilize. Current representations of A, B and C include:

X, Y, and Z in the CIE 1931 (XYZ)-space.

R, G, and B in calibrated RGB space.

L^*, a^*, b^* in the CIE 1976 ($L^*a^*b^*$)-space.

Y, I, and Q in the National Television Systems Committee (NTSC) space.

Y, U, and V in the Sequence and Memory (SECAM) and Phase Alteration Line (PAL) spaces.

NTSC, SECAM and PAL are standards for transmitting color television signals.

The adoption of multiple options within Level 2 is probably due in part to the lack of a single international color standard coupled with the need to accommodate a broad range of existing peripheral devices. This open choice is one which should accommodate your

environment, allowing users to continue color specification in the coordinate space they are accustom to.

The "setcolorspace" command is used to specify the maximum range of values for color space information when building an image. The attributes associated with this command include white point, black point, and transformation matrix into XYZ color space. Having specified your image information, it must now be transformed for rendering on the appropriate output device. The rendering attributes of a specific device are contained within the Color Rendering Dictionary(CRD). Transforming from the device independent color specification requires the following:

- Transformation of the original CIEBaseABC or CIEBaseA into the CIE 1931 XYZ color space.
- Adjust the XYZ values to accommodate differences in established white and black points producing an adjusted intermediate values X', Y', Z'.. This transformation is based on the MatrixPQR and TransformPQR information contained in the color rendering dictionary. MatrixPQR specifies the linear interpretation of the CIE 1931 X, Y, Z components with respect to the intermediate values. TransformPQR accounts for differences in white and black points between source and device, while preserving color appearance and visual contrast. (Note: The specification of White and Black point may not be as straight forward as anticipated. A color darker than absolute white and a color lighter than black may be utilized to avoid blocking of highlights and shadows respectively.)
- Transform the X'Y'Z' values into the specific device's color space values DEF.
- If a rendering table is supplied within the Color Rendering Dictionary (CRD), index into the supplied table for an interpolated device color. The values indexed here consist of three or four entries which are transformed by a vendor supplied process into the device color space. When no rendering table is supplied, the values DEF represent the red, green and blue respectively within the DeviceRGB color space.

Within the transformation from CIE-based specifications to device-dependent specifications, color gamut mapping will be applied for those colors outside the range of those producable for the destination device. This process, based on values supplied within the PostScript Level 2 operator: setcolorspace and the CRD, attempts to maintain color appearance and visual contrast. It should be noted, that while this is the intention of PostScript Level 2, appearance and contrast are not easily maintainable.

An advantage of a system with this many choices is that those users desiring multiple means of specifying the attributes of an image have a system that meets their needs. These choices may be seen as a hindrance in that all the different choices must be transformed into device dependent color space. The accommodation of numerous sources of information could be viewed as a disadvantage by the device and/or software manufactures.

6.2 Pantone

The Pantone systems grew from a graphics requirement to produce consistent predictable colors. Initially, producable colors were chosen by those needing to produce color consistently in areas such as product packaging. Pantone solicited the input from graphics community, identifying approximately three hundred colors it needed to be able to consistently reproduce. Working within the parameters of subtractive color mixing, Pantone developed the ink formulas necessary to produce the identified colors for offset press.

Having established a color communications scheme for the graphic arts environment, Pantone continues to expand that range of available colors. This expansion has lead to availability of reproducible metallic and pastel colors, along with extensive color tint specifications. Pantone recognized that the graphic artists are no longer restricted to the paint and marker environment, but are utilizing the full expanse of computer equipment available to them. It created the Pantone Electronic Color Division in 1984 to meet the challenge of the expanding electronic color community. With an increasing number of original press work being done on the computer, Pantone established a means of selecting Pantone colors on the computer screen and outputting them to a printer. Available printers for the desktop community were rather limited at first, while peripheral vendors began to sign up in support of the Pantone color system. As printers became available, users were capable of selecting and viewing printed output prior to going to press.

The Pantone system has expanded over the years to approximately one thousand colors. The needs of the graphic arts community are centered around two selected illuminates:

D50 - a standard graphic arts illuminate
D65 - a common daylight illuminant

Coupled with this ongoing expansion has been the adoption of a variant of the chromaticity coordinates discussed in the CIE section: x, y, Y. This variant is based on the two dimensional x, y chromaticity diagram, extended in the third dimension. The luminance-factor, Y, originates from the white point of the designated illuminant, rising from 0 (black) to 100 (white) percent.

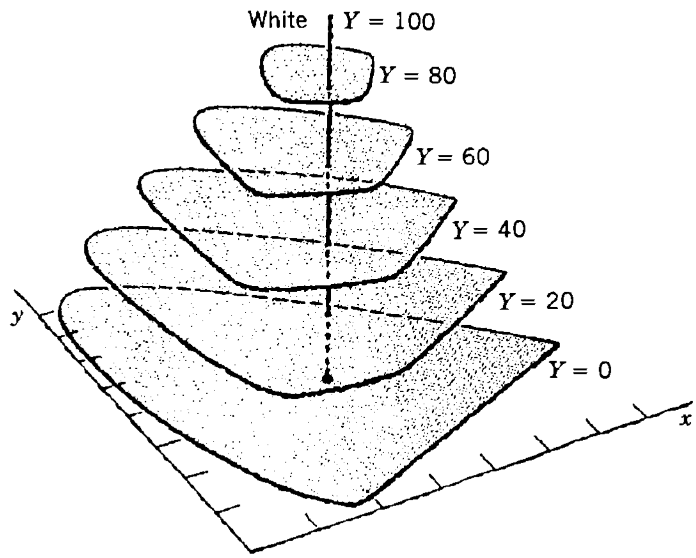

Figure 14.xyY diagram. white is clearly defined at the top of the Y axis (Y = 100), while black has no unique definition [Billmeyer & Saltzman]

In adopting this definition, Pantone inherited a basic problem of this system, the color black has no unique value. While white has a unique description where Y = 100, black is defined by the plane where Y = 0, The above figure depicts the numerous values associated with black across the x, y plane.

With expanding acceptance of the Pantone Matching System different idiosyncrasies have been noted in its use and implementation. Pantone colors continued to be correlated with Pantone color charts and color chips. Final color determinations are associated with specific Pantone certified colors, either specific inks or process colors. User selection is not based on the color displayed on the video display, but on the Pantone specified color to be printed. The video display provides a means of specifying, subjectively previewing and directing to a printer for initial proof, Pantone specified colors.

As the number of Pantone certified software packages and peripheral devices has expanded, the variety of implementations have also increased. The source of the problem is two fold: implementation and variability of output quality. The implementation differences stem from individual applications applying color correction and transfer functions such as dot gain on the Pantone specified colors. This alteration of data

produces less than optimal results when compared with the comparative color chart. Variability of printed output quality results from different printing technologies as well as the differences in inks used to produce the output. It appears that Pantone has supplied vendors with the tools and defined standards for implementation of the Pantone Matching System, but each vendor has incorporated them by applying their own rules.

Through the evolution of the Pantone Matching system from strictly a color chart specification to its growth into electronic definitions, the foundation of accurate color correction has remained: Select, Specify and Control. The selection process can be applied for approximations of Pantone colors on current computer systems. The specification and control steps have not changed.

6.3 PhotoYCC

Eastman Kodak, a giant in the field of color photography, has recognized the disarray associated with color rendering in the computing environment and has seized the opportunity to define its own color-encoding scheme, PhotoYCC. The foundation of this work is in support of encoding Photo CD (Compact Disc) disc image data, a new means of bringing high quality still images to the home and desktop computing environment.

The PhotoYCC system is built upon two industry standards for video displays: encoding parameters of digital television for studios and high-definition television (HDTV) production and exchange. The reasoning behind this is that while final images are produced on a variety of media, they are viewed and edited on a video display.

Utilizing the photographic science of film as the foundation on which to build this encoding scheme, Kodak has eliminated the device dependencies associated with models based on monitor or printer color spaces. This device independence is the color-encoding scheme for data storage, it does not reference the initial means of image capture. The image information remains limited to and dependent on the image capturing capabilities of the film on which the image is captured. The figure below compares the limitations of the computer display with printed output.

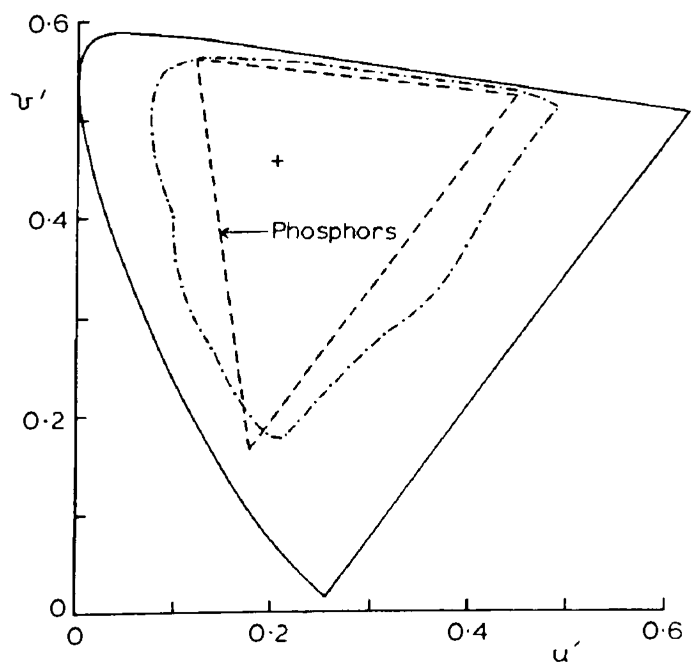

Figure 15.The triangle represents the chromaticities of phosphors while the dot-dash line represents the gamut of dyes and inks illuminated in daylight. [HUNT - *The Reproduction of Colour*]

Being designed on the premise that at some point in time an image will be displayed on a video screen, one of the key components of the PhotoYCC encoding scheme is the ability to rapidly display images on computer monitors and television screens. This premise accommodates the anticipated future of television, HDTV. Understanding the limitations of video display and HDTV, PhotoYCC covers a gamut larger than both.

The attributes of the image captured on film are based on the combination of several spectral attributes of various components which make up the scene: scene element, reference illuminant and reference image capturing device. The resultant RGB values are converted into PhotoYCC values based on this three step process. The YCC components correspond to Luma, Chroma1 and Chroma2.

1. Nonlinear transformation applied to the RGB values: The transformation is built based on the need for rapid translation into the video metric without sacrifice of gamut or color fidelity while maintaining device independence.

For R, G, B ≥ 0.018:[4]

$R' = 1.099\,R^{0.45} - 0.099$

$G' = 1.099\,G^{0.45} - 0.099$

$B' = 1.099\,B^{0.45} - 0.099$

For R, G, B ≤ -0.018:

$R' = -1.099\,|R|^{0.45} - 0.099$

$G' = -1.099\,|G|^{0.45} - 0.099$

$B' = -1.099\,|B|^{0.45} - 0.099$

For $-0.018 < R, G, B < 0.018$:

$R' = 4.5R$

$G' = 4.5G$

$B' = 4.5B$

[4]Source - *KODAK Photo CD System A Planning Guide for Developers*

2. Conversion of the results of the Nonlinear transform to one luma and two chroma values. This conversion preserves the photographic color quality for continuous tone devices, while providing maximum compatibility with current equipment.

$$\begin{aligned} \text{Luma} &= 0.299R' + 0.587G' + 0.114B' \\ \text{Chroma1} &= -0.299R' - 0.587G' + 0.886B' \\ \text{Chroma2} &= 0.701R' - 0.587G' - 0.114B' \end{aligned}$$

3. The final step of the PhotoYCC encoding scheme involves the conversion of the three components into a 24-bit value (three 8-bit components). Each of the resulting values is in the range of 0 to 255, inclusive.

$$\begin{aligned} \text{Luma}_{8\text{-bit}} &= (255/1.402)\text{Luma} \\ \text{Chroma1}_{8\text{-bit}} &= 111.40(\text{Chroma1}) + 156 \\ \text{Chroma2}_{8\text{-bit}} &= 135.64(\text{Chroma2}) + 137 \end{aligned}$$

With the image information encoded in PhotoYCC format, the decoding for your monitor or other output/display device must accommodate the limitations of such. This accounting for the limitations is necessary due to the preservation of photographic qualities in the encoded data. Accommodating the conversion to RGB values as required for video signals can be accomplished as indicated:

$$\begin{aligned} L &= 1.3584\ \text{Luma}_{8\text{-bit}} \\ C1 &= 2.2179(\text{Chroma1}_{8\text{-bit}} - 156) \\ C2 &= 1.8215(\text{Chroma2}_{8\text{-bit}} - 137) \end{aligned}$$

$$\begin{aligned} R_{display} &= L + C2 \\ G_{display} &= L - 0.194(C1) - 0.509(C2) \\ B_{display} &= L + C1 \end{aligned}$$

The initial application of nonlinear transformations on the RGB data enables the rapid transformation of information to video displays. This process reinforces the concept on which Kodak built this system: final output of images is on a variety of media but images

are almost always displayed on video terminals somewhere in their life. Though seen as a probable means of viewing the image, the PhotoYCC data is limited by the photographic qualities of the original image on film, not the RGB displays.

The encoding scheme is a component of the Photo CD system implemented for the storage of photographic quality images in a compact form. Commercially available Photo CD's store information corresponding to the following five different resolutions for each image stored:

Image Component	Resolution
Base/16	128 lines X 192 pixels
Base/4	256 lines X 384 pixels
Base	512 lines X 768 pixels
4Base	1024 lines X 1536 pixels
16Base	2048 lines X 3072 pixels

The storage of these resolutions incorporates a combination of subsampling and compression techniques. The largest image, 16Base, would require approximately 18 megabytes of space if it is stored using conventional methods. Utilizing the subsampling and compression techniques the storage of all five resolutions is compacted into approximately 4.5 megabytes. A common feature shared by the three lower resolutions along with the 16Base image is the subsampling of chrominance data. This feature is based on the characteristics of human vision which are more sensitive to changes in relative luminance than chrominance. The expansion of the chrominance data is based on interpolation of available information resulting in an insignificant loss of image quality. The 4Base and 16Base images accomplish further reduction in storage needs by storing the difference between individual pixel values from the preceding image reconstruction, then applying Huffman encoding to the resulting information. This methodology has resulted in no chroma data being stored for the 4Base image, as suitable reconstruction of these channels can be accomplished through the interpolation of the Base chroma information.

The Base image accommodates the needs of the television viewing audience, with the smaller resolutions providing a means of quickly previewing multiple images simultaneously and/or providing a thumb nail copy of the image. The larger image formats

accommodate the needs for photographic quality output devices (dye sublimation printers) as well as a path into HDTV.

6.4 TekHVC

Tektronix introduced its first color terminals in the late 1970's. Coupled with this entry into the color computer monitor market, Tektronix introduced the HLS system in an attempt to address perceptual inconsistencies associated with RGB. Being touted as easier to use than RGB, HLS suffered from lack of color uniformity and parameter interdependencies. These factors together with technological advances in the color rendering devices (displays and printers) led Tektronix to the development of an updated color definition scheme, TekHVC (future reference will be to "HVC"). This system maintains the intuitive nature of the color definition of HLS, while providing a link to international color standards, with the capability of specifying any visible color.

The introduction of the HLS system by Tektronix was an attempt to address the perceptual inconsistencies of the color specification for display hardware, RGB. Defining the perceptual characteristics of Hue, Lightness and Saturation (H, L, S), the mathematical model consisted of a three-dimensional polar coordinate system (See figure on the next page).

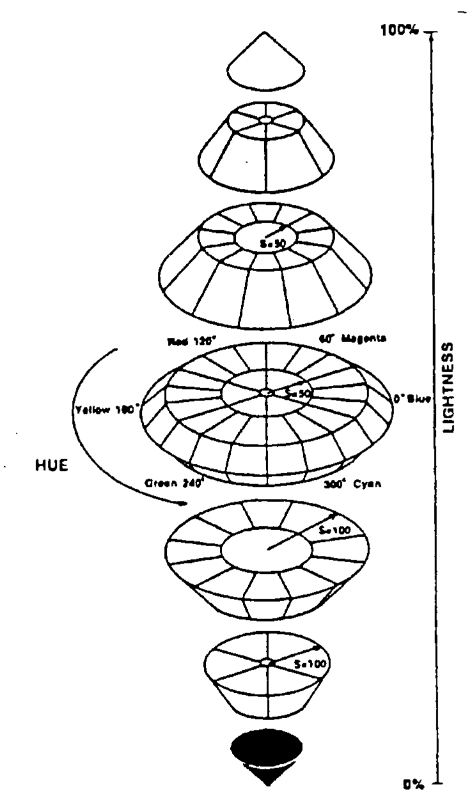

Figure 16.The TekHLS color space
[*TekColor Color Management System, System Implementor's Manual*]

This system is based on a design that made it easier from a computer implementation point of view, a symmetric double-ended cone. Maximum saturation was required to occur at a lightness value of 50, thus HLS suffered from a defined flaw of the RGB data definition in that it was mathematically convenient. The adoption of hue, lightness and saturation components attempted to address the definition of colors in an appearance based fashion while accommodating some of the perceptual non-linearities of human color vision.

Having the capability to specify over a million colors (101^3; each of three components has a range of values from 0 to 100), the number of distinguishable colors was far less. The uniformity of the system was such that changes of one unit in one of the components would result in detectable color differences in some regions, while other regions of the model could tolerate changes of ten units with no perceptible difference. This non-uniformity can be traced to the adoption of the symmetric double ended cone, incorporating the requirement that regardless of hue, maximal saturation would always have a value of 100 and occur at the defined level of lightness of 50. These system definitions caused an interdependency of attributes, in that altering the value of one component would automatically alter the values of one or both of the remaining components. An additional flaw in the definition of HLS was its device dependency, in that colors defined with an HLS specification would look different when displayed on another device.

Because of the lack of uniformity and consistent implementation of HLS, Tektronix developed HVC. Visual space uniformity, colorimetric precision, and the definition of the independent attributes Hue, Value and Chroma are seen as progress in the process of color rendering in computers.

Unlike the device dependent RGB, CMYK and HLS color spaces which are capable of producing a wide range of colors, TekHVC is capable of representing all realizable colors as defined by the CIE 1976 (u', v') Uniform Chromaticity Scales Diagram. The term realizable is based on the premise that HVC is a better scheme than currently available CIE schemes, for the evaluation and detection of color differences. As a result of this expansive gamut, accessible colors of any particular device are seen as a subset of TekHVC. This concept leads to the conclusion that the definition of a color within the TekHVC system is truly device independent, regardless of the gamut of that device. TekHVC is purported to possess colorimetric precision, in that it was derived from the 1976 CIE u', v' chromaticity diagram. The mathematical model describing TekHVC gives

an irregularly shaped 3-dimensional color gamut, enabling maximal saturation to be determined by the mathematics of the model, not a predefined symmetrical sphere. This irregularity enables detectable differences to be equidistant from each other, while accounting for the sensitivity of human vision. The end result of this is a broader definition of colors where the human eye is capable of detecting them.

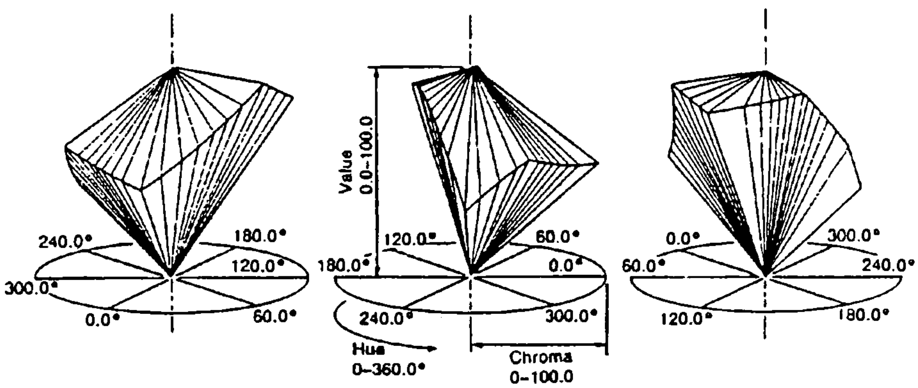

Figure 17. Various views of TekHVC color space depicting the range of colors for a typical display monitor [*TekColor Color Management System, System Implementor's Manual*]

TekHVC consists of three independently defined components: Hue, Value and Chroma. Hue carries the same definition here as defined with Human Vision: The scale of perception, appearance, such as red, green and blue. Within the mathematical description, hue is determined by the angular displacement from 0.0 to 360.0 degrees as rotated around a two dimensional plane (see figure above). At 0.0 degrees, the best achievable Red is rendered. As each of the HVC components is correlated to $L^*u^*v^*$, the hue angle (h_{uv}) is defined as:

$$h_{uv} = \tan^{-1}(v^*/u^*)$$

The relationship of hue angle to the components from which it is derived is as follows:

h_{uv}	u^*	v^*
$0 < h_{uv} < 90$	> 0	> 0
$90 < h_{uv} < 180$	< 0	> 0
$180 < h_{uv} < 270$	< 0	< 0
$270 < h_{uv} < 360$	> 0	< 0

Differing from its HLS counterpart, h_{uv} at zero degrees (0°) is the best red, not blue and must be calculated or subjectively determined by observers to accommodate the "best perceived red". The resulting red may differ from the process or physical red of the device. The angular difference between the system red, the white point and the "best red" defines an offset which is utilized in determining correct hue angles.

The Value component correlates to lightness, i.e.: the tendency of a color towards white or black. Within the model this argument has its largest range, spanning from a minimum of 0.0 (Black) to a maximum of 100.0 (White) when the chroma is equal to 0. Notice that two colors can be distinguished with this parameter alone: White and Black. For these two colors alone, the Chroma is always 0 and the Hue is irrelevant. Such conclusions reinforce the concept that the irregular shape used to describe HVC is pointed at either end. The relationship of the value to the $L^*u^*v^*$ color space is:

$$V = L^*$$

The Chroma component is described by saturation: The vibrancy of a color, the intensity. This component rotates 360.0 degrees around the Value axis, depicting differences from neutral to fully saturated at an established lightness. Chroma has a range from 0.0 to over 100 units. On average these values fall short of 100 (approximate CRT maximum), as most colors achieve full perceptual saturation well before that. This contrasts with the HLS system in which all colors achieved maximum saturation at the same distance from the Y axis and at the same lightness for all colors.
Being derived from the chroma C^*_{uv} component of $L^*u^*v^*$, the chroma value within HVC has a scaling factor C_f applied to it , based on the result of psychophysical experiments. The value of this factor, 7.50725, enables this system to provide a more perceptually uniform color appearance defining chroma as:

$$\text{HVC Chroma} = C^*_{uv} * C_f / 13$$

The advantages of this system beyond the enhanced visual uniformity is that changes in either Hue, Value or Chroma of equal distance within the system result in equally perceived color differences. Having the distinctions of being mathematically derived from CIELUV, TekHVC provides a color space with an enhanced perceptual uniformity. This uniformity concept can be applied to each of the individual components of the system.

Thus for two color pairs, in which the same two components are held constant, equal differences in the third component are perceived as equal color differences. The application of this process indicates that the colors defined as HVC = 5,35,75 and HVC = 5,35,80 will have the same perceptible difference as the colors defined as: HVC = 45,50,20 and HVC = 45,50,25.

7.0 Design of an experiment for system comparison

Each solution represents a unique approach to the achievement of color reproduction in the computing environment, while none of them provide a solution which by itself can consistently and accurately produce colors across all computing environments. With the exception of the Pantone Matching System, each system identifies a path within its color definition into a CIE standard. The Pantone standard, though initially targeted to the offset press color production environment has expanded into the color computing arena due in part to its acceptance within the graphic arts industry. Through the identification of a common thread, a comparison of the four solutions and their contribution to solving the problems of color in the computing environment can begin. Working with an established test target available in reflection print and PhotoYCC format, we can trace the effects of the various systems to the definition and reproduction of color. The differences in the means of producing information for display on a computer screen, coupled with the difference in the quality and technologies involved in the printed output have steered me towards comparison color quality versus image quality.

7.1 Experimental Process

The standard color targets used in this study are the Macbeth ColorChecker and Kodak Q60. The ColorChecker consists of 24 color patches arranged in four rows by six columns. The top three rows contain a variety of colors, including primaries such as red, green, blue, cyan, magenta, and yellow. The last row consists of a grey scale starting with white, progressively moving towards black. In an effort to include a wider range of grey scale information, portions of the KODAK Q-60 target will also be utilized, along with cyan, magenta, yellow and black patches from this target. The Q-60 target contains a larger number of colors consisting of gradient patches of selected colors.

Initial measurements will be recorded for each color patch, referencing the patches as they are named on the Macbeth ColorChecker. The patches from the Q60 target will be referenced by their color, or row column position for the grey scale patches. The targets are measured, in both XYZ and CIELAB format, using an X-rite 938 Spectrodensitometer, under D_{50} light source and 2° observer. The X-rite 938 is a desktop user configurable device with a 0° illumination angle and 45° viewing angle. Recording of

both values will facilitate future conversions (initial values to HVC) and computer definition and readings (tools available in PhotoShop).

Documents created for comparison are displayed using commercially available products. The viewing of the color swatches facilitates the comparison of the selected data points with original data obtained from the standard test targets. The documents processed by various techniques will be printed. The output will be measured to enable comparison with the original values as well as among the various technologies.

For the YCC technology the images being measured had to be encoded in YCC format on a Photo CD. Photographic negative slides of the Macbeth ColorChecker and Q60 were submitted to be scanned and placed on a Photo CD. Opening the Photo YCC encoded image required the use of a KODAK supplied PhotoShop plug in, selecting the RGB metric upon opening. Based on the ability to display PhotoYCC encoded images, the CIELAB values of the selected color patches were recorded. Acquiring the CIELAB values was done using the PhotoShop feature of the color picker which displays the RGB, CMYK and CIELAB values of selected areas. Output for each of the targets was directed to a KODAK XLT 7720, using the default print tables. The 7720 is a 203 dpi raster dye diffusion printer capable of producing photographic quality output utilizing a three color (cyan, magenta, and yellow) donor cartridge. From this hard copy, the CIELAB values were measured.

Capabilities within PhotoShop enabled the creation of a document for use in the PostScript Level 2 testing. PhotoShop allows users to define the color of selected areas with either CMYK, RGB, or CIELAB values. Individual squares of at least 1/2" were created, then their color defined through the input of the CIELAB values from the original target measurements via the PhotoShop color picker. Output was directed to a KODAK ColorEase printer utilizing the UltraColor setting. This setting is defined as the general purpose PostScript Level 2 option. The ColorEase is a 300 dpi dye diffusion PostScript Level 2 printer. Measurements of the hard copy output were recorded.

Bringing the Tektronix solution into a format comparable to the previously recorded values required additional data manipulation . Utilizing conversion routines outlined in section 6.4, the original target CIEXYZ values were manually converted to HVC values.

(Note: There was no attempt to adjust the system to the best red.) Having calculated the HVC values, we can change the PhotoShop color picker capabilities to utilize a Tektronix supplied color picker. Use of this tool enables input of HVC values. Individual squares of at least 1/2" were created, then their color defined through the input of the calculated HVC values. With the data points input, hard copy output was produced on a Kodak ColorEase printer utilizing the PostScript Level 1 path. This output was then measured. Due to the design of PhotoShop 2.5 to automatically invoke Level 2 PostScript, a non-Level 2 literate application needs to be utilized when printing this image. MacDraw Pro 2 was utilized.

The Pantone portion of the experiment requires additional caution. Pantone and various Pantone certified products indicate that their video display and printed output are for the simulation of Pantone defined colors. Color output expectations should always be compared to Pantone supplied color charts. Due to the limitations of these systems, tools supplied by Pantone for direct printer output were utilized to produce Pantone simulation colors on a Tektronix Phaser II PX. The Pantone supplied tool did not support the definition or viewing of the output prior to directing it to the printer. Output from the Pantone tool consisted of a variety of test patches. From this output, patches were selected based on color names similar to those chosen from the Macbeth ColorChecker and their CIELAB values measured.

Having the CIELAB values recorded for each of the systems in test ΔH_{ab} and ΔE_{ab} measurements with respect to the original data points were calculated. From these data points conclusions were drawn. The following figure is a schematic diagram of the color image processing for the four technologies.

Experimental Process comparison across Technologies

Photo YCC	PostScript Level 2	TekHVC	Pantone
Use Photo CD with test documents already scanned and encoded in YCC format	Measure CIELAB values from test targets	Measure CIEXYZ values from test targets & convert to HVC	Measure CIELAB values of selected Pantone colors from Process Color Image Guide
Display Photo YCC images on video using PhotoShop	Enter numerical CIELAB values for chosen color patches into PhotoShop; display on video	Using manually converted HVC numbers, enter the values via a special PhotoShop accessory; display on video	
Print on XL 7700 printer	Print on PS level 2 capable ColorEase printer	Print on ColorEase printer, in PS level 1 format as an RGB device.	Print Test patches with Pantone supplied utility on Tektronix Phaser II, a Pantone certified printer
Measure patches in CIELAB	Measure patches in CIELAB	Measure patches in CIELAB	Measure patches in CIELAB
Compare measurements with test target data.	Compare measurements with test target data	Compare measurements with test target data	Compare measurements with Process Color Image Guide data

Figure 18. Experimental Process comparison

7.2 Experimental Results

A complete listing of all CIELAB measurements are given in the appendix. These measurements are the foundation for the comparisons among the four techniques with respect to color reproduction accuracy.

7.2.1 Photo YCC Video Results

Following the steps defined in the design of this experiment, the MacBeth ColorChecker and Kodak Q-60 were individually displayed on the monitor. The color patches from the targets were selected and their CIELAB values as indicated by PhotoShop recorded. Attempts to duplicate this process needed to ensure the utilization of the Kodak supplied plug in, utilizing a RGB metric. For each of the selected colors, the ΔE_{ab} and ΔH_{ab} with respect to the initial patch measurements were calculated. The ΔH_{ab} of selected colors is graphed below. The initial measurements from the ColorChecker and Q-60 targets represent the tail of each ray, with the experimental measurements, as recorded with the PhotoShop color picker, representing the head.

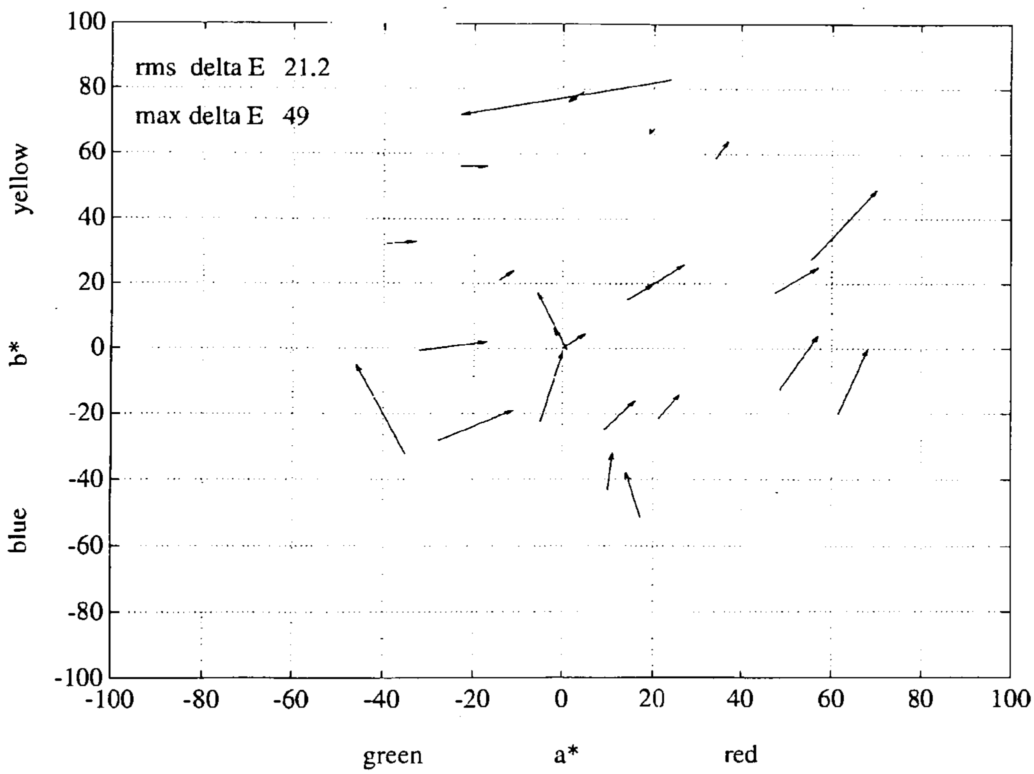

Figure 19.Comparison of original measurements (tail of each ray) with the results of the Photo YCC video measurements (head or arrow or each ray).

7.2.2 Photo YCC Print Results

As our interest lies not only with the displayed image but with the reflection print also, the displayed Photo CD images were directed to an XLT 7720[5], utilizing the default print table. The following figure shows the H_{ab} between the hard copy printed by the XLT 7720 and the measured data from the ColorChecker and Q-60 test targets.

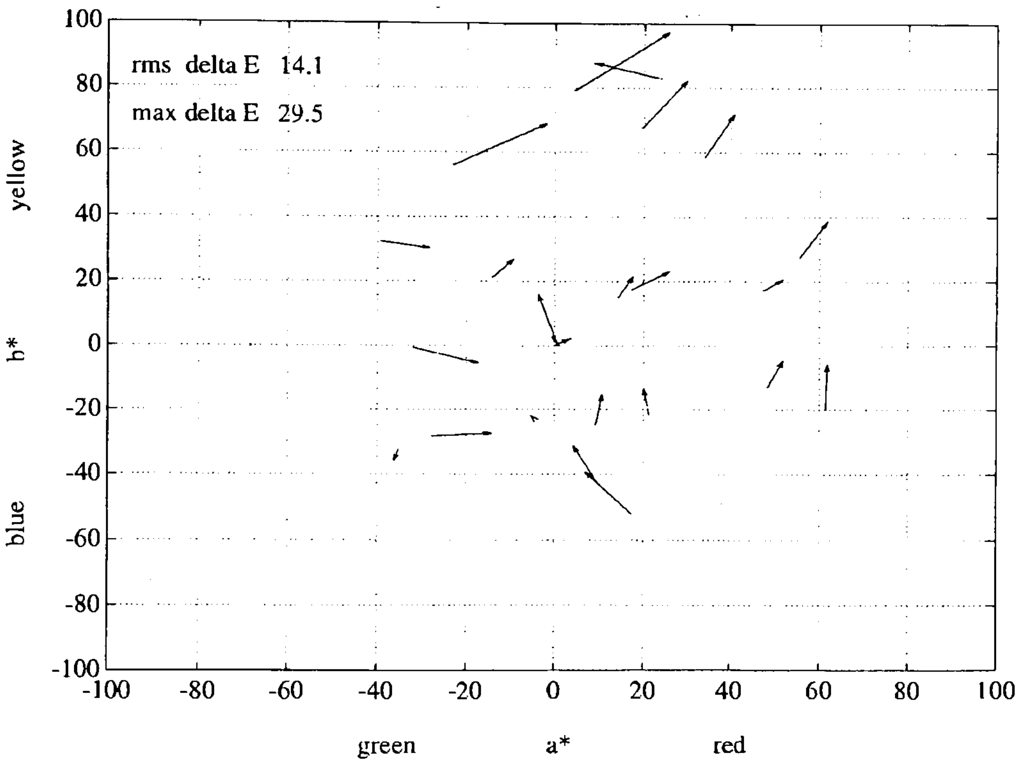

Figure 20.Comparison of original measurements (tail of each ray) with the results of the Photo YCC print measurements (head or arrow or each ray).

[5]Dye Sublimation, 203 dpi printer from Eastman Kodak

7.2.3 PostScript Level 2 Results

Selecting the software package for the production of PostScript Level 2 output had to take into account the capability of defining color patches with CIELAB values. Additionally it had to be capable of communicating with a PostScript Level 2 printer. Based on the fact that is was built by a common vendor, Adobe PhotoShop was chosen as the application of choice and connected to a PostScript Level 2 printer. Tools within PhotoShop were used to define color blocks, utilizing the initial CIELAB measurements from the ColorChecker and Q-60 targets. The process of printing this data on a Level 2 printer resulted in the following as compared to the original target values:

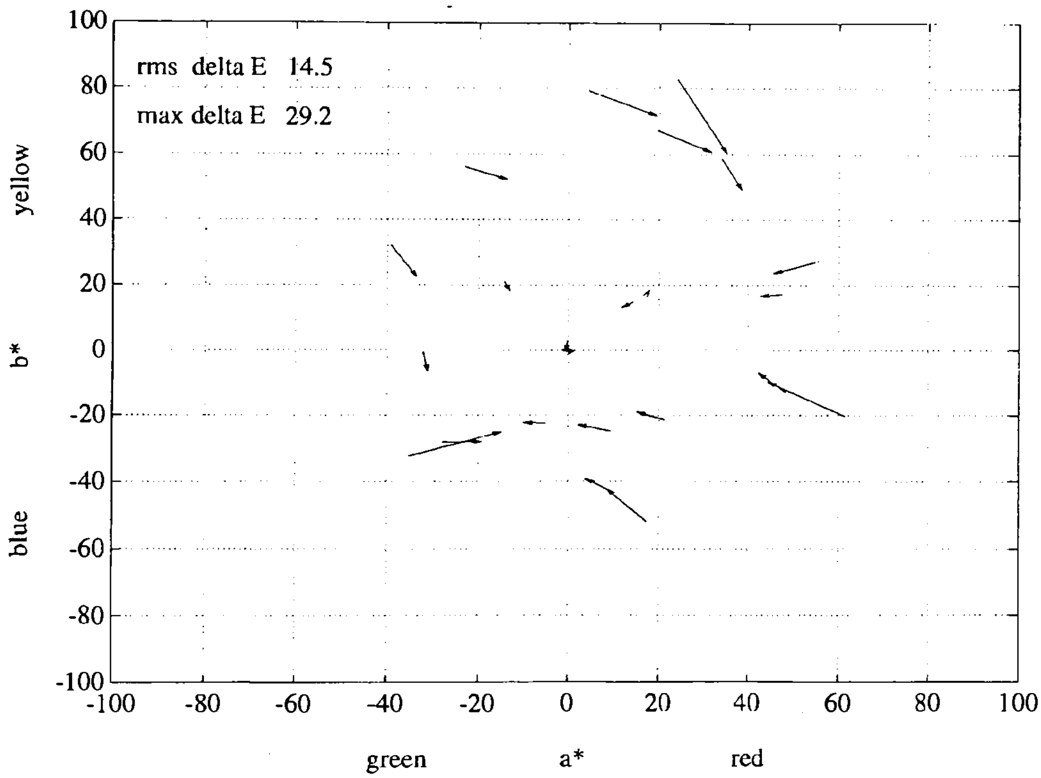

Figure 21.Comparison of original measurements (tail of each ray) with the results of the PostScript Level 2 measurements (head or arrow or each ray).

7.2.4 TekHVC Results

Tektronix supplied a tool which replaced the PhotoShop color picker enabling the creation of a target where the color patches were defined with the calculated HVC attributes. The recorded CIEXYZ values were translated into CIELUV values which were consistent with the needs of the HVC system, using D_{50} illuminant. The conversion process was outlined earlier in the CIE section. The HVC values could then be calculated based on the following formulae:

$$h_{uv} = \tan^{-1}(v^*/u^*)$$

$$V = L^*$$

$$\text{HVC Chroma} = C^*_{uv} * C_f / 13$$

The results of these calculations can be found in the Appendix.

The image was then printed and the color blocks measured (CAUTION: Users must be aware that use of Adobe PhotoShop 2.5 for the Mac with a PostScript Level 2 certified printer will automatically invoke utilization of Level 2 in the printing process. Use of non-PostScript Level 2 applications, such as MacDraw Pro, will prevent this side effect.) Comparison of the HVC measured values and the original target values is charted below.

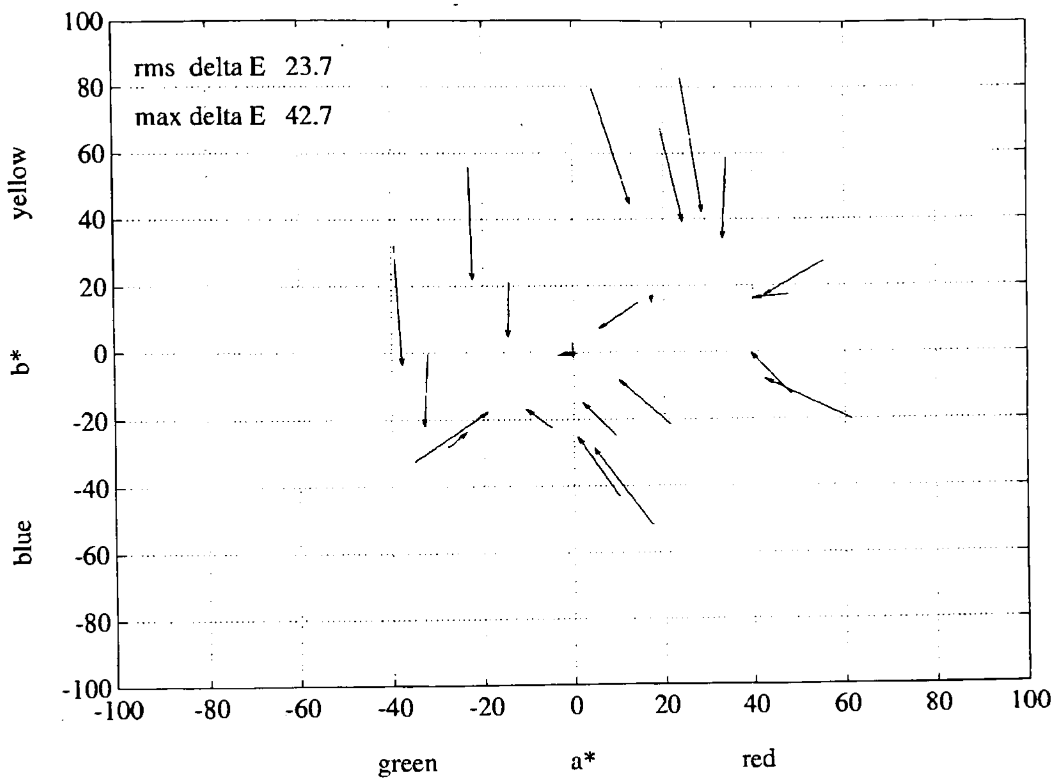

Figure 22.Comparison of original measurements (tail of each ray) with the results of the TekHVC measurements (head or arrow or each ray).

7.2.5 Pantone Results

Having produced output via three of the four implementations, the Pantone Matching system presented a different challenge. One of the bases of the Pantone Matching system is the definition of Pantone colors, a well defined subset of all possible colors that can be generated in the XYZ system. This limitation prevented the comparison of Pantone colors to the selected color patches from the MacBeth ColorChecker and Kodak Q-60 targets. Using a Pantone approved utility we were able to output a subset of the Pantone colors, and measure their color specifications. The resulting color differences between Pantone supplied colors and printed output are plotted below:

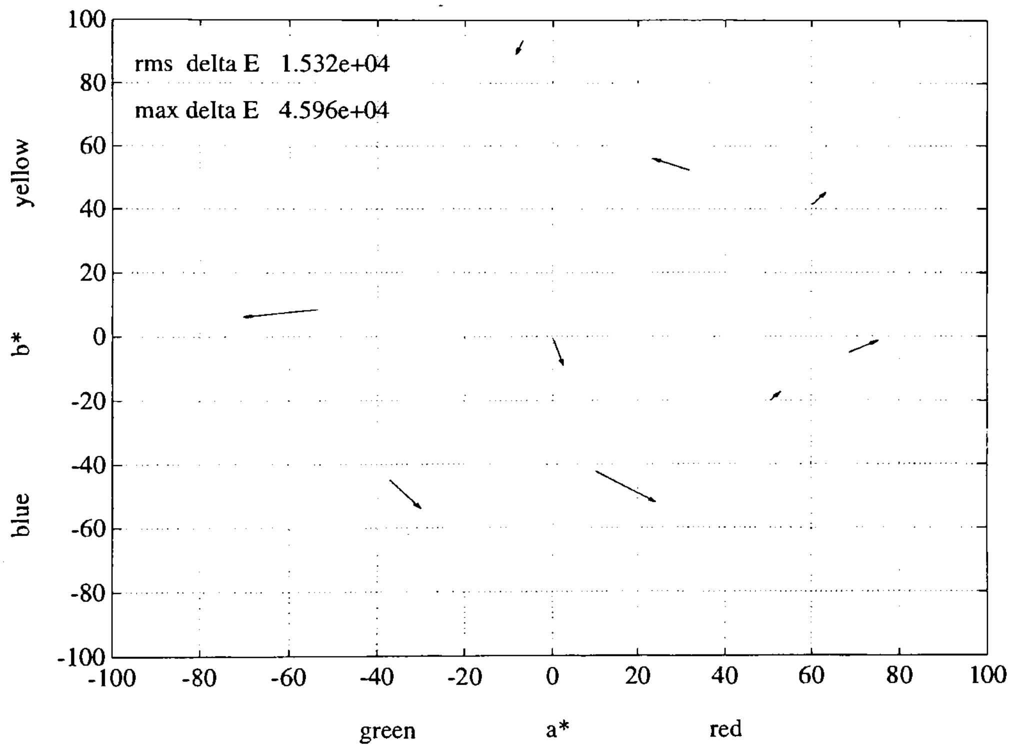

Figure 23. Comparison of original measurements from Pantone Process Color Image guide (tail of each ray) with the results of the Pantone measurements (head or arrow or each ray).

The Pantone system required us to select new data points against which to measure. While we seemingly shoehorned the Pantone system into our experiment, the ability to reproduce these colors consistently on an offset press is the added value. Due to the lack

of production tools for the other color specifications (Photo YCC, PostScript Level 2 and TekHVC), translation to mass production on an offset press would require an artistic edge to produce the desired color consistently.

7.2.6 Summary of results

Review of the plotted tables raises the question, which system produces the best results? From purely a numeric standpoint it would appear that PostScript Level 2 comes out on top. Having made such a statement, extreme caution should be taken when drawing such a conclusion. The comparison of these multiple systems is difficult at best due to the variability involved in creating and producing the video and printed output. In addition each system is capable of producing color output which resembles the image displayed on the monitor, but are they "good enough"?

Dealing with an emerging technology in the computer environment, this experiment did not posses the control necessary for comparison among these systems. The initial targets and destination printers were not the same across the technologies, the printers were not calibrated.

While additional questions are generated from the results of this experiment, one seemingly consistent factor is that the production of yellow and related colors appears to be the most difficult within the data measured, while black and nearly black patches experience the least deviation from the initial selected colors. Even these conclusions should be questioned. The fundamental result of this experiment is that it provides the basis for additional, more tightly controlled experimentation, not indisputable facts.

8.0 Conclusion, looking to the future

Color in the computing environment is quickly becoming a more accessible and an increasingly utilized means of communications. Only with its expanded utilization are the problems associated with the use of color going to surface to the point that a common solution will be generated. Incorporation of color, as a standard means of communications within the computing environment, will not achieve its full potential until consistent color, from system to system and across operating systems, is enabled. Each system evaluated purports to promote a standard of some kind, be it newly developed or based on pre-existing standards. The current thread binding these solutions[6] is their tie to standards established by the Commission Internationale de l'Eclairage. The problem within this common thread, is that multiple standards have been adopted along with multiple flavors within individual standards, thus the common thread begins to unravel.

The common foundation within the standards established by the CIE is the source of some of the current difficulties. These systems adopted the concept that individual colors are encompassed in an area. Accommodation of this philosophy does reflect the results one would get when soliciting input from a group of observers relative to identification of specific colors, but could make it difficult as this technology begins to mature and expand in use within the computer environment. While technological advances have resulted in equipment which has automated the measurement of color, reducing error, the resulting numbers do not identify a specific color such as red. This problem can be related to the basic question, "What color is a fire truck?". Formulating this question based on the assumption that the fire truck being viewed is red, what color red is it? Is the red the same color as the red street light? This type of question requires additional education coupled with a standardization of color terminology. One could say we already have all the terms necessary for the identification of color. What is lacking is a clear consistent definition and understanding of the terms, coupled with the ability of the user community to correctly articulate their meanings. Everything does not need to be understood by the common user, but the fundamentals need to be articulated to the common user. An analogy can be drawn here to the use of word processors. The general public is unaware of the details of type fonts and sizes. What is understood is the effects of their use.

[6]Note, the Pantone system was not initially designed around or for the CIE system. Only recently has a transformation been developed and supported by Pantone from Pantone colors to CIEXYZ values.

Different fonts promote easier reading in different formats, while the size of the printed letters is directly associated with the type size. How many users are aware that each type's point size is measured in units of 1/72 of an inch? As an association, the vendors across the multiple operating environments must begin to standardize in their use of terminology and its effect. Each implementation may differ in the details associated with its use, but the fundamentals need to remain the same.

Attempting to leverage off this common thread, we explored a comparison of the four systems, recording their ability to reproduce a selected set of colors.

Each of these systems has its own merit and use regardless of the values recorded. What needs to be highlighted within this experiment is the numerous steps and the introduction of error within each step. A leading point of interest related to all printed outputs was the calibration of the printer. In other words, when directing a print to the selected printers, "Was that printer printing the colors correctly?". A tightly controlled experiment would require calibration of each printer prior to directing output to it, to ensure it is functioning as designed. Due to this point alone, conclusions drawn from the results of this experiment should be considered starting points for additional experimentation. An additional unknown affecting all the experimental results were the effects of the applications used in printing the selected output. Less the Pantone portion of the experiment, the applications involved could affect the printed results based on proprietary output rendering schemes, including screening angles, color transformation, etc. Each of the systems utilized in the experiment contain further potential as well as experimentation error which is discussed below.

The PostScript level 2 experiment utilized a relatively new printer for the production of the tested output. Use of this or any PostScript level 2 printer draws attention to the ability of the printer in question to accurately produce documents under the level 2 standards. Verification of the printer capabilities requires an in depth understanding of the level 2 standards coupled with knowledge of the internal implementation of PostScript within the printer. A reduction in the number of choices in which the user can define their color, could only enhance vendors' abilities to produce consistent results, enabling a focus on a few better solutions, rather than a broad range of good solutions.

The Pantone Matching System gives a broader range of users the opportunity to create images, information and documentation in a way that enables them to be mass produced in

a consistent fashion. The Pantone output was the only output not produced on a dye sublimation printer. Further experimentation utilizing similar printing technology would lead to results which are more easily compared. Experimentation on the effects of the various printing technologies would enhance our understanding of how best to utilize the different solutions. The use of the Pantone tool enables a glimpse into the end product prior to a trial press run. After much experience, the users will adjust their expectations of the final press run versus the initial printed output, thus rework time will be reduced. Within the scope of this research, Pantone appeared to lead the technologies in capabilities of understanding and migrating the computer work to the pre-press environment.

TekHVC presents an opportunity that never caught on. The results of this experiment did not accommodate any adjustments for best red, thus conclusions drawn must account for this shortfall. The attempts of Tektronix to have the industry adopt this solution as the industry standard for color definition and reproduction were unsuccessful. As a result Tektronix has looked inward and incorporated features of TekHVC into drivers supplied with their color printers. The adoption of this policy, coupled with the incorporation of PostScript Level 2 processing within their printers could lead to a nice complement. User acceptance and use of these combined features has yet to be determined as they are just recently becoming available to the public.

PhotoYCC, used in the Photo CD system, presents a unique combination of photography and electronic imaging and is viewed by some as the savior of electronic imaging. Others view this as an attempt to curb the movement into electronic imaging by a leading photography giant. PhotoYCC presents a technique to store, for later retrieval, multiple resolutions of the same image. The color capture mechanism remains proprietary. This is one of the potential impediments to its expanded utilization. While being the only one of the four solutions to provide a capture/retrieval mechanism, the consistency of the capture remains in the hands of the operator. Like the prints you currently receive back from the photo finisher, the contents of the Photo CD are subject to proprietary "pleasing" algorithms. When these fail, the results of the system are based on what "looks good" to the operator using uncalibrated video displays. However, an advantage to this system is that it is based on another system where we know what to expect: film processing. The images are only as good as the person behind the lens. An additional advantage is the potential image bank that can be created, duplicated, processed and viewed with amazing consistency.

Each of these systems has merit within the limitations of its initial definition. The best system is not only the one that has least mathematical error, but also that which is easiest to use and produces the most pleasing results. Keep in mind, accuracy does not necessarily indicate satisfaction. The results from this experiment raise questions concerning the capabilities of each of the systems coupled with the basic design of the experiment. Variance within the experiment and resulting data provide the foundation for additional experimentation under tighter controls.

8.1 Future Directions

The choices in color production and reproduction continue to improve while the prices continue to plummet. One basic question is, what does the future hold for us? The fundamental components to this question include ease of use, consistency, cost and quality. Consistency refers to the ability to produce similar results from page to page while quality refers to the ability to produce acceptable and pleasing results. The order is based on perceived level of importance. The question of ease of use requires an investment of time. One might contend that the incorporation of color into presentation and the creation of color images is just an extension of the black and white world of the document production of today. This could not be farther from the truth. Users need not become color scientists, but they must build their knowledge of color fundamentals and realize the boundaries. They must have an understanding of color basics.

Once a steady state of color production has been achieved, consistency of the color reproduction coupled with cost containment of the new technology will follow. The consistency will require the incorporation of color definition and management software within the operating system. The extension of the operating system to accommodate the color management of the user community will be the foundation, not the total solution of consistent color. As an extension of this concept, manufactures of hardware, operating systems and software must begin to incorporate color management into the development of their product lines. Each manufacturer continues to control the unique features of its product, but it must accommodate a common definition for source of color, enabling users to accurately anticipate the results of their work.

The ongoing development of different means of color reproduction, such as HiFi color[Fraser], will only serve to complicate the issues for the average user. HiFi color extends current color reproduction methods to include seven or more primaries in output

production. Based on a current lack of understanding, at the layman level, of the interaction of CMYK, the comprehension of even more colors is not likely. Surely the invention of advanced, more accurate color reproduction schemes will enhance the capabilities of those requiring more accurate color, but for the basic user, they care little of the technology utilized as compared to the questions; "Is it what I expected?" and "Is it good enough?".

Appendix

Measurement of The Macbeth ColorChecker
Color Rendition Chart

Color Description	CIE L	CIE a	CIE b
Dark Skin	38.15	14.14	14.95
Light Skin	66.61	17.22	17.44
Blue Sky	50.10	-4.88	-22.39
Foliage	43.01	-14.19	21.03
Blue Flower	55.68	9.23	-24.78
Bluish Green	70.28	-32.18	-.63
Orange	62.28	34.09	58.55
Purplish Blue	39.41	9.93	-43.10
Moderate Red	51.96	47.64	17.26
Purple	30.74	21.25	-21.42
Yellow Green	71.94	-23.11	55.97
Orange Yellow	72.30	19.38	67.33
Blue	28.52	17.24	-51.93
Green	55.28	-39.36	32.28
Red	42.56	55.48	27.38
Yellow	82.52	4.42	79.24
Magenta	51.57	48.48	-12.81
Cyan	49.60	-27.84	-28.16
White	95.40	-.23	2.86
Neutral 8	81.12	-.01	.52
Neutral 6.5	66.42	.20	.49
Neutral 5	51.06	-.26	-.27
Neutral 3.5	35.20	-.09	-.11
Black	20.30	.02	-.50
MacBeth Neutrals[7]	50.82	-0.028	0.026
Selected measurements from Kodak Q-60 target			
Cyan	38.63	-35.22	-32.41
Magenta	35.25	61.41	-20.21
Yellow	68.05	23.97	82.84
Q60 Neutrals[8]			
Black	6.64	.66	-2.10
N 1	91.07	.62	-1.39
N 3	83.95	1.46	-.62
N 5	76.23	1.15	-.28
N 7	67.55	1.51	-.07
N 9	58.20	1.56	.61
N 11	48.95	1.71	.76
N 13	40.09	1.27	1.05
N 15	30.90	.32	1.04
N 17	21.13	-.39	-.10
N 19	11.15	-.73	-1.75

[7] MacBeth Neutrals consist of an average of the 5 Neutral (including Black) patch measurements from the MacBeth ColorChecker®

[8] Q60 Neutrals consist of an average of the 11 Neutral (including Black) patch measurements from the Q60 target.

PhotoYCC converted to monitor RGB's
Measured values

Color	L	a	b	ΔE_{ab}	ΔH_{ab}
Dark Skin	47	20	20	11.75	7.74
Light Skin	78	27	26	17.28	13.00
Blue Sky	60	0	-1	24.07	21.94
Foliage	50	-11	24	8.24	4.36
Blue Flower	67	16	-16	15.84	11.09
Bluish Green	77	-17	2	16.81	15.41
Orange	73	37	64	12.37	6.18
Purplish Blue	51	11	-32	16.08	11.15
Moderate Red	66	57	25	18.56	12.15
Purple	44	26	-14	15.92	8.81
Yellow Green	79	-17	56	9.34	6.11
Orange Yellow	81	19	66	8.81	1.38
Blue	40	14	-38	18.34	14.30
Green	63	-33	33	10.03	6.40
Red	60	70	49	31.34	26.04
Yellow	88	1	76	7.23	4.71
Magenta	69	57	4	25.67	18.85
Cyan	57	-11	-19	20.55	19.17
White	99	-2	6	5.09	3.60
MacBeth Neutrals	60	5	4.6	11.42	6.80
Neutral 8	92	6	9	15.05	10.39
Neutral 6.5	77	5	7	13.32	8.09
Neutral 5	61	5	1	11.32	5.41
Neutral 3.5	45	4	3	11.07	5.14
Black	25	5	3	7.69	6.09

Selected measurements from Q-60 target

Cyan	67	-46	-5	40.89	29.45
Magenta	55	68	0	29.02	21.26
Yellow	77	-23	72	49.03	48.20
Q60 Neutrals	47.09	-5.55	17.18	18.64	18.57
Black	11	1	8	11.01	10.11
N 1	93	-12	32	35.75	35.70
N 3	80	-4	29	30.38	30.12
N 5	67	-3	20	22.66	20.70
N 7	58	-3	17	20.07	17.66
N 9	51	-6	16	18.60	17.15
N 11	44	-7	15	17.41	16.69
N 13	39	-7	15	16.25	16.22
N 15	32	-6	13	13.57	13.53
N 17	25	-8	12	14.81	14.29
N 19	18	-6	12	16.24	14.73

Reflection print of Photo CD source

Measured values

Color	L	a	b	ΔE_{ab}	ΔH_{ab}
Dark Skin	39.24	17.5	21.42	7.37	7.29
Light Skin	70.4	25.97	23.08	11.08	10.41
Blue Sky	52.59	-5.36	-21.76	2.61	0.79
Foliage	42.46	-9.21	26.88	7.70	7.68
Blue Flower	61.44	10.66	-15.13	11.33	9.76
Bluish Green	70.4	-17.2	-5.47	15.74	15.74
Orange	59.5	40.82	71.85	15.16	14.91
Purplish Blue	43.98	4.19	-31.2	13.98	13.21
Moderate Red	51.02	51.84	20.67	5.49	5.41
Purple	35.4	19.97	-13.35	9.41	8.17
Yellow Green	71.79	-1.83	68.91	24.91	24.91
Orange Yellow	68.29	29.91	82.29	18.73	18.29
Blue	30.99	6.83	-39.15	16.67	16.48
Green	53.5	-28.18	30.25	11.50	11.36
Red	37.12	61.66	38.64	13.95	12.84
Yellow	73.45	25.73	97.44	29.46	28.02
Magenta	54.84	51.91	-4.39	9.66	9.09
Cyan	48.55	-14.1	-27.37	13.80	13.76
White	94.33	0.06	1	2.17	1.88
MacBeth Neutrals	54.014	3.58	2.264	5.31	4.25
Neutral 8	86.45	8.49	4.11	10.66	9.23
Neutral 6.5	71.81	4.24	3.54	7.39	5.06
Neutral 5	56.78	2.59	1.05	6.53	3.14
Neutral 3.5	39.11	0.32	0.83	4.04	1.03
Black	15.92	2.26	1.79	5.43	3.20

Selected measurements from Q-60 target

Cyan	43.15	-36.32	-35.84	5.78	3.60
Magenta	35.21	61.71	-5.83	14.38	14.38
Yellow	62.63	8.6	87.9	17.07	16.18
Q60 Neutrals	40.63	-3.75	15.98	18.70	16.87
Black	3.45	1.8	0.07	4.02	2.45
N 1	86.77	-4.68	33.57	35.62	35.36
N 3	76.14	-0.49	30.53	32.17	31.21
N 5	62.93	-2.6	23.05	27.12	23.63
N 7	53.23	-4.19	17.44	23.33	18.41
N 9	45.31	-6.01	14.69	20.54	15.99
N 11	38.67	-6.23	12.88	17.77	14.49
N 13	31.46	-6.08	13.67	16.96	14.60
N 15	24.54	-5.23	13.23	14.83	13.39
N 17	16.18	-5.34	11.4	13.46	12.52
N 19	8.29	-2.16	5.22	7.67	7.12

Reflection print on PostScript Level 2 printer
of described Lab values
measured values

Color	L	a	b	ΔE_{ab}	ΔH_{ab}
Dark Skin	35.08	11.69	13.14	4.32	3.05
Light Skin	61.03	17.88	18.58	5.73	1.32
Blue Sky	44.32	-9.92	-22.2	7.67	5.04
Foliage	38.53	-12.92	18.1	5.50	3.19
Blue Flower	50.12	2.16	-22.81	9.21	7.34
Bluish Green	59.25	-31.29	-6.49	12.52	5.93
Orange	48.74	38.58	49.12	17.10	10.44
Purplish Blue	31.56	3.82	-39.05	10.74	7.33
Moderate Red	42.3	42.83	16.73	10.80	4.84
Purple	26.66	15.04	-18.87	7.86	6.71
Yellow Green	58.81	-13.67	52.27	16.59	10.14
Orange Yellow	57.17	31.71	60.66	20.63	14.02
Blue	23.25	8.55	-42.23	14.05	13.02
Green	43.08	-33.68	22.55	16.61	11.27
Red	32.49	45.79	23.66	14.46	10.38
Yellow	67.78	19.33	71.76	22.26	16.68
Magenta	42.56	42.44	-6.85	12.38	8.49
Cyan	41.38	-19.18	-28.07	11.94	8.66
White	86.95	-0.5	-0.39	9.06	3.26
MacBeth Neutrals	44.718	-1.404	-0.012	6.26	1.38
Neutral 8	73.06	0.31	1.21	8.10	0.76
Neutral 6.5	58.39	-0.54	-0.38	8.11	1.14
Neutral 5	44.77	-1.99	-0.19	6.52	1.73
Neutral 3.5	29.95	-3.12	-0.18	6.06	3.03
Black	17.42	-1.68	-0.52	3.34	1.70

Select measurements from Kodak Q-60 target

Cyan	35.26	-14.64	-24.95	22.15	21.89
Magenta	29.02	44.47	-9.58	20.95	20.00
Yellow	53.13	35.17	60.39	29.19	25.09
Q60 Neutrals	44.85	1.44	0.02	3.92	0.68
Black	9.12	0.16	-1.77	2.55	0.60
N 1	83.31	2.65	-1.54	8.02	2.04
N 3	75.63	4.38	0.4	8.88	3.09
N 5	68.19	2.79	-0.13	8.21	1.65
N 7	60.55	2.66	1.27	7.22	1.77
N 9	51.88	1.97	2.44	6.59	1.88
N 11	43.61	1.65	0.73	5.34	0.07
N 13	34.79	0.53	0.11	5.43	1.20
N 15	27.48	-1.19	-0.23	3.95	1.97
N 17	20.1	0.03	0.06	1.12	0.45
N 19	18.68	0.26	-1.09	7.62	1.19

Color Description	Calculated HVC values input to produce corresponding output		
	H	V	C
Dark Skin	23.65	38.14	16.26
Light Skin	23.84	66.62	22.25
Blue Sky	236.54	50.10	18.75
Foliage	115.23	46.00	14.22
Blue Flower	267.47	55.67	19.07
Bluish Green	183.75	70.28	25.48
Orange	26.80	62.28	51.51
Purplish Blue	256.97	39.41	32.69
Moderate Red	4.74	51.95	49.60
Purple	298.02	30.74	17.27
Yellow Green	103.89	71.93	33.40
Orange Yellow	42.27	72.30	44.99
Blue	259.67	28.51	36.08
Green	136.3	55.27	31.84
Red	6.18	42.57	59.81
Yellow	61.25	82.52	43.57
Magenta	339.76	51.56	40.50
Cyan	214.78	49.61	32.44
White	72.45	95.39	2.19
Neutral 8	69.39	81.12	.37
Neutral 6.5	44.18	66.42	.42
Neutral 5	209.96	51.06	.34
Neutral 3.5	205.48	35.20	.12
Black	244.98	20.28	.29

Selected measurements from Kodak Q-60 target

Cyan	215.73	38.63	35.50
Magenta	336.37	35.25	47.21
Yellow	38.99	68.05	50.27
Black	267.35	6.64	.61
N 1	95.2	91.07	1.10
N 3	149.59	83.95	1.24
N 5	159.53	76.23	.95
N 7	169.66	67.55	1.25
N 9	9.22	58.20	1.46
N 11	11.33	48.95	1.58
N 13	22.70	40.09	1.32
N 15	49.71	30.90	.71
N 17	184.94	21.13	.26
N 19	225.94	11.15	.83

Reflection print of TekHVC
measured values

Color	L	a	b	ΔE_{ab}	ΔH_{ab}
Dark Skin	34.89	5.67	7.14	11.97	11.52
Light Skin	55.79	17.1	15.07	11.08	2.37
Blue Sky	40.39	-10.48	-16.77	12.54	7.93
Foliage	38.34	-14.42	4.85	16.84	16.18
Blue Flower	45.34	2.02	-14.96	15.98	12.18
Bluish Green	51.36	-33.05	-21.68	28.32	21.07
Orange	51.63	33.27	34.19	26.60	24.37
Purplish Blue	32.52	0.9	-25.15	21.24	20.09
Moderate Red	41.19	39.94	16.23	13.28	7.77
Purple	27.64	9.9	-8.29	17.63	17.36
Yellow Green	58.66	-22.36	22.06	36.43	33.92
Orange Yellow	60.32	24.24	39.28	30.89	28.47
Blue	26.46	4.41	-28.44	26.84	26.77
Green	39.13	-37.76	-3.64	39.42	35.96
Red	32.78	42.42	17.05	19.31	16.65
Yellow	70	12.48	44.51	37.79	35.65
Magenta	40.03	39.44	-0.29	19.28	15.44
Cyan	37.52	-23.78	-23.56	13.55	6.14
White	86.24	-0.07	-1.73	10.25	4.59
MacBeth Neutrals	44.116	-3.296	-0.948	7.52	3.41
Neutral 8	69.22	-2.1	-0.39	12.12	2.28
Neutral 6.5	54.87	-2.26	-0.21	11.83	2.56
Neutral 5	41.4	-4.41	-2.63	10.78	4.77
Neutral 3.5	31.45	-4.19	-1.14	5.65	4.23
Black	23.64	-3.52	-0.37	4.87	3.54

Selected measurements from Kodak Q-60 target

Q60 Cyan	32.34	-19.05	-17.61	22.81	21.92
Q60 Magenta	23.54	42.64	-8.09	25.23	22.34
Q60 Yellow	56.14	28.66	42.06	42.74	41.05
Q60 Neutrals	44.05	-2.69	-0.91	5.88	3.58
Q60 Black	16.08	-1.38	-0.38	9.81	2.67
N 1	81.41	-0.72	-2.59	9.83	1.80
N 3	72.15	-1.84	-0.96	12.26	3.32
N 5	65.33	-3.76	-0.72	11.96	4.93
N 7	56.07	-4.72	-1.41	13.13	6.37
N 9	48.45	-2.75	-0.51	10.72	4.45
N 11	40.24	-2.69	-0.87	9.89	4.69
N 13	34.01	-2.4	0.28	7.14	3.75
N 15	28.95	-3.47	-0.67	4.59	4.16
N 17	22.83	-3.56	-0.85	3.67	3.26
N 19	19.06	-2.3	-1.35	8.07	1.62

Measurements of selected patches from
Pantone Process Color Imaging Guide
(CMYK Edition)

Color	L	a	b
Dark Skin			
Light Skin			
Blue Sky			
Foliage			
Blue Flower			
Bluish Green			
Orange	65.93	31.86	52.31
Purplish Blue			
Moderate Red			
Purple	40.27	50.47	-20.06
Yellow Green			
Orange Yellow			
Blue	33.50	10.09	-42.21
Green	60.09	-53.74	8.48
Red	52.20	60.25	41.42
Yellow	87.74	-6.95	93.53
Magenta	52.75	68.82	-4.97
Cyan	58.94	-37.03	-44.98
White			
MacBeth Neutrals			
Neutral 8			
Neutral 6.5			
Neutral 5			
Neutral 3.5			
Black	11.59	.26	-1.23

Reflection print of simulation of Pantone Process Colors
Measured Values

Color	L	a	b	ΔE_{ab}	ΔH_{ab}
Dark Skin					
Light Skin					
Blue Sky					
Foliage					
Blue Flower					
Bluish Green					
Orange	66.39	23.29	56.09	9.38	9.37
Purplish Blue					
Moderate Red					
Purple	36.53	52.86	-17.29	5.23	3.66
Yellow Green					
Orange Yellow					
Blue	14.26	24.29	-52.11	25.88	17.31
Green	41.50	-70.39	6.14	25.07	16.81
Red	46.14	63.50	45.32	7.91	5.08
Yellow	85.73	-8.52	89.24	4.99	4.57
Magenta	43.93	75.35	-1.30	11.57	7.49
Cyan	45.46	-29.91	-53.97	17.70	11.47
White					
MacBeth Neutrals					
Neutral 8					
Neutral 6.5					
Neutral 5					
Neutral 3.5					
Black	8.85	2.47	-9.13	8.65	8.20

Color Differences Across systems ΔE_{ab}

Color Description	PhotoYCC Video	PhotoYCC Print	PostScript Level 2	TekHVC	Pantone Matching System	Average ΔE_{ab}[9]
Dark Skin	11.75	7.37	4.32	11.97		8.91
Light Skin	17.28	11.08	5.73	11.08		10.98
Blue Sky	24.07	2.61	7.67	12.54		11.91
Foliage	8.24	7.70	5.50	16.84		8.79
Blue Flower	15.84	11.33	9.21	15.98		12.46
Bluish Green	16.81	15.74	12.52	28.32		15.31
Orange	12.37	15.16	17.10	26.60	9.38	15.51
Purplish Blue	16.08	13.98	10.74	21.24		14.34
Moderate Red	18.56	5.49	10.80	13.28		10.77
Purple	15.92	9.41	7.86	17.63	5.23	11.02
Yellow Green	9.34	24.91	16.59	36.43		17.73
Orange Yellow	8.81	18.73	20.63	30.89		19.33
Blue	18.34	16.67	14.05	26.84	25.88	18.87
Green	10.03	11.50	16.61	39.42	25.07	16.52
Red	31.34	13.95	14.46	19.31	7.91	15.10
Yellow	7.23	29.46	22.26	37.79	4.99	22.86
Magenta	25.67	9.66	12.38	19.28	11.57	15.40
Cyan	20.55	13.80	11.94	13.55	17.70	15.73
White	5.09	2.17	9.06	10.25		5.80
Neutral 8	15.05	10.66	8.10	12.12		10.27
Neutral 6.5	13.32	7.39	8.11	11.83		9.33
Neutral 5	11.32	6.53	6.52	10.78		9.20
Neutral 3.5	11.07	4.04	6.06	5.65		8.80
Black	7.69	5.43	3.34	4.87	8.65	7.18
Cyan	40.89	5.78	22.15	22.81		24.18
Magenta	29.02	14.38	20.95	25.23		22.87
Yellow	49.03	17.07	29.19	42.74		34.86
Black	11.01	4.02	2.55	9.81		5.70
N 1	35.75	35.62	8.02	9.83		20.68
N 3	30.38	32.17	8.88	12.26		19.64
N 5	22.66	27.12	8.21	11.96		16.40
N 7	20.07	23.33	7.22	13.13		14.92
N 9	18.60	20.54	6.59	10.72		14.08
N 11	17.41	17.77	5.34	9.89		13.25
N 13	16.25	16.96	5.43	7.14		13.22
N 15	13.57	14.83	3.95	4.59		11.82
N 17	14.81	13.46	1.12	3.67		10.51
N 19	16.24	7.67	7.62	8.07		9.48
Average	18.09	13.83	10.49	17.01	12.93	14.68

[9]Due to the nature of original colors for the Pantone system, these values have not been included in these averages

Color Description	Color Differences Across systems ΔH_{ab} PhotoYCC Video	Print	PostScript Level 2	TekHVC	Pantone Matching System	Average ΔE_{ab}[10]
Dark Skin	7.74	7.29	3.05	11.52		7.40
Light Skin	13.00	10.41	1.32	2.37		6.77
Blue Sky	21.94	0.79	5.04	7.93		8.93
Foliage	4.36	7.68	3.19	16.18		7.85
Blue Flower	11.09	9.76	7.34	12.18		10.09
Bluish Green	15.41	15.74	5.93	21.07		14.54
Orange	6.18	14.91	10.44	24.37	11.08	13.98
Purplish Blue	11.15	13.21	7.33	20.09		12.95
Moderate Red	12.15	5.41	4.84	7.77		7.54
Purple	8.81	8.17	6.71	17.36	31.88	10.26
Yellow Green	6.11	24.91	10.14	33.92		18.77
Orange Yellow	1.38	18.29	14.02	28.47		15.54
Blue	14.30	16.48	13.02	26.77	7.05	17.64
Green	6.40	11.36	11.27	35.96	40.57	16.25
Red	26.04	12.84	10.38	16.65	19.65	16.48
Yellow	4.71	28.02	16.68	35.65	16.35	21.27
Magenta	18.85	9.09	8.49	15.44	29.23	12.97
Cyan	19.17	13.76	8.66	6.14	25.89	11.93
White	3.60	1.88	3.26	4.59		3.34
MacBeth Neutrals	6.80	4.25	1.38	3.41	9.49	3.96
Q60 Cyan	29.45	3.60	21.89	21.92		19.22
Q60 Magenta	21.26	14.38	20.00	22.34		19.50
Q60 Yellow	48.20	16.18	25.09	41.05		32.63
Q60 Neutrals	18.57	16.87	0.68	3.58	0.87	9.92
Neutral 8	10.39	9.23	0.76	2.28		5.67
Neutral 6.5	8.09	5.06	1.14	2.56		4.21
Neutral 5	5.41	3.14	1.73	4.77		3.76
Neutral 3.5	5.14	1.03	3.03	4.23		3.36
Black	6.09	3.20	1.70	3.54	8.97	3.63
Q60 Black	10.11	2.45	0.60	2.67		3.96
N 1	35.70	35.36	2.04	1.80		18.72
N 3	30.12	31.21	3.09	3.32		16.94
N 5	20.70	23.63	1.65	4.93		12.73
N 7	17.66	18.41	1.77	6.37		11.05
N 9	17.15	15.99	1.88	4.45		9.87
N 11	16.69	14.49	0.07	4.69		8.99
N 13	16.22	14.60	1.20	3.75		8.94
N 15	13.53	13.39	1.97	4.16		8.26
N 17	14.29	12.52	0.45	3.26		7.63
N 19	14.73	7.12	1.19	1.62		6.16
Average	14.47	12.40	6.11	12.38	18.28	11.34

[10] Due to the nature of original colors for the Pantone system, these values have not been included in these averages

Glossary

achromatic	Perception of a color having no saturation or hue such as neutral gray, this roughly correlates with lightness.
bit	The smallest unit of information storage having a value of either 0 (zero) or 1 (one), representing off or on. The term evolved from **Bi**nary Digi**t**.
bit **depth**	Determines the number of distinct numerical values (colors) a single pixel can display. Only one color can be displayed at a time by one pixel. Number of colors = $2^{\text{bit depth}}$.
black generation	See grey component replacement
brightness	Relates to the relative intensity of light illuminating an object. Higher intensities are said to be bright and lower intensities are said to be dull.
color	That aspect of things that is caused by differing qualities of the light reflected or emitted by them. It may be defined in terms of the observer (sense a), or of the light (sense b): **a.** The appearance of objects or light sources described in terms of the individual's perception of them, involving *hue*, *lightness*, and *saturation* of objects, and hue, *brightness*, and saturation for light sources. **b.** The characteristics of light by which the individual is made aware of objects or light sources through the receptors of the eye, described in terms of dominant wavelength, luminance, and purity.[11]
	Perception of an observer due to the interaction of three components of light: source, object and observer.
gamma	The non-linearity response of signal changes in a monitor display. This equates to the fact that equal changes in the signal for a specific color do not result in equally detectable changes in the color.

[11] The American Heritage Dictionary of the English Language, editor William Morris, Houghton Mifflin Company, 1976

gamut	The total set of colors a device is capable of producing.
Grey Component Replacement (GCR)	An extension of UCR, this system is no longer limited to the replacement of cyan, magenta and yellow in the grey and black areas, but has been expanded to any area where all four colors are being utilized. See Under Color Removal.
hue	The scale of perception, appearance, or color family such as: red, green, blue and yellow.
illuminance	Measurement of light emitted by a source which falls on an object which is being observed
lightness	The tendency of a color towards white, gray or black which is an actual property of the object
luminance	Reference to the amount of light emitted by a display or any light source which the observer is looking at.
metameric	Two colors of distinctly different power distributions appear the same under defined lighting conditions. This is achievable if and only if the area under the power distribution curves of the two observed colors within the spectral sensitivity of the different types of cones is the same.
Moiré pattern	Undesired detectable pattern caused by incorrect choice in screening angles
monochromatic	Imaging dealing with only one color and its intensity.
Pixel	Picture element, the smallest addressable unit within an image.
Primary Color	One of a set of colors which, when combined in different amounts, yields a full spectrum of colors.
Process Color	Color created through the combination of one or more of the primary colors in varying intensities.
Saturation	The vibrancy of a color, the intensity.
Screening Angles	The angle at which lines of the various colors are placed on paper. The difference between the various colors is usually 30°, but can be altered based on the application and/or printer in use.

Spot Color — Specific color created by preblended inks. No other colors are over printed by the press in an area where a spot color is specified.

UnderColor Removal (UCR) — Within the black or grey portion of an image where all four inks are being used to create the desired color, undesirable results can surface due to the abundance of inks. In an effort to reduce and/or eliminate this problem some of the cyan, magenta and yellow are removed and replaced with (extra) black.

WYSIWYG — Pronounced ("wiz ee wig"), this acronym stands for **W**hat **Y**ou **S**ee **I**s **W**hat **Y**ou **G**et. This concept applies to the theory that when a system (software and hardware combination) are said to be WYSIWYG that what you see on your screen is what will be produced on your output device.

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